Journal of Hydrology 544 (2017) 1–9

Contents lists available at ScienceDirect

Journal of Hydrology

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

Research papers

Discovering historical rainfall erosivity with a parsimonious approach: A case study in Western Germany

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ARTICLE INFO

Article history:
Received 28 July 2016
Received in revised form 31 October 2016
Accepted 12 November 2016
Available online 12 November 2016

This manuscript was handled by K. Georgakakos, Editor-in-Chief, with the assistance of Marco Borga, Associate Editor

Keywords:
Long-term reconstruction
Parsimonious modelling
Rainfall erosivity

ABSTRACT

An in-depth analysis of the interannual variability of storms is required to detect changes in soil erosive power of rainfall, which can also result in severe on-site and off-site damages. Evaluating long-term rainfall erosivity is a challenging task, mainly because of the paucity of high-resolution historical precipitation observations that are generally reported at coarser temporal resolutions (e.g., monthly to annual totals). In this paper we suggest overcoming this limitation through an analysis of long-term processes governing rainfall erosivity with an application to datasets available the central Ruhr region (Western Germany) for the period 1701–2011. Based on a parsimonious interpretation of seasonal rainfall-related processes (from spring to autumn), a model was derived using 5-min erosivity data from 10 stations covering the period 1937–2002, and then used to reconstruct a long series of annual rainfall erosivity values. Change-points in the evolution of rainfall erosivity are revealed over the 1760s and the 1920s that mark three sub-periods characterized by increasing mean values. The results indicate that the erosive hazard tends to increase as a consequence of an increased frequency of extreme precipitation events occurred during the last decades, characterized by short-rain events regrouped into prolonged wet spells.

1. Introduction

Models provide a means of deconstructing the complexity of environmental systems and, through experimentation, of understanding the univariate contribution to multivariate complexity.

[Mark Mulligan and John Wainwright, 2004. Modelling and model building. In: *Environmental Modelling*, Wiley, p. 10.]

The large amounts of energy present in rainstorms cause rainfall splash erosion and a number of runoff related erosion features (Toy et al., 2002) as a function of rainfall amount and intensity. The erosive force of rainfall, expressed as rainfall erosivity (Wischmeier and Smith, 1978), is a major driver of soil erosion resulting from the kinetic energy of raindrop's impact and the rate of associated runoff (e.g. Boardman and Poesen, 2006). Moreover, it is assumed that rainfall erosivity will potentially increase due to climate change because of the associated change in precipitation characteristics (e.g., Nearing et al., 2004). The underlying assumption is that rainfall is getting more variable and hence more extreme rainfall events could be expected (Knapp et al., 2008) resulting in increasing rainfall erosivity. Changes in seasonal and annual erosivity are driven by single extreme events. This makes difficult to quantify them, as it requires long-term (>22 years), high resolution (30 min) rainfall data. For central Europe, only two long-term rainfall erosivity data have been published with 70 and 100 years of observations respectively (Verstraeten et al., 2006; Fiener et al., 2013), calculated from rainfall data with 5–10 min temporal resolution. Such datasets highlight the presence of some increasing trends in rainfall erosivity between the 1940th and the 2000th (Fiener et al., 2013). However, these two datasets are too limited to gain better insights into longer historical periods, where indication for periodic variability could be found. Climatic variability can drive events grouped in some particularly rainy years or months

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http://dx.doi.org/10.1016/j.jhydrol.2016.11.023
0022-1694/

according to storms climatic variability over interannual to century scales (Peterson et al., 2002; Cavazos and Rivas, 2004; Wetter et al., 2011). Changes in precipitation extremes over the time period 1951–2010 have been studied by van den Besselaar et al. (2013) in Europe, considering five consecutive 20-year time intervals with 10-year overlap. Despite considerable decadal variability, the results of these authors indicate that 5-, 10- and 20-year events of 1-day and 5-day precipitation for the first 20-year period generally became more common during this 1951–2010-year period. In spite of this, and the enormous today's information technology capabilities, the impact of rainstorm perturbations on lands still remains an uncertain issue for the scarcity of quantitative studies (Higgitt and Lee, 2001; Wainwright and Mulligan, 2004; Diodato and Bellocchi, 2010b; Walsh et al., 2011). Climate information uncertainty poses, in fact, challenges especially for the analysis of observed and simulated rainstorm data since areas with the heaviest precipitation may just be between recording stations (Willmott and Legates, 1991; Fiener and Auerswald, 2009). Changes in erosive rainfall distributions could have more impact than the more often cited global warming due to a more vigorous hydrological cycle and concentration of rainfall in sporadic but more irregular and intense events (Allen and Ingram, 2002; Mullan, 2013). These particular erosive storm events are associated with rainfall conditions occurring locally.

