Applied Geography 84 (2017) 23–41

Contents lists available at ScienceDirect

Applied Geography

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

Using geomorphic understanding of catchment-scale process relationships to support the management of river futures: Macaé Basin, Brazil

Mônica Marçal [a], [*], Gary Brierley [b], Raphael Lima [a]

[a] Department of Geography, Federal University of Rio de Janeiro, Av. Athos da Silveira Ramos 274, CCMN, Bloco I, sala I-11, Ilha do Fundão, Code 21941-909, Rio de Janeiro, Brazil
[b] School of Environment, The University of Auckland, 10Symonds Street, Auckland City, 1142, New Zealand

ARTICLE INFO

Article history:
Received 1 June 2016
Received in revised form
17 April 2017
Accepted 24 April 2017

Keywords:
River diversity
Landscape evolution
Channel adjustment
Land use
Landscape connectivity
Future scenarios

ABSTRACT

Impacts of colonial settlement upon catchment-scale fluvial geomorphic relationships are reported for a relatively small catchment in northern Rio de Janeiro State, Brazil. Structural controls have induced the type and patterns of rivers in Macaé Basin. Fault block activity has resulted in steep, incised headwater streams above the escarpment. Confined and partly confined rivers in mid-catchment reaches of the rounded foothills have limited potential for geomorphic adjustment. Fluvial, estuarine and marine sediments in low relief landscapes of the lowland plain have supported the development of meandering sand bed rivers, with many cut-and-fill (intact valley fill) deposits in tributary systems. Indigenous people exerted relatively minor, localized impacts upon the geomorphology of this river system. Portuguese settlement since the sixteenth century brought about clearance of much of the Atlantic Forest of lowland reaches, and subsequent establishment of sugar cane and coffee plantations. Lowland reaches were channelized from the 1940s-1980s for flood protection and to support the expansion of pastoral agriculture. Significant adjustments have occurred to these geomorphologically sensitive reaches. In contrast, although rivers in the rounded foothills were impacted by forest clearance, the limited availability of sediment stores along these reaches has limited the extent of geomorphic responses to human disturbance. Relatively inaccessible upland reaches were even less impacted, and are now major conservation areas. Building on principles of the River Styles framework, catchment-scale evolutionary trajectories of rivers in the Macaé Basin are assessed based on analysis of patterns of river types, their capacity for adjustment and connectivity relationships, and responses to disturbance events. From this, three future scenarios of prospective evolutionary traits are developed: a 'steady as she goes' scenario, an optimistic (effective, proactive management) scenario, and a 'doomsday' scenario.

1. Introduction

Adaptive and proactive approaches to river management are informed by understandings of past geomorphic adjustment, but recognize that future traits are likely to be different, in ways that are not entirely knowable (e.g. Brierley & Fryirs, 2016). Given this situation, concerted efforts have been made to use evolutionary trajectories to inform scenarios of prospective river futures (e.g. Baker et al., 2004; Surian, Ziliani, Comiti, Lenzi, & Mao, 2009). Proactive approaches to river management apply catchment-scale management plans in efforts to avoid over-reactions to disturbance events framed as 'emergency management responses'. Holding steady in efforts to achieve ongoing (long term) management goals and appropriate prioritization of management activities to meet these goals are critical steps in the design and implementation of strategic management practices that seek to meet the ecological needs of a river while addressing concerns for societal wellbeing (see Dufour & Piégay, 2009). Such practices are likely to be most effective when they 'work with' the inherent diversity of

---

* Corresponding author.
E-mail addresses: monicamarcal@ufrj.br (M. Marçal), g.brierley@auckland.ac.nz (G. Brierley), raphaelgeo85@gmail.com (R. Lima).

http://dx.doi.org/10.1016/j.apgeog.2017.04.008
0143-6228/

rivers within a catchment, their behavioural regimes, patterns and longitudinal (tributary-trunk stream) connectivity, and their evolutionary traits (e.g. Beechie et al., 2010; Brierley & Fryirs, 2005, 2009; Downs, Dusterhoff, & Sears, 2013; O'Brien et al., 2017; Wohl, Lane, & Wilcox, 2015). This allows careful consideration of prospective 'treatment responses' (Schmidt, Webb, Valdez, Marzolf, & Stevens, 1998), assessing the nature and consequences of altered conditions in one reach upon adjacent or more distant reaches in efforts to maximize benefits of management interventions while minimizing their negative off-site impacts (see Fryirs, Spink, & Brierley, 2009; Jain & Tandon, 2010). In this study, the River Styles framework (Brierley & Fryirs, 2005) is used to apply these principles to scope geomorphically-informed river futures in the Macaé Basin, located 200 km north-east of Rio de Janeiro in Brazil.

To date, there are many parts of the world in which limited use has been made of catchment-scale geomorphic understandings to guide river management applications (cf., Downs & Gregory, 2004; Hillman & Brierley, 2005). This is the case in Brazil, where despite long recognition of the impacts of colonial settlement on landscapes and increasing socio-economic pressures for development to meet the needs of a growing population, formal literature documenting catchment-scale responses to land use change are severely lacking. How sensitive to disturbance are rivers in Brazil? How much change has taken place since Portuguese settlement? What types and rates of off-site impact have occurred? What are the prospects for landscape recovery (*sensu* Fryirs & Brierley, 2016)? This paper documents an initial attempt to address these issues for a relatively small catchment near Rio de Janeiro. Building upon various background studies, river responses to impacts of 400 years of colonial settlement are used to appraise the evolutionary trajectory of the Macaé River, providing guidance on realistically achievable prospects in the geomorphologically-informed management of river futures in this basin.

2. Macaé Catchment – regional setting

2.1. Location

The 140 km long Macaé River emerges from a spring in the Serra Macaé de Cima Mountains (southern side of the Serra do Mar Mountains, maximum elevation 1600 m) in Nova Friburgo Municipality in the east-central sector of Rio de Janeiro state (Fig. 1). This 7th order catchment (1:50,000 scale) drains a catchment area of approximately 1800 km^2, has a drainage density of 1.983 km/km^2 and has five main tributaries: Bonito (89 km^2), Sana (109 km^2), Ouriço (63 km^2), D'Antas (57 km^2), and São Pedro (484 km^2). The river discharges into the Atlantic Ocean near Macaé City, one of the leading agro-industrial centers in the region.

2.2. Geology, geomorphology and valley setting

Brazil lies in the centre of the South American tectonic plate. The topography of the Macaé Basin is a relatively typical product of a rift margin continental landscape setting. Precambrian and subsequent Mesozoic and Cenozoic tectonic events formed the Ribeira fold belt Mountains (the Serra do Mar), which cross Rio de Janeiro State in the form of a large and extensive escarpment parallel to the coastline (Heilbron et al., 2004). Regional faults are aligned with the strong NNE-SSW and NE-SW structural trend (see Fig. 1A). Neotectonic activity is prominent, associated with the reactivation of faults and pre-existing lines of weakness (e.g. Hasui, 1990). Contemporary drainage networks, and their associated patterns of river types, reflect the influence of structural blocks, tectonic extension and fault activity upon the distribution of landscape units, the shape of longitudinal profiles, and patterns of valley width. For example, Sana, Ouriço and D'Antas tributaries in mid-catchment of the Macaé Basin are clearly aligned along NE-SW structures (see Fig. 1). The upper and middle catchment is dominated by garnet-biotite gneisses with widespread granite pockets (Fig. 1A). The post-tectonic Sana Granite in mid-catchment generates steep, dissected relief (Almeida, 2012).

There are three morphostructural regions in the Macaé Catchment, namely plateau and escarpment landscapes of the "Serra do Mar" mountains region, the hills and eastern hills region (rounded foothills), and the lowland plain that is made up of fluvial-marine floodplains and adjacent terraces (Fig. 2A). Higher regions are not necessarily the steeper areas.

The *Mountain escarpment* landscape unit makes up most of the Macaé Catchment (Fig. 2). Areas between 860 and 1820 m range in slope from 8 to 45%. Narrow and steep headwater streams are deeply entrenched within V-shaped valleys, many of which are aligned along fault lines. Vegetation cover is dense. Lower parts of this landscape unit, in mid-catchment areas between 860 and 350 m, have an average slope of 45–75%, with steeper and longer hillslopes than upstream. Sana granite and gneiss outcrops are common along steep, confined valleys, with dense vegetation cover.

Much of the mid-lower catchment lies within a *Rounded foothills* landscape unit. This unit lies between 350 and 20 m, with typical slope ranging from 0 to 8% (Fig. 2). It is prominent in the D'Antas and São Pedro subcatchments. Bedrock outcrops occur recurrently along partly confined valley settings (Fryirs, Wheaton, & Brierley, 2016). Tree cover is presently restricted to patches on some hills.

Sub-horizontal and smooth, low gradients of the *Lowland plain* landscape unit have generated unconfined valley settings at elevations <20 m (Fig. 2). The contemporary channel and floodplain are inset within sandy Quaternary deposits, with terraces at valley margins. OSL dating of three terraces along upper-middle and lower river courses yielded age estimates ranging from 8000 to 35,000 years (Marçal, Ramos, Sessa, & Fevrier, 2015).

2.3. Contemporary climatic conditions and the discharge regime

Macaé Catchment has a typical tropical maritime climate, locally influenced by physical factors such as elevation, topography and proximity to the Atlantic Ocean. The average annual temperature is above 18 °C. The high surface roughness of the mountainous relief promotes orographic rainfall, with annual totals ranging from 1200–2800 mm (Fig. 1B). The region is characterized by high interannual and seasonal variability, with relatively dry winters, but rainfall may be very intense in summer and autumn (Fig. 3A).

The lower Macaé River has a well-defined discharge peak (around 80 m^{3}s^{-1}) during the rainiest months (December, January and March), with a mean flow in dry months (June and July) of around 2.5 m^{3}s^{-1}. Since 1950, major flood events have occurred in 1952, 1965, 1970, 1981 and 1994 (Fig. 3B). These data indicate interannual clustering of significant flood events. Analysis of historical data (1968–2009) by Villas Boas and Marçal (2013) showed that rainfall totals >60 mm in 24 h bring about notable channel adjustments. Marked increases in discharge for events with a recurrence interval beyond 20 years reflect the high coefficient of variability of discharge (CV) in the catchment (Fig. 3C; CV = 3.49).

2.4. Historical land use and vegetation cover

Indian inhabitants of the Puri family (Goitacá) previously occupied the plains and beach ridges of the northern Rio de Janeiro region. Sixteenth century reports by André Thevet and Jean de Lery mention the inaccessibility of complex and quite vegetated plains. In his book 'Seven Captains Script', Sousa (1938) reported availability of fresh water in the Macaé area (Soffiati, 2010). As a result of

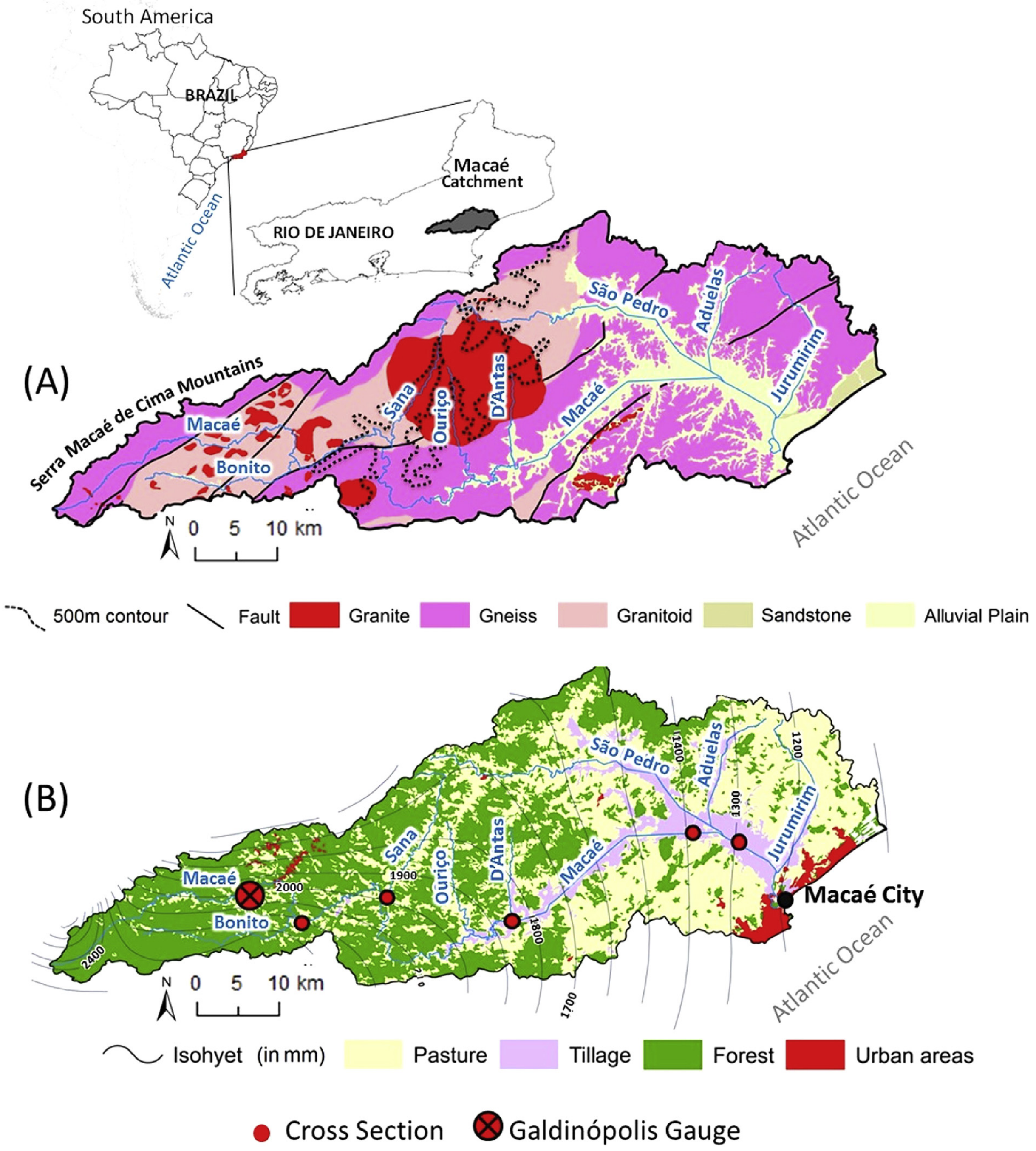

Fig. 1. Location map of Macaé Catchment. (A) Simplified geology map with 500 m contours indicated. (B) Land use map, with annual isohyets indicated.

