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Article *in* Journal of Hydrology · February 2014

DOI: 10.1016/j.jhydrol.2013.11.045

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Journal of Hydrology 509 (2014) 266–281

Contents lists available at ScienceDirect

Journal of Hydrology

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

Freshwater discharge into the Caribbean Sea from the rivers of Northwestern South America (Colombia): Magnitude, variability and recent changes

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ARTICLE INFO

Article history:
Received 18 March 2013
Received in revised form 19 October 2013
Accepted 23 November 2013
Available online 1 December 2013
This manuscript was handled by Konstantine P. Georgakakos, Editor-in-Chief, with the assistance of Ana P. Barros, Associate Editor

Keywords:
Streamflow variability
Hydrologic oscillations
ENSO
River discharges
Wavelet analyses

SUMMARY

The monthly averaged freshwater discharge data from ten rivers in northern Colombia (Caribbean alluvial plain) draining into the Caribbean Sea were analysed to quantify the magnitudes, to estimate long-term trends, and to evaluate the variability of discharge patterns. These rivers deliver $\sim$340.9 km^3 yr^{-1} of freshwater to the Caribbean Sea. The largest freshwater supply is provided by the Magdalena River, with a mean discharge of 205.1 km^3 yr^{-1} at Calamar, which is 26% of the total fluvial discharge into this basin. From 2000 to 2010, the annual streamflow of these rivers increased as high as 65%, and upward trends in statistical significance were found for the Mulatos, Canal del Dique, Magdalena, and Fundación Rivers. The concurrence of major oscillation processes and the maximum power of the 3–7 year band fluctuation defined a period of intense hydrological activity from approximately 1998–2002. The wavelet spectrum highlighted a change in the variability patterns of fluvial systems between 2000 and 2010 characterised by a shift towards a quasi-decadal process (8–12 years) domain. The Intertropical Convergence Zone (ITCZ), El Niño – Southern Oscillation (ENSO) events, and quasi-decadal climate processes are the main factors controlling the fluvial discharge variability of these fluvial systems.

1. Introduction

Fluvial discharges play a major role in the hydrological cycle, the thermodynamic stability of the oceans, and biogeochemical processes. Therefore, the quantification of the magnitude and variability of fluvial discharges is fundamental when dealing with coastal and continental shelf oceanography. Dramatic changes in hydrological patterns, high seasonal variability, and a growing anthropogenic intervention have been reported for several major rivers of the world during the last two decades (e.g., Huntington, 2006; Pinter et al., 2006; Varis et al., 2012; Walling and Fang, 2003). The streamflow of a river can be used as an integral of the annual or interannual climatic fluctuations that characterise its basin. Thus, streamflow changes have been repeatedly analysed to detect significant trends, identify major oscillation periods, and determine the relationships between climatic forcing and hydrological responses. In this context, river flows have been used as a type of climatic indicator, as have long-period streamflow fluctuations, to identify and characterise different climatic periods (e.g., Dai et al., 2009; Labat et al., 2004, 2005; Labat, 2008; Milliman et al., 2008; Pasquini and Depetris, 2007; Pekarova et al., 2003; Probst and Tardy, 1987; Walling and Fang, 2003).

In recent years, some studies have reported contrasting results regarding streamflow trends, but there are some agreements regarding the major oscillatory components that control streamflow fluctuations. Based on a time series analysis of the annual streamflow data of fifty major rivers distributed throughout the world, Probst and Tardy (1987) observed that during the first half of the last century, Europe and Asia were affected by a significant humid regime. In contrast, Africa, North and South America were exposed to a humid regime throughout the last half of that century. Furthermore, it was concluded that in a given relatively

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http://dx.doi.org/10.1016/j.jhydrol.2013.11.045

small region, the streamflow fluctuations are generally synchronous and closely related to pressure oscillations of different scales (Probst and Tardy, 1987). According to Pekarova et al. (2003), there was no evidence of significant trends (neither increasing nor decreasing) in the annual streamflow of the 24 major rivers of the world, but they identified the alternation of wet and dry periods and of extreme cycles of high-low discharge almost every 3.6, 7, 13–14, 20–22, and 28–32 years. In addition, Pekarova et al. (2003) identified a geographical control in these hydrological shifts, consequently the extreme cycles do not occur simultaneously around the world. Milliman et al. (2008) indicated that the cumulative discharge of 137 rivers, representative of regions of the entire world, remained statistically unchanged between 1951 and 2000, thus offering little support to a global intensification of the hydrological cycle. However, the authors noted significant changes in individual rivers and at regional levels. For example, streamflow from large South American rivers (Amazon, Orinoco and Magdalena) remained relatively constant, with the noteworthy exception of the Parana River, whose discharges rose to 45% throughout 1950–2000. However, the streamflow of most rivers draining into the Mediterranean Sea and Indian Ocean declined considerably (Milliman et al., 2008).

Thus far, the streamflow of the main rivers of South America have been analysed to identify historical trends, regional hydrological patterns, variability cycles or relationships with climatic forcings (i.e., Amarasekera et al.,1997; García and Mechoso, 2005; Genta et al., 1998; Labat et al., 2005; Pasquini and Depetris, 2007; Robertson and Mechoso, 1998; Restrepo and Kjerfve, 2000). Amarasekera et al. (1997) identified a weak correlation between Pacific surface sea temperature anomalies and the annual discharge of the Amazon River, with the ENSO (El Niño – Southern Oscillation) explaining less than 10% of the annual streamflow variability. In contrast, a wavelet spectrum analysis of the annual streamflow from the Amazon River indicates a 3–6 year oscillation, typical of ENSO variability, and a nearly permanent 2-year coherence between the Southern Oscillation Index (SOI) and Amazon discharge (Labat et al., 2005). An analysis of the hydrological data (1930–2000) in the main rivers draining the southeastern areas of South America also displayed contrasting historical trends. The Parana basin experienced a steady increase in its streamflow during the second half of the last century, whereas the Patagonia basins underwent a sharp discharge decrease (Genta et al., 1998; Pasquini and Depetris, 2007; Robertson and Mechoso, 1998). Spectral analyses of streamflow time series indicated that the ENSO phenomenon and pressure anomalies over the South Atlantic Ocean control the shifts and oscillations of the hydrologic regimes in southeastern South America (Pasquini and Depetris, 2007).

Streamflow variability has a direct effect on the littoral morphodynamic and coastal circulation processes, as found for the Caribbean Rivers of Colombia, especially the Magdalena River (Fig. 1), thus regulating coastal and estuarine processes at the regional scale (Restrepo and Kjerfve, 2004; Restrepo and Lopez, 2008). Based on a statistical analysis of annual streamflow data and SOI anomalies, the ENSO might be responsible for up to 65% of streamflow interannual variability in rivers such as the Magdalena, Cauca, Cesar, Rancheria, and Sinú (Gutiérrez and Dracup, 2001; Mesa et al., 1997; Restrepo and Kjerfve, 2000). However, until now, there has only been sparse information available on recent hydrological changes and other oscillation periods and their relationship to known climatic forcing and the corresponding hydrological responses of the rivers draining the Caribbean plain of northern Colombia (Fig. 1). What are the dominant time scales in the hydrological signal of these rivers given the atmospheric circulation/air mass dynamics and setting of drainage basins (i.e. buffering capacity)? Are there regional patterns of hydrological change, especially during the last decades? How important is the co-occurrence of oscillations of different period for generating extreme streamflow events? The lack of data on these subjects has hampered the effective implementation of water resource management plans oriented towards prevention or mitigation of the adverse effects of hydrologic events. In recent years, such plans have gained importance due to an increase in the number, duration and intensity of hydrological events such as floods and droughts (Hoyos et al., 2013). Therefore, new analyses are made in this study on hydrological data (monthly mean streamflow) from ten rivers draining the Caribbean plain of Colombia to (1) quantify recent fluvial discharges into the Caribbean Sea, (2) to estimate long-term streamflow trends, and (3) to identify patterns of freshwater discharge variability at different time scales.

2. Study area

The Caribbean plain of Colombia is located in the northernmost region of South America. It extends from the *Darien* tropical rainforest, in the Colombia-Panamá border, to the *Península de La Guajira* in the east and the slopes of the *Cordillera de los Andes* in the south (Fig. 1). Compressional stresses generated at the collision between the South American plate, the Nazca oceanic plate, the Panamá volcanic arc, and the western part of the Caribbean oceanic plate fractured the continental crust, promoting large-scale horizontal and vertical movements of blocks. Thus, the blocks of the South American crust emerged and horizontally displaced along major thrust and strike-slip faults, conforming the ranges of the North Andean Block (Kellog, 1984). Hence, the Caribbean plain of Colombia comprises extensive lowlands with heights below 100 m, ranges and plateaus with heights between 200 and 1000 m in the southwest (*Serranías de Abibe*, *San Jerónimo* and *Ayapel*) and northeast (*Serranía de Macuira*), and one of the highest coastal mountain ranges in the world, the *Sierra Nevada de Santa Marta*, with heights up to 5000 m (Fig. 1). The lowlands are dominated by savannah ecosystem used for agriculture and grazing. According to temperature/rainfall conditions tropical dry/rain forest can also be found in the lowlands and plateaus. The mountainous zones are characterised by a progressive transition from basal forest (1000–1200 m.a.s.l.) to Andean forest (1000–4000 m.a.s.l.), Paramos (3000–4800 m.a.s.l.) and permanent glaciers (>4700 m.a.s.l.). The latter in the Sierra Nevada de Santa Marta (IDEAM, 1998). By the 1990's almost 30% of the Caribbean lowland forest had been converted into agricultural crops and extensive grazing lands. Consequently, the Caribbean plain of Colombia was identified as a hot spot of deforestation within the country. In the last years, however, deforestation rates in this zone have diminished significantly (Etter et al., 2006).

