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Land use impact on overland flow: micro-scale field experimental analysis

Gabriel MINEA¹⁾ ABCDEF, Gabriela IOANA-TOROIMAC²⁾ CDEF

¹⁾ National Institute of Hydrology and Water Management, Bucharest, Romania; e-mail: gabriel.minea@hidro.ro

²⁾ University of Bucharest, Department of Meteorology and Hydrology, Faculty of Geography, Bucharest, Romania

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Abstract

The objective of this paper was to experimentally investigate the hydrological effect of land use on overland flow at micro-scale.

The research was based on field experiments made with stationary and expeditionary measurements on runoff plots. Plots are located in the Curvature Subcarpathians, form part of the Aldeni Experimental Basin (Romania) and cover an area of 80 m². The land is covered with perennial grass and bare soil. The experiments in this field were performed under natural and simulated rainfalls. The plots data (rainfall and discharges) obtained during the experiments conducted in the warm semester (IV–IX) and one artificial rainfall (1 mm·min⁻¹) were used. Significant variations in hydrological responses to rainfall rates were identified for the two land uses. On average, overland flow parameters on runoff plots covered with grasses were reduced to maximum 28% for discharges and to 50% for volumes while in the case of simulated rainfalls, the runoff rates were significantly increased on the bare soil plot. Grasses have a very important function as they cover and protect the soil and slow down the overland flow.

Key words: *fields experiment, grasses, micro-scale, overland flow, runoff plots*

INTRODUCTION

Land use changes, abandonment and degradation of the hydrotechnical and pedoameliorative works (bench terraces, slope stabilization), under aggressive pluvial conditions are disturbance factors of hydrological processes [CALDER 1992; FOHRER *et al.* 2001].

Grasses (graminoids) are one of the conditional factors of the surface runoff or Hortonian overland flow process [MUSY, HIGY 2010; VAN DE GIESEN *et al.* 2011]. BENAVIDES-SOLORIO and MACDONALD [2001] showed that graminoids are notable for high infiltration rates, low values of overland flow and reduced erosion rates.

Therefore, in hydrological terms, the listed processes and factors play a major role in water balance [LVOVICH 1980].

In USA, hydrological studies have been based on experimental data obtained at plot scale even since 1920 [HUDSON 1993] – 1930's [HAYWARD 1967] and have contributed to understanding interrelations between rainfalls and runoff processes. The importance of the study performed on runoff plots at a hydrological micro-scale: 1 cm² → 1 km² [BECKER, NEMEC 1987; HUDSON 1993] consists in the possibility to control genetic factors (rainfalls) and the integration or extrapolation of the results obtained at the crop rotation or slopes level and small catchments [BLOSCHL, SIVAPALAN 1995; HAYWARD 1967; MUTCHLER 1963; TOEBES, OURYVAEV 1970; VÖRÖ-SMARTY *et al.* 1993].

In the specialized literature, many papers show that runoff plots have been used in various studies, such as: pedological (to predict erosion and soil loss)

by MOȚOC *et al.* [1975], IONIȚĂ *et al.* [2006], MIRCEA *et al.* [2010; 2015], MAETENS *et al.* [2012]; hydrological: PETRESCU [1974], STANCIU [2002], YU *et al.* [1997], BENAVIDES-SOLORIO, MACDONALD [2001], JOEL *et al.* [2002]; forestry by ABAGIU *et al.* [1973], HARTANTO *et al.* [2003]; biological factors [WAINWRIGHT *et al.* 2000]; ecologic by GBUREK and SHARPLEY [1998], DEBANO [2000], COVINO *et al.* [2010], ATUCHA *et al.* [2013].

In Romania, after the 1990s, the consequences of changing the land ownership in accordance with the Land Law No 18/1991 – amended and supplemented, had also an impact on the hydrological sector [MUICĂ, ZĂVOIANU 1996]. Because of the land use conversion, the massive parcelling of agricultural lands – which were “often processed following a hill-valley direction” [MIRCEA *et al.* 2010], the abandonment of pedoameliorative works, particularly on slopes and in small catchments, amplified the severity and the intensity of extreme hydric phenomena [CHENDEȘ *et al.* 2010; COSTACHE 2014; ZAHARIA *et al.* 2015].

Within this study, there were preliminary quantified hydrological parameters at micro-scale level (runoff plots) of overland flows on two types of land uses: grassland vs. bare soil.

