Assessment of natural and anthropogenic conditions for soil erosion by water in agricultural catchment in Poland

Jolanta ŚWIĘCHOWICZ

Assessment of natural and anthropogenic conditions for soil erosion by water in agricultural catchment in Poland

Abstract: *The main objective of the paper is to examine the natural and anthropogenic conditions for soil erosion by water in agricultural catchment in southern Poland. The Dworski Potok catchment is situated on the edge of the Carpathian Foothills, in the northern part of the Wiśnicz Foothills (the Brzesko Foreland). It covers the area of 0.29 km*^{2}*, the ranges of altitude being 223 – 278 m a.s.l. The dominant lithology in the area consists of flysch series belonging to the sub-Silesian overthrust, and the Miocene clays and sandstones, which are covered with the Quaternary loess-like formations. The soil cover is weakly differentiated with Stagnic Luvisols. Low hills are typical in the morphology of the area.. The ridges and the slopes are covered with thick, loess-like formations. Soil erosion by water in this catchment is determined mainly by catchment area, relief, climate, bedrock and land use. It has been established that slope wash is an occasional process. The morphological effectiveness of soil erosion by water is variable during the year and differentiated along the slope in the catchment. The amount of the sediment depends mainly on the type of vegetation cover and the crop structure. Only sporadic short-duration and high-intensity rainfall events may trigger overland flow and soil erosion causing serious loss of topsoil and significant damage to agriculture.*

Keywords: *soil erosion by water, slope wash, linear erosion, ephemeral gully erosion, rainfall erosivity, Carpathian Foothills, Poland*

Introduction

In the temperate climate zone, one of the main factors causing soil erosion on slopes is water. Thick forests protect the soils from erosion very efficiently (Gerlach 1976). Agricultural slopes, however, which are devoid of vegetation cover undergo intensive soil erosion (Cerda et al. 2007, Novara 2011). Deforestation and long-term agricultural practices have resulted in a change of conditions for slope transformation, which are becoming similar to those prevailing in the semi-dry zone (Cerda et al. 2009). Agricultural slopes, devoid of natural vegetation cover, react very quickly to any changes in the environment and are one of the most dynamically developing relief forms (Stankoviansky 2002, Święchowicz 2008).

Soil erosion by water, which causes the reduction of the thickness of soil layer leading at times to its complete removal. Erosion not only causes permanent impoverishment of soil and the reduction of crop yield, but also makes farming difficult, and sometimes it permanently damages large land areas (Auzet et al. 1990, Boardman 1995, Clark et al. 1985). The amount of soil eroded depends on soil erodibility, field topography, vegetation cover and tillage practice (Święchowicz 2002, Rejman 2006, Garcıa-Ruiz 2010). Soil erosion is the most intensive as a result of local downpours, continuous rains and wet years. Soil erosion rarely happens on all the slopes in a catchment simultaneously and its intensity is differentiated along the longitudinal profile of the slope.

The aim of this paper is to assess the natural and anthropogenic conditions for soil erosion by water in agricultural catchment in southern Poland in three contrasting, in terms of annual totals of precipitation, hydrological years (2007 – 2009).

Study area

The Dworski Potok catchment is located in the village of Łazy, in the lowest marginal zone of the Carpathian Foothills (Brzesko Foreland). Dworski Potok is the tributary of Stara Rzeka (Fig. 1).

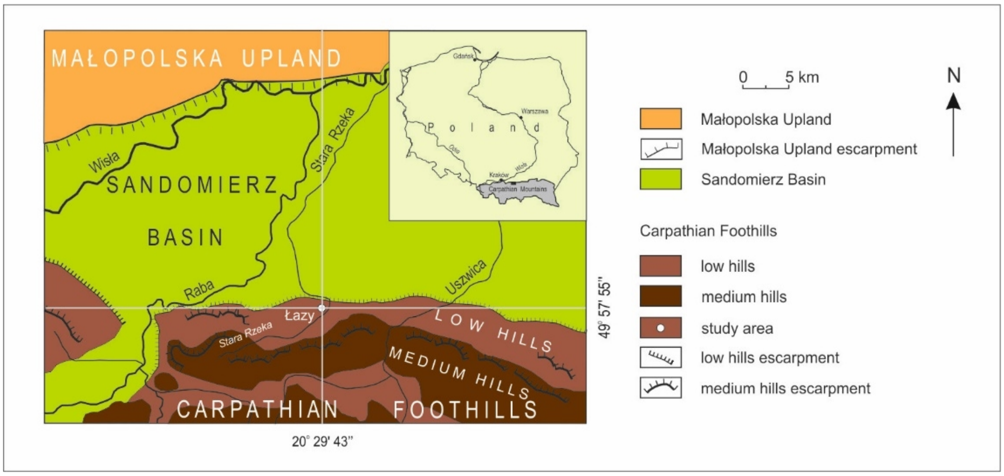

Fig. 1. *Location of study area*

It covers the area of 0.29 km^2, the ranges of altitude being being 227 – 278 m a.s.l. The dominant lithology in the area consists of flysch series belonging to the sub-Silesian overthrust (Bochnia unit), and Miocene clays and sandstones, which are covered with Quaternary loess-like formations. The soil cover is weakly differentiated with *Stagnic Luvisols*. The dominant relief type are low hills. The Dworski Potok valley bottom varies in width from 5 m in its upper part to 50 m in its lower part and is incised by a channel, which is 0.5 m deep. The Dworski Potok valley bottom is separated from slopes by a clear edge which has been formed as a result of farming. Its height is 1 – 8 m above the valley bottom. Above the edge, at the foot of slope, there is a footslope deluvial flattening, 10 m wide (Fig. 2). The slopes in the catchment are convex-concave and their inclinations are 2 – 10^o.

The Dworski Potok catchment is almost entirely a farmland which belongs to the Jagiellonian University. There are no houses, farm buildings or dense network of plot boundaries, dirt roads and mosaic pattern of plots characteristic of the Carpathian Foothills in southern Poland. During the research period, most of the catchment was arable land (80%) which was used mainly for sugar beet, wheat and rape crops, while the valley floors of Dworski Potok and its tributaries are covered with grassland (Fig. 2).

According to M. Hess (1965) classification, the Carpathian Foothills belongs to temperate warm climatic vertical zone. Mean annual precipitation from 1987 to 2009 amounted to 665.9 mm. Annual precipitation totals varied from 442.1 (2003) to 814.1 mm (2007) (Fig. 2). The most precipitation took place in the summer half-year (V – X) and it constituted from 55.4% (1998) to 78.6% (1997) of the annual precipitation total.

