Catena 151 (2017) 191–201

Contents lists available at ScienceDirect

Catena

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

Controls on peak discharge at the lower course of Ameca River (Puerto Vallarta graben, west-central Mexico) and its relation to flooding

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ARTICLE INFO

Article history:
Received 1 March 2016
Received in revised form 15 November 2016
Accepted 20 December 2016
Available online 28 December 2016

Keywords:
Peak discharge
Ameca River
ENSO
Nays2DFlood
Subtropical rivers
Mexico

ABSTRACT

Rivers are dynamic features sensitive to climatic oscillations. While in some settings the warm (El Niño) and cold (La Niña) phases of ENSO are related with an increase in peak discharge events, in other zones like subtropical rivers, floods are caused by different meteorological events. Here we evaluate the potential controls on river peak discharge of the Ameca River, within a tectonically active landscape located on west-central Mexico, by using stream discharge and rainfall data spanning ~60 years. We evaluated the flooding produced by maximum peak discharges in the landscape by simulating different flood scenarios using the solver *Nays2DFlood* (http://i-ric.org). Our results indicate that the warm, cold and normal phases of ENSO, as well as moderate meteorological events, coincide with the highest peak discharges recorded on stream gauging stations. Further analysis of rainfall data reveals that the largest peak discharges are positively correlated with the amount of rainfall accumulated two weeks before the day of the peak discharge. Our flood simulations indicate that when stream discharge exceeds ~1114 $m^3\ s^{-1}$, a column of water >0.5 m of depth inundates ~2.5 km^2 of Ameca's floodplain. Such condition can leave the inhabitants in hazardous condition and damage the infrastructure. We found that the highest peak discharges in the Ameca River are produced in summer and in all phases of ENSO, however, these events are more frequent in the normal phase of ENSO (~50%), followed by the phase of La Niña (~37%). Our results highlight the importance of seasonal rainfall in the geomorphic work of the subtropical rivers of west-central Mexico.

1. Introduction

Rivers are one of the most important geomorphic agents that erode the landscape, mobilize large volumes of sediments and are related with the transfer of terrestrial organic carbon (e.g., Hilton et al., 2008; Larsen et al., 2014; Summerfield and Hulton, 1994; Wohl, 2007). Studying the sensitivity of rivers to climate fluctuations is key in understanding fluvial systems because the frequency and magnitude of peak discharges, which are also related with floods, are controlled by the amount and distribution of rainfall in a given catchment (e.g., Goel et al., 2000; Singh, 1997). Floods are extreme geomorphic processes that cause many human deaths worldwide as well as large economic losses (e.g., Alcántara-Ayala, 2002; Gaume et al., 2009; Herget et al., 2014). Because most floods result from an excess of precipitation, it is necessary to determine under which circumstances the precipitation triggers a peak discharge in a river. Stream flow is known to change according to latitude (Dettinger and Diaz, 2000). In some regions, the analysis of peak discharge indicates that the different modes of El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) are related with the increase in number floods (e.g., Andrews et al., 2004; Hamlet and Lettenmaier, 1999; Neal et al., 2002; Schmidt et al., 2001; Ward et al., 2010). Andrews et al. (2004) found that in the rivers of coastal California (USA), the magnitude of floods increased during the warm (El Niño) phase of ENSO, surpassing the discharge of the normal phase. These authors also identified that for the different modes of ENSO, latitude is a factor controlling the response of rivers to floods. Studying the rivers of west Florida (USA), Schmidt et al. (2001) found that the peak discharges are enhanced during the warm phase of ENSO. Ward et al. (2010) made a global assessment of the susceptibility of rivers to the warm (El Niño) and cold (La Niña) phases of ENSO. In their maps, the rivers located at medium and high latitudes are more sensitive to the warm and cold phase of ENSO, as a result, stream discharge increases more in these regions than in those rivers located in low latitudes. Subtropical rivers are likely to be less sensitive to the effects of extreme phases of ENSO since stream discharge is mostly controlled by seasonal rainfall (Dettinger and Diaz, 2000).