The rivers examined in this study originate from headwaters in the *Cordillera de los Andes* (Sucío, Mulatos, Sinú and Magdalena Rivers) and the *Sierra Nevada de Santa Marta* (Aracataca, Fundación, Frío, Palomino and Rancheria Rivers) (Fig. 1). The headwaters of the Sucío, Mulatos and Sinú Rivers are located in the *Nudo de Paramillo*, where the Cordillera Occidental bifurcates into the *Serranías de Abibe*, *San Jerónimo* and *Ayapel*. The Sucío River runs northwestward from its headwater at a height of 4080 m before it joins the Atrato River, where it turns to the north until it empties into the *Uraba* gulf. The Mulatos River drains a plateau in the *Serranía de Abibe* over $\sim$115 km from south to north, before discharging directly into the Caribbean Sea. The Sinú River has a drainage basin of 14.7×10^3 km^2, which comprises a steep mountainous zone in the headwater, an alluvial valley formed by the *Serranías de Abibe* and *San Jerónimo*, and extensive alluvial flood plains where significant water storage occurs (i.e., lagoon systems). The Sinú River measures 415 km from its headwater at a height 3960 m to its mouth in the Caribbean Sea. The Magdalena

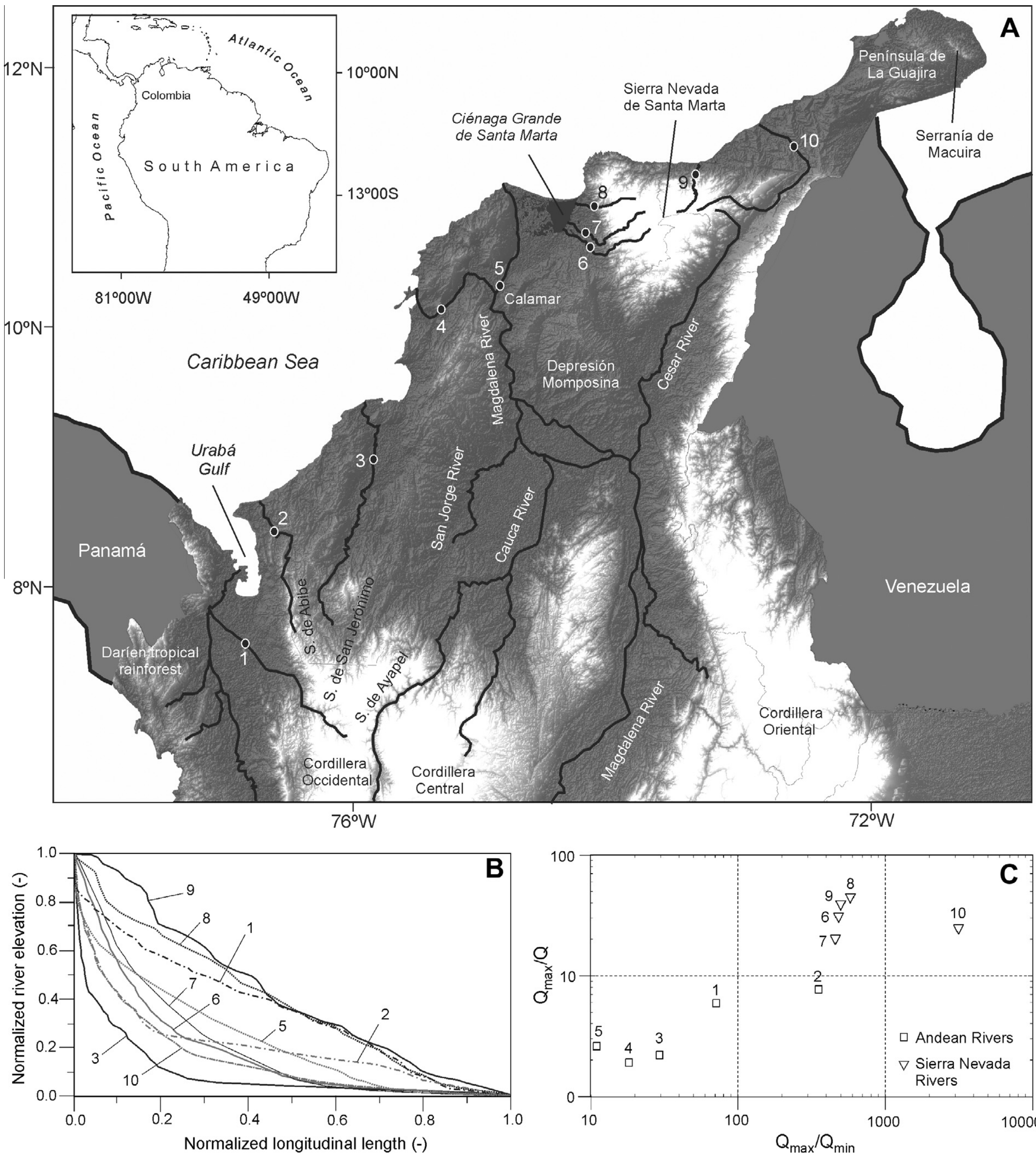

Fig. 1. (A) Caribbean plain of Colombia in northwest South America with major topographic features, selected rivers and gauge stations: 1. Sucío River, 2. Mulatos River, 3. Sinú River, 4. Canal del Dique, 5. Magdalena River (Calamar), 6. Fundación River, 7. Aracataca River, 8. Frío River, 9. Palomino River, and 10. Ranchería River; (B) longitudinal river profiles; (C) flood regimes (Q_{max}/Q) and the discharge variability (Q_{max}/Q_{min}) of rivers draining the Caribbean plain of Colombia.

River is the largest fluvial system in the Caribbean plain with a length of 1540 km and a drainage basin of 257.4×10^3 km^2. Its headwater is located in the *Cordillera Central* (south of Colombia, 1°45′N, 76°30′W) at 3600 m. The river runs northward along the Magdalena valley, between the *Cordillera Central* and *Oriental*, before turning to the west and entering an active tectonic depression, the *Depresión Momposina*, where significant sediment deposition and storage occur. At this site, the Magdalena River follows a meandering course and receives fluvial inputs from the Cesar, Cauca and San Jorge Rivers (Restrepo and Kjerfve, 2004). The Magdalena River crosses the *Depresión Momposina*, heads further north to *Calamar* and forms two distributaries. One distributary is directed northwestward to the Cartagena bay (i.e., Canal del Dique), whereas the major distributary continues to the north, building up the Magdalena Delta at the shore of the Caribbean Sea. The rivers of the *Sierra Nevada de Santa Marta* drain small mountainous basins (<5000 km^2) with steep gradients and limited alluvial flood plains, except for the Rancheria River, which crosses extensive lowlands in the Península de la Guajira. The Frío, Aracataca and Fundación Rivers drain the western slopes of the *Sierra Nevada de Santa Marta* and discharge into the *Ciénaga Grande de Santa Marta*, which has a direct connection with the Caribbean Sea. Both the Palomino River and the Ranchería River drain the eastern slopes of the *Sierra Nevada de Santa Marta*, from southwest to northeast, and discharge directly into the Caribbean Sea (Fig. 1).

The meridional oscillation of the Intertropical Convergence Zone (ITCZ) controls the annual hydrological cycle and defines two rainy seasons for the Caribbean plain. The first season extends from May to June, when the ITCZ is migrating from north to south. The second and stronger season lasts from September to October, when the ITCZ shifts northward. However, different local patterns can be distinguished as a consequence of westerly and northerly jet streams (i.e., the *Chocó* and *San Andrés* jets) and orographic effects caused by the Andes range slopes and the *Sierra Nevada de Santa Marta* (Bernal et al., 2006; Poveda, 2004). Humid air masses from the Pacific Ocean are advected by the westerly jet stream (i.e., *Chocó Jet*), which rises rapidly along the *Cordillera Occidental*. This process promotes deep convection of these air masses, enhancing meso-scale convective systems and then promoting intense rainfall rates (Poveda and Mesa, 2004). The interaction between the northeastern trade winds and low pressure belts (<900 hPa) located at 13°N–14°N promotes a northerly jet wind current (i.e., the *San Andrés Jet*). This jet current causes a humidity divergence in northwest South America that enhances the uplift 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 the *Chocó Jet*, whereas the dry season corresponds to maximum strength of the *San Andrés Jet*. Thus, the western Caribbean plain close to the Darien tropical rainforest as well as the *Sierra Nevada de Santa Marta* both exhibit maximum rainfall rates and mean annual temperatures with values of >2000 mm yr^{-1} and <20 °C, respectively. In contrast, the lowlands are drier with rainfall rates below 1000 mm yr^{-1} and warmer with mean annual temperatures >27 °C (Mesa et al., 1997). In longer time scales, major anomalies in hydrological patterns are associated to both phases of El Niño – Southern Oscillation (ENSO). The ENSO warm phase (El Niño) promotes an increase in mean air temperature, a decrease in soil moisture and vegetation index, and thus the rainfall rates decline, but anomalies during the ENSO cold phase (La Niña) generate abundant and intense rainfall (Poveda et al., 2001; Poveda, 2004). According to Restrepo and Kjerfve (2004) the Caribbean Rivers of Colombia exhibit a strong seasonal variability in their streamflow, usually as high as a factor of 5–10 comparing low monthly to high monthly streamflow. Furthermore, the interannual variability associated to ENSO can be equally great, typically a factor of 2–4 comparing low annual to high annual streamflow.

3. Data and methods

For this study, the IDEAM (*Instituto de Hidrología, Meteorología y Estudios Ambientales de Colombia*) kindly provided monthly freshwater discharge data of nine drainage basins with different climatological and topographical settings along the Caribbean coast of Colombia, reflecting the period between 1941 and 2010 (Fig. 1 and Table 1). The selection of the different rivers and their corresponding gauging stations was based on two important conditions: (1) the gauging stations had to be located close to the downstream part of the basin, and (2) the hydrological data records had to exceed thirty years. (1) The streamflow time series measured at the mouth of the watershed was considered as a valuable integrated signal between gain and loss of the continental water cycle (i.e., precipitation, evapotranspiration, runoff). Thus, the time series was a suitable tool for evaluating freshwater discharge from continents to oceans (e.g., Milliman et al., 2008; Labat, 2010; Probst and Tardy, 1987). (2) Defining T as the total length of the hydrological record, the cutoff frequency ($T/2$) and the edge effects ($T/2\sqrt{2}$) limited the statistical significance of identified signals from the time series analysis (Shumway and Stoffer, 2004). Thus, the water discharge records ranged between 31 and 70 years (Table 1) to be able to identify interannual and decadal oscillations in these rivers.

Continuity and homogeneity tests were applied. Time series analyses were conducted, including (1) fluvial indices calculation, (2) the Mann–Kendall Test (Gradual Trend Test) to identify and quantify long-term hydrological trends (Yue et al., 2002), (3) cross-correlation between monthly streamflow and monthly anomalies of Southern Oscillation Index (SOI) to quantify the effects of the ENSO on freshwater discharges, and (4) continuous wavelet transform analyses (Morlet Wavelet Spectrum) to estimate periodicities and variability patterns (Labat, 2005; Shumway and Stoffer, 2004). Data on monthly SOI anomalies were obtained from NOAA – Climate Prediction Center (NOAA, 2012).