On average, in hydrological years 1987 – 2009 there were 168 days with precipitation. Dominant were days with very weak (0.1 – 1.0 mm) and weak (1.1 – 5.0 mm) precipitation and they constituted 62.9% of all the days with precipitation in the summer half-year. Days with strong and very strong precipitation (above 20.0 mm) constituted only 7.2% of all the days with precipitation and occurred mainly in the summer half-year. Maximum daily precipitation (83.4 mm) was in in June in 2006. In the research period the highest monthly total of precipitation were in September (2007), July (2008) and June (2009) (Fig. 3).

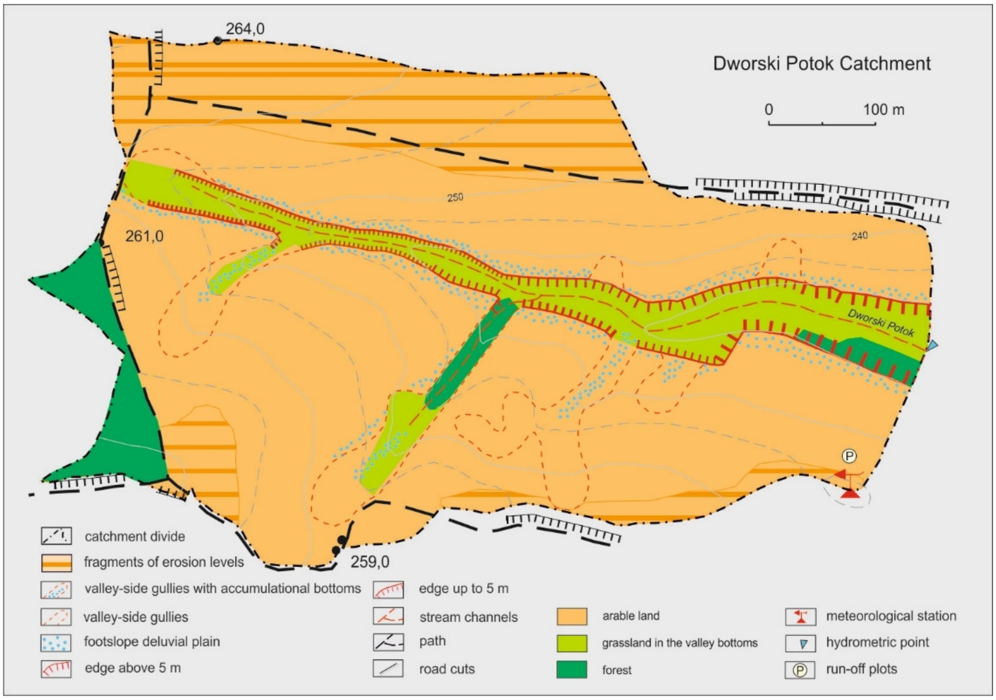

Fig. 2. Dworski Potok catchment – relief and land use

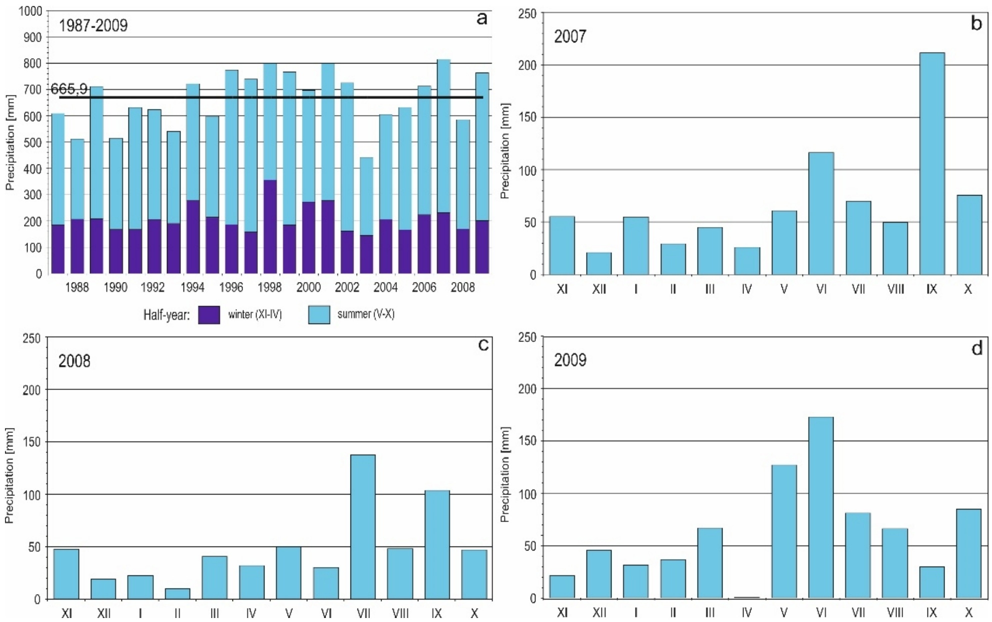

***Fig. 3.** Rainfall characteristic: annual totals of precipitation in 1987–2009 (a) and monthly totals of precipitation in 2007 (b), 2008 (c) and 2009 (d)*

Methods

Precipitation data were collected at Łazy Field Research Station in hydrological years 1987 – 2009. In this study, a single erosive rainfall is defined as a rainfall with a minimum of 5 mm of precipitation and it comes after a period of 6 hours without rain or with rainfall depth lower than 1.3 mm. The formula was calculated on the basis on hyetograph records, kinetic energy of rainfall according to Brown & Foster (1987):

$$E_{kin} = \sum_{i=1}^{n} 0{,}29 \cdot \left[1 - 0{,}72 \cdot \exp(-0{,}05 I_i)\right] \cdot \Delta P_i \qquad (1)$$

where: E_{kin} – kinetic energy (MJ·ha^{-1})
I_i – the rainfall intensity in the i-th increment (mm·h^{-1})
ΔP_i – the depth of rainfall for the i-th increment of storm hyetograph (mm)

