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RESEARCH ARTICLE

Changes in seasonal streamflow extremes experienced in rivers of Northwestern South America (Colombia)

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Abstract A measure of the variability in seasonal extreme streamflow was estimated for the Colombian Caribbean coast, using monthly time series of freshwater discharge from ten watersheds. The aim was to detect modifications in the streamflow monthly distribution, seasonal trends, variance and extreme monthly values. A 20-year length time moving window, with 1-year successive shiftments, was applied to the monthly series to analyze the seasonal variability of streamflow. The seasonal-windowed data were statistically fitted through the Gamma distribution function. Scale and shape parameters were computed using the Maximum Likelihood Estimation (MLE) and the bootstrap method for 1000 resample. A trend analysis was performed for each windowed-serie, allowing to detect the window of maximum absolute values for trends. Significant temporal shifts in seasonal streamflow distribution and quantiles (QT), were obtained for different frequencies. Wet and dry extremes periods increased significantly in the last decades. Such increase did not occur simultaneously through the region. Some locations exhibited continuous increases only at minimum QT.

Keywords Discharge · Time series analysis · Streamflows · Extremes analysis · Trends

Introduction

Streamflow variability is a key element within hydrologic cycle analysis, especially when dealing with evaluating combined effects of global change and anthropogenic intervention (Vörösmarty and Sahagian 2000; Walling and Fang 2003; Hungtinton 2006; Milliman et al. 2008; Stosic et al. 2016). Several studies have analyzed streamflow changes for detecting significant trends, identifying major oscillations periods, and determining relationships between hydrological responses and climate forcings (e.g., Probst and Tardy 1987; Genta et al. 1998; Robertson and Mechoso 1998; Pekarova et al. 2003; Labat et al. 2004; Pasquini and Depetris 2007; Labat 2008, 2010; Milliman et al. 2008; Dai et al. 2009; Telesca et al. 2012, 2013a, b; Pierini et al. 2012, 2015; Shaban et al. 2014). Some of these studies have shown contrasting results regarding streamflow trends and variability. For example, Milliman et al. (2008) indicated that cumulative discharge of 137 rivers, representative for the entire regions of the world, remained statistically unchanged between 1951 and 2000, offering little support to a global intensification of the hydrological cycle. Pekarova et al. (2003) also found no evidence of significant trends (neither increasing nor decreasing) in the annual streamflow of the 24 major rivers of the world. However, both noted significant changes in individual rivers at regional levels and relatively accelerated

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transitions between wet and dry periods (Pekarova et al. 2003; Milliman et al. 2008). On the contrary, dramatic changes in the hydrological patterns and long-term trends, as well as a crescent anthropogenic intervention, were reported for several major rivers of the world, especially during the last two decades (e.g., Probst and Tardy 1987; Labat et al. 2004; Pinter et al. 2006; Varis et al. 2012; Walling and Fang 2003; Stosic et al. 2016). A comprehensive analysis of trends in the runoff from major rivers worldwide, from 1920 to 1995, showed an increase in the world continental runoff during the twentieth century (Labat et al. 2004). According to Hungtinton (2006), these latter results, in conjunction with evidence of increasing runoff from smaller rivers in the northern hemisphere, provide possible evidence for a warming-associated intensification of the water cycle. There is a general agreement regarding those differences in regional responses to climatic oscillation and anthropogenic intervention lead to significant differences in streamflow long-term trends (Alcamo et al. 1997; Vörösmarty and Sahagian 2000; Pekarova et al. 2003; Milliman et al. 2008; Dai et al. 2009).

A central question in fluvial hydrology is to determine whether long-term trends might mask or hide short-term changes, especially in rivers where seasonal changes of streamflow are higher than interannual changes. In the rivers draining the Caribbean alluvial plain of Colombia (northern South America) (Fig. 1) the annual cycle, related to Inter Tropical Convergence Zone—ITCZ—shiftment, appears as the main oscillatory component of hydrologic variability, wherein the ENSO-related band (3–7 year) and the quasi-decadal band (associated with sea surface temperatures anomalies in the Tropical North Atlantic) represent the second-order oscillatory components of this variability (Restrepo et al. 2012, 2014). Despite most of these rivers do not exhibit any long-term trends in their streamflows (e.g., Mesa et al. 1997; Poveda 2004; Restrepo et al. 2012, 2014), some evidence suggests that hydrological changes occurred at intra-annual scale. A Mann–Kendall Test applied to monthly data highlighted significant upward trends during wet seasons in most of these rivers (Restrepo et al. 2014). These trends could lead to substantial differences in quantiles within a hydrologic year, which poses new challenges for effective water resource management across the Caribbean littoral of Colombia. For example, the Magdalena River experienced extremely low streamflow values at the beginning of 2010, during the dry season, whereas the wet season was one of the most intense and extensive of the hydrological record (1941–2010) (Hoyos et al. 2013). Analysis of historical discharges in these rivers showed a strong connection between long-term trends and hydrologic periodicities (Restrepo et al. 2014). A detailed study of intra-annual variability of streamflow, comprising the detection of

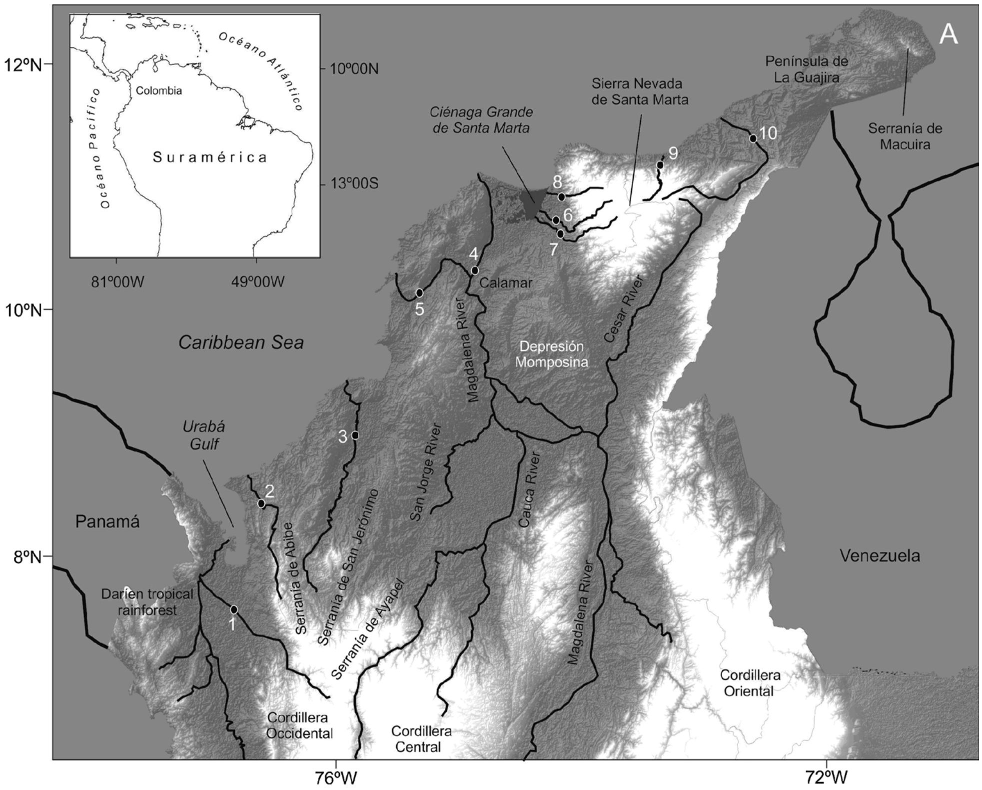


Fig. 1 Caribbean plain of Colombia in northwest South America. Major topographic features, selected rivers and gauge stations: *1* Sucío River, *2* Mulatos River, *3* Sinú River, *4* Magdalena River (Calamar), *5* Canal del Dique, *6* Aracataca River, *7* Fundación River, *8* Frío River, *9* Palomino River, and *10* Ranchería River

gradual or abrupt changes in season length and minimum and maximum streamflow values (e.g., Xu 2000; Chen et al. 2010), will improve our capabilities for monitoring and predicting the consequences of changing hydrologic regimes.

Many methods exist for detecting potential changes in the historical hydrological records (e.g., linear trend analysis, Mann–Kendall test, Wavelet analyses, scanning *t* test, scanning *F* test). Some of these tests were previously used in Colombian rivers, mainly at annual scale (Mesa et al. 1997; Poveda 2004; Restrepo et al. 2012, 2014). The streamflow extremes are typically defined based on the frequency of occurrence and/or their return periods. Thus, several fundamental probability frequency distributions can be used for estimating streamflow values; amongst which the most commonly used are the Generalized Extreme Value (GEV), Gumbel, Gamma and Weibull distributions (e.g., Wilks and Eggleston 1992; Vogel and Wilson 1996; Martins and Stedinger 2000; Katz et al. 2002; McMahon et al. 2007). In this study, we propose to establish a measure of the variability experienced in the extreme streamflows at seasonal scale, from the middle of the twentieth century to present time. Besides, we seek to detect whether there are modifications in their statistical characteristics, as well as changes in the variance of seasonal streamflow of the Caribbean Colombian rivers. We analyze in detail quantiles defined through a theoretical distribution function over (below) the 90th (10th) percentile, and variability of extreme streamflows amongst different stations. In fact, a change in a climate variable will also result in a change in the shape of its distribution. The main aim is focusing on the changes produced in extreme dry and wet values through time, to discern the impact of climate change in streamflow variability of the rivers draining the Caribbean littoral of Colombia. So far, no studies have dealt with changes in streamflow series as long as those hereby shown, available in Colombian, pursuing analysis on seasonal extremes over (below) 80th, 90th, 95th (20th, 10th, 5th) percentiles. In recent years, such knowledge has gained importance due to an increase in the number, duration and intensity of hydrological events such as floods and droughts (Hoyos et al. 2013). Thus, this study aims to establish the characteristics of temporal changes in the extreme streamflows of the conterminous Caribbean Colombian rivers, during the latter half of the twentieth century. An additional aim is to determine whether the changes in extreme streamflows could be characterized as a gradual change or as an abrupt change.