early reports of a village inhabited by the Mamluks who lived upon abundant catfish, the river was initially known as Bagres River (Soffiati, 2010). Available evidence indicates the good ecological condition of the river at this time, with much of the Macaé catchment covered by Atlantic rainforest.

Colonial settlement of Macaé Catchment occurred from the coast to inland areas. Transitions to extensive monocultural production of sugarcane occurred in the seventeenth and eighteenth century (Table 1). An increase in sugar production led the imperial government to build the Macaé-Campos channel between 1845 and 1861 to assist trade with Rio de Janeiro city. The channel connected three major basins in the São Tomé region: Paraiba do Sul, Lagoa Feia and Macaé. Although its construction was a significant engineering achievement, its importance declined just three years after its opening following development of the Macaé-Campos railroad (Soffiati, 2010).

Channel straightening and channel enlargement of the lowland trunk stream of the Macaé River and primary tributaries (São Pedro and D'Antas Rivers) took place from the 1940s to the 1980s (Table 1). The now defunct Sanitation and National Work Department (DNOS) undertook these actions to reduce flooding and the incidence of malaria and other mosquito-borne spread diseases, while expanding areas for pastoral agriculture. This greatly diminished the area of wetlands, swamps and floodplain ponds.

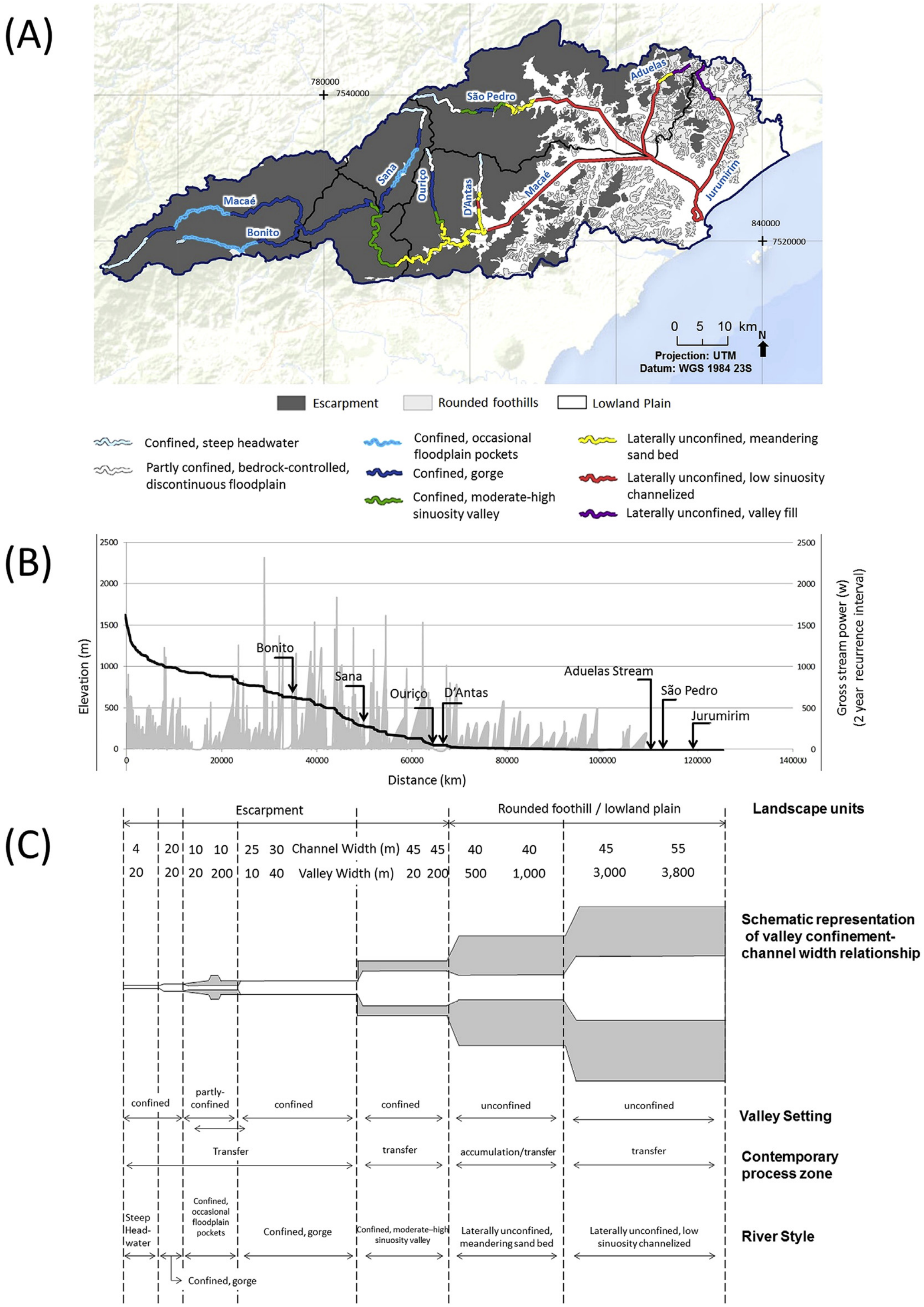

Fig. 2. Downstream patterns of rivers in the Macaé Catchment. (A) Distribution of landscape units and River Styles. (B) Longitudinal profile and downstream trend in total stream power for the 1 in 2 year flood. (C) Downstream trend in valley width and relation to geomorphic process zones along the Macaé River. Note that Fig. 2B and C are aligned allowing easy comparison of downstream controls upon River Styles.

Riparian forests were decimated at this time. Officially, there are four sand extraction points in the lower Macaé Catchment (Assumpção & Marçal, 2012).

Given its steep relief and dense tropical forest cover, upland areas of Macaé catchment are relatively inaccessible, and the forest cover is protected to a much greater degree than elsewhere (only 20% of the Atlantic Forest biome in Brazil retains an intact forest cover; see Brasil, 2006) (see Fig. 1B; Table 1). Most soils in this area are not conducive to agricultural production. Two important sustainable use conservation units were established in 2001: the “APA Macaé de Cima” within Nova Friburgo municipality (350 km^2) and the “APA Sana” in Macaé municipality (118 km^2).

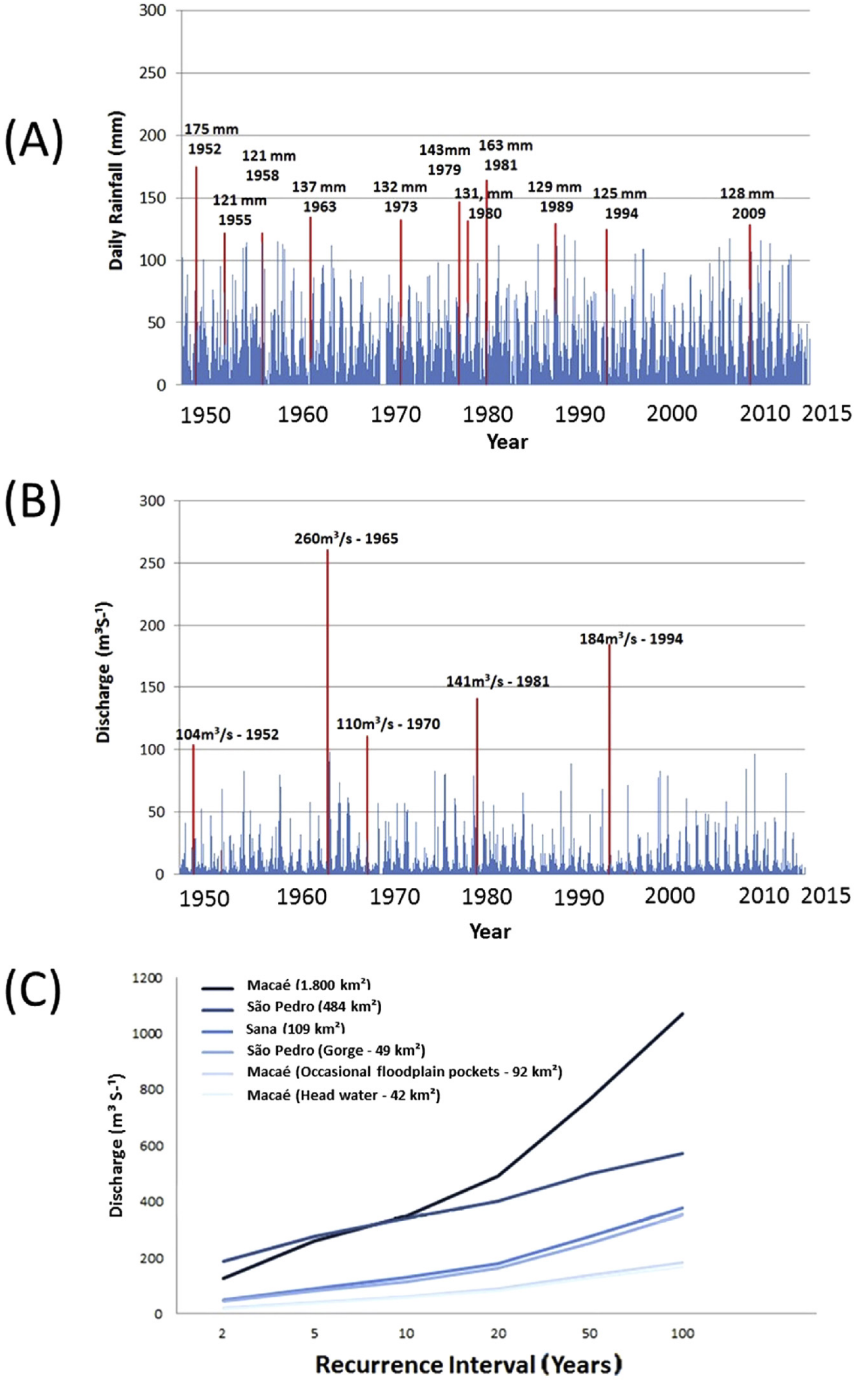

Fig. 3. Rainfall/Discharge attributes and the recent flood history of the Macaé River. (A) Rainfall record at Galdinópolis gauge (1950–2015). (B) Hydrograph for Galdinópolis gauge (1950–2015). Labelled discharge events exceed 100 m3s-1. (C) Flood recurrence intervals at 6 sites across the Macaé Catchment (cross-sections are located on Fig. 1B; numbers in brackets refer to catchment areas at the gauge sites). Source: ANA (National Water Agency). Note the non-linear relationship between rainfall and discharge.

The arrival of the oil industry in the Campos sedimentary basin in the 1970s provided a significant economic boost to the northern region of Rio de Janeiro. The urban population has increased three-fold in the last 30 years, inducing significant additional demand for water resources.

Today, about 65% of the catchment area is occupied by forest and 35% by agriculture and other uses (see Fig. 1B). Urban areas make up less than 1% of the total area (Villas Boas & Marçal, 2013).

