Geomorphology 272 (2016) 68–77

Contents lists available at ScienceDirect

Geomorphology

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

Upper limits of flash flood stream power in Europe

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ARTICLE INFO

Article history:
Received 4 May 2015
Received in revised form 2 November 2015
Accepted 8 November 2015
Available online 10 November 2015

Keywords:
River
Flash flood
Peak discharge
Channel slope
Stream power
Geomorphic changes

ABSTRACT

Flash floods are characterized by strong spatial gradients of rainfall inputs that hit different parts of a river basin with different intensity. Stream power values associated with flash floods therefore show spatial variations that depend on geological controls on channel geometry and sediment characteristics, as well as on the variations of flood intensity: this stresses the need for a field approach that takes into account the variability of the controlling factors. Post-flood assessment of peak discharge after major floods makes it possible to analyse stream power in fluvial systems affected by flash floods. This study analyses the stream power of seven intense (return period of rainfall > 100 years at least in some sectors of the river basin) flash floods that occurred in mountainous basins of central and southern Europe from 2007 to 2014. In most of the analysed cross sections, high values of unit stream power were observed; this is consistent with the high severity of the studied floods. The highest values of cross-sectional stream power and unit stream power usually occur in Mediterranean regions. This is mainly ascribed to the larger peak discharges that characterize flash floods in these regions. The variability of unit stream power with catchment area is clearly nonlinear and has been represented by log-quadratic relations. The values of catchment area at which maximum values of unit stream power occur show relevant differences among the studied floods and are linked to the spatial scale of the events. Values of stream power are generally consistent with observed geomorphic changes in the studied cross sections: bedrock channels show the highest values of unit stream power but no visible erosion, whereas major erosion has been observed in alluvial channels. Exceptions to this general pattern, which mostly occur in semi-alluvial cross sections, urge the recognition of local or event-specific conditions that increase the resistance of channel bed and banks to erosion or, like short flow duration, reduce the geomorphic effectiveness of the flood.

1. Introduction

Stream power, which incorporates river discharge and channel morphological setting to express river energy expenditure, has been proposed as an index of the geomorphic work of major floods (e.g., Baker and Costa, 1987; Magilligan, 1992; Thompson and Croke, 2013) as well as of near-bankfull flows (Knighton, 1999; Fonstad, 2003). Stream power related to bankfull discharge permits homogeneous comparisons of geomorphic work between different parts of a channel network. However, stream power assessment for rare, large floods provides important insights on river energy expenditure for events that are often responsible for major and abrupt morphological changes in the fluvial system.

Baker and Costa (1987) computed the stream power of extreme historical floods and paleofloods in the U.S. and underlined the complexity of the relationships between energy expenditure and accomplished geomorphic work. These authors noted that boulder and bedrock channels are modified only by rare, paroxysmal floods, whereas modest flows may play a major role in rivers where channel bed and banks feature fine materials mobilisable by smaller, more frequent floods. Baker and Costa (1987) also identified an upper envelope in the plot of unit stream power (i.e., the energy expenditure per unit area of the channel bed) versus catchment area for catastrophic floods: the envelope is curvilinear, with maxima at 10–50 km^2 approximately. Subsequent studies on stream power of major floods largely built on the pioneering work by Baker and Costa (1987). Miller (1990), based on the study of several historical floods in the central Appalachians in the eastern U.S., indicates a value of unit stream power of 300 $W\,m^{-2}$ as 'a reasonable minimum estimate' of the threshold to be exceeded for producing severe floodplain erosion. However, he noted that, because of the complex interactions between local site characteristics and flood flow, stream power is a rather poor predictor of erosion at individual locations. Magilligan (1992) also referred to a value of unit stream power of 300 $W\,m^{-2}$ as an approximate minimum threshold for significant channel adjustment and analysed the flood frequency (expressed as the ratio of peak discharge to Q_{100}) above which this threshold is likely to be exceeded.

Several authors (see Barker et al., 2009 and references therein) have observed and discussed variations of stream power, both analysing

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http://dx.doi.org/10.1016/j.geomorph.2015.11.005
0169-555X/

downstream variations along a channel and comparing values observed in different streams. Assessing the downstream variations of stream power can provide useful insights on its relationships with morphological changes along the longitudinal profile of channel reaches. Curvilinear trends of stream power for varying catchment area, already observed by Baker and Costa (1987) for the upper envelope of unit stream power of extreme floods in different river basins, have been observed for downstream variations of cross-sectional stream power and unit stream power for bankfull or near-bankfull discharge (Lecce, 1997; Knighton, 1999; Fonstad, 2003). Recent papers (Barker et al., 2009; Krapesch et al., 2011; Vocal Ferencevic and Ashmore, 2012; Thompson and Croke, 2013; Parker et al., 2014; Bizzi and Lerner, 2015) have analysed the variability of stream power and other hydraulic and topographic variables by means of geographic information systems and by using high-resolution digital elevation models; this has enabled significant advances in the spatially distributed representation of the factors that control channel adjustment. Costa and O'Connor (1995) observed that floods of very short duration ('flash floods in small basins that rise quickly and are gone in a matter of minutes' Costa and O'Connor, 1995, p. 55) may produce limited landform changes, notwithstanding high values of peak discharge and maximum stream power; whereas the most effective floods combine high peak discharge (and, hence, large maximum stream power) with long duration. A major role in the capability of floods to produce important geomorphic effects was attributed by Costa and O'Connor (1995) to flow duration and total energy expenditure, computed by integrating the stream power per unit channel width over the flood hydrograph. Magilligan et al. (2015) performed a detailed analysis of the hydraulic and geomorphic processes/effects produced by the tropical storm Irene in two gravel-bed rivers of the northeastern U.S. and refined the interpretation of the role of flood duration proposed by Costa and O'Connor (1995): short duration, high peak discharge floods may actually show limited erosivity and produce little channel widening but have major sedimentological effects, including entrainment and transport of coarse sediment and its deposition across floodplains. Another recent contribution aimed at improving the capability of hydraulic parameters in predicting channel changes is the new metric related to the stress on bends developed by Buraas et al. (2014), which has been successfully applied, in combination with stream power, in two gravel-bed rivers of the northeastern U.S. affected by a major flood.