Study area

The Fig. 2 presents streamflow histograms for the rivers draining the Caribbean plain of Colombia, based on the entire record of monthly data (Table 1). Almost all locations are characterized by a bimodal distribution with peaks around May and October; it has been estimated that these seasonal changes are higher than the interannual changes of streamflow (Restrepo et al. 2014). According to Restrepo et al. (2014) the mean monthly streamflow of these rivers ranges between 4.63 and 6497 $m^3 s^{-1}$, pouring collectively ~ 330.5 $km^3 year^{-1}$ of freshwater into the Caribbean Sea. The Magdalena River provides the largest supply of freshwater into the Caribbean Sea, with a mean discharge of 205.1 km^3 $year^{-1}$.

Spectral analyses performed by Restrepo et al. (2012, 2014) revealed that the annual (related to Intertropical Convergence Zone—ITCZ—smigration) and quasi-decadal (associated with Sea Surface Temperatures anomalies) bands appear as the main oscillatory components of the hydrologic variability of the rivers draining the Caribbean alluvial plain of Colombia, whereas the ENSO-related band represents a second-order oscillatory component of this variability. Thus, the meridional oscillation of the ITCZ controls the annual hydrological cycle, defining two rainy seasons in the Caribbean plain. The first season extends from April to May, when the ITCZ is migrating from south to north; whilst the second and stronger season goes from September to November, when the ITCZ shifts southward. However, some local patterns can be distinguished as a consequence of orographic effects over air masses dynamics (Bernal et al. 2006; Poveda 2004; Poveda et al. 2006). Humid air masses from the Pacific Ocean are advected by the Chocó Jet. These masses rise rapidly along the Cordillera Occidental, promoting their deep convection, which in turn enhances the mesoscale convective systems causing intense rainfall rates (Poveda and Mesa 2004). The Caribbean or San Andrés jet current causes a humidity divergence in the northwest of South America that enhances the uplifting of air masses along the Sierra Nevada de Santa Marta slopes and causes strong superficial winds and dryness in the Peninsula de la Guajira (Bernal et al. 2006). The stronger rainy season coincides with maximum intensity of Chocó Jet, whilst the dry season corresponds to the maximum strength of the Caribbean Jet (Poveda et al. 2006). Hence, the western of the Caribbean plain, close to the Darien tropical rainforest, and the Sierra Nevada de Santa Marta exhibit the maximum rainfall rates and the lower mean annual temperatures, with values of >2000 mm $year^{-1}$ and <20 °C, respectively. On the contrary, the lowlands are hotter and drier with mean annual temperatures >27 °C and rainfall rates below to 1000 mm $year^{-1}$ (Mesa et al. 1997). At interannual scales, the major anomalies in hydrological patterns have been associated to both phases of El Niño/Southern Oscillation (ENSO) and to climatic and oceanographic processes of low-periodicity (i.e., quasi-decadal) such as Pacific Decadal Oscillations (PDO) and/or Tropical North Atlantic (TNA) (Restrepo et al. 2014). The ENSO warm phase (El

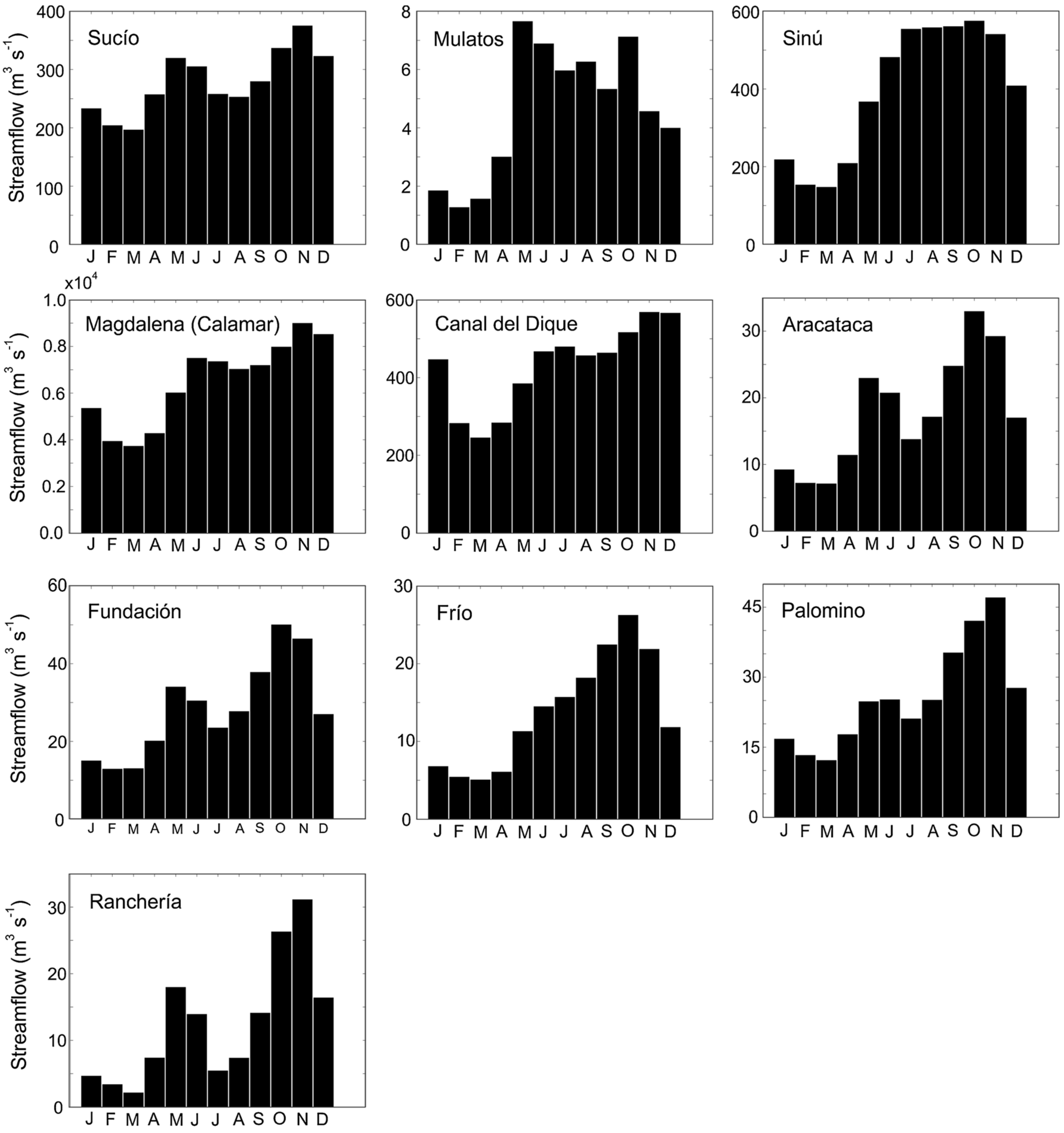


Fig. 2 Histograms of monthly streamflow for each gauge stations

Niño) promotes an increase in mean air temperature; a decrease in soil moisture and vegetation index, and thus the rainfall rates diminishes. The opposite anomalies during ENSO cold phase (La Niña) generate abundant and intense rainfalls (Poveda et al. 2001; Poveda 2004). Furthermore, the climate/oceanographic oscillations of low frequency act as a source of variability that enhance or diminish the ENSO effects on these rivers. For example, the concurrence of the strengthening of the quasi-decadal oscillation, between 1990 and 2010, and the major oscillations of the ENSO-related band, during 1998–2002 and 2009–2010, led to periods of intense hydrologic activity, wherein anomalously high streamflows occurred (Hoyos et al. 2013; Restrepo et al. 2014).

Data and methods

Data

The IDEAM (Instituto de Hidrología, Meteorología y Estudios Ambientales de Colombia) provided monthly streamflow data in ten drainage basins located along the Caribbean coast of Colombia. These drainage basins comprise different climatological and topographical settings (Fig. 1; Table 1). Time series selection was based both on its length and reliability. The verification of missing data was carried out before performing the statistical analysis. Time series employed in this study correspond to the locations listed in Table 1. The streamflow

Table 1 Rivers and gauging stations

River		Gauging station	Location				Monthly record
			Elevation (m.a.s.l.)	Drainage basin (10^3 km^2)	Longitude	Latitude	
1	Sucío	Mutata	132	4.52	76°26W	7°13N	1976–2010
2	Mulatos	Pueblo Bello	84	0.01	76°31W	8°12N	1977–2010
3	Sinú	Cotoca Abajo	5	14.73	75°51W	9°13N	1970–2010
4	Magdalena	Calamar	8	257.43	74°55W	10°15N	1941–2010
5	Canal del Dique	Santa Helena	3		75°24W	10°04N	1979–2010
6	Aracataca	Puente Ferrocarril	37	0.93	74°11W	10°35N	1965–2010
7	Fundación	Fundación	55	1.87	74°11W	10°31N	1958–2010
8	Frío	Rio Frío	30	0.32	74°09W	10°34N	1965–2009
9	Palomino	Puente Carretera	30	0.68	73°34W	11°14N	1973–2010
10	Ranchería	Hacienda Guamito	76	4.23	72°37W	11°10N	1976–2007

time series measured at the mouth of the watershed might be considered as a valuable integrated signal between gain and loss of the continental water cycle (i.e., precipitation, evapotranspiration, runoff). Thus, gauging stations analyzed in this study are situated close to the downstream part of the basin. Besides, they are located far enough apart to avoid spatial dependence problems. According to the descriptions performed by Restrepo et al. (2014) each of the selected sites can be associated to a hydrologic region.

