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The Influence of Extreme Rainfall on Flow, Soil Moisture, Nutrients and Tracer Pathways

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Abstract

On two agricultural experimental catchments with different vegetation cover we have carried out experiments with leaching or wash off nutrients due to high artificial rain intensities: grassland after grazing, arable land, river bank covered with grass and during different seasons (spring, summer, autumn). Rainfall total and soil moisture have been automatically recorded in two depths. The concentration of nutrients was analysed in the laboratory. From the results, it is possible to formulate the following conclusions: flow of nutrients during extreme precipitation is high at the beginning of the soil profile saturation and then gradually decreases; increasing concentration occurs in the period just after grazing or after fertilisation with manure; the highest concentration of nutrients occurred in experiments on the field after tillage. The outcomes correspond to results from rainfall-runoff events, when extreme rainfall causes the wash off the soil into the stream. Before and after the experiment the samples of soils have been taken. The change in POlsen (Olsen P) on the pasture slope was less than 1 mg/kg of dry matter of soil while on the catchment used for crops it was larger than 10 mg/kg. Understanding flow pathways in a catchment requires carrying out field experiments with conservative tracers. The contribution brings results from such experiments on a meadow and in forest. Both types of field experiments with sprinkling contribute to the understanding of the flow and nutrient pathways during an extreme rainfall.

Keywords: *agricultural pollution, sprinkling experiments, flow pathways, tracing experiments*

Rezumat. Influenta ploilor extreme asupra scurgerii, umidităţii solului, nutrienților și formele de curgere a trasorilor

În două bazine hidrografice experimentale agricole s-au efectuat experimente cu scurgeri şi diluția nutrienților cu intensități ridicate ale unor ploi artificiale, pe diferite moduri de acoperire cu vegetație: pășuni, după pășunat, teren arabil, mal acoperit cu iarbă și în diferite anotimpuri (primăvara, vara, toamna).
Precipitațiile, și umiditatea solului au fost înregistrate automat la două adâncimi. Concentrația de nutrienți a fost analizată în laborator. Din rezultate, este posibil să se formuleze următoarele concluzii: scurgerea nutrienților în timpul precipitației extreme este ridicată la începutul saturării profilului de sol și apoi scade treptat; creșterea concentrației are loc în perioada imediat după pășunat sau după fertilizarea cu gunoi de grajd; cea mai mare concentrație de nutrienți a avut loc în experimente pe teren după cultivarea solului. Rezultatele provin din evenimentele ploaie-scurgere, atunci când precipitațiile extreme provoacă spălare solului şi scurgerea în râuri. Înainte și după experiment s-au prelevat probe de sol. Schimbarea POlsen pe versantul pășunat a fost mai mică de 1 mg/kg de materie uscată de sol, în timp ce pe bazinul utilizat pentru culturi a fost mai mare de 10 mg/kg. Înțelegerea căilor de curgere într-un bazin hidrografic necesită efectuarea de experimente pe teren cu trasori. Contribuția unor asemenea experimente pe pajiște și în pădure, constă în producerea de rezultate. Ambele tipuri de experimente pe teren cu ploi artificiale contribuie la înțelegerea formelor de scurgere a nutrienților în timpul unei ploi extreme.

Cuvinte-cheie: *poluarea agricolă, experimente cu ploi, forme de curgere, experimente cu trasori*

Introduction

Getting the best possible knowledge of runoff generation processes is indispensable for a number of technical applications. It means that we need to know not only the usual (more probable) hydrological situations, but also the very extreme ones. „To know" means here to observe in the field. We cannot rely on the computer simulations only. They must be constrained by observed values. Simulations bring the possibility to interpolate between observed values, with a lot of caution to extrapolate outside observed ranges and to bring to our attention further variables which should be observed (Beven, 2005, 2012).

If we are working in the field at the plot scale we can produce a large flood by sprinkling the plot with a large intensity. In practice, such a situation could bring about an important wash off and leaching into the stream. Computer simulations, however, are difficult. The often-used Richard's equation for variably saturated flow might not work. Alternative modelling techniques are being developed, e.g. based on tracing (see Davies and Beven, 2011).

A number of authors used artificial rainfall on plots in order to find out the possible amounts of wash off and leaching from the plots both for practice and for the development of new simulation methods (Sharpley and Kleinman, 2003).

