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DOUBLE SIZE FULLJET FIELD RAINFALL SIMULATOR FOR COMPLEX INTERRILL AND RILL EROSION STUDIES

Petr Kavka, Luděk Strouhal, Barbora Jáchymová, Josef Krása, Markéta Báčová, Tomáš Laburda, Tomáš Dostál, Jan Devátý and Miroslav Bauer

The Czech Technical University in Prague, Faculty of Civil Engineering, Department of Irrigation, Drainage and Landscape Engineering, Prague,Thákurova 7, 16629, Czech Republic; barbora.jachymova@fsv.cvut.cz

ABSTRACT

Field observations and consecutive modelling of soil erosion events proved to be essential for understanding and predicting erosion and sediment transport. An experimental approach often utilizes a large variety of rainfall simulators. In this technical note a complex methodology is introduced, using a mobile rainfall simulator developed at the Czech Technical University in Prague. An experimental setup with two watered plots (16 + 1 m^2) was established, which enables simultaneous measurements in two scales and monitoring of surface runoff, flow velocity, infiltration, sediment subsurface flow, vegetation cover effect suspended solids and phosphorus transport, surface roughness and surface evolution under rainfall and other variables. The simulator is built on a trailer transportable by car with folding arm carrying four FullJet WSQ nozzles operating independently. The configuration and water pressure 0.7 bar leads to the total watered area 2.4 x 9.6 m. Average drop size (d50) reaches 1.75 mm for 0.7 bar pressure. Christiansen uniformity index CU reaches 85%. A selection of experimental results highlights both the advantages and the weaknesses of the presented experimental setup.

KEYWORDS

Rainfall simulation, Surface runoff, Subsurface runoff, Mobile rainfall simulator

INTRODUCTION

Water erosion is the most widespread form of soil degradation. Reducing the erosion is one of the major challenges in landscape management. Sediment transport from arable land into surface waters (streams, rivers, reservoirs) induces many significant problems in water bodies [1]. This problem was highly accelerated when the landscape patterns were destructed during technical improvement of agro technology and land consolidations. In Eastern Europe this effect was accelerated by collectivization of agriculture [2]. Based on research it is known that sediment transport can be reduced by inhibition of the surface runoff and proper agricultural management.

Rainfall simulation experiments are widely used as a method to study various flow and transport processes induced by rainfall [3]. They have been used on different land uses, slopes, scales, soils and climate conditions [4], [5], [6]. But most of the experiments have been driven by rather narrow objectives and therefore do not provide data for complex description of rainfall runoff and sediment transport processes. That is one of the actual scientific objectives nowadays - to describe the driving mechanisms of the physical processes in details and consequently to implement the plot scale data in optimization of the catchment scale parameters.

Surface runoff rate and sediment yield in the form of suspended solids concentration are standard variables observed in experiments oriented on soil erosion research with use of rainfall simulators. The review of small portable simulators used across Europe provides [7]. Due to the nature of the device the small simulators with watered area around 1 m^2 are more frequent. Larger simulators can be found as well [8], [9], [10], [11]. They are essential for a consequent mathematical modelling of both surface and subsurface runoff and related processes.

Together with eroded soil particles various nutrients are transported in the surface runoff. Phosphorus is the most significant and monitored particulate nutrient in the environment [12], [13]. It enters the water courses and is retained in the ponds and water dams where it impairs the environmental balance and water quality [14].

Another runoff component is the quick subsurface flow also known as hypodermic flow or interflow [15]. On the arable land it mostly occurs on the interface between the shallow ploughed topsoil and compacted subsoil. Since these two flow components may interact and lead to implications for both erosion and hydrologic response to the rainfall event, it is important to observe and model the subsurface processes as well.

