Original Research

Erosion Processes and Sediment Transport during Extreme Rainfall-Runoff Events in an Experimental Catchment

Jana Konečná*, Jana Podhrázská, Josef Kučera

Research Institute for Soil and Water Conservation,
Lidická 25/27, 602 00 Brno, Czech Republic

Received: 19 September 2013
Accepted: 17 February 2014

Abstract

Research on the influence of land use changes and erosion and flood control measures on a reduction of harmful effects of extreme rainfall-runoff events has occurred at the experimental Němčický stream basin since 2005. It has been documented by obtained results of rainfall and discharge gauging and by water sample analyses that sediment transport significantly corresponds with the cover efficiency of agricultural crops. Based on the analysis of particular comparable rainfall-runoff episodes, it can be stated that the protection (e.g. grassing, growing of narrow-row crops) of slopes adjacent to watercourses has a crucial influence on the reduction in surface water pollution with insoluble substances. In such cases the efficiency of grass cover is 90-99% compared to bare soil, while the efficiency of narrow-row crops is 50-80% in comparison with bare soil. The efficiency of narrow-row crops at the time of maximum vegetation stand is close to that of permanent grasslands.

Keywords: water erosion, runoff, sediment transport, measurement, crop efficiency

Introduction

In the territory of the Czech Republic on average five to six short-term rainstorms with precipitation amounts above 10 mm occur at any place per year. If rainfall total and intensity exceed initial soil accumulation and infiltration intensity, then increased surface runoff on slopes occurs. A similar phenomenon occurs during spring thaw. Due to water or snow melt, erosion surface water runoff carries away soil particles that are deposited on lower parts of the slope, in a valley, or are transported into watercourses.

A number of scientific studies have aimed at runoff and transport processes in small catchments [e.g. 1-3]. In spite of these efforts the knowledge, description, and quantification of erosion events are still limited [4] because erosion, transport, and sedimentation processes in a rural countryside are influenced by many factors. Quantity of sediment load carried in consequence of a certain extreme storm depends on relief characteristics and land use of a catchment [5]. Concerning agricultural land, the soil properties, type of crops and soil cultivation method are key factors in the erosion process [6]. Based on the results of monitoring of the quantity of insoluble substances in 19 experimental catchments, Zheng et al. [7] stated that there was no relationship between discharge and concentration of suspended sediments in conditions of base flow. On the contrary, in rainfall-runoff events the concentration of suspended sediments increases with discharge. A similar conclusion was

*e-mail: konecna.jana@vumop.cz

published by Kliment [8, 9] for the outlets of four model catchments; the resultant values of suspended sediment transport were found to be influenced by the total erosion potential of a given territory and unstable rainfall-runoff balance of particular watersheds.

The aim of our research on erosion processes and suspended sediment transport in extreme rainfall-runoff events in the Němčický stream catchment is to contribute to the knowledge of these phenomena. Simultaneously, attention is paid to possibilities of reducing their negative impacts both on degradation of agricultural land and on water bodies.

Material and Methods

Natural Conditions of the Experimental Catchment

Němčický stream empties into the Luha River, which flows (under the name Punkva) through the Moravian Karst and feeds the Svitava River (Fig. 1). The relief of the experimental catchment is composed of moderately broken, long gentle slopes of the Drahanská Vrchovina uplands. Average altitude of the catchment is 606 m a.s.l. Climatically, the territory of interest belongs to a moderately warm region and moderately humid district. Soil cover mostly consists of modal eubasic to mesobasic Cambisols on the rocks of the culm, mostly medium-heavy textured and medium skeletal.

Out of the total catchment area of 352 ha, arable land takes 183 ha, there are 10 ha of permanent grasslands and 124 ha of forests. Average slope of agricultural land in the carchment is 6.5%. Cereals and rapeseed are dominate crop rotation, but maize and perennial fodder crops are also grown there [10]. Conventional cultivation is used.

Gauging Facilities and Methods

On the right-side tributary of Němčický stream (Fig. 2) two Thomson spillways were constructed in 2005. The area of the whole experimental catchment related to the lower gauging profile N1 is 352 ha. Profile N1 was built below the designed retention reservoir and the distance between profiles is 275 m. Profile N2 is situated in the interior of the catchment (above the designed reservoir) to control surface runoff to the stream from the slope most vulnerable to erosion. Profiles were equipped with ultrasound devices for measuring discharges and with automatic samplers of suspended sediments. Ultrasound probes measure in a 5-minute interval the water level that is automatically recalculated to discharge. The control unit reports on the above-limit discharge and provides information on the present stage to a mobile phone. There is a classic rain gauge near profile N2. All data are stored in a data logger and they are downloaded several times a year. Water samples from the rising flood wave collected by an automatic sampler were analyzed for the content of insoluble substances.

