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Sediment load trends in the Magdalena River basin (1980–2010): Anthropogenic and climate-induced causes

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ABSTRACT

The Colombian Andes and its main river basin, the Magdalena, have witnessed dramatic changes in land cover and further forest loss during the last three decades. For the Magdalena River, human activities appear to have played a more prominent role compared to rainfall (climate change) to mobilize sediment. However, environmental authorities in Colombia argue that climate change is the main trigger of erosion and floods experienced during the last decade. Here we present the first regional exercise addressing the following: (1) what are the observed trends of sediment load in the northern Andes during the last three decades? and (2) are sediment load trends in agreement with tendencies in land use change and climate (e.g., precipitation)? We perform Mann-Kendall tests on sediment load series for 21 main tributary systems during the 1980–2010 period. These gauging stations represent 77% of the whole Magdalena basin area. The last decade has been a period of increased pulses in sediment transport as seen by the statistical significant trends in load. Overall, six subcatchments, representing 55% of the analyzed Magdalena basin area, have witnessed increasing trends in sediment load. Also, some major tributaries have experienced changes in their interannual mean sediment flux during the mid- 1990s and 2005. Further analysis of land cover change (e.g., deforestation) indicates that the basin has undergone considerable change. Forest cover decreased by 40% over the period of study, while the area under agriculture and pasture cover (agricultural lands 1 and 2) increased by 65%. The highest peak of forest loss on record in the Magdalena basin, 5106 km^2 or 24% of the combined deforestation in Colombia, occurred during the 2005-2010 period. In contrast, Mann-Kendall tests on rainfall series for 61 stations reveal that precipitation shows no regional signs of increasing trends. Also, increasing trends in sediment load match quite well with the marked increase in forest clearance during the 1990–2000 and 2005–2010 periods. Such signs of increasing sediment fluxes should not be attributed to climate change and rainfall variability alone. As a whole, the Magdalena, one of the top 10 rivers in terms of sediment delivery to the ocean (184 Mt y^{-1}), and its tributaries have experienced increasing trends in sediment load during the 1980–2010 period; increases in close agreement with trends in land use change and deforestation. During the last decade, the Magdalena River drainage basin has witnessed an increase in erosion rates of 34%, from 550 t km^{-2} y^{-1} before 2000 to 710 t km^{-2} y^{-1} for the 2000–2010 period, and the average sediment load for the whole basin increased to 44 Mt y^{-1} for the same period. Similar to the global picture of human contribution to sediment generation, the rate of anthropogenic soil erosion in the Magdalena basin probably exceeds the rate of climate-driven erosion by several orders of magnitude.

1. Introduction

The most productive large rivers in terms of sediment yield are related to orogenic belts such as the Himalayas and the Andes (Latrubesse et al., 2005; Aalto et al., 2006). It has been estimated that between 2.57 and 3.33 Gt y^{-1} of sediments are currently eroded from the Andes and flowing through the fluvial systems, mainly toward the Amazon, Paraná, Orinoco, and Magdalena rivers. In the Andes of Colombia, a region with a mean sediment yield of 1485 t km^{-2} y^{-1}, geologic and geomorphic provinces are characterized by large intramontane rivers such as the Magdalena and the Cauca in the Caribbean divide, which collects much of the Andean tributaries of Colombia (Latrubesse and Restrepo, 2014).

Studies analyzing physical and anthropogenic controls on sediment yield in Andean catchments have shown that sediment yield is controlled by (i) runoff and maximum water discharge in the Magdalena River basin (Restrepo et al., 2006a); (ii) rainfall variability along the eastern range of the Andes from Ecuador to Bolivia (Pepin et al., 2013); (iii) cover, soil types, and road networks in the Paute River in Ecuador (Molina et al., 2008, 2015); (iv) mining activity in specific lithologies in the western central Andes of Perú (Morera et al., 2013); (v) lithology and slopes in the Bolivian Andes (Aalto et al., 2006); and (vi)

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slope and runoff in Chilean catchments from northern Chile to southern Patagonia (Pepin et al., 2010). Despite the importance of these studies on understanding the main natural controls on sediment yield in Andean basins, they did not assess the combined effect of natural and human-induced activities (e.g., deforestation) on temporal trends in sediment yield.

Most studies in large South American rivers have documented changes in water discharge as a function of land cover change. In eastern Amazonia, studies at a large scale in the Tocantins and Araguaia Rivers indicate that land cover changes since 1960 are associated with an increase in annual mean discharge despite no significant change in precipitation. Observed discharge increased by 25% from the 1970s to 1990s and about two-thirds of the increase is from deforestation, the remaining one-third from climate variability (Costa et al., 2003; Coe et al., 2009, 2011, 2013). Also, deforestation alone caused a 6% increase in annual discharge in the Xingu River basin, the fourth largest catchment of the Amazon (Panday et al., 2015).

In contrast, few studies have evaluated the impact of land cover change on sediment load in meso- or large-scale river basins in South America. Latrubesse et al. (2009) showed that large changes in sediment load and river morphology occurred in the Araguaia River basin, the main system draining the savannas of central Brazil. An increase of 31% in the bedload sediment transport, from 6.6 Mt in the 1960s to 8.8 Mt in the 1990s, has been driven by the rapid human-induced changes suffered by the Cerrado biome. More recently, a study on the cumulative impacts of tropical forest loss on soil erosion in the Magdalena River shows that 9% of the sediment load in the Magdalena is caused by deforestation; 482 Mt of sediments was produced owing to forest clearance over the last three decades (Restrepo et al., 2015). Other studies have documented the impacts of land cover conversions on erosion in small and highly degraded Andean catchments in southern Ecuador (Molina et al., 2008; Guns and Vanacker, 2013, 2014; Vanacker et al., 2014).

In large South American rivers, hydrological patterns, temporal trends in water discharge, and variability cycles have been documented in the Magdalena (Restrepo and Kjerfve, 2000; Restrepo et al., 2014), the Amazon (Amarasekera et al., 1997; Labat et al., 2004; Espinoza Villar et al., 2009; Marengo et al., 2011), and rivers draining southeastern South America, including the Paraná (Robertson and Mechoso, 1998; Pasquini and Depetris, 2007). Many studies have shown the strong relationship between the interannual variation of water discharge and sediment load and the ENSO or El Niño-La Niña cycle (Richey et al., 1986; Depetris et al., 1996; Vörösmartry et al., 1996; Restrepo and Kjerfve, 2000).

However, studies analyzing the climatic and human-induced drivers explaining temporal trends in sediment load on a basin scale in South America are few. Temporal trends of bed and suspended loads in the Araguaia River during the 1970–1998 period were compared to trends of basin deforestation and land use (Latrubesse et al., 2009). The variability in sediment discharge of the Amazon River was studied at the decadal scale, showing that suspended sediment discharge increased by about 20% since 1995. In particular, the interannual variability is much more significant in the sediment discharge than in the river discharge (Martinez et al., 2009). By using a scaling model (BQART) that combined natural and human forces (like basin area, relief, temperature, runoff, lithology, and sediment trapping) and soil erosion induced by humans (e.g., deforestation), Restrepo et al. (2015) described some features of the Magdalena River temporal trends in sediment load. However, this study failed to present the regional variation of sediment load and its relationship with spatial scale and other environmental factors. Overall, temporal analyses of sediment load at intrabasin scale in large South American rivers are not common and have not been addressed in major basins in the northern Andes, including the Magdalena River basin.

In this paper, we address this knowledge gap by examining trends of sediment load and rates of change for the main tributaries of the Magdalena River basin. Now the relevant questions are: (i) what are the observed trends of sediment load in the northern Andes during the last three decades? and (ii) are sediment load trends in agreement with trends in land use change, precipitation, or both?

The Magdalena River is a major and unique fluvial system in South America for the following reasons: (i) it ranks as the highest sediment-yielding river (~710 t km^2 y^{-1}) among the large rivers that drain South America (Latrubesse et al., 2005; Restrepo et al., 2015); (ii) it is a morphologically and climatologically diverse basin with large floodplains, high mountains, and episodic local climate events (Kettner et al., 2010; Carmona and Poveda, 2014); and (iii) there is a diversity of anthropogenic influences, including deforestation, poor soil conservation, mining practices, and increasing rates of urbanization, that have accounted for overall increasing trends in erosion and sedimentation on a regional scale (Restrepo and Syvitski, 2006). Being able to quantify spatially variable sediment fluxes and their temporal trends within a drainage basin like the Magdalena provides a framework to (i) better understand the redistribution of sediments through weathering and erosion, (ii) analyze river basins for anthropogenic influences (i.e., deforestation, mining, reservoirs), (iii) quantify factors of influence (e.g., climate), (iv) improve management decisions on the basis of better estimates of within-basin sediment yield, and (v) estimate future scenarios of sediment flux under different conditions of climate change and human perturbations (Kettner et al., 2010).

2. Materials and methods

2.1. The Magdalena River basin

The Magdalena River, one of the top 10 rivers in terms of sediment delivery to the ocean (184 Mt y^{-1}; Restrepo et al., 2015), covers a drainage basin area of 257,438 km^2, 24% of the territory of Colombia (Fig. 1).

The river drains the Andes, an active orogenic mountain belt characterized by high relief and intense seismic and igneous activity (volcanism and plutonism). The geologic and geomorphic setting of the Magdalena River comprises subsidence foreland areas, anastomosing pattern, and tributary systems with high vertical aggradation (Latrubesse et al., 2005).

According to Potter (1997), late Miocene deposits in the Magdalena valley between the Eastern and Western Cordilleras indicate a late Miocene initial age for the Magdalena River. The paleo-Magdalena and its principal tributary, the paleo-Cauca, developed in tectonic lows when the Eastern and Central Cordilleras were uplifted. Thus, tectonic control is evident in the entire Magdalena River and has created a watershed characterized by hillslopes commonly exceeding 45°, landslides, steep gradients, and high relief tributary basins (Restrepo and Syvitski, 2006).