Soil erosion intensity (in particular splash type) is decreased with the vegetation growth [16]. The soil surface is protected largely due to the plant's leaves, which absorb part of the kinetic energy of the raindrops. Farming operations also directly affect soil movement through activities such as tillage [17], root crop harvesting, and the trampling of soil and removal of vegetation by livestock. Combination of the current state of vegetation and farming operations influenced state of soil aggregates. Soil aggregates are less exposed to the direct impact of the raindrops and associated crumbling, which is considered as a trigger of the erosion process [18]. In order to evaluate the effect of the vegetation on particular soil erosion event it is therefore necessary to document the actual leaves extent. To this end two most common parameters are used: Canopy Cover and Leaf Area Index (LAI). Repetitions of the experiments in the same site during the growing season as well as comparing results from vegetated and bare experimental plots enable the vegetation cover and state of the soil surface effects to be assessed.

Together with detaching soil particles from the aggregates by the impact of raindrops also the surface runoff plays an important role in soil erosion, in particular its volume and flow velocity. Higher velocity induces larger shear stress and dragging forces to carried soil particles. From the known particle-size distribution of the eroded material basic physical principles of soil erosion can be verified [19].

METHODS

Device and setup description

Mobile rainfall simulator operated by CTU in Prague was constructed in 2012 in cooperation with Research Institute for Soil and Water Conservation (VÚMOP). Its detailed description can be found in [20] and only basic information will be given here. The essential part of simulator is a folding boom with four nozzles by Spraying Systems – FullJet 40WSQ [10] controlled by electromagnetic valves. The boom consists of a dural steel framed structure and eight supporting telescopic legs. The boom can be folded out directly from the trailer and heaved by a pulley into desired height. Once the legs are joined it is completely standalone and can be detached and moved independently, constrained only by the length of the control wires and water supplying hosepipes. The whole construction was designed to be easily and quickly set out and packed back again without any interfering with the plot marked for the simulation. In order to prevent the wind from affecting the simulation the supporting construction is covered with the tarpaulin.

The device includes a 1 m^3 tank, portable generator, pump producing a constant pressure with minimum delivery 40 l/min and a control unit for managing the rainfall intensity by triggering the electromagnetic valves. The electromagnetic valves trigger the separate pairs of nozzles. Their opening and closing in an arbitrary time interval produces the desired intensity of simulated rainfall. Coupling the nozzles into pairs reduces hydraulic shocks in the water distribution system and therefore helps maintaining a uniform spatial distribution of water over the experimental plot.

Four nozzles FullJet 40WSQ are positioned 2.65 m above the ground and 2.4 m apart. Type of the nozzles as well as the position were selected after many calibration tests aimed at reaching as uniform spatial distribution and droplet characteristics as similar to natural raindrops as possible. These tests were carried out on the plot 2.1 x 2.8 m centred under the first nozzle (for exact position see Figure 1), assuming that the rest of the area is symmetric. Final configuration yielded the Christiansen's uniformity index [21] of 80% and more for all rainfall scenarios commonly used in the field simulations.

This configuration and water pressure 0.7 bar leads to the total watered area 2.4 x 9.6 m. It can be used for variable setup of experimental plots, although limited by decreasing rainfall intensity towards the edges of the watered area. In CTU simulations there are two separate plots used simultaneously, one with dimensions 1 x 1 m and another 2 x 8 m with the longer edge along the slope, as illustrated in Figure 1.