DATA AND METHODS

GEOGRAPHICAL FRAMEWORK

In this paper, experimental hydrological data (rainfalls and runoff) at plot scale, measured in a stationary programme and field experiments throughout 2014 at the Aldeni Experimental Basin (45°19'30"N latitude and 26°44'43"E longitude) were used.

The experiments were carried out at the Aldeni Experimental Basin (AEB), which is located in the hilly region of the Curvature Subcarpathians, near Buzău City, Romania (Fig. 1A). Specifically, AEB represents the determination of the surface runoff and the infiltration parameters during natural and simulated rainfalls; research of genetic runoffs and soil erosion processes [MINEA, MOROȘANU 2016]. The geomorphological region of the Curvature Subcarpathians is characterized by high torrentiality, strong soil erosion and the highest sediment transport of rivers in Romania [COSTACHE *et al.* 2014; MOȚOC 1984; RĂDOANE 2005; ZAHARIA *et al.* 2011].

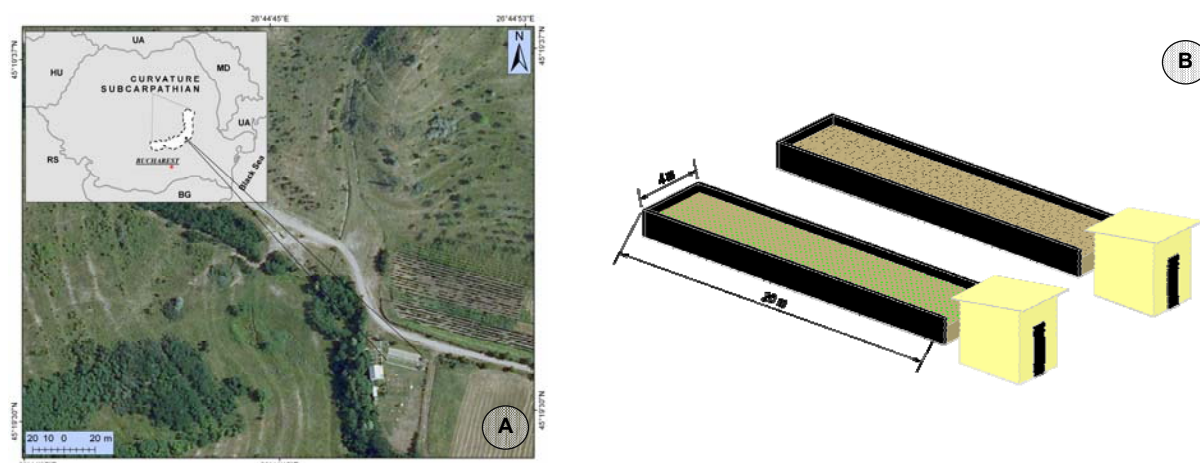


Fig. 1. Geographical location of the Aldeni Experimental Basin (A) and design of runoff plots (B); source: own elaboration

AEB's characteristics are: (i) moderate temperate-continental climate with a mean annual precipitation of 550 mm (with a pluviometric maximum occurring in June), and a mean annual temperature of 9.5°C (for the period 1983–2013); (ii) the soil of the plots is “colluvic alluviosoil” and it was formed by the deposit of parental materials resulted from colluvio-deluvial deposits and it comprises the following physico-chemical characteristics (0–60 cm depth): clay content (33%), humus (3.28%), phosphorus (24%) and pH = 7.2 – a neutral reaction – mildly alkaline [MUȘAT 2006; RADU *et al.* 2010]; (iii) the current land use is grassland-specific, with lands covered with perennial grass vegetation (e.g. graminoids of *Festuca*, *Poa* and *Agrostis species*), partial abandonment and/or unproductive orchards; from 1982 to 1990, the catchment underwent controlled anthropogenic inter-

ventions resulting in hydrotechnical (dams, drains) and agrotechnical works (terracing, the plantation of fruit trees and shrubs) in order to reduce soil erosion; at present, these anti-erosion works are damaged while the hydrological effect amplifies diffused (wavy) overland flow.

EXPERIMENT DESIGN

In order to investigate the hydrological effect of land use on the runoff of a hilly area in Romania, a hydrological study at a micro-scale level on runoff plots was performed. The field experiments were conducted under natural and simulated rainfalls.