3. Methods

Assessment of the character, behaviour and evolution of rivers in Macaé Catchment followed procedures outlined within the River Styles Framework (Brierley & Fryirs, 2000, 2005), associated publications on reach-scale geomorphic sensitivity (Reid & Brierley, 2015), catchment-scale connectivity (sediment flux) relationships (Fryirs & Brierley, 2001), and analyses of moving targets to evaluate prospective river futures (Brierley & Fryirs, 2016). This study also

Table 1
Timeline showing the influence of human activities in each landscape unit in Macaé Catchment.

Landscape Unit	Century			
	XVI-XVIII	XIX	XX	XXI
Escarpment	–	Subsistence agriculture	Dam São Pedro (1926) Road access (1960) Trans-basin transfer São Pedro (1970)	Conservation Park (2001) APA Macaé de Cima Conservation Park (2001) APA Sana Tourism
Rounded foothills	–	Forest clearance	Extensive livestock	Tourism
Lowland plain	Brazil wood Sugar cane	Forest clearance Sugar cane Coffee Extensive livestock Macaé-Campos channel (1845) Road access (1900)	Extensive livestock Channelization Macaé (1964)	Extensive livestock

builds upon historical work by Veloso, Rangel Filho, and Lima (1991) and extensive geomorphological investigations in the Macaé Catchment (Assumpção & Marçal, 2012; Lima & Marçal, 2014; Marçal, 2013; Marçal & Luz, 2003; Marçal et al., 2015; Souza & Marçal, 2015; Villas Boas & Marçal, 2013).

A multitemporal series of aerial photos and cross-section topographic surveys has been used to analyze reach scale geomorphic adjustments. Aerial photographs from 1968 (USAF), 2000 (AMPLA) and 2014 (Google Earth) (at scales of 1:50,000, 1:10,000 and 1:5000 respectively) are used alongside hydrological data from 1950 to 2015 (ANA- National Water Agency) to interpret channel adjustments and changes to longitudinal and lateral connectivity. Older maps (1815, scale 1:100,000) were used to qualitatively assess the channel morphology, but were not included in the quantitative analysis because of the potential for significant error. GIS analysis entailed orthorectification and georeferencing of each image, digitization of channel margins, and measurement of planform attributes using ArcGis. Orthorectification was performed using ENVI 5. The maps and aerial photographs were coregistered using 1:5000 maps as a base layer; for each aerial photo, a series of ground-control points was used. The root mean square errors (RMSE) derived from orthorectification were estimated to be lower than the pixel size of the images. Following well-established and well-documented procedures, maximum error for air photographs is estimated to be 6 m (cf., Bollati, Pellegrini, Rinaldi, Duci, & Pelfini, 2014). Cross-section surveys have been carried out since October 2007, with intervals of 3–5 months between each measurement.

4. Results

4.1. River diversity, behaviour and adjustment (sensitivity)

Eight river styles were identified in the Macaé Catchment (see Figs. 2, 4 and 5, Tables 2 and 3).

River diversity is most pronounced in the mountain escarpment area, where local variability in slope, valley confinement and valley sinuosity induce downstream transitions in river character and behaviour (Fig. 2A and C). These confined high energy systems have significant erosive potential (Fig. 2B). However, geomorphic adjustments are localized, typically restricted to incremental bedrock erosion, local reworking of coarse boulders (up to 1.5 m wide) and occasional flushing of sand sheets (Tables 2 and 3). The dense riparian vegetation cover accentuates flow resistance in many reaches.

The **Confined, steep headwater River Style** occurs predominantly at elevations above 200 m (Fig. 2A). These bedrock and boulder reaches have slope- and confinement-induced assemblages of 'forced' geomorphic units such as waterfalls, step-pool sequences, cascades and riffle-pool features (Figs. 4 and 5). These reaches have limited capacity for channel adjustment and little potential for sediment storage. Average valley floor slope is around 6% (Tables 2 and 3). Adjacent reaches where the valley locally widens, and sediments can be stored along the valley floor, make up the **Confined, occasional floodplain pockets River Style** (Figs. 2A, 4 and 5). Floodplain pockets are often associated with tributary confluence zones or shifts in valley alignment. Valley floor slopes are slightly lower than upstream. Moving downstream, riffle-pool sequences are increasingly evident. Bedload sand deposits are locally prominent, especially in areas where the valley is wider and flow divides around islands (Fig. 4, Tables 2 and 3). Occasional terraces extend up to 14 m above the contemporary channel bed (Marçal et al., 2015). Riparian vegetation cover is less pronounced than in upstream reaches.

Two forms of gorge are evident within the lower parts of the mountain escarpment zone of the Macaé Catchment. The **Confined, gorge River Style** has a deeply-incised V-shaped valley with a topographic extent exceeding 400 m (Figs. 2A, 4 and 5). The bedrock channel occupies the entire valley floor, with forced geomorphic units such as pool-riffle sequences, rapids and occasional steps or shallow waterfalls (Fig. 4, Tables 2 and 3). Reaches have dense forest and riparian vegetation cover. Gorges cut within Sana granite blocks in mid-catchment are transitional in character between confined and partly confined valleys (see below). **The Confined, moderate-high sinuosity valley River Style** is located within narrow, asymmetrical and structurally-controlled sinuous valleys (Figs. 2A, 4 and 5). These reaches have deeper pools in the bends relative to the low sinuosity gorges (Fig. 4, Tables 2 and 3).

In some tributaries, such as D'Antas and Ouriço catchments, gorges are not found downstream of Steep headwaters and Confined valleys with occasional floodplain pockets. Rather, the lower part of the mountain escarpment landscape unit is characterized by reaches of the **Partly confined, bedrock controlled, discontinuous floodplain River Style** (Figs. 2A, 4 and 5). In these reaches the relatively narrow valley width and the sandy substrate conditions result in channel and floodplain geomorphic units that are prone to reworking during extreme flow events (Tables 2 and 3; see Ferguson & Brierley, 1999; Fryirs & Brierley, 2010). The valley floor gradient of this river style averages 0.8%, notably lower than upstream areas (for which average gradient is 1.2%; cf., Jain, Fryirs, & Brirley, 2008). Occasional waterfalls, steps and rapids are found alongside floodplain geomorphic units in these reaches.

Given controls exerted by foliated bedrock and associated faultlines, tributaries in the eastern part of the catchment drain from much lower relief landscapes of rounded foothills in their headwaters, rather than the mountain escarpment landscape unit (Fig. 1). Granite lithologies and less pronounced relief support the development of relatively wide valley floors, with headwater reaches characterized by the **Laterally unconfined, valley fill River**

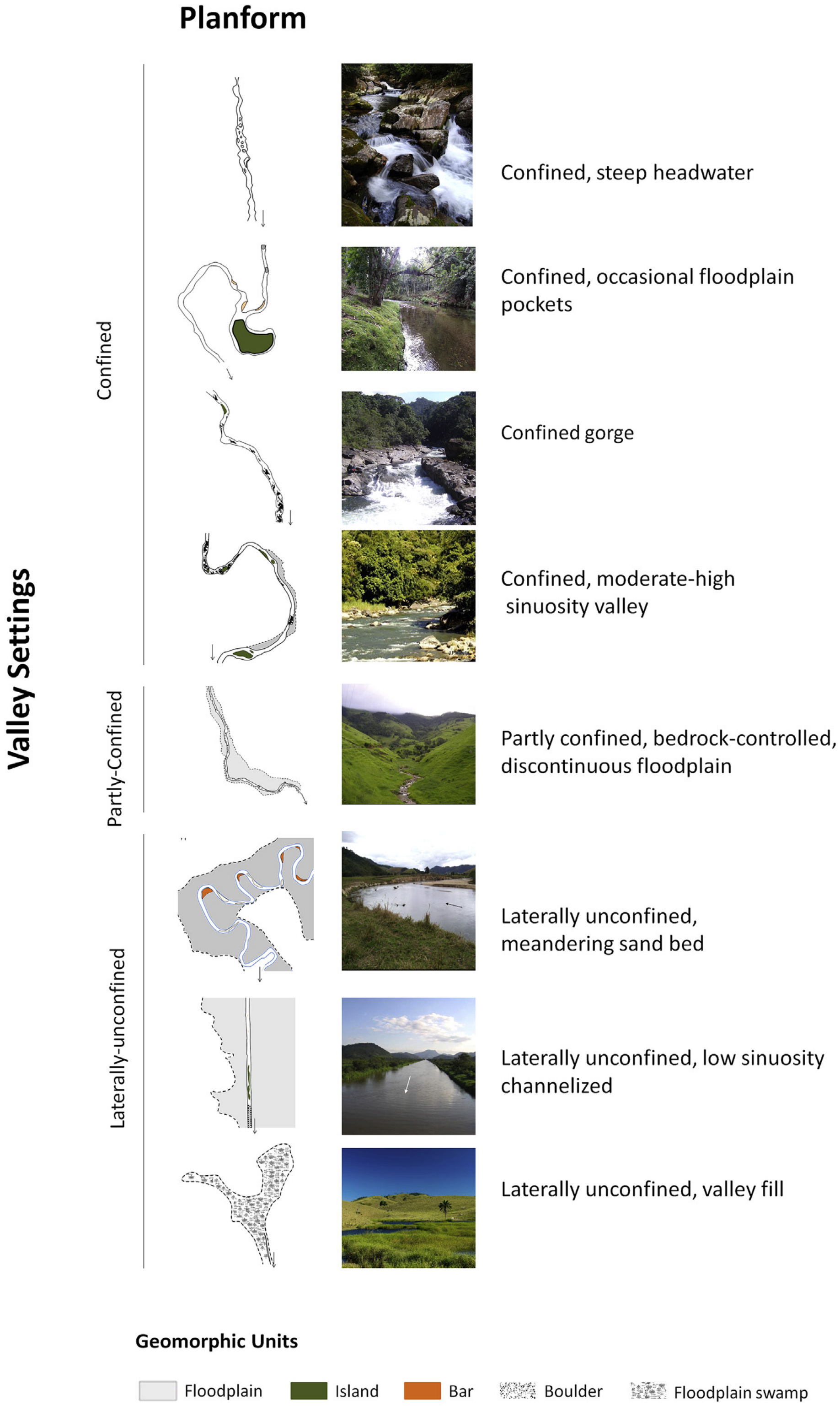

Fig. 4. Planform diagram and field photographs for the eight River Styles in Macaé Catchment. Images are shown in an approximate downstream sequence, alongside valley-setting.

Style (Fig. 2A and C). These cut-and-fill landscapes have discontinuous watercourses. Relatively flat and featureless swamps accumulate suspended load sediments as flows are dispersed across the valley floor (Fig. 4, Tables 2 and 3). Importantly, the organic-rich sediments of the valley fill deposits support the maintenance of base flow conditions to downstream reaches during dry periods. Intact valley fills are also prominent in many small tributary systems that drain directly to the lowland plain.

While erosion is the dominant process in upstream reaches in the western parts of the catchment, sediment storage is much more prominent in the transfer zone of the rounded foothills landscape unit. This reflects declining valley floor slope and notable increases

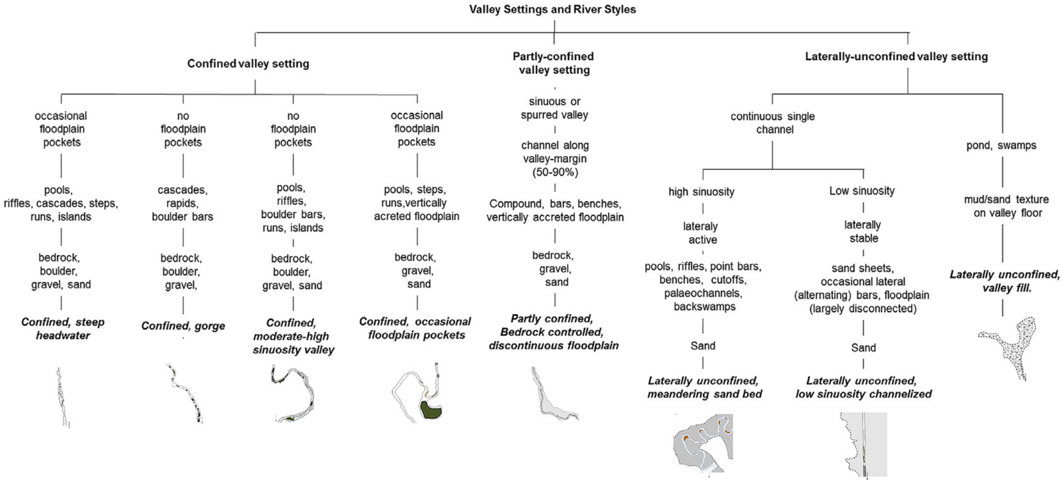

Fig. 5. River Styles tree for Macaé Catchment. Each River Style is identified based on its valley setting, planform, assemblage of geomorphic units and bed material texture.

in valley width (Fig. 2C). As these areas can support agricultural development, human activities are much more prominent and forest clearance is near complete in areas that today are characterized by pasturelands. This zone is characterized by the **Partly confined, bedrock controlled, discontinuous floodplain River Style** (described above) and the **Laterally unconfined, meandering sand bed River Style** (Fig. 2A). Moving downstream from the rounded foothills to the lowland plain, the slope of the meandering sand bed river decreases from 2.5 to less than 1% and sinuosity increases from 1.6 to 2.3. Given the low gradient, sandy substrate and space for lateral adjustment, tortuous meanders are extremely active, with numerous cut-off channels (abandoned bends, meander loops and avulsed sections of former channel courses) on the floodplain (Fig. 4, Tables 2 and 3).