The results of water sample analyses were systematically processed in the form of tables. Each sample was attributed average discharge and time of duration in the course of rising discharge until its peak in order to determine the total volume (quantity) of transported insoluble matter in the rising wave. Those rainfall-runoff events were evaluated when maximum discharge exceeded 50 $l \cdot s^{-1}$. The instantaneous situation of the catchment was continuously recorded, especially the type and condition of crop stands.

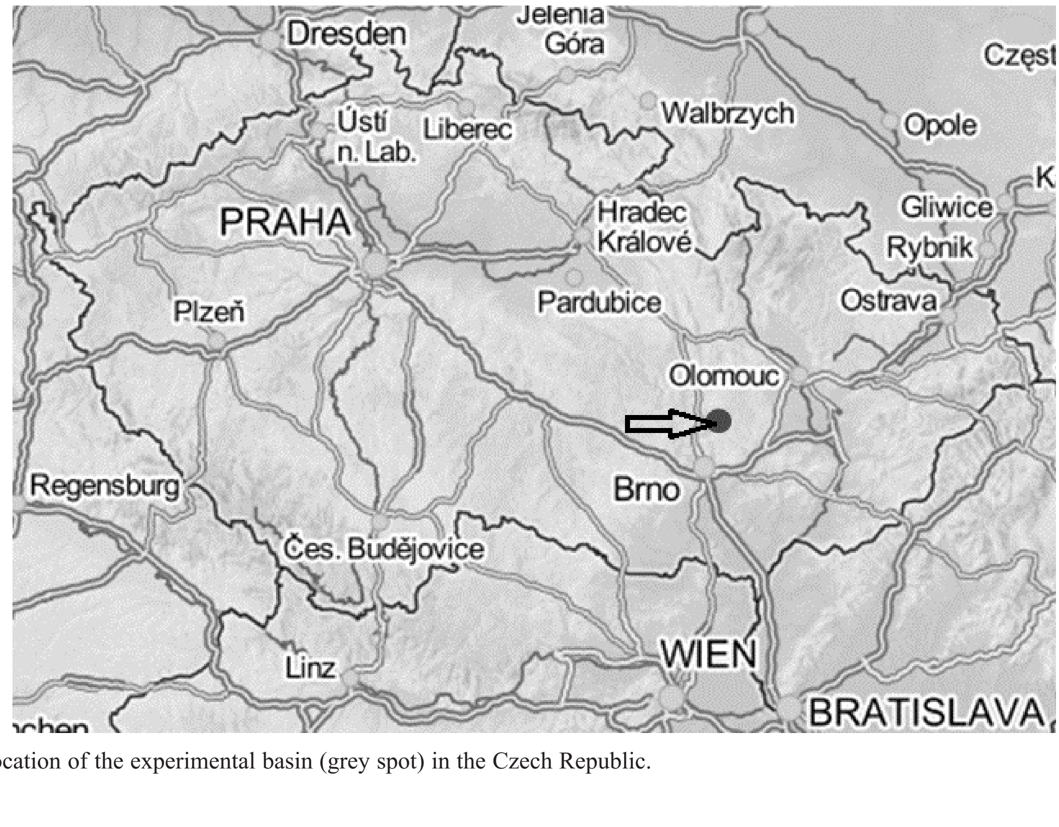

Fig. 1. Location of the experimental basin (grey spot) in the Czech Republic.

Results

Measured runoff and precipitation characteristics with calculated volume of sediment load evoked with extreme storm events in the experimental catchment are presented in Tables 1 and 2 and contain information about crops grown and their cover quality. Poor cover quality was noted for emergent states of vegetation when evolving plant roots and above-ground parts provides only week efficiency in erosion restriction.

Over the entire period of observations the highest discharge and suspended sediment concentration in the stream was caused by extreme snow melt on 29 March 2006. In general it can be stated that snow melt has a significant share in the input of insoluble substances into surface waters. In N1 profile in the Němčický stream catchment this share was 24% (2008) to 84% (in 2006). Snow melting in 2005 was not recorded because the profile equipment did not fully operate.