The Magdalena catchment, formed by 151 subcatchments of which 42 are second-order watersheds, is characterized by high precipitation with an average rainfall of 2050 mm y^{-1} for the basin as a whole (Restrepo et al., 2006a). Rainfall regime is bimodal and similar throughout the watershed. There are two wet and two dry seasons. December–March and June–September are low rainfall periods and March–May and October–November are high rainfall periods. The complex topography along the basin makes it difficult to present generalizations of rainfall patterns. Nevertheless, some characteristics and similarities are present throughout the drainage basin. In both major valleys, the Magdalena and Cauca, between 6° and 7°N, the highest rainfall values, >3000 mm y^{-1}, are received at intermediate elevations, normally below 1500 m. The floor of the Magdalena valley receives 1700 mm y^{-1}, windward slopes 3000 mm yr^{-1}, and leeward slopes 1500 mm y^{-1}. The higher the elevation of the floor of the Magdalena basin, the lower the total rainfall, specifically if the floor elevation is >1000 m and the annual rainfall is 1000 mm. In addition, above 3000 m the annual rainfall is 1000 mm (López and Howell, 1967; Snow, 1976; Restrepo et al., 2006a).

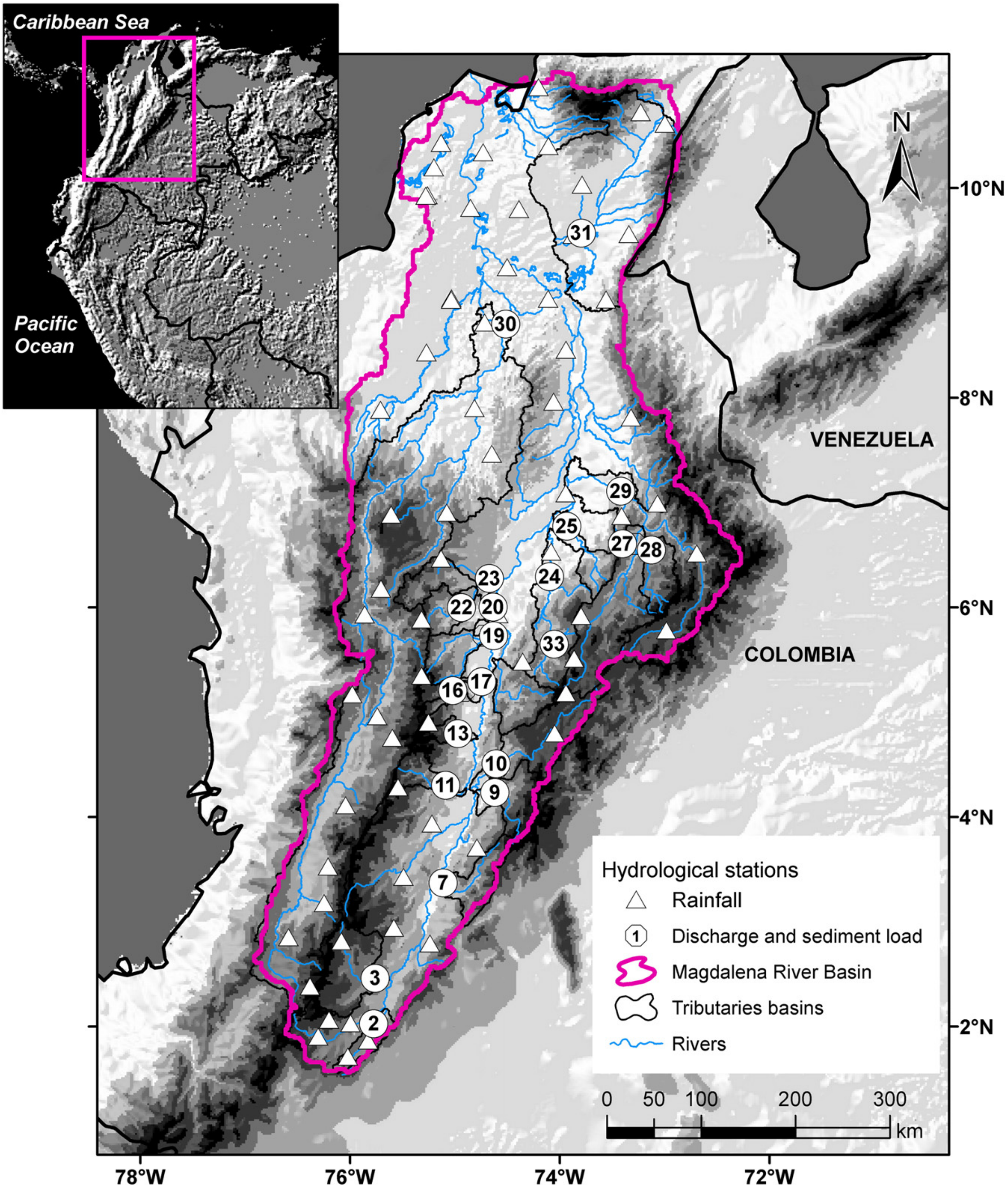


Fig. 1. Location of the Magdalena drainage basin in the northern Andes, showing the 21 analyzed tributary basins and their hydrological stations (circles). Numbers indicate the station code used in the regional analysis. Meteorological stations, where precipitation data were gathered, are also shown (triangles).

A regional study focusing on precipitation trends on the northwestern Department of Antioquia within the Magdalena basin (Poveda et al., 2001) found statistically significant trends in the quantiles of the probability density functions of monthly rainfall and average river flow series, interestingly identifying increasing trends in the upper quantiles and decreasing trends in the lower quantiles, thus confirming the intensification of extreme events during the most recent decades.

The 21 tributary catchments of the Magdalena River selected in this study to examine trends in sediment load cover an area of 198,506 km^2 or 77% of the whole Magdalena basin (Fig. 1). Drainage areas vary between 60,000 and 500 km^2, but most analyzed tributaries have drainage basins <6000 km^2 and tend to be more responsive to natural and human-induced change. Average rainfall ranges from 900 to 4500 mm yr^{-1}. In general, tributary basins are in elevations higher than 1000 m with hillslopes commonly ranging between 16° and 35°. Suspended sediment discharge varies between 0.16 and 49 Mt y^{-1}. The mean sediment yield of the analyzed catchments is ~749 t km^{-2} y^{-1}, and values range from ~10 to 2200 t km^{-2} y^{-1}. Maximum values of sediment yield are observed in the Negro, Carare, and Opón rivers, with 1730, 2200, and 1973 t km^{-2} y^{-1}, respectively. These three catchments are located in the middle Magdalena basin and correspond to tributaries descending from the Eastern Cordillera (Fig. 1; Restrepo et al., 2006a).

Besides the natural factors that lead to excessive erosion, including high runoff over steep slopes undergoing tectonic activity, forest cover in the Colombian Andes has greatly decreased caused by population expansion and changes in land use. The first studies assessing the human impact on soil erosion in the Andes of the Magdalena basin (Restrepo and Syvitski, 2006; Restrepo et al., 2006a) showed that most of the erosion can be explained by natural variables, including runoff and peak discharge. These two estimators explain 58% of variance in erosion rates.

Many socioeconomic features demonstrate that the Magdalena basin drives the economic growth of Colombia. Eighty percent of the population lives in the catchment and 86% of the Colombian GDP is produced here. Recent economic indicators at a national level show that the basin produces 75% of its agricultural products, 70% of its hydroelectricity, 90% of its thermal energy, and 80% of its coal mining (Restrepo, 2013; Restrepo et al., 2015).

2.2. Suspended sediment load and rainfall data

In this study, monthly suspended sediment load data (17–32 years in length) were obtained for 21 sites throughout the Magdalena basin from the Hydrological Institute of Colombia, IDEAM (IDEAM, 2014a; Fig. 1, Table 1). The long-term interannual trend of sediment load is derived from monthly data for the 1980–2010 period. The gauging stations in each major tributary system correspond to the lowest point in the subbasin for which water discharge and sediment load data are available, although this is not always near where the tributary joins the main course of the Magdalena (Fig. 1). The 21 selected catchments capture the variability of rainfall, topography, lithology, land cover, and human-induced pressures that the Andes represent (Kettner et al., 2010). Rainfall data were assessed using climate archives of the IDEAM (2014a). We used monthly precipitation data sets (1980–2010) collected from 61 meteorological stations located within the Magdalena watershed (Fig. 1).

2.3. Assessing the interannual variability of sediment load

To identify anomalies of sediment load, we plotted the cumulative sum of the normalized sediment load (*Qs*) and fitted a curve. The plots, which summarize the variation of sediment flux in the Magdalena River tributaries, were developed in five steps: (i) normalization of the original daily series by subtracting the interannual mean and dividing by the interannual standard deviation; (ii) calculation of the monthly averages of sediment load; (iii) plot the $\pm 1\sigma$ and $\pm 2\sigma$ confidence band around the mean; (iv) plot the cumulative normalized sediment load; and (v) smoothing time series data based on a fourth-order polynomial fit. This method is useful in discovering certain traits in a time series, such as long-term trend and interannual components (Shumway and Stoffer, 2000).

To understand how much variability in discharge is caused by episodic events (e.g., the rivers deliver a large proportion of their fluvial discharge in short periods of time), we plotted annual deviations from the interannual mean sediment load in the Magdalena River tributaries.

2.4. Temporal trend of sediment load and precipitation

Sediment load and precipitation were analyzed using non parametric Mann-Kendall trend method (M-K test). The Sen's slope, a non-parametric procedure for estimating the slope of trend in the sample of any *N* pair data, was used to test the trends in sediment load and rainfall. The sign of this slope estimator reflects the data trend, while its value indicates the steepness of the trend. In addition, this slope indicator is widely used to analyze the magnitude of discharge and rainfall per unit time period or rate of change, by dividing the Sen's slope to mean stream flow or precipitation (Mann, 1945; Kendall, 1955; Kendall and Stuart, 1967). Trends of sediment load for 1980–2010 are compared with observed deforestation rates and precipitation trends (Yue et al., 2002). We also applied a modified M–K test (Hamed and Rao, 1998) to avoid possible errors associated with positive autocorrelations in the analyzed

Table 1

Results of Mann-Kendall tests and Sen's slopes of the mean monthly sediment load time series of the Magdalena River tributaries for the two selected time periods, including pre-2000 and post-2000[a].