Methods

Differentiation between natural variability and trends constitutes a major concern amongst hydrologist. Hydrological time series are usually analyzed by concentrating on differences in 30-year normal's along the whole period of record. This timeframe is also suitable for describing hydrologic time series as non-stationary signals with local periods of stationary patterns. Consequently, the data set length of our study, mostly 30 years (Table 1), suffices the minimum required length for examining evidence of climatic change in hydrologic time series. The local significance of long-term trends of streamflow was analyzed by Restrepo et al. (2014) through the non-parametric Mann–Kendall (MK) test. The MK test is a rank-based procedure, especially suitable for non-normally distributed data, which contains outliers and non-linear trends (Salas 1993). It has been demonstrated that the presence of serial correlation decreases the power of the MK test and leads to an erroneous rejection of the null hypothesis (Type II error) (Helsel and Hirsch 1992; Kulkarni and von Storch 1995; Yue et al. 2002; Yue and Wang 2002; Yue and Pilon 2003). One of the most common corrections applied in previous studies has been to remove the serial correlation in the data by pre-whitening; applying the MK test to the series data ($X'_i = X_i - r_{-1}X_{i-1}$) and then extract the lag-1 serial correlation coefficient (r_{-1}) of the detrended series (Yue et al. 2002; Yue et al. 2003; Yue and Pilon 2003; Restrepo et al. 2014). The pre-whitening was applied only to time series with lag-1 serial positive correlation to test the effect of the pre-whitening on the results. Therefore, we analyzed both, original data as well as pre-whitened data (X'_i), because serial correlation coefficients were generally low for the seasonal time series. The differences between the two approaches were not large.

The original dataset was divided on Dry1 (i.e., the sum of streamflows from December to March—first Dry climatic season), Wet1 (i.e., the sum of streamflows from April to May), Dry2 (i.e., the sum of streamflows from June to August), and Wet2 (i.e., the sum of streamflows sum from September to November). The analysis of streamflow focused on changes experienced in the extremes values of the dry and wet seasons along the historic record. Streamflow extremes values are typically defined based on the frequency of occurrence by percentile (e.g., upper 5, 1, or 0.1%) or by the return period. Several fundamental Probability Density Functions (PDF) can be adopted for estimating streamflow amounts. Amongst which the most commonly used are the Generalized Extreme Value (GEV), Gumbel, Gamma and Weibull distribution. The Kolmogorov–Smirnov (K–S) test is used to establish if a sample comes from a hypothesized continuous PDF. It is based on the largest vertical difference between a theoretical and empirical PDF. After testing several fit tests for different theoretical distributions (i.e., Gamma, Weibull, GEV, Gumbel, Lognormal; not shown for brevity), the Gamma distribution provides the best statistical fit to the seasonal patterns of streamflow in the Caribbean Colombian plain. Thus, according to the available monthly streamflow data, the most suitable procedure is based on fitting data to Gamma distributions. The gamma distribution is an arbitrary, but convenient choice, to represent variations in streamflow (Wilks and Eggleston 1992; Wilks 1995). Within the continuous theoretical distributions of probability this function is defined by the PDF,

$$f(x) = \frac{(x/\beta)^{\alpha-1}\exp(-x/\beta)}{\beta\,\Gamma(\alpha)},\ x,\ \alpha,\ \beta > 0 \qquad (1)$$

The quantity $\Gamma(\alpha)$ is a value of the mathematical Gamma function. The two distribution parameters are α and β; shape and scale parameter, respectively. These parameters control the distribution of the Gamma function. The variance of the Gamma distribution is equal to $\alpha\beta^2$ (Wilks 1995).

Non-stationarity properties are present in time series of streamflow. Thus, a return period estimation for a given event should exhibit significant changes when different subseries are extracted from the whole hydrological record, demonstrating significant changes over the streamflow monthly events (magnitude and frequency). Furthermore, it is known that return periods are commonly used for fitting Gamma probability distributions (Yu 2003; Davison and Hinkley 1997; Hall et al. 2004). Thus, return periods (RP) of 5, 10 and 20 years were selected within this study to fit the Gamma distribution to each seasonal pattern of streamflow. The extreme dry or wet quantile (QT), such as the streamflow value that reaches or exceeds the probability of 0.20, 0.10, 0.05 or 0.80, 0.90, 0.95, respectively, was defined for each RP. The evaluation of the time variation of the oscillation processes employed a 20-year time-windows, with 1-year shifting through the series. Each time-window selects a subseries of seasonal streamflow data (i.e., 20 years for Dry1/Dry2/Wet1/Wet2, is thus used for each extracted series). For example, in the Magdalena the first data subseries of Dry1 season is (1941–1960), the second is (1942–1961), and so on until the last subseries (1991–2010). We employed a length of 20 years for the window after several evaluations on the concurrence of the major hydrological oscillation processes and the occurrence of the maximum power of the interannual and quasi-decadal bands, which defined period of intense hydrological activity (Restrepo et al. 2014, 2015). In addition, Restrepo et al. (2014) highlighted a change in the variability patterns of the fluvial systems of the Colombian Caribbean between 2000 and 2010, characterized by a shift toward the domain of quasi-decadal processes. Thus, it is considered that these sub-periods guarantee the probability of occurrence of significant oscillation processes during this time framework (i.e., 20 years).

When adjusting a theoretical distribution to a finite data sample, the estimation of the parameters presents uncertainties. Therefore, such procedure has an effect on the calculations of the quantiles and return periods. Thus, to minimize such effects, the maximum likelihood estimation (MLE) and a parametric bootstrap approach with 1000 iterations were used to estimate the parameters of the Gamma distribution. This method is based on random samples which are drawn from the fitted Gamma distribution. The subsequent analysis of quantiles employed the mean parameters from the bootstrapping to estimate the changes in the occurrence of wet and dry years. The confidence intervals of quantiles for different periods are compared with each other in order to decide whether a change in the mean QT estimate is statistically significant at a given error.

Results

Times series analysis

The general procedure employed for all the time series is presented in detail for the Magdalena River. Table 2 presents the Gamma distribution parameters (α and β) for the corresponding Wet and Dry streamflow seasons (Dry1, Wet1, Dry2, Wet2) in the same six windows, as mentioned in Fig. 3. Both parameters were estimated using the MLE and 1000 bootstrap methods. The 95% confidence interval estimated for such procedures is shown (Table 2). The skewness and kurtosis were added, as well as the variance estimated through bootstrapping. Wet and Dry streamflow seasons showed an increase in its variability since 1941 until recently. Figure 3 shows the time series and mean value of streamflow for the Dry1 (Fig. 3a), Wet1 (Fig. 3b), Dry2 (Fig. 3c) and Wet2 (Fig. 3d) seasons (upper panel) and the corresponding Gamma distributions (bottom panel), only for six different 20-year window periods (i.e., 1941–1960, 1951–1970, 1961–1980, 1971–1990, 1981–2000, 1991–2010). The rest of window periods are not shown for clarity of the figure. The streamflow of the Magdalena River exhibited a trend in the mean value, as well as in the extreme values during wet and dry years. The bottom panel illustrates changes in the location and shape of Gamma distributions. A shift of the Gamma distribution toward a lower mean (i.e., positive skewness) reflects a decrease in the streamflow when comparing different periods. On the contrary, the years of high streamflows observed after the second 20-year period and on, led to a negative skewness. Moreover, a positive trend in the streamflow was observed during the shift of the Gamma distribution toward higher means, from the first to the last of the six time-window periods shown in the Fig. 3. For example, the Wet1 and Wet2 seasons experienced an increase in its variability during the last decades, particularly between 1991 and 2010. Such change was reflected in a deformation (flattening and/or widening) of the Gamma distribution curve with respect to the other periods.

The Fig. 4 presents the linear trend values and its respective variance for each streamflow season and time-window evaluated in the Magdalena. The Dry1 (Fig. 4a) showed a period with positive significant trend values

Table 2 Mean value of shape (α) and scale (β), Skewness, Kurtosis and Variance parameters of Gamma distribution estimated for different 20-year period of Dry1/Wet1/Dry2/Wet2 streamflow time series for Magdalena using method of maximum likelihood, MLE, and 1000 bootstrap samples with 95% confident intervals

Period	(α) MLE	(β) MLE	(α) Bootstrap	(β) Bootstrap	Skewness	Kurtosis	Variance bootstrap ($\times 10^7$)
Dry1							
1941–1960	11.1	1758.2	12.7 ± 4.0	1671.8 ± 461.9	0.58 ± 0.08	0.52 ± 0.15	3.55 ± 0.09
1951–1970	20.8	972.8	24.4 ± 8.7	926.9 ± 305.9	0.42 ± 0.07	0.27 ± 0.09	2.10 ± 0.08
1961–1980	19.5	1093.1	24.0 ± 13.1	1060.0 ± 400.2	0.44 ± 0.08	0.30 ± 0.10	2.70 ± 0.21
1971–1990	17.6	1279.6	21.0 ± 8.9	1211.5 ± 393.6	0.46 ± 0.08	0.32 ± 0.10	3.08 ± 0.14
1981–2000	17.0	1302.1	20.7 ± 7.6	1203.4 ± 417.2	0.46 ± 0.08	0.33 ± 0.11	3.00 ± 0.13
1991–2010	15.2	1531.2	17.3 ± 5.2	1456.8 ± 411.2	0.49 ± 0.07	0.37 ± 0.10	3.67 ± 0.09
Wet1							
1941–1960	15.4	640.0	17.6 ± 4.9	604.0 ± 165.0	0.49 ± 0.06	0.36 ± 0.09	0.64 ± 0.01
1951–1970	31.9	288.3	36.0 ± 11.5	277.9 ± 76.0	0.34 ± 0.05	0.18 ± 0.05	0.28 ± 0.01
1961–1980	14.4	682.5	17.3 ± 6.5	647.1 ± 238.3	0.50 ± 0.09	0.39 ± 0.13	0.72 ± 0.04
1971–1990	14.4	716.6	16.9 ± 6.1	682.4 ± 227.3	0.51 ± 0.08	0.40 ± 0.13	0.79 ± 0.03
1981–2000	17.4	601.6	20.3 ± 7.0	573.7 ± 186.8	0.46 ± 0.07	0.33 ± 0.10	0.67 ± 0.02
1991–2010	15.3	730.9	17.1 ± 5.2	706.8 ± 192.8	0.50 ± 0.07	0.38 ± 0.10	0.85 ± 0.02
Dry2							
1941–1960	19.7	1046.2	22.0 ± 6.6	1008.1 ± 266.9	0.44 ± 0.06	0.29 ± 0.08	2.24 ± 0.05
1951–1970	25.3	854.7	28.1 ± 7.4	812.6 ± 178.0	0.39 ± 0.04	0.23 ± 0.05	1.86 ± 0.02
1961–1980	28.7	759.9	33.3 ± 11.2	714.9 ± 198.4	0.36 ± 0.05	0.20 ± 0.06	1.70 ± 0.04
1971–1990	24.5	891.4	29.7 ± 14.1	848.9 ± 297.5	0.39 ± 0.07	0.23 ± 0.08	2.14 ± 0.12
1981–2000	16.1	1379.4	18.9 ± 6.4	1289.0 ± 386.3	0.48 ± 0.07	0.35 ± 0.11	3.14 ± 0.10
1991–2010	12.6	1835.4	14.3 ± 4.4	1745.4 ± 448.3	0.54 ± 0.07	0.45 ± 0.12	4.36 ± 0.09
Wet2							
1941–1960	29.2	730.3	32.9 ± 10.2	699.6 ± 175.3	0.36 ± 0.05	0.20 ± 0.05	1.61 ± 0.03
1951–1970	35.0	644.4	40.8 ± 13.5	600.3 ± 162.3	0.32 ± 0.05	0.16 ± 0.04	1.47 ± 0.04
1961–1980	27.5	899.0	31.2 ± 9.3	859.5 ± 236.4	0.37 ± 0.05	0.21 ± 0.06	2.30 ± 0.05
1971–1990	24.0	1078.2	26.7 ± 6.3	1019.3 ± 235.5	0.39 ± 0.04	0.24 ± 0.05	2.77 ± 0.03
1981–2000	18.3	1390.6	21.5 ± 8.5	1346.0 ± 466.7	0.45 ± 0.08	0.32 ± 0.11	3.90 ± 0.19
1991–2010	11.3	2240.9	13.0 ± 4.5	2154.2 ± 686.6	0.58 ± 0.09	0.51 ± 0.15	6.03 ± 0.21