In this contribution, we are dealing with the experimental part of our hydrological research. Two types of experiments are described:

1. Agricultural pollution
2. Tracing for theoretical purposes

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Materials and methods

Agricultural catchments

Selected experimental catchments are situated in different climatic, terrain and soil regions (Table 1). Experimental catchment on Smrzovsky Brook lies on the border of Protected Ecological Area of the Jizera Mountains where only cattle grazing is going on. Because of the restrictions due to ecology the use of industrial fertilisers and pesticides is not allowed. The other catchment (Kralovsky catchment) lies in the foothills of Krkonose. The crops are winter wheat, winter barley, winter rapeseed (*Brassica napus*), opium poppy (*Papaver somniferum*), caraway (*Carum carvi)*, buckwheat (*Fagopyrum esculentum*), and maize or corn (*Zea mays*).

The fields are fertilised with both industrial fertilisers and manure.

Table 1. Climatic and soil conditions of selected agricultural catchments (DAM – artificial fertilizer with Nitrogen, DASA – artificial fertilizer with Nitrogen and Sulphur)

Parameter	Watershed	
	Smržovský creek	Královský creek
Watershed area	3,6 km^2	3,1 km^2
Above the sea level	645-836 m	450-490 m
Average annual discharge	0.072 m^3 s^{-1}	0.042 m^3 s^{-1}
Total rainfall all year	1100 mm	716 mm
Type of soil	etnic podzols,haplic podzols	brown acid
pH of soil	acid slender	weakly acid
Sorption complex	unsaturated	weakly saturated
Type of management	only pasturage	active
Fertilizer	no artificial fertilizer, no pesticides	manure- on field in autumn, dung- on meadows, fertilizer (DAM, DASA)

Several experiments have been carried out both on a meadow and in forest on the watershed divide of the Smrzovsky Brook and the Nisa River. The meadow plot is about 150 m upstream of the outlet of the Smrzovsky catchment. The forest plot is about 500 m distance from the meadow plot (Fig. 1). The area on the watershed divide between the Nisa and the Jizera catchments (in which the Smrzovsky Brook and Kralovsky Brook are nested) has been quite intensively studied by several cooperating institutions for a number of years. The impulse for the research has been given by the forest die-off during the 80s in the Jizera Mountains.

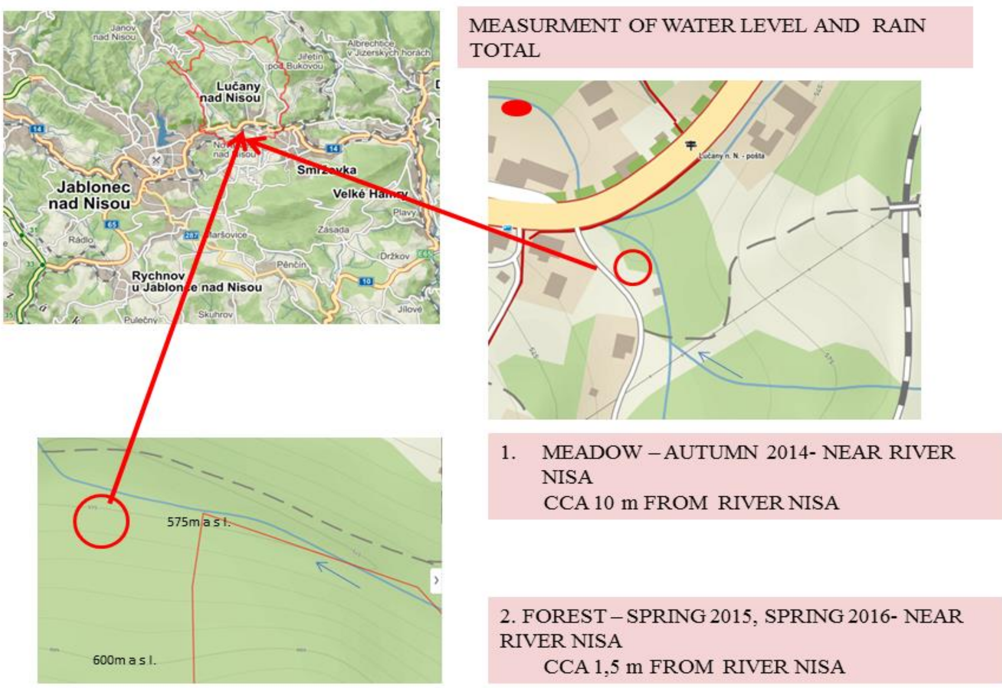

Fig. 1: Map showing the meadow and forest slopes used for tracer experiments (red circles – experimental sites, full red elipse – water level and rain measurement, brown line – the border of Lucany nad Nisou)

Experimental design and automatic sprinkling system

On the sprinkling area of 25 m^2 nine sprinklers have been installed. Water is brought from a nearby source (e.g., a tributary outside the plot). Data (artificial rain, soil moisture) are recorded in the data logger. The moisture sensors have been installed at 20 cm and 50 cm depths for agricultural and tracer experiments, respectively.