For each potentially erosive rainfall, average intensity, maximum 30-minute [I_{30}] intensity and single rainfall erosivity [EI_{30}] were calculated according to the following formula (Wischmeier & Smith 1978):

$$EI_{30} = E_{kin} \cdot I_{30} \qquad (2)$$

where: EI_{30} – single rainfall erosivity (MJ mm ha^{-1} h^{-1}), E_{kin} – kinetic energy of the whole rainfall event, I_{30} – the maximum 30-minute rainfall intensity during the storm (mm·h^{-1}).
Results presented in the paper come from measurements of soil erosion by water on seven run-off plots in 2007 – 2009 hydrological year. The plots were located on a convex–concave slope facing north, ~50 m from a catchment divide. The meteorological station that collected the precipitation data used in this paper is located close to this plot. All the plots were 2 m wide. Four of them were 22.1 m each (P1 – P4), the remaining three were 11.1 (P5), 5.5 (P6) and 2.8 m (P7) respectively. The slope steepness of the plots was 8°. The plots were protected using plastic foil and closed off with a 2-m Gerlach gutter, which catches water and material eroded from each plot and then sends them to a separate water tank with a limnigraph. After each rainfall, measurements of surface flow and soil erosion were taken. Measurements were performed following each precipitation event characterized by effective erosion. Water levels were measured in bodies of water and this metric was used to calculate the volume of surface runoff. The next step consisted of an extensive mixing of water and the collected material, followed by the collection of three samples. Once it was established that differences in the concentration of suspended matter are not significant, only one sample was collected in subsequent study years. The collected water and soil samples were filtered and the solid fraction was dried until it reached a constant weight at a temperature of 105°C. The concentration of the solid fraction in each sample with a known volume was used to calculate the amount of soil material in water tanks (Święchowicz 2012b).

In 2007 out of the seven plots – one was fallow plot, one was grassland and one was a potato field whereas the remaining four, which differ in length, had winter wheat crops (Fig. 4a). In 2008 out of the seven plots – one was fallow plot, one was grassland and one was winter wheat whereas the remaining four were potato field (Fig. 4b). In 2009 out of the seven plots – one was fallow plot, one was grassland and one was sugar-beet field whereas the remaining four had winter wheat crops (Fig. 4c).

To assess the influence of plant cover for soil erosion by water the C factor was calculated. The crop/vegetation and management factor (C factor) is a ratio comparing the soil loss from plot under a specific crop to the corresponding loss from continuously fallow plot. To assess the susceptibility of soil particles to detachment and transport by rainfall and run-off soil erodibility factor (K factor) was calculated. K factor is a ratio comparing the soil loss from fallow plot to the rainfall erosivity (EI_{30}). C and K factors are from the Wischmeier & Smith (1978) USLE formula.

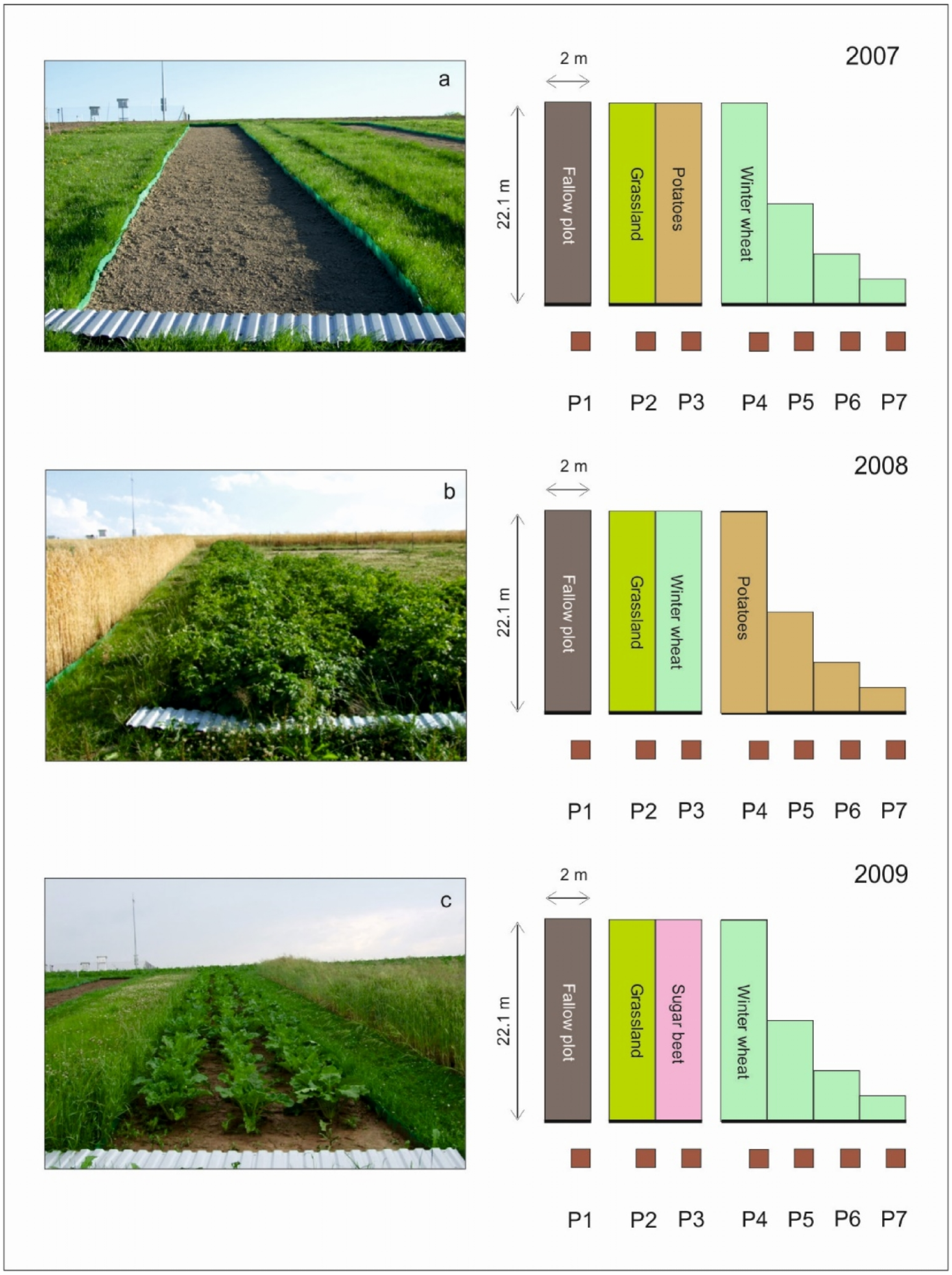

Fig 4. *Land use pattern on run-off plots in hydrological years 2007 – 2009 (photo by J. Święchowicz)*

Results and Discussion

Rainfall character

The hydrological year 2007 was wet with annual precipitation total 814.1 mm. The most precipitation took place in the summer half-year (May – October) and it constituted 71.6% of the annual precipitation total. In the summer half year there were 65 days with precipitation. Dominant were days with very weak (0.1 – 1.0 mm) and weak (1.1 – 5.0 mm) precipitation which constituted 70.8% of all the days with precipitation. Days with strong and very strong precipitation (above 20.0 mm) constituted 12.3% of all the days with precipitation in summer half-year. Maximum daily precipitation was 60.4 mm.

