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Trends in hydrological extremes in the Senegal and Niger Rivers

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ABSTRACT

In recent years, West Africa has witnessed an increasing number of damaging floods that raise the question of a possible intensification of the hydrological hazards in the region. In this study, the evolution of extreme floods is analyzed over the period 1950–2015 for seven tributaries in the Sudano-Guinean part of the Senegal River basin and four data sets in the Sahelian part of the Niger River basin. Non-stationary Generalized Extreme Value (NS-GEV) distributions including twelve models with time-dependent parameters plus a stationary GEV are applied to annual maxima of daily discharge (AMAX) series. An original methodology is proposed for comparing GEV models and selecting the best for use. The stationary GEV is rejected for all stations, demonstrating the significant non-stationarity of extreme discharge values in West Africa over the past six decades. The model of best fit most commonly selected is a double-linear model for the central tendency parameter (μ), with the dispersion parameter (σ) modeled as either stationary, linear, or a double-linear. Change points in double-linear models are relatively consistent for the Senegal basin, with stations switching from a decreasing streamflow trend to an increasing streamflow trend in the early 1980s. In the Niger basin the trend in μ is generally positive since the 1970s with an increase in slope after the change point, but the change point location is less consistent. The recent increasing trends in extreme discharges are reflected in an especially marked increase in return level magnitudes since the 1980s in the studied Sahelian rivers. The rate of the increase indicated by the study results raises urgent considerations for stakeholders and engineers who are in charge of river basin management and hydraulic works sizing.

1. Introduction

River floods are one of the deadliest natural hazards in the world. They produce major damages on infrastructure, lead to economic losses, and favor water-borne diseases. In order to better understand such floods, hydrologists have long focused on assessing the rare (large in magnitude) river discharge values, represented by the tails of underlying statistical distributions (Gumbel, 1957). The primary aim, besides theoretical understanding, is to provide practical tools for flood risk management and civil engineering structure design. The main challenge for practical applications is estimating return levels for high return periods (typically 10, 50, or 100 years). The more the return period is larger than the length of the series, the greater the challenge of estimating the tail of the distribution.

Extreme Value Distributions (EVDs) are statistical tools designed for the study of such rare values (see e.g. Coles et al., 2001; Katz et al., 2002). For several decades, the main challenge when applying EVDs was to have a proper estimation of the tail (heavy, light, or bounded). The focus was then on developing robust estimation procedures (Regional Frequency Analysis – Hosking and Wallis, 1997; GRADEX and adaptation – Guillot, 1993; Paquet et al., 2013; Bayesian inference – Coles and Tawn, 1996 among many other developments) and then applying them to the longest hydrological series available (Koutsoyiannis, 2004). The stationarity assumption reigned during this “old hydrological world” (Milly et al., 2008).

However, both increases and decreases of extreme discharges have been reported via the evaluation of historical series around the world (e.g. Kundzewicz et al., 2005; Bower, 2010; Condon et al., 2015). A main challenge of hydrological extremes thus concerns the validity of the stationarity assumption and the implications of its rejection. Ongoing global changes are expected to increase flood hazard mainly through the intensification of the hydrological cycle due to global warming (Hirabayashi et al., 2013; Arnell and Gosling, 2016) and the degradation of land surfaces due to anthropic pressure (Brath et al.,

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2006; Elmer et al., 2012). Other factors also tend to reduce flood hazards, including negative precipitation trends found in drying regions and flood protection structures such as dams. While some regions witness resulting changes in flood frequency, in other regions, no changes have been detected (Villarini et al., 2009). This could be a result of either the absence of substantial changes in drivers that could trigger/influence flood trends or competing phenomena that act in opposite ways. It could also be due to the use of non-robust methodology to detect concrete changes in the EVD of discharge. The last case necessitates improved methods able to detect trends in series characterized by low signal to noise ratio.

While numerous studies on flood hazard evolution have been undertaken for developed countries, less has been done in the developing world. This is the case in particular over the tropics (Kundzewicz et al., 2005) which contain two thirds of the developing countries, including the poorest. Populations living in the tropics are notoriously vulnerable to climate hazards, including droughts and floods that can occur within the same year at a given place. Global changes are expected to strongly impact flood risks in the tropics with studies already reporting significant increases in the frequency of rainfall extremes (Allan et al., 2010; O'Gorman, 2012; Asadieh and Krakauer, 2015), land use/cover changes (Lambin et al., 2003; Erb et al., 2016), rapid rates of urbanization (Di Baldassarre et al., 2010), and increasing vulnerability of populations due to very high demographic growth; the population of the least developed countries is expected to double from now to 2050 (Population-Reference-Bureau, 2016). The strong internal variability of tropical climates, the lack of long-term hydrological observations, and the large uncertainty of climate projections in the tropics challenge the scientific community to provide reliable and relevant information to stakeholders so they can define suitable flood risk management strategies.

West Africa is one of the most critical tropical regions for examining hydrological non-stationarities as it is a region in which the issues described above are exacerbated. West Africa is known for having strong precipitation variability, especially at the decadal level (Nicholson, 2013). It underwent a devastating and long-lasting drought that abruptly started in the late 1960s and persisted through the 1970s and 1980s (Lamb, 1983; Barbé et al., 1997; Nicholson, 2000; Camberlin et al., 2002; Barbé et al., 2002; L'hote et al., 2002; Dai et al., 2004; Panthou et al., 2014; Bodian et al., 2011; Bodian et al., 2016). At the regional scale, this led to a decline in the flow of large rivers that was proportionally greater than the decrease in rainfall (Lebel et al., 2003; Andersen and Golitzen, 2005; Mahé and Paturel, 2009).