			Pre-2000 (1980–1999)				Post-2000 (2000 − 2010)			
River/tributary	Area (km^2)	% Study area	Sa (Mt y^{-1})	*p* Value	Sen's slope (t y^{-1})/y	Sy (t km^{-2} y^{-1})	Sa (Mt yr^{-1})	*p* Value	Sen's slope (t yr^{-1})/y	Sy (t km^{-2} y^{-1})
2. Suaza	989	0.6%	0.57	<0.0001	−1748	575	0.24	<0.0001	−1589	246
3. Páez	4078	2.7%	3.02	0.025	3990	740	3.26	0.016	19,342	800
7. Cabrera	2446	1.6%	1.88	0.010	−2801	767	0.75	0.002	−7858	305
9. Sumapaz	2435	1.6%	0.50	<0.0001	−1059	205	0.18	0.161	138	72
10. Bogotá	5544	3.6%	1.25	0.001	−1442	225	1.41	0.158	1008	255
11. Coello	1580	1.0%	1.64	0.002	−2179	1035	0.43	0.048	−770	270
13. Recio	610	0.4%	0.16	<0.0001	−506	258	0.17	0.001	683	274
16. Gualí	480	0.3%	0.19	0.160	−381	405	0.32	<0.0001	2407	668
17. Guarinó	976	0.6%	0.45	0.001	814	462	0.82	0.135	351	838
18. La Miel	2121	1.4%	2.44	0.013	−3562	1151	1.56	0.338	2108	735
19. Negro	4604	3.0%	6.25	<0.0001	−15,959	1357	5.06	0.142	−4759	1100
20. Cocorna	799	0.5%	0.45	<0.0001	−993	563	0.22	0.072	706	273
22. Samaná	1490	1.0%	0.94	0.709	−218	631	0.86	0.005	−3010	579
23. Nare	5711	3.7%	2.36	<0.0001	−12,607	414	1.42	0.797	351	249
24. Carare	4943	3.2%	10.87	0.504	−5585	2200	10.69	0.067	60,485	2163
25. Opón	1698	1.1%	3.32	0.661	−789	1954	3.10	0.068	18,384	1828
27. Suárez	9312	6.1%	1.42	<0.0001	4645	153	2.30	0.008	40,490	247
28. Fonce	1849	1.2%	0.59	0.973	−12	320	0.83	0.170	3196	447
29. Sogamoso	21,513	14.1%	11.22	<0.0001	103,028	522	13.61	0.241	48,873	493
30. Cauca	59,615	39.1%	49.72	<0.0001	123,460	834	51.77	0.015	162,496	862
31. Cesar	16,657	10.9%	0.14	<0.0001	−633	8	0.13	0.175	429	8

[a] Note: Sa: sediment load; Sy: sediment yield.

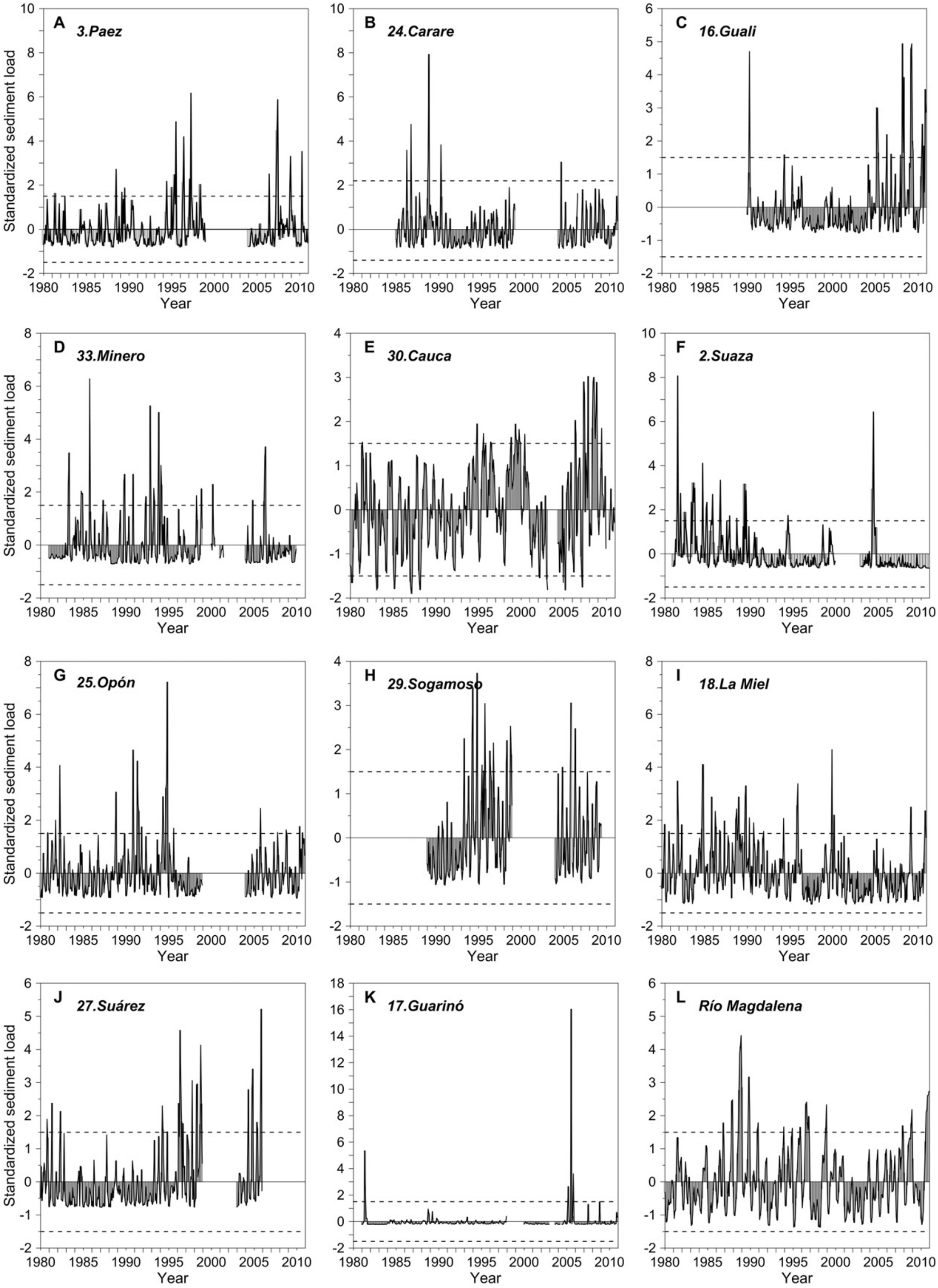


Fig. 2. Annual deviations from the interannual mean sediment load for selected Magdalena River tributaries and the most downstream station of the main Magdalena at Calamar (L) (Fig. 9) during the 1980–2010 period.

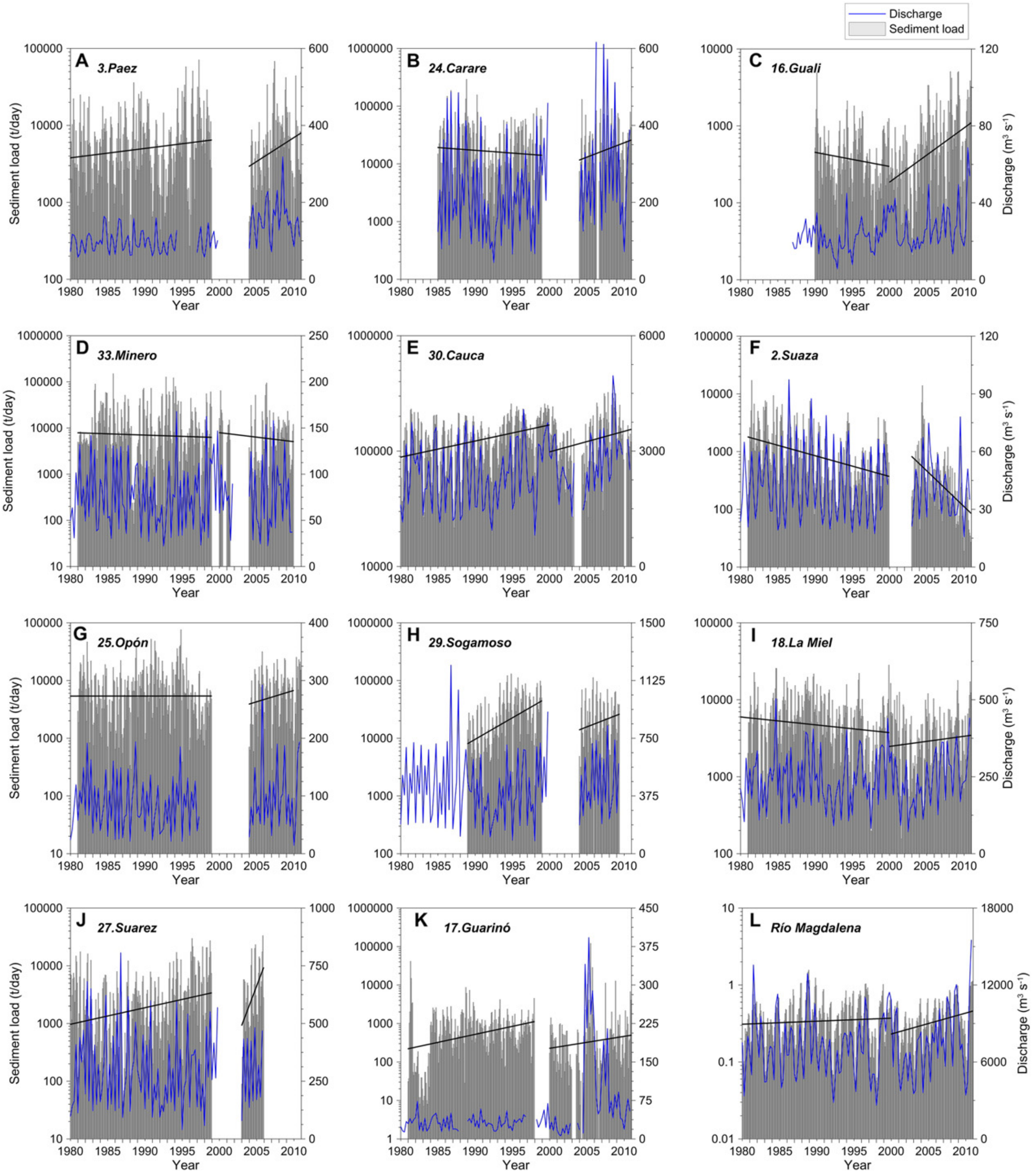


Fig. 3. Monthly series plots of sediment load (grey line) and water discharge (blue line) for selected tributaries in the Magdalena River drainage basin and the most downstream station at Calamar (L) (Fig. 9), showing linear trends in sediment load during the 1980–2000 (left) and 2000–2010 (right) periods, estimated by least-square linear regression for each tributary time series (bold line).

sediment load series (Blain, 2013). The C values calculated with progressive and retrograde series are named $C1$ and C2, respectively. The intersection point of the two lines, C1 and C2 ($k = 1, 2\dots n$), located within the 95% confidence interval provides the beginning of a step change point within a time series. Assuming a normal distribution with a significant level of $P = 0.05$, an M–K statistics $C > 1.96$ indicates a significant increasing trend; while a $C < -1.96$ indicates a significant decreasing trend (Gao et al., 2015).