Transport of suspended matter corresponds with the canopy quality, i.e. with the covering effect of farm crops. In comparable rainfall-runoff events the concentration of insoluble substances, and also the washing away of the soil, are lower in summer months than in spring or in autumn. One of the examples documenting the above statement is a comparison of the events on 1st May and 7th August 2006 in profile N2 (Table 1). The August rainfall-runoff event was more intensive than the May event, but a distinctly higher (ca. threefold) volume of insoluble matter was recorded in May, when the cereal stands were not sufficiently matured (Table 2).

Similarly, before the rainfall-runoff event on 12th September 2005 a field on the slope near profile N1 was freshly ploughed. Therefore the volume of insoluble substances in the rising wave was almost four times higher than in profile N2 situated upstream. Comparing other values, we can estimate that the efficiency of narrow-row crops is 50-80% in such a case in comparison with the ploughed surface without cover, i.e. they can decrease the transport of soil particles into water to more than half. In the summer season the covering effect of cereals is almost the same as that of grass swards (e.g. events on 15th August 2005 and 22nd June 2007 in N2 – Tables 1 and 2).

For two years (2007-08) the erosion slope above profile N2 was covered with a clover grass mixture. Figs. 3 and 4 represent maximum runoff and volume of suspended sediments in the rising wave of rainfall-runoff events for the period 2005-06 in comparison with the period 2007-08 (profile N1). There was a decrease in peak discharge by 72% and in suspended sediment transport by 96% in the period 2007-08 for the realization of protective grassing. But these two years were also characterized by lower precipitation amounts and intensity than 2005-06. According to the values recorded in Tab. 1, the amount of precipitation that caused increased runoff in 2005-06 was 405 mm and 230 mm in 2007-08. Hence it is difficult to conclude how the influence of grass cover and lower precipitation participated in the above difference.

Higher variations in the values of suspended sediment transport in relation to the year, season, and cultivation practices compared to more balanced discharges are evident from 2008 data. Classic ploughing was carried out in