At the subregional scale however, two diametrically opposed hydrological behaviors were observed (Descroix et al., 2018). In the Sudano-Guinean subregion of West Africa (south of 12°N), a decrease in river flow was observed for small to regional scale catchments (Mahé et al., 2005; Descroix et al., 2009) until the 1970s and 1980s (Diop et al., 2017). The decrease in flow was attributed to a gradual drying up of the groundwater and thus a gradual decrease in the base flow of the rivers (Mahé et al., 2000; Mahé and Paturel, 2009). In the Sahelian region (belt between roughly 12°N and 16°N), runoff coefficients and runoff volumes increased despite the drought. This phenomenon – the so-called "Sahelian paradox" – was understood to have been caused by a change in surface conditions (Albergel, 1987; Descroix et al., 2009; Aich et al., 2015; Cassé et al., 2016). Droughts played a role in increasing surface crust and decreasing vegetation (Gal et al., 2017), which consequently increased runoff coefficients and counterbalanced the effects of drought (Boulain et al., 2009). Anthropogenic changes (including land use change) appear to be a major factor in some basins (Seguis et al., 2004; Li et al., 2007; Leblanc et al., 2008; Gal et al., 2017). Other factors such as an increase in the density of the drainage network may have played a role in the increase of flow (e.g. Favreau et al., 2009; Gal et al., 2017).

Since the early 1990s, both total rainfall and streamflow amounts have increased compared to the drought decades of the 1970s and 1980s, though they remain lower than in previous pre-drought decades (Lebel and Ali, 2009; Mahé and Paturel, 2009; Panthou et al., 2014; Tarhule et al., 2015; Diop et al., 2017). In the Sahel, the increase was accompanied by higher interannual variability (Ali and Lebel, 2009; Panthou et al., 2014) and overall persistence of drought conditions under certain indices (L'hote et al., 2002; Ozer et al., 2009). Of note is the increase in the intensity of rainfall during recent years (Ly et al., 2013; Panthou et al., 2014; Sanogo et al., 2015; Taylor et al., 2017). During the same period, an increase in the number and magnitude of extensive floods has been reported (Tarhule, 2005; Tschakert et al., 2010; Samimi et al., 2012; Sighomnou et al., 2013; Cassé and Gosset, 2015), causing extensive fatalities, damages, and population displacement. From the mean hydrographs of the Niger River at Niamey plotted for six decades from 1951 to 2010, Descroix et al. (2012) and Sighomnou et al. (2013) illustrated a strong increase in the intensity of the summer flood peak of the Sahelian tributaries during the 2000s, while the flood peaks coming from the remote Guinean tributaries and arriving at Niamey later in the year at Niamey were as low as in the 1970s. They also noted successive discharge records produced by Sahelian floods in 2010 and 2012, exceeding the Guinean flood.

The strong current and projected demographic growth in West Africa (Population-Reference-Bureau, 2016) is likely to increase the exposure of populations to floods, both from intensive and unplanned human settlements in flood-prone areas (Di Baldassarre et al., 2010), and from human-induced changes in land cover which affect runoff. Changes in hydrological extremes consequentially are particularly pressing for decision makers in West Africa, as the statistical tools used for infrastructure design have not been updated since the 1970s (Amani and Paturel, 2017). An improved quantitative understanding of how extreme flows are changing over time in the region has generated an urgent demand to design and manage structures such as dams and dikes and, as a result, aid in risk mitigation, as well as the development of hydroelectric energy and irrigation systems.

However there is still very little literature on quantifying extreme flow changes in West Africa. For Sudano-Guinean regions, Nka et al. (2015) found an overall decreasing trend that closely followed rainfall indices (although decreasing at a higher rate); this was the case for the Falémé branch of the Senegal River at Fadougou. When only a more recent time period is considered (since 1970), no significant trends were found in the Sudano-Guinean catchments, including the Falémé. Bodian et al. (2013) explored trends in annual maximum daily discharge (AMAX) values on the Bafing tributary of the Senegal River (Bafing Makana and Daka Saidou stations). They found that high points in the series occurred during the pre-drought period (1967 and 1955), whereas the minima of the AMAX occurred in 1984. Diop et al. (2017) found that extreme highs in the Bafing Makana series decreased by 18% over the series and especially since 1971, while extreme lows stayed stable. Aich et al. (2016) analyzed time series of AMAX values at several stations along the Niger River. They found that changes in AMAX series followed the decadal variability of mean annual precipitation over Guinean and Benue-area catchments (a wet period during 1950s and 1960s, followed by a dry period during 1970s and 1980s, and values close to the long-term mean after), while the floods produced by Sahelian tributaries have recorded a monotonic increase since the beginning of the 1970s. Nka et al. (2015) found positive trends in the extreme values of three Sahelian catchments studied (Dargol River at Kakassi, the Gorouol River at Koriziena, and the Goudebo River at Falagontou). They also found significant (Mann–Kendall test) increases in extreme values in both AMAX series and peak-over-threshold (POT) series for the Dargol River at Kakassi. Breaks in AMAX were detected in 1987, and for POT in 1993. Mean extreme values were found to be greater (twice as high) during the later subperiods.

The aim of this paper is to detect and quantify trends in extreme hydrological values in West Africa. Discharge series are analyzed in tributaries of the Niger and the Senegal rivers, two catchments that reflect two differing hydrological and climatic processes of the Sahelian and the Sudano-Guinean West Africa. The temporal evolution of the