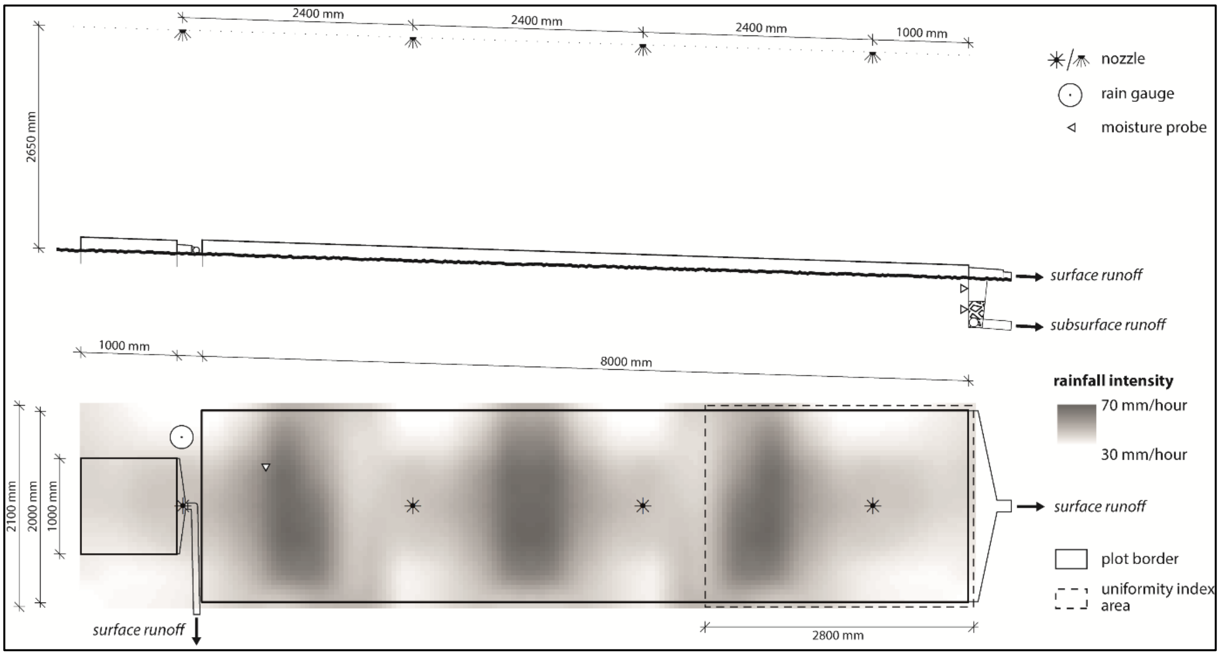

Fig. 1 - Scheme of the rainfall simulator with two plots and with position of the nozzles, rain gauge and soil moisture probe.

Rainfall characteristics

The most crucial variable influencing the course of the simulations are the rainfall intensity (spatial distribution and average over the plot) and droplet characteristics. Droplet size and impact velocity were analysed by a disdrometer, spatial distribution of intensity by a network of small buckets [22]. Average drop size (d50) reaches 1.75 mm for 0.7 bar pressure. Christiansen uniformity index CU [23] reaches 85%.

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In order to maintain uniform spatial distribution of water over the plots, the experimental setup was designed with rather large overspray of the experimental plots. Therefore only part of the sprinkled water falls onto the plots and a final intensity needs to be checked in each simulation.

First the outflow rate at the nozzles is checked by collecting and weighing the sprinkled water in a four minutes test, as it differs slightly depending on the exact water pressure in the system. Next a reference measurement is performed at the beginning of every campaign on the fallow plots covered with an impervious tarpaulin. The rainfall intensity is derived from the total discharge after the steady state is reached. From the acquired values from a whole set of campaigns a calibration curve describing the relationship between the outflow at the nozzles and resulting intensity onto the plots is being derived and consecutively refined. The curve is then used for rainfall intensity determination in simulations on the vegetated plots.

The precipitation intensity is checked in 10 a step during every simulation run with the tipping bucket rain gauge with collecting area 200 mm^2 and resolution of 0.2 mm set on a fixed location above the upper end of the larger experimental plot (Figure 1). Its output represents point values which cannot be used for deriving mean rainfall intensity over the plot but is valuable for verification of the temporal uniformity. Second continuously recorded variable is the water pressure at the first nozzle, which is monitored with the digital pressure sensor. Recording interval of 4 s is used due to the short intervals of valves operation. Acquired data serves for detecting eventual pressure changes in the water distribution system, which could affect the rainfall intensity and bias the simulation outcomes. As illustrated in Figure 2 lapses in rainfall intensity or even stoppage of the simulator occur and have a fast response in observed runoff. Data from both rain gauge and pressure sensor is necessary for correct water budget balancing and explanation of induced variability in observed variables. Moreover it is essential in experiments with variable rainfall intensity when reproducing natural rainfall events.