The hydrological year 2008 was dry with annual precipitation total of 585.3 mm. The most precipitation took place in the summer half-year (May – October) and it constituted 70.9% of the annual precipitation total. In the summer half year there were 79 days with precipitation. Dominant were days with very weak (0.1 – 1 mm) and weak (1.1 – 5.0 mm) precipitation which constituted 63.3% of all the days with precipitation. Days with strong and very strong precipitation (above 20.0 mm) constituted 6.3% of all the days with precipitation in summer half-year. Maximum daily precipitation was 26.2 mm.

The hydrological year 2009 was wet with annual precipitation total of 763.0 mm. The most precipitation took place in the summer half-year (May – October) and it constituted 73.6% of the annual precipitation total. In the summer half-year there were 71 days with precipitation. Dominant were days with very weak (0.1 – 1.0 mm) and weak (1.1 – 5.0 mm) precipitation which constituted 63.4% of all the days with precipitation. Days with strong and very strong precipitation (above 20.0 mm) constituted 8.5% of all the days with precipitation in summer half-year. Maximum daily precipitation was 59.2 mm.

Frequency of soil erosion events on the run-off plots

In the wet 2007 hydrological year in the summer half-year there were 21 rain events, in the dry 2008 hydrological year – 28 and in wet 2009 – 25. Each of them might have been a potential source of erosion. However, only 13 (2007), and 9 (2009) events of soil erosion were observed in the wet hydrological years in the summer half-year whereas in the dry 2008 hydrological year not a single soil wash event was observed (Fig. 5).

The majority of events in 2007 occurred in summer (June, July, and August) and autumn (September). Slope wash events took place mainly during heavy and very heavy rains, although there were single events caused by moderate rains. The number of slope wash events on plots of the same length differed in relation to their agricultural use. The most events was expressed on P1 plot (bare fallow) and P3 (potatoes). The least – on P4 (winter wheat). Slope wash did not occur simultaneously on all the plots during the same rainfalls.

In the hydrological year 2007, rain events with daily totals of precipitation above 20 mm always resulted in overland flow and slope wash. However, in 2008 hydrological year in the summer half-year there were 28 single rains but none of them did not cause runoff or soil erosion on the slope. Among them, three rains were characterised with amount of precipitation above 20 mm but they were continuous rains with low intensity. Therefore, their erosivity was low (below 50 MJ mm ha^{-1} h^{-1}). Two of the rains had their erosivity above 50 MJ mm ha^{-1} h^{-1} and high 30 minute maximum intensity but they lasted for a very short time and were not able to cause erosion. The power of all the rains was low (Fig. 6).

The majority of the events in 2009 occurred in summer (June and July). Slope wash events took place mainly during heavy and very heavy rains, although there were single events caused by moderate rains. The number of slope wash events on plots of the same length differed in relation to their agricultural use. The most events occurred on P1 plot (bare fallow plot) and P3 (sugar-beet plot). The least – on P4 (winter wheat). Slope wash did not occur simultaneously on all the plots during the same rainfalls.

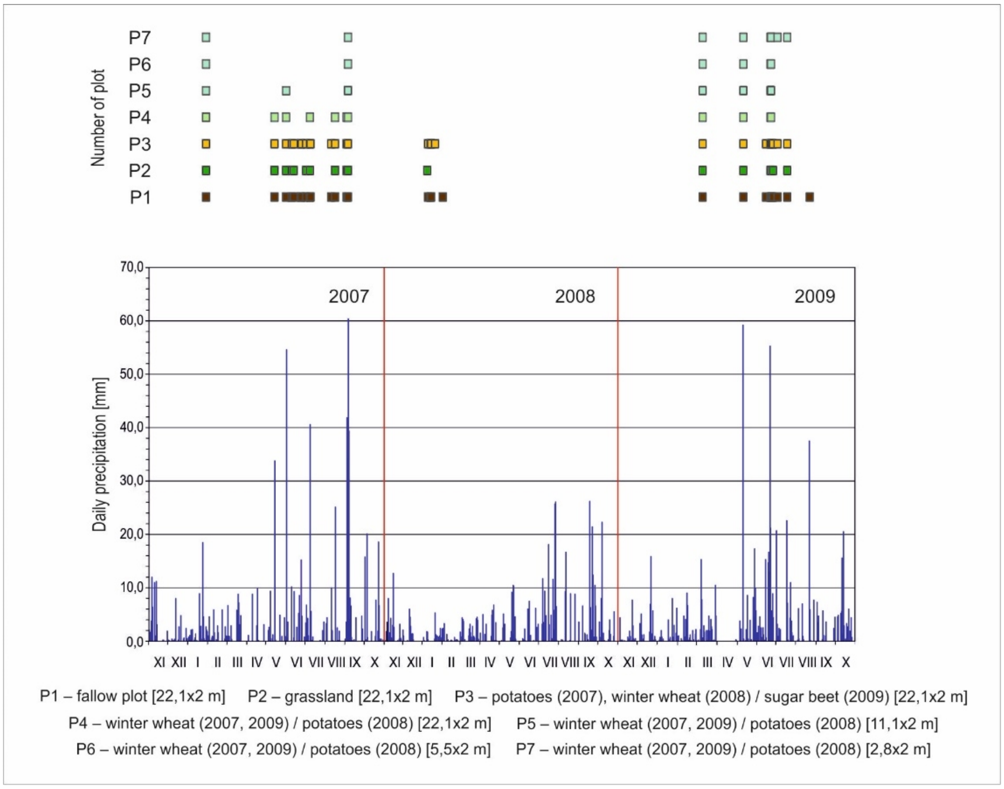

Fig. 5. *Number of slope wash events in relation to daily totals of precipitation in hydrological year 2007 – 2009*

