Journal of Hydrology 519 (2014) 3651–3663

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

The internal structure of erosive and non-erosive storm events for interpretation of erosive processes and rainfall simulation

F. Todisco *

Department of Agricultural, Food and Environmental Sciences, Agricultural and Forestry Hydraulic Unit, University of Perugia, Borgo XX Giugno, 06121 Perugia, Italy

ARTICLE INFO

Article history:
Received 21 May 2014
Received in revised form 11 September 2014
Accepted 1 November 2014
Available online 13 November 2014
This manuscript was handled by Konstantine P. Georgakakos, Editor-in-Chief, with the assistance of Joanna Crowe Curran, Associate Editor

Keywords:
Erosive events
Event properties
Event profile
Natural event simulation
Event time distribution

SUMMARY

The paper presents an analysis of the rainfall structure for 228 events defined using a minimum inter-event time MIT = 6 h recorded in the experimental station of Masse (Central Italy). The events were further sub-sampled to define a set of *storms*, these being events in which at least one 5 min interval had a rainfall rate of at least 9.6 mm/h. Some *storms* were erosive and some non-erosive respectively if the corresponding runoff volume and soil loss measured at Masse were greater than zero or not. The selected rain rate threshold is not able, alone, to sample all and only the erosive events recorded at Masse. The properties of the *storms* were further analyzed in terms of the properties of blocks (or runs) of 5 min periods that had rain above the nominated threshold rainfall rate and of the corresponding antecedent and subsequent rainfall. The goal was to develop ways of representing the time distribution of rainfall that might have explanatory power in terms of soil loss and that might be useful to select compound criterion (overall and profile characteristics) for the identification of erosive events from pluviograph records and to simulate rainfall corresponding with those of natural erosive events in Central Italy. Some statistical erosive storm hyetographs have been simulated according to the results of the analysis.

1. Introduction

The rate of rainfall in storms shows large fluctuations between periods of showers, low-rain, or no-rain, which follow one another over various time intervals. An understanding of intra-storm variations has been proven to be very important, not only in runoff generation and soil erosion studies (Cerdà, 2002; Dunkerley, 2012; Frauenfeld and Truman, 2004; Jebari et al., 2012; Mermut et al., 1997; Parsons and Stone, 2006; Ran et al., 2012; Watung et al., 1996), but also in partitioning water among interception, evaporation, infiltration, ponding, and overland flow (Hanke et al., 2004; Struthers et al., 2007) in urban flash flooding studies, geochemical and nutrient balancing (Angermann et al., 2002), and water use efficiency in agriculture. However, while the literature contains a wealth of papers describing rain event properties that are globally shown to be significant in generating infiltration, overland flow, and erosion, there has been less discipline-specific exploration analyzing the influence of the geographical and temporal variability of rain on the above-mentioned processes (Dunkerley, 2008b; 2012).

Rainfall is typically classified and described using overall properties (such as mean intensity, total depth and duration, rainfall energy, and drop size distribution), or by particular properties related to rainfall periods (such as instantaneous intensity or maximum intensity in a specific time interval). Intensity (I) and duration (D) are considered to be the two dominant rainfall characteristics controlling the hydrologic response, and they are therefore widely used to describe rainfall events, to classify rainfall rates, and to investigate their frequency (Hammad et al., 2006; Kumar et al., 2002; Marques et al., 2008a; Nolan et al., 1997; Shi et al., 2012; Tokay and Short, 1996; Vandenberghe et al., 2010). Moreover, the event rainfall depth (P) and the largest intensity ($I_{d,max}$) encountered in a sub-period (d) of a rain event, are rainfall characteristics typically considered for use in distinguishing between erosive and non-erosive events (even if recently the distinction has not been always performed and all events were included in the estimation of the erosivity index due to the lower difficulty encountered in abstracting and analyzing rainfall intensity data using personal computers). In Wischmeier and Smith (1978), the pluviograph records are subdivided into rainfall events using the minimum inter-event time (MIT) approach with MIT = 6 h and an event was omitted in estimating the erosivity index, if the condition $P \leqslant 12.7$ mm (0.5 in.) occurs, unless a $P \geqslant 6.35$ mm (0.25 in.) falls in 15 min. In Renard et al. (1997), all events were included in the estimation of the erosivity index for the western United States, while for the eastern United States events with

* Tel.: +39 075 5856052.
E-mail address: francesca.todisco@unipg.it

http://dx.doi.org/10.1016/j.jhydrol.2014.11.002
0022-1694/

$P \leqslant 12.7$ mm were omitted and considered insignificant, unless the maximum 15 min intensity, $I_{15,max}$, exceeded 24.13 mm/h (0.95 in./h). Further to the numerous studies that have proven that rainfall characteristics affect runoff generation and soil loss, the parameter $I_{d,max}$ is typically selected as the best for estimating processes, with d varying from 5 min, 10 min, 15 min, 30 min, to 60 min (Capolongo et al., 2008; Cattan et al., 2006; Fang et al., 2012; Merz et al., 2006; Meusburger et al., 2012; Obi and Salako, 1995). In addition, in evaluating the effect of rainfall temporal variability on the hydrological process, the use of $I_{d,max}$ (instead of the mean event intensity) is important because a large amount of the event total rainfall falls within a small fraction of its duration (Huff, 1967), and because rainless gaps within a longer rain event can clearly alter the mean rain rate recorded for that event.