Agricultural catchments

Sprinkled area on grass or on ploughed field has been bordered by a piece of plastic down to 15 cm. Sprinkled water was led into a vessel under the topsoil (at depths of 15 to 25 cm) with discharge into a collecting vessel. During the sprinkling samples of water have been taken for determination of $N\text{-}NH_4$, $N\text{-}NO_3$, K, $P\text{-}PO_4^-$, and P. Samples of soil have been taken before and after the experiment.

Plot experiments with tracing

The sprinkled area has been bordered by a higher piece of plastic and the slope has been dug into 80 to 120 cm depth (Fig. 2). Troughs have been installed at depths 20 and 50 cm. Flow in them is measured with large tipping buckets.

Fig. 2: Troughs (flumes/gutters) in the dug-off slope

Experimental area was first sprinkled with „clean" water from the stream, then with water containing tracer (5mg/l NaCl). Samples of NaCl have been taken from a ditch at the foot of the slope and from the stream (upstream, middle and downstream the slope), outflow from the slope, which was clearly visible in the stream, and a more distant site on the stream (Fig. 3).

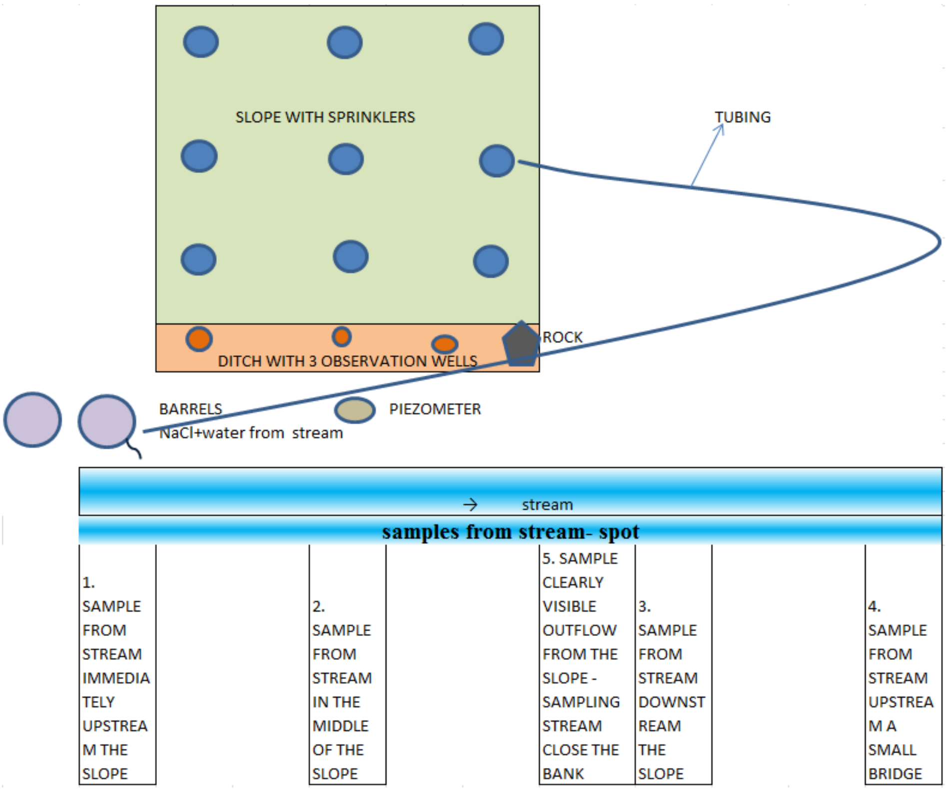

Fig. 3: The set-up of the forest experiment

Results and discussions

Agricultural catchments - In April 2013 the experiment on ploughed field in the Kralovsky catchment was carried out before sowing maize. The sprinkling was done in two phases. In both first and second phases the large sprinkling intensity brought about overland flow.

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The number of samples collected was 37. Maximum concentrations of chemical substances occurred in the first phase. The nitrates showed some fluctuation in concentrations (Fig. 4), with maximum concentration 31 mg/l.