To identify patterns of sediment load variability at various time scales, the Continuous Wavelet Transform (CWT) is used to examine the time series with generalized local base functions (i.e., mother wavelets) that were stretched and translated to a frequency and a time resolution (Torrence and Compo, 1998; Restrepo et al., 2014). This robust technique supports the evaluation of time series containing nonstationarities with different frequencies, providing a time-scale localization of a signal. Thus, the CWT, applied on monthly deseasonalized sediment load at tributary basins, is used to estimate periodicities and variability patterns, as well as to distinguish temporal oscillations in sediment load, identifying the intermittency of each time-scale process (Restrepo et al., 2014).

To identify the time at which a shift in sediment load occurs, we applied the Pettitt test (Pettitt, 1979), a nonparametric test that requires no assumption about the distribution of data. The Pettitt test, an adaptation of the rank-based Mann-Whitney test (Wijngaard et al., 2003), is

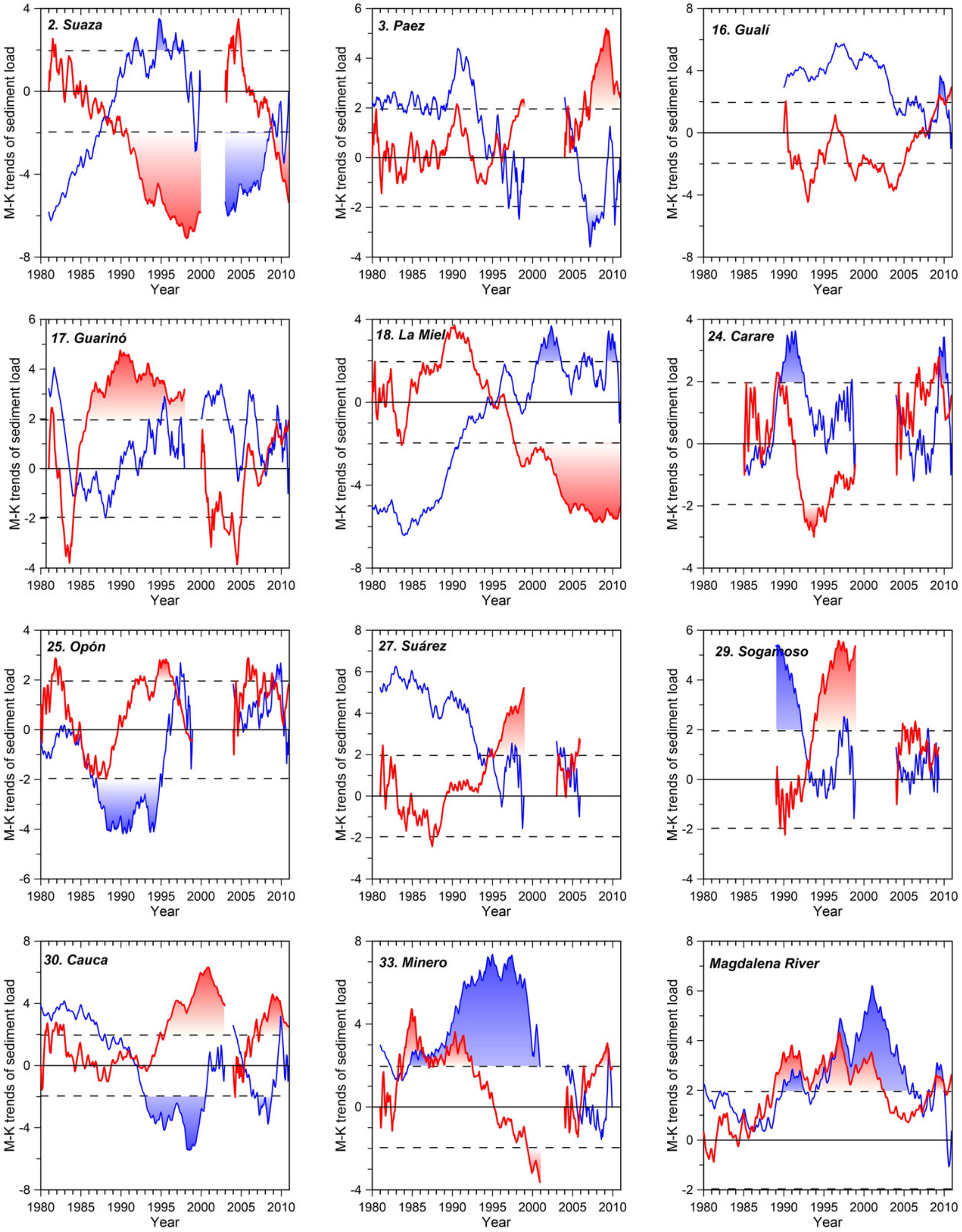


Fig. 4. The modified M-K trends of sediment load for selected Magdalena tributaries and the most downstream station of the main Magdalena at Calamar (Fig. 9). Progressive and retrograde series are shown in red and blue, respectively.

commonly used to detect a single change-point in a continuous hydrological or climate series.

2.5. Land cover analysis and human-induced impacts

Land cover analysis for each subcatchment during the 1980–2000 period was prepared from classification of MSS and TM LANDSAT images, providing total area of deforestation and estimates of change throughout the period 1980–2000 (Restrepo and Syvitski, 2006). Erosional areas during the same period were obtained from the Environmental Assessment of the Magdalena drainage basin (IDEAM, 2001). Forest covers and percentages of deforested areas during the 2000–2005 period were obtained from Armenteras and Rodríguez (2005), Restrepo (2005, 2008), and IDEAM (2011). Finally, we estimated forest

Table 2
Pettitt test showing years at which major shifts in mean sediment load occurred in the Magdalena basin tributaries during the 1980–2010 period; we also show increments and reductions in mean sediment load experienced at major breaking times.

River/tributary	Sediment load ($t\ d^{-1}$)	*P* value	Year of shift (A)	Sediment load ($t\ d^{-1}$)	
				1980-(A)	(A)-2010
2. Suaza	1295	<0.0001	1990	2279	739
3. Páez	8446	<0.0001	1994	6540	10,758
7. Cabrera	4273	0.561	–	–	–
9. Sumapaz	1056	1.907	–	–	–
10. Bogotá	3582	1.572	–	–	–
11. Coello	3180	<0.0001	2000	4398	1044
13. Recio	440	0.674	–	–	–
16. Gualí	714	<0.0001	2004	463	1225
17. Guarinó	1612	0.006	1983	1881	1578
18. La Miel	5830	0.040	1996	7234	4232
19. Negro	15,720	**0.077**	–	–	–
20. Cocorna	1050	<0.0001	1985	2822	614
22. Samaná N.	2491	1.586	–	–	–
23. Nare	5675	0.217	–	–	–
24. Carare	29,630	1.683	–	–	–
25. Opón	8931	<0.0001	1995	10,090	7151
27. Suárez	4240	0.007	1993	2394	6823
28. Fonce	1803	<0.0001	1992	1526	2088
29. Sogamoso	29,972	0.011	2005	13,785	36,180
30. Cauca	137,680	0.687	–	–	–
31. Cesar	370	0.134	–	–	–
32. Minero	14,838	0.643	–	–	–
Magdalena River		**<0.0001**	**2005**	**393,609**	**489,836**

cover change 2005–2010 for each tributary basin using deforestation maps from the National Assessment of Deforestation (IDEAM, 2014b), which are derived from MODIS MOD13Q1 vegetation indices with a 250-m resolution (Restrepo et al., 2015).

To make comparisons between sediment load trends and human activities that promote sediment production in the Magdalena River basin, including deforestation, agriculture, mining, urbanization, and energy, we analyzed data of a global nature (FAO, 2010; Ferretti-Gallon and Busch, 2014) or more regional such as the humid tropics (Geist and Lambin, 2001, 2002; Kim et al., 2015), and national Colombian deforestation assessments (Etter et al., 2005, 2006a, 2006b, 2006c, 2008; IDEAM, 2014b).

3. Results

3.1. Interannual deviations of sediment load 1980–2010

The analysis of annual deviations from the 30 year mean sediment load indicates that more than ~40% of the total sediment load variability of the Magdalena major tributaries (such as Cauca, Páez, Carare, Opón and Sogamoso) could be attributed to flashy peak events. The sediment load experienced major deviations from the interannual-year mean since the mid-1980s (Fig. 2). Further analysis of the standardized sediment load series reveals that 12 tributary basins experienced more pronounced positive deviations during the 2000–2010 period compared to the pre-2000 period (Fig. 2).