Runoff plots cover an area of 80 m² (20 m × 4 m), with a slope of 5.6% and WNW-ESE aspect. In terms of land cover, the runoff plots mimic the local land

use. The land of the first plot (P1) was covered 100% with a typical vegetation pattern, graminoids (*Festuca*, *Poa* and *Agrostis* – the main mass of roots is in the 10–20 cm soil layer) (Fig. 2A); while the second

plot (P2) is maintained without the protective herbaceous cover, only by hoeing the superficial soil layer of 20 cm depth (Fig. 2B).



Fig. 2. Experimental rainfall on runoff plots P1 (A) and P2 (B); source: own elaboration

TERMINOLOGY

In this paper, specialized terms were used with the following abbreviations: R_e – rainfall event (meaning the entire amount of rainfalls during a rainfall event – depth in mm or hp in mm); R_a – average intensity of R_e (is the R_e divided by the time of duration – $\text{mm}\cdot\text{min}^{-1}$); R_m – maximum intensity of R_e in $\text{mm}\cdot\text{min}^{-1}$; overland flow expressed as the maximum flow rate (Q_{\max} in $\text{l}\cdot\text{s}^{-1}$), the total drained volume (V_t in m^3), total depth (Dt – mm or hs in mm); maximum specific flow (q_{\max} in $\text{l}\cdot\text{s}^{-1}\text{ km}^2$) and the runoff coefficient R_c – the ratio between rainfall depth (R_e) and runoff depth (R_t).

DATA COLLECTION AND ANALYSIS

Rainfall and overland flow parameters were cumulative measured and continuously recorded (e.g.: pluviographs, tipping bucket rain gauge; limnigraphs) starting from the warm semester IV–IX 2014 (April to September), when precipitation events represented 67% of the multiannual average (1983–2013).

The reading of the diagrams (pluviograms and limnigraphs) allowed the identification of the duration and depth of the rainfall and overland flow events. Hydrological measurements were performed using tank collector which stored the whole quantity of water. The calibrated tanks were equipped with water stage recorders such as limnigraphs (mechanic shaft encoder) and radar sensors. Water level measurements were transformed into flow rate by a calibration curve $V = f(H)$ and $Q = f(H)$. The data measurement and processing methodology was applied according to the guidelines and instructions of the National Institute of Hydrology and Water Management [ADLER, MINEA 2014; MUSTAȚĂ 1973]. These data are used for hydrologic analyses.

In order to extend the data base a portable rainfall simulator with nozzles was used. The simulation of

rainfall on runoff plots allowed obtaining of hydrological experimental data in a shorter period, under special rainfalls with high intensity [HUMPHRY *et al.* 2002; MEYER, MCCUNE 1958; TOSSELL *et al.* 1987]. Regarding the research conducted since 1930 and involving the use of the rainfall simulator [HUMPHRY *et al.* 2002; SUKHANOVSKII 2007], it allowed the performance of successful research activities focused on micro-scale studies of surface runoff rates, erosion, etc. These tools also have limitations in terms of performance, surface, etc. [HUDSON 1993; MEYER, MCCUNE 1958], while certain drawbacks occur because of the uneven distribution of rain per plot, caused by technical malfunctions (e.g. conduit and nozzles sanding).

Evaluation was performed on rainfall and runoff data (e.g. percentile rank, determination coefficient – R^2) to detect the hydrological effect for each type of land use. All graphics and statistical analysis of hydrological data, was made with OriginPro version 9.3.

The results obtained during the experiments were interpreted, underwent first-stage processing, validated and/or invalidated (error data) and then structured and divided into two categories: rainfalls and overland flows.

RESULTS AND DISCUSSION

RAINFALLS

To quantify the production of overland flow from different land uses: grasslands (with perennial grass) and bare soil (the soil is hoeing) on runoff plots, the daily rainfalls: within 24 hours (A), rainfalls events (B), and artificial rainfalls (C) of the warm semester (IV–IX) of 2014 were analysed.

(A) The sum of precipitation reached 758 mm (67% of annual precipitations), ranging from excessive periods (June–July) to shortfall periods (August–September); in pluviometric terms, the largest

quantities fell accidentally in April (131 mm), while June, the month with the pluviometric maximum, summed up 112 mm; the number of rainy days ranged from 4 (August and September) to 16 (June); the categories of these cumulated rainfalls were predominately thin: 37% of the precipitations were of 5 mm or less; 31% were of 10 mm or less; 14% were of 15 mm or less; 11% were of 20 mm or less and only 7% exceeded 25 mm; the box and whisker diagram (Fig. 3A) highlights August (39.8 mm·day⁻¹, 24 IX – the maximum recorded quantity), June and July (27 mm·day⁻¹, 3 VI and 10 VII) with extreme values while May registered an unstable rainfall regime (Fig 3A).