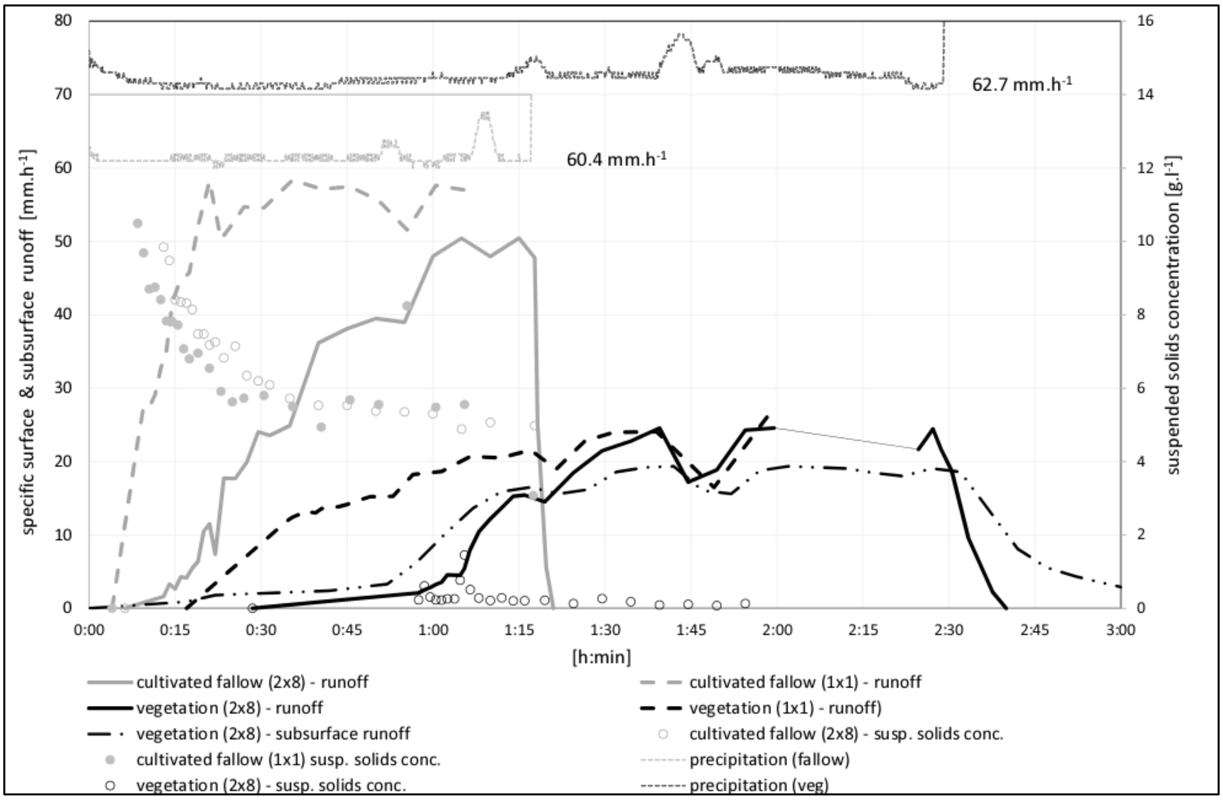

Fig.2 - Surface and subsurface flow, suspended solids concentration and precipitation intensity during presented experiment

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Surface runoff and plot scale effect

Time to initiation of the surface runoff is determined visually by observing the discharge from the plot in the lower outlet. The runoff rate is measured in situ gravimetrically for variable time intervals. Within first 10 minutes after the runoff initiation the interval is 1 minute, another 10 minutes the runoff rate measurements are performed in 2 minute intervals and for the rest of the simulation (until 1 hour after the runoff initiation or reaching steady state) the interval is increased to 5 minutes. The purpose of this arrangement is to capture the dynamics of the runoff rate and suspended solids concentration. They change considerably within the initial phase and tend to steady in the course of the simulation, as shown in Figure 2.