The Mann–Kendall test (MKT), a non-parametric rank-based statistical test, was used to detect and evaluate the significance of monotonic trends in the time series (Yue et al., 2002). Non-parametric tests do not assume any special form for the distribution function of the data. Therefore, it was suitable for the analysis of non-normally distributed data. Furthermore, the MKT is considered one of the most robust technique available to identify and estimate linear trends in environmental data, especially in time series analyses of fluvial discharges (e.g., Garcia and Mechoso, 2005; Milliman et al., 2008; Pasquini and Depetris, 2007; Yue et al., 2002; Zhang et al., 2008). In the MKT, no trend in the time series was considered as a null hypothesis; a standardised variable (Z) was calculated for verification. The null hypothesis was rejected for a significance level α if $Z > Z_{(1-\alpha/2)}$, where $Z_{(1-\alpha/2)}$ was the standard value of a normal distribution with a probability of $\alpha/2$ (Yue et al., 2002). Considering that streamflow data after 2000 have

Table 1
Names of rivers and gauging stations used in this study. The location and historic record of freshwater discharge data are also included.

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

not been analysed previously in these rivers and the MKT can be considered as an indicator of hydrologic change, a selective MKT was applied to 2000–2010 streamflow data to (1) evaluate the influence of new data on long-term trends, and (2) detect recent hydrological changes using this statistical test as a *proxy* (e.g. Dai et al., 2009).

The continuous wavelet transform (CWT) was used to examine the time series, using generalised local base functions (i.e., mother wavelets) that were stretched and translated with a both a frequency and time resolution (Torrence and Compo, 1998). This robust technique supported the evaluation of time series containing non-stationary functions with different frequencies, providing a time-scale localisation of a signal. Thus, the CWT, applied on monthly deseasonalised streamflows, was used to estimate the periodicities and variability patterns and to distinguish temporal oscillations in time series, identifying the intermittency of each time-scale process. In addition, power-frequency analysis was applied. The power of the continuous wavelet spectrum across time for a specified frequency band was computed by integrating the interpolated wavelet spectrum surface based on the frequency range (Labat, 2005). This test allows the isolation of several frequency bands, obtaining detailed information on the power of a specific periodicity across time. To identify major significant fluctuations, the 95% confidence level for contours and edge effects area were calculated following the Torrence and Compo (1998) methodology. Applications of the CWT to the streamflow series allowed the detection of oscillations of different time-scale that might be associated to some hydro-climatic driving mechanisms (e.g., Labat, 2008, 2010; Labat et al., 2004, 2005; Pasquini and Depetris, 2007; Rossi et al., 2009). In addition, the wavelet spectrum was averaged in time to quantify the main scales of the underlying processes, allowing the determination of the variance signal distribution between the different scales (Torrence and Compo, 1998). The decisive advantage of the global wavelet spectrum consists of its efficient estimation of the characteristic scales of the long-term processes (Labat et al., 2005).

4. Results

4.1. Freshwater discharge into the Caribbean Sea: magnitude and long-term trends

The mean monthly streamflow of the rivers draining the Caribbean plain of Colombia ranges between 4.63 $m^3\,s^{-1}$ and 6497 $m^3\,s^{-1}$ (Table 2). The differences between the maximum and mean monthly streamflows are up two orders of magnitude for each river, whereas for the maximum and minimum monthly streamflows the differences can be as high as three orders of magnitude (Table 2). These ratios characterise the discharge variability (Q_{max}/Q_{min}) and flood regimes (Q_{max}/Q). The rivers of the Sierra Nevada, with high to extremely high discharge variability, also correspond to a high-flood regime. Considering that these fluvial systems have drainage areas smaller than 5.0×10^3 km^2 in mountainous zones, the topographical setting is a primary factor controlling extreme flows and flood variability. The Andean Rivers, which drain extensive plateaus or low-lying alluvial valleys, are characterised by low- to medium-discharge variability and a low-flood regime (Fig. 1). The Colombian Rivers of the Caribbean plain collectively contribute ~330.5 $km^3\,yr^{-1}$ of freshwater into the Caribbean Sea. The major contribution comes from the Magdalena River with 205.1 $km^3\,yr^{-1}$ of freshwater, which represents 62% of the total freshwater discharge of these rivers.

Significant trends in annual streamflows were noted in reference to the MKT, for the Mulatos, Magdalena (at Calamar), Canal del Dique, and Fundación Rivers, which displayed increasing trends, significant at 90%, 95%, 99%, and 95% confidence levels, respectively (Table 3). These upward trends are more pronounced

Table 2
Drainage basin (A), headwater elevation, mean monthly streamflow (Q), maximum monthly streamflow (Q_{max}), minimum monthly streamflow (Q_{min}), flood regimes (Q_{max}/Q) and discharge variability (Q_{max}/Q_{min}) of the rivers draining the Caribbean plain of Colombia.

River	A (10^3 km^2)	Headwater (m.a.s.l.)	Q ($m^3\,s^{-1}$)	Q_{max} ($m^3\,s^{-1}$)	Q_{min} ($m^3\,s^{-1}$)	Q_{max}/Q (–)	Q_{max}/Q_{min} (–)
Sucío	4.52	4080	278.57	1630.0	22.80	5.9	71.5
Mulatos	0.01	1118	4.63	35.4	0.01	7.7	3539.0
Sinú	14.73	3960	398.09	858.2	29.10	2.2	29.5
Magdalena		3600					
Canal del Dique	–		430.30	818.0	44.59	1.9	18.3
Calamar	257.43		6497.21	16913.0	1520.0	2.6	11.1
Fundación	1.87	2986	28.20	872.5	1.80	30.9	484.7
Aracataca	0.93	4408	14.70	360.0	0.78	20.2	459.8
Frío	0.32	3716	13.80	618.0	1.06	44.8	583.0
Palomino	0.68	4785	25.71	1000.0	2.0	38.9	500.0
Ranchería	4.23	3700	12.83	316.5	0.01	24.7	31,650

Table 3
Results of the Mann–Kendall and Sen's slope test of the mean annual freshwater discharge time series of Caribbean Rivers.

River	Gauging station	Mann–Kendall test					Sen's slope
		First year	Last year	No. years	Test Z	p Value	($m^3\,s^{-1}\,yr^{-1}$)
Sucío	Mutata	1976	2010	35	1.36	n.s.	1.152
Mulatos	Pueblo Bello	1977	2010	34	1.79	$p < 0.10$	0.044
Sinú	Cotoca Abajo	1970	2010	41	1.22	n.s.	0.982
Magdalena							
Canal del Dique	Santa Helena	1979	2010	32	3.78	$p < 0.01$	7.051
Calamar	Calamar	1941	2010	70	2.02	$p < 0.05$	17.260
Fundación	Fundación	1958	2010	53	2.01	$p < 0.05$	0.131
Aracataca	Puente Ferrocarril	1965	2010	46	0.55	n.s.	0.025
Frío	Rio Frío	1965	2009	45	1.46	n.s.	0.049
Palomino	Puente Carretera	1973	2010	38	0.72	n.s.	0.078
Ranchería	Hacienda Guamito	1976	2007	35	0.37	n.s.	0.039

after the year 2000 (Fig. 2 and Table 4). The magnitude of discharge change per unit time period, calculated as the ratio of Sen's slope (Table 3) to mean streamflow (Table 2), is highest for Canal del Dique and Mulatos Rivers. Although most of the rivers do not display significant trends in hydrological records, the annual streamflow of all fluvial systems increased by as much as to 30% from 2000 to 2010 (Table 4). For example, the mean annual streamflow of 6334.9 $m^3 s^{-1}$ (Magdalena River) and 24.4 $m^3 s^{-1}$ (Palomino River) is lower before 2000, compared with flow during the time frame between 2000 and 2010 marked by rates of 7391.6 $m^3 s^{-1}$ and 28.4 $m^3 s^{-1}$, respectively (Table 4).

4.2. Seasonal variability and preliminary ENSO effects

The annual cycle of freshwater discharge was estimated using the entire hydrological record (Table 1). The rivers have a strong annual cycle with maximum freshwater discharges in April–May and October–December. January–March and June–September correspond to dry and transition seasons, respectively (Fig. 3). The seasonal changes of streamflow are higher than interannual changes (Figs. 2 and 3). The monthly streamflow data based on the MKT are listed in Table 5. In general, the months that display a significant flow increase are those of the first wet season (April–May). Upward trends during months of the transition and second wet season are less common and significant. There were no significant trends in the dry season months (Table 5).

Mean monthly streamflows were estimated for normal, El Niño, and La Niña years, to explore the ENSO-induced impacts on the annual cycle of freshwater discharges (Fig. 3). The Sucío, Sinú, Canal del Dique, and Magdalena Rivers exhibit higher and lower streamflows during La Niña and El Niño, respectively. These differences are noticeable at extremes of the annual cycle, and they are lower from April to June than in other months (Fig. 3). These results correspond with the expected patterns of ENSO influence. In contrast, noticeable differences between normal, El Niño and La Niña years were not observed for the Mulatos, Fundación, Aracataca, Frío, Palomino, and Ranchería Rivers during some part of the year (i.e. at least four months). In these latter rivers, from April to June the highest streamflows occur during normal or El Niño years. These findings do not correspond exactly with the expected patterns of ENSO influence (Fig. 3).

The results of a cross correlation analysis between the monthly streamflow and monthly anomalies of Southern Oscillation Index (SOI), performed to quantify the preliminarily effects of the ENSO on the freshwater discharges time series, are given in Fig. 4. Between 1950 and 2010, there were 11 and 8 moderate to strong El