Accurate rainfall measurements on short time scales are required to obtain rainfall erosivity values according to the RUSLE methodology (Renard et al., 1997) or to similar procedures (Panagos et al., 2015). There are examples in Switzerland (Meusburger et al., 2012), Greece (Panagos et al., 2016a) and Italy (Borrelli et al., 2016), where erosivity has been modelled based on high temporal resolution rainfall data. This is an issue for long-term studies, because records of this type are not available for years antecedent to the modern instrumental period (Diodato et al., 2008). This is also true for exploring erosive storm-land interactions and modelling the climatic implications for European landscapes. For that, parsimonious models can be used because they overcome the limitations imposed from sophisticated models. The latter are data demanding and therefore less ideally applied to historical times for which data availability and resolution are usually limited. At present, studies are rare which make use of parsimonious modelling approaches to integrate historical data with contemporary knowledge. Previous works paid attention on Mediterranean sites in great detail (e.g., Romano and Santini, 2000; Diodato and Bellocchi, 2014). Alternative models have been developed to estimate the long-term average rain-erosivity when only average precipitation data, such as mean monthly or/and annual totals (Lo et al., 1985; Renard and Fremund, 1994; Yu and Rosewell, 1996; Mikhailova et al., 1997; Licznar, 2005) are available. Other approaches generate annual rainfall erosivity values based on rainfall data (e.g. Diodato and Bellocchi, 2010a). They are however not suitable to estimate rainfall erosivity amount in individual years. In the recent past, instead, a number of studies concerning the European environment reported on the possibility to model the rain erosivity as a continuous process from scarce precipitation data and then to derive rainfall erosivity time series, also thanks to the retrieval of historical information (Diodato, 2004; Diodato et al., 2008). Most of these studies have a local value and are conditional to the access of sufficiently complete historical datasets in the region or basin of interest.

Aims of this study are (i) to develop and test a parsimonious rainfall erosivity model using long-term erosivity data derived from 10 stations in Western Germany (71 years; 5-min resolution rain data; Fiener et al., 2013), and (ii) to analyse changes in erosivity since 1701 applying the model along the long-term precipitation dataset (1701–2011) for Europe presented by Pauling et al. (2006).

2. Materials and methods

2.1. Study area

The study area (51°33′N; 6°41′E to 52°00′N; 8°55′E) defined through the availability of long-term high resolution precipitation data is located in the central Ruhr region, in Western Germany, ranging from the Lower Rhine Basin in its eastern part to the Westphalian Plain in its western part. In its South, it is bordered by the hills of the Rhenish Massif. The area is relatively flat with altitudes increasing from approximately 30 m a.s.l. in the west to 150 m a.s.l. in the east.

The climate is strongly influenced by the variability of the atmospheric circulation, with westerly flows bringing mild, rainy weather in winter and cool, rainy weather in summer (van Ulden et al., 2007). In the last decades, increasing convective precipitation events have tended to be associated with higher temperatures (Berg et al., 2013).

Fig. 1a shows, for the period 1950–2014, the 95th percentile of annual daily rainfall across Germany. For the study area, certain division exists between west and east, with differences in the magnitudes ranging from 7–8 to >10 mm d^{-1}. The mean annual precipitation is equal to 773 mm, which increases up to about 150 mm from west to east.

2.2. Rainfall erosivity data

The annual rainfall erosivity data (1937–2002) were extracted from a long-term high resolution precipitation dataset of high resolution (5 min) measurements at 10 locations. The measuring stations (Fig. 1b) are located in a distance of approximately 60 km (over an area of about 10,000 km^2) exhibiting a relatively low spatial variability in annual precipitation (coefficient of variation equal to 4%). The used rain gauges follow the standards of the German weather service, which also uses these data in the analysis of recurrence intervals of high-intensity rainfall (Bartels et al., 1997).

The data were collected by local water authorities (Emschergenossenschaft and Lippeverband, http://www.eglv.de/en) and were provided by the environmental agency of North-Rhine Westphalia (LANUV-NRW). The data were used for several projects focusing on extreme events and therefore intensively tested for consistency including minor gap filling (for details see Anonymous, 2010; Fiener et al., 2013). The non-equidistant time series (time step ⩽5 min) were resampled to equidistant 5-min values and thereafter grouped in rainfall events subdivided form each other through rain gaps >6 h to calculate rainfall erosivity. Event rainfall erosivity (consisting of n time-steps) was calculated following Eqs. (1) and (2) (Schwertmann et al., 1990; Deutsches Institut für Normung, 2005):

$$R_E = \begin{cases} \sum_{=1}^{n} R_i = \sum_{i=1}^{n} E_i \cdot I_{\max 30} & P_E \geqslant 10\,\text{mm or } I_{\max 30} \geqslant 10\,\text{mm h}^{-1} \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

with

$$R_E = \begin{cases} 0 & I_i < 0.05 \\ [11.89 + (8.73 \cdot \log I_i)] \cdot P_i \cdot 10^{-3} & 0.05 \leqslant I_i \leqslant 76.2 \\ 28.33 \cdot P_i \cdot 10^{-3} & I_i > 76.2 \end{cases} \quad (2)$$

where R_E is the erosivity of one event (kJ m^{-2} mm h^{-1}), R_i is the erosivity in time step i (kJ m^{-2} mm h^{-1}), E_i is kinetic energy during time step i (kJ m^{-2}), I_i is rainfall intensity in time step i (mm h^{-1}), P_i is rainfall depth in time step i (mm), P_E is rain depth during event, $I_{max\,30}$ is maximum 30-min rain intensity during event.