The runoff needs to be measured independently for each of the two parallel plots. However the discharges are measured in the same intervals and samples are taken at the same relative time with respect to corresponding times of initiation. This way the runoff dynamics in both plots ($1m^2$ and 16 m2) can be compared.

Soil water regime and shallow subsurface flow

The runoff monitoring is accompanied with soil water regime monitoring. The soil water content is measured in two ways. Undisturbed 100 cm^3 soil samples are taken both before and after the simulation and later they are analysed in the lab. The soil water regime in the top 5 cm of the soil profile is continuously monitored with the ThetaProbe ML2x and recorded in 1 minute interval. Additional probes are installed in the depths of 30 cm and 50 cm below the surface.

To monitor shallow subsurface runoff a trench is being excavated along the lower edge of the larger experimental plot. It is 2 m long and 0.6 m deep. At the bottom of the trench a drainage pipe with diameter of 100 mm is installed. Both the bottom and the walls of the trench from the topsoil / subsoil divide below are covered with an impermeable plastic foil so that only shallow runoff from the topsoil reaches the drainage pipe. The trench is partly filled with the gravel and enclosed by the topsoil. The drainage pipe is connected through the collection pipes to a tipping bucket, where the subsurface runoff is continuously measured or sampled. The collection system was designed in a way which does not require removing prior to each agrotechnical operation.

Maximum flow velocity

For the flow velocity determination, two methods are used in parallel. For the maximum flow velocity which corresponds to the rillflow in the preferential flow paths the progress of the dye tracer Brilliant Blue FCF is observed. This method is especially used on the cultivated fallow plots. From the top of the plot the time intervals are measured for the tracer to travel each 1 m distance. In order to highlight the head of the moving tracer an extra dose of the dye is added at the beginning of each 1 m section. This measurement is repeated three times for each simulation after reaching the steady outflow and ideally close to the moments when the suspended soils samples are taken. The timing is important for the verification of the relationships between flow velocity and the grain size of suspended particles.

Average flow velocity

The dye tracer method is partially subjective due to the need of visual tracing and it is hard to use in case the surface is covered with full-grown vegetation. Besides the maximum flow velocity the mean velocity represents the process of sediment transport. This variable is obtained by measuring the electric conductivity after the application of potassium bromide (KBr) or sodium chloride (NaCl) solution. It is usually applied subsequently in 2, 4 and 6 meters from the lower end of the plot, so it is possible to derive the velocities in separate sections of the sloping plot. Using a conductometer (WTW Cond 3310) the beginning of the rise and the time of the peak of the conductivity wave is observed. Due to normally very long recession limb of the conductivity wave this measurement is being stopped once a distinct lapse in conductivity is observed. Beside the

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difficult manipulation (conflict with other measurements) another disadvantage of this method is a slow yet unwanted soil salinization which might in the long term lead to the inhibition of vegetation growth and impairing the soil fauna in the location.

Suspended solids

In order to evaluate the dynamics of suspended solids concentration the runoff samples are taken in the same time intervals as in the runoff rate measurements. The samples are weighed in the field and later analysed in the laboratory according to the standards [24]. Suspended solids are filtered from the solution, dried and their weight is converted into concentrations. Final sediment yield results from relation of concentrations to the runoff rates in respective time intervals of sampling.

Along with the samples for concentration analysis another set of samples is taken for determining the particle-size distribution. Since such determination is rather time-consuming, these samples are taken in 10 minute interval only. Based on results of particle-size analysis the changes in sediment composition during the erosion event may be monitored. When related to the runoff velocity the particle-size may also be used for determination of friction and dragging forces in the overland flow.