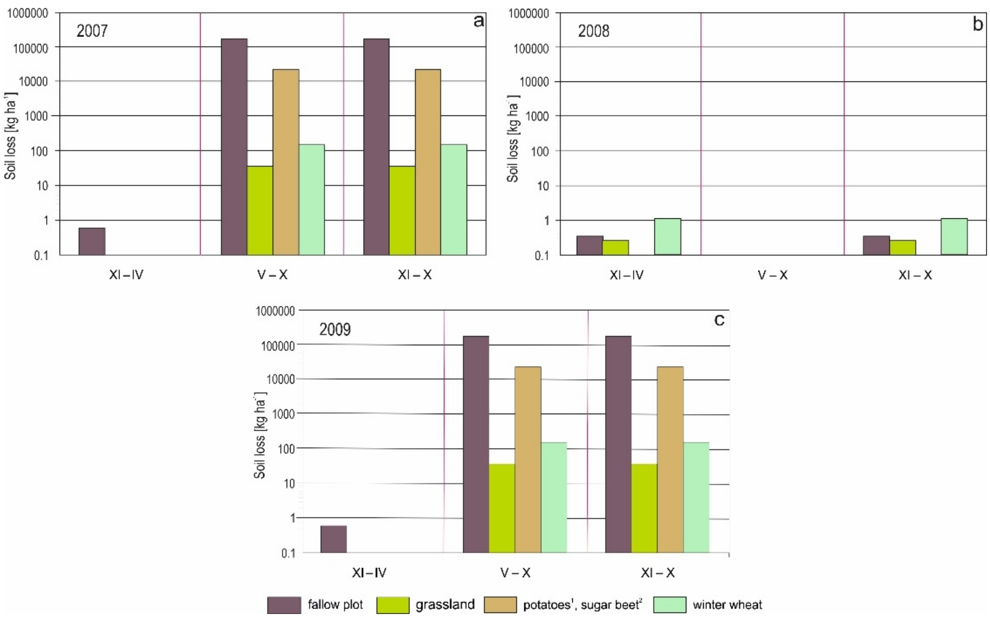

Fig. 6. *Soil loss (kg ha*$^{-1}$*) in 2007 – 2009 on the different land use run-off plots*

In the hydrological year 2009, rain events with daily totals of precipitation above 20 mm always resulted in overland flow and slope wash. Among them, three rains were characterised with amount of precipitation above 20 mm but they were continuous rain with low intensity. Therefore, their erosivity was low (below 50 MJ mm ha^{-1} h^{-1}). Two of the rains had their erosivity above 50 MJ mm ha^{-1} h^{-1} and high 30 minute maximum intensity but they lasted for a very short time and were not able to cause erosion. The power of all the rains was low (Fig. 6).

Sediment loss assessment on the run-off plots

In the 2007, the highest sediment loss occurred on the fallow plot. Soil erosion on the potato plot was by 8.3% lower than in the fallow plot. Erosion on winter wheat plots was low and 25% lower than on grass plots. 31.4 kg ha^{-1} in winter wheat, 41.9 kg ha^{-1} on meadow, 43 396.0 kg ha^{-1} on potatoes, and fallow plot – 47 340.2 kg ha^{-1} (Tab. 1). The ratio of soil erosion was 1: 1.3: 1350.2: 1507.7 respectively.

For all crops close to 100% of the soil is washed away in the summer hydrological half. The most dynamic process was in the summer months (June, July, August) and autumn (September). Only on the meadow a high share of soil drainage was observed during the summer–spring period (Fig. 6).

In the hydrological year 2009 the highest values of soil erosion occurred on fallow plot. The sediment loss on the sugar beet plot was more than 7.5 times smaller than in the fallow plots. Soil loss on a winter wheat plot was small and almost four times higher than on a grass-covered plot. Annual soil erosion in 2009 on plots was 35.8 kg ha^{-1} on grass, 151.4 kg ha^{-1} on winter wheat, 22 463.7 kg ha^{-1} on sugar beet and 171 505.6 kg ha^{-1} on fallow plot (Tab. 1). Nearly 100% of the soil was washed away in the summer half-year (Fig. 6). The most dynamic process was in the summer months (June, July, August) and autumn (September). Only on the meadow a large part of the soil was drained during spring and summer. The soil loss ratio was 1: 4.2: 627.9: 4793.8 respectively.

Influence of land use pattern on soil erosion by water on the run-off plots

Soil erosion rarely occurs on all slopes in catchment, and its intensity depends on the type of crops. Agricultural slopes, devoid of vegetation cover, react very quickly to short-duration, high-intensity rainfall events. An assessment of the impact of a crop on the limitation of water erosion is made by comparing the mass of soil transferred from the plant plots to the plot without plant (C factor). In 2007, for the whole potato growing season it amounted to 0.92, and in 2009 for the sugar beet growing season amounted to 0.13. C factor decreased with the growth of the plant cover (Tab. 2).

In the initial period of potato growth, soil washing was significantly larger in potato plots than in fallow plot (Tab. 2). The precipitation that occurred at the beginning of the potato crop (15 May) caused stronger surface run-off in the potato plot than in the plots without plants. On a plot of potatoes that were planted in ridges with a spacing of rows of 65 cm, the concentration of surface runoff in the furrows between the ridges was much faster than in the straight line without the plants. The value of C factor during this event was very high and the mass of the displaced soil in the potato plot was more than 4 times higher than in the fallow plot (Tab. 2). The value of C factor was reduced with the growth of the plant cover and during the very high erosion precipitation that occurred on June 2, the soil loss on the potato plot and on the plot with plants was almost the same (Tab. 2). This was due to the growth of plants and the covering of rows. In successive phases of plant growth (flowering, early leaf dryness), the value of C was below 1. The well-developed vegetation significantly reduced soil erosion during rainfall erosivity over 200 MJ mm ha^{-1} h^{-1}, which took place on 9 July 2007 (Tab. 2). During the rain of low erosivity, which occurred the next day with high soil moisture, a small soil mass was drained between the ridges, but the value of C factor exceeded 1. Significant increase in C factor occurred at the end of the growing season when the ridges and furrows were covered with potato peelings and in September there were two rainfalls with very high amount and low intensity. The value of C factor was significantly higher during the second event when soil was fully saturated with soil.