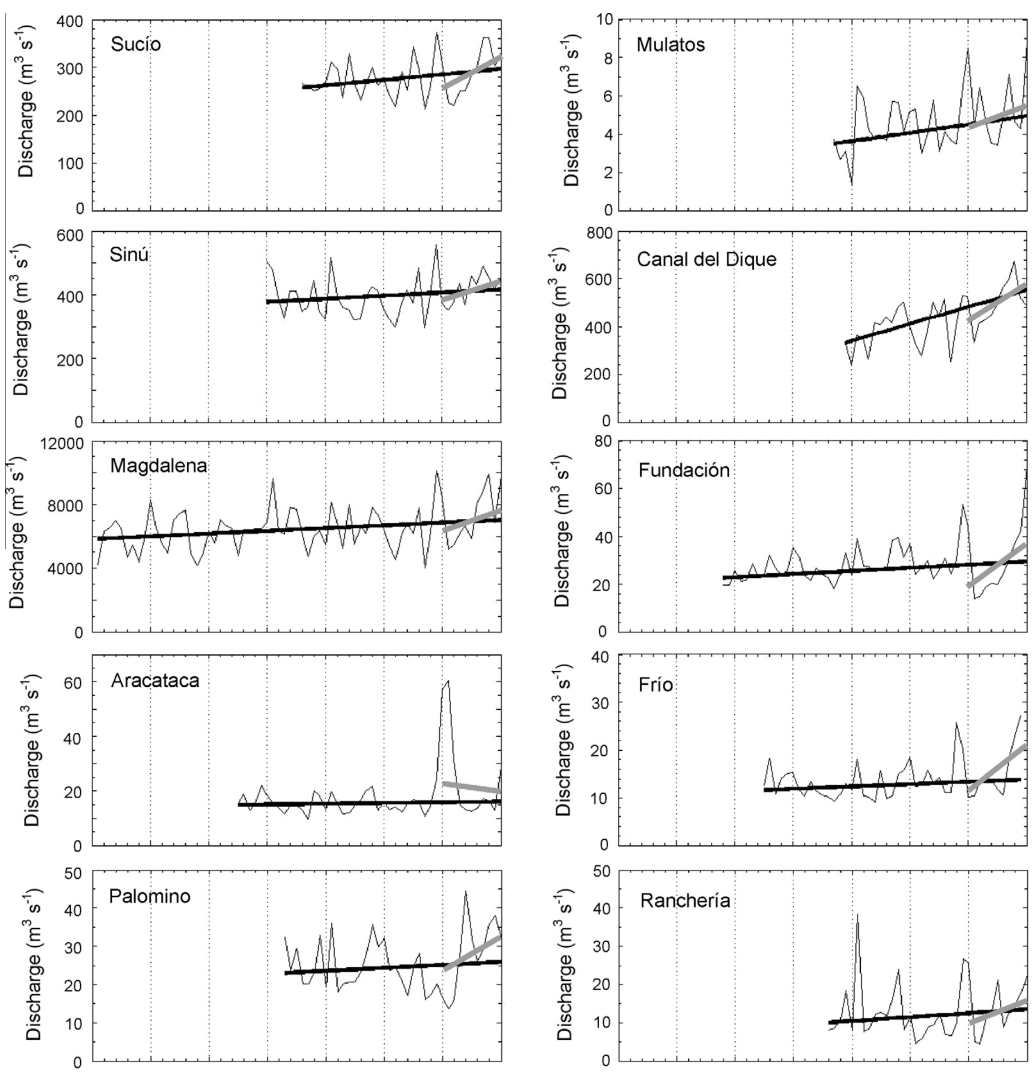

Fig. 2. Mean annual streamflow (thin line), long-term (black bold line) and 2000–2010 trend with Sen's slope (grey bold line) for the Caribbean Rivers.

Table 4
Caribbean Rivers: results of the Mann–Kendall, Sen's slope test, and mean annual freshwater discharge for two selected periods (Pre-2000 and Post-2000).

River	Pre-2000					Post-2000				
	Mann–Kendall test			Sen's slope	Q	Mann–Kendall test			Sen's slope	Q
	First year	Last year	Test Z	($m^3 s^{-1} yr^{-1}$)	($m^3 s^{-1}$)	First year	Last year	Test Z	($m^3 s^{-1} yr^{-1}$)	($m^3 s^{-1}$)
Sucío	1976	1999	0.32	0.465	273.4	2000	2010	**2.34**	11.854	290.6
Mulatos	1977	1999	0.56	0.025	4.3	2000	2010	0.00	0.018	5.51
Sinú	1970	1999	−0.54	−0.886	390.7	2000	2010	*1.71*	9.974	419.3
Magdalena						2000	2010			
Canal del Dique	1979	1999	**2.02**	7.278	393.9	2000	2010	**2.33**	34.850	498.3
Calamar	1941	1999	0.94	10.199	6334.9	2000	2010	**2.18**	493.697	7391.6
Fundación	1958	1999	***2.82***	0.178	27.6	2000	2010	***2.65***	3.280	30.45
Aracataca	1965	1999	−0.17	−0.014	16.6	2000	2010	−1.25	−1.690	25.35
Frío	1965	1999	0.85	0.045	13.3	2000	2009	**2.50**	1.540	15.3
Palomino	1973	1999	−0.90	−0.150	24.4	2000	2010	**2.02**	2.030	28.4
Ranchería	1976	1999	−0.27	−0.056	12.3	2000	2007	1.56	1.381	14.3

Note: Italicisation and bolding indicates significance at the 99% confidence level.
Bolding without italicisation indicates significance at the 95% confidence level.

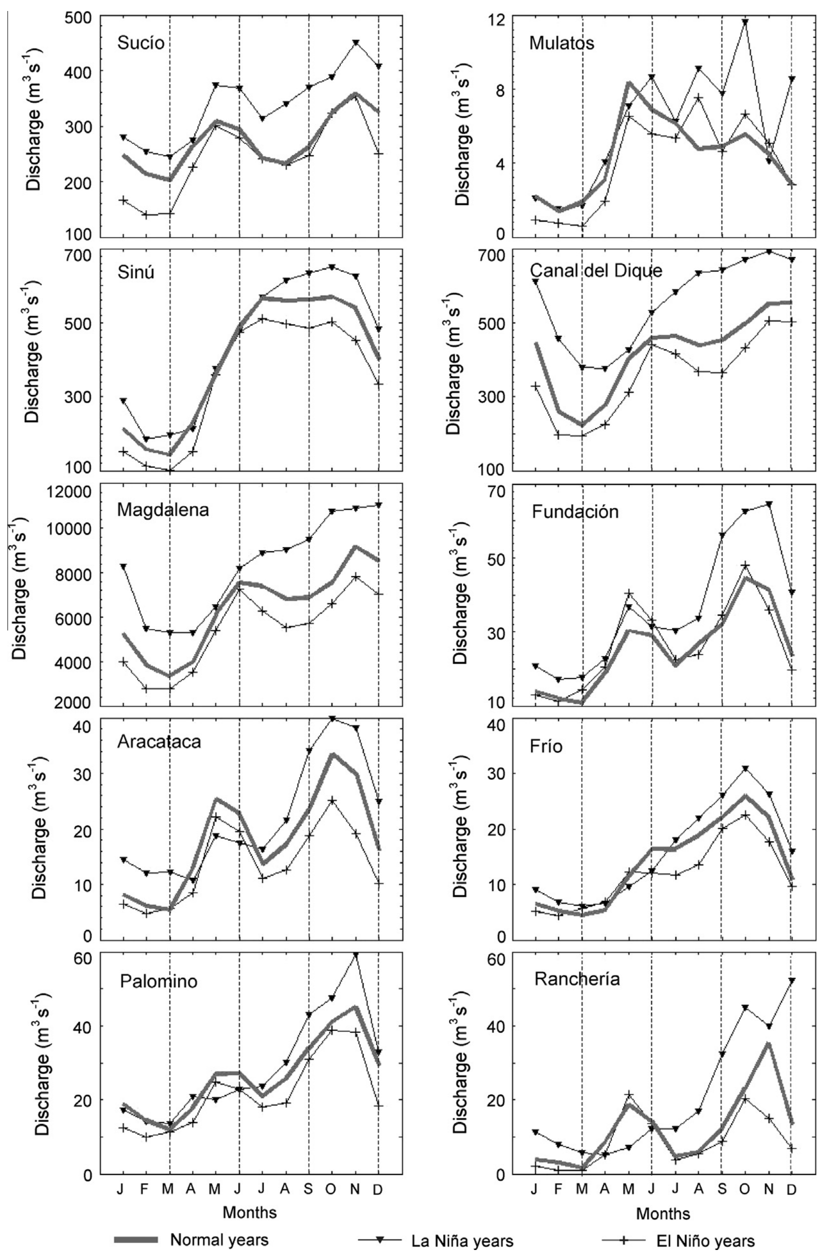

Fig. 3. Seasonal freshwater discharge of Caribbean Rivers during normal, La Niña, and El Niño years.

Table 5
Results of the Seasonal Mann–Kendal test for the monthly mean freshwater discharge time series of Caribbean Rivers.

	Sucío	Mulatos	Sinú	Canal del Dique	Calamar	Fundación	Aracataca	Frío	Palomino	Ranchería
January	1.15	0.00	0.28	***2.12***	***2.56***	−0.88	−0.63	1.24	0.21	0.00
February	0.68	0.04	1.27	***2.48***	1.35	0.25	0.82	**2.53**	−0.55	−1.22
March	0.38	1.16	**3.32**	***2.19***	1.27	***2.43***	**3.17**	**2.58**	0.10	−1.35
April	−0.10	1.23	***2.15***	**3.23**	1.69	1.94	***2.45***	**2.73**	***1.99***	0.08
May	0.62	***2.05***	1.38	**3.81**	1.95	1.81	0.99	**2.79**	0.58	−0.24
June	0.91	0.85	1.22	**3.21**	1.82	1.51	0.32	1.46	0.54	−1.35
July	***2.24***	0.92	1.34	**3.00**	1.48	1.48	1.70	***2.28***	0.55	−0.28
August	1.25	0.77	1.34	**3.23**	0.59	0.59	−0.40	***2.11***	0.31	0.00
September	0.84	0.18	0.86	**2.71**	0.73	1.40	0.11	1.07	−0.75	0.44
October	−0.17	−0.03	−1.03	***2.47***	***2.04***	1.70	0.62	1.42	−0.93	−0.15
November	1.55	−1.07	−1.07	***2.30***	**3.17**	0.99	−0.45	−0.17	0.10	0.37
December	1.05	1.25	−1.09	***2.04***	***2.35***	0.88	−0.15	1.68	1.43	1.12

Note: Italicisation and bolding indicates significance at the 95% confidence level.
Bolding without italicisation indicates significance at the 99% confidence level.