3.2. Trends in sediment load 1980–2010

Previous linear trends analysis of sediment load revealed that 17 watersheds on the Magdalena basin (68% of the drainage basin area) included in the regional database showed increasing trends during the 1980–2000 period, whereas 12 locations or 31% of the land basin area displayed decreasing trends. Only three stations, representing 1% of

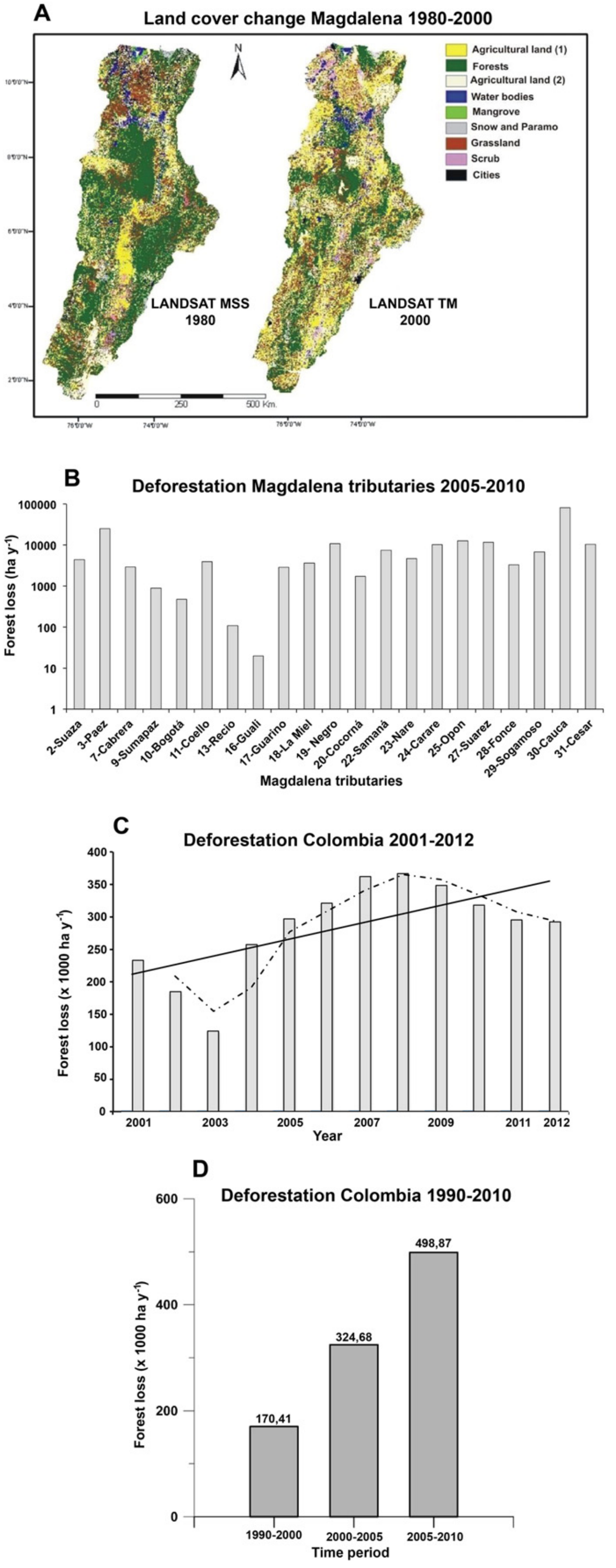
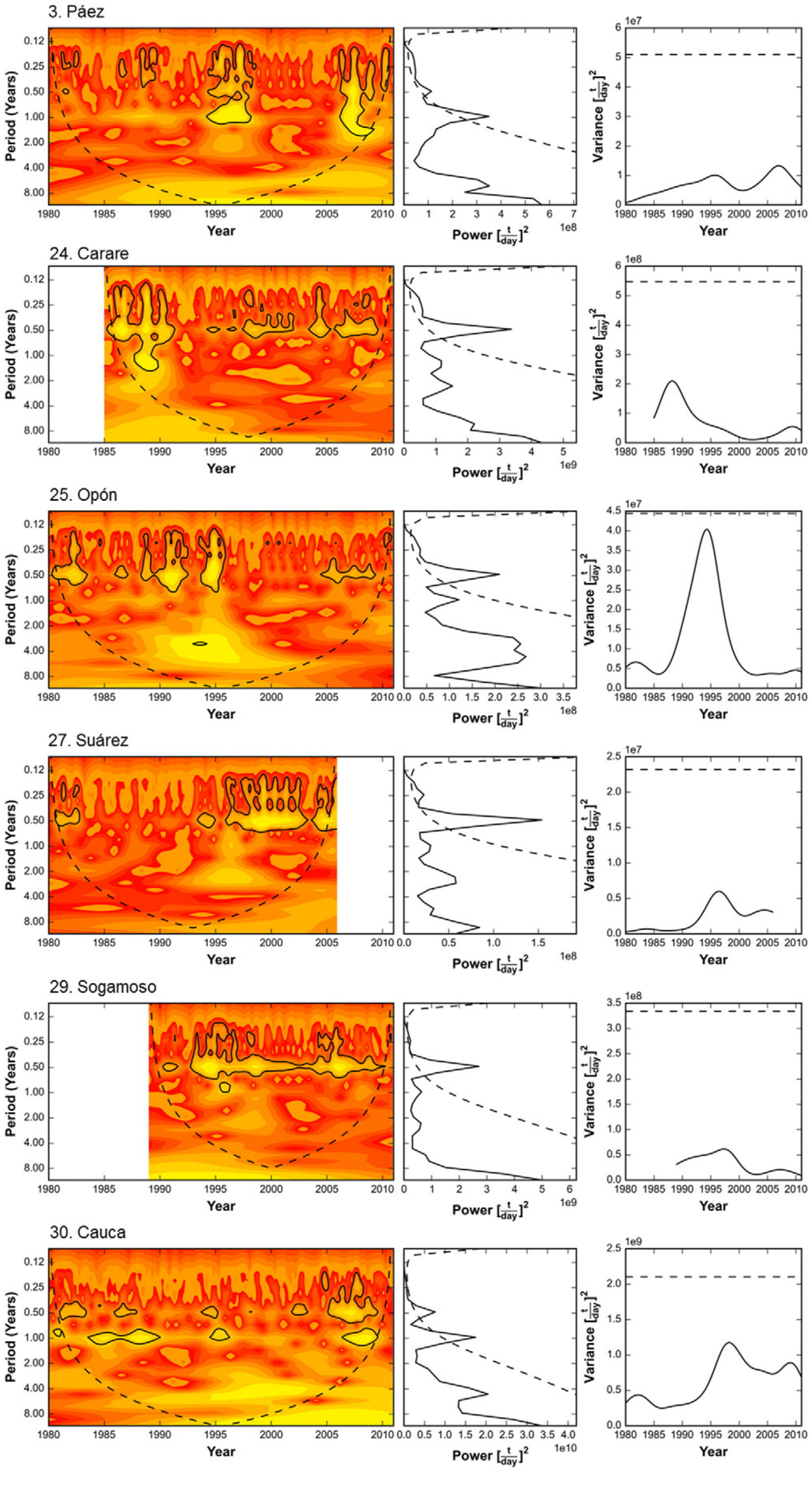


Fig. 5. (A) Land cover maps of the Magdalena drainage basin for 1980 and 2000 prepared from the classification of MSS and TM Landsat images (Restrepo and Syvitski, 2006). (B) Deforestation rates for the 21 tributary basins of interest for the 2005-2010 period, based on MODIS image classification by IDEAM–Colombia. (C) Deforestation rates in Colombia during the 2001–2012 period (data from IDEAM, 2014b; Global Forest Watch, 2014; Hansen et al., 2013). (D) Deforestation rates in Colombia during the 1990–2000, 2000–2005, and 2005–2010 periods (data from Kim et al., 2015).



3. Páez

24. Carare

25. Opón

27. Suárez

29. Sogamoso

30. Cauca

Fig. 6. Sediment load wavelet analysis for selected Magdalena tributaries during the 1980–2010 period. Continuous wavelet transform spectrum, showing high values of the transform coefficients (yellow) and the 95% confidence level (dashed line) (left). Global wavelet spectrum (center). Power analysis of sediment load in the frequency domain at average variance of 2-8 year band (right).

the drainage basin area, showed no significant trend in sediment load (Restrepo and Syvitski, 2006).

In this study we extend this analysis for another decade, to investigate rates of change and continued trends in sediment load for the main tributaries during the last three decades. Overall, most of the tributaries in the upper basin (including the Páez, Gualí and Suárez rivers) have experienced significant increases in sediment load over the last 10 years. Also, the Opon, Carare and Sogamoso rivers in the middle and eastern basin have witnessed increases since 2000 (Fig. 3).

Two examples of rivers where increased sediment fluxes have been continuous and prolonged during the last three decades are presented in Fig. 3. The Cauca River (59,200 km^2), the large tributary of the Magdalena River, saw its sediment loads increase by ~30% from 1979 to 1999. Between 1979 and 1989, average sediment load was 44 Mt y^{-1}. Since 1990, the average load has increased to 52 Mt y^{-1} (Fig. 3E). The second example is from the Sogamoso River (21,500 km^2), a large tributary in the eastern margin of the basin (Fig. 3H), where the annual sediment loads have increased by ~53% over the 1980–2000 period.

Time series analysis of sediment load 2000–2010 for 21 gauging stations for the Magdalena basin indicates that six watersheds (55% of the drainage basin area) included in the regional database show increasing trends (Table 1), whereas 15 locations or 45% of the land basin area display decreasing trends (Table 1).

Modified M–K tests were applied to test the statistical significance on upward and downward trends in sediment load 1980–2010 (Fig. 4). Some tributaries witnessed upward trends during the 1980s, 1990s, and post-2000, including the Páez, Carare, Gualí, Opón, Sogamoso, Guarinó, and Suárez (Fig. 4). The Cauca River, the main Magdalena tributary, witnessed statistically significant upward trends at the 95% confidence level between 1995 and 2002 as well as during the 2005–2010 period (Fig. 4). The latter period witnessed an increase in sediment load of 1.7 Mt y^{-1}.

Monthly series of sediment load 1972-2011 were also obtained at the most downstream station of the Magdalena River at Calamar (Fig. 9). The modified M-K test for the Magdalena reveals significant upward trends in annual sediment load during the mid-1980s, 1990s, and post-2000 (Fig. 4). Between 2000 and 2010, the annual sediment load increased 33% with respect to the pre-2000 period and more positive interannual deviations are observed during this period. The Magdalena drainage basin has witnessed an increase in mean erosion rates from 550 t km^{-2} y^{-1} before 2000 to 710 t km^{-2} y^{-1} for the 2000–2010 period. The average sediment load for the whole Magdalena basin increased 44 Mt y^{-1} during the last decade.

Major shifts in mean sediment load during the 1980–2010 period occurred in 11 tributaries. The Páez, Gualí, Suárez, Fonce, and Sogamoso rivers witnessed increments in mean sediment load during the mid-1990s and 2005. The Magdalena River at the most downstream station, Calamar (Fig. 9), also experienced a major shift in mean sediment load in 2005, from 394 × 10^3 to 490 × 10^3 t d^{-1} (Table 2).

3.3. Human-induced drivers of increasing sediment load trends

The percentage forest cover in the Magdalena basin was estimated to have declined from 66% in 1980 to 22% in 2000, with an annual deforestation rate of 274,000 ha y^{-1} (Restrepo and Syvitski, 2006; Fig. 5A). An assessment of deforestation by IDEAM between 2000 and 2010 indicates that the national rate of forest loss is 336,000 ha y^{-1} (IDEAM, 2011), with a percentage forest reduction from 22% in 2000 to 13% in 2010.