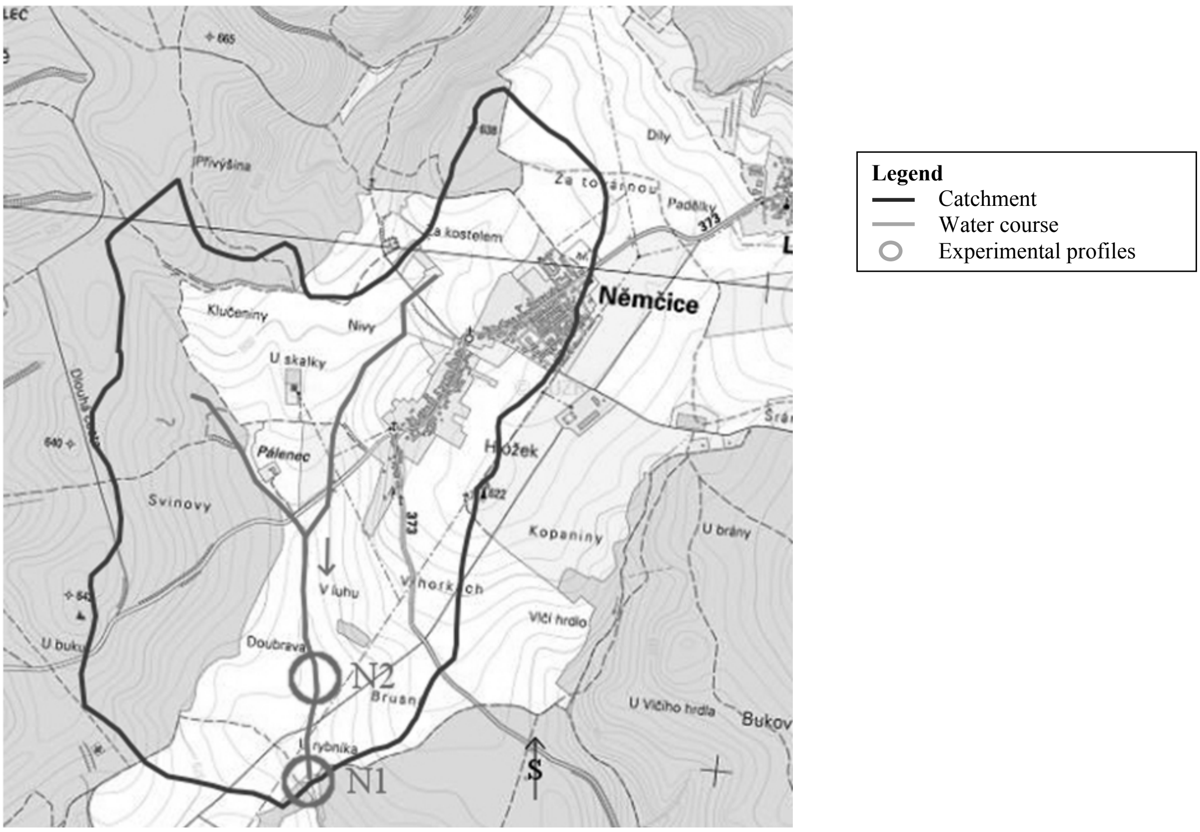

Fig. 2. Situation map of the experimental basin.

Table 1. Measured characteristics and suspended sediment transport of the rising part of the flood wave.

Date	Event No. for Figures 1 and 2	Precipitation amount (mm)	Profile N1		Profile N2	
			Q_{max} ($l \cdot s^{-1}$)	Volume of insoluble substances (kg)	Q_{max} ($l \cdot s^{-1}$)	Volume of insoluble substances (kg)
23.5.2005	1	6	161	922	163	772
15.8.2005	2	19	96	12	95	28
12.9.2005	3	77	1122	27351	760	7262
29.9.2005	4	33	120	21	113	4
29.3.2006	5	Snow melt	1153	145370	1110	131616
1.5.2006	6	69	378	17797	282	14974
22.6.2006	7	2	113	3	107	9
7.8.2006	8	199	960	8894	744	5292
24.3.2007	9	Snow melt	370	5707	240	1069
6.6.2007	10	35	161	108	152	33
22.6.2007	11	33	129	39	119	30
21.7.2007	12	8	312	82	267	95
20.8.2007	13	32	68	13	227	16
6.9.2007	14	10	214	3626	169	1241
23.10.2007	15	2	63	23	55	5
23.11.2007	16	8	177	3205	129	911
1.3.2008	17	Snow melt	108	426	81	262
22.4.2008	18	13	131	526	99	62
7.7.2008	19	26	73	6	66	6
12.7.2008	20	29	91	80	112	97
16.8.2008	21	8	70	669	66	251
15.9.2008	22	26	50	73	90	65

Rem. Some lower discharges in N1 than N2 were caused by natural clogging and overflowing of the channel.

Table 2. State of crops on slopes near gauging profiles.

Date	Cover of arable land		Date	Cover of arable land	
	Near profile N1	Near profile N2		Near profile N1	Near profile N2
23.5.2005	wheat – GC	rye – GC	21.7.2007	wheat – GC	grass – GC
15.8.2005	wheat – GC	rye – GC	20.8.2007	rape – PC	grass – GC
12.9.2005	bare soil	rye stubble	6.9.2007	rape – PC	grass – GC
29.9.2005	bare soil	bare soil	23.10.2007	rape – PC	grass – GC
29.3.2006	bare soil	bare soil	23.11.2007	rape – PC	grass – GC
1.5.2006	maize – PC	barley – PC	1.3.2008	rape – PC	grass – GC
22.6.2006	maize – PC	barley – GC	22.4.2008	rape – GC	grass – GC
7.8.2006	maize – GC	barley – GC	7.7.2008	rape – GC	grass – GC
24.3.2007	wheat – PC	grass – GC	12.7.2008	rape – GC	grass – GC
6.6.2007	wheat – GC	grass – GC	16.8.2008	bare soil	bare soil
22.6.2007	wheat – GC	grass – GC	15.9.2008	wheat – PC	rape – PC

PC – poor cover, GC – good cover

the majority of the land blocks in the catchment before the event on 16 August 2008, which was reflected in the increased transport of suspended sediments.

If we take into account comparable rainfall-runoff events in 2008 and consider the other relevant data, it is possible to estimate the efficiency of the grass cover on the slope near profile N2. A comparison of suspended sediment transport in the period with fully matured clover-grass cover (7th July 2008) and in the period with ploughed up land (18th August 2008) and consideration of other similar conditions of stands and runoffs in the catchment show that the efficiency of the clover-grass cover is 90-99% in comparison with the bare soil. This value corresponds with the theoretical efficiency of permanent grassland according to the universal soil loss equation [11].