during the central years surveyed—the time-window between 1958 and 1977 (Table 3), corresponding to the extreme interval in Fig. 4a and an increasing trend since the 1986–2005 time-window, which exhibited a fairly consistent pattern. The maximum positive trend in streamflow (Fig. 4a) was more noticeable to this season during the 1957–1976 time-window, whilst a dramatic reversion in the sign of the trend was observed afterwards (Table 3). This remarkable feature was present also in other time series from Table 4.

Variances were analyzed to distinguish whether there is a climate change associated to the streamflow variability. For the Magdalena, the present Dry1 streamflow variances exhibited such high values as those at the beginning of the period surveyed [3.4×10^7 $(\mathrm{m}^3\ \mathrm{s}^{-1})^2$]; whilst in central years, the fluctuations were around 2.2×10^7 $(\mathrm{m}^3\ \mathrm{s}^{-1})^2$. The variance at the beginning and at the end of the surveyed period exhibited comparable high values (Fig. 4a). The streamflow pattern of the Wet1 season indicates that observed variances have been lower than the other seasons, exhibiting strong variability in the last decades (Fig. 4b). During the Wet2 season (Fig. 4d) the streamflow pattern indicates that actual variances have overcome the previous values observed through the entire record [5.8×10^7 $(\mathrm{m}^3\ \mathrm{s}^{-1})^2$]. Thus, there has been a shift in the streamflow distributions, as presented in Fig. 3, as well as irregular changes in the variance throughout time of the Wet1 and Dry2 streamflow seasons; whilst the streamflows of the Dry1 and Wet2 seasons experienced a greater variability. Along the whole record, the final segments of Wet1 and Dry2 seasons exhibited the highest variances [$\sim 4.1 \times 10^7$ $(\mathrm{m}^3\ \mathrm{s}^{-1})^2$], whereas the variance was close to 2.1×10^7 $(\mathrm{m}^3\ \mathrm{s}^{-1})^2$ in the central years (1970–1995) (Fig. 4). All seasons patterns indicate that their variability has increased significantly during the last decades; other rivers, such as Frío, Sinú, C. Dique, among others, exhibited similar

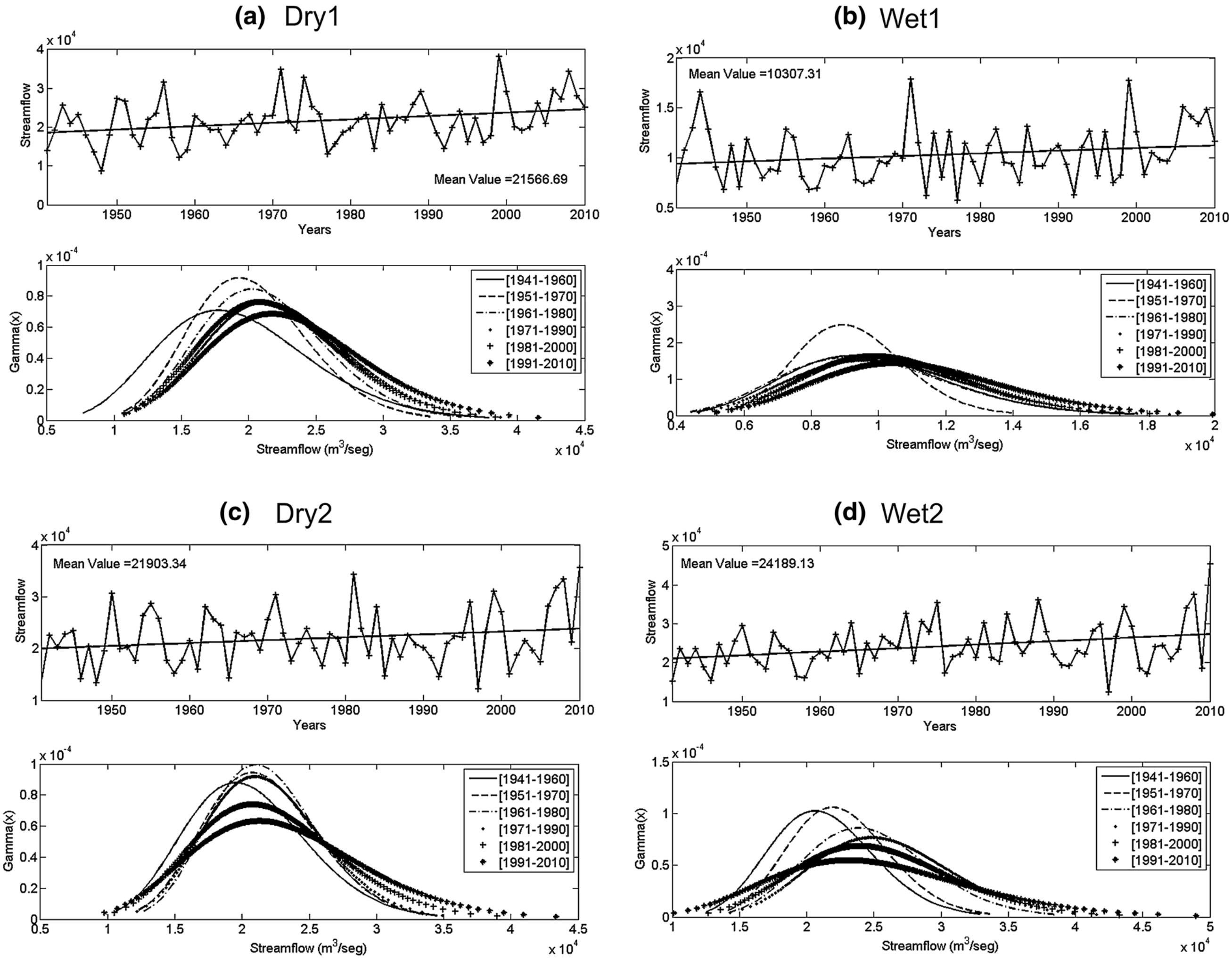


Fig. 3 Magdalena river seasonal streamflow values (*top*) and Gamma distribution for six different 20-year period (*bottom*) during 1941–2010 period in **a** Dry1, **b** Wet1, **c** Dry2, **d** Wet2 seasons

patterns (Table 4). From a retrospective view, the variance has increased four times from its original values (Fig. 4d).

Quantile analysis

Figure 5 represents the temporal evolution of QTs (in $m^3 s^{-1}$). The extremes from Dry1/Wet1/Dry2/Wet2 (upper/lower frame) are plotted for three return periods (RPs): 20, 10 and 5 years. Figure 5a, c correspond to Dry1 and Dry2, whereas Fig. 5b, d, represent the Wet1 and Wet2. If we consider the temporal variation for the entire 20-year time-window periods, Dry1 and Wet1 extremes (Fig. 5a, b) showed an increment throughout the century for the same RP (upper frame). This positive trend was enhanced during almost all the twentieth century in the Dry2 and Wet2 seasons (Fig. 5c, d). Besides, recent QTs for a return period of 20 years (percentile 0.8 in Fig. 5c, d), for instance, are similar to those observed at the beginning of the record. Additionally, some inter-decadal fluctuations can be observed. During the first part of the record, QTs were dominated by an oscillatory trend reaching a maximum peak around 1980–1990. Then, they exhibited an oscillatory pattern with decreasing trend. The same analysis applied to Dry1 and Wet1 seasons showed increasing streamflows in correspondence with the positive trends experienced from 1980.

