

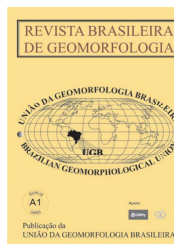


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# THE USE OF THE RIVER STYLES FRAMEWORK AS A TOOL TO 'WORK WITH NATURE' IN MANAGING RIVERS IN BRAZIL: EXAMPLES FROM THE MACAÉ CATCHMENT

## O USO DA METODOLOGIA DOS ESTILOS FLUVIAIS COMO FERRAMENTA PARA 'TRABALHAR EM PARCERIA COM A NATUREZA' NO PROCESSO DE GESTÃO DE RIOS NO BRASIL: EXEMPLOS DA BACIA DO RIO MACAÉ

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### Abstract:

Integrative approaches to land and water management apply scientifically informed policies that build upon a landscape template. The River Styles Framework supports the development and application of proactive, strategic and cost-effective management plans. This paper outlines eight key principles that build upon the River Styles Framework: (1) use a landscape template as an integrative platform; (2) respect the inherent diversity of river forms and processes; (3) work with variability, adjustment and change; (4) know your catchment, understanding patterns of river types and tributary-trunk stream relationships; (5) compare like with like in assessing geomorphic river condition; (6) forecast prospective river futures to set moving targets for management; (7) apply a conservation-first and recovery enhancement ethos in the development of visionary yet realistically

achievable management plans that have a clear evidence base for prioritization of actions; and (8) monitor and learn effectively using adaptive management principles. The application of each of these principles is demonstrated using a case study from the Macaé Catchment in Rio de Janeiro State.

### Resumo:

Abordagens integrativas voltadas para a gestão das águas e do solo aplicam políticas baseadas em informações científicas construídas a partir de um modelo de paisagem. A metodologia dos Estilos Fluviais auxilia no desenvolvimento e aplicação de planos de gestão proativos, estratégicos e economicamente eficazes. O artigo traça oito princípios para a gestão ambiental que constituem a metodologia dos Estilos Fluviais: (1) utilize um modelo da paisagem como plataforma de integração; (2) respeite a diversidade inerente aos processos e formas fluviais; (3) trabalhe com variabilidade, ajuste e mudança; (4) conheça sua bacia, compreenda os padrões de tipologias de rios e relações entre afluentes; (5) compare semelhante com semelhante para avaliar a condição geomorfológica de um rio; (6) projete cenários futuros para estabelecer metas flexíveis; (7) aplique o princípio de ‘conservar primeiro’ e da recuperação ambiental ao desenvolvimento de planos de gestão visionários e exequíveis, com uma clara base de evidências para a priorização de ações; e (8) monitore e aprenda com eficiência, utilizando princípios de gestão adaptativa. A aplicação desses princípios é demonstrada a partir dos resultados de um estudo de caso na Bacia do rio Macaé, no Estado do Rio de Janeiro.

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### Introduction

There is an urgent need to address many land and water management issues in Brazil. The current National Water Resources Policy (PNRH) and the National Water Resources Management System (SNGRH), framed as the Water Law (Law No. 9.433), was implemented in 1997 (LANNA, 1997; MAGALHÃES JR, 2007). Although it represents one of the most modern legal water management frameworks in the world, increasing water demands and stresses continue to present many management challenges. The goals of the Water Law are admirable. In principle, Basin Plans (or Water Resources Plans) co-ordinated by basin committees incorporate environmental aspects. Short, medium and long term goals and actions that incorporate multiple uses in a sustainable manner are established through integrated management of environmental and water resources policies (DUARTE; MARÇAL, 2010). In reality, however, many shortcomings are evident. As methodologies for environmental analyses are not specified, there is a gap between the intent of the law and its implementation. Associated terms of reference emphasize collection of information for different thematic axes, covering the physical, biotic, socioeconomic and legal-institutional environments according to guidelines advocated by decree 4.297/2002 and by the methodological guidelines of ecological economic zoning of Brazil (ZEEs). However, this framework places undue emphasis upon hydrological studies while disregarding other critical

attributes, such as fluvial geomorphology and interactions with aquatic ecology (MAGALHÃES JR, 2007). This is a major oversight. Unless management efforts build upon integrated scientific understandings of fluvial geomorphology, hydrology and ecology, tied specifically to social, economic and cultural information in a catchment-specific and cross-scalar manner, sustainable and equitable outcomes will not be achieved. Rivers are intimately tied to the landscapes that make up their basins – in a sense, they are the lifeblood of the land.