- (B) The rainfall events that determined the overland flow were characterized by the following parameters: (i) the medium layer (hp) of 9.49 mm while the maximum value reached 26.6 mm on 9 VII (Fig 3A); in pluviometric terms, the quantity of 52% of the rainfalls was insignificant (hp < 10 mm) while 48% of them may be deemed as moderate (hp ≥ 10–25 mm); (ii) the average duration was of 177 minutes (up 10 to 610), which indicates the rare downpour nature of rainfalls; (iii) the medium intensity (I_{med}) was encoded with the value of 0.120 mm·min⁻¹, and the maximum average value was established at 0.670 mm·min⁻¹ (13

IV) (Fig 3B); as regards the maximum intensity (I_{max}) of a rainfall, it reached 1 mm·min⁻¹ (e.g.: 0.980 mm·min⁻¹ on 9 VII and 0.890 mm·min⁻¹ on 16 VIII), while the rest of the period predominantly registered lower values of 0.100 mm·min⁻¹.

- (C) The use of the mobile system to generate a controlled amount of artificial rainfalls, during expeditionary campaigns, enabled the successful extension of the data series, in order to know their hydrological behaviour under extreme rainfall conditions; artificial rainfalls were used on both runoff plots, with an average intensity of 1 mm·min⁻¹; the characteristics of these rainfalls (depth and duration) were measured and recorded using an automatic tipping bucket rainfall collectors (RG3-M type, resolution: 0.2 mm) at 1.5 m elevation interception and by collecting the droplets at ground level (0.2 m) in 10 containers, with a collecting surface of 0.02 m² and placed at equal distances (Fig 3A); on runoff plot P1, the artificial rainfalls was distinguished by a strong vegetal retention while on runoff plot P2, the highest values of the rainfall layer at ground level were measured on the upper part of the plot and the lowest on the lower part (Fig 3A); at ground, the rainfall layer irregularity was found.

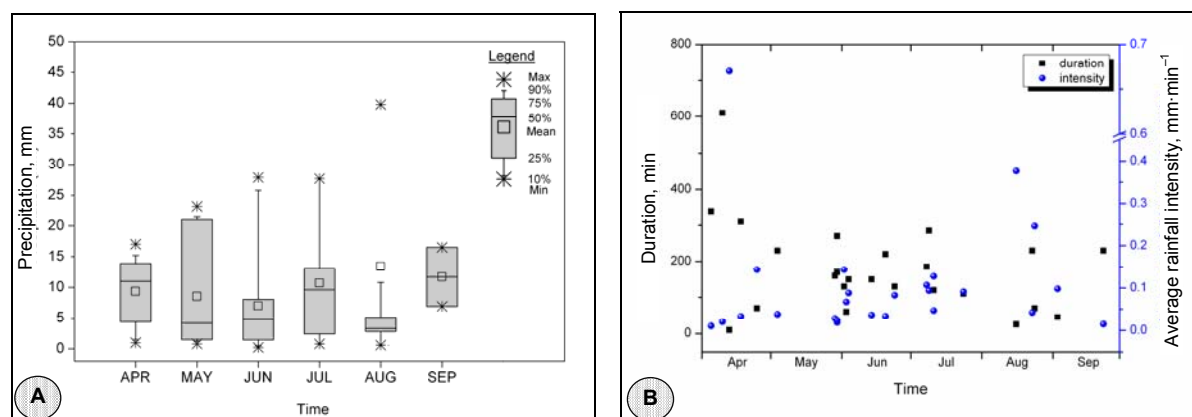


Fig. 3. Frequency distribution of rainfall days (A) and rainfall event parameters (B) of the warm 2014 semester in the Aldeni Experimental Basin; source: own study

OVERLAND FLOW

Hydrological data investigation points out the land use effect, with dissimilar features, both for P1 and P2. Quantitatively, the different amount of water between rainfall depth (R_e) and runoff depth (R_r) consists in the infiltrated water, in the case of P2. Specifically, the difference between the two layers (R_e and R_r), was found in P1, where could not be clearly determined the percentage of the water infiltration mass and the one of the mass of the water intercepted by grasses or lost due to evaporation. In this case, a general indicator (G) was used, which integrates infiltrated water, water intercepted by vegetation and water evaporation.