Human activities have modified the former Meandering sand bed River Style and estuarine reaches in the lower part of the Macaé Catchment creating a **Laterally unconfined, low sinuosity channelized River Style**. Channels are enlarged, symmetrical (trapezoidal) and straight, conveying significant volumes of sand to the estuary (Figs. 2A and 4, Tables 2 and 3). The channel is largely laterally disconnected from its floodplain. Sediment storage is limited by significant sand extraction and dredging. Three islands have formed at the river mouth near the Atlantic Ocean.

4.2. Downstream patterns of river styles and their controls

Several bedrock steps are evident in the escarpment zone of the longitudinal profile of the trunk stream of the Macaé River (see Fig. 2B). Large parts of the headwaters of the trunk stream and Bonito subcatchment drain from the mountain escarpment landscape unit, with a downstream sequence from steep headwaters through confined valleys with occasional floodplain pockets through to low sinuosity gorges (sequence 1 on Fig. 6). Sediment storage is limited in these confined, highly connected landscapes.

A different downstream sequence of river types is evident in tributaries that drain from the mountain escarpment zone in mid catchment (Sana, Ouriço, D'Antas and São Pedro Rivers; sequences 2 and 3 on Fig. 6). In these instances, the steep headwaters are transitional to partly confined valleys and then gorges, with meandering sand bed reaches beyond (Fig. 7A). While the Ouriço River has a convex longitudinal profile, the trunk stream of the adjacent D'Antas subcatchment has a typical concave-upwards profile (see Fig. 7C). Flow has sufficient energy to transfer available sediment through relatively steep (1.6%), confined valleys along the Ouriço River, and the channel is characterized by stable vegetated islands and fixed bars. In contrast, the D'Antas River has a shallower gradient (0.06%), a marked downstream decrease in bed material size (from gravel (40 mm)) to sand deposits (0.5 mm), and considerable capacity for channel adjustment. Base levels set by the Macaé River promote sediment accumulation, inducing a sinuous channel thread that is subject to significant migration (80 m over 46 years). Oversupply of sediment has resulted in the formation of a sediment slug that acts as a barrier to sediment conveyance (*sensu* Fryirs, Brierley, Preston, & Kasai, 2007) in the laterally unconfined valleys at the downstream end of this tributary (Fig. 7B).

Tributaries that join the trunk stream along the lowland plain (Aduelas and Jurumirim Streams) have intact valley fills in their low relief headwater settings (sequence 4 on Fig. 6).

Moving downstream, all rivers that drain from the escarpment zone are transitional to partly confined valleys with recurrent (though discontinuous) floodplains in the rounded foothills landscape unit. These reaches, in turn, are transitional to the continuous floodplains and terraces of the lowland plain, where sediment storage is dominant.

4.3. History of channel adjustments in Macaé Catchment

Essentially, geomorphic adjustments over the last 400 years of Portuguese settlement have been restricted to the partly confined valleys, intact valley fills and meandering reaches of the lowland plain and adjacent sections of the rounded foothills landscape unit (Table 2). In contrast, imposed (bedrock-controlled) rivers have very limited capacity for geomorphic adjustment in the densely vegetated upper and middle Macaé catchment areas (Figs. 1 and 2).

Localized reworking of floodplains by high magnitude floods has occurred along partly confined valleys in mid-catchment reaches of the upper Sana, Ouriço, D'Antas and São Pedro tributary subcatchments. Research by Villas Boas and Marçal (2013); Marçal (2013) indicates that flushing of sand sheet deposits and reworking of floodplain materials occurs during moderate magnitude events (>60 m^3s^{-1}; 2 year recurrence interval). Relatively steep slopes of the valley floor, along with sufficient catchment area to generate significant discharge, results in pronounced peaks in stream power along these reaches (see Fig. 2B).

In their intact state, valley fills of 'cut and fill' rivers gradually accumulate fine-grained suspended load deposits. However, these rivers are prone to incision if intrinsic or extrinsic threshold conditions are breached (Schumm, Harvey, & Watson, 1984, p. 200). In

Table 2
Attributes of river styles in Macaé Catchment.

River Styles	Valley setting/ Landscape Unit	Elevation (m)	Average channel width (m)	River Character			River Behaviour	Ease of adjustment (Geomorphic sensitivity)
				Channel planform	Geomorphic units	Bed material		
Confined, steep headwater	Confined/ Escarpment	1580–970	4	n.a.	No floodplain, bedrock steps, riffles and pools, waterfalls, runs and cascades.	Boulder-bedrock-gravel-sand	Heterogeneous mix of imposed (forced) geomorphic units. Flushes sediment through a confined valley. The bedrock channel limits the capacity for channel adjustment in lateral, vertical and wholesale dimensions.	Low – an imposed (forced) river morphology.
Confined, occasional floodplain pockets	Confined/ Escarpment	970–813	10	n.a.	Floodplain pockets, terrace remnants, bedrock outcrops, sand sheets, pool-riffle sequences, occasional islands	Bedrock-sand	Stable channel. Bedrock induced pool-riffle sequences activated during high flows. Local island development in wider sections of channel. Floodplain pockets form and are reworked at high flow stages. Local downstream propagation of sand sheets along narrow valleys.	Low – bedrock channels limit geomorphic adjustments other than conveyance of sand sheets. Localized lateral adjustment of floodplain pockets may occur during high magnitude events.
Confined, gorge	Confined/ Escarpment	813–236	25	n.a.	No floodplain, bedrock steps, waterfalls, riffles and pools, cascades	Boulder-bedrock	Steep, bedrock controlled river with an alternating sequence of bedrock steps and pool–riffle–cascade sequences. Efficiently flushes all available sediments. Stable channel cannot adjust within the confined valley setting.	Low – an imposed (forced) river morphology within a relatively straight valley.
Confined, moderate –high sinuosity	Confined/ Escarpment	236–45	45	n.a.	Bedrock steps, riffles and pools (deep in bends), islands, bars, occasional floodplain pockets	Boulder-bedrock-sand	Steep, bedrock controlled river with an alternating sequence of bedrock steps and pool–riffle–cascade sequences. Efficiently flushes most sediments. Boulders act as substrate core for sandy and vegetated islands. Stable channel cannot adjust within the confined valley setting, other than local lateral reworking of floodplain pockets.	Low – an imposed (forced) river morphology within a sinuous valley.
Partly confined, bedrock controlled, discontinuous floodplain	Partly-confined/ Rounded Foothill and base of escarpment	510–320	40	Single, sinuous channel, prone to lateral adjustment.	Cascades, local steps and waterfalls, pool-riffle sequences, recurrent (alternating) floodplain pockets	Bedrock-boulders-sand	Instream features are formed and reworked during moderate-high magnitude flow. Local adjustment of floodplains via accretion and reworking during floods. Bends are prone to lateral adjustment via migration or translation.	Low-moderate – able to adjust channel dimensions and adjust channel position on the valley floor.
Laterally unconfined, meandering sand bed	Partly-confined/ Rounded Foothill/ Lowland	20–0	40	Single sinuous channel, laterally unstable	Point bars, pool-riffle sequences, runs, continuous floodplain with wetlands, backswamps, oxbow lakes and palaeochannels, terraces, occasional longitudinal bars	Sand	Point bars form and concave banks erode at moderate-bankfull stage. Bankfull flows move sediment from bar to bar. Channel is prone to lateral migration and avulsion, creating oxbow lakes and abandoned channels (palaeochannels) on the floodplain.	High – channel readily adjusts its size and position with recurrent reworking (aided by sand substrate conditions)
Laterally unconfined, valley fill	Laterally unconfined/ Rounded Foothill/ base of escarpment/ lowland plain	20–0	–	No channel	Continuous, intact swamp	Mud-sand	Intact swamps are formed from dissipation of flow and sediment over a wide valley floor. Suspended and bedload materials are deposited as sheets or floodout lobes. Prone to incision if threshold conditions are exceeded.	Typically low sensitivity, but prone to rapid and dramatic change if incision occurs

(*continued on next page*)

Table 2 (*continued*)

River Styles	Valley setting/ Landscape Unit	Elevation (m)	Average channel width (m)	River Character			River Behaviour	Ease of adjustment (Geomorphic sensitivity)
				Channel planform	Geomorphic units	Bed material		
Laterally unconfined, low sinuosity channelized	Laterally unconfined (Alluvial)/lowland plain	4–0	50	Single, straight channel, imposed stability in channel position	Trench-like channel, with alternating bars, sand sheets, occasional benches. Flat-topped floodplain has a multitude of abandoned features.	Sand	Incised channel has cut into valley fill deposits of former meandering sand bed rivers, releasing large volumes of sediment. The channel has a stepped cross-section with a series of inset features that are prone to reworking at different flow stages. The over-enlarged channel is now largely disconnected from its floodplains. Most flows are constrained within the enlarged trench, and are prone to significant reworking/erosion, depositing sand sheets at the waning stages of floods. This gives the appearance of excess sediment, but this is unlikely to be the case.	Channelized trench has low sensitivity to adjustment, but instream forms adjust recurrently in response to changing flow and sediment conditions

addition to river responses to land use change over the last 400 years, many short reaches of previously intact valley fill in tributary subcatchments of the Macaé Basin have been trenched or channelized, increasing longitudinal connectivity of the channel network (Fig. 8A). Areas of valley fill with discontinuous watercourses inferred from old maps and field evidence were greatly reduced from 1950 to 2014 relative to 1600–1950 (Fig. 8A).

The meandering sand bed river in downstream parts of the Macaé River, and its primary tributary, the São Pedro River, has a history of significant channel adjustment, with many abandoned channels evident on the floodplains (see Fig. 8C). Slow rates of lateral migration over thousands of years, with occasional phases of channel avulsion, can be inferred under prior forested conditions (cf., Brooks & Brierley, 2002). However, profound geomorphic adjustments occurred following forest clearance in the sixteenth century (cf., Brooks, Brierley, & Millar, 2003). These notable changes in channel geometry and position on the valley floor from 1600 to 1950 pale in significance relative to adjustments since 1950. For example, adjacent to the D'Antas confluence, meander bends shown at cross-section positions A, B and C on Fig. 8C shifted by 170, 90 and 145 m from 1968 to 2014, with associated increases in channel width from 50 to 70, 40–50 and 65–68 m respectively. The sinuosity of this reach increased from 2.3 to 2.5 from 1970 to 2015. Repeat surveys of channel cross-sections in the bend immediately prior to the channelized reach of the Macaé River, 500 m downstream from the D'Antas confluence, indicate that channel width contracted from 34 to 20 m from 2007 to 2014, likely in response to pulsed sediment inputs associated with upstream channel changes (Fig. 9A and B; see Marçal, 2013; Souza & Marçal, 2015).

The reach of the São Pedro River shown in Fig. 8B and C experienced major shift in channel position upstream of cross-section A between 1968 and 2000. Lateral adjustment of 268, 117 and 120 m occurred at cross-sections A, B and C respectively from 1968 to 2000, and a further 45, 30 and 42 m took place from 2000 to 2014. Over the same periods (1968–2000 and 2000–2014), channel width increased from 15 to 22 to 26 m at section A, 18 to 20–25 m at section B, and 16 to 25 to 35m at section C.

Although the reaches shown in Fig. 8 have continued to operate as a Meandering sand bed river style, a much greater length of this type of river has been transformed by channelization since the 1940s (Fig. 10). Often, the straightened and enlarged channel was positioned in an entirely different part of the valley floor, separated by up to 1.5 km in some places from the previous channel position; elsewhere, it simply cut through a suite of former bends. Channelization has greatly reduced the channel length of the lower Macaé River and affected reaches of São Pedro and D'Antas tributaries (Table 4). The resulting channel was not only straight and relatively featureless (homogeneous), its capacity was increased by 270%. Width increased from around 37 to 57 m and depth increased from around 3 to 5 m, as the channel was designed to accommodate a 1 in 20 year flood event (630 m^3s^{-1}). Channel lengths of affected reaches along the Macaé, São Pedro and D'Antas Rivers were reduced by 36.2, 42.7 and 12.9% respectively (Table 4).