The USLE/RUSLE rainfall erosivity factor (EI_{30}), the *drop size*, and *kinetic energy* are additional properties considered when studying the relationship between soil erodibility, rainfall erosivity, and the interconnected effects of rill, inter-rill, and splash erosion. EI_{30} is also widely adopted in the empirical estimation of event soil loss (Bagarello et al., 2008, 2011a, 2011b, 2013; Kinnell, 2010). In particular, empirical relationships have been found between the runoff amount and E, and between the peak runoff rate and I_{30}; hence, an empirical rainfall–runoff model is embedded in the USLE/RUSLE models. However, in some cases, EI_{30} is not able to deal with the effect of runoff on soil loss, and as a consequence the model efficiency associated with the EI_{30} index can also be low (Todisco et al., 2009; Bagarello et al., 2008). Therefore, to improve soil loss prediction at an event temporal scale by using USLE-type empirical models, some researchers have been required to insert in the erosivity term features of the hydrograph (and thus indirectly of the intra-storm intensity); for example the runoff coefficient, the product of runoff amount, and the peak runoff rate (Bagarello et al., 2008, 2011a, 2013; Foster et al., 1982; Kinnell, 2010; Williams, 1975; Williams et al., 2008). This fact clearly emphasizes the importance of using a deeper interpretation of rainfall phenomenon for investigating erosional processes, and for use in other studies using rainfall, runoff, and soil loss measures such as the investigation of the reason for the temporal variability of the erosive phenomena (Nearing et al., 1999; Todisco et al., 2009). For example, it has been shown that in events that have the same overall characteristics, the soil loss (t/ha) varies in time, which therefore determines a dispersion of the data (and the associated limited accuracy of estimation models), and can be explained only by using different intra-event characteristics and pre-event conditions. In such cases, a more careful analysis of the significant features of hyetographs could provide answers and clarify reasons for the seemingly inexplicable temporal variability of erosive events.

Drop size and *kinetic energy* properties of real and simulated rains have been widely discussed in literature, and they are parameters typically included in the design of rainfall simulation apparatus and experiments. However, in designing rainfall simulation apparatus and experiments, the key event properties employed in soil erosion studies to date lack a complete correspondence with the comparable measures of natural events (Agassi and Bradford, 1999; Dunkerley, 2008b; Mathys et al., 2005; Kinnell, 2005) both because used simulated rain rates are typically constant and too high with reference to the natural ones (Hanke et al., 2004).

The growing awareness that intra-storm intensity variations could have an important range of effects on hydrologic and erosion responses, and that there is a possibility of incorporating these into simulated rain event pre-determined intensity variations, have recently driven further investigations (Parsons and Stone, 2006; Ran et al., 2012) in relation to the effects of intra-storm properties on soil loss dynamics. In particular, the effects of the position of maximum rainfall intensity (during an event) and of the rainless intervals have been analyzed. Dunkerley (2012) demonstrates that event profile exerts an important effect on infiltration and runoff. Uniform events of unvarying intensity yielded the lowest total runoff, the lowest peak runoff rate and the lowest runoff ratio. These parameters increased for early peak profiles and reached maxima for late peak profiles. As the largest percentage changes are seen in the peak runoff rate it follows that splash dislodgement of soil particles and overland flow transport and raindrop impacted flow transport are likely to also vary among the rainfall event profiles. In cases of friable soils, transport limitation would apply and marked differences in sediment load would be expected as a function of the rainfall event profile. To explore the validity of these findings in different area of applications event-based measures like peak sediment concentration or maxima eroded particle size distribution are required. Currently, the use of studying intra-event erosive rainfall characteristics in developing rainfall hyetographs that are as similar as possible to natural storms is considered relevant in the understanding hydrological and erosive processes on the surface of the earth. Similarly, introducing more significant storm characteristics in the event soil loss estimation models, selecting erosive events from among rainfall data, and investigating the reasons for soil loss in erosive events in a similar way to investigating overall rainfall properties (or vice versa) are also relevant in understanding hydrological and erosive processes. Another field in which the rainfall' properties exert a role is the stemflow production in plants. How the rainfall intensity and the event profile affect stemflow behavior on woody plants have been the object of an experimental study of Dunkerley (2013) and more recently the effect of varying intensity profiles on stemflow flux, stemflow volume and stemflow fraction have been explored by Dunkerley (2014). In other words, knowing the time distribution of rainfall in storms is of the utmost importance for use in various research and applied fields, and therefore requires further investigation as this aspect has been partially explored only in few papers until now. From rainfall records for Illinois, Huff (1967) derived statistical expressions for the time distribution of storm rainfall, and described storm factors that influence the time distribution characteristics. More recently, the structure of rain intervals and the intervening rainless gaps has been investigated in some studies. Peters and Christensen (2002) showed that the temporal pattern has scale invariant properties revealing a critical self-organization, and that rain has been described as a relaxation process akin to the episodic release of accumulated strain in seismic events (Peters and Christensen, 2006). Vandenberghe et al. (2010) proposes a stochastic design rainfall generator by combining the traditional concept of Huff curves for the analysis of internal storm structure with the concept of copula based secondary return period of a storm. Furthermore, daily rainfall disaggregation models have been described as being common, and storm event disaggregation models rare, but available (Gyasi-Agyei and Melching, 2012).

This paper introduces concepts of rainfall disaggregation and of rainfall deviation sequences using reference values in erosion studies. The methodology presented uses a modified theory of *runs* to define a new concept of rainfall disaggregation specific to describing the internal structure of the *storms* with particular attention to the high intensity rainfall periods. The *storms* are events in which the rain rate exceeds a selected threshold. Some *storms* are erosive and some non-erosive respectively if the corresponding runoff volume and soil loss measured at the station of Masse (Todisco et al., 2012), are greater than zero or not. The statistical time distribution (Huff curves) of erosive and non-erosive *storms* is also determined. The statistics describing the internal structure of the erosive and non-erosive *storms* are used to formulate compound criteria, to sample only erosive storms from pluviograph records at the experimental station of Masse and then to simulate erosive rainfall profiles.