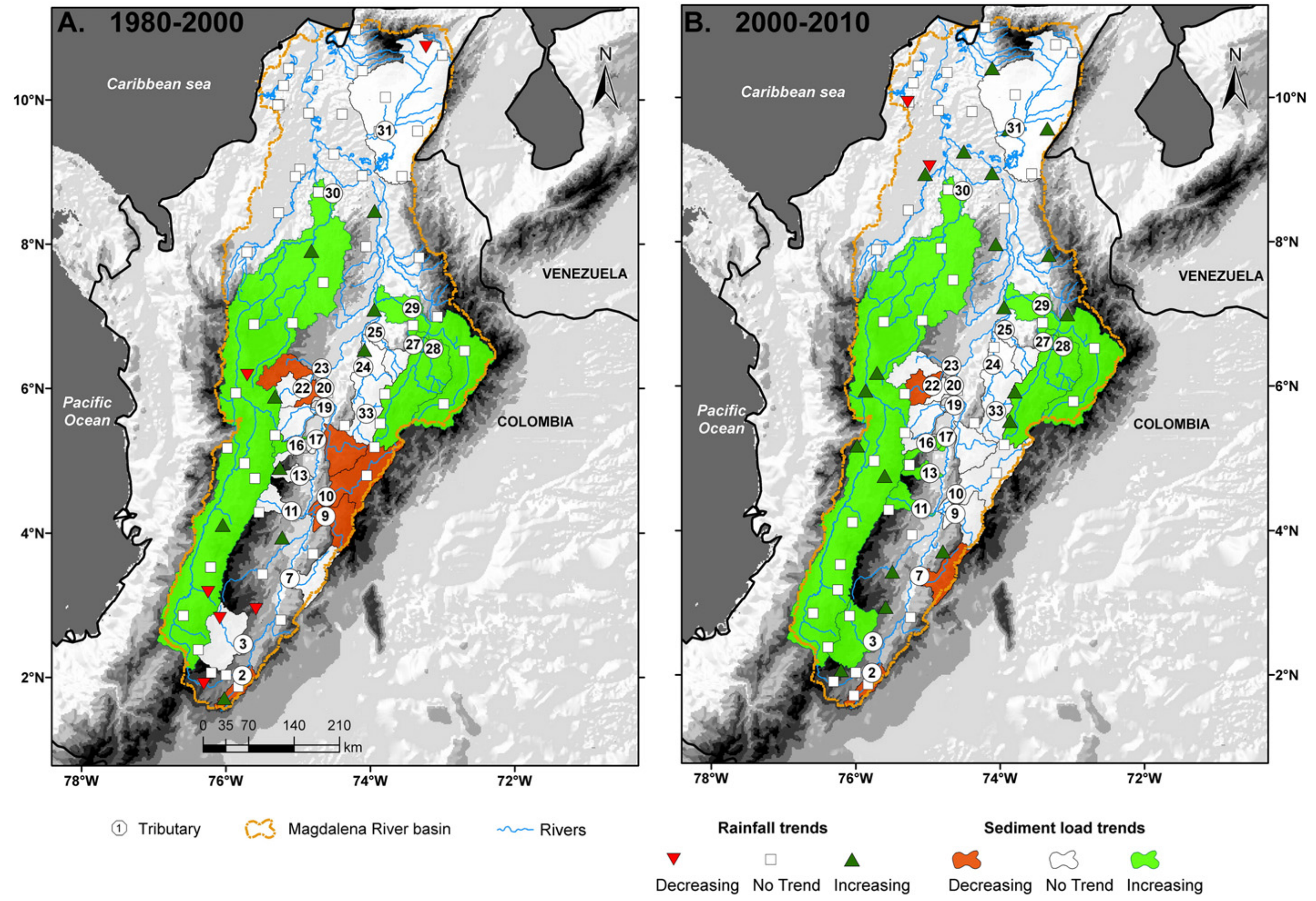


Fig. 7. Maps of the Magdalena drainage basin showing sediment load and rainfall trends during the 1980–2000 (A) and 2000–2010 (B) periods.

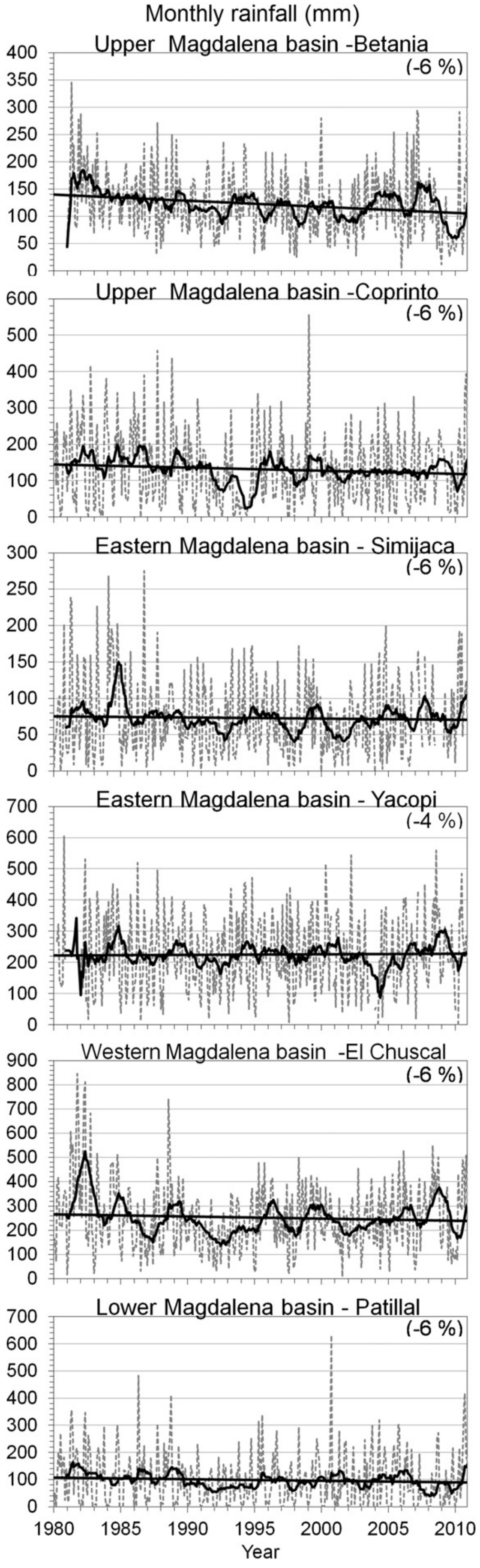


Fig. 8. Precipitation in different reaches of the Magdalena drainage basin from 1980 to 2010. We show monthly variations (dashed lines) and 3 year running averages (solid lines). Percentage changes were calculated using linear regression.

When compared to global rates of deforestation (FAO, 2010), Colombia, with an area of 1.14 million km^2 and representing $0.1% of the global land, contributes $5% to the global forest loss (Restrepo, 2013; Restrepo et al., 2015).

Land cover in the Magdalena basin has undergone considerable change. Forest cover decreased by 40% over the period of study, while the area under agriculture and pasture cover (agricultural lands 1 and 2) increased by 65% during the same 20 year period (Fig. 5A). Many Magdalena subcatchments, including the Cauca, Opón, Suarez, Negro, and Páez rivers, witnessed an order of magnitude higher deforestation rates compared to other tributaries during 2005–2010 (Fig. 5B). The total forest clearance in the Magdalena basin of 5106 km^2 between 2005 and 2010 represents 24% of the combined deforestation in Colombia. This deforestation rate is on average 145% lower than the more accurate value obtained by Kim et al. (2015); Fig. 5D. For instance, the highest peak of forest loss on record in Colombia occurred during the 2005–2010 period (Fig. 5C).

To estimate the periodicities and variability patterns and to distinguish temporal oscillations in sediment load of the main Magdalena tributaries, the continuous wavelet transform was applied on monthly deseasonalized time series of sediment load (Fig. 6). In the Cauca River, sediment load series show an annual signal during the mid-1970s, late 1980s and 1990s, and at the end of the 2005–2010 period (Fig. 6). These annual oscillations are significant at the 95% confidence level (Fig. 6). Similarly, the average variance of sediment load at the 2–8 year band shows peaks during the late 1980s and 1990s and a progressive upward trend between 2005 and 2010 (Fig. 6). Other tributaries, including the Páez and Carare rivers, also show an annual signal during the mid-1980s and late 1990s and at the end of the 2005–2010 period. Rivers such as Opón, Suárez, and Sogamoso reveal highly intermittent periods of 5–6 months. Nevertheless, some inter-annual fluctuations appear visible in these rivers during the 1990s. Finally, interannual periodicities ranging between 2 and 7 years are well observed in all tributaries (Fig. 6).

As noted by Restrepo et al. (2015), when analyzing the participation (million pesos) in the gross domestic product of human activities that promote soil erosion in the Magdalena basin for the 1927–2000 period (including agriculture, mining, energy, and urbanization), a large part of the land conversion and further deforestation resulted from agricultural activities. All human drivers show clear increases during the 1970s, 1980s, and 1990s. The trends match well with the observed increasing trends in sediment transport of the Magdalena tributaries and with the main Magdalena River at Calamar (Figs. 4 and 9) and also with the annual pulses observed in the wavelet spectrums (Fig. 6). Cattle ranching and population in the Andes of Colombia also increased exponentially during the last two centuries, with major increases between the 1970s and 2000. These regional analyses of land use (Fig. 5) and sediment load trends (Fig. 4 and Table 1) appear to indicate that the extent of erosion within the Andes of Colombia has severely increased over the last 30 years. The last decade has been a period of increased pulses in sediment transport as seen by the statistically significant trends (Fig. 4) and by the observed interannual patterns of temporal oscillations (Fig. 6).

3.4. Precipitation trends 1980–2010

During the 1980–2000 period, 15 meteorological stations (25%, statistically significant) witnessed increasing trends in precipitation, whereas 26 stations (75%, statistically significant) showed no trend. In contrast, 10% of the analyzed stations experienced a decline in precipitation (Table S1). Spatial analysis of rainfall shows no regional pattern in the distribution of trends throughout the Magdalena drainage basin.

For instance, most changes of basinwide precipitation were statistically insignificant in tributary basins experiencing increasing trends in sediment load during this period (Fig. 7A, Table S1).