4.4. Landscape connectivity changes in Macaé Catchment

Macaé catchment has a typical pattern of source, transfer and accumulation zones with associated downstream transitions in slope and valley width (e.g. Brierley & Fryirs, 2005; Schumm, 1977). As most reaches have limited capacity for channel adjustment, prospects for changes to landscape connectivity are also quite limited (cf., Brierley & Fryirs, 2009; Fryirs et al., 2009). The low availability of sediment stores in the upper and middle catchment has limited off-site impacts of river responses to human disturbance. It is only along alluvial (previously meandering sand bed,

Table 3
Controls on river character and behaviour in Macaé Catchment. Presented values correspond to Macaé River Styles. The upper confined gorge reach was not considered.

River Style	Reach length (km)	Elevation (m)		Elevation range (m)	Average valley floor slope (%)	Catchment area (km^2)	Discharge		Average Valley width (m)	Average channel width (m)
		Max	Min				Q95% (m^3/s)	Bankfull (m^3/s)		
Confined, steep headwater	10	1580	970	610	6.1	51	0.01–0.50	10	20	4
Confined, occasional floodplain pockets	15	970	813	157	1.1	40	0.51–1.00	38	20–200	10
Confined, gorge	30	813	236	577	2.0	266	2.00–4.00	48	10–40	25
Confined, moderate–high sinuosity valley	15	236	45	191	1.2	183	4.01–5.00	58	10–200	45
Partly confined, bedrock controlled, discontinuous floodplain	4.5	490	300	190	3.4	45	0.01–1.00	–	10–200	10
Laterally unconfined, meandering sand bed	19	45	4	41	0.2	203	5.00–10.00	117	500–1.000	40
Laterally unconfined, valley fill	2	40	10	30	0.2	60	0.01–0.50	–	50–100	–
Laterally unconfined, low sinuosity channelized	38	4	0	4	0.01	1038	10.00–20.00	126	3000	50

now largely channelized) reaches of the lowland plain, and the cut-and-fill valley fills of tributaries that join the trunk stream in the middle and lower catchment that marked geomorphic adjustments have occurred in the period since Portuguese settlement (see Fig. 11). This has induced marked alterations to longitudinal and lateral process linkages in these reaches. Incised valley fills are less laterally connected, but these areas now convey flow and sediment much more readily (i.e. longitudinal connectivity has been greatly increased). Forest clearance and subsequent channelization of the meandering sand bed reaches of the lower Macaé River and tributaries brought about profound adjustments in lateral (channel-floodplain) connectivity. Sediment accumulation in this reach prior to forest clearance likely maintained a low capacity channel. Recurrent inundation of floodplains replenished swamp and wetland areas, regulating flow and sediment delivery to the estuary and the ocean beyond. By 1950 the river was characterized by enlarged, more rapidly migrating channels with reduced riparian forest cover. The greater channel capacity reduced lateral (channel-floodplain) connectivity relative to the intact (pre-disturbance) period. Channelization resulted in a much larger, straighter channel trough. By design, this enhanced longitudinal connectivity (flow and sediment flux), but greatly reduced lateral connectivity. Abandoned channels on the floodplain have partially infilled, but they retain a strong visual presence of former channel size and alignment because of the limited lateral conveyance of flood flows and associated deposition of suspended load deposits (see Fig. 10A). Previous channel-floodplain interactions, including migration processes, sand sheet development and recharge of wetland areas, backswamps and floodplain ponds have been almost entirely inhibited since 1968.

5. Discussion: prospective future rivers in the Macaé Catchment

Based on the information on reach-scale river character, behaviour, downstream patterns and evolutionary traits (including changes to landscape connectivity), future evolutionary trajectories of rivers in headwater, foothill and lowland plain settings of the Macaé Catchment are shown in Fig. 12. Prospective future geomorphic adjustments for 2050 are derived for three scenarios: continuance of present trends (steady as she goes), a proactive (geomorphologically-informed) management plan, and a

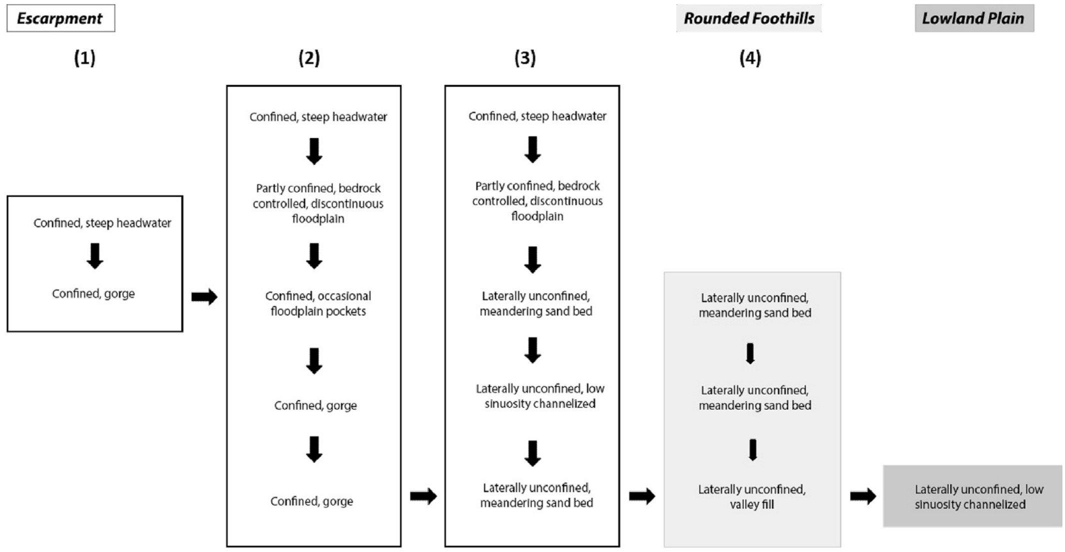

Fig. 6. Downstream patterns of River Styles in the Macaé Catchment. The boxes convey trunk/tributary streams as follows (1) Macaé and Bonito Rivers, (2) Sana, Ouriço, São Pedro Rivers, (3) D'Antas River, (4) Aduelas and Jurumirim streams.

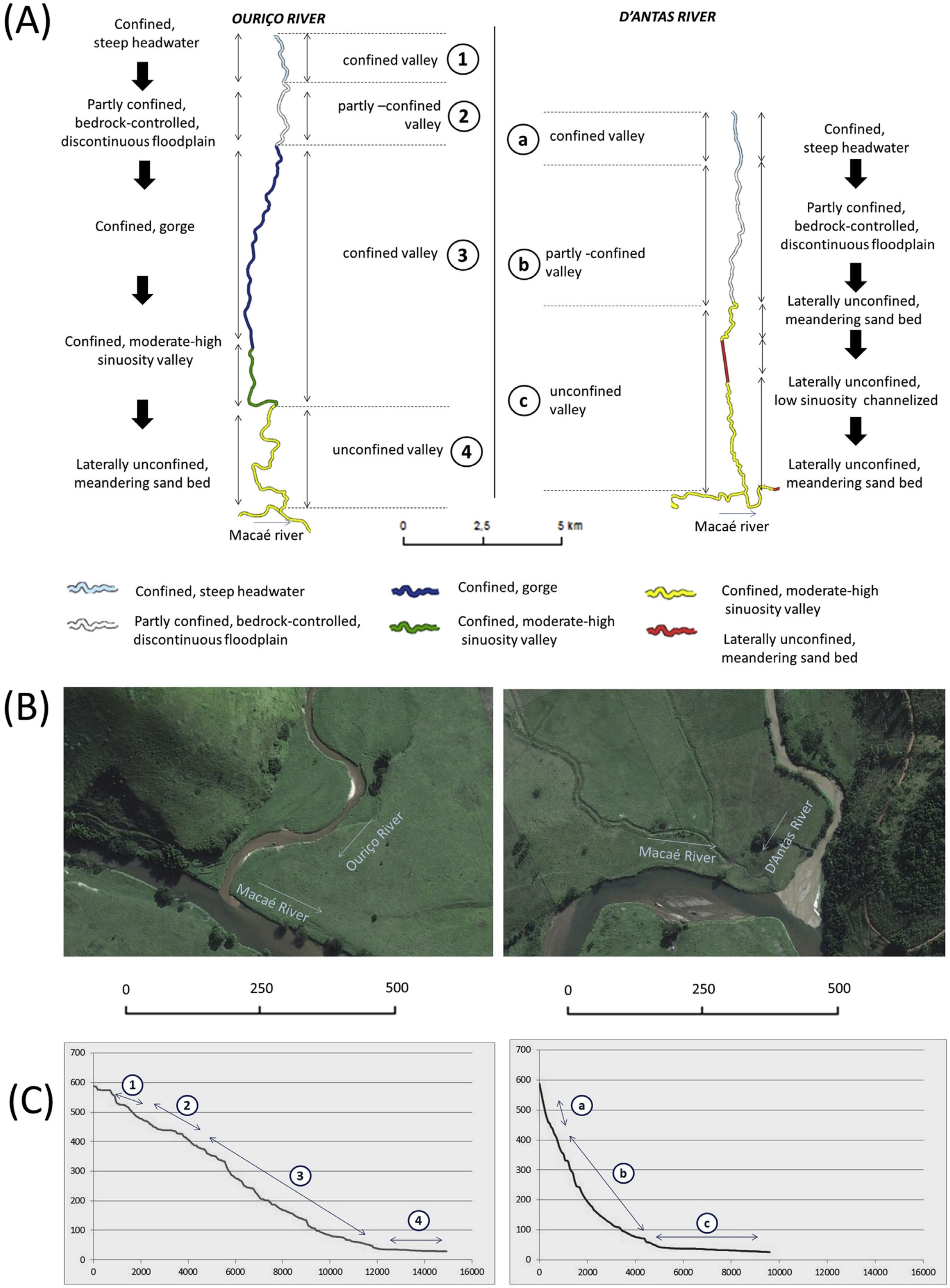

Fig. 7. Downstream patterns of River Styles in Ouriço and D'Antas tributaries. (A) Planform view of the Ouriço and D'Antas tributaries and their downstream sequence of River Styles and valley-setting. (B) Satellite images of confluences with the Macaé River. (C) Longitudinal profiles, showing the convex form of the Ouriço River while the adjacent D'Antas River has a typical concave-upwards profile. Differences in trends of valley floor slope result in different patterns of River Styles (numbers and letters shown along the longitudinal profile refer to the sections of river indicated on Fig. 7A). These differing type and patterns of river result in marked differences in tributary-trunk stream relationships (clearly evident on Fig. 7B).