Phosphorus transport

Concerning the chemicals the phosphorus is monitored. Phosphorus concentration analyses are carried out on mixed samples composed of several 50 ml of runoff taken at different times. Resulting 5 samples represent three 5 minute and two 15 minute intervals of runoff. There are two basic forms of phosphorus in surface runoff: particle-bound and dissolved phosphorus. Mixed samples are stabilized in the field with highly concentrated HNO2 (0.5 ml HNO2 in 100 ml of sampled water) in order to avoid dissolved phosphorus decay. Later in the laboratory two types of samples are analysed using ICP-OES, Inductively coupled plasma optical emission spectrometry [25]. In the original unfiltered samples the total phosphorus concentration is determined. For dissolved phosphorus determination the suspended solids are removed from the samples using 0.45 μm filter. The particle-bound phosphorus is determined then as the dissolved phosphorus subtracted from the total.

Vegetation stage and soil protection

Leaf Area Index

LAI is measured within the LAI-2000 Plant Canopy Analyzer. The device is based on comparison of the light intensities above the vegetation and near the soil surface. Advantage of this method is that it is fast and enables repetitive or multiple measurements for obtaining a representative value. The measurement is always performed on the vegetated experimental plot and in the open crop field next to it. The value from the latter site serves as a reference value for detecting significant variance in the vegetation growth in the experimental plot due to previous simulations.

Canopy Cover

The measurement of CC is performed by sensing of the surface with the camera and analysing the images using a supervised classification in GIS software. The analysed plot is delimited with a metal squared frame of the area 1 m^2, which is used for referencing and scaling of pictures.

Soil Loss Ratio (SLR)

The sheltering effect of the vegetation is quantified with use of Soil Loss Ratio (SLR). It is determined by referencing the sediment yield from the vegetated plot to the sediment yield from a standard, reference plot maintained as a fallow with seedbed conditions. The reference fallow is cultivated before each simulation according to the procedures stated in the technical standard [26]. First, the topsoil is ploughed into the depth of about 10 cm, aggregates loosened with the rake and levelled with the wooden batten. Large stones and remains of the plants are removed and at the end the surface is carefully rolled with a manual turf roller. Main goal of these procedures is to ensure the surface conditions as close to the reference state as possible for every simulation.

Soil surface roughness and surface changes

The soil surface changes and roughness are evaluated by a photogrammetric technique. The accuracy of derived surface representation depends on the camera specifications. The plausible spatial resolution is about 1-2 mm as reported e.g. in [27] and height accuracy compared to more precise laser scanning may be below 2 mm for smooth surfaces, as reported in [28]. Photogrammetric evaluation is based on the stereo imaging of the field plot surface before and after the rainfall simulation. Since the ground control points (GCPs) are necessary for the image referencing, a dural reference frame with 40 equally distributed GCPs was designed. The frame encloses the maximum area of 1.6 x 1.1 m and is equipped with a mobile cross bar labelled by GCPs which makes the size of the evaluated frame variable. The reference frame is kept in horizontal position with four threaded rods driven into the plot before the rainfall simulation. Sony NEX-5N, interchangeable lens Compact System Camera is utilized for the sensing. The reference frame is removed before the simulation start, whereas the rods are left in the plot to allow the frame being put in the same position after the simulation end. Photographs are always taken with the same camera settings (aperture f-8, exposure time 1/40 and less, focal length 16 or 18 mm depending on selected lens). Thanks to the tarpaulin covering the rainfall simulator the lighting has a diffuse character, which makes the sensing less sensitive to the changes in cloudiness and direct sunlight. The images are taken manually with camera oriented vertically in the height of approximately 1.3 m above the ground and the image distance of 0.3 m. Each captured photo covers the whole frame area and all reference points. Usually more than one stereo pair images are taken for providing larger sample for the evaluation.

