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Detecting surface runoff location in a small catchment using distributed and simple observation method

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SUMMARY

Surface runoff is one of the hydrological processes involved in floods, pollution transfer, soil erosion and mudslide. Many models allow the simulation and the mapping of surface runoff and erosion hazards. Field observations of this hydrological process are not common although they are crucial to evaluate surface runoff models and to investigate or assess different kinds of hazards linked to this process. In this study, a simple field monitoring network is implemented to assess the relevance of a surface runoff susceptibility mapping method. The network is based on spatially distributed observations (nine different locations in the catchment) of soil water content and rainfall events. These data are analyzed to determine if surface runoff occurs. Two surface runoff mechanisms are considered: surface runoff by saturation of the soil surface horizon and surface runoff by infiltration excess (also called hortonian runoff). The monitoring strategy includes continuous records of soil surface water content and rainfall with a 5 min time step. Soil infiltration capacity time series are calculated using field soil water content and *in situ* measurements of soil hydraulic conductivity. Comparison of soil infiltration capacity and rainfall intensity time series allows detecting the occurrence of surface runoff by infiltration-excess. Comparison of surface soil water content with saturated water content values allows detecting the occurrence of surface runoff by saturation of the soil surface horizon. Automatic records were complemented with direct field observations of surface runoff in the experimental catchment after each significant rainfall event. The presented observation method allows the identification of fast and short-lived surface runoff processes at a small spatial and temporal resolution in natural conditions. The results also highlight the relationship between surface runoff and factors usually integrated in surface runoff mapping such as topography, rainfall parameters, soil or land cover. This study opens interesting prospects for the use of spatially distributed measurement for surface runoff detection, spatially distributed hydrological models implementation and validation at a reasonable cost.

1. Introduction and context

Heavy or long lasting rainfall events may trigger surface runoff and induce major flood hazards, even far from river networks. In France flooding by surface runoff represents 43% of flooding recognized as natural disaster (Dehotin and Breil, 2011a). This statistic was obtained using 140,000 natural disaster declarations in the French official national database since 1983. Thus surface runoff appears as one major cause of flooding in France, the other one being flooding by river overflow.

Surface runoff generation is a topic addressed by many authors in various research fields. These researches include for example understanding of surface runoff processes in various natural contexts (Lange and Haensler, 2012; Latron and Gallart, 2008; Muñoz-Villers and McDonnell, 2012; Wemple and Jones, 2003) or evaluating the role of surface runoff in pollution transfer or soil erosion (Beven, 2006; Bryan, 2000; Carey and Simon, 1984; El Kateb et al., 2013; Hudson, 1993; Wu et al., 1993). Several authors focused on the role of different landscape factors (microtopography, roughness, vegetation, land use, antecedent soil water

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content, water table, soil water potential etc.) and rainfall characteristics (rainfall intensity, drop size, storm kinetic energy etc.) on surface runoff generation (Arnaez et al., 2007; Braud et al., 2001; Castillo et al., 2003; Dunjó et al., 2004; Dunne et al., 1991; Dutton et al., 2005; Lafforgue, 1977; Latron and Gallart, 2008; Nicolas, 2010). Hydraulic features designing in engineering is also a domain for surface runoff investigation, mainly for evaluating surface runoff discharge, velocity or water depth (Boughton and Droop, 2003; Chanasyk et al., 2003; Jain and Singh, 2005; Koutroulis and Tsanis, 2010). Flood forecasting, groundwater recharge and irrigation are other topics of surface runoff survey (Harbor, 1994). There are two main approaches for surface runoff study and prediction: modeling-based and field observation-based methods.

Several models are used for surface runoff processes simulation or mapping. The Lisem model simulates surface runoff and rill erosion (De Roo et al., 1996a,b). The WEP and the RUSLE models (Nearing et al., 1989), are based on universal equation of soil losses (Renard et al., 1991). The RuiCells® model uses cell automaton method for surface runoff simulation (Douvinet et al., 2006; Langlois and Delahaye, 2002). These models are based on infiltration estimation combined with the overland kinematic wave equation to compute runoff discharge. Their parameterization or calibration can be performed using field experimentation (Connolly et al., 1997; Connolly and Silburn, 1995; Smith et al., 2004; Wu et al., 1993). Soil erosion mapping models are based on combinations of landscape factors such as soil type, land use and several topographic parameters (de Jong van Lier et al., 2005; Le Bissonnais et al., 1998; Le Gouée and Delahaye, 2008; Renard et al., 1991). Other models, like KINEROS2 (Smith et al., 1995; Woolhiser et al., 1990) and SEAGIS (DHI, 2002) are designed to simulate sediment yield time series and the effect of management strategies to limit the erosion process. These models need field parameters such as distributed soil parameters or agricultural practices that are difficult to obtain. Moreover, the temporal dynamics of field parameters are generally not measured nor taken into account.