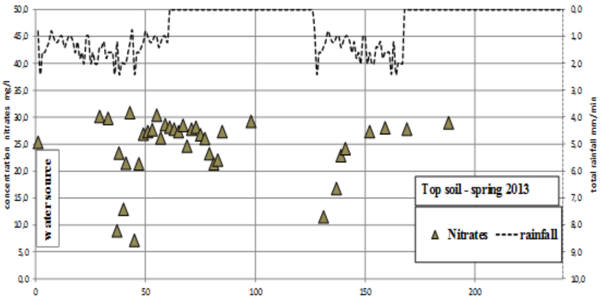

Fig. 4: Kralovsky catchment experiment in April 2013 – sprinkling and concentration of nitrates; x-axis is in minutes

Maximum concentrations of total P and phosphates were 0.73 and 1.31 mg/l, respectively. A comparison of 3 experiments in different conditions is given in Table 2.

Table 2. Duration of sprinkling, total rain and the amount of water used

DATE	Time			Total rainfall (mm)	Used amount of water (l)
	Start	End	Minutes		
	KRÁLOVSKÝ STREAM - TOP SOIL				
17.4.2013	13:41	14:42	61	86,2	1683
	15:47	16:30	43	61,4	1202
	KRÁLOVSKÝ STREAM - RIVER BANK - GRASS				
12.5.2014	15:06	15:58	52	132,4	3300
	17:46	18:50	64	162,4	4060
	SMRŽOVSKÝ STREAM AFTER GRAZING - GRASS				
7.8.2013	12:29	12:53	36	36,8	920
	13:47	14:18	31	46,8	1170
	15:01	15:27	26	27	675

Experimental plots

In the first phase of experiment from 7th to 10th October 2014 we sprinkled the plot directly with water with NaCl during 3 days. The lateral flow from the slope occurred only on the third day from the lower trough, i.e. on 9th October and later also from the upper one. Before the second phase started, the plot was sprinkled only with water on 20th October. The addition of NaCl followed on 21st Octobre 2014. Already the first day lateral flow started from the lower trough and at about midday from the upper one.

On the second day, i.e. 21st October the highest conductivity in samples from both tipping buckets was measured. At the same time the conductivity has been measured also in the stream, but it did not change much because of the distance between them. In Table 3 the duration of sprinkling, the amount of water and the concentrations of NaCl are given. Table 4 shows the average and maximum values of conductivity.

Table 3: Times of applications of NaCl on meadow and forest plot

	DATE	START	FINISH	AMOUNT OF WATER		TOTAL RAINFALL	CONCENTRATION NaCl
				l		mm/m^2	IN BAREL
MEADOW - AUTUMN 2014	7.10.2014	10:50	17:10	4662	H_2O+NaCl	186,5	5g/l
	8.10.2014	10:32	13:07	2096	H_2O+NaCl	83,8	5g/l
		13:26	16:20	3093	H_2O+NaCl	123,7	5g/l
	9.10.2014	7:47	8:08	550	H_2O+NaCl	22	5g/l
		8:10	11:23	4359	H_2O	174,4	
	20.10.2014	7:37	11:34	3857	H_2O	154,3	
		11:53	14:56	3425	H_2O+NaCl	137	5g/l
	21.10.2014	7:36	11:04	3392	H_2O+NaCl	135,7	5g/l
		11:05	13:00	3091	H_2O+NaCl	123,6	5g/l
FOREST- SPRING 2016	14.5.2016	16:45	17:31	789	H_2O	46	
	15.5.2016	11:00	15:30	6245	H_2O	250	
	16.5.2016	13:45	16:30	3120	H_2O	125	
	17.5.2016	10:10	11:35	7656	H_2O	76	
	17.5.2016	11:36	16:20	5774	H_2O+NaCl	231	5g/l
	18.5.2016	10:00	16:07	7656	H_2O+NaCl	303	5g/l
	19.5.2016	9:03	14:00	4270	H_2O+NaCl	171	5g/l
	1.1.1900	15:20	16:55	5125	H_2O+NaCl	172	5g/l
	20.5.2016	7:50	13:30	5663	H_2O+NaCl	226	5g/l

Table 4: Average and maximum values of conductivity on experimental plot in October 2014

Location	**Parameter**				
		Conductivity (µS/cm)		NaCl (mg/l)	
	Time	7-9.10.2014	20-21.10.2014	7-9.10.2014	20-21.10.2014
The creek- immediately upstream the slope	average	140	147	31	30
	maxim value	8.10.2014	20.10.2014		
		151	153		
The creek - immediately downstream the slope	average	146	160	30	34
			20.10.2014		
	maxim value	(3x) 148	183		
tipping bucket on the upper trough	average	129.3	5820.1		
	maxim value	9.10.2014 12:35	21.10.2014 11:55	9.10.2014 11:55	21.10.2014 14:30
		139	8700	42	707
tipping bucket on the lower trough	average	475.5	4850		
	maxim value	9.10.2014 17:45	21.10.201 12:50	9.10.2014 10:50	20.10.2014 10:00
		807	8270	707	689

In 2015 and 2016 the forest plot experiments have been carried out (Figs 2 and 3). Because of extreme drought in 2015, the best experiment showing the functioning of the plot, is the one in May 2016, when there was enough water in the brook after snowmelt.