In subtropical rivers stream discharge is largely controlled by the heavy rains produced under tropical storms, depressions, hurricanes and monsoons, but the warm and cold phase of ENSO also influence the amount of rainfall and hence the intensity of stream discharge (e.g., Dettinger and Diaz, 2000; Kostaschuk et al., 2001; Restrepo and

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http://dx.doi.org/10.1016/j.catena.2016.12.019
0341-8162/

Kjerfve, 2000; Hudson, 2003a). Hudson (2003a) observed that in the Pánuco river basin, which extends from the central highlands of Mexico to the Gulf of Mexico, in winters and summers of La Niña the river has the highest rates of stream flow and transport of sediment load. The increase in stream discharge in the Pánuco River is also related with the response time of this river to transport the sediment load downstream (Hudson, 2003b). Muñoz-Salinas and Castillo (2013) extended the analysis made by Hudson (2003a) studying the Santiago river basin, which extends from the central highlands of Mexico to the Pacific coast. These authors observed that during the warm and cold phases of ENSO stream discharge slightly increased in comparison to the normal phase of ENSO. In the Pánuco River they found that the largest stream discharges take place in La Niña summers and in the Santiago River the major increase in stream discharge was produced during the phase of El Niño. Studying the tenth largest basin of North America Muñoz-Salinas and Castillo (2015) found that in the Usumacinta and Grijalva rivers (southern Mexico) there was a minor increase in their stream flow during the winters of La Niña. The effect of the different phases of ENSO on the stream discharge of the Mexican rivers suggests that the susceptibility to floods increases during El Niño or La Niña events.

Although in subtropical rivers the rainfall and peak discharges mostly occur during the rainy season (e.g., Dettinger and Diaz, 2000), these types of rivers are variable in their annual rainfall and climate ranges from wet-dry humid (annual rainfall between 700 and 1800 mm) to humid (annual rainfall exceeding 1800 mm) (Latrubesse et al., 2005). In rivers the amount of rainfall, topography, frequency and magnitude of meteorological events are factors that influence the intensity of peak discharge but in tropical rivers events such as tropical depressions and hurricanes are associated with heavy rainfalls that can trigger the peak discharge of rivers. Thus, the peak discharge of rivers located in the humid tropics, where there is markedly pattern of rainfall, are expected to directly respond to rainfall intensity. For example, in the rivers of India the peak discharge is controlled by the heavy rains produced during the monsoon (Kale, 2003). In the Island of Fiji the rainfall produced by hurricanes has been related with the increase in the peak discharge of rivers and these are more frequent during El Niño events (Kostaschuk et al., 2001). The rivers flowing along the Pacific coast of North America are of great interest because they exhibit a great variability in their peak discharges, which may be enhanced during the different phases of ENSO, the PDO, and the presence of the North American Monsoon (Andrews et al., 2004). The rivers of the west coast of North America located in the northernmost part of the subtropics, including those of the western coast of Mexico, are within the zone affected by the North American Monsoon and by rainfalls produced by the low pressure systems formed during the summer (Adams and Comrie, 1997). Nevertheless, no data are available for the potential effects of the warm and cold phases of ENSO on the peak discharge of most of the Mexican rivers flowing into the Pacific. Also, the triggering mechanisms of peak discharge for these rivers remain unknown. Some studies have evaluated the effect of ENSO on the precipitation of Mexico indicating that most of the rainfall increases during the summers of La Niña and decrease in the summers of El Niño (e.g., Jauregui, 1995; Cavazos and Hastenrath, 1990; Magaña et al., 2003). Thus, it is possible that ENSO may be related with the magnitude and frequency of the peak discharge of the Mexican rivers.