Approaches to land and water management reflect negotiations among practitioners with divergent aspirations, values and goals. These deliberations are fashioned by historical, geographical, socio-cultural, economic, political and institutional considerations, and are influenced by differing mindsets, paradigms, knowledge frameworks and governance arrangements (TORRES; FERREIRA, 2012). Decisions made, and the actions, responses and outcomes that ensue, have significant legacies (and costs) for future generations. In many parts of the world, past river management practices have applied high intervention, engineering-based approaches. Locked-in path dependencies induced by channelization, or construction of dams and stopbanks, may be very difficult to revoke, limiting the range of management options in the medium-long term (i.e. over decades to centuries). Failure of structures, devastating environmental impacts, ongoing risks/hazards and significant maintenance costs reduce community confidence

in management activities. An alternative approach is required, as contemporary approaches to river management are not sustainable and are struggling to cope with the rate and unpredictability of environmental change and associated socio-economic and political crises.

Historically, policy and investment have been directed at the management of single issues in isolation from their broader implications, often targeting the most degraded river reach. Piecemeal management can only deliver fragmented outcomes, compromising our capacity to implement sustainable practices. A whole of system approach to land and water management applies integrative and co-ordinated plans within a coherent policy context (e.g. BRIERLEY *et al.*, 2011). Compromise solutions will not work - there is no such thing as ‘half a habitat’.

Prospects for an era of environmental repair emphasize the mutual interdependence of human and environmental needs (BRIERLEY; FRYIRS, 2008). Our economy and wellbeing are reliant on a healthy environment. Coherent, strategic and proactive actions are required to achieve this. As highlighted in a recent UN report, ‘working with nature’ is a critical part of effective management practice (WWAP, 2018).

Towards the end of the twentieth century, many

researchers recognized that engineering-based ‘command and control’ approaches to river management were unsustainable. Such practices sought to tame or train a river, emphasizing concerns for channel stability, hydraulic efficiency and hazard mitigation. They called for a shift towards a more holistic ‘ecosystem’ approach to river management, working with nature in efforts to address concerns for river health (see Table 1; DOWNS; GREGORY, 2004; HILLMAN, 2009; HILLMAN; BRIERLEY, 2005). Moves towards a river restoration ethos in an era of river repair reflect a growing realization of the extent to which environmental values of river systems have been degraded. Prevailing management activities not only induced loss of habitat and biodiversity, they also compromised a range of aesthetic and amenity qualities of the river (BRIERLEY; HOOKE, 2015). Transitions in practice incorporate a fundamental shift in the information bases which guide management actions, recognizing that healthy rivers are products of healthy societies. However, the uptake of an ecosystem approach to river management has been anything but a smooth ride, as divergent values, vested (political) interests and change resistance play out in different ways in different situations (BOULTON *et al.*, 2008; HILLMAN, 2009; HILLMAN; BRIERLEY, 2008).

**Table 1: Contrasting scientific and managerial attributes of ‘Command and Control’ and ‘Ecosystem’ approaches to environmental management (based on BRIERLEY; FRYIRS, 2005, 2008; HILLMAN; BRIERLEY, 2005).**

<b>COMMAND &amp; CONTROL</b>	<b>ECOSYSTEM APPROACH</b>
Discipline-bound, reductionist, typically with a technical (engineering) focus	Holistic, cross-disciplinary, incorporating understandings of socio-ecological considerations
Single-purpose, deterministic	Multi-purpose, probabilistic
Site-specific or reach-scale applications	Catchment-framed approach
Quest for stability over decadal timeframes, with a construction focus	Work with natural variability and change over centuries or millennia, applying a continuum of interventions - including the ‘do nothing’ option and space to move programmes
Desire for certainty in outcomes	Recognizes uncertainty and complexity
Top-down, politically driven	Bottom-up, participatory
Short-term focus, with limited monitoring	Long-term commitment, applying adaptive management and learning principles

Emerging debates in scientific enquiry highlight challenges that are faced in living in an emergent, less predictable world. Controversial debates about tipping points, novel ecosystems, planetary boundaries and

trajectories of adjustment emphasize greater recognition and appreciation of complexity, non-linearities and contingency. Such (re)framings reflect a move away from overly-simplistic ‘cause-and-effect’ science, and

the idea that environments can be returned to a previous state – perspectives that are largely based upon linear relationships, typically framed around notions of ‘stability’, ‘endpoints’ or ‘equilibrium’. They give far greater acknowledgement to inherent uncertainties – and the imperative to report and communicate this in a more effective manner. Increasingly, engineering-based approaches to uniformity and predictability (certainty) that strive to ‘make rivers the same’ (TADAKI *et al.*, 2014) are being replaced by place-based analyses that respect the diversity, variability and evolutionary trajectory of each river system (e.g. BEECHIE *et al.*, 2010; BRIERLEY; FRYIRS, 2005; FRYIRS; BRIERLEY, 2009). Such practices acknowledge and incorporate risk and uncertainty in different ways, adopting conservation-first and process-based, recovery-enhancement approaches to management that build upon a sound information base and provide a clear and rational evidence base for decision-making (see BEECHIE *et al.*, 2010; FRYIRS *et al.*, 2018). These practices are less costly to implement and maintain than traditional, engineering-based approaches to river management (BRIERLEY *et al.*, 2002, 2008).