Confidence Interval (CI) was computed for each one of the seasonal QTs obtained through the 20-year time-windows. The last time-window corresponds to the period 1991–2010. Its Confidence Interval was set as a Control Interval, in order to provide a statistical value to compare and measure the observed changes. Hence, we established the year in which the difference between the CI and the Control Interval exceed the zero value or is less than zero, depending if a negative or positive trend occurred. Thus, when there is no overlapping between both segments, the observed QT becomes significant for identifying changes in streamflow. Then, significant climate change periods were

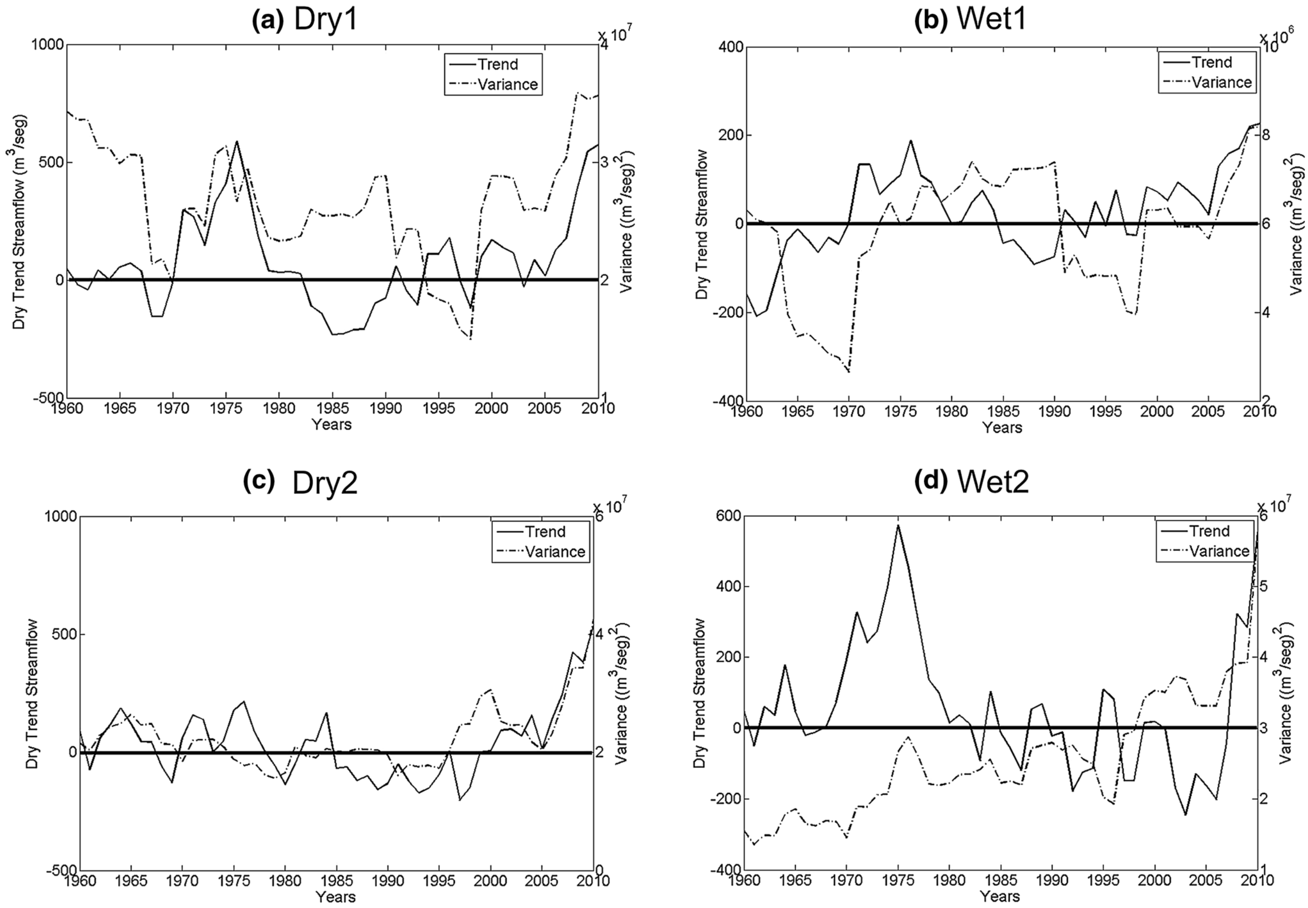


Fig. 4 Variance (*dashed line*) and linear trend (*full line*) for all 20-year window of Magdalena river seasonal streamflow in **a** Dry1, **b** Wet1, **c** Dry2, **d** Wet2 seasons (Note that the values are assigned to the end of the interval analyzed, e.g., 1941–1960 is assigned to 1960 and so on)

defined as those successive years in which there was no overlapping between the observed CI and Control Interval.

Figures 6 and 7 display the estimated QTs and CI for the Dry1/Dry2 (left) and Wet1/Wet2 (right) seasons in the Magdalena and Mulatos rivers, respectively. For these examples, the extremes at 10 and 90% probability levels were selected. For these examples, the extremes for the 10 and 90% probability levels were selected. Horizontal band corresponds to the Control Interval and the bars to the CI, for each QT. They were estimated using the 1000 bootstrap procedure. In general, a QTs increase were observed along the surveyed period with a negative difference between CI and Control Interval (extremes or mean CI minus extremes or mean Control Interval, respectively). Besides, a difference (positive or negative) is statistically significant (at a given error) when the 100% of the CI of the associated QT do not overlap with the Control Interval. It is then considered that the corresponding QT differs significantly from the Control Interval; and thus, the last of the 20-year time-windows is identified as the starting year of climate change.

Further, the QT for Dry1 (10% probability level), as well as the CI, in the Magdalena (Fig. 6a) showed a significant difference, with an oscillating pattern from the beginning of the record until the 1948–1967 time-window, when a major leap in the streamflow occurred. From this point until the mid-1980s the QT trend was positive and remained almost constant through the end of the record. When it reached approximately 16,000 m^3 s^{-1}. Similarly, for Wet1 at the 10% probability level (Fig. 6b), it can be appreciated an oscillatory pattern from the beginning to the 1958–1977 time-window, when a significant difference emerged up. Subsequently, an increasing in the variability and a positive trend of QT were experienced until the end of the surveyed period. The values in the trend reached approximately 7900 m^3 s^{-1} at this final period. The QTs values from the Dry2 and Wet2 seasons are shown in Fig. 6c, d. Values estimated at the 10% probability level showed a remarkable wave form, with a period of approximately 24 years. According to the aforementioned definition, there are no years in which significant changes in QTs can be detected for Dry2 (Fig. 6c). Instead, for Wet2 (Fig. 6d) there were some significant changes for QT between the 1966–1985 and 1973–1992 time-windows,

Table 3 Seasonal Kendall trend significance test estimated for different 20-year period of Dry1/Wet1/Dry2/Wet2 streamflow time series for Magdalena and Mulatos

Dry1	Significant period with p: 0.05				
Magdalena	[1956–1975] ↑	[1957–1976] ↑	[1958–1977] ↑	[1990–2009] ↑	[1991–2010] ↑
Mulatos	[1983–2002] ↑	[1984–2003] ↑	[1985–2004] ↑		
Wet1	**Significant period with p: 0.05**				
Magdalena	[1957–1976] ↑	[1990–2009] ↑	[1991–2010] ↑		
Mulatos	None				
Dry2	**Significant period with p: 0.05**				
Magdalena	[1991–2010] ↑				
Mulatos	None				
Wet2	**Significant period with p: 0.05**				
Magdalena	[1956–1975] ↑	[1957–1976] ↑	[1958–1977] ↑		
Mulatos	None				

↑, positive trend; ↓, negative trend, –, no trend

which lead to an increase in the streamflow variability over the end of the surveyed period.

In the QTs analysis at the 90% probability level, the Magdalena showed the lowest extreme values for the Dry1 (Fig. 6e) in the 1946–1965 and 1979–1998 time-windows. The Wet1 experienced a similar pattern of significant changes during the same time-windows (Fig. 6f); although, a sudden increase in both streamflow and variability were experienced until the end of the surveyed period. The opposite occurred for the Dry2 values (Fig. 6g). There is evidence of significant changes in the QTs from the beginning to 1951–1970, 1955–1974 to 1961–1980, 1972–1991 to 1977–1996 and 1982–2001 to 1987–2006 time-windows; during the rest of period there was a continuous increase. Figure 6h shows the QT for Wet2 at the 90% probability level. It is observed a significant difference with an oscillatory pattern from the beginning of the record until the 1955–1974 time-window, where a little jump in the streamflow was generated. From this point until the mid-1980s the QTs trend is practically stable. Then, it remains oscillating until the end of the record, where it reached values of approximately 35,000 $m^3 s^{-1}$.

Figure 7a shows the QTs and the CI, at the 10% probability level, for Dry1 in the Mulatos river. The analysis highlighted a significant difference from the beginning of the record until the 1981–2000 time-window; afterwards, it exhibited oscillatory patterns, reaching its highest variability and values of approximately 3.1 $m^3 s^{-1}$. Similarly, for the Wet1 at the 10% probability level (Fig. 7b), it can be appreciated an oscillatory pattern with a positive trend since the beginning of the record. Such patterns generated a significant difference after the 1981–2000 time-window, reaching values of approximately 5 $m^3 s^{-1}$. The streamflow QTs values, estimated at the 10% probability level, for Dry2 and Wet2 are shown in Fig. 7c, d. According to the aforementioned definition, there were no years in which significant changes in QTs can be detected. Instead, for the Dry2 and Wet2 (Fig. 7c, d) there were some trend changes since the 1981–2000 time-window; particularly, the decrease in the streamflow values over the end of the surveyed period.

In the QTs analysis at the 90% probability level, Mulatos showed the extremes values for the Dry1 season (Fig. 7e) in the 1946–1965 and 1979–1998 time-windows, exhibiting also a similar variability in the intervening years. Such pattern was similar in the Wet1 (Fig. 6f) during the same time-windows. Afterwards, the streamflow and variability experienced a sudden increase at the end of the surveyed period. On the contrary, the Dry2 values did not exhibited significant changes in the QTs from the beginning of the record to the 1979–1998 time-window. The rest of the period underwent a continuous increase (Fig. 6g). Figure 6h shows the QT for Wet2 at the 90% probability level. There were no years in which significant changes in QTs can be detected. The oscillatory pattern was prominent. Such pattern remained stable until the end of the record, when values of approximately 29 $m^3 s^{-1}$ were reached.