Rainfall events have not always caused runoffs on both runoff plots, because the rainfalls regime favoured the development of perennial vegetation and thus the grasses cover effect resulted in the reduction or cancellation of overland flow on P1, especially for the rainfalls with hp < 10 mm. Before the occurrence of the overland flow, the initial state of the soil was wet.

Overland flow occurs only when natural rainfall rates exceed vegetation retention, in the case of P1 and soil infiltration rates for P1 and P2. Overland flow events are different as number and especially in water discharge rates. The total number of the overland flow events was 16 on P1 and 26 on P2. The most significant hydrological effects of the average

land use (Tab. 1) were reported for the following parameters:

- time, total time events for overland flow were relatively symmetric; differences were found at limb and falling rise; average time of rising limb was of 52 min (54 min for P1 and 49 min for P2) and 123 min on falling limb (103 min for P1 and 148 min for P2); comparing the liquid runoff on P1 and P2, under similar rainfall conditions (the layer of the rain was of 18.6 mm), the temporal gap in generating the maximum flow (Fig. 4B) is pointed out;
- maximum discharges were strongly attenuated; significant quantitative differences being reported: $1.2 \text{ m}^3 \cdot \text{s}^{-1}$ on P2 and $0.364 \text{ m}^3 \cdot \text{s}^{-1}$ on P1;
- water volumes were reduced by 58% (0.513 m^3 on P1 and 0.882 m^3 on P2);
- water depth medium on P1 was reduced by 49% (4.9 mm on P1 and 10.1 mm on P2).

Runoff rates from artificial rainfall on runoff plots show that in case of high rain values, the hydrological elements are controlled by land use. Thus, runoff rates increased by over 200% (e.g. maximum discharge was higher by 235%) on a runoff plot with land devoid of vegetation (P2). Obviously, the attenuation role of the herbaceous layer on P1 was determined by the lowest runoff rates and the time gap of the flows rise.

The results of the attempt to identify and establish interdependence between the rainfalls layer (hp) and that of the runoff (hs), outlined: a relatively random dispersion of quantitative variables (insignificant correlation; diagram of spreading the hp and hs data sets (Fig. 4A), where P2 suggests a linear correlation characterized by a high level of interdependence $R^2 = 0.80$).

Table 1. Hydrological summary of the main characteristics for five selected runoff events

Rainfall event	Runoff plot	Initial soil humidity condition	Time, min			Hydrological parameters						
			total	rise	fall	Q_{\max} $\text{l} \cdot \text{s}^{-1}$	V m^3	D mm	q_{\max} $\text{l} \cdot \text{s}^{-1} \cdot \text{km}^{-2}$	R_c	I mm	G mm
I	1	moist	70	20	50	0.057	0.294	3.68	712.5	0.22	–	13.3
	2		160	10	150	2.5	0.436	5.45	31 250	0.32	11.5	–
II	1	wet	190	100	90	0.106	0.270	3.38	1 325	0.23	–	11
	2		165	41	124	0.542	0.902	11.30	6 775	0.78	3.10	–
III	1		210	113	97	0.50	0.698	4.56	6 250	0.17	–	22
	2		380	146	234	1.08	0.820	10.20	13 500	0.39	16	–
IV	1		230	18	212	0.42	0.799	6.94	5 250	0.50	–	7.06
	2		220	10	210	0.63	0.952	7.46	7 875	0.53	6.54	–
V*	1	dry	60	20	40	0.74	0.507	6.33	9 250	0.317	–	13.7
	2		60	11	49	1.74	1.300	16.20	21 750	0.464	18.7	–

Explanations: * = artificial rainfall; 1 = perennial grass covered, 2 = bare soil; Q_{\max} = maximum discharge; V = total volume of runoff; D = total depth of runoff; q = specific maximum flow; R_c = runoff coefficient; I = total depth of infiltrated water; G = global term that integrates infiltrated water, vegetation water intercepted and water evaporation.

Source: own study.