Obtained stereo pair images are processed in PhotoModeler Scanner software, which derives accurate, high quality 3D models and enables measurements based on photographs. The process is known as photo-based 3D scanning [29] or image-based modelling [30] and is used for producing a dense point cloud (Dense Surface Modelling) from images of textured surfaces. The multi-sheet camera calibration is executed before the automatic Dense Surface Modelling.

Subsequently, dense surface point clouds created with PhotoModeler Scanner are processed in ArcGIS software. At first the digital surface model (DSM) is generated in the form of triangulated irregular network (TIN) which is then converted to a 1 mm raster DSM. Then the surface raster DSMs created before and after the rainfall simulation are subtracted. This subtraction is used in evaluation of soil volume replacement caused by the rainfall-runoff process. Other analyses are performed on the derived DSMs in order to quantify soil surface roughness parameters such as random roughness, tortuosity, mean upslope depression or other indices. The soil volume replacements as well as the roughness and surface indices are valuable for validation of physically based runoff and erosion models.

SELECTED 2014 STUDY RESULTS

A selection of typical outputs from CTU rainfall simulations is presented. Full results and their in-depth analysis are out of scope of this technical note, provided outputs are to illustrate the most important variables and phenomena discussed in previous sections. During an experimental campaign in June 26th 2014 the rainfall simulation was carried out on two parallel experimental plots in Bykovicky stream catchment. The field is located in Central Bohemia in the mean altitude of 440 m a. s. l. with mainly well drainable soils – 67 % sandy loam, 10 % loamy sand and 8 % sand [31]. The plot steepness is 9 %. The presented experiments were (1) fully grown barley *(Hordeum vulgare L.)*, and (2) reference fallow.

Surface and shallow subsurface flow

Figure2 shows surface flow for both experiments and for both plot sizes (16 m^2 a 1 m^2). From the chart a significant impact of the presence of vegetation is obvious on the total volume of surface runoff. From the cultivated fallow in a total of 307 l outflowed during the simulation, the total amount of surface runoff produced on the plot with vegetation cover was half (152 l). At the same time for both surfaces the velocities of the formation of surface runoff differ for different plot size. For the 1m^2 plot the surface runoff occurs earlier than for the 16 m^2 plot.

Figure 2 also shows the progress of the subsurface runoff also under the plot with a vegetation cover. Recorded values show that the emergence of subsurface runoff occurs earlier than the emergence of surface runoff. The total volume of subsurface runoff from the plot is approximately the same as the volume of surface runoff.

Vegetation cover and soil protection

At the time of the experiments the vegetation has already been fully grown and ready to harvest. Its Canopy Cover was 100%. In this case, therefore, vegetation fully protected the soil surface from direct impact of rain drops.

Measured by LAI-2000 the Leaf Area Index reached 3.8 but as it had been found already in 2013 during comparative measurements, the aging vegetation can affect the results of the LAI-2000 device. This fact is confirmed by the device manual [32] and the published studies [33]. Transmittance of senescent leaves may be larger than that of green leaves, which can result in underestimated LAI [22]. The protective effect of vegetation was assessed by Soil Loss Ratio in 60 minutes from the beginning of the simulation, until then the SLR was close to zero since there was only limited flow of suspended solids recorded in first 40 minutes. The terminal SLR in 60 minutes reached 0,013. Concerning the total average concentrations of suspended solids in runoff from vegetation it reached 0.31 g/l while from the cultivated fallow it was approximately 20 times higher (7.10 g/l).

Suspended solids and phosphorus transport

The total amount of transported suspended solids from fallow plot was 1770 g, approximately 50 times higher than the quantity transported from areas with vegetation (30 g). Both surfaces also varied in terms of the concentration of total and dissolved phosphorus. The concentration of total phosphorus in the cultivated fallow outflow ranged from 2.5 to 7.3 mg/l. In the outflow from the vegetation plot the total phosphorus concentration values were significantly lower (0.4 – 1.7 mg/l). On the other hand higher values of the concentration of dissolved phosphorus were measured in the outflow from vegetation (0.136-0.187 mg/l). The concentration of dissolved phosphorus in runoff from the cultivated fallow ranged from 0.071 to 0.088 mg/l.