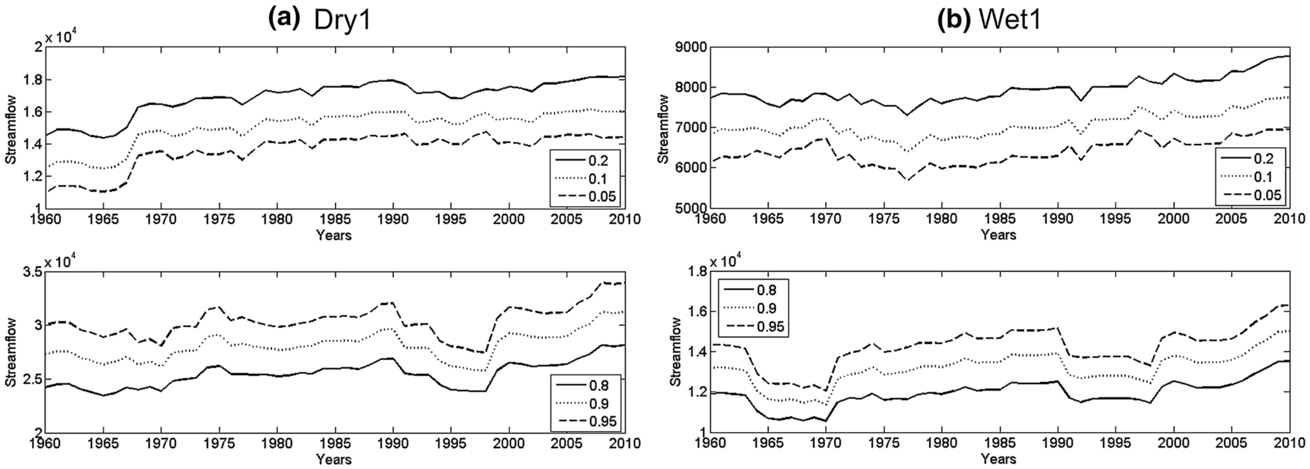
Applying in detail the procedure described with the rest of time series corresponding to locations in Table 1, years with statistically significant changes in streamflow QTs were obtained, for both Dry and Wet seasons. As summary, the Dry1/Wet1/Dry2/Wet2 seasons with changes at the 10 and 90% probability level for each site

Table 4 Seasonal Kendall trend significance estimated for different 20-year period of Dry1/Wet1/Dry2/Wet2 streamflow time series

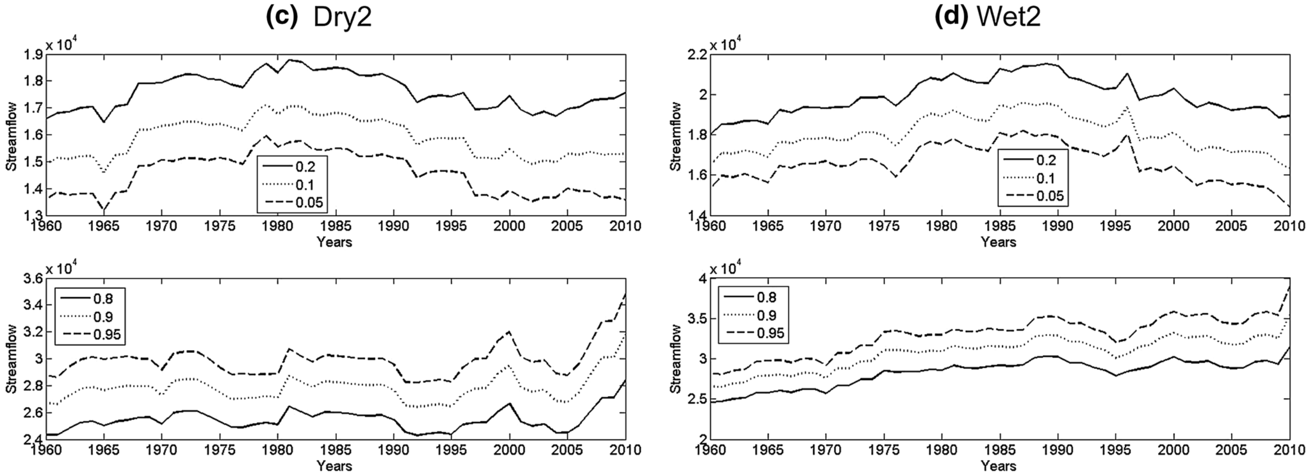
Dry1	Significant period with p: 0.05					
Frio	None					
Palomino	None					
Rancheria	None					
Sucio	None					
Sinú	[1985–2004] ↑	[1986–2005] ↑	[1990–2009] ↑	[1991–2010] ↑		
C. Dique	[1990–2009] ↑	[1991–2010] ↑				
Aracataca	[1972–1991] ↓	[1973–1992] ↑	[1974–1993] ↑	[1975–1994] ↑	[1976–1995] ↑	[1977–1996] ↑
Aracataca	[1978–1997] ↑	[1979–1998] ↑	[1980–1999] ↑	[1981–2000] ↑	[1982–2001] ↑	[1983–2002] ↑
Aracataca	[1984–2003] ↑	[1985–2004] ↑				
Fundación	[1966–1985] ↓	[1967–1986] ↓	[1968–1987] ↓	[1969–1988] ↓		
Wet1	**Significant period with p: 0.05**					
Frio	[1973–1992] ↑	[1974–1993] ↑	[1975–1994] ↑	[1976–1995] ↑	[1982–2001] ↑	[1983–2002] ↑
Frio	[1984–2003] ↑	[1985–2004]↑				
Palomino	[1973–1992] ↑	[1974–993] ↑				
Rancheria	[1988–2007] ↑					
Sucio	None					
Sinú	[1989–2008] ↑	[1990–2009] ↑	[1991–2010] ↑			
C. Dique	[1980–1999] ↑	[1981–2000] ↑	[1990–2009] ↑			
Aracataca	None					
Fundación	None					
Dry2	**Significant period with p: 0.05**					
Frio	[1971–1990] ↑	[1972–1991] ↑	[1973–1992] ↑	[1974–1993] ↑	[1975–1994] ↑	[1976–1995] ↑
Frio	[1977–1996] ↑	[1980–1999] ↑				
Palomino	[1983–2002] ↓					
Rancheria	None					
Sucio	[1991–2010] ↑					
Sinú	[1989–2008] ↑	[1990–2009] ↑	[1991–2010] ↑			
C. Dique	[1988–2007] ↑	[1989–2008] ↑	[1990–2009] ↑	[1991–2010] ↑		
Aracataca	None					
Fundación	[1971–1990] ↑	[1973–1992] ↑				
Wet2	**Significant period with p: 0.05**					
Frio	None					
Palomino	[1983–2002] ↓	[1984–2003] ↓	[1986–2005] ↓			
Rancheria	None					
Sucio	[1989–2008] ↑	[1991–2010] ↑				
Sinú	None					
C. Dique	[1991–2010] ↑					
Aracataca	None					
Fundación	[1971–1990] ↑	[1972–1991] ↑	[1984–2003] ↓	[1985–2004] ↓	[1986–2005] ↓	[1987–2006] ↓

↑, positive trend; ↓, negative trend, –, no trend

included in Table 1 were evaluated. However, all results are not shown due to brevity. Only the periods of consecutive 20-years time-windows with significant variability in seasonal streamflow of the Magdalena and Mulatos are shown (Figs. 6 and 7). Figures 8 and 9 show the statistical significance (black) for the QTs at the 10 and 90% probability level, respectively, for each station through the 20-year time-windows.



(a) Dry1 **(b)** Wet1



(c) Dry2 **(d)** Wet2

Fig. 5 Magdalena river Quantiles ($m^3\ s^{-1}$) for extreme Dry/Wet seasonal streamflow (*top/bottom panel*) with return periods of 20 (*full*), 10 (*point*) and 5 (*dashed*) years. **a** Dry1, **b** Wet1, **c** Dry2, **d** Wet2 (Note that the values are assigned to the end of the interval analyzed, e.g., 1941–1960 is assigned to 1960 and so on)

Fig. 6 Magdalena river Quantiles and bootstrapping confidence ▶ intervals for each consecutive 20-year window of seasonal streamflow (Dry1/Wet1/Dry2/Wet2) at probability of 10% (**a**–**d**) and 90% (**e**–**h**). Horizontal full line band shows confidence interval (Control) of last 20-year period. See text for details (note that the values are assigned to the end of the interval analyzed, e.g., 1941–1960 is assigned to 1960 and so on)

Discussion

Concerning the seasonal streamflow, the region under study presents well differentiated wet and dry seasons (Fig. 1). However, extreme dry QTs have increased through the record, except for the Mulatos at the 10% probability level (Fig. 7a). On the contrary, no significant QT variability have been found for the wet extreme in the locations, except for the Magdalena (Calamar) at the 90% probability level (Fig. 6e–h). Thus, the streamflow values of Dry1 and Dry2 seasons have increased through the entire record, indicating that dry extremes in the current distribution of streamflows are not as low as used to be before.

QT for extreme dry conditions increased over practically all the study region, except in the Mulatos River (i.e., Dry1 and Dry2), where no significant differences in QTs of the dry extreme streamflow were detected (Fig. 7). However, Wet1 and Wet2 extremes (at the 90% probability level) showed positive differences across the whole study area, indicating that current values are significantly higher than those experienced previously. For a fixed return period, the extreme Wet1 and Wet2 streamflows have been rising over the surveyed rivers, although with different time length and different change points. For example, the Caribbean Colombian region, represented by the Magdalena river, experienced a positive change several decades later.

Currently, the evidence indicates that the occurrence of hydrologic disasters in the Caribbean plain of Colombia is favored as a consequence of anthropogenic activities, the