Between 2000 and 2010, 33% (statistically significant) of the analyzed stations experienced increasing trends in precipitation, while 64% (39 stations, statistically significant) showed no trend. Only 3% experienced decreasing trends in precipitation (Table S1). A closer look at the spatial distribution of precipitation trends reveals that rainfall has increased in the Magdalena valley and in the Cauca River basin (only four stations), but most tributary basins showed no significant increases in rainfall. Once again, no regional increasing trend in precipitation was observed, especially in watersheds witnessing increasing trends of sediment load (Fig. 7B).

Overall, precipitation showed a broad belt of decline trending from the south to the northeast and northwest. Major decreases occurred in the western margin of the basin, including the Cauca River catchment, as well as in the middle-eastern basin, a region characterized by high sediment yield and increasing trends of sediment load (Fig. 7). Comparison of the results for the sediment load and rainfall trends indicate that nonstationary trends are considerably more frequent for sediment load than for rainfall. This is not unexpected, since sediment yields are likely to be more sensitive to changes in catchment condition than precipitation, at least in terms of annual totals.

Linear regression was also used to calculate the changes of precipitation from 1980 to 2010 at each meteorological station (Fig. 8, Table S1). Since 1980 there was a moderate decline in basinwide annual precipitation in different reaches of the Magdalena basin (e.g., −6% in the upper, middle, and lower sections, statistically significant; Fig. 8).

As a whole, sediment load of the Magdalena River increased by 33% over the period extending from 2000 to 2010 (Table 2). Part of this increase can be ascribed to forest clearance and expansion of agriculture (Fig. 5), but the record of annual precipitation totals indicates that rainfall showed no significant increase (Fig. 7B). The greater number of rainfall stations characterized by stationary series suggests that climate change is unlikely to be a primary cause of changing sediment loads for the Magdalena River basin, as annual rainfall totals are likely to be sensitive to climate change (e.g., Walling, 2006).

4. Discussion

4.1. Underlying human drivers of increasing sediment load trends

Denudation processes are influenced by paleo conditions within the drainage basins. For example, landscape-scale erosion rates, estimated by the concentration of ^{10}Be in the southeastern United States river catchments, revealed that soil erosion and sediment transport during the late 1800s, when most of the region was cleared of native forest and was used most intensively for agriculture, exceeded background erosion rates by more than hundredfold (Reusser et al., 2014).

To the best of our knowledge, studies of human influence on denudation processes in the Magdalena River basin during Precolumbian times and the nineteenth century are not available. Nevertheless, a study to estimate the amount of sediments produced under modern and pre-anthropocene conditions on a global scale (Syvitski et al., 2005) reveals that levels of sediment transport in the Magdalena are one order of magnitude higher in modern times than during pre-human conditions. The differences between pre-human and modern sediment load in South American rivers were more pronounced for the Magdalena River, with a difference ranging between 100 and 150 Mt y^{-1}. Thus, during pristine conditions, the Magdalena could have had an annual sediment load between 34 and 84 Mt y^{-1} during pre-human times compared to the current load of 184 Mt y^{-1} (Restrepo et al., 2015).

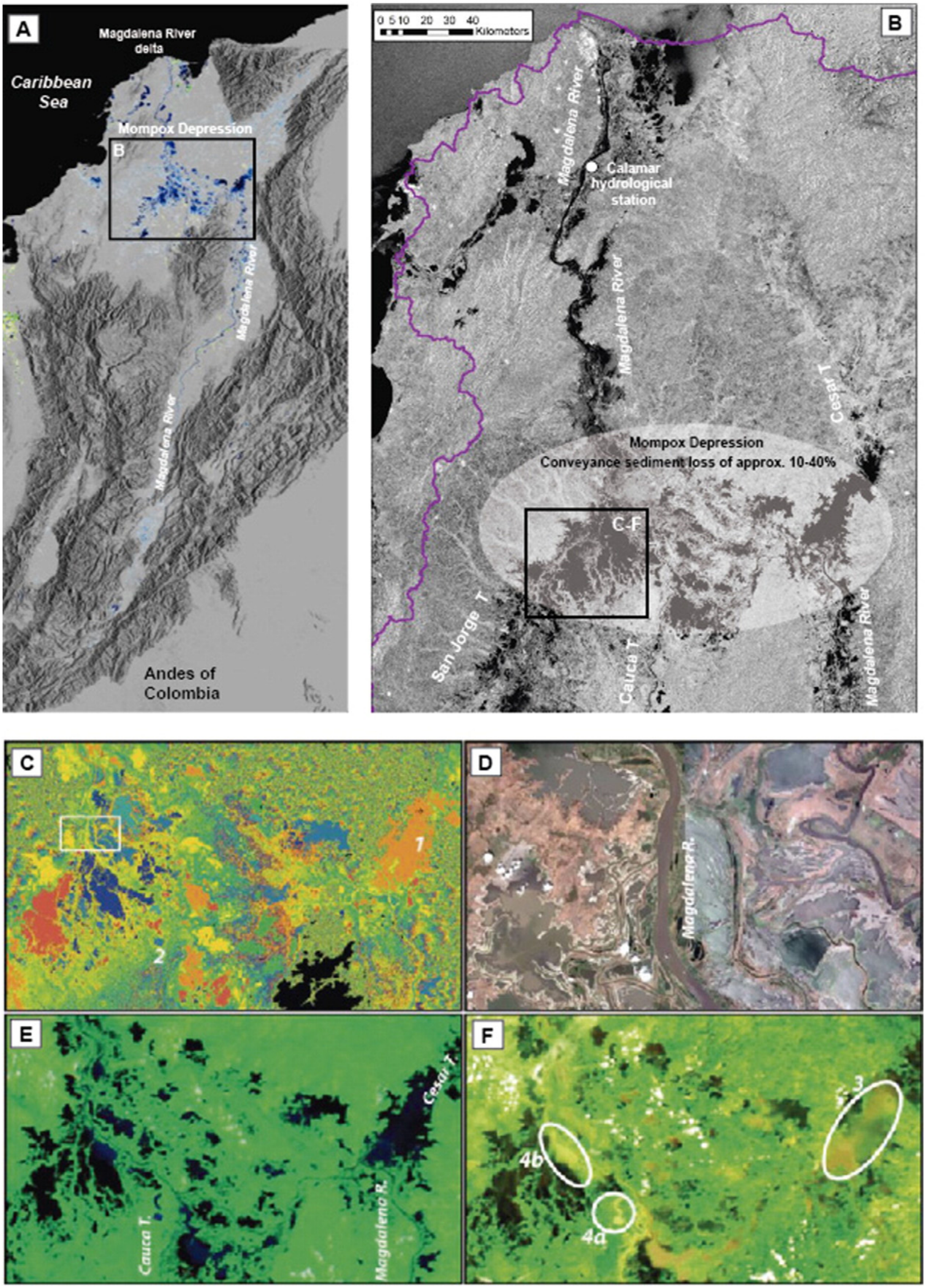
Contrary to the common understanding, which suggests that major land conversion took place since the 1970s, a study on historical patterns and drivers of landscape change in Colombia since 1500 (Etter et al., 2008) reveals that land conversion in the Andes started five centuries ago. The forest-transformed area in the Andean region rose from 15 M ha in 1500 to 42 M ha in 2000. During the last two centuries, the annual rate of forest clearance increased two orders of magnitude, from 4330 ha y^{-1} in 1800 to 171,190 ha y^{-1} in 2000. By the year 2000, 80% of the natural vegetation in the Andes was cleared, with 20% remaining as scattered remnants. An assumed value of 30% was cleared in pre-conquest agricultural landscapes (before 1500), increasing to 80% in 2000. Demographic impacts of colonization and the introduction of cattle were the major drivers of this change (Etter et al., 2008).

During the twentieth century, the population of Colombia increased ten fold and surpassed 40 million in 2000. Historically, most of the Colombian population (<65%) has been concentrated in the Andean and Caribbean regions of the Magdalena basin (Etter et al., 2006b). In addition, beef cattle industry, the largest contributor to the spatial footprint of agricultural land uses in Colombia at national and regional levels, has been a major driver of forest clearance. Biologically diverse tropical forests were transformed into ecologically simplified grasslands and cropping areas (Etter et al., 2006b), and cattle grazing is now the most widespread land use in the Andes of Colombia. The national herd size increased from 2 million cattle in 1920 to 11 million cattle in 2000; and this is still growing, as estimates indicate, to a size of 30 million cattle in 2005 (Etter et al., 2005). Currently, cattle dominate over 75% of the transformed landscapes in the Colombian Andes (Etter et al., 2008).

According to Geist and Lambin (2002), agricultural expansion is by far the leading land use change associated with nearly all deforestation cases in tropical regions (96%). Also, this study on proximate causes and underlying drivers of tropical deforestation indicates that permanent agriculture displays low geographical variation in tropical areas; that is, regional values for permanent cultivation in Latin America, for example, are close to the global value (i.e., 50%). In the Colombian Andes, the agricultural spatial footprint in 1500 was ~7.5 M ha, dropping to 6.5 M ha in 1600, increasing to 12 M ha in 1850, and then exponentially increasing to 33 M ha in 2000 (Etter et al., 2008). There is no doubt that agriculture has been the major driver of land conversion and forest clearance in the Andes.

A recent deforestation study spanning over 34 tropical countries that take into account the majority of the global land of humid tropical forests (Kim et al., 2015) indicates a 62% acceleration in net deforestation from the 1990s to the 2000s, contradicting a 25% reduction reported by FAO (2010). Analyzing the data presented in this study, net forest loss in Colombia peaked from 1990 to 2010, a period of exponential increase in forest clearance, from 170,000 ha y^{-1} between 1990 and 2000 to 499,000 ha y^{-1} during the 2005–2010 period (Fig. 5). After Brazil, Colombia has the highest deforestation rate of all Latin American countries (Kim et al., 2015).

Large systems can react rapidly to widespread human disturbances like deforestation in the basin. In the Araguia River, the main fluvial artery draining the Cerrado and the most important wetlands of central Brazil, the bedload transport increases 31% from the 1970s to 2000 from 6.7 Mt of sandy sediments to 8.8 Mt. The period of the fluvial system reaction after the anthropic perturbation was on the order of a decade, which could be expected to be a characteristic reaction time for small - or medium - sized basins (Latrubesse et al., 2009). Similarly, the Magdalena River drainage basin witnessed an increase in erosion rates of 34% from the 1980s to 2010, from 550 to 710 t km^{-2} y^{-1}. In general, the observed trends of land use and deforestation during the last decades indicate that increasing erosion rates in different large South American rivers, such as the Magdalena and Araguaia, are triggered by the regional GDP growth (Latrubesse et al., 2009; Restrepo et al., 2015). Overall, our results agree with the findings presented in major Amazon tributary basins (e.g., Tocantins, Araguaia, and Xingu), in which observed fluvial discharge increased despite little precipitation change in the last decades. For instance, all these basins have been converted from forests and Cerrado to pasture and agriculture (Costa et al., 2003; Coe et al., 2009, 2011, 2013; Panday et al., 2015).