Flow velocity

For both types of land cover the values of the velocity differ significantly. For cultivated fallow the top velocity measured by the dye tracer reached 0.19 m/s in average. By using the KBr tracer the change in conductivity indicating the fastest particles corresponded to the result of the "dye tracer" (i.e. 0.19 m/s). The maximum concentration shift corresponding the mean flow velocity of the surface runoff was less than half (0.08 m/s). After the application of the same amount (0.75 l) of KBr in the area with vegetation cover the change in the conductivity was minimal and it was difficult to determine the exact time of the fastest particles. The velocity was only about 0.01 m/s, which is 5% of the velocity on the fallow plot.

Soil surface roughness and surface changes

The rectangle of 1.3 x 0.9 m inside the reference frame was analysed for surface changes of the fallow plot. Point clouds (each about a million points) and digital terrain models with a pixel size of 1 x 1 mm were generated before and after the rainfall. The rain and runoff caused a slight decrease in surface random roughness from 17.61 mm to 16.60 mm and the overall surface layer decrease of 2.13 mm as a result of the consolidation of a loosened layers and soil loss.

DISCUSSION AND CONCLUSION

Mobile Rain Simulator represents an important alternative to watching real rainfall-runoff events in-situ [7]. The presented device is a comprehensive system to enable detailed monitoring of a wide range of processes associated with rainfall-runoff episodes. The quest for the maximum amount of the measured quantities is motivated by inter alia, time and financial savings.

Recent experiments also help reveal some shortcomings of the device itself and the procedures applied. In Figure 2 there are evident differences and uncertainties in the pressures in the system. During the experiments, it turned out that the chosen type of the pump during the experiments at its maximum power and any increase in the roughness in pipes is affecting the flow. At the same time, the operator is not able to monitor the minor differences in the pressure in the system, it is therefore necessary to use automatic pressure control device to maintain constant pressure. Because a considerable amount of values is processed, it is convenient to store all the recorded data to by single multichannel data logger for processing. The essential and limiting factor for fully functional use of a similar device is the service staff. The minimum number is a trained and experienced team of five researchers. Another limiting factor is the need for adequate water supply. For rain intensity of 60 mm/hour the consumption is around 1.5 m^3 of water per hour of operation.

The combination of the surface without vegetation and areas with vegetation allows monitoring the impact of the presence and state of the vegetation and the generation of surface and shallow subsurface runoff. Repeated tests can then monitor the effect of vegetation in different development stages. Examples of the use of simulators to monitor the effect of vegetation on the genesis of the surface runoff are presented in a series of studies [34], [35], [36], [37]. Furthermore, it is possible to use the results of experiments to refine the description infiltration process. The device offers an opportunity to monitor processes of shallow subsurface flow in controlled conditions [38].

Last but not least the device is a suitable tool for monitoring the process of transport of nutrients (especially phosphorus) with the water flow. Phosphorus is limiting, on the one hand, the fertility of arable land and the quality of the aquatic ecosystem on the other hand. It is changing the forms from particulate to dissolved, and for this reason, it is very difficult to monitor the major forms of phosphorus during real rainfall-runoff and erosion events. A rainfall simulator is an alternative for these types of experiments under vegetation covers [6], [5] or under alternative erosion control practices [39].

There are many types of simulators. Most of them work with rained area up to 1.5 m^2, because operation of the DS with larger areas is demanding. The devices are described in detail in a number of studies [40], [41], [42]. The presented equipment thanks to its complexity covers the range of series of published studies that are focused on one or two phenomena related to rainfall-flow events. The arrangement of two parallel areas of 16 + 1 m^2 allows monitoring of both rill and interill runoff process simultaneously. The obtained data is a valuable input for the calibration and validation of new and existing mathematical models.

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