Among the various types of floods, flash floods are particularly interesting in connection with Costa and O'Connor's (1995) observations concerning the role of duration and cumulative energy expenditure for flood effectiveness. Flash floods are associated with short, high-intensity rainfalls, mainly of convective origin that occur locally. As such, flash floods usually affect basins <1000 km^2, with response times typically less than one day. Runoff rates often far exceed those of other flood types as a result of the rapid response of the catchments to intense rainfall, modulated by soil moisture and soil hydraulic properties. Flash floods are often associated with complex orography, in that relief may affect flash flood occurrence in specific catchments by a combination of two mechanisms: orographic effects augmenting precipitation and anchoring convection, and steep relief promoting rapid concentration of streamflow (Marchi et al., 2010). Owing to these reasons, flash floods are often geomorphically effective floods at catchment scales <1000–2000 km^2, producing significant changes in the pre-flood landforms that persist over several years and that could not have been accomplished by less intense and long-duration floods (Hicks et al., 2005). The small spatial and temporal scales of flash floods, relative to the sampling characteristics of conventional rain and discharge measurement networks, make these events particularly difficult to observe (Borga et al., 2008). In an investigation of 25 major flash floods that occurred in Europe, Marchi et al. (2010) showed that less than one-half of the cases were properly documented by conventional stage measurements. Moreover, streamgauge measurements of flash floods are almost absent at basin area <100 km^2, which is of great interest for stream power analysis. Consequently, the assessment of flash flood stream power is remarkably rare. A further motivation is the great variability of the geomorphic effects of flash floods, which urges investigations on the relationships with hydraulic conditions and the geological and morphological settings of affected channels.

This paper presents cross-sectional and unit stream power values for a sample of recent, intense (return period >100 years) flash floods in Europe and discusses possible climatic and morphological controls on stream power values and geomorphic effects of the studied floods. The aims of the study are to extend experimental information on stream power of flash floods and its relationships with the geomorphic effects produced in different climatic and geographical regions of central and southern Europe where such data are still rather sparse. The large spatial variability of precipitation forcing and geomorphological settings associated with the occurrence of flash floods in complex terrains implies that the associated geomorphic response would vary even within small catchments and makes the assessment and analysis of controlling factors, including stream power, particularly challenging. Spatially distributed analysis of stream power for flash floods can provide a metric of energy expenditure for these events and helps to explore the relationships with geomorphic impacts along the channel network.

2. Flash floods and stream power data

The database consists of seven flash floods that occurred in Europe from 2007 to 2014 under different climates and in catchments of different morphological settings. Fig. 1 shows the location and related climate classification according to Köppen–Geiger (Peel et al., 2007) of the studied flash floods, whose main characteristics are reported in Table 1. The criteria adopted for flash flood selection are high intensity (the recurrence interval of the flood-generating rainfall exceeds 100 years at least for some rainfall duration and in some sectors of the river basin) and availability of data collected and validated by means of homogeneous procedures; the sample includes only rainfall-caused floods.

Data were collected for 110 cross sections; the number of cross sections per event ranges between 2 (Vizze) and 24 (Magra), mostly depending on the overall area impacted by the flood. Only two cross sections were surveyed in Vizze, which were considered sufficient to document the flood in the main river, whereas the tributaries were affected by debris flow. The catchments corresponding to the surveyed cross sections range in area between 0.5 and 1981 km^2; however, only two catchments are larger than 1000 km^2 in size, which fits the space scale definition of flash flood adopted in this study (see also Gaume et al., 2009; Marchi et al., 2010). The duration of the events is linked to the maximal drainage areas, with the rainstorms lasting 20 h or more in the case of those impacting areas larger than 500 km^2 (Argens, Magra, and Cedrino–Posada). Interestingly, these three events occurred in the Mediterranean region. This is consistent with observations by Gaume et al. (2009) and Marchi et al. (2010), who noted that the spatial extent and duration of the flash flood events is generally smaller for continental floods with respect to those occurring in the Mediterranean area. Actually, shorter duration and smaller affected areas characterize the floods in continental and alpine areas (Starzel, Selška Sora, and Vizze), as well as the Lierza. The Lierza catchment (Fig. 1) is located in a hilly area of northern Italy; although Lierza lies close to the Adriatic sea, the local climate lacks typical features of Mediterranean areas and is classified as humid subtropical (*Cfa*) according to the Köppen–Geiger classification (Peel et al., 2007). The maximal local channel slope at the surveyed sites can be divided into two main groups: the first with the steepest slopes ranging between 0.015 and 0.040 (Starzel, Vizze, Cedrino–Posada, and Lierza) and the second with that between 0.06 and 0.15 (Selška Sora, Argens, and Magra). The maximal unit peak discharges can also be divided into two main groups: the first includes events with the values varying between 10.0 and 11.7 m^3 s^{-1} km^{-2}