Motivated by the need for detecting the controls on the peak discharge of subtropical rivers located on southwestern part of North America, we studied the peak discharges of the Ameca River by using water discharge and rainfall that span ~60 years. The study area is within a tectonically active zone where some hurricanes impact into the steep topography of west-central Mexico, as recently happened in 2015 with Hurricane Patricia. Historical records indicate that floods at the Ameca River have destroyed roads and bridges (Salas and Jiménez, 2004). Our main hypothesis is that, because the basin of the Ameca River is located in a subtropical latitude where seasonal rainfall is controlled by low-pressure systems, the highest peak discharges take place during the intense rainfalls produced under high-intensity hurricanes (category >3). In order to evaluate the effect of the ENSO on the peak discharge of rivers we used the Oceanic Niño Index (ONI) series published by the National Weather Service of the National Oceanic and Atmospheric Agency (NOAA). ONI series were contrasted with water discharge and rainfall data of two stations situated at the lower course of the Ameca River. Finally, in order to assess how peak discharges produce floods along the lower course of the Ameca River, we simulated different flood scenarios using the solver *Nays2DFlood* (http://i-ric.org).

2. Study area

The Ameca River is a subtropical river located in west-central Mexico. The river basin is ~12,214 km^2 and discharges ~2236 × 10^6 m^3 annually (CONAGUA, www.conagua.gob.mx). The source of the Ameca River is located in the volcanic highlands of the State of Jalisco, where it cuts into mountains and plateaus. Along its course downstream the river progressively incises into volcanic and granitic rocks. Along the lower course the river flows along the Puerto Vallarta graben (Ferrari et al., 2012), where it forms a wide-open floodplain where the Atenguillo and s join the Ameca River (Fig. 1). The Ameca River flows into Bahía de Banderas (Fig. 1).

The whole fluvial system of the Ameca River flows over a tectonically active landscape, which is part of the northern sector of the Jalisco Block. Erosion rates are particularly high for this sector of the block (Castillo et al., 2014) where rates can be ~6 mm yr^{-1} as estimated from ^{36}Cl exposure ages of bedrock surfaces in the Atenguillo River (Righter et al., 2010). The mean annual sediment load of the Ameca River is ~111 × 10^3 m^3.

Two types of climate are present in the Ameca river basin according to Köppen's classification: (1) a humid temperate climate (Cw) that has the rainy season during the summer and predominates in the mountainous zone (Figs. 1 and 2), and (2) a sub-humid warm climate (Aw) distributed in the coastal zone, with most of the rainfall occurring during the summer (Garcia, 1973). Annual rainfall ranges from 680 to 1526 mm (Fernández-Eguiarte et al., 2016). The driest zones are confined in the high elevated areas of the northern portion of the basin. The wettest zones are located north of the Atenguillo River and in the mountains bounding the graben of Puerto Vallarta (Fig. 2). The highest rainfalls of these two areas are distributed in the zone where many low pressure systems impact into the mainland. During the boreal summer (May to October) the northern position of the Intertropical Convergence Zone (ITCZ), the North American Monsoon and the easterly low pressures systems produce the seasonal rainfall of this region (Wallén, 1955; Cavazos and Hastenrath, 1990; Magaña et al., 2003). The maximum peaks of rainfall for west-central Mexico occur between July and August (Cavazos and Hastenrath, 1990). Unlike the coast of the Gulf of Mexico where winter cold fronts, known as *Nortes*, produce rainfalls (Wallén, 1955; Jauregui, 1995), on the coast of the west-central Pacific of Mexico rainfall rapidly drops during this season.

The Mexican Commission of Water (CONAGUA) is the office in charge of stream gauging and meteorological stations. There are 10 stream gauging stations in Ameca's river basin but most of them have 2 to 5 years of stream flow records containing many gaps of missing data. The most complete records available are for stations 14,007 (known as "*Las Gaviotas II*") and 14,008 (known as "*La Desembocada*"), these stations have ~60 years of almost continuous records of stream discharge (Fig. 1). Station 14,007 records the discharge of the Ameca River, it is located ~30 km upstream the river's mouth. Station 14,007 is close to the transition from the mountainous zone to the floodplain (Fig. 1). The drainage area upstream station 14,007 is ~9367 km^2. Station 14,008 is located ~22 km downstream of station 14,007 and records the stream discharge of the Mascota River (Fig. 1). The drainage area upstream station 14,008 is ~2047 km^2. In this study, we used daily and