Field observations of surface runoff are usually achieved using various techniques. One of the most used is rainfall simulation devices (Abudi et al., 2012; Hartanto et al., 2003; Navas et al., 1990; Nicolas, 2010; Pérez-Latorre et al., 2010; Roose, 1977; Roose et al., 1993; Silva and Oliveira, 1999; Singh et al., 1999). It consists in field simulation of rainfall events with various intensities at fixed plots or using a mobile simulator. They allow estimating the rate of rainfall which infiltrates the soil and the one which flows overland. This technique allows testing the impact of different and realistic rainfall intensities. Nevertheless results are different from those of natural rainfall conditions because rainfall spatial heterogeneity is not integrated and soil initial conditions are not realistic for all simulations. Several field observation studies are based on tracer experiments. They use dye tracers or natural water isotopes (^{18}O of precipitation and stream waters) for chemically based hydrograph separations (Holzmann and Sereinig, 1997; Weiler et al., 1999). These experiments sometimes show the role of event water on surface runoff flow (Holzmann and Sereinig, 1997; Weiler et al., 1999). However meaningful identification of flow components and their generation mechanisms by these techniques needs coupling with other field data (Rice and Hornberger, 1998). These field experiment techniques of surface runoff observation are often heavy to install, to monitor and also difficult to replicate (installation and maintenance). Because the usual techniques are generally of large dimension and need specific skills, their deployment and monitoring on several sites are difficult. Usually they do not provide usable information about surface runoff mechanisms (Hudson, 1993). They are seldom used for validation purposes, to understand the role of several parameters on surface runoff processes or for soil parameters estimation in hydrological models. Thus existing observation techniques are not relevant for studying the spatially distributed occurrence of surface runoff in natural conditions. They do not allow a comprehensive mapping of areas sensitive to surface runoff at a catchment scale.

A method for surface runoff susceptibility mapping, (called IRIP: French acronym for Intense Pluvial Runoff Index) was proposed by Dehotin and Breil (2011b). It is based on spatial analyses of landscape factors and allows a comprehensive mapping of areas sensitive to surface runoff production, transfer paths and accumulation at a catchment scale, without explicit hydrological modeling. The objective of the experimental study presented in this paper is to assess the relevance of this mapping method, i.e. to verify that runoff occurrence is larger in areas pointed out to be prone to surface runoff by the method. We are therefore interested in getting a spatialized evaluating of runoff occurrence. For this purpose, we use a distributed network of soil water content measurement sensors and rain gauges stations, with a high temporal resolution to estimate surface runoff occurrence frequency.

The experimental catchment and the observation strategy are presented in Section 2, follows by the monitoring protocol for surface runoff occurrence detection and the analysis methods. Section 3 details and discusses field observations. Section 4 synthetizes the experimental results, discusses the limits of the proposed field instrumentation and illustrates its potential for holistic field observations of catchment response.

2. Materials and methods

2.1. Experimental catchment description

The Mercier stream catchment (7 km^2) is located near Lyon city in France (Fig. 1). It is a small rural catchment with low urbanization, covered mainly with forests located upstream and crops located downstream of the catchment. The upstream part of the catchment should not be very sensitive to surface runoff because of the mitigation role of vegetation. Catchment's geology is composed of granite and gneiss with soils characterized by a large spatial variability (SIRA, 2012). The catchment is characterized by permeable soils with permeability values ranging from 0.01 to 0.001 mm h^{-1} (Gonzalez-Sosa et al., 2010). The high soil permeability is expected to lead to a low sensitivity of the catchment to surface runoff by infiltration excess. Upstream of the catchment, soils are very shallow (<0.1 m). This catchment is part of a long term Field Observatory (OTHU project)[1]. Collected data were used in several research programs such as the AVuPUR project (Assessing the Vulnerability of PeriUrban Rivers) described in Braud et al. (2010) and Braud et al. (2013). This project also provided a part of the data used in this study, such as a LIDAR digital elevation model (Sarrazin, 2012), a high resolution land use map derived from aerial photos (Jacqueminet et al., 2013), and *in situ* soil hydraulic properties (Gonzalez-Sosa et al., 2010).

2.2. Presentation of the IRIP method for surface runoff mapping

The IRIP method is based on a spatial analysis, from upstream to downstream a watershed, of potential occurrence of surface runoff, using landscape factors relevant to describe surface runoff generation, transfer and accumulation (Dehotin and Breil, 2011b). These factors include topographic factors (slope, wetness index, drained area index and break slope), soil parameters (soil thickness, soil permeability and soil erodibility) and land use (urbanized, agricultural or forest areas). The method produces three maps depicting

[1] Field Observatory for Urban Water Management, http://www.graie.org/othu/.