4.2. Precipitation and climate change

Global on-land precipitation between 1951 and 2000 remained statistically unchanged [+1% ΔP] (Milliman et al., 2008), which is not dissimilar from the +2% ΔP calculated for the 20th century (Dai et al., 1997; Hulme et al., 1998). In South America, precipitation decreased in the northwestern whereas it increased throughout much of the southeastern of the continent, including the major Paraná basin (Milliman et al., 2008).

In the Andes of Colombia, results of trend detection in hydroclimatological signals demonstrate that the maximum trend magnitudes in rainfall are located in the Colombian Pacific region (increasing trends), whereas toward the rest of the country no clear spatial pattern could be recognized (Carmona and Poveda, 2011). Overall, Colombian monthly rainfall series exhibit no clear trend pattern given the similarity of percentages of rain gauges having increasing and decreasing trends. This finding confirms previous results with shorter time series reported by Mesa et al. (1997) and (Ochoa and Poveda, 2008) (Carmona and Poveda, 2011).

Based on the existence of long-term trends in 25- to 50-year long series of monthly rainfall in Colombia, Carmona and Poveda (2014) concluded that precipitation series are inconclusive owing to the mixing between increasing trends (41%, between 0.1 and 7.0 mm y^{-1}) and decreasing trends (44%, between 0.1 and 7.4 mm y^{-1}), with no clear cut geographical pattern, except for the increasing trend identified along the Pacific region.

Our results of precipitation trends in the Magdalena drainage basin are in close agreement with the findings of the mentioned studies on hydroclimatic variability and trends in Colombia (Carmona and Poveda, 2011, 2014). For instance, our precipitation series, spanning over 30 years, show a greater number of stations experiencing decreasing or no trends. Nevertheless, the central Andean region of Colombia, which hosts a large part of the Magdalena and Cauca drainage basins, have not experienced increasing rates of rainfall during the last three decades.

In terms of global climatic extremes of precipitation, precipitation changes witnessed a widespread and significant increase during the second half of the last century, but the changes are much less spatially coherent compared with temperature change. When averaged across the globe, the more extreme precipitation events in a year have been increasing. Also, there have been significant increases of up to 2 days per decade in the number of days in a year with heavy precipitation in the south-central United States and parts of South America. However, the northern Andes have experienced a decrease in heavy precipitation days (Alexander et al., 2006).

A more detailed analysis of climate variability in the Magdalena River basin shows increasing trends in high intensity precipitation events, mainly in the upper and middle sections of the basin. However, high sediment yield catchments such as the Sogamoso, Carare, Opón, and Suárez, have not experienced increasing trends in extreme rainfall events (TNC, 2016). Under the ongoing environmental deterioration of the Magdalena basin, expressed in high rates of deforestation and land cover change caused by agriculture and mining activities, increased manifestation of extreme climatic events will exacerbate human-induced erosion processes.

In the latest report of the ecosystem-based adaptation in the Magdalena basin by the Nature Conservancy and USAID-Colombia (Angarita, 2014), which assessed the fitness of different global climatic models in reproducing the climate variability in the Magdalena drainage basin, the MPI-ESM-MR model, developed by the Max Planck Institute for Meteorology, was the best predictor of the climatic conditions in the catchment. The precipitation has been predicted to be almost constant over the twenty-first century. For instance, rainfall projections in the upper and middle reaches of the Magdalena basin show increases of around 5% by 2060. The lower section of the basin shows no changes in rainfall during the next five decades. Thus, observed changes in sediment load during the last three decades are not the result of long-term climate change. Despite increased precipitation in few Magdalena tributaries, there is a remarkable increase in sediment transport that very likely results from direct anthropogenic disturbances after land cover change. In addition, scenarios of rainfall in the Magdalena basin do not appear to be the main triggers of future erosion rates.

4.3. Buffering the sediment load trend by floodplains and fluxes to the coastal zone

Floodplains of large rivers are still acting as sediment sinks (incomplete floodplains). In avulsive anabranching flood basins, avulsions are the natural processes by which flow diverts out of an established river channel into a new permanent course on the adjacent floodplain abandoning the former channel. This process can happen from the decadal scale to millennia and is the main mechanism that favors the widespread distribution and storage of fluvial sediments (Latrubesse, 2015). In addition, sediment trapping in floodplains can also buffer the sediment response in large river basins and, more particularly, can attenuate increases in sediment transport caused by human activity within the upstream catchment (Walling, 2006).

The lower reach of the Magdalena River, the Momposina (Mompox) depression wetlands (Fig. 9), is an avulsive anabranching flood basin with an area of 25,000 km^2 and at least 55 m thick of Holocene deposits (Smith, 1986; Latrubesse, 2015). Assuming average deposition rates of 3–4 mm y^{-1} (Smith, 1986; Plazas et al., 1988), 24–45 Mt y^{-1} of sediment is trapped on the floodplains of the Cesar distributary given a density of 1700–1800 kg m^{-3}. Approximately 17–72 Mt y^{-1} of sediment could similarly be trapped in the lower reaches of the Cauca tributary (Kettner et al., 2010).

Previous findings estimate that the foreland basin-trapping zone of the Momposina depression may store ca. 21 Mt y^{-1} of suspended sediment (Restrepo et al., 2006b), while an estimated 53% of the incoming bedload is deposited in the Magdalena foreland (Smith, 1986). The sediment storage in the active sedimentary basin of the lower Magdalena, between 21 and 72 Mt y^{-1}, is of the same magnitude as the sediment trapped into the Pantanal from the Brazilian highlands (ca. 8 Mt y^{-1} or near 50% of the total sediment entering the region) and sediments deposited in the middle Paraná floodplain in Argentina (17–60 Mt y^{-1}; Latrubbesse, 2015). Despite the effects of extensive alluvial storage in the Momposina depression (Fig. 9), deposition has not masked the trend of increasing sediment yields demonstrated in the upstream reaches.

The impacts of heavy sediment loads and freshwater discharges from the Magdalena River to the coastal zone have greatly contributed to the partial disappearance of coral formations and also to a considerable reduction in health of coastal ecosystems (Restrepo et al., 2006b, 2016). During the last decade, Magdalena streamflow and sediment

Fig. 9. Radar images (ALOS-PALSAR) of the Andes of Colombia (A) and the lower reaches of the Magdalena River (B), showing the Mompox depression floodplains and the approximate conveyance sediment loss (images from Quiñones, 2013). (C-E-F) Representations of the same area and a detailed view (D) of the Mompox tectonic depression (modified from Kettner et al., 2010). (C) Display of 1-m vertical intervals of space shuttle radar topography mission data obtained during an 11-day mission in February 2000 (i.e., during the dry season). Each color represents a 1-m interval; lakes bordering the Magdalena River as well as the Cesar (1) and the Cauca (2) tributaries are shown. (D) Digital Globe 2009 (Google Earth) detailed view (contents of the white box in C) of the lakes created as a result of the tectonic depression. (E) Near-infrared aqua moderate resolution imaging spectroradiometer (MODIS) satellite image during the La Niña event in 10 September 2008. Black shading indicates bodies of water surrounding the Magdalena River and the Cesar and Cauca tributaries. (F) True-color MODIS satellite images (same day and time as image in D) clearly showing the sediment plumes in various lakes close to the Magdalena River as well as to the Cesar (3) and the Cauca (4a, 4b) tributaries, indicating that suspended sediment spills into bordering lakes where most of it will be deposited.

load have increased by 24% and 33%, respectively; these fluvial fluxes to the coast coincide with associated declines in healthy coral cover and water quality (Restrepo et al., 2016). Overall, trends in sediment flux of the Magdalena to the coastal zone during the last three decades are in close agreement with the observed trends in human-induced upstream erosion.

5. Conclusions

This study is the first regional exercise estimating temporal trends of sediment load and comparing them to tendencies in land use change (e.g., deforestation) and rainfall for major drainage basins or subbasins in the northern Andes during the last decades.

Our results of sediment load trends 1980–2010 indicate that the extent of erosion within the Andes of Colombia has severely increased over the last 30 years. For example, the last decade has been a period of increased pulses in sediment transport as seen by the statistical significant trends in load (Fig. 4, Table 1). Overall, six subcatchments, representing 55% of the analyzed Magdalena basin area, have witnessed increasing trends in sediment load during the last decade (Table 1, Fig. 7B). Also, some major tributaries have experienced changes in their interannual mean sediment flux during the mid-1990s and 2005.

Further findings show that increasing trends in sediment load match quite well with the marked increase in forest clearance during 1980–2000 and 1990–2010 periods (Figs. 4 and 5). In contrast, such signs of increasing sediment fluxes should not be attributed to climate change and rainfall variability alone, as argued by many environmental authorities in Colombia. In fact, precipitation trends in the Magdalena drainage Colombia during the last three decades show no regional signs of increasing trends (Fig. 7). Evidently, sediment load and deforestation (and therefore, denudation) show signs of acceleration in the Magdalena subbasins. That argument can hardly be attributed to precipitation change alone because only 29% of the analyzed meteorological stations experienced increasing trends of rainfall during the last three decades.

As a whole, the Magdalena drainage basin has witnessed an increase in erosion rates of 33%, from 550 t km^{-2} y^{-1} before 2000 to 710 t km^{-2} y^{-1} for the 2000–2010 period. As highlighted by many studies focusing on global trends of sediment load, most large rivers show decreases in sediment load caused by the large amount of sediment captured by reservoirs. In contrast, the Magdalena may be one of the few large world rivers experiencing such dramatic increases in sediment load during the last decade.

If our working hypothesis was correct, i.e., that humans are the main cause of erosion, this finding would have important consequences toward mitigation and adaptation. Thus, the institutional policies should also consider land use change owing to human activities in addition to climate change. The latter depends on international policies, while the first is easier to address at local and regional scales. In fact, soil deterioration and increasing trends in erosion in the Andes of Colombia require capacity building in environmental governance in addition to climate change mitigation policies.

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