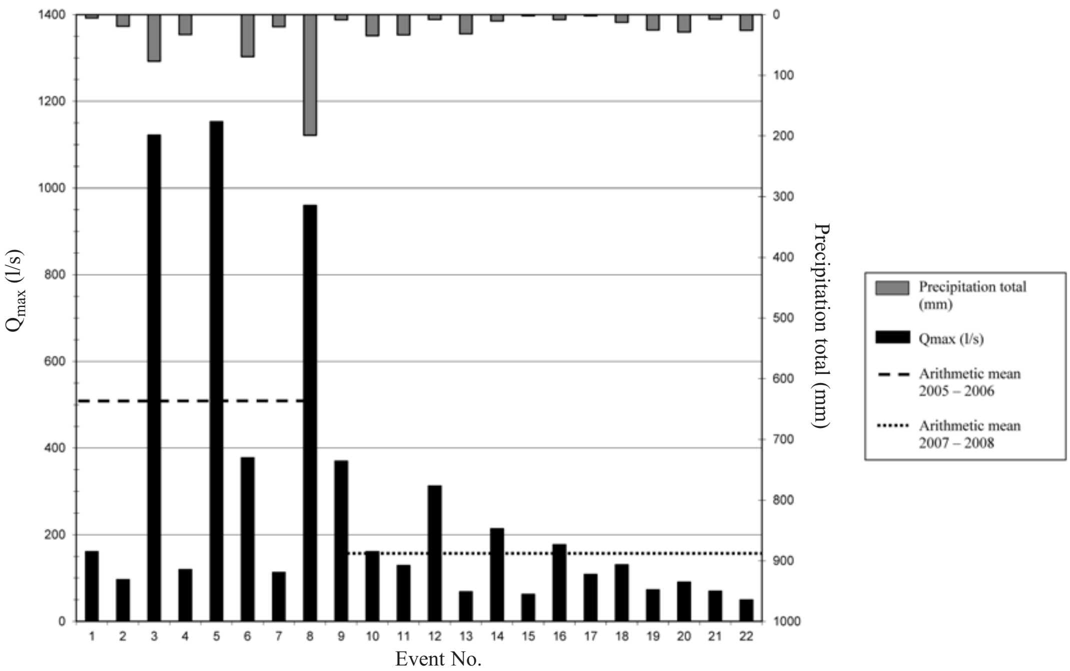

Fig. 3. Discharges (Q_{max}) in profile N1 and causative precipitation totals in 2005-08.