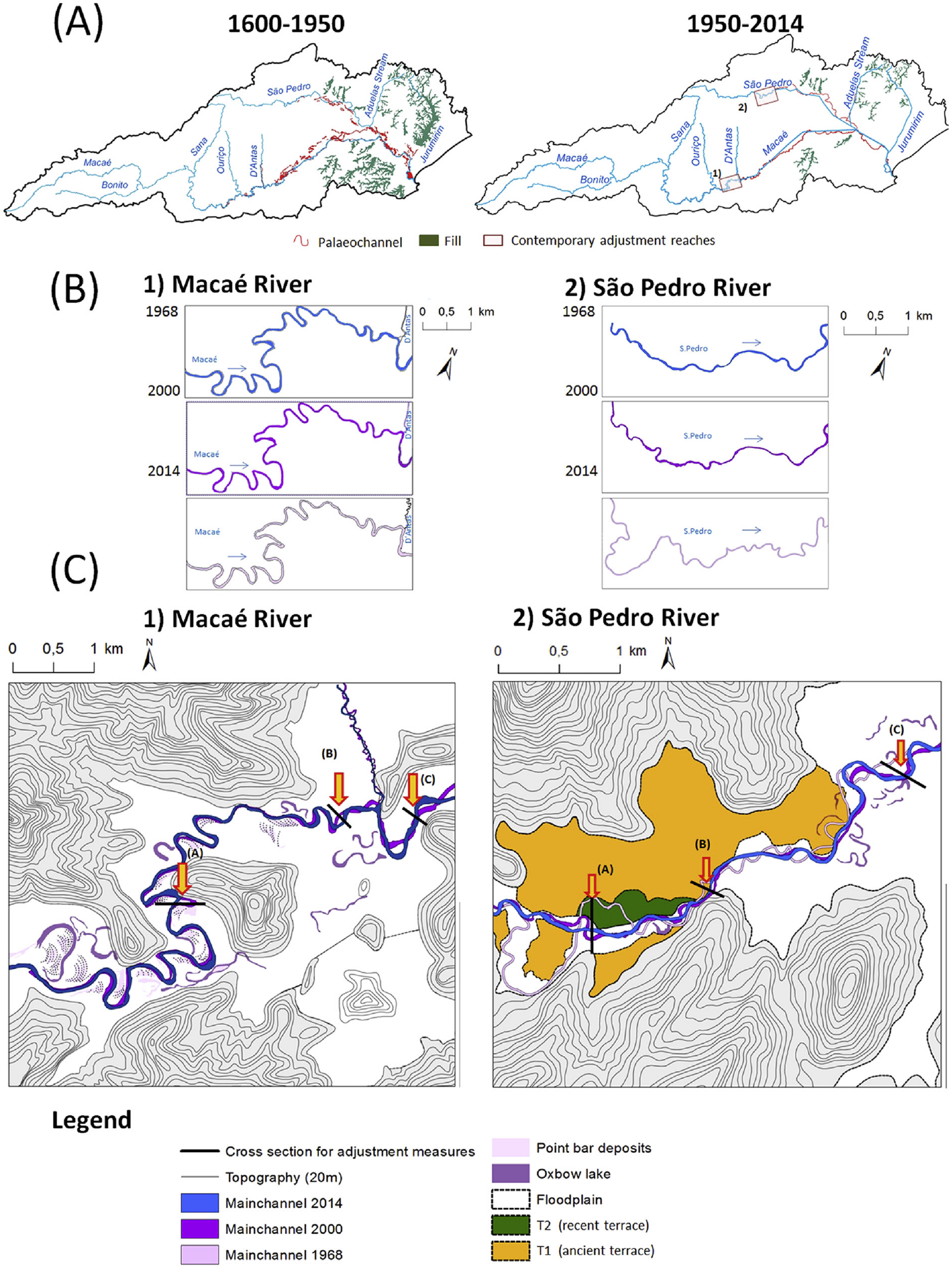

Fig. 8. Geomorphic river adjustments in Macaé Catchment in the period since Portuguese settlement. (A) Catchment-scale river change from pre channelization (1600–1950) to post channelization (1950–2014). Channel adjustments are predominantly restricted to meandering sand bed (now largely channelized) and cut-and-fill reaches of the lowland plain. (B) Planform map showing adjustments in channel position for the Macaé River adjacent to the D'Antas confluence and the São Pedro River (reach locations are shown in Fig. 8A). (C) Planform adjustments along the Macaé and São Pedro Rivers from 1968 to 2014 (reach locations are shown in Fig. 8A).

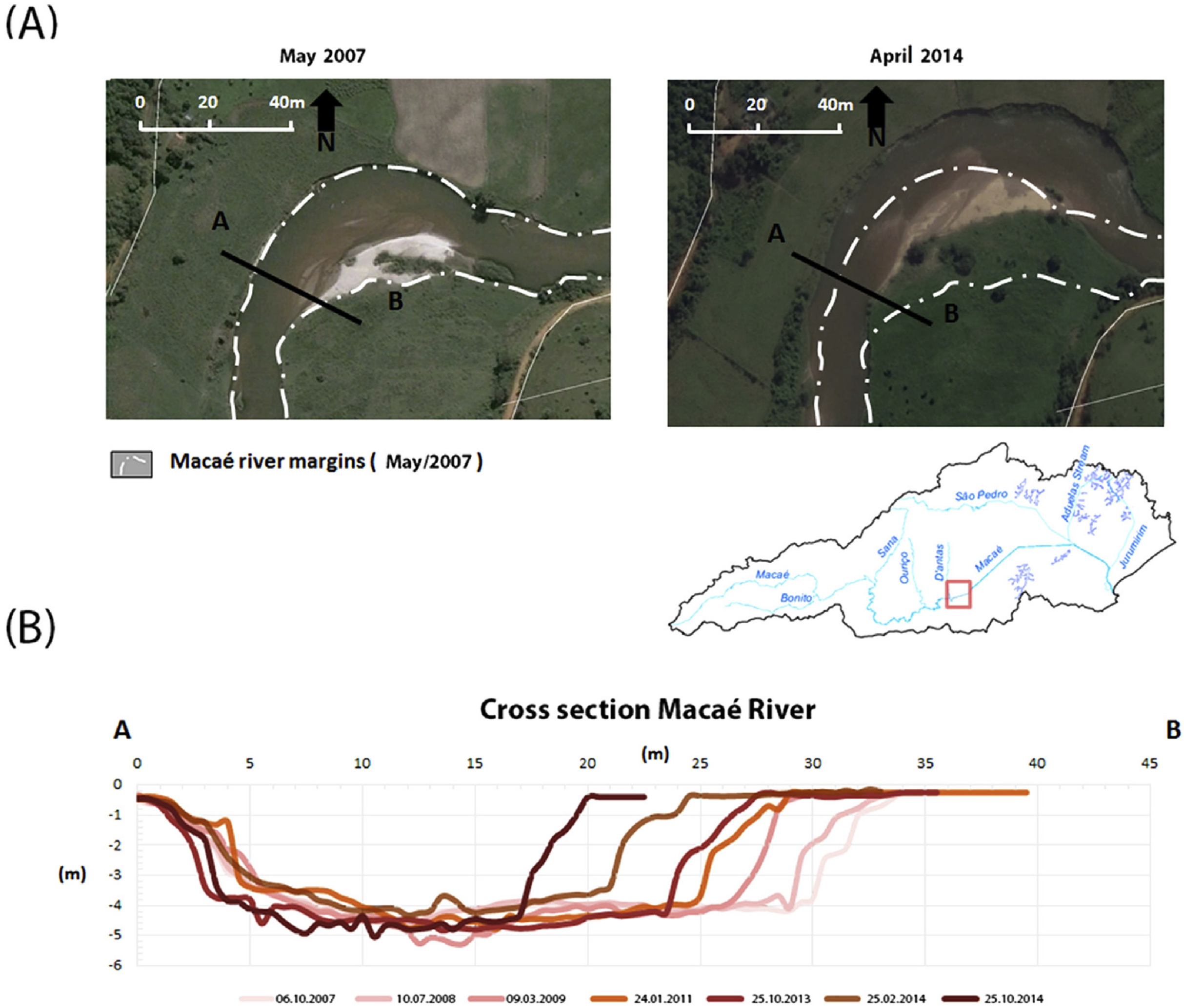

Fig. 9. Recent adjustments to channel planform and geometry along the Macaé River immediately downstream of its confluence with the at the D'Antas River. (A) Satellite images show distinct channel contraction at the entrance to this bend (i.e. point bar deposition), while the channel shifted position by around 60 m at the downstream part of the bend (essentially, the radius of curvature of the bend increased). (B) Recent channel cross-section adjustments at the head of the point bar immediately upstream of the channelized reach, 500 m downstream of D'Antas confluence, from 2007 to 2014. While the concave bank eroded by around 2 m, around 20 m of lateral deposition occurred on the inside of the bend (the cross-section is located on Fig. 1A).

doomsday scenario (extreme land use changes and ineffective management actions). In this conceptualization, land use and river management scenarios are considered independent from climate change and prospective intensification of flood events, which would likely accentuate forms and rates of geomorphic adjustment outlined here.

In the ‘steady as she goes’ scenario (Fig. 12A), upstream River Styles maintain the same good geomorphic condition, with high ability to transfer sediment downstream with strong longitudinal connectivity. The operation of mid-catchment (rounded foothill) reaches as transfer zones with limited capacity for geomorphic adjustment has been maintained from around 1600 to present. Localized channel adjustments, primarily in the form of reworking of instream deposits and occasional floodplain inundation, will retain a balance of erosion and depositional processes, thereby maintaining a similar flow and sediment regime (Fig. 11). In lowland reaches, the meandering sand-bed and channelized rivers, along with incised cut and fill tributary streams, will continue to flush available sediments (i.e. longitudinal connectivity will be maintained or enhanced). Enlarged channels will continue to be largely disconnected from floodplains and valley floors. Reworked bedload materials will continue to act as transient stores such as lateral and mid-channel bars. As a result, prospects for geomorphic river recovery are limited (sensu Fryirs & Brierley, 2016).

There is some cause for optimism in considering future river management options for the Macaé Catchment, as the local city hall is already assessing prospects to implement a meander renaturalization initiative, incorporating recovery of riparian vegetation cover along the lower course of the river. Essentially, the ‘optimistic’ scenario of proactive geomorphically-informed planning outlined in Fig. 12B maintains ongoing functionality of the upper and middle reaches of the Macaé Catchment. Rivers retain a good geomorphic condition, and a prioritized conservation status will help to maintain this level of functionality into the future. In lowland reaches, the maintenance of sediment supply and enhanced ability of the channel to trap sediments are fundamental steps in efforts to promote geomorphic river recovery (Fryirs & Brierley, 2016). Efforts to reduce channel capacity will enhance the physical heterogeneity of the river (range of instream geomorphic units and habitat diversity, such as bars, benches, pool-riffle sequences, enhanced pool depth, etc). This, in turn, will increase lateral connectivity with the floodplain, thereby supporting

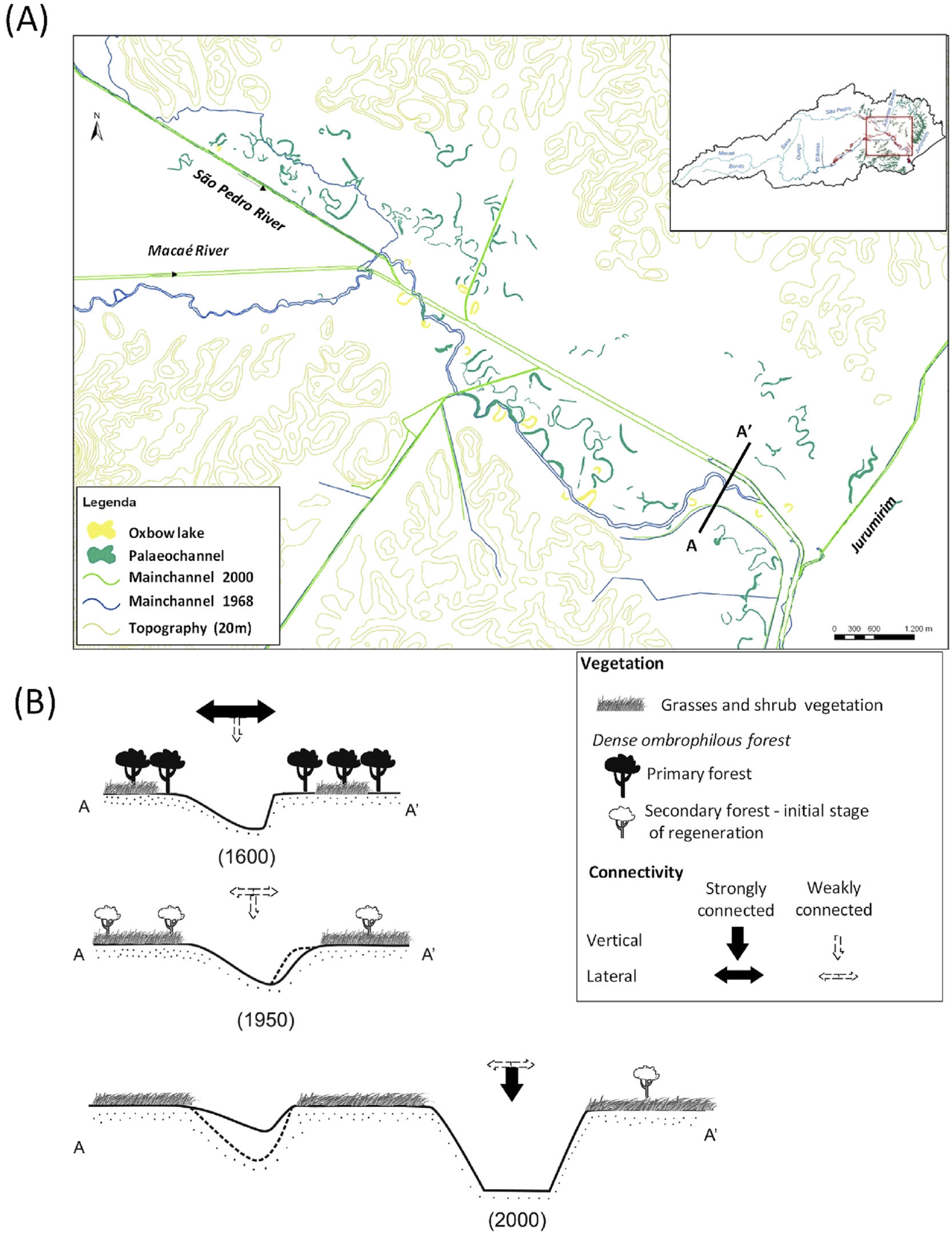

Fig. 10. Impact of channelization on the rivers in the lower Macaé Basin. (A) Channel outlines of a channelized section of the Macaé River at the Sao Pedro confluence. Seventy-one oxbow lakes and palaeochannels are evident on this mapped area (Assumpção & Marçal, 2012). (B) Schematic representation of channel adjustments for the former meandering sand bed reaches of the Macaé River that have now been channelized. Note the increase in channel width from 1600 to 1950. Channelization by 2000 brought about a complete shift in channel position and a greatly enlarged channel size, with partial infilling of the former channel (now abandoned on the floodplain). Arrows indicate changes to lateral and longitudinal connectivity associated with these channel changes.

the ecological functionality of the broader riparian corridor (especially wetlands and backswamps). Essentially, this proactive management scenario accords directly with ‘space to move’ interventions applied in various parts of the world (e.g. Biron et al., 2014; Kondolf, 2011; Piégay, Darby, Mosselman, & Surian, 2005).