Tab. 1. *Soil erosion by water [kg ha^{-1}] on 22.1 m long run-off plot in 2007 – 2009 year in Dworski Potok catchment*

Year	Month	Soil erosion by water [kg ha^{-1}]			
		fallow plot	grassland	potatoes[1], sugar beet[2]	winter wheat
2007	XI				
	XII				
	I	0,5	0.2	0.4	n
	II				
	III				
	IV				
	V	417.2	14.4	1731.4	n
	VI	20438.4	9.7	17817.2	24.2
	VII	19617.6	15.9	16304.7	2.6
	VIII	4877.2	1.0	3183.5	n
	IX	1989.3	0.8	4358.7	3.8
	X				
	XI–IV	0.5	0.2	0.4	n
	V–X	47339.2	41.7	43395.6	n
	XI–X	47340.2	41.9	43396.0	31.4
2008	XI				
	XII				
	I	2.9	2.3		8.0
	II				
	III				
	IV				
	V				
	VI				
	VII				
	VIII				
	IX				
	X				
	XI–IV	2.9	2.3		8.0
	V–X				
	XI–X	2,9	2.3		8.0
2009	XI				
	XII				
	I				
	II				
	III	0.6	n	n	0.1
	IV				
	V	96438.5	1.6	16094.4	23.8
	VI	68481.4	34,1	6287.3	127.5
	VII	6585.0	0.1	82.0	
	VIII	n			
	IX				
	X				
	XI–IV	0.6	n	n	0.1
	V–X	171505.0	35.8	22463.7	151.3
	XI–X	171505.6	35.8	22463.7	151.4

Source: author's own study; [1] – 2007, [2] – 2009, n – inconsiderable

On the winter wheat field the soil erosion was minimal because the wheat was very well planted and was in the growth phase. Mean value of C factor for winter wheat was 0.0008. The impact of winter wheat was very effective even during the most erosive rainfalls events that occurred on June 2 and July 9. C factor for these events were 0.00177 and 0.00014 respectively.

***Tab. 2**. C factor on potato/sugar beet runoff plot in summer half-year (V – X) in 2007 – 2009*

Year	No.	Date	Factor EI_{30} [$MJ \cdot mm\ ha^{-1} \cdot h^{-1}$]	Fallow plot [$kg \cdot m^{-2}$]	Potato[1] / sugar beet[2] [$kg \cdot m^{-2}$]	C factor
2007	1.	15.05	125.6	0.04	0.17	4.15
	2.	02.06	233.3	1.36	1.43	1.05
	3.	11.06	40.0	0.14	0.02	0.13
	4.	14.06	35.5	0.12	0.01	0.13
	5.	25.06	39.5	0.33	0.26	0.78
	6.	26.06	5.9	0.09	0.07	0.70
	7.	03.07	8.4	0.02	0.01	0.58
	8.	09.07	226.8	1.94	1.62	0.83
	9.	10.07	3.8	0.00	0.00	1.24
	10.	11.08	41.3	0.14	0.07	0.52
	11.	17.08	112.6	0.35	0.25	0.70
	12.	04.09	184.1	0.06	0.09	1.45
	13.	06.09	198,5	0.14	0.35	2.51
	Sum		**1255.3**	**4.73**	**4.34**	
	Average		**96.6**	**0.36**	**0.33**	**0.92**
2009	1.	11.05	907.4	9.64	1.61	0.17
	2.	15.06	91.5	0.67	0.10	0.15
	3.	22.06	543.9	4.87	0.40	0.08
	4.	23.06	82.7	1.24	0.13	0.10
	5.	24.06	8.8	0.06	0.00	0.00
	6.	26.06	7.6	0.01	0.00	0.00
	7.	02.07	194.5	0.65	0.01	0.01
	8.	18.07	40.5	0.01	0.00	0.00
	9.	22.08	65.5	0.0	–	–
	Sum		**1942.4**	**17.15**	**2.25**	
	Average		**234.6**	**2.14**	**0.28**	**0.13**

[1] – 2007, [2] – 2009

In 2009 the value of C factor decreased as plant cover grew (Tab. 2). In the early period of sugar beet growth, soil erosion during the unusually erosive rain, which occurred on May 11, was significantly smaller than on the plots without plants. On a field with beets that were planted in 3 rows at a spacing of 65 cm, the soil after sowing was rolled, which hindered the concentration of surface run-off and soil erosion. The value of C factor during this event was the highest although the mass of the displaced soil in the beet plot was more than 6 times lower than in the non-planted plot (Tab. 2). The value of C factor decreased with the growth of the plant cover and during the rain of very high erosivity, which occurred on June 22, the soil erosion on the beet plot was 12 times smaller than on the fallow plot (Tab. 2). This was related to the growth of plants and the complete covering of rows.

On the winter wheat plot, soil erosion by water was low, as the wheat was very well planted and was in the growth phase (Tab. 2). Mean value of C factor for winter wheat was 0.0009. The impact of winter wheat was very effective especially during the rain with the highest erosivity which took place on May 11. C factor for this event was 0.002377.

Erosion on plots of different length

The measurements obtained on plots of different length, and similarly used (winter wheat) show differentiation in the number of events in relations to the length of the plots (Fig. 5, Tab. 3).

***Tab. 3**. Soil erosion by water on run-off plots covered with winter wheat in summer half-year in 2007 and 2009*

Year	No	Date	Factor EI_{30} [MJ·mm·ha^{-1}·h^{-1}]	Area of run-off plot [m^2]							
				44,2	22,1	11,0	5,5	44,2	22,1	11,0	5,5
				Soil erosion by water [kg]				Soil erosion by water [kg·m^2]			
2007	1.	15.05	125,6	n				n			
	2.	02.06	233,3	0,11	0,01			n	n		
	3.	11.06	40,0								
	4.	14.06	35,5								
	5.	25.06	39,5								
	6.	26.06	5,9								
	7.	03.07	8,4								
	8.	09.07	226,8	0,01				n			
	9.	10.07	3,8								
	10.	11.08	41,3								
	11.	17.08	112,6	n				n			
	12.	04.09	184,1	n				n			
	13.	06.09	198,5	0,02	0,03	0,06	n	n	n	n	n
Sum (winter wheat)			718,8	0,12	0,01	n	n	n	n	n	n
Sum (stubble)			536,5	0,02	0,03	0,06	n	n	n	n	n
Total			1255,3	0,14	0,04	0,06	n	n	n	n	n
2009	1.	11.05	907,4	0.11	–	0.04	0.04	n	–	n	n
	2.	15.06	91,5								
	3.	22.06	543,9	0.49	0.05	0.03	0.08	0.01	n	n	0.01
	4.	23.06	82,7	0.07	–	0.18	–	n	–	0.02	–
	5.	24.06	8,8								
	6.	26.06	7,6								
	7.	02.07	194,5								
	8.	18.07	40,5								
	9.	22.08	65,5								
Total (winter wheat)			1942,4	0.67	0.05	0.25	0.12	0.01	n	0.02	0.01

Influence of rain erosivity on soil erosion by water on the run-off plots

Soil loss during all erosive rainfall events was poorly correlated with the sum of precipitation (Święchowicz 2010). High correlation was found between soil loss and erosivity index EI_{30}. This relationship in 2007 best described linear function with a coefficient of determination (R^2) of 0.49, and in 2009 power function with a coefficient of determination (R^2) of 0.98 (Fig. 7). However, the weight of the eroded soil was more determined by the maximum 30-minutes intensity than the sum of the precipitation (Święchowicz 2008).