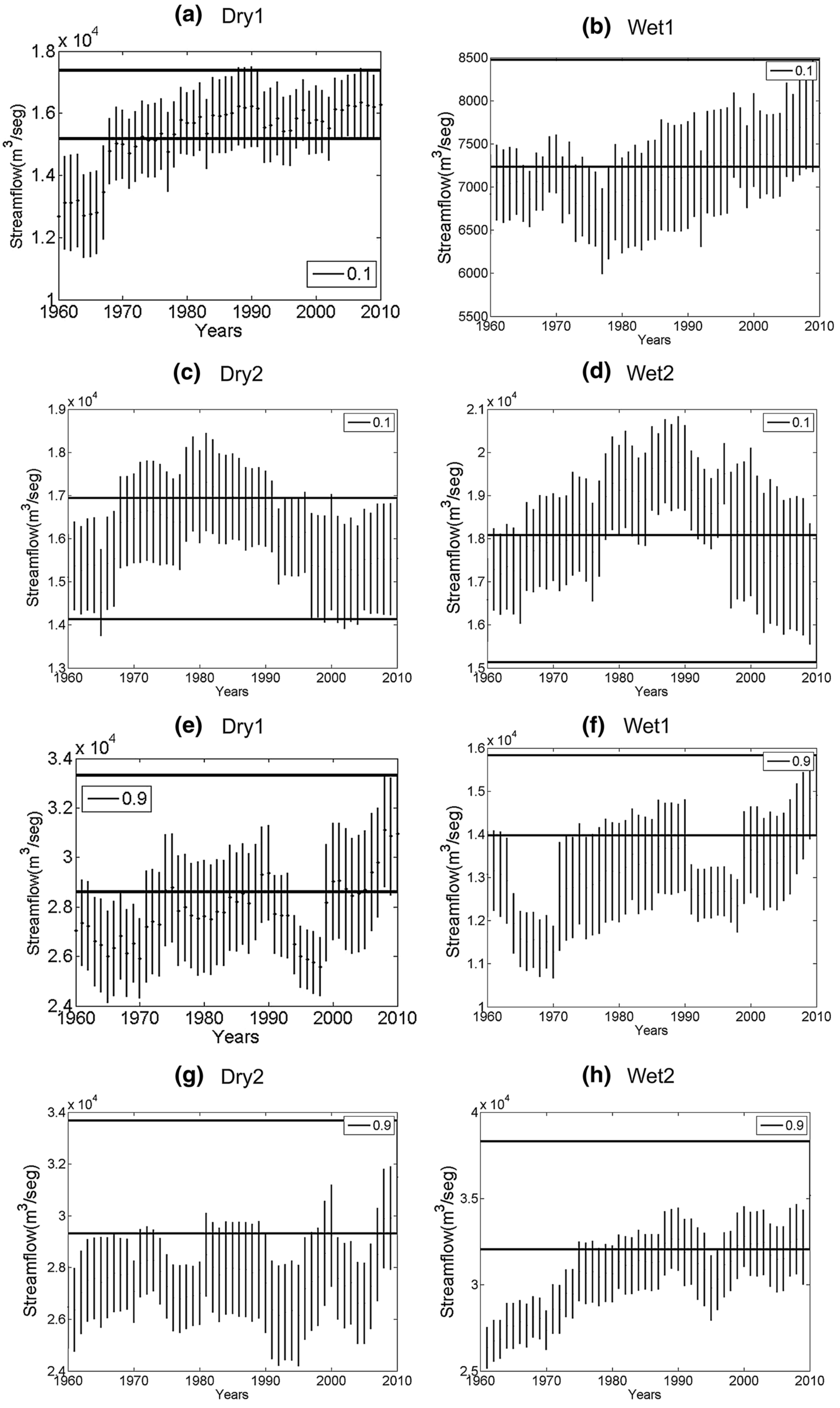
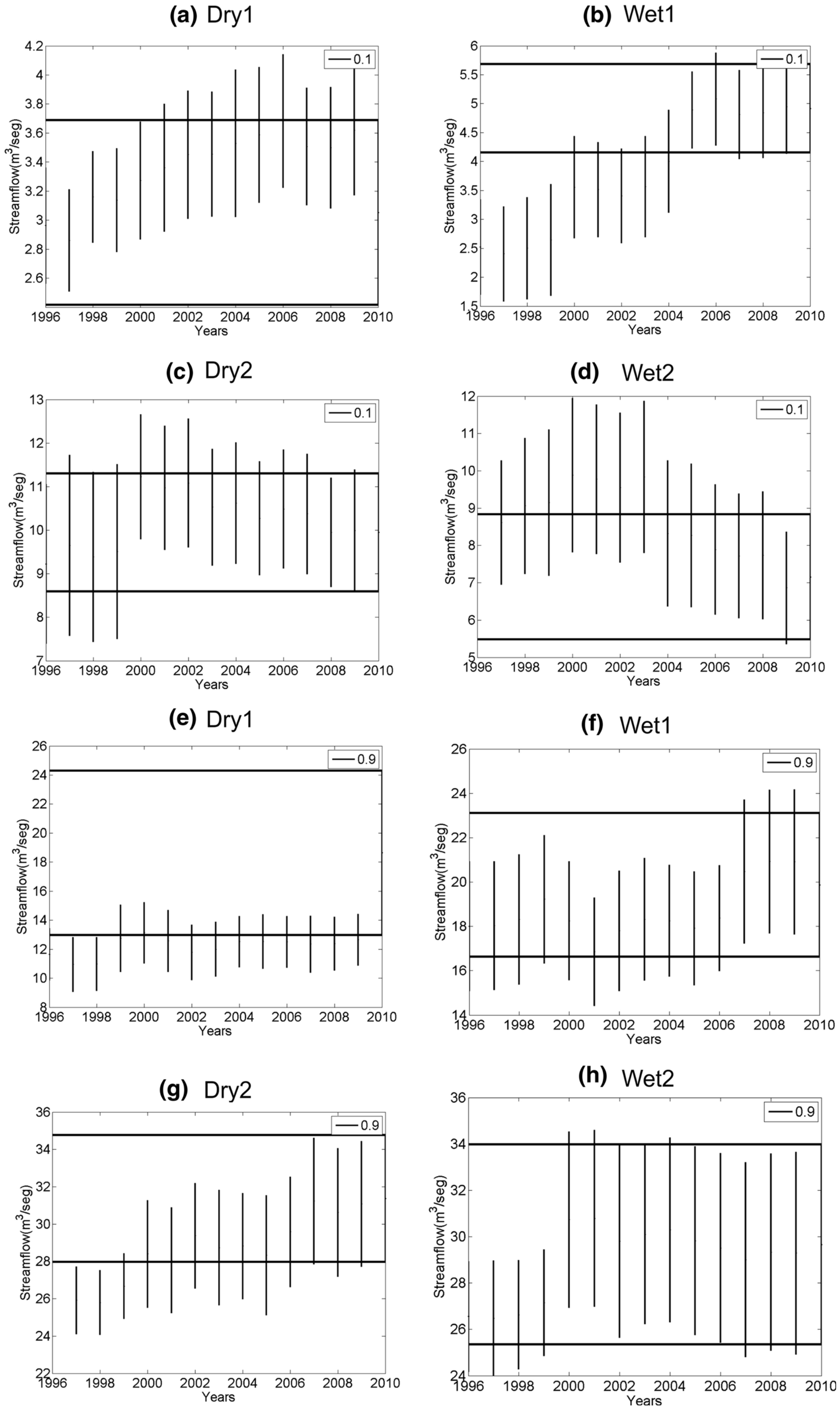

(a) Dry1
x 10^4
1.8
1.6
1.4
1.2
1
Streamflow(m^3/seg)
0.1
1960
1970
1980
1990
2000
2010
Years
(b) Wet1
8500
8000
7500
7000
6500
6000
5500
Streamflow(m^3/seg)
0.1
Years
(c) Dry2
x 10^4
1.9
1.8
1.7
1.6
1.5
1.4
1.3
Streamflow(m^3/seg)
0.1
Years
(d) Wet2
x 10^4
2.1
2
1.9
1.8
1.7
1.6
1.5
Streamflow(m^3/seg)
0.1
Years
(e) Dry1
x 10^4
3.4
3.2
3
2.8
2.6
2.4
Streamflow(m^3/seg)
0.9
Years
(f) Wet1
x 10^4
1.6
1.5
1.4
1.3
1.2
1.1
1
Streamflow(m^3/seg)
0.9
Years
(g) Dry2
x 10^4
3.4
3.2
3
2.8
2.6
2.4
Streamflow(m^3/seg)
0.9
Years
(h) Wet2
x 10^4
4
3.5
3
2.5
Streamflow(m^3/seg)
0.9
Years

Fig. 7 Mulatos river Quantiles and bootstrapping confidence intervals for each consecutive 20-year window of seasonal streamflow (Dry1/Wet1/Dry2/Wet2) at probability of 10% (**a**–**d**) and 90% (**e**–**h**). Horizontal full line band shows confidence interval (Control) of last 20-year period. See text for details (note that the values are assigned to the end of the interval analyzed, e.g., 1977–1996 is assigned to 1996 and so on)



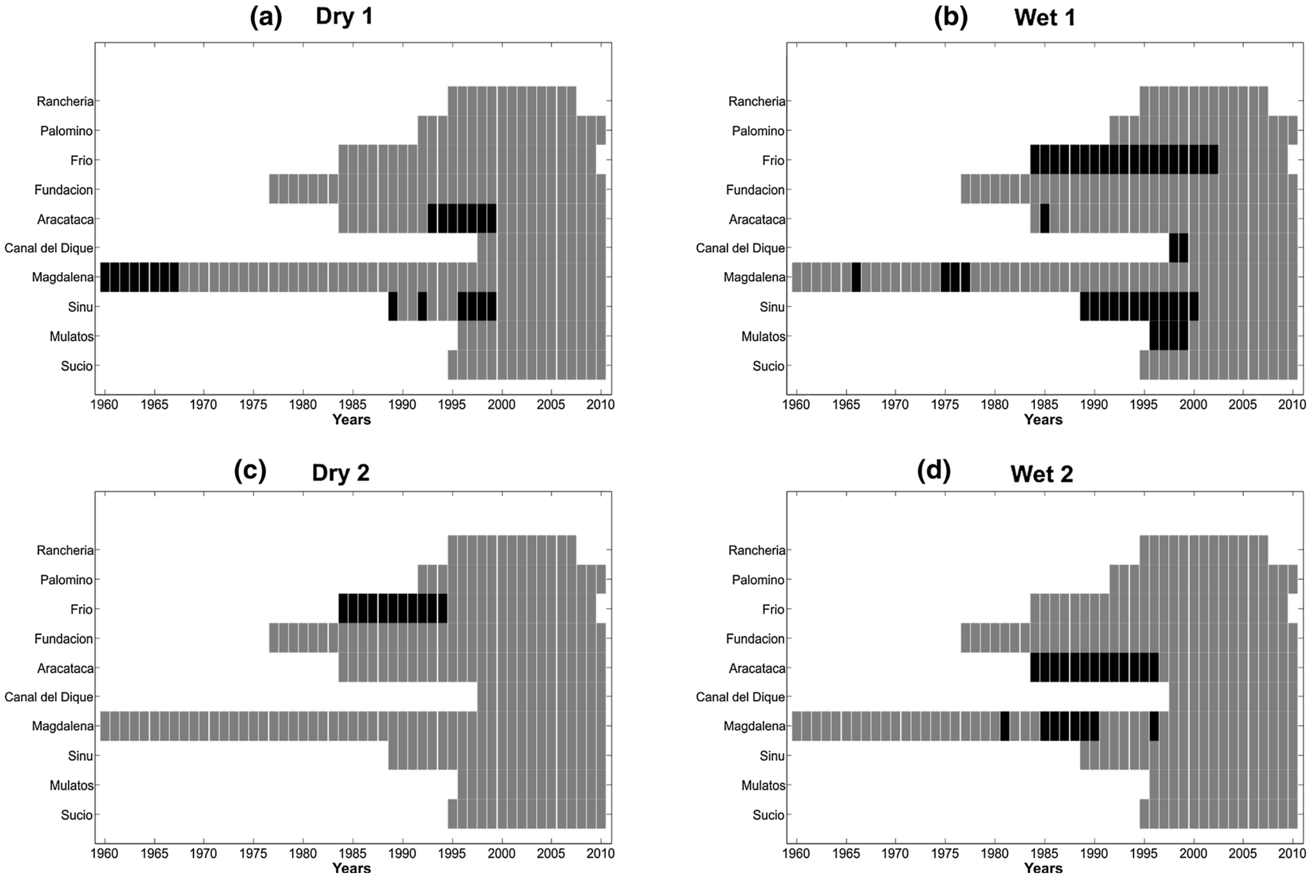


Fig. 8 Significant difference between Control and bootstrapping confidence intervals for each consecutive 20-year window of seasonal streamflow (Dry1/Wet1/Dry2/Wet2) at probability of 10% (**a**–**d**) (note that the values are assigned to the end of the interval analyzed, e.g., 1977–1996 is assigned to 1996 and so on)