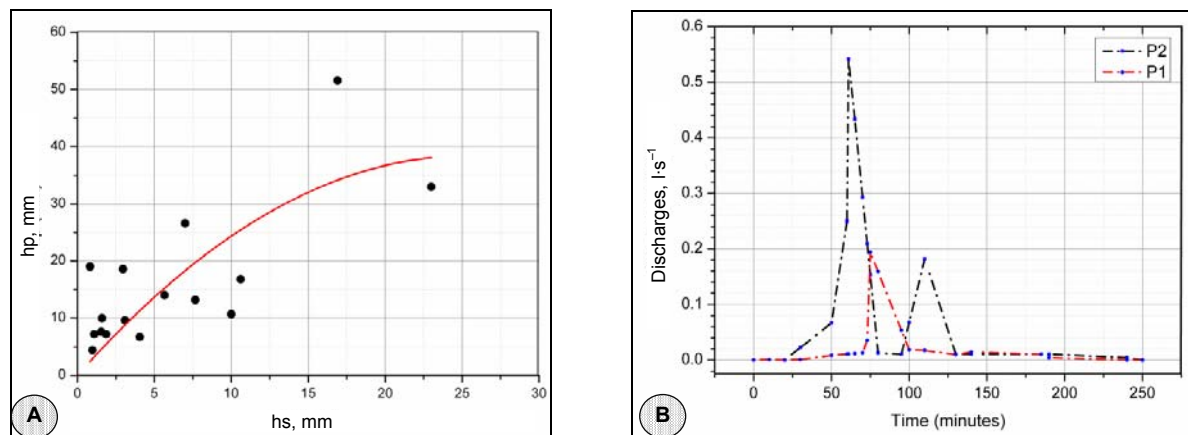


Fig. 4. The relation between rainfalls (hp) and runoff (hs) for P2 (A) and the surface runoff on P1 and P2 (B); source: own study

CONCLUSIONS

The results of experimental investigations contributed to understanding hydrological processes at micro-scale, under the land use effect.

The obtained results have a preliminary character and show that the formation and transmission of the overland flow on runoff plots is genetically conditioned by precipitations depth size while being strictly dependent on previous rainfall conditions, soil moisture and vegetation water storage capacity.

On runoff plots, the overland flow recorded the maximum intensity in April, June, and July, when the largest amounts of water fell, often in the form of downpour rain. Scarce rainfalls of low intensity quantitatively heavy rains, under dry initial soil moisture conditions, do not have the capacity to generate overland flows. The particularity of the runoff is also conditioned by the pheno aspects sequence. Grasses cover has the very important function of slowing down the runoff. The highest water flow rates, layers, and volumes drained on P2 runoff plots.

The data series obtained, especially for P1; do not allow establishing correlations (e.g. hp–hs) of high precision. In order to identify and establish correlations between genetic and control factors of the overland flow, it is necessary to continue conducting field experiments during the warm semester of 2016.

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Gabriel MINEA, Gabriela IOANA-TOROIMAC

Wpływ użytkowania ziemi na spływ powierzchniowy: analiza polowego eksperymentu w skali mikro

STRESZCZENIE

Słowa kluczowe: doświadczenie polowe, poletka do pomiaru odpływu, skala mikro, spływ powierzchniowy, trawy

Celem badań było doświadczenie zbadanie wpływu użytkowania ziemi na spływ powierzchniowy w skali mikro. Badania prowadzono w ramach eksperymentu polowego realizowanego metodą stacjonarnych i ekspedycyjnych pomiarów spływu z poletek. Poletka znajdują się w łuku pogórza Karpat, stanowią część eksperymentalnego Basenu Aldeni (Rumunia) i mają powierzchnię 80 m². Pokrywają je wieloletnie trawy lub sama gleba. Eksperymenty prowadzono w warunkach naturalnego i symulowanego opadu. Do badań użyto danych (opad

i odpływ) uzyskanych w eksperymencie prowadzonym w półroczu letnim (kwiecień–wrzesień) oraz z zastosowaniem sztucznego deszczu ($1 \text{ mm} \cdot \text{min}^{-1}$). Stwierdzono istotne zróżnicowanie reakcji hydrologicznej na wielkość opadów między dwoma sposobami użytkowania ziemi. Wartości parametrów spływu powierzchniowego na poletkach porośniętych trawą średnio zmniejszyły się do 28% odpływu i do 50% objętości. W przypadku symulowanego opadu deszczu szybkość odpływu istotnie zwiększyła się na poletkach pokrytych samą glebą. Trawy pełnią istotną funkcję, ponieważ pokrywają i chronią glebę oraz spowalniają spływ powierzchniowy.