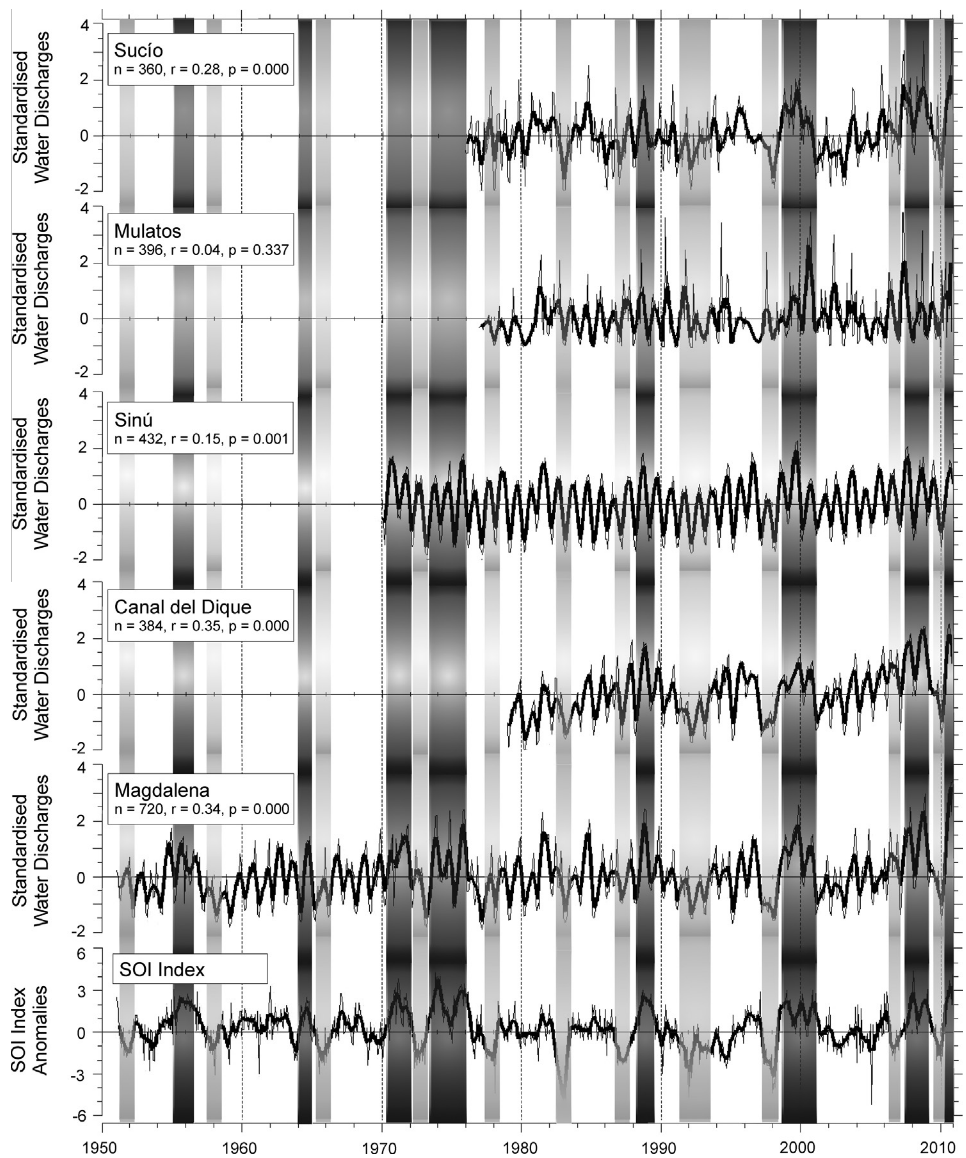

Fig. 4. Monthly standardised streamflows and SOI Index anomalies (thin line); a five-month moving average is superimposed on time series (black bold line). The grey and light grey boxes represent the cold and warm phases of the ENSO phenomenon, respectively. Statistics of cross-correlation between the monthly streamflow and monthly anomalies of (SOI) are shown.

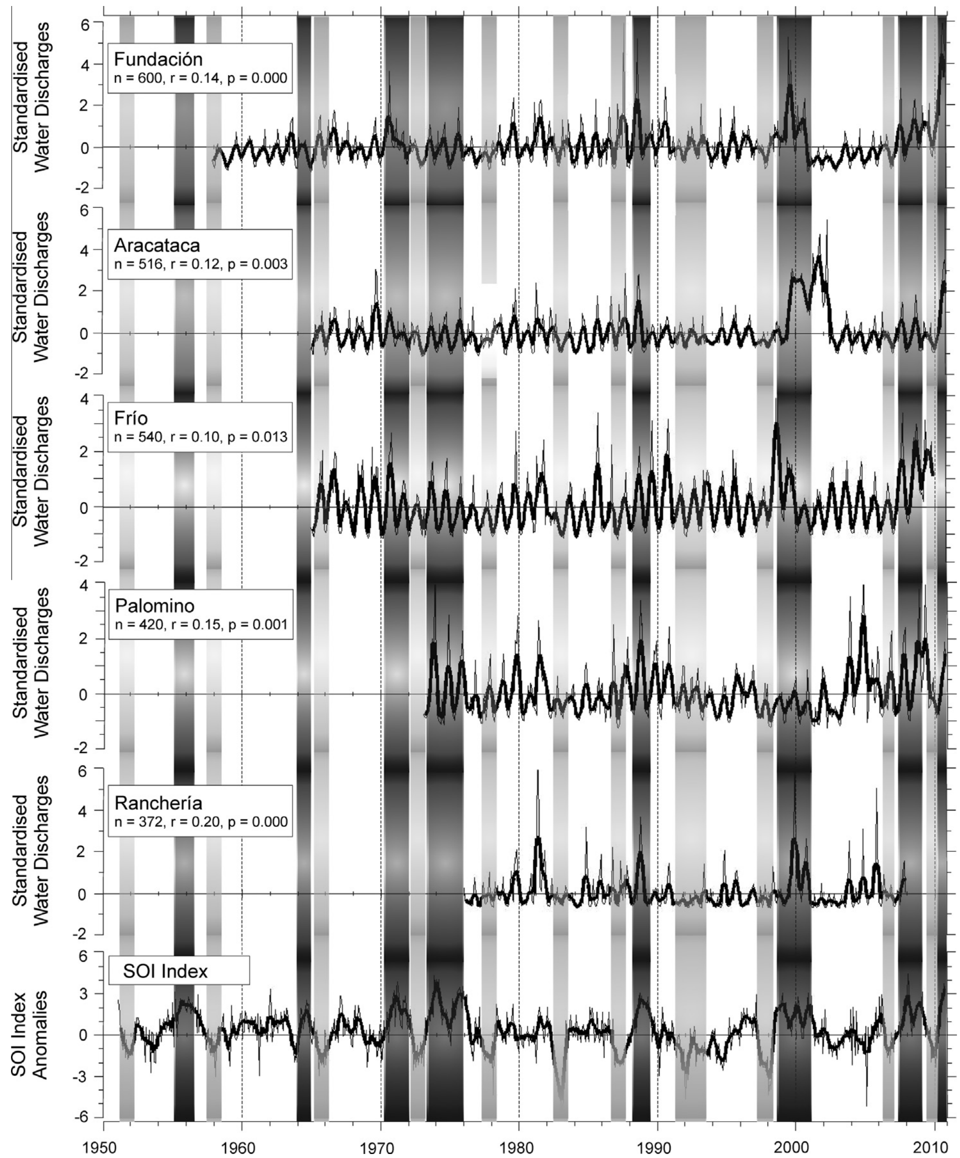

Fig. 4 (*continued*)

Niño and La Niña events, respectively (Fig. 4). In general, high monthly streamflow and SOI-positive anomalies are moderately to well correlated, and thus, high freshwater discharges correspond to positive SOI anomalies. For example, the anomalously high streamflow (i.e., >2 standard deviation), present in most of the rivers (except the Mulatos) during the 1988–1989 period coincides with a long and strong cold ENSO phase (La Niña), extending from April 1988 to July 1989 (Fig. 4). In contrast, low monthly streamflows and SOI-negative anomalies are moderately to poorly correlated for the Andean Rivers and poorly correlated for the rivers of the Sierra Nevada. Although the El Niño event from 1982 to 1983 is the strongest in the SOI record (1951–2010), the event does not correspond to the severely decreased streamflow in most of these rivers and failed to have the expected adverse effects on freshwater discharge (Fig. 4). In addition, the negative SOI anomalies of 1977–1978, 1987 and 2006–2007 do not coincide with excessively low streamflows, especially in those rivers draining the *Sierra Nevada de Santa Marta* (Fig. 4). The highest correspondences between SOI anomalies and freshwater discharges can be found in the record during 1998–2001 and 2010. Strong positive-SOI anomalies in these periods coincide with anomalously high streamflows (Fig. 4) and consequently severe floods in the Caribbean plain of Colombia (Hoyos et al., 2013). However, a similar positive-SOI anomaly from April 1973 to April 1976 is not linked to any such dramatic increases in streamflow (Fig. 4).

4.3. Periodicities: short- and long-term processes of freshwater discharge

The 6-month process appears highly intermittent and relatively scarce for most of the rivers. The Sucío, Canal del Dique and Magdalena streamflows 6-month component is visible approximately 1976–1994 and 2002–2010. The Fundación, Aracataca and Ranchería Rivers reveal 6-month fluctuations that were temporally localised from 1980 to 1990 and 2000 to 2010 (Fig. 5). The temporal dynamics of the annual oscillation also vary among these rivers. The annual signal appears stationary for the Sinú River, whereas the Magdalena and Frío Rivers are characterised by a quasi-continuous 1-year process of comparable magnitude across the hydrological record. Some streamflows highlight an intermittent annual process. For example, the Mulatos, Canal del Dique, Fundación, Aracataca, Palomino and Ranchería Rivers exhibit short periods of

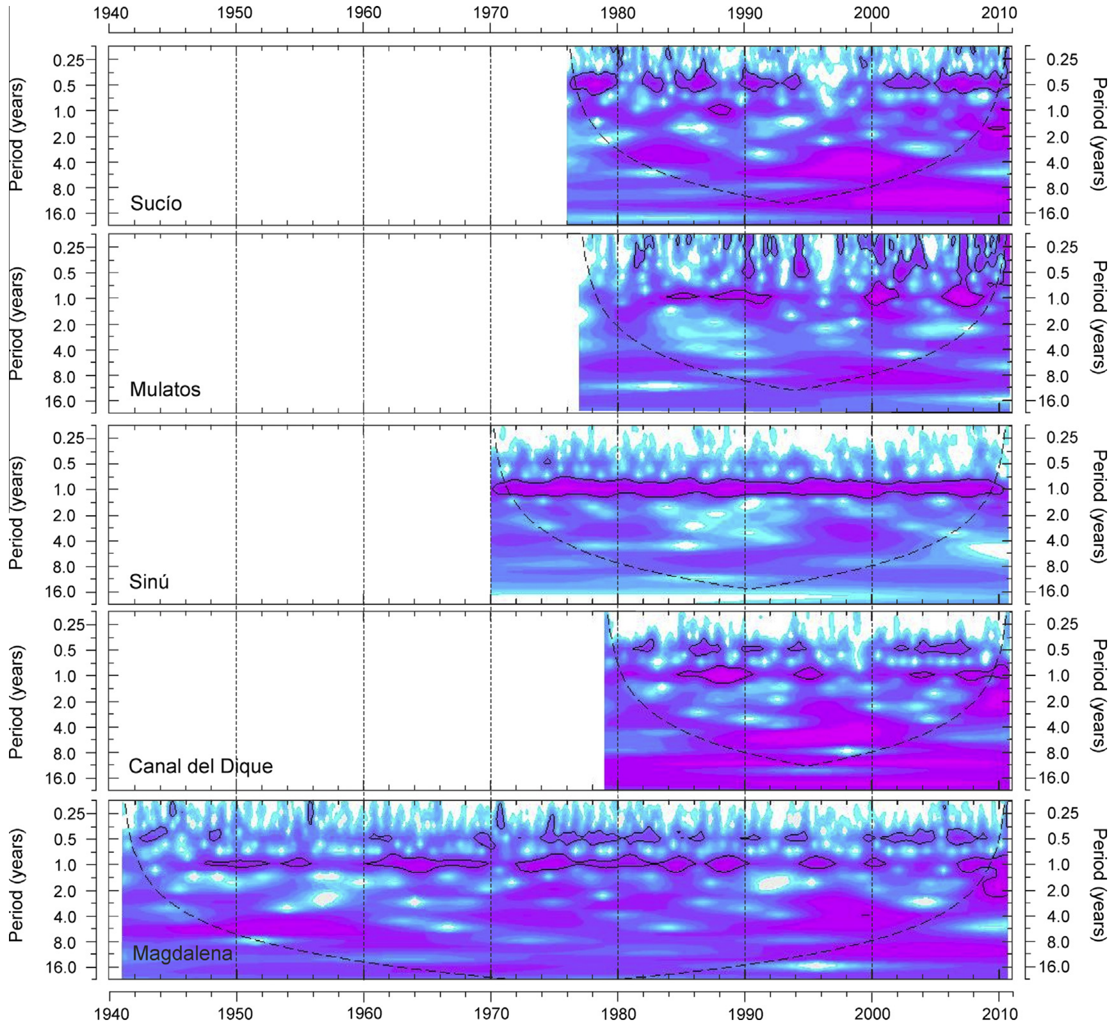

Fig. 5. Continuous wavelet transform spectrum for the Caribbean Rivers. The dark purple/light colours in the wavelet spectra correspond to high/low values of the transform coefficients (power). The thick black contour delimits the 95% confidence level against AR (1) red noise, and the cone of influence where edge effects $(T/2\sqrt{2})$ are not negligible is shown as a black dashed line.