A prospective doomsday scenario for management of the Macaé River is shown in Fig. 12C in relation to land use changes that remove vegetation cover on hillslopes and valley floors. Increased supply of hillslope sediments from the upper catchment and erosion of sediment stores in mid-catchment would reduce habitat heterogeneity, as channel beds are smothered by sediment. High longitudinal connectivity would be maintained because of limited accommodation space and capacity for sediment storage. However, lateral connectivity would be reduced in areas where channel-floodplain connectivity exists today. Increased delivery of sediments to downstream reaches would continue to be conveyed

Table 4
Adjustments to channel form induced by channelization of the Macaé, São Pedro and D'Antas Rivers.

	Length of amended channel (km)		Sinuosity index		Average channel width (m)	
	1968	2000	1968	2000	1968	2000
Macaé River	61.43	39.17	1.58	1.01	37	57
São Pedro River	28.58	19.37	1.50	1.01	15	22
D'Antas River	6.88	5.99	1.41	1.22	22	17

through the homogeneous, high capacity channel on the lowland plain. This would retain lateral disconnectivity between the homogeneous (habitat-poor) channel and the floodplain. The enlarged channel capacity would be able to retain flows from a wider range of flood events, increasing their erosional potential and maintaining accelerated rates of sediment delivery to offshore areas. Such circumstances could be compounded further by other management actions, such as unsustainable mining of instream sediments, application of hard engineering structures or inappropriate water management initiatives.

Essentially, prospects for river futures reflect societal and managerial choices. Importantly, a catchment-wide geomorphic information base is now available to guide such deliberations. This study has shown how a relatively limited resource base can be utilised to generate such understanding. However, as noted by Rogers (2006), uptake of such principles is entirely dependent upon decisions made by river and water managers. Critically, necessary expertise is required to support such applications of the River Styles Framework, requiring appropriate training in fluvial geomorphology. Ideally, this kind of work would be undertaken in direct collaboration with regional and/or national land and water resource management agencies.

Technological and methodological advances in remote sensing and field techniques support the development of catchment-framed information bases to support geomorphological investigations and their application to process-based and proactive (visionary) land and water management. This provides a basis for monitoring and modelling applications that quantify rates of adjustments, and their impacts throughout a river system. For example, numerical modelling is required to quantify rates of channel adjustment and sediment transport/deposition, incorporating assessment of alterations to hydrological conditions/regimes and vegetation (roughness) factors. This could include appraisal of 'thresholds of potential concern', identifying and specifying prospective tipping points in geomorphic and ecological conditions. There is enormous potential to establish clearly rationalized and prioritized catchment-specific, place-based management applications in light of such emerging understanding. However, it is critical to ask the 'right questions' in conducting such analyses. The River Styles Framework provides an appropriate basis to inform such analyses, providing a sound platform to ground and substantiate subsequent predictive investigations.

Finally, it is important to consider implications for the uptake of findings presented in this paper. Caution is urged in assessing the transferability of insights from one catchment to another unless an appropriate commitment to place-based investigations is used to apply consistent procedures in a rigorous manner (see Brierley et al., 2013). Much remains to be learnt from regional-scale comparative analyses of such information bases (see Scorpio et al. (2015) and Surian and Rinaldi (2003) for excellent examples).

6. Conclusions

This application of the River Styles Framework (Brierley & Fryirs, 2005) has used historical resources, maps, remotely sensed and field evidence to generate a catchment-wide geomorphic understanding of rivers in the Macae Basin as a basis to assess likely future trajectories of adjustment for various land/river management scenarios. Other than downstream reaches, geomorphic changes since 1600 have been relatively limited in scope across this catchment. Although lower reaches of the Macaé River may be relatively 'sick', the system as a whole has retained a reasonable

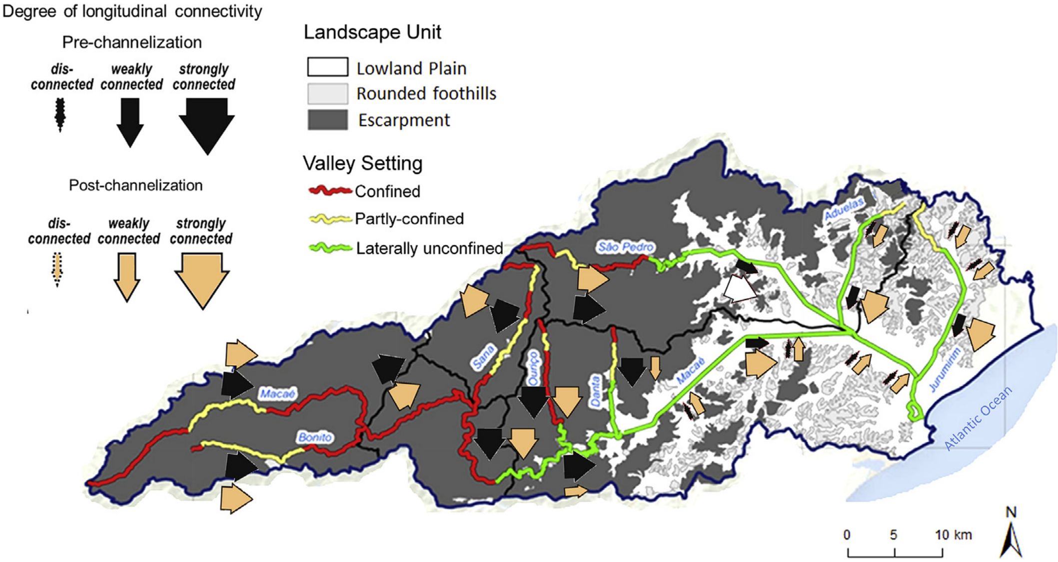

Fig. 11. Changes to landscape connectivity in the Macaé Basin associated with channelization of several reaches in the lower catchment. Channelization resulted in increased longitudinal connectivity along the trunk stream downstream of D'Antas confluence and along Sao Pedro. This has been coincident with increased connectivity from incised valley fills in various lowland tributary catchments. Sediment build-up along lower D'Antas River (shown in Fig. 7) reduced longitudinal connectivity along this tributary and along the trunk stream upstream of the Macaé-D'Antas confluence.

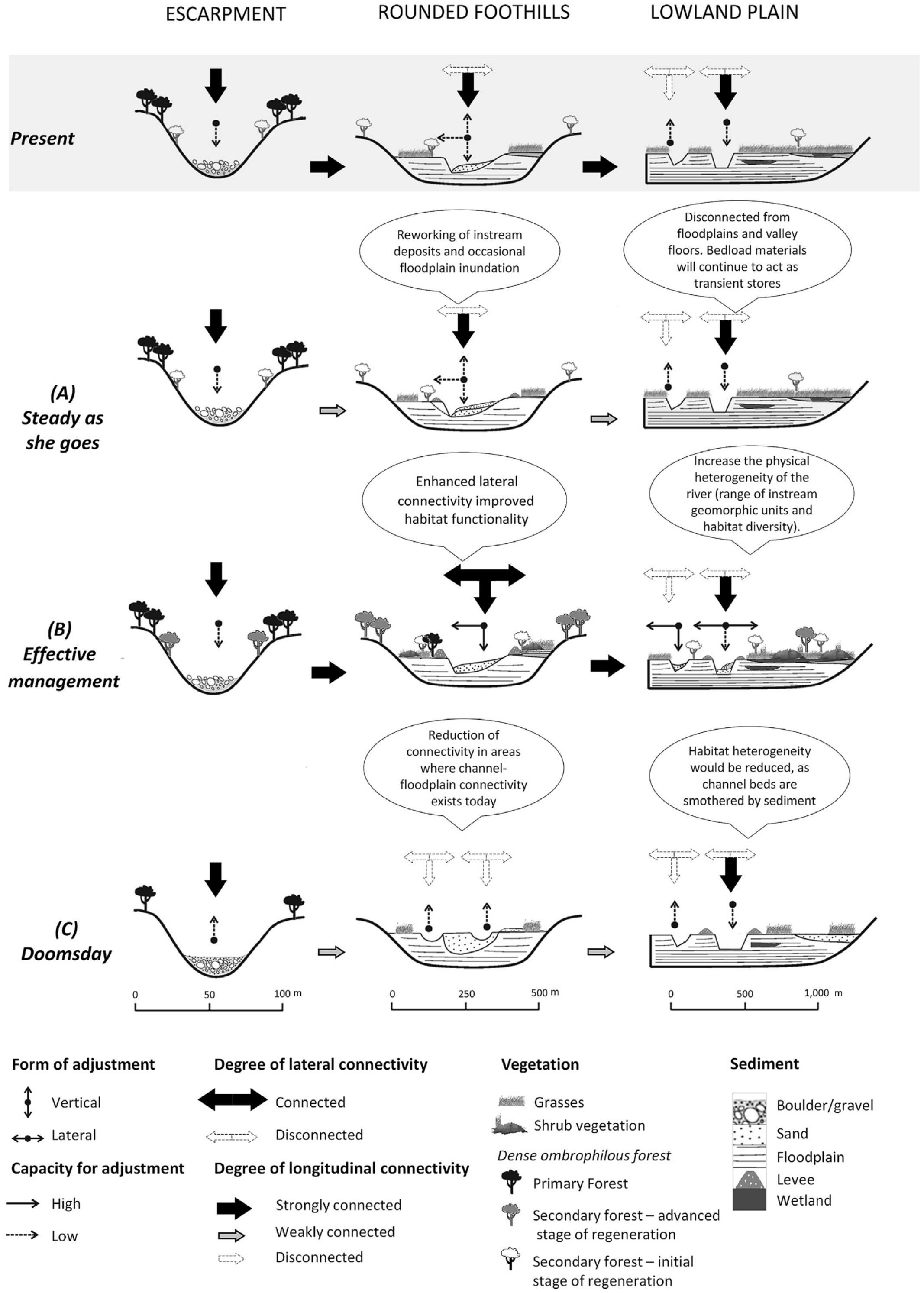

Fig. 12. Three prospective scenarios for future evolutionary trajectories of rivers in headwater, foothill and lowland plain settings of the Macaé Basin, shown in relation to river management activities from today to 2050. (A), (B) and (C) present visual representations for 'Steady as she goes', 'Effective environmental management' and a 'Doomsday' scenario. Schematic valley cross section images convey changes in channel geometry, relationships to the floodplain, forms/rates of geomorphic adjustment, and changes to landscape connectivity. Longitudinal connectivity is represented at the catchment scale (from the Steep Headwaters through the Rounded Foothills to the Lowland Plain) and at the reach scale (arrows indicated for each valley cross section). Lateral connectivity is shown for channel-floodplain linkages for each valley cross section. Geomorphic adjustments associated with each scenario are outlined in the text.

level of geomorphological and ecological functionality, such that there are significant prospects for river recovery and associated conservation goals if appropriate management strategies are applied. Such opportunities are relatively rare in the area around Rio de Janeiro.

Funding

This work was supported by Brazilian Research Council (CNPq - 473542/2012-9); Rio de Janeiro Research Foundation (FAPERJ - E-26/110.883/2013).

Acknowledgement

The Foundation Affiliated with the Ministry of Education of Brazil (CAPES - BEX 2689/15-4) supported the first author to develop her research as a Visiting Scholar at The University of Auckland. We thank Professor Antonio Carlos Correa, UFPE, who co-coordinated Professor Brierley's visit to Brazil in November 2011 and many students who supported different stages of field and laboratory work. We thank four reviewers for their helpful and supportive comments on this paper.

References

Almeida, J. C. H. (2012). *Geologia e recursos minerais da folha Macaé SF.24-Y-A-I, estado do Rio de Janeiro escala 1:100.000. Programa Geologia do Brasil, PGB, CPRM/UERJ, Mapa Geológico, escala 1:100.000 (série Geologia do Brasil): Belo Horizonte*. ISBN 978-85-7499-104-7.