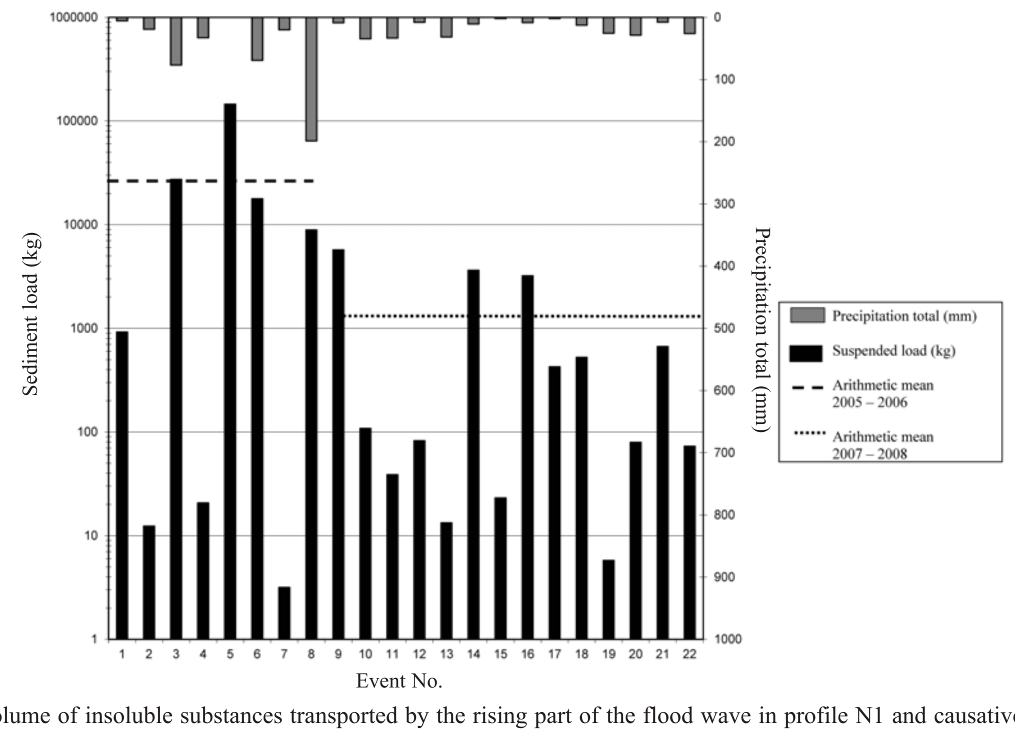

Fig. 4. The volume of insoluble substances transported by the rising part of the flood wave in profile N1 and causative precipitation totals in 2005-08.

Conclusions

Due to a rainfall deficit in 2007 and 2008 it is not possible to explicitly evaluate the influence of protective grassing on a decrease in discharges and sediment transport in the years 2007-08 compared to the period of 2005-06 before the grass-clover growth establishment. Based on the analysis of particular comparable rainfall-runoff episodes, it is to state that the protection (e.g. grassing, growing of narrow-row crops) of slopes adjacent to watercourses has a crucial influence on a reduction in surface water pollution with insoluble substances. In such cases the efficiency of grass cover is 90-99% compared to bare soil, while the efficiency of narrow-row crops is 50-80% in comparison with bare soil. The efficiency of narrow-row crops at the time of maximum vegetation stand is close to that of permanent grasslands.

Measurements of runoffs and suspended sediment transport in extreme rainfall-runoff situations confirmed and partly quantified the influence of narrow-row crops and permanent grasslands on a reduction of soil loss and surface water pollution. More complex conclusions about soil-conservation and flood-control measures require a long series of measurements and are limited by the frequency and occurrence of comparable rainfall-runoff events. The results document the substantial influence of snow melt on suspended sediment transport in small agricultural watersheds. Research on this problem has not been paid sufficient attention in the Czech Republic until now.

Acknowledgements

This paper was supported by Projects MZE 0002704902 and QI92A012 of the Ministry of Agriculture of the Czech Republic.

References

1. GAO P., PASTERNACK G. B., BALI K. M., WALLENDER W. W. Suspended sediment transport in an intensively cultivated watershed in southeastern California. Catena, **69**, 239, **2007**.
2. FUČÍK P., KVÍTEK T., LEXA M., NOVÁK P., BÍLKOVÁ A. Assessing the stream water quality dynamics in connection with land use in agricultural catchments of different scales. Soil and Water Research, **3**, (3), 98, **2008**.
3. RUSSEL M.A., WALLING D.E., HODGKINSON R.A. Suspended sediment sources in two small lowland agricultural catchments in the UK. J. Hydrol., **252**, 1, **2001**.
4. BOARDMAN J. Soil erosion science: Reflections on the limitations of current approaches. Catena, **68**, (2-3), 73, **2006**.
5. SWIECHOWICZ J. Linkage of slope wash and sediment and solute export from a foothill catchment in the Carpathian Foothills of South Poland. Earth Surf. Proc. Land., **27**, (13), 1389, **2002**.
6. MROZIK K. D., PRZYBYLA C. T. An attempt to introduce cultivation and planning measures into the decision-making process in order to improve water-retaining capacity of river catchments. Pol. J. Environ. Stud., **22**, (6), 1767, **2013**.
7. ZHENG M., YANG J., QI D., SUN L., CAI Q. Flow-sediment relationship as functions of spatial and temporal scales in hilly areas of the Chinese Loess plateau. Catena, **98**, 29, **2012**.
8. KLIMENT Z. Transport of suspended sediments in various regions of the Czech Republic. AUC Geographica, **38**, (1), 157, **2003**.
9. KLIMENT Z., MATOUŠKOVÁ M. Runoff changes in the Šumava Mountains (Black Forest) and the foothill regions: Extent of influence by human impact and climate changes. Water Resour. Manag., **23**, 1813, **2009**.
10. UHLÍŘOVÁ J. Survey of efficiency of erosion and flood control measures at Němčický stream. Soil and Water Research, **2**, (3), 85, **2007**.
11. JANEČEK M. et al. Erosion control of agricultural soil. Praha: VÚMOP, v.v.i., 2007, 76. ISBN 978-80-254-0973-2. **2007**.