intense activity over the 1985–1990 and 2005–2010 intervals (Fig. 5) that coincide with an increase of freshwater discharge during these periods (Fig. 4).

The interannual streamflow fluctuations in these fluvial systems are characterised by an intermittent 3–7 year process. The Sucío and Ranchería streamflow wavelet spectra highlight a 3–4 year process over the 1980–1988 interval and a 4–7 year process between 1995 and 2005. The 3–7 year process also appears in the Sinú, Fundación and Aracataca Rivers during 1995–2005, extending from 1996 to 2010 in the Frío and Palomino Rivers, whereas the Canal del Dique reveals a 3–7 year fluctuation from 1998 to 2002. The freshwater discharge of the Magdalena River exhibits a 5–7 year oscillation over the 1948–1960 period, a 3–4 year process between 1970 and 1976, and a major 3–7 year oscillation over the interval between 1994 and 2004. Most of the 3–7 year signal exhibits a maximum power between 1998 and 2002 (Fig. 5). A quasi-decadal oscillation (8–12 year) appears in most of the rivers in 1990 and extends to 2010; this signal is particularly strong between 1998 and 2010 for the Sucío, Magdalena, Fundación, Aracataca and Frío Rivers (Fig. 5).

The wavelet spectrum highlights a period of intense activity from 1998 to 2002, where the major concurrent oscillations appear. For example, the Magdalena, Fundación and Ranchería freshwater discharges exhibit superimposed oscillations of 0.5–1 year, 4–7 years, and 9–12 years over the 1998–2002 interval, whereas the 4–7 year oscillations co-occur with quasi-decadal signals in the Sucío, Canal del Dique, Aracataca and Frío Rivers across this same period (Fig. 5). The superposition of oscillatory signals also occurs in the Palomino River between 2004 and 2010 (Fig. 5). Finally, a strong quasi-biennial oscillation arises in for the streamflow of the Sucío, Canal del Dique, Magdalena and Fundación Rivers in 2009 (Fig. 5). This fluctuation conjugates with a 9–10 year process and coincides with a period of severe floods in the Caribbean alluvial plain.

The wavelet power-frequency range, which allows the collection of detailed information on the power of a specific periodicity across time, was computed for the 2–8 year and 8–12 year bands in Fig. 6. The 2–8 year component reveals a low-power period prior to 1998, followed by major fluctuations with two maxima in 1998–2002 and 2009–2010, observed in nine and five rivers, respectively. The peak of 1998–2002 is almost in phase in most fluvial systems, except for the Palomino River, where 2005 is highlighted. The Mulatos and Ranchería Rivers also display a major oscillation of this band from 1981 to 1982 (Fig. 6a). The 8–12 year component exhibits a quasi-stationary state that is disrupted by a single major oscillation starting in 1990, with a maximum power peak at 2005. This oscillation is almost in phase in these fluvial systems, with the

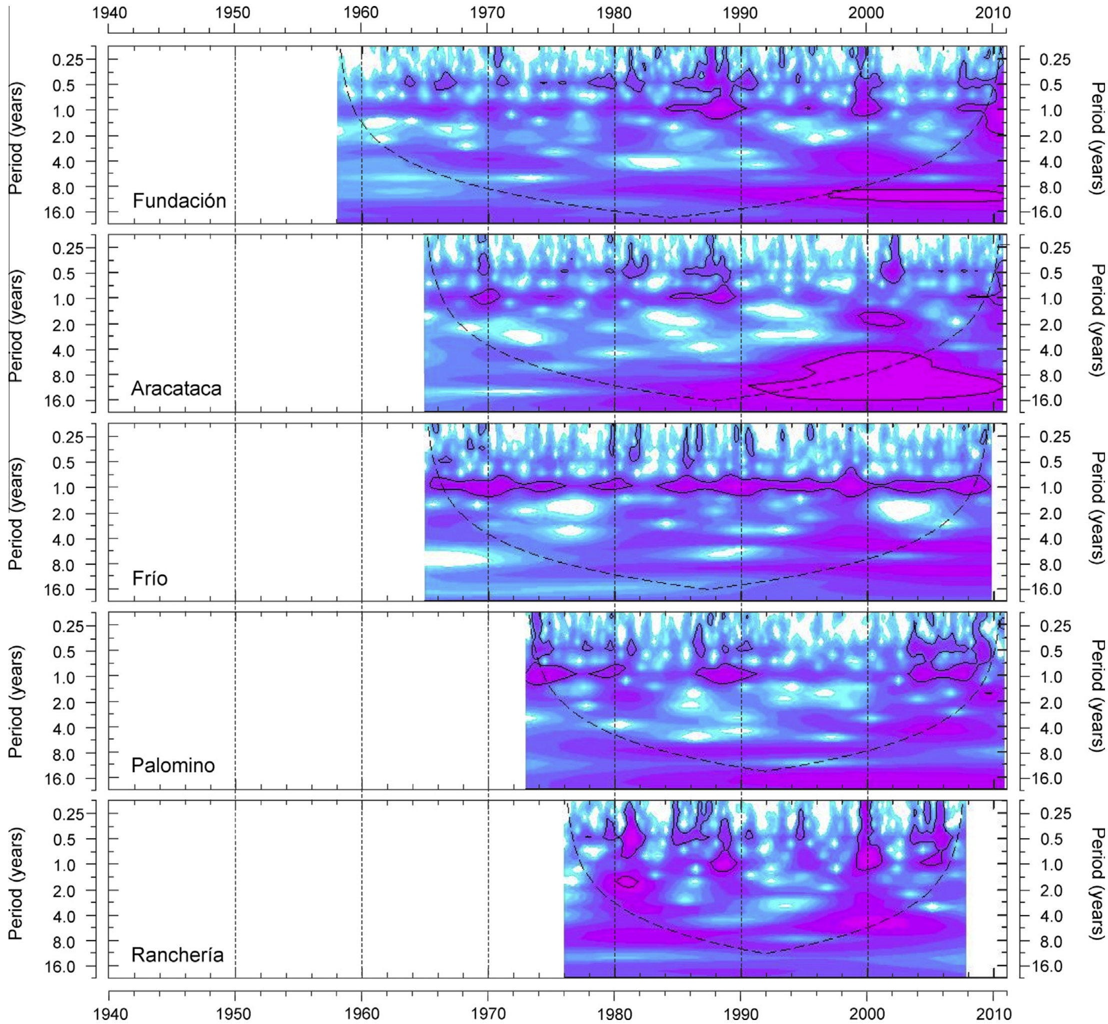

Fig. 5 (*continued*)

noteworthy exception of the Palomino and Ranchería Rivers, whose maximum power peaks are located at 1985 and 1995, respectively (Fig. 6b).

Time averaging processes led to the global wavelet spectrum, as shown in Fig. 7. The 6-month and 1-year components are visible after using this averaging technique. Their intensity is of the same magnitude (or lower) as that of the large-scale processes. In the Mulatos, Magdalena and Frío Rivers, the annual band appear as the main oscillatory component, whereas the 3–7 year band arises as a second-order source of hydrologic variability. On interannual scales, a 3–7 year oscillation is common in all fluvial systems, except in the Sinú and Aracataca Rivers, which exhibit a strong annual and quasi-decadal oscillation, respectively (Fig. 7). This interannual band usually appears as a second-order oscillatory component. Most of the streamflow series also display an 8–12 year fluctuation (quasi-decadal), which in the Sucío, Dique, Fundación and Aracataca Rivers constitutes the main oscillatory component (Fig. 7). Oscillations greater than one year were not statistically significant (except in Aracataca River), so it must be interpreted carefully. These information, however, were considered useful because (1) are within the range defined by cutoff frequency and edge effects, (2) the zero padding technique might reduce the true power of lower frequencies, and (3) the CWT isolates signals hidden in noise (not revealed by through other techniques). More data is needed to test the true statistical significance of these oscillations.

5. Discussion

5.1. Magnitude and long-term trends of freshwater discharges

The cumulative streamflow (330 km^3 yr^{-1}) of Caribbean Colombian Rivers represent 43% of the total freshwater fluxes (789.6 km^3 yr^{-1}) into the Caribbean basin (GRDC, 2009). The Magdalena River provides the largest supply of freshwater into the Caribbean Sea, with a mean discharge at Calamar of 205.1 km^3 yr^{-1} (Table 2), which represents the 26% of the entire fluvial discharge into this basin. The previous estimates of Magdalena freshwater discharge ranged between 224 km^3 yr^{-1} and 254 km^3 yr^{-1} (e.g., Dai et al., 2009; Milliman and Meade, 1983; Pekarova et al., 2003; Restrepo and Kjerfve, 2000, 2004; Walling, 2009). However, these estimates were either limited by short times series (<26 years) (Milliman and Meade, 1983; Restrepo and Kjerfve, 2000, 2004; Walling, 2009) or based on numerical approaches (Dai et al., 2009; Pekarova et al., 2003). The new data-set presented in this study comprises longer time series (32–70 years) and is based on instrumental records. Hence, the data-set provides more reliable estimates of the freshwater discharge into the Caribbean Sea. As a consequence of the relatively high freshwater discharge, the fluvial inputs of these rivers (especially the Magdalena River) are one of the main morphodynamic agents in the Caribbean littoral and display major control of the thermodynamic stability and biochemical cycles of the Caribbean Sea.