Unlike the meadow plot here the brook was quite near to the plot. The plot was sprinkled in the beginning only with water (3 and half days) and another 3 and half days with water plus NaCl. Conductivity was measured on selected sites in the stream. During sprinkling with the tracer, the samples were also taken. Unfortunately, during the whole period we did not observe the flow in the troughs, but the ditch/well at the foot of the slope filled up with water containing the tracer.

The highest values of both conductivity and NaCl occurred in samples taken in stream close to the bank at the experimental plot. Times of sprinkling are shown in Table 3. Average and maximum values of conductivity and NaCl are in Table 5. The increase in conductivity is plotted in Fig. 5.

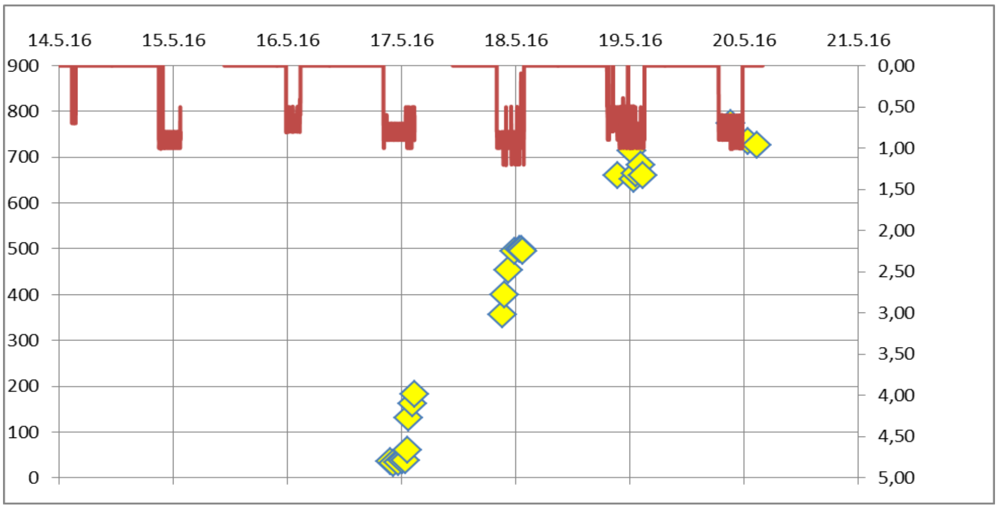

Fig. 5: Artificial rainfall (mm/min) and conductivity (μS/cm) during the tracing experiment in May 2016

Table 5. Average and maximum values of conductivity and NaCl on experimental plot in forest in May 2016

Location	Value	Parameter	
		Conductivity (μS/cm)	NaCl (mg/l)
The creek-immediately upstream the slope	average	164	31.3
		19.5.2016	18.5.16 15:00
	maxim	172	34.6
sample from creek near the bank in the place of distinct outflow from the slope (bank)	average	183	53.175
		19.5.16 16:00	17.5.2016 16:00
	maxim	211	62.6
The creek - immediately downstream the slope	average	174	40.1
		19.5.2016 15:30	20.5.2016 10:30
	maxim	195	44.5
The creek – upstream a bridge	average	167	33.4
		19.5.2016 13:40	20.5.2016 13:00
	maxim	185	37.9
The observation well	average	5450	2496
		20.5.2016 10:30	20.5.2016 10:30
	maxim	7740	4951

Conclusion

The agricultural experiment - Increased concentrations occur in the period just after grazing or after fertilisation with manure. The highest concentration of nutrients occurred in experiments on the field after ploughing. The results correspond to results from rainfall – runoff events, when extreme rainfall causes the wash off the soil into the stream.

The tracer pathways - The flow pathways are dependent on the soil cover, soil saturation and degree of the sloping down of the terrain. The infiltration in forest soils is quite large due to a larger number of preferential pathways (e.g. pipes created by the roots). This might be the reason why we have not seen the lateral flow into the troughs, but only in the ditch/well at the foot of the slope.

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