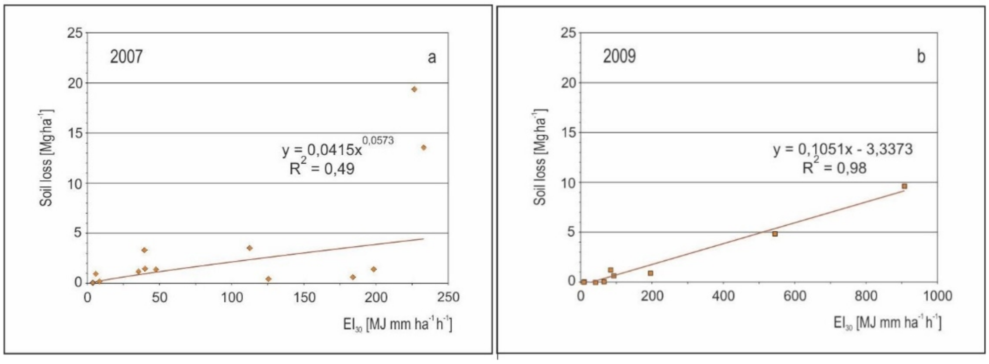

Fig. 7. *Relation between soil loss (kg ha^{-1}) and rainfall erosivity index EI_{30} (MJ·mm ha^{-1}·h^{-1}) in summer half-year (V-X) in 2007(a) and 2009(b) on the bare fallow run-off plot*

The soil loss and economic damage due to extreme rainfall in 2006

The part of the study was also mapping of geomorphic effects of extreme rainfall, which took place in the Dworski Potok catchment and adjacent area in 2006. The strong soil erosion by water on the slopes took place on 17th June 2006, during daily rainfall of the amount of 83.4 mm, which lasted only 85 minutes and its maximum intensity was slightly above 3.8 mm·min^{-1} (Święchowicz, 2009; Fig. 9). The downpour lasted from 15.45 pm to 17.10 pm producing 82.6 mm of precipitation. Mean intensity amounted to 0.97 mm·min^{-1}. In the first 16 minutes 59.2 mm of rainfall was measured. Mean intensity at that time was almost 4 mm·min^{-1}, the highest intensity was measured within the first 5 minutes with 29.6 mm of precipitation with mean intensity of almost 6 mm·min^{-1}. The downpour caused intensive runoff on the field with sugar-beet, which covered 12% of the of the arable land in 2006. On an 0.5 ha plot, all the plant seedlings were washed away together with the eroded soil (Fig. 9a). On the remaining fields with sugar-beets, the crops were silted up and consequently the yields were reduced. On the land with cereals there was intensive surface flow too. Ephemeral gully was form in the axis of the sub-catchments along the natural drainage line (Fig. 9bc). Soil erosion was strong only along the episodic channel and sediments were accumulated in form of wide and broad deluvial fan in the outlet of the gully (Fig. 9de). On the remaining area soil erosion was not intensive because of dense vegetation cover.

The results of the extreme rainfall were most visible on the grape-vine field (Fig. 9hij). The vineyard was established in spring 2005 on the area of 0.3 ha. In spring (May) 2006 grape-vines were planted on additional 0.7 ha. Thus in June, when the rainfall took place, 0.7 ha of the vineyard was devoid of vegetation cover. Between the rows of grape-vine (which were 2.5 m apart) an intensive surface flow took place in several sections (Fig. 9h). Along the rows of grape-vine rills formed which were typically several to over ten cm deep (Fig. i). The eroded material was accumulated in the footslope deluvial plain above the edge which separated it from the valley bottom (Fig. 9j).

Extreme rainfalls not only cause sediment loss on agricultural fields, change landforms, leading to the build-up of footslope deluvial plains, but also cause financial losses and economic damage. As a result of rainfalls, intensive erosion took place on fields where sugar-beet was sown. Although the sugar-beet crop of that year covered only 12% of the farm's arable land On slopes on the area of about 0.5 ha, the sugar-beet plants were totally washed off the field together with the soil (Fig 9a), and on the footslope area the soil was accumulated, which brought about the silt-up of crops. The immediate result of the silting-up was that the growth of plants was stopped for 2 – 3 weeks. This and the subsequent drought in July were responsible for the decrease of the sugar-beet crop yield in 2006 by 45% in comparison to previous years. Intensive slope wash destroyed the herbicide protection and caused the spread of weeds, which in turn lowered the crop yield (Święchowicz 2008).

Fig. 8. *Soil loss during intensive rainfall which took place on 17th June 2006 (photo by J. Święchowicz)*

Despite the high intensity of the rainfall and the accumulation of the washed-off soil in the footslope area covered by the vineyard, there was no damage to the grape-vine plants (Fig. 9i). Water flowed freely between the rows forming in several sections erosion rills several to more than 10 cm deep. During the extreme rain technical structures or facilities (pond's dike, the fence) were destroyed (Fig. 9j).

In the Flysh Carpathians on arable slopes soil erosion by water has high intensity (Gil 2009, Święchowicz 2008). Even there the number of events during the year is varied because it is often conditioned by the lack of dense vegetation in many crops cover in many crops during a vegetation period, as well as by rainfalls that trigger erosion (Święchowicz 2012a, Gil 1999).

On agricultural slopes soil erosion by water in the summer half-year may not occur at all, if the year is characterized by a low total rainfall, and single rainfall erosivity is too small to cause erosion when the area is cover with plants. This situation occurred in dry 2008, when two rains with erosivity of slightly over 80 MJ mm ha $^{-1}$h^{-1}, did not cause soil erosion – even on fallow plot, completely in vegetation season devoid of protection of plant cover. In contrast, in wet 2007, seven rains with low erosivity (from 3.8 to 41.3 MJ mm ha^{-1}h^{-1}) escaped from a fallow plot near 18%, and from a potatoes plot slightly over 10% of the soil eroded in the summer- half year.

The obtained results refer to the Carpathian Foothills marginal zone covered with loess like formation with *Stagnic Luvisols*. The soils are very susceptible to soil erosion. Mean annual soil erodibility factor (K factor) reached the value of 0.0377 Mg ha h MJ^{-1}mm^{-1}ha^{-1} in 2007 which was significantly lower than the value calculated on the basis of the USLE model (0.0738). In 2009 mean annual value of K factor was 0.0914 Mg ha h MJ^{-1}mm^{-1}ha^{-1} which was not much below the value calculated according to USLE (Święchowicz 2012a).

Measurements taken in Łazy confirm regularities observed in other regions of the Carpathians, namely that that slope wash on agricultural slopes is most dynamic in the summer half-year and that the greatest soil loss takes place in crops like potatoe and beet root (Gerlach 1976, Gil 1999, 2009, Święchowicz 2002, 2008, 2009). The values obtained in the summer half-year in the Łazy region in potatoe crops are similar to the values in the summer half-year in 1969 – 2000 obtained in the region of Szymbark. They are, however, lower by half in relation to the maximum values for that period.

The annual value of soil erosion in Łazy (Wiśnicz Foothills) in potato crops was 2.3 times lower than the maximum annual value of slope wash observed in Szymbark (northern, foothill part of the Bystrzanka catchment, situated on the border of Niski Beskid Mts and Ciężkowice Foothills. It was also 1.7 times higher than the mean values of slope wash for that region in 1969 – 2000. The series of measurements in Łazy is too short to determine which region of the Carpathians has the highest intensity of soil erosion: the Carpathian Foothills, where the soils are silty sands or higher foothills (Szymbark), where the soils contain fractions of stone and clay. The comparisons are merely indicative but in Szymbark in 1969 – 2000 the annual soil wash, which was higher than in Łazy, was measured only three times while in the remaining years it was much lower.

Although on agricultural slopes the intensity of soil erosion by water is very big, transport of the eroded material happens on short distances and accumulation takes place on plots with dense vegetation cover, furrows on borders between plots, on parts of slopes with lower inclination or at the foot of slopes. The mosaic of plots separated with furrows, balks and cart roads characteristic for the flysh Carpathians, makes the mechanism of supply of the material from slopes to river channel quite complex Material reaches river channels mainly during heavy rains and downpours (Gil 1999, Froehlich 1982, Święchowicz 2012a).

Conclusions

The study was carried out in the Dworski Potok catchment located in the lowest marginal zone of the Wiśnicz Foothills (Brzesko Foreland). It is small agricultural foothill catchment, situated in a moderate climate zone, with slope covered with loess-like formations. The study was based on erosion plots and mapping of geomorphic effects of one extreme rainfall.

The measurements taken show a changeable number of erosive events and changeable intensity of soil erosion by water particularly in the summer halfyear, which depend on rainfall erosivity, type and structure of crops. The biggest values for soil erosion took place during rains of the highest erosivity (above 200 MJ mm $ha^{-1}h^{-1}$) and high maximum 30-minute intensity (above 20 mm h^{-1}).

Soil erosion by water in Łazy, in the lowest marginal zone of the Wiśnicz Foothills, during the study period was characterized by a smaller intensity in comparison to Szymbark (northen part of the Bystrzanka catchment, situated on the border of Beskid Niski Mts and Ciężkowice Foothills) in 1969 – 2000. As for the potato crops, mean annual values of slope was were slightly smaller (by 15%), and the wheat crops were halved.

The research period covered three contrasting years, one dry (2008) and two wet (2007 and 2009). Monthly totals of precipitation varied a lot. Soil erosion by water is occasional process. During 93% (2007), 100% (2008) and 95% (2009) of days in summer half years the slope are stable because rainfalls do not occur or are too small to initiate soil erosion by water. Only sporadic short-duration and high intensity rainfall events may trigger severe soil erosion causing serious loss of topsoil.

Soil erosion rarely took place on all the fields simultaneously and its intensity is differentiated along the longitudinal profile of the slope. In the transformation of slopes a greater role is played by land use, the area of crops and how big the crops are during the rainfall rather than by the parameters of rainfall. Soil resistance to erosion depends on the type of crops and spatial crop structure.

Identical rainfall (same amount, intensity and duration) causes different soil loss depending on land use. Mean annual soil loss in 2007 – 2009 amounted to 63,6 kg ha^{-1} for winter wheat, 26,7 kg ha^{-1} for meadow, 43,396.0 kg ha^{-1} for potato, 22463.7 for sugar-beet and 72949.6 kg ha^{-1} for fallow.

Vegetation cover significantly limited erosion: the value of crop factor (C factor) in hydrological year 2007 was 0.92 for the whole vegetation period of the potato crop and was much lower for winter wheat (0.0008) and grassland (0.0009). C factor in hydrological year 2009 was 0.13 for the whole vegetation period of the sugar beet crop.

The C factor which is used to assess the effectiveness of a given crop in limiting water erosion processes changed dynamically. On potato plot average value of the C factorin 2007 was littlebelow 1. During consecutive rains the ratio of soil erosion on potato field to bare fallow land usually was higherthan 1. On sugar-beet plot average value of the ratio in 2009 was much below 1. The C factor was very low also during single soil erosion events, which shows the protective role of sugar-beet crop. Differences in the C factor values also point to the decisive role of rainfalls of high erosivity, which took place in the middle period of vegetation growth.

In 2007 the mean annual index of erodibility to erosion (K factor) was 0.0377 $Mg \cdot ha \cdot h \cdot MJ^{-1} \cdot mm^{-1} \cdot ha^{-1}$ and this was a smaller value than that provided by the USLE model based on soil grain size, soil organic matter content, structure class, and soil water permeability (0.0738 $Mg \cdot ha \cdot h \cdot MJ^{-1} \cdot mm^{-1} \cdot ha^{-1}$). In 2009 this value stood at 0.0914 $Mg \cdot ha \cdot h \cdot MJ^{-1} \cdot mm^{-1} \cdot ha^{-1}$ and was larger than that provided by the USLE model.

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Author´s address:
dr hab. Jolanta Święchowicz
Institute of Geography and Spatial Management,
Jagiellonian University in Kraków,
ul. Gronostajowa 7, 30-387 Kraków
Poland
jolanta.swiechowicz@uj.edu.pl