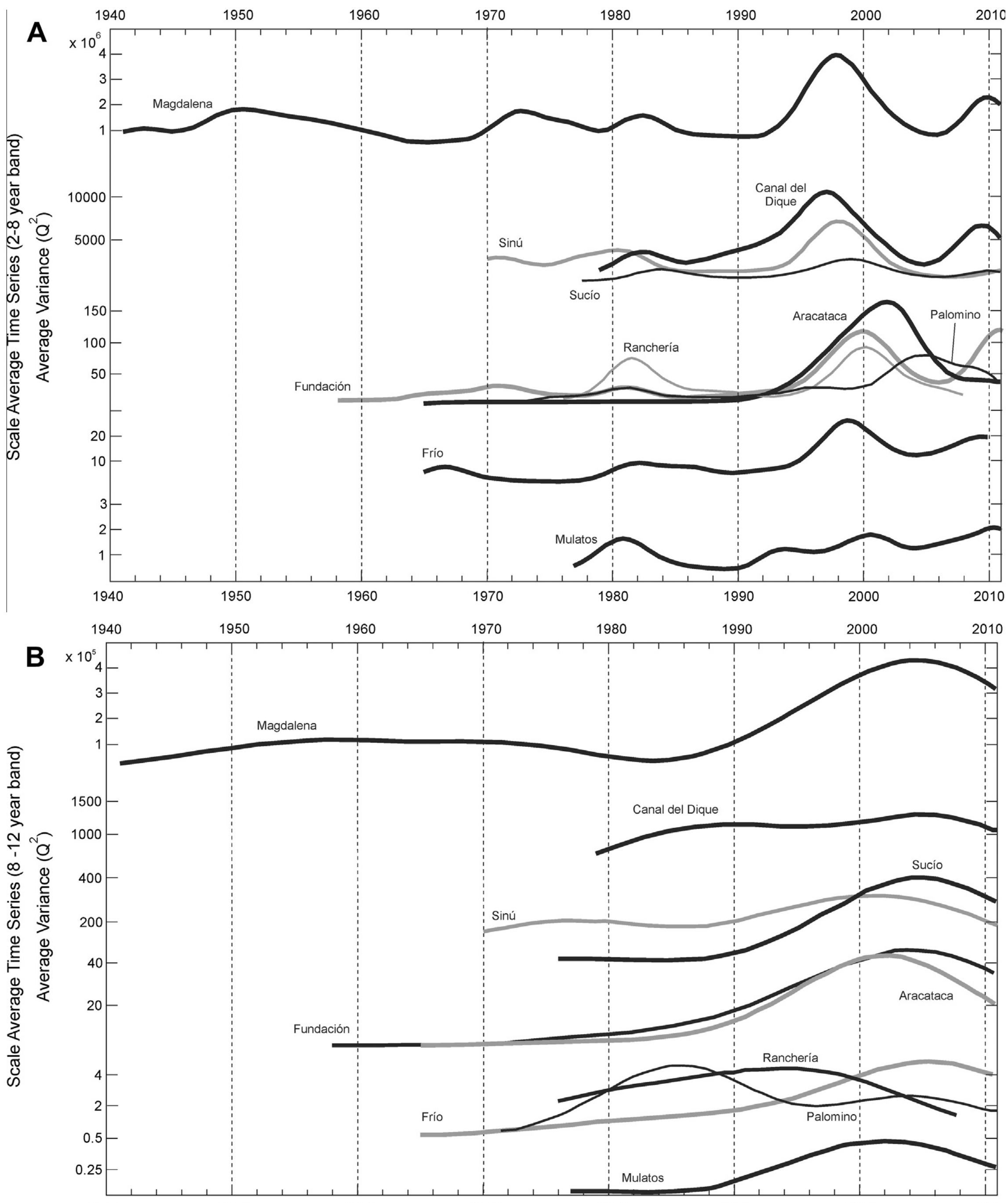

Fig. 6. Power analysis – frequency range: average variance of (a) 2–8 year band and (b) 8–13 year band.

Our Mann–Kendall analyses indicated positive flow trends, significant at 90% or higher confidence levels in the Mulatos, Magdalena, Canal del Dique and Fundación Rivers. Moreover, Sen's slope analyses highlighted a general increase of freshwater discharge (Table 3), especially between 1998 and 2010, when higher rates of increase occurred (Fig. 2). Significant trends in the annual streamflows of the rivers draining the Caribbean alluvial plain of Colombia have not been reported in previous studies (Mesa et al., 1997; Poveda, 2004). In particular, the annual freshwater discharges in the Magdalena River have been estimated to be relatively constant (Dai et al., 2009; Milliman et al., 2008; Walling, 2009). The differences between the long-term trends, as identified in this study and previous works, are based on (1) the temporal window of analysis and (2) the non-stationary setting of the hydrological processes. The magnitude and statistical significance of the long-term trends are sensitive to the exact time period examined, in particular, whether the data of the most recent years are included. Although different hydrological records are used in previous studies, none of them covered the period from 2000 to 2010, when the annual streamflow of these fluvial systems rose as high as 65% (Fig. 3 and Table 4). In addition, the major oscillatory signals in this period reach their maximum power in most of the rivers (Fig. 5), and thus, these oscillatory signals enhance the freshwater discharges and determine the emerging long-term trend of these fluvial systems. Dai et al. (2009) argues that a linear trend is not expected for any given period but does

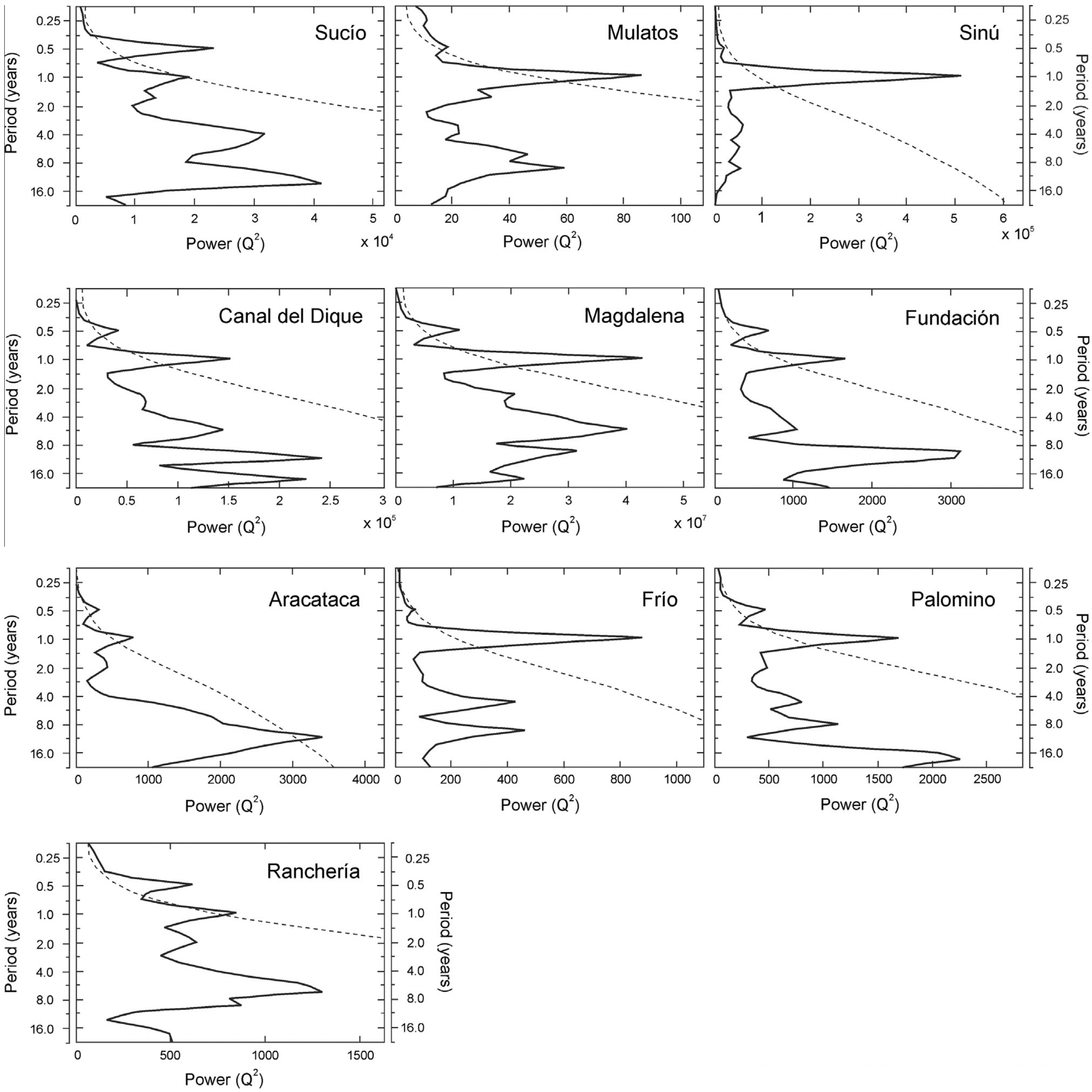

Fig. 7. Global wavelet spectrum for the Caribbean Rivers.

provide one measure of change over that period. Significant linear trends were identified for the 1977–2010, 1979–2010, 1941–2010, and 1958–2010 time periods for the Mulatos, Canal del Dique, Magdalena, and Fundación Rivers. These observations do not imply that these trends existed before or will continue after those respective periods but do indicate significant hydrological changes.

The new analysis of this historical discharge series indicates a strong connection between the long-term trends, as indicator of hydrological changes, and hydrologic periodicities. Since 1998–2002, when linear trends become pronounced in most of the fluvial systems and are significant for the Sucío, Canal del Dique, Magdalena, Fundación, Frío and Palomino Rivers (Table 4), a conjugated strong annual, interannual (3–7 year), and quasi-decadal (8–12 year) signal appears for almost all river systems. The simultaneity of these signals, trends and increasing freshwater discharge across the entire region suggests that the mechanism of generation has a large spatial scale. Such synchronous fluctuations are also observed in North America, South America and Africa at continental scale (Pasquini and Depetris, 2007; Pekarova et al., 2003; Probst and Tardy, 1987). In spite of simultaneity features, relevant differences also arise between these rivers. For example, the distinctive annual signal in Sinú an Frío Rivers or the absence of any significant trends in Aracataca, Sinú and Ranchería Rivers (Table 3 and Table 4). The streamflow responses to large-scale atmospheric circulations seems to be however modulated by local-scale natural processes and large-scale anthropogenic impacts (e.g. Walling and Fang, 2003; Dai et al., 2009; Walling, 2009), which in turn are regulated by watershed features (i.e. drainage basin size, relief, vegetation cover, soils). These differences should be explored thoroughly in future research.