This paper applies findings from a case study in the Macaé Catchment in Rio de Janeiro State to show how the River Styles Framework (BRIERLEY; FRYIRS, 2005) provides an appropriate platform to develop coherent approaches to land and water management.

## Overview of the River Styles Framework

The River Styles Framework promotes management practices that ‘work with nature’ in a catchment-specific manner (BRIERLEY; FRYIRS, 2005). The procedures are generic and can be applied in any river system (e.g. regulated and non-regulated; rural and urban). This process-based framework incorporates both channel and floodplain features, framing contemporary river character and behaviour in an evolutionary context. Each reach is placed in its catchment setting, analysing patterns of physical linkages (and associated concerns for flux, fragmentation, landscape connectivity and lagged and off-site responses). Critically, the framework is a learning tool – it is open-ended, such that new variants of river can be added as required (e.g. FRYIRS; BRIERLEY, 2009).

The River Styles Framework has four stages (Figure 1). The first stage entails determination of river character and behaviour at the reach scale. River Styles are defined in terms of valley setting, channel planform, assemblages of channel and floodplain landforms (termed geomorphic units) and bed material texture. Some of these analyses can be semi-automated using emerging technology and datasets (FRYIRS *et al.*, 2019b). A carefully crafted convention supports identification and naming of River Styles (FRYIRS; BRIERLEY, 2018). The pattern and connectivity of reaches within a catchment are explained in relation to variability in controls along the longitudinal profile.

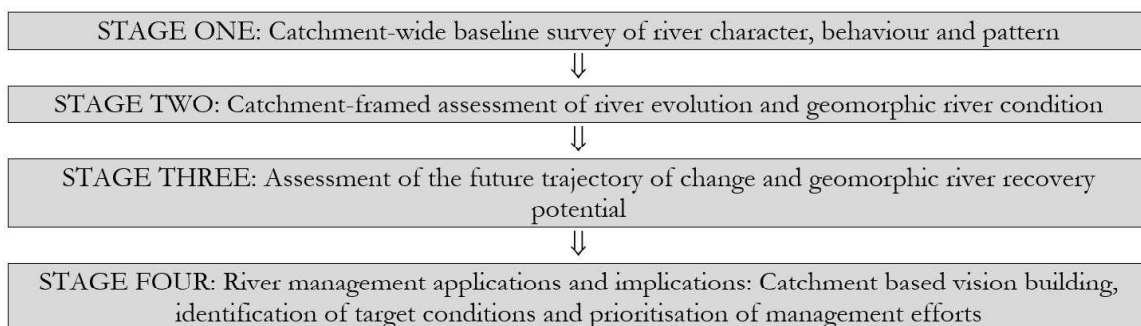


Figure 1 - The four stages of the River Styles Framework (from BRIERLEY; FRYIRS, 2005).

Stage Two of the River Styles Framework analyses geomorphic river condition. The present condition of a reach of a given River Style is appraised relative to ‘expected’ conditions for that type of river. Determining causes of geomorphic condition requires that this reach-based analysis is placed within an evolutionary context. Appropriate geoinicators are used to assess and measure the condition of different types of rivers

and their capacity to adjust (FRYIRS, 2015). These reach-scale procedures are then combined to analyze patterns of river condition at the catchment scale.

Proactive management strategies apply an understanding of evolutionary trajectory to determine what is realistically achievable in rehabilitation terms. River recovery potential is assessed in Stage Three of the River Styles Framework. Appraisal of prospective

river futures reflects the sensitivity of any given reach to human disturbance, on the one hand, and the catchment-scale linkage of disturbance responses (i.e. how adjustments in one reach affect other reaches) on the other (see BRIERLEY; FRYIRS, 2009; FRYIRS *et al.*, 2009). Reaches that continue to operate as the same River Style despite human disturbance are differentiated from those reaches that have experienced a fundamental change in process-form relationships (i.e. a transition to a different set of geomorphic units with a different behavioural regime; see Brierley *et al.*, 2008). Appraisal of whether adjustments have been reversible or irreversible, over management timeframes of 50-100 years, is used to determine the range of optimal conditions that can be achieved through rehabilitation practice. Catchment-scale analyses are used to identify threatening processes that may compromise future geomorphic river condition (e.g. downstream passage of pulses of sediment, headward extension of knickpoints). Assessment of key pressures and limiting factors on functionality helps to ