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How can the grasslands under rainfall events modify water balance in drought conditions

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Abstract

Taking into account the well-established influence of hillslopes grasslands on runoff processes, the purpose of this study was to investigate how grasslands can affect the water flow pathways on hillslopes, in drought conditions. This study was performed in experimental grassland at plot-scale (e.g., *Festuca pratensis*), in temperate humid continental climatic conditions of Curvature Subcarpathians, Romania. The rainfall, evapotranspiration, and soil moisture daily data, respectively 208 rainfall and 16 rainfall-runoff events data measured in grassland hills during the growing season (1 April up to 30 September 2015 and 2016) were used. Our results suggest that a runoff event response in extreme drought conditions occurs on grasslands only if precipitation exceeds the threshold of 31 mm Hortonian overland flow (HOF), while this threshold drops to 17 mm during moderate droughts and up to 8 mm for wet conditions. The rainfall events up to 16 mm proved to be insufficient to completely saturate the soil. Therefore, HOF has only a minor contribution in drought conditions, on grassland and light on bare soil. A complementary and negative effect of grasslands in drought conditions is the water resources suppressing on hillslopes.

Key words: *grasslands, hydrological drought, plot-scale, rainfall-runoff events, water flow pathways*

INTRODUCTION

Hillslope grasslands are sensitive area to rainfall events. One of the major hydrological challenges that have dominated experimental hydrology for many years concerns the hydrological behaviour of land use and land cover change [CERDA *et al.* 2018; HOLKO, LEPISTÖ 1997; LATRON *et al.* 2003; MACLEOD *et al.* 2013; STANCIU, ZLATE-PODANI 1987]. Over the past decades, increasing drought phenomena [KHEZAZNA *et al.* 2017], coupled with heavy rainfall events have produced severe extreme hydrological processes (e.g.,

flash floods) [WARWADE *et al.* 2018]. The climate changes (decrease in the amount of precipitation and a large increase in air temperature and evapotranspiration) recorded in the 21st century in southern Europe, favoured increased frequency and magnitude of drought episodes and heavy rainstorm events [BĄK, KUBIAK-WÓJCICKA 2017; DAI 2013; VICENTE-SERRANO *et al.* 2011]. In this context, the hydrological investigate of secondary grasslands can provide a good information about runoff generation processes and water resources.

In the last few decades, extensive studies have been conducted on identify of runoff variation under changing environment (e.g., land use) at different scale. Few studies regarding runoff generation have been carried out in small catchments (e.g., HOLKO, LEPISTÖ [1997]; LATRON et al. [2003]; BROCCA et al. [2008]; MIȚĂ, MĂTREAȚĂ [2016]) and on field or laboratory experimental plots (e.g., DE LIMA, SINGH [2002]; IONIȚĂ et al. [2006]; SCHERRER et al. [2007]; GHOLAMI et al. [2014]; MARZEN et al. [2015]; MINEA et al. [2015]; ABRANTES et al. [2017]; DUAN et al. [2017]). Scientists have examined the hydrological effect of grasslands (e.g., HORTON [1919]; BLIDARU [1965]; FULLEN [1992 1998]; MAETENS et al. [2012]; MACLEOD et al. [2013]; JOYCE et al. [2016]) and suggested that grasslands can regulate both runoff and soil erosion, by trough their potential to intercept rainfall [HORTON 1919; MACLEOD et al. 2007], so called „biological flood control measure" [JANKOWSKA-HUFLEJT 2006]. DE LIMA and SINGH [2002] observed that local rainfall patterns (uniform, intermediate, advanced, and delayed) are important in determining the peak discharges and hydrograph shapes of the overland flow hydrograph. SCHERRER et al. [2007] conducted a field-plot study to evaluate the factors influencing the dominant runoff processes. Their findings have revealed that runoff formation can be influenced by a complex interaction of factors (e.g., infiltration rate, soil water storage, and drainage of soil moisture). Runoff ranging from 2% to more than 90% of the applied rainfall rate was reported. To investigate the runoff formation along the hillslopes transects, SCHMOCKER-FACKEL et al. [2007] used sprinkling (1 m^2) and/or infiltration experiments with a double ring infiltrometer. One of the results of this study, besides maps of the dominant runoff processes, is that runoff formation during intense precipitation is immensely variable and that the interactions involved are complex. In previous work, MINEA et al. [2015] investigated the role of land use in the dynamics of water resources on a soil-water balance plot following 2014 natural spring rainfalls. Their results showed that the "bare soil" creates heterogeneous conditions for the runoff surface, such as micro-depressions, and thus flow rates have been reduced in comparison to those recorded on the "grassland" soil water balance plot.

However, there is limited information about the relationship between rainfall and grasslands with respect to the water flow pathways on/along grassland hillslopes in drought conditions during natural rainfall. In general, these studies were focused on the runoff process, but failed to identify the hydrological behaviour of grasslands under storm events in dry conditions. The aim of this work was to obtain a greater understanding of the hydrological effect/behaviour on water flow pathways of grasslands in drought conditions (dry periods) under natural rainfall events and to determinate a rainfall event threshold triggering runoff. Due to practical constraints (e.g., catchment heterogeneity), this paper cannot provide

an upscaling approach, but we still continue working to find a solution. Therefore, a key issue that will need more attention in the future is transferring data plot to catchment scale [BLÖSCHL, SIVAPALAN 1995]. Our hypothesis is that grassland can generate a regular runoff, but we want to know under drought conditions, which are rainfall event thresholds triggering the runoff. Also, we want to determine grassland effect over successive rainfall events and how can grasslands change water balance. In this respect, our work is focused on rainfall thresholds for runoff process at the plot-scale (soil water balance plots), with the aim of experimentally investigating mechanisms of driving runoff and the role of land use under dry conditions in the Curvature of Subcarpathians, Romania.

EXPERIMENTAL DESIGN AND SAMPLING

GEOGRAPHICAL FRAMEWORK

This study is conducted on experimental plot-scale situated in the Voinești Experimental Basin – VEB, instrumented in the 1960s, at an elevation of 500 m a.s.l. and it is under administration of National Institute of Hydrology and Water Management. From a geomorphologic viewpoint, the study area is located in Curvature Subcarpathians (hilly region) precisely on the left side of Dâmbovița River (Fig. 1a), highly exposed to erosion [MIRCEA et al. 2015; ZAHARIA, IOANA-TOROIMAC 2009]. The principal land use of VEB is grassland (67%) dominated by perennial grass, e.g., Festuca pratensis, Centaurea cyanus. The secondary land use is forest.

The soil is described as a Luvosoil, being composed of 51% sand, 21% silt, and 28% clay [MAFTEI et al. 2002]. According to the Köppen System for climate classification, Curvature Subcarpathians are described by "Dfb" subtype or temperate humid continental climate [PEEL et al. 2007].

Based on observations in 1980–2016, the average evapotranspiration on grassland and bare soil, are 487 mm·yr^{-1} and respectively 351 mm·yr^{-1}. Average multi annual precipitation and average air temperature (1980–2016) are 818 mm (± 192 mm) and 9.8°C, respectively. Most rainfall events (63%) occur in the warm/growing period (April–September), and the highest number of rainfalls was recorded in summer, from June (12.5%) to July (12.3%). July is the wettest month receiving an average of 100 mm with a standard deviation (SD) = 64 mm, while February is the driest, with 40.1 mm, SD = 26 mm precipitation.

Important water resources from rainfall in July – the month with maximum pluviometric regime, were concentrated, while a high incidence of short rainfall events (rain shower) was specific for May. Heavy and severe storm events are rare (few episodes per season) and are specific to late summer-early autumn [MINEA et al. 2016]. The highest monthly evapotranspiration measured on bare soil and on grassland occurs in June
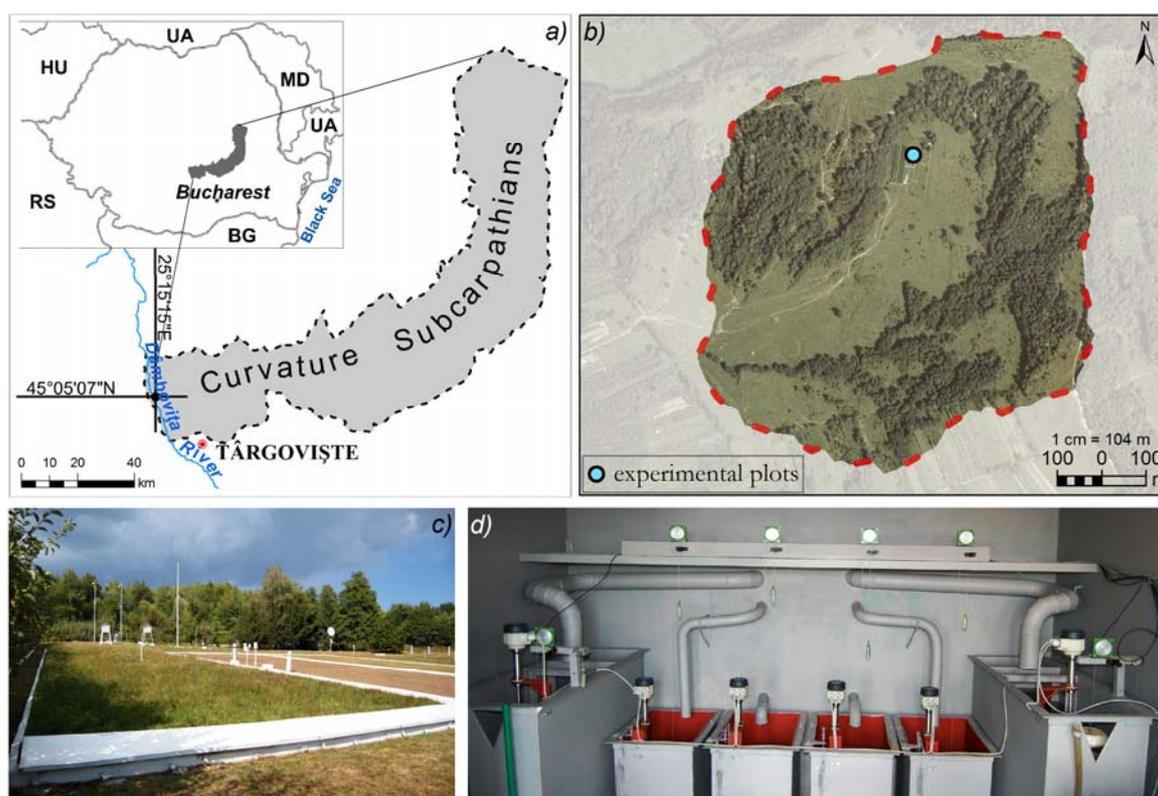
Fig. 1. Site diagram: study area and its location in Curvature Subcarpathians (a), VEB and experimental plot setup (b), "grassland" water soil balance plot (c), and shelter house equipped with calibrated tanks and water level sensor (d); source: own elaboration

(126 mm) or July (72.4 mm) when the climatic conditions favours the increasing of transpiration for both soil and plants [STAN *et al.* 2014]. The highest monthly evapotranspiration values correspond to the driest months [OUDA *et al.* 2015], according to the standardized precipitation evapotranspiration index (*SPEI*) values [VICENTE-SERRANO *et al.* 2010]. For VEB, the *SPEI*-12 months showed that the interval June–August 1980–2016 was characterized by a moderate drought and severe drought until 2011, and by an extreme drought after 2011 [SPEI 2017].

SAMPLING AND FIELD MEASUREMENT

The equipment has been installed for small experimental plot study in the centre of the VEB (Fig. 1b). The terminology of water flow pathways introduced by SCHERRER *et al.* [2007] has been used: Hortonian Overland Flow (*HOF*), SubSurface Flow (*SSF*) or interflow and Deep Percolation (*DP*) or Base Flow. The main elements of water balance events investigated in this study are defined in Table 1.

Rainfalls were collected by a pluviometer (24 h rainfall amount – mm) at the height of 1.5 m above the ground. The daily accumulated rainfall during 24 hours (07–19–07 h; local time Eastern European Summer Time – ESST), from an IMC – Romanian precipitation storage gauge (reception area 200 cm^2, at 1.5 m above the ground) were investigated. Rainfall events data were collected and recorded by tilting-si-

Table 1. Abbreviations, definitions, and units for the main parameters used to characterize water balance events

Abbreviation	Parameter definitions	Unit
ETR	evapotranspiration defined by the amount of soil water lost to the atmosphere via evaporation from the ground surface and from the plant leaves	mm day^{-1}
P	rainfall depth (meaning the entire amount of rainfalls during a rainfall event)	mm
I$_{max}$	maximum intensity of *P*	mm min^{-1}
R	runoff (overland flow; subsurface flow and base flow) expressed as the maximum discharge (*Q*$_{max}$), volume (*V*), or total depth (*R*$_{td}$)	*Q*$_{max}$, dm^3·s^{-1} *V*, dm^3 *R*$_{td}$, mm
R$_{ai}$	rainfall average intensity of *P* is the *P* divided by the time of duration	mm min^{-1}
SVC	volumetric soil moisture content (θ_v)	m^3·m^{-3}
RC	runoff coefficient is the ratio between *R* and *P*	
ETR$_g$	grass evapotranspiration	mm day^{-1}
ETR$_b$	bare soil evapotranspiration	mm day^{-1}

Source: own elaboration.

phon gauge (pluviograph), production of the former USSR. MINEA *et al.* [2016] described the mechanism and specifics of this pluviograph. For rainfall-runoff analysis, we used only rainfall events defined by precipitation ≥ 0.2 mm and where there was no precipitation for the following 1 hour.

Soil moisture content – determination of soil water content in grassland is important for water bal-

ance calculation. Our study uses daily volumetric soil moisture content (θ_V), indirectly acquired through field measurements (use of electromagnetic signals to measure the permittivity of the soil (ε) by operating a Delta-T Profile probe, type PR2/6 and its technical operation procedure [DELTA-T 2016]. To provide soil moisture data an epoxy access tube was installed in the grassland of the VEB. Soil moisture content was measured daily around 9:00 ESST, in the upper 1 m of the soil layer – depths starting at 0.10 m and up to a 1.00 m of the soil profile; other measurement depths were 0.20, 0.30, 0.40, and 0.60 m.

Evapotranspiration was measured by using a lysimeter, based on the changes of the soil mass. For this study, the evapotranspiration (*ETR*) was measured by using two large soil tanks (G1 lysimeters) with 1 m² surface area (circular section) and 1.5 m depth; one lysimeter measures the *ETR* of the grass (Photo 1b) and the second lysimeter measures the *ETR* of the bare soil. The amount of water lost by evapotranspiration is calculated by taking the difference between the weight before and after the precipitation input, daily at 7:00 ESST.

Runoff – for water flow pathways measures (overland flow, subsurface flow, and base flow) a pair soil water balance plots were used. Soil water balance plots (SWBP's) cover an area of 300 m² (*L* = 30 and *l* = 10 m), with a slope = 13%, *S* aspect and 500 m a.s.l. (Fig. 1c). The land use of the plots falls in the following categories:

1) grasslands – corresponding to secondary perennial grass – *SWBPg* (Fig. 1c; Photo 1a); the *SWBPg* were never grazed, but herbage was cut (in July), according to traditional practices; the average height of grasses surrounding the *SWBPg* was about 40 cm and a dense superficial network of grass roots-dominated in the top ~20 cm of the soil;

2) bare soil or "working soil" plot was kept spade under bare soil through manually digging in spring, which consists of tilling with a long-handled shovel to ~20 cm deep, creating microdepressions that enable rainfall water infiltration and retention of eroded soil, and regular application of the herbicide treatments (*SWBPb*).

The area of the plots was bordered by an impervious (concrete) wall, a number of collection channels composed of gutters, underground pipes (subsurface flow and base flow), and at their lower part, there were shelters containing calibration water tanks with drainage installation for evacuated water. The concrete walls were dug in at a depth of 1.50 m and raised above ground by 0.20 m. To stop rainfall collection and its influence on the collecting channel, these were protected by metal caps. Data about subsurface flow were collected from a depth of 0.40 m (after effective root zone Photo 1c, and sandy clay Bt horizon) and base flow was measured at a depth of 1.30 m [BLIDARU 1965], using hydrometrical devices (e.g., water tank; water level sensors: OTT SE 200 model; see Fig. 1d) and the volumetric method $V = f(H)$, previously described by MINEA and MOROȘANU [2016]. Rating curve $Q = f(H)$ were used to determine overland flow discharges.

DATA AND METHODS

Data in our study includes of daily depth rainfall, evapotranspiration depth, volumes of soil moisture content, and runoff event elements (depths, discharges and volumes), and rainfall event elements (depths, duration, intensities) respectively from 1 April up to 30 September 2015 and 2016 (two consecutive dry seasons).

The data have been subject to individual quality control procedures of the Institutul Național de Hidrologie și Gospodărire a Apelor – National Institute of Hydrology and Water Management (NIHWM). Unfortunately, for technical reasons (e.g., water infiltration through a concrete wall, land use management), we were unable to use the subsurface flow and base flow database over a larger period.

Missing data were identified in the time series of rainfall events and soil moisture content. These errors were due to incorrect processing and consisted of the temporal continuity of a rainfall event, between two sequences (rainfalls with 1-hour break). After data check operation, the series (rainfall data) were divided into events. For soil moisture data in rainy days (1 or 2 days periods) with no measurements (missing data value) or with an ambiguous quality of records, we used an interpolation method following the protocol described by HOTTENSTEIN *et al.* [2015]. According to previous studies, the soil moisture data were interpolated by averaging the soil moisture values from the first measured values on dates before and after missing data.

Photo. 1. Grass from the soil water soil balance plot (a) lysimeter (b) and root system (c) in VEB; phot. *G. Minea, F.-I. Stan, G. Niță*

ANALYSIS METHODS

From the point of view of field experiment method, these are often used to measure *in situ* daily rainfall, soil moisture contents, and evapotranspiration data, rainfall-runoff events (overland flow, subsurface flow, and base flow or deep percolation). Supplementary details about the field and devices are given by STAN *et al.* [2014], MINEA and MOROSANU [2016].

The methodological approach chosen for this study is a mixed design based on water balance equation. To detect the hydrological influence of grasslands on drought conditions, the periods and drought intensity were identified. An indicator used to identify long-term drought periods (e.g., minimum 1 month) was *SPEI*.

For soil water statute (deficit or excess), an indicator called daily soil water balance (*DSWB*) was chosen. The *DSWB* is based on the water balance equation and takes into account: rainfall, evapotranspiration, and soil water reserve. All the water input are expressed in mm. According to RODRÍGUEZ-BLANCO *et al.* [2012], firstly, the rainfall minus outflow (*P* and *ETR*) was calculated to represent the soil water available for each day (Eq. 1) and secondly, the soil water balance for each day (mm) was calculated to tell on whether there is a surplus or a deficit (Eq. 2).

$$P - ETR_g = \pm \Delta S \qquad (1)$$

Where: P = amount of rainfall (mm); ETR_g = amount of grass evapotranspiration (mm); ΔS = amount of soil storage change, plus = increase, minus = decrease (mm).

$$DSWB = \Delta S_{PSD} - \Delta S_{PVD} \qquad (2)$$

Where: $DSWB$ = daily amount of soil water balance; ΔS_{PSD} = present-day amount of soil storage; ΔS_{PVD} = previous-day amount of soil storage.

DSWB allowed quantitative estimation of hydrological soil deficit and identification of drought periods (intensity/asperity). Further, *DSWB* was classified by using percentiles, and reclassified as follows: extreme drought, moderate and wet. The severity degree of rainfall-runoff events was studied when compared to drought periods.

STATISTICAL ANALYSIS

Rainfall, soil moisture content, and runoff elements for water flow pathways (e.g., volumes, discharge), Standard deviation and coefficient of variation were condensed in tables and represented in graphical form including discharge, amounts, comparison of runoff volumes, runoff coefficients (*RC*). Correlations and other types of analysis using the descriptive statistics (e.g., location and variability: percentiles, skewness and kurtosis as numerical measures of the shape of data) were calculated.

In order to understand how grasslands can affect the water flow pathways at microscale in drought conditions, 208 rainfall events, and 16 natural experiments (rainfall–runoff) were studied. Hydrological grasslands effects were assessed based on soil water balance elements and *RC*. Depending on rainfall event size, we identified a pluviometric threshold of hillslope runoff generation.

All analyses of the water balance data were conducted by using OriginPro 9.3 software [OriginLab 2016].

RESULTS AND DISCUSSION

For the period of 2015–2016, rainfall events, rainy days, *ETR* and drought periods with different intensity/rates, respectively rainfall-runoff events were registered. Runoff events were individualized both by land use, water flow pathways, and through *RC*. To investigate the relationship between grassland and rainfall (daily and events data), we first used descriptive statistics. Tables 2 and 3 reflect the water resources variability of this study.

GROWING SEASON 2015

The data of the rainfall events revealed non-periodic variability of the number of days with precipitation in alternation with drought periods (meteorological droughts), and few extreme rainfall (highest rainfall events).

We found 59 rainless days (32.2% during the analyzed period) with the longest dry periods: August, July, and September with 13, 12 and 11 consecutive days without any rain. The most severe dry periods during the drought were from the second half period of July to September (exceptional in terms of its duration and intensity), when corresponding soil moisture content deficits increased. On a monthly scale, the maximum number of rainy days (35.5%) were recorded in September and June (155.3 and 103.9 mm) and the minimum in July (11.1 mm). The lowest daily rainfall was recorded in the lower quartile (the 25th percentile mark) (minimum 0.2 mm in April and 0.25 mm July), while an important increase was noticed by the third quartile (maximum 23 mm in September followed by 14.7 mm in June) (Tab. 2 a). In September, a wet period with 7 rainfall days (128.3 mm) produced important runoff on hillslopes and flash floods. The *ETRg*, between April and September 2015 was 567 mm, while the evapotranspiration on bare soil was only 246.3 mm. The maximum daily evapotranspiration for the bare soil was measured in June (7 mm·day^{-1} on 06 June 2015) and for the grassland in July (9 mm·day^{-1} on 08 July 2015). Daily values of evapotranspiration vary more significantly for the bare soil (Cv = 0.8–1.1), than for the grass (Cv = 0.4–0.8), due to the fact that the bare soil lost supplementary water, more quickly the covered soil retained the water for a longer period of time. The monthly evapotranspiration on grassland values started to increase from 65 mm·month^{-1} (in April) to 121 mm·month^{-1}

Table 2. Descriptive statistics of monthly rainfalls, soil moisture content and evapotranspiration at VEB (2015 and 2016)

Parameter	Rainfall (mm)						Soil water content (m³·m⁻³)						Evapotranspiration (mm)											
													grassland						bare soil					
	IV	V	VI	VII	VIII	IX	IV	V	VI	VII	VIII	IX	IV	V	VI	VII	VIII	IX	IV	V	VI	VII	VIII	IX
	2015																							
Mean	3.49	5.52	7.99	1.41	7.79	15.53	0.354	0.362	0.370	0.359	0.340	0.333	2.2	3.7	3.7	3.9	2.0	1.1	0.8	1.5	1.3	1.0	1.1	0.9
SD	3.54	7.55	8.72	2.50	9.51	14.98	0.005	0.005	0.017	0.014	0.005	0.017	1.0	1.3	1.9	2.2	1.2	0.9	0.7	1.2	1.4	0.9	1.1	1.0
Sum	34.9	55.2	103.9	11.3	62.3	155.3	10.6	11.2	11.1	11.13	10.5	9.98	65.0	116.1	99.1	121.2	60.8	33.6	24.6	45.7	37.6	32.2	35.6	27.0
Skewness	0.59	1.75	1.05	2.65	1.26	0.74	1.834	1.618	0.318	0.469	0.047	3.23	0.3	-0.9	0.2	0.5	-0.1	1.1	1.0	1.0	3.2	0.9	0.8	1.6
Kurtosis	-1.36	1.65	-0.61	7.15	0.93	-0.47	3.874	2.857	-0.202	-1.266	-0.772	11.3	-0.3	0.8	-0.8	-0.4	-1.1	1.6	0.5	0.7	13.3	0.3	-0.6	2.6
Cv	1.01	1.37	1.09	1.77	1.22	0.96	0.014	0.013	0.047	0.040	0.016	0.051	0.5	0.4	0.5	0.6	0.6	0.8	0.9	0.8	1.1	0.8	1.0	1.1
Minimum	0.10	0.50	0.90	0.10	0.20	0.20	0.347	0.357	0.340	0.341	0.331	0.320	0.5	0	0.7	0.7	0	0	0	0	0	0	0	0
1st quartile	0.20	1.70	1.50	0.25	0.55	4.20	0.350	0.359	0.358	0.347	0.336	0.324	1.5	3.0	2.0	2.0	1.0	0.5	0.4	0.5	0.5	0.5	0.1	0
Median	2.45	2.20	3.70	0.45	3.60	12.2	0.353	0.361	0.369	0.354	0.340	0.329	2.4	4.0	4.0	3.5	2.0	1.0	0.75	1.0	1.0	0.8	0.7	0.6
3rd quartile	6.50	4.30	14.7	1.15	13.6	23.0	0.355	0.363	0.382	0.371	0.344	0.333	2.8	5.0	5.0	6.0	3.0	1.6	1.0	2.5	1.7	1.8	1.8	1.6
Maximum	8.80	21.5	24.4	7.50	26.6	44.0	0.369	0.377	0.408	0.386	0.350	0.403	4.6	6.0	7.0	9.0	4.0	3.8	2.5	5.0	7.5	3.3	3.7	4.0
P90	8.80	19.6	22.1	7.50	26.6	38.25	0.360	0.370	0.396	0.379	0.347	0.345	3.5	5.0	7.0	6.1	3.0	2.15	1.85	2.7	2.4	2.0	2.8	1.95
P99	8.80	21.5	24.4	7.50	26.6	44.0	0.369	0.377	0.408	0.386	0.350	0.403	4.6	6.0	7.0	9.0	4.0	3.8	2.5	5.0	7.5	3.3	3.7	4.0
	2016																							
Mean	6.8	4.6	6.5	4.5	8.1	19.9	0.382	0.403	0.403	0.356	0.343	0.348	1.28	2.57	4.61	2.85	1.92	1.32	1.7	1.6	1.9	1.1	1.2	1.2
SD	6.5	5.5	7.8	4.9	8.1	39.9	0.012	0.018	0.023	0.011	0.011	0.023	0.71	1.11	1.64	1.25	0.78	0.49	0.8	0.7	1.2	1.5	0.6	0.6
Sum	75	87.4	85.1	31.8	56.7	159.1	11.45	12.49	12.08	11.04	10.63	10.44	38.4	79.7	138.3	88.3	59.4	39.5	50.6	50	58.2	35.1	35.9	34.9
Skewness	1.5	1.4	1.8	1.0	1.4	2.7	1.493	0.532	0.321	-0.973	1.579	0.349	0.41	1.38	0.41	0.52	0.63	0.40	0.2	0.4	0.7	5.1	0.3	0.8
Kurtosis	1.6	0.7	3.6	-1.0	1.6	7.2	1.575	-1.184	-0.456	1.509	1.918	-1.564	-0.54	3.27	-0.92	0.42	0.14	-1.18	-0.6	-0.5	-0.2	27.6	-1.6	-0.2
Cv	1.0	1.2	1.2	1.1	1.0	2.0	0.032	0.044	0.058	0.031	0.033	0.066	0.56	0.43	0.36	0.44	0.41	0.37	0.4	0.4	0.6	1.3	0.5	0.5
Minimum	0.1	0.1	0.5	0.1	0.2	0.3	0.370	0.378	0.370	0.322	0.333	0.322	0.2	0.6	2.2	1.0	1.0	0.5	0.3	0.3	0.3	0.2	0.5	0.2
1st quartile	3.4	0.8	1.4	0.4	2.0	0.4	0.373	0.389	0.386	0.349	0.335	0.325	0.7	2.0	3.2	2.0	1.0	1.0	1.1	1.1	0.9	0.6	0.5	0.8
Median	4.8	1.8	3.6	2.7	5.3	3.2	0.377	0.395	0.401	0.356	0.341	0.338	1.25	2.4	4.5	3.0	2.0	1.0	1.65	1.4	1.9	0.9	1.0	0.9
3rd quartile	7.6	7.4	11.8	11.3	14.0	17.3	0.387	0.419	0.418	0.366	0.344	0.373	1.7	2.8	6.2	4.0	2.0	2.0	2.3	2.0	2.8	1.0	1.8	1.5
Maximum	21.0	16.9	27.5	11.6	23.7	117.0	0.412	0.434	0.457	0.372	0.375	0.385	2.7	6.1	7.9	6.2	4.0	2.0	3.2	3.0	4.7	9.0	2.0	2.5
P90	17.1	16.1	12.9	11.6	23.7	117.0	0.404	0.430	0.434	0.369	0.358	0.380	2.35	3.8	6.8	4.0	3.0	2.0	2.8	2.6	3.9	1.1	2.0	2.1
P99	21.0	16.9	27.5	11.6	23.7	117.0	0.412	0.434	0.457	0.372	0.375	0.385	2.7	6.1	7.9	6.2	4.0	2.0	3.2	3.0	4.7	9.0	2.0	2.5

Explanations: *SD* = standard deviation; *Cv* = coefficient of variation; 1st quartile = 25th percentile; 3rd quartile = 75th percentile; P90 = 90th percentile; P99 = 99th percentile.
Source: own study.

Table 3. Characteristics of the main rainfall events during the growing season (2015 and 2016)

No. events	Time (day.month.year hour: minute)		Duration (min)	D (mm)	I_{avg}	I_{max}
					mm·min^{-1}	
1	5.06.2015 19:20	5.06.2015 20:00	40	17.8	0.445	0.900
2	25.05.2015 18:00	25.05.2015 20:40	160	20.8	0.130	1.040
3	17.06.2015 2:00	17.06.2015 5:10	190	24.5	0.129	0.140
4	27.06.2015 7:20	27.06.2015 21:20	840	24.0	0.029	0.220
5	31.07.2015 22:00	1.08.2015 1:40	220	31.0	0.141	0.587
6	28.09.2015 00:30	28.09.2015 12:00	690	27.9	0.040	0.100
7	28.09.2015 13:10	29.09.2015 11:00	1310	35.9	0.027	0.100
8	1.06.2016 1:20	1.06.2016 7:00	340	29.8	0.088	0.260
9	21.04.2016 6:00	21.04.2016 11:00	300	35.3	0.118	0.700
10	13.05.2016 2:50	13.05.2016 6:20	210	16.4	0.078	0.540
11	16.07.2016 02:30	16.07.2016 03:40	70	10.2	0.146	0.700
12	19.09.2016 8:20	19.09.2016 11:10	170	47.5	0.259	0.513
13	20.09.2016 0:00	20.09.2016 13:40	820	78.0*	0.100	0.420
14	25.09.2016 14:40	25.09.2016 15:50	70	16.0	0.229	0.400

Explanations: D = depth; I_{avg} = average rainfall intensity; I_{max} = maximum intensity rainfall; * = this rainfall event had two peaks. Source: own study.

(in July), whereas the bare soil evapotranspiration varied from 24.6 mm·month^{-1} (in April) to 45 mm·month^{-1} (in May); both parameters were decreasing until September (less than 34 mm·month^{-1}) due to the lower air temperature and higher air humidity (Tab. 2).

During growing season, 91 rainfall events characterized by insignificant depths (e.g., for the 95th and 75th percentiles where 24.3 mm and 5.75 mm, respectively time 667.5 min for the 95th and 170 min at 75th percentiles) were recorded. Rainfall events ranged in depth from 0.20–35.9 mm over 10–1310 min with low average intensity, 0.004–0.445 mm·min^{-1}. Exceptional rainfall events occurred on 28–29.09.2015, with a depth about 63.8 mm (27.9 mm over 690 min on 28.09 and 35.9 mm over 1310 min on 29.09); 1.04, by a depth of 31 mm over 220 min; 25.05 by a depth de 20.8 mm over 160 min; 6.06, by a depth 17.8 mm over 40 min. In Table 3, the main elements of rainfall events from the study, which generated runoff in growing season 2015/2016, are centralized.

GROWING SEASON 2016

Time series of daily rainfalls showed drought periods (meteorological droughts), rainfall days and few extreme rainfalls (highest rainfall events).

We found 118 rainless days (64.5% during analysed period) with 3 long driest periods: i) beginning of April with 10 days; ii) the last two decades of July and the beginning of August (24 days); iii) the last decade of August and the first two decades of September (31 days). The most severe dry periods during the drought were August to September (exceptional in terms of its duration and intensity) and corresponding to highest deficits of soil moisture content.

Generally, the number of rainy days (35.5%) was highest in May (19 days; 87.4 mm) and lowest in July (7 days; 31.8 mm) – August (7 days; 56.7 mm). The lowest daily rainfall was emphasized by lowest quartile (minimum 0.4 mm in July and September) and by an important increase to the third quartile (maximum 17.3 mm in September) – Table 2. Statistically (location and variability), the lack of symmetry was visible by skewness and kurtosis values despite data constraints available for short periods (Tab. 2). The number of rain-days with soil moisture content excess was greatest in May (19 rain-days with 6 rain-days consecutive). On 20–21 September 2016, an extreme rainstorm led to a significant runoff on the hillslopes and flash floods (e.g., on 20 September of 117 mm, of which 81.8 mm fell between 00:00 and 13:40 ESST). *ETR*, between April and September 2016, was approximately 200 mm higher on grass soil than from the bare soil, the greatest difference being registered between May and August (Tab. 2). Daily values did not vary significantly from one day to another (*ETR*s, $Cv = 0.6$; *ETRg*, $Cv = 0.4$) – Table 2. The maximum possible daily value attained during the growing period for grassland was 7.8 mm·day^{-1} (22.06.2016), while for bare soil it was 4.7 mm·day^{-1} (8.06.2016). These differences could be due to the water loss by evaporation. The grassland evapotranspiration started to increase from April to July, from 50 mm·month^{-1} to 130 mm·month^{-1}, and then it decreased until attending 40 mm·month^{-1} in September, in accordance with the air temperature variation and humidity annual distribution.

Regarding rainfall events, during the growing season, 117 rainfall cases occurred. Compared to 2015, these events were characterised by insignificant depths (e.g., for the 95th and 75th percentiles where 16 mm and 3.53 mm, respectively; lifetime 295 min for the 95th and 80 min for 75th percentiles). Rainfall events ranged in depth from 0.2 to 81.8 mm over 10–910 min with low maximum intensity, and average intensity 0.004–0.430 mm·min^{-1}. Exceptional rainfall events occurred similarly to 2015, in September.

Thus, persistent heavy rains from 19–20.09.2016 recorded the most considerable depths of 125.8 (81.8 mm over 820 min on 20.09). This rainfall had two peaks: first time 00:00–04:30, depth = 42.8 mm; second time: 05:00–13:40, depth = 39 mm); 44 mm over 170 min on 19.09); 20.04 with a layer of 35.3 mm over 300 min; 1.06 with a depth 29.8 mm over 340 min; 17.08 with a layer of 22.48 mm over 70 min (Tab. 3).

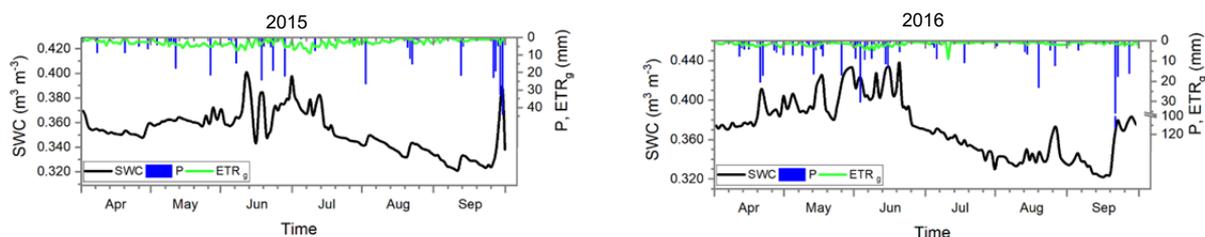**The effect of soil water storage due to daily rainfall.** Soil moisture content – higher precipitation

Fig. 2. Daily values of soil water content (*SWC*), rainfall (*P*) and grass evapotranspiration (*ETRg*) during the growing season (from April 1 up to September 30) of 2015 and 2016 in VEB; source: own study

Table 4. Runoff characteristics for all rainfall-runoff events on *SWBP*'s during growing seasons 2015–2016

Number and data events		P (mm)	θ_v (m³·m⁻³)	Runoff volume (dm³) in water flow pathways						RC	
				$HOF^{\cdot}$	HOF_*	$SSF^{\cdot}$	SSF_*	$DP^{\cdot}$	DP_*	$SWBPg^{\cdot}$	$SWBPs_*$
1	25.05.2015	20.8	0.358	10	215.2	3.75			515	0.00	0.12
2	06.06.2015	17.8	0.360	6	242			0.5	670	0.00	0.17
3	17.06.2015	24.5	0.355	2.5	7.5				171	0.00	0.02
4	27.06.2015	24.0	0.374	1.5	3.5	107.7		204.5	3044	0.00	0.42
5	31.07.2015	31.0	0.341	14.8	1994	17	2.5	16.25	85	0.00	0.22
6	21.04.2016	17.3	0.352				3	67.5	1253	0.00	0.12
7	13.05.2016	16.7	0.387	4.43	16.2	31			191	0.00	0.04
8	16.05.2016	7.6	0.424	13.2	1.97	28.5			203	0.00	0.09
9	24.05.2016	17.0	0.394	2.95		5		4.8	14,3	0.00	0.00
10	30.05.2016	8.8	0.405	8.36	132					0.00	0.05
11	02.06.2016	30.4	0.420	1770	1738					0.01	0.19
12	17.07.2016	11.0	0.354	1.48					40	0.00	0.01
13	19.09.2016	47.5	0.322	7.38	2452	5.5	35		24,2	0.00	0.18
14	20.09.2016	42.0	0.353	3.94	7310	100	37.7		225,3	0.00	0.60
15	20.09.2016	36.0	0.384	261	3524	475	342	1682	2958	0.01	0.63
16	25.09.2016	16.8	0.368				7.25	27.8	801	0.00	0.16

Explanations: P = rainfall event depth; θ_v = moisture soil content-antecedent condition; *HOF* = Hortonian overland flow, *SSF* = subsurface flow, and *DP* = deep percolation (base flow); *RC* = runoff coefficients; *SWBP* with subscript land use = soil water balance plot, and g$^{\cdot}$ = grassland, s$_*$ = soil; an empty cell is an event without flow.
Source: own study.

period juxtaposed with lower evapotranspiration in April–June was higher in the first part of the studied period (Fig. 2). Over the favourable pluviometric period (21.04–19.06.2016), a daily maximum soil moisture content occurred on 19.06.2016 reaching a water content of 0.457 m³·m⁻³. The wettest conditions occurred on 21.04 (0.412 m³·m⁻³) and 30.05 (0.434 m³·m⁻³). After the longest dry period, the highest rainfall event on 20–21.09 led to an important amount of infiltration and soil moisture content increase (0.042 m³·m⁻³) of 384 mm. Drought periods (including light precipitation) and higher evapotranspiration in summer months triggered a strong deficit in soil moisture. The pronounced long driest conditions occurred on 24.06 up to 18.09 (maximum 0.322 m³·m⁻³) and also on 30.07 up to 15.09 2016 (Fig. 2).

WATER FLOW PATHWAYS AT THE PLOT-SCALE

Using *DSWB*, we quantified the hydrological soil deficit and identified drought intensity. In order to identify the triggering and dominant runoff processes at the plot-scales in hydrological drought conditions (extreme, moderate and wet) we studied 208 rainfalls and a 16 rainfall-runoff events that occurred in growing season, during drought episodes of 2015 and 2016.

Hydrological characteristics of the analysed rainfall-runoff events are presented in Table 4, while here, it is worth mentioning that only 16 natural rainfall events (7.7%) had the capacity to generate a hydrological response (13 rainfall events produced Hortonian overland flow – *HOF*, 11 rainfall events produced subsurface flow – *SSF* and 14 produced deep percolation – *DP*), at least on one of the water flow pathways.

Extreme drought conditions. Two rainfall-runoff events in extreme drought conditions (θ_v = 0.322 m³·m⁻³ and θ_v = 0.341 m³·m⁻³), generated by 2 extreme heavy rainfall events 47.5 mm (19.09.2016), respectively 31 mm (31.07.2015), showed similar conditions of water flow pathways. In the case of *HOF*, the largest amounts of runoff on bare soil were 17.2% for the first event and 21.4% for the second one. Most of the runoff (82.4%, respectively 78%) was distributed in the porous soil (θ_v = 0.362 m³·m⁻³, θ_v = 0.350 m³·m⁻³), the infiltrating water passing to the groundwater or to the storage. The grassland effect associated with extremely dry conditions has shown that runoff minimizes all water flow pathways and close quantitative values (*HOF* 0.16%; *SSF* 0.18%; *DP* 0.17%, for second events), otherwise *RC* was expressive in this case (0.01). The rainfall events with 16.8 mm depth did not produce a hydrological response to drought conditions.
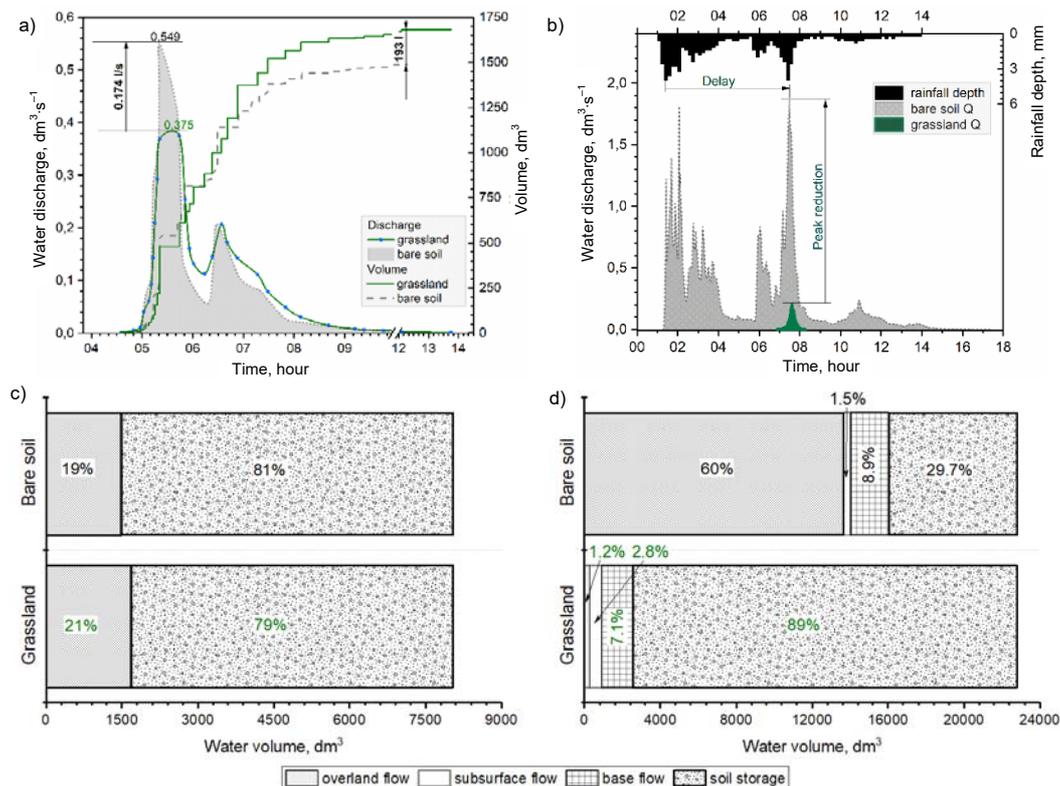
Fig. 3. Rainfall events hydrographs of discharge and volume (lag time, peak discharge, mass curve) for: a) Hortonian overland flow (*HOF*), 2.06.2016, b) *HOF*, 20.09.2016, c) water volume pathways on soil water balance plots (*SWBP*), 2.06.2016, d) *SWBP*, 20.09.2016; source: own study

Moderate drought conditions (θ_v = 0.345 m³·m⁻³ … θ_v = 0.368 m³·m⁻³). The rainfall-runoff events of this drought category have revealed the role of rainfalls size and intensity and of land use. Runoff events for 20.8 mm rainfall were characterized by unimportant values of runoff coefficients (0.12 for bare soil and 0.001 for grass cover) e.g., on *SWBPg*, in the case of *HOF* and *DP* these did not generate runoff, while the *SSF* volume was 3.75 dm³; a similar effect was observed on *SWBPs* – high water storage; and permeability of topsoil for *SSF*. Main runoff features were: the decrease of *HOF* on *SWBPg* (*RC* = 0) and even the absence of runoff comparative on *SWBPs* (*RC* = 0.12).

A second rainfall-runoff event consisted of a heavy rainfall with 17.8 mm depth (40 min; R_{ai} = 0.445 mm·min⁻¹) and revealed the same runoff conditions, highlighted by runoff processes occurrence for *HOF* (Fig. 3). This highly torrential rainfall (I_{max} = 0.900 mm·min⁻¹), but weaker start than above, highlights the influences over the conditioning of surface water formation and rain intensity. However, on *SWBPs* there was a high capacity of soil water retention (low volume and discharge of *HOF*, for duration of 40 minutes) compared to *SWBPs* (high volume and discharge of *HOF*, for a duration 60 minutes), *RC* = 0.17 *to SWBPg*, *RC* = 0.17 to *SWBPs*.

Light drought (wet) conditions ($\theta_v \geq$ 0.370 m³·m⁻³). In September (19–20.09.2016), high runoff was comprised of two consecutive heavy rainstorms events with rainfall reaching 125.5 mm. These rainfalls caused three successive major runoff events

(20.09.2016), and the first peak (47.5 mm) of the rain were considered responsible for the increase in the soil–surface moisture content and for the runoff generation. Subsequently, a heavy rainfall on 20.09.2016 (42 mm, 36 mm and cumulated 78 mm; see Tab. 3) produced massive runoff, especially for the second runoff events, with double peak hydrographs for bare soil (Fig. 3b). In terms of water flow pathways, we observed a preferential flow for *DP* (which was identified as the dominant process on the bare soil) and *SSF* (especially on bare soil, with negligible volumes) (Fig. 3d).

The present study shows that, in drought conditions, values of rainfall depth events have varied suggestively (Tab. 2), secondary grasslands have modified the soil water balance and attenuated *HOF* peaks, and both land use patterns retain much of the rainfall stored in the soil. In this context, the following questions are to be asked:
1) how can secondary grasslands modify soil water balance (1ˢᵗ)?
2) can the secondary grasslands attenuate *HOF* over successive rainfall events (2ⁿᵈ)?

1. We appreciate that in drought conditions, in particular in extreme conditions, rainfall event characteristics (e.g., rainfall intensity), in relation to grassland (e.g. vegetation phenology, root-depth, decayed and live plant roots), can play a decisive role in water balance. Also, the storage capacity of the soil remains a function of the porosity, which can control short-term storm and storage capacity.
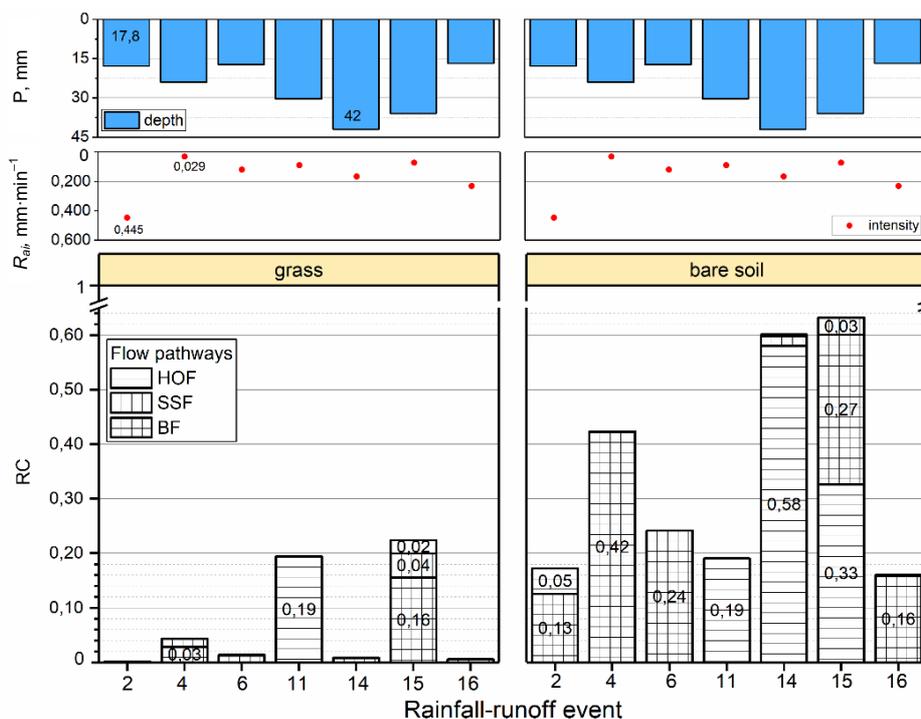
Fig. 4. Rainfall depth (*P*) and average intensity of rainfall event (*R_ai*), and associated runoff coefficients (*RC*),
HOF = Hortonian overland flow, SSF subsurface flow, BF = base flow;
note: rainfall–runoff number of events corresponds to the number from Table 4; source: own study

For the studied events, we have noticed that the grassland exerts a strong and similar retention effect on the water flow pathways in time spread, peak plot-hydrographs of *HOF*, and runoff coefficients (Fig. 3). In fact, in extreme dry conditions a rain of 16.8 mm depth or more could be totally retained in the soil. Otherwise, the most visible discharge element, peak discharge, was for the *HOF* grassland in most cases attenuated and lagged (see example Fig. 3a, b). Thus, we consider that for these conditions, rainfall events with a layer less than 16 mm can certainly improve the hydric soil deficiency and the hydric stress of the grass. Under low drought conditions (wet), grassland capacity for interception, retention, and drain coefficients, decreases, and volumes for *HOF* were higher than bare soil (see Fig. 3c, d).

However, we can say that the grass effect manifest as diminishing peak discharges, and even more; the infiltration has prompted that *DP* discharge to be dominant in both land use types. In general, by observing the quasi-total retention of rain, especially for *HOF*, from the point of view of the formation of water resources, in extreme dry conditions, it was possible to ascertain the negative effect of the secondary grasslands in the dry conditions in the suppression of water resources on hillslopes.

2. As regards the hydrological attenuation capacity of *HOF* over the successive rainfall events, from the data analysed, it is reasonable to assume that successive rainfall events can generate a runoff, but we have thoroughly found the following: (i) grass can reduce *HOF* during events up to 90% as compared to bare soil (e.g., see 14 event from Fig. 4); (ii) the

length and intensity of rainfall events is a key factor (see Figure 3 c, d; Fig. 4). Certainly, it was observed that after a dry period (September 2016), 3 storm events contributed to the restoration of moisture content, and secondary grassland had high potential of precipitation redistribution, to regulate the runoff in *HOF* (minor runoff, strong *Q_max* and reduced runoff coefficients; see Fig. 4). The particularity of the secondary grassland influence on the runoff is noted at the *SSF* level, where the most important volumes are specific on the grassland. In contrast, the *DP* response was substantial – preferential flow (see 15 rainfall-runoff event from Fig. 4).

In addition, we need to strongly assess the relationship between rainfall events, storm events in particular, under dry conditions, with respect to water flow pathways. In the present work, we found that the rainfall-runoff response did not help to adequately explain and predict the water flow pathways process. Further work is necessary to improve rainfall-runoff data sets (more storm events to study, more sprinkler experiments) that cover all periods with vegetation phenology in extreme dry conditions.

CONCLUSIONS

In this research, we aimed to investigate how secondary grassland can affect the runoff generation in drought conditions on hillslopes at plot-scale. The runoff generation on flow pathways (Hortonian overland flow (*HOF*), subsurface flow (*SSF*) or interflow and deep percolation (*DP*)) in drought conditions after heavy rainfalls turned out to be a complex process.

The runoff generation process and the identification of the water flow pathways on hillslopes during drought are not easily explained. Our investigation revealed that the differing runoff coefficients and water flow pathways (like *HOF*) of land use (grasslands vs. bare soil) under given drought conditions in relation to natural rainfall events can be better understood by carrying out some extended experiments.

In temperate continental climate, we found that runoff processes on secondary grassland hillslopes under drought conditions are governed by high infiltration and, secondly soil storage. Also, hydrologic differences in runoff formation on different land use types (grasslands vs. bare soil) were observed.

Importantly, in extreme drought conditions, only rainfalls of 31 mm have ability to produce runoff (*HOF*), and decreases to 17 mm for moderate drought and to 8 mm for wet conditions. These thresholds were conditioned by the duration and intensity of precipitation. From 208 rainfall events that have occurred with different depths and intensities, only 16 of them (7.7%) generated runoff.

The results showed that rainfall events of low intensity infiltrate into the soil. Rainfall event characteristics was followed in importance by the type of land use, which was highly responsive to minor runoff events in drought conditions.

The rainfall events up to 16 mm were insufficient to completely saturate the soil. Therefore, we observed a minor contribution of *HOF* on grassland and a slight one on bare soil. In severe drought conditions, slightly larger volumes of *HOF* and *DP* were drained on bare soil. Soil-water deficiencies limited water flow pathways, especially for SSF.

On bare soil, important water volumes were accumulated in matrix and macropores, followed by delayed gravity drainage to the base flow.

Grasslands affected the water flow pathway, *HOF* in particular. Grasslands have reduced the discharge peak and most of the water volumes, comparatively with bare soil conditions. These circumstances can be explained by interception and retention followed by water absorption in the root layer and soil water storage. A complementary and negative effect of grasslands in drought conditions is the suppression of water resources on hillslopes.

The obtained results allowed a preliminary identification of water flow pathways by showing the dominant runoff processes and the influence of temperate grasslands on runoff process on hillslopes. Answers to some key questions remain open regarding the hydrological interaction between grasslands and soil in drought conditions, such as if a linear relationship between rainfall and runoff exists for the grassland and if this relationship can be used to predict water flow pathways.

However, in order to reach a good understanding of hydrologic grasslands effects at plot-scales, further analyses extended to large data sets from growing seasons are needed.

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W jaki sposób użytki zielone w okresie opadów mogą modyfikować bilans wodny w warunkach suszy

STRESZCZENIE

Biorąc pod uwagę dobrze znany wpływ użytków zielonych na stokach na odpływ wody, celem było zbadanie, jak te siedliska mogą wpływać na drogi przepływu wody w warunkach suszy. Badania prowadzono na eksperymentalnych poletkach porośniętych na przykład przez *Festuca pratensis* w warunkach umiarkowanie wilgotnego klimatu kontynentalnego na Pogórzu Karpackim w Rumunii. Do analizy użyto dane o opadach, ewapotranspiracji i wilgotności gleby (208 danych o opadach i 16 kombinacji opad–odpływ) pozyskanych z pomiarów na pagórkach pokrytych roślinnością trawiastą w sezonie wegetacyjnym od 1 kwietnia do 30 września w latach 2015 i 2016. Uzyskane wyniki wskazują, że odpływ w warunkach skrajnej suszy występuje w siedliskach trawiastych jedynie wtedy, gdy opad przekroczy wartość 31 mm powierzchniowego odpływu Hortona (*HOF*). Wartość *HOF* maleje do 17 mm w warunkach umiarkowanej suszy i do 8 mm w warunkach wilgotnych. Okresy opadów do 16 mm okazały się niewystarczające do całkowitego nasycenia gleby. Z tego powodu przepływ powierzchniowy ma w warunkach suszy znikome znaczenie w siedliskach trawiastych i niewielkie na odkrytej glebie. Komplementarnym i ujemnym skutkiem występowania użytków zielonych jest ograniczenie zasobów wodnych na stokach.

Słowa kluczowe: *drogi przepływu wody, poletka badawcze, susza hydrologiczna, użytki zielone, zdarzenia opad–odpływ*