increase of population and infrastructure development as well as others factors that modify land use conditions and the water cycle (Hoyos et al. 2013; Restrepo et al. 2015). In such context, it is useful to examine the observed shift in the theoretical distribution of streamflow with respect to both, time and space variability. In the evaluation of the Gamma parameters for each station, it becomes apparent that locations receiving a minimal amount of streamflow are described by either large shape or scale parameters. Values of shape and scale parameters in the Magdalena River (Table 2) exhibited substantial change during the 1951–1970 period, as well as a significant increasing trend since the 1955–1974 period. Distributions with a low shape parameter are positively skewed; as the shape value increases, the distribution curve becomes more symmetrical. These results indicate that significant changes in the frequency and intensity of extreme events might result from a relatively small shift in the average of streamflow distribution (e.g., Karl et al. 2008). Whenever a trend of extreme events is identified and a kind of persistence is determined, more evidence is added to the probable human effect on hydrological changes. However, a reverse in the trend sign and return to initial conditions would reflect the natural fluctuations of climate. Such is the case for the Magdalena and Mulatos rivers highlighted in the present study.

Although the QTs of the Wet1 and Wet2 showed a sustained increase during the last decades (Fig. 6), these values were similar to those observed at the beginning of the records. Both locations, Magdalena and Mulatos, experienced a shift in their mean streamflow values (see Figs. 6, 7) during the surveyed period. Opposite, the variance for Mulatos did not show a noticeable increase, just a slight fluctuation or even a decrease respect to its initial values; whilst at the Magdalena, a positive trend accompanies the larger variances. Thus, it is possible to distinguish certain period of years in which the increasing trends are followed by increasing variances, reflecting the increase in the intensity and variability of streamflows. This particular pattern is also present in the other locations along the surveyed area, such as in the Sucio, Sinú, Canal del Dique Magdalena and Mulatos rivers. Analyzing the properties of the distribution parameters whilst assessing long-term trends constitutes a primary approach aimed to

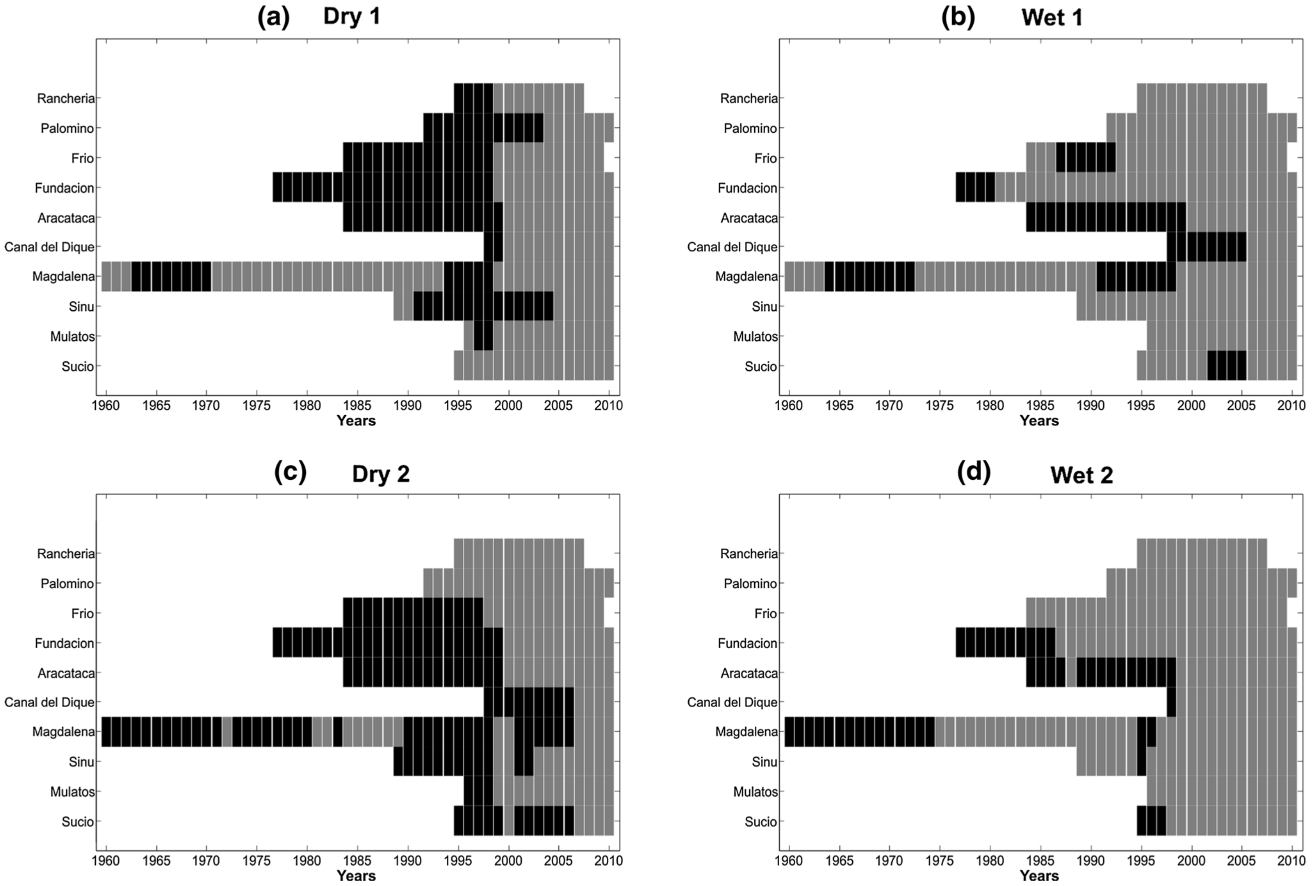


Fig. 9 Significant difference between Control and bootstrapping confidence intervals for each consecutive 20-year window of seasonal streamflow (Dry1/Wet1/Dry2/Wet2) at probability of 90% (**a**–**d**) (note that the values are assigned to the end of the interval analyzed, e.g., 1977–1996 is assigned to 1996 and so on)

classify climatic change, with respect to the location of the station.

The significant difference of QTs between the control and the last of the 20-year time-windows was identified as the starting year of climate change. Extreme dry QTs have changed significantly through the records, except in the Aracataca, Frío and Sinú rivers, between 1960 and1985 (see Fig. 8a, c at the 0.1 probability level). On the contrary, no significant QTs variability have been found for the wet extreme, except for the Frio, Aracataca, Magdalena, Sinú and Mulatos rivers at the 0.1 probability level (Fig. 8b, d). Similarly, extreme QTs at the 90% probability has changed within surveyed area, showing a significant change in the dry season since 1960–1980 in most of the Caribbean plain. Such changes have been triggered by the increase in climate variability generated by the strengthening of the ENSO during those decades (Poveda et al. 2001). However, wet extremes (at the 0.9 probability level) showed no significant differences within the surveyed area. The actual values are significantly lower than those observed previously. For a fixed return period, the extreme wet have changed as a whole for the study regions although with different time length and changing points.

Conclusion

Changes in quantiles of seasonal streamflow extremes were detected in ten different rivers through the Caribbean Colombian plain. Using a 20-year time-window to analyze series larger than fifty years of streamflow, it has been shown that extremes values from Dry1/Wet1/Dry2/Wet2 have varied (increased) significantly in the last decades. However, such changes have not occurred simultaneously in the whole region. The general diminishing in trend values observed at Mulatos, Sinú and Sucio (Tables 3, 4) provides an explanation of why this area exhibit a very particular behavior, which might be related to their highest susceptibility to the variability of sea surface temperature of the Caribbean The proximity of this watersheds to the warm pool forming off the coast of Urabá-Cordoba might induce anomalies in rainfall patterns due to the advection of humidity from the ocean and their relatively low buffering capacity to filter out meteorological inputs (i.e., small/medium drainage basins).

In addition, the analysis highlighted significant differences between the Wet and Dry seasonal extremes. While increases in streamflow were experienced in both quantiles, some rivers showed continuous increases just at minimum QTs. Others rivers presented a pluri-annual variability of different length, whereas certain regions suffered a noticeable change in trend sign.

One of the mayor challenges encountered when quantifying extreme climatic events and their changes is the lack of information on long records, which besides are not always presented adequately for the analysis. Even when this information is available, it must go through processes of digitally processing, quality controls and homogeneity testing, and data interpolation. The lack of any of these factors affects the analysis. The monthly series employed in this work comes from the IDEAM; thus, comprising "long" reliable and official series subjected to well-known systematic control processes.

With the experience acquired performing this research, and considering that significant changes in quantiles at the seasonal scale are driven by changes in the amount of flow associated with daily rainfall or severe storms, further analysis of extremes based in daily and hourly data on streamflow and rainfall are needed in the future.

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