5.2. Variability of freshwater discharges

Analyses of the seasonal differences among La Niña, El Niño and normal years (Fig. 3), as well as a cross-correlation analysis between monthly streamflow and monthly anomalies of the SOI, indicate that the ENSO signal for rivers draining the Caribbean plain of Colombia is not as strong as was previously shown (e.g., Gutiérrez and Dracup, 2001; Restrepo and Kjerfve, 2000). Moderate to good correlation between streamflow and SOI at seasonal and interannual scales exists for the Andean rivers, whereas poor to moderate correlation exists for those draining the Sierra Nevada de Santa Marta. Poveda et al. (2001) had already noted the weak simultaneous correlation between the ENSO and streamflows at the seasonal scale, especially during April–June in Colombia, because the ENSO either just starts to develop or declines at that time of the year. Furthermore, the influences of the ENSO on Caribbean fluvial discharge are weaker in comparison with its effects in rivers draining the Pacific and Andean regions of Colombia. In contrast, other authors argue that 65% of the streamflow interannual variability in rivers such as the Magdalena, Cauca, Cesar, Rancheria, and Sinú might be explained with ENSO (Gutiérrez and Dracup, 2001; Restrepo and Kjerfve, 2000). However, this is based on cross-correlation and coherence analyses using filtered-softened time series of monthly streamflow and ENSO indexes (i.e., MEI, Niño 3.4 SST, SOI), thus promoting a higher statistical association between the data.

The influence of the ENSO on the hydrological cycle has been analysed at seasonal and interannual scales in South America with conflicting results (i.e., Amarasekera et al., 1997; Garcia and Mechoso, 2005; Robertson and Mechoso, 1998; Labat et al., 2004, 2005; Pasquini and Depetris, 2007). For example, Amarasekera et al. (1997) observed a weak correlation between Pacific surface sea temperature anomalies and the annual discharge of the Amazon River, with less than 10% of the annual streamflow variability attributed to the ENSO. In contrast, a wavelet spectrum analysis of the annual streamflow of the Amazon River highlighted a 3–6 year oscillation typical of ENSO variability and a nearly permanent 2-year coherence between the SOI index and Amazon discharge (Labat et al., 2005). Garcia and Mechoso (2005) indicated that ENSO signals do not contribute to the major proportion of hydrological variability in rivers draining northeastern South America such as the Orinoco (Venezuela), Tocantins (Brazil) and Sao Francisco (Brazil) Rivers. For these rivers, the ENSO only explains a small fraction of the interannual variability of streamflow, similar to our findings of the rivers draining the Caribbean alluvial plain of Colombia, especially the Sierra Nevada Rivers (Fig. 7).

The lack of a strong correlation between SOI and streamflow suggests that other climate drivers might contribute to the streamflow variability of rivers draining the Caribbean alluvial plain of Colombia. Our wavelet analyses indicate that there are other processes at regional scale that significantly modulate the streamflow variability (Fig. 5). Thus, different climate/oceanographic oscillations act as a source of variability that enhance or diminish the ENSO effects (e.g., Labat et al., 2005; Labat, 2008; Pasquini and Depetris, 2007). For most of the rivers, the new analyses highlight the strengthening of a quasi-decadal oscillation from 1990 to 2010, which coincide with the major oscillations of the ENSO-related band (2–8 year), as recorded in 1998–2002 and for some rivers in 2009–2010 (Fig. 6). The concurrence of these oscillatory signals indicates periods of intense hydrologic activity, wherein anomalously high streamflows occurred (Fig. 4). These features might be related to climatic and oceanographic processes of low-periodicity (i.e. quasi-decadal), such as Pacific Decadal Oscillation or sea level pressure anomalies (SLP) and sea surface temperature gradients of the tropical Atlantic Ocean (SST) (i.e., Tropical North Atlantic Index – TNA, Tropical Atlantic Meridional SST Gradient – TAMG, sea surface temperature anomaly index – NATL). Both processes have been associated to atmospheric/climatic perturbations in Northwestern South America (e.g. Enfield and Alfaro, 1999; Hastenrath, 1990; Mantua and Hare, 2002; Melice and Servain, 2003), and have also experienced a shift in its phase during the last decades (Fig. 8). According to Mantua and Hare (2002) the PDO might have experienced a change from warm to cool PDO phases in 1998, coincident with the demise of the 1997/98 El Niño and the beginning of the subsequent La Niña episode (Fig. 8). Evidences suggest that cool phases of PDO coincide with anomalously wet

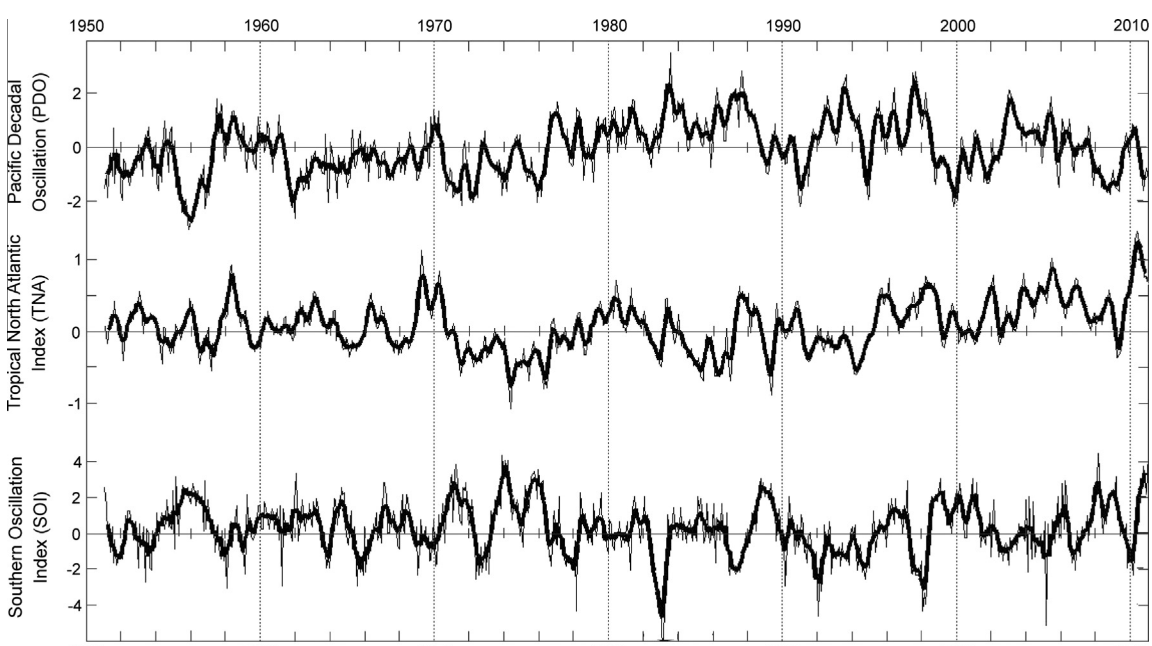

Fig. 8. Monthly values of Pacific Decadal Oscillation (PDO), Tropical North Atlantic Index (TNA) and SOI Index anomalies (1951–2010); a five-month moving average is superimposed on time series (black bold line).

periods in northern South America (Mantua and Hare, 2002). The TNA exhibit positive anomalies since mid 1990's decade (except around 2009) (Fig. 8) and displayed a powerful association at the end of the 1990s with the ENSO conditions (Enfield and Alfaro, 1999; Melice and Servain, 2003). Oppositely signed SST anomalies in the eastern Pacific and Tropical North Atlantic are associated with enhanced rainfall departures, and hence streamflows, over the Caribbean (Enfield and Alfaro, 1999). Particularly, low SST in the Pacific and high SST in the Caribbean, as occurred in 1998–2002 and 2010, might have led to enhanced rainfall departures over the Caribbean during La Niña events (Fig. 8). Other studies also have noted the importance of superimposed hydrological-oscillatory processes, mainly the co-occurrence of the ENSO and sea pressure anomalies with quasi-decadal dominant signals (hence, sea surface temperature anomalies), in regulating the hydrological variability of the rivers draining northeastern South America (e.g. Garcia and Mechoso, 2005; Genta et al., 1998; Hastenrath, 1990; Labat et al., 2005; Pasquini and Depetris, 2007; Robertson and Mechoso, 1998).

6. Conclusions

The historical freshwater discharge data of northern Colombia (Caribbean alluvial plain) rivers were analysed in this new study to quantify the magnitude, to estimate long-term trends as indicator of hydrological change, and to evaluate the variability patterns of freshwater discharges into the Caribbean Sea. These Colombian Rivers contribute 330 $km^3\,yr^{-1}$ of freshwater into the Caribbean Sea, and this cumulative discharge represents 43% of the entire supply to this basin. The Magdalena River provides the largest supply of freshwater into the Caribbean Sea with a mean discharge of 205.1 $km^3\,yr^{-1}$. Most of the rivers do not show significant trends in the hydrological record. However, from 2000 to 2010, the annual streamflow of all fluvial systems increased up to 65%. In particular, the Mulatos, Magdalena, Canal del Dique, and Fundación River data indicate increasing trends that are significant at the 90%, 95%, 99%, and 95% confidence level, respectively.

There is a strong interrelation between long-term trends and hydrologic periodicities. Evidence of annual, interannual (3–7 year), and quasi-decadal (8–12 year) periodicities were identified based on the wavelet analysis. Moreover, this analysis highlights the strengthening of the quasi-decadal oscillation from 1990 to 2010, which coincided with the major oscillations of the inter-annual band (ENSO-related) recorded in 1998–2002 and 2009–2010. The concurrence of these oscillatory signals indicates periods of intense hydrologic activity wherein anomalously high streamflows occurred. The annual (associated to ITCZ migration) and quasi-decadal (associated possibly to climatic and oceanographic processes of low-periodicity such as PDO and/or TNA) bands appear as the main oscillatory components of the hydrologic variability of the rivers draining the Caribbean alluvial plain of Colombia, whereas the inter-annual band (3–7 year) represents a second-order oscillatory component of this variability.

Acknowledgments

This research was funded by the Universidad del Norte (Dirección de Investigación, Desarrollo e Innovación – DIDI Grant) and the Universidad Pontificia Bolivariana – Sede Medellín (Centro de Investigación para el Desarrollo y la Innovación Grant). The support of the Universidad del Norte Fellowship and the CEMarin Fellowship (Colombian Center of Excellence for Marine Science Research sponsored by the German Academic Exchange Service – DAAD), awarded to one of the authors (J.C. Restrepo), is gratefully acknowledged. We thank two anonymous reviewers for providing insightful and constructive suggestions for improving an early draft of this article.

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