Assumpção, A. P., & Marçal, M. S. (2012). Retificação dos Canais Fluviais e Mudanças Geomorfológicas na Planície do Rio Macaé (RJ). *Revista de Geografia (Recife), 29*, 19–36.

Baker, J. P., Hulse, D. W., Gregory, S. V., White, D., Van Sickle, J., Berger, P. A., et al. (2004). Alternative futures for the willamette river basin, Oregon. *Ecological Applications, 14*, 313–324. http://dx.doi.org/10.1890/02-5011.

Beechie, T. J., Sear, D. A., Olden, J. D., Pess, G. R., Buffington, J. M., Moir, H., et al. (2010). Process-based principles for restoring river ecosystems. *BioScience, 60*(3), 209–222. http://dx.doi.org/10.1525/bio.2010.60.3.7.

Biron, P. M., Buffin-Bélanger, T., Larocque, M., Choné, G., Cloutier, C. A., Ouellet, M. A., et al. (2014). Freedom space for rivers: A sustainable management approach to enhance river resilience. *Environmental Management, 54*(5), 1056–1073. http://dx.doi.org/10.1007/s00267-014-0366-z.

Bollati, I. M., Pellegrini, L., Rinaldi, M., Duci, G., & Pelfini, M. (2014). Reach-scale morphological adjustments and stages of channel evolution: The case of the Trebbia River (northern Italy). *Geomorphology, 221*, 176–186. http://dx.doi.org/10.1016/j.geomorph.2014.06.007.

Brasil. (2006). *Mapeamento da Cobertura Vegetal do Bioma Mata Atlântica, ano base 2002. Ministério do Meio Ambiente (MMA). Projeto de Conservação e Utilização Sustentável da Diversidade Biológica (Probio)*. Projeto Integrado para Mapeamento da Cobertura Vegetal do Brasil na escala 1:250.000.

Brierley, G., & Fryirs, K. (2000). River styles, a geomorphic approach to catchment characterization: Implications for river rehabilitation in Bega catchment, New South Wales, Australia. *Environmental Management, 25*(6), 661–679. http://dx.doi.org/10.1007/s002670010052.

Brierley, G., & Fryirs, K. (2005). *Geomorphology and river Management: Applications of the river styles framework*. Blackwell: Oxford.

Brierley, G., & Fryirs, K. (2009). Don't fight the site: Geomorphic considerations in catchment-scale river rehabilitation planning. *Environmental Management, 43*, 1201–1218. http://dx.doi.org/10.1007/s00267-008-9266-4.

Brierley, G., & Fryirs, K. (2016). The use of evolutionary trajectories to guide 'moving targets' in the management of river futures. *River Research and Applications, 32*, 823–835. http://dx.doi.org/10.1002/rra.2930.

Brierley, G., Fryirs, K., Cullum, C., Tadaki, M., Huang, H. Q., & Blue, B. (2013). Reading the landscape: Integrating the theory and practice of geomorphology to develop place-based understandings of river systems. *Progress in Physical Geography*, 1–21. http://dx.doi.org/10.1177/0309133313490007.

Brooks, A. P., & Brierley, G. (2002). Mediated equilibrium: The influence of riparian vegetation and wood on the long-term evolution and behaviour of a near-pristine river. *Earth Surface Processes and Landforms, 27*(4), 343–367.

Brooks, A. P., Brierley, G., & Millar, R. G. (2003). The long-term control of vegetation and wood debris on channel and floodplain evolution: Insights from a paired catchment study in southeastern Australia. *Geomorphology, 51*(1), 7–29. http://dx.doi.org/10.1016/S0169-555X(02)00323-9.

Downs, P. W., Dusterhoff, S. R., & Sears, W. A. (2013). Reach-scale channel sensitivity to multiple human activities and natural events: Lower Santa Clara River, California, USA. *Geomorphology, 189*, 121–134. http://dx.doi.org/10.1016/j.geomorph.2013.01.023.

Downs, P., & Gregory, K. (2004). *River channel management: Towards sustainable catchment hydrosystems*. Routledge.

Dufour, S., & Piégay, H. (2009). From the myth of a lost paradise to targeted river restoration: Forget natural references and focus on human benefits. *River Research and Applications, 25*, 568–581. http://dx.doi.org/10.1002/rra.1239.

Ferguson, R. J., & Brierley, G. J. (1999). Downstream changes in valley confinement as a control on flood-plain morphology, lower tuross river, new South Wales: A constructivist approach to floodplain analy-sis. In A. J. Miller, & A. Gupta (Eds.), *Varieties of fluvial form* (pp. 377–407). Chichester: John Wiley & Sons.

Fryirs, K., & Brierley, G. J. (2001). Variability in sediment delivery and storage along river courses in bega catchment, NSW, Australia: Implications for Geomorphic river recovery. *Geomorphology, 38*(3), 237–265. http://dx.doi.org/10.1016/S0169-555X(00)00093-3.

Fryirs, K., & Brierley, G. (2010). Antecedent controls on river character and behaviour in partly confined valley settings: Upper Hunter catchment, NSW, Australia. *Geomorphology, 117*(1), 106–120. http://dx.doi.org/10.1016/j.geomorph.2009.11.015.

Fryirs, K., & Brierley, G. (2016). Assessing the geomorphic recovery potential of rivers: Forecasting future trajectories of adjustment for use in management. *WIRES Water, 3*, 727–748. http://dx.doi.org/10.1002/wat2.1158.

Fryirs, K., Brierley, G., Preston, N. J., & Kasai, M. (2007). Buffers, barriers and blankets: The (dis)connectivity of catchment-scale sediment cascades. *Catena, 84*, 297–316. http://dx.doi.org/10.1016/j.catena.2006.07.007.

Fryirs, K., Spink, A., & Brierley, G. (2009). Post-European settlement response gradients of river sensitivity and recovery across the upper Hunter catchment, Australia. *Earth Surface Processes and Landforms, 34*(7), 897–918. http://dx.doi.org/10.1002/esp.1771.

Fryirs, K. A., Wheaton, J. M., & Brierley, G. J. (2016). An approach for measuring confinement and assessing the influence of valley setting on river forms and processes. *Earth Surface Processes and Landforms, 41*, 701–710. http://dx.doi.org/10.1002/esp.3893.

Hasui, Y. (1990). Neotectônica e Aspectos Fundamentais da Tectônica Ressurgente no Brasil. In *Workshop sobre Neotectônica e Sedimentação Cenozóica Continental no Sudeste Brasileiro: Belo Horizonte*.

Heilbron, M., Pedrosa Soares, A. C., Campos Neto, M. C., Silva, L. C., Trouw, R. A. J., & Janasi, V. A. (2004). Província mantiqueira. In *Geologia do Continente Sul-Americano: evolução da obra de Fernando Flávio Marques de Almeida, Mantesso Neto V, Bartorelli A, Carneiro CDR, Brito Neves BB (org). Beca: São Paulo* (pp. 203–236).

Hillman, M., & Brierley, G. (2005). A critical review of catchment-scale stream rehabilitation programmes. *Progress in Physical Geography, 29*(1), 50–76. http://dx.doi.org/10.1191/0309133305pp434ra.

Jain, V., Fryirs, K., & Brirley, G. (2008). Where do floodplains begin? The role of total stream power and longitudinal profile form on floodplain initiation processes. *Geological Society of America Bulletin, 120*(1), 127–141. http://dx.doi.org/10.1130/B26092.1.

Jain, V., & Tandon, S. K. (2010). Conceptual assessment of (dis) connectivity and its application to the Ganga River dispersal system. *Geomorphology, 118*(3), 349–358. http://dx.doi.org/10.1016/j.geomorph.2010.02.002.

Kondolf, G. M. (2011). Setting goals in river restoration: When and where can the river 'heal itself'? In A. Simon, S. J. Bennett, & J. M. Castro (Eds.), *Geophysical monograph series: Vol. 194. Stream restoration in dynamic fluvial Systems: Scientific approaches, analyses, and tools* (pp. 29–43). Washington DC: American Geophysical Union.

Lima, R. N. S., & Marçal, M. S. (2014). Avaliação da Condição Geomorfológica da bacia do rio Macaé RJ a partir da Metodologia de Classificação dos Estilos Fluviais. *Revista Brasileira de Geomorfologia, 14*, 171–179.

Marçal, M. S. (2013). Análise das Mudanças Morfológicas em Seções Transversais ao Rio Macaé - RJ. *Revista Brasileira de Geomorfologia, 14*, 59–68.

Marçal, M. S., & Luz, L. M. (2003). Planejamento e gestão da Bacia do Rio Macaé, Litoral Norte Fluminense, com base em estudos integrados de geomorfologia e uso do solo. In *IX Congresso da Associação Brasileira de Estudos do Quaternário: Recife*.

Marçal, M. S., Ramos, R. R. C., Sessa, J. C., & Fevrier, P. V. R. (2015). Sedimentação Fluvial Quaternária no Vale do Alto Curso do Rio Macaé, Estado do Rio de Janeiro, Brasil. *Revista Brasileira de Geomorfologia, 16*(3), 449–467.

O'Brien, G., Wheaton, J., Fryirs, K., McHugh, P., Bouwes, N., Brierley, G., et al. (2017). A geomorphic assessment to inform strategic stream restoration planning in the Middle Fork John Day Watershed, Oregon, USA. *Journal of Maps*. http://dx.doi.org/10.1080/17445647.2017.1313787.

Piégay, H., Darby, S. E., Mosselman, E., & Surian, N. (2005). A review of techniques available for delimiting the erodible river corridor: A sustainable approach to managing bank erosion. *River Research and Applications, 21*(7), 773–789. http://dx.doi.org/10.1002/rra.881.

Reid, H. E., & Brierley, G. (2015). Assessing geomorphic sensitivity in relation to river capacity for adjustment. *Geomorphology, 251*, 108–121. http://dx.doi.org/10.1016/j.geomorph.2015.09.009.

Rogers, K. H. (2006). The real river management challenge: Integrating scientists, stakeholders and service agencies. *River Research and Applications, 22*, 269–280. http://dx.doi.org/10.1002/rra.910.

Schmidt, J. C., Webb, R. H., Valdez, R. A., Marzolf, G. R., & Stevens, L. E. (1998). Science and values in river restoration in the Grand Canyon. *BioScience, 48*, 735–747. http://dx.doi.org/10.2307/1313336.

Schumm, S. A. (1977). *The fluvial system*. Chichester, UK: John Wiley and Sons.

Schumm, S. A., Harvey, M. D., & Watson, C. C. (1984). *Incised Channels: Morphology, dynamics, and control*. Littleton: Colorado: Water Resources Publications.

Scorpio, V., Aucelli, P. P., Giano, S. I., Pisano, L., Robustelli, G., Rosskopf, C. M., et al. (2015). River channel adjustments in Southern Italy over the past 150years and implications for channel recovery. *Geomorphology, 251*, 77–90. http://dx.doi.org/10.1016/j.geomorph.2015.07.008.

Soffiati, A. (2010). Macaé em quatro tempos. In *Oficina sobre Impactos Sociais, Ambientais e Urbanos das Atividades Petrolíferas: o caso de Macaé (RJ), Herculano S, Correa HD (org). Capitulo 2: Niterói UFF* (pp. 130–148).

Sousa, G. S. (1938). *Tratado descritivo do Brasil em 1587*. São Paulo: Companhia Editora Nacional.

Souza, P. A., & Marçal, M. S. (2015). Hidrossedimentologia e Conectividade do Rio Macaé, Norte do Estado do Rio de Janeiro, Brasil. *Revista GeoUERJ, 27*, 176–201. http://dx.doi.org/10.12957/geouerj.2015.16436.

Surian, N., & Rinaldi, M. (2003). Morphological response to river engineering and management in alluvial channels in Italy. *Geomorphology, 50*, 307–326. http://dx.doi.org/10.1016/S0169-555X(02)00219-2.

Surian, N., Ziliani, L., Comiti, F., Lenzi, M. A., & Mao, L. (2009). Channel adjustments and alteration of sediment fluxes in gravel-bed rivers of north-eastern Italy: Potentials and limitations for channel recovery. *River Research and Applications, 25*, 551–567. http://dx.doi.org/10.1002/rra.1231.

Veloso, H. P., Rangel Filho, A. L. R., & Lima, J. C. A. (1991). *Classificação da vegetação brasileira, adaptada a um sistema universal*. Rio de Janeiro: Departamento de Recursos Naturais e Estudos Ambientais.

Villas Boas, G. H., & Marçal, M. S. (2013). Avaliação da sensitividade do sistema fluvial no alto-médio vale do rio Macaé (RJ). *Revista Brasileira de Geomorfologia, 14*, 93–102.

Wohl, E., Lane, S. N., & Wilcox, A. C. (2015). The science and practice of river restoration. *Water Resources Research, 51*(8), 5974–5997. http://dx.doi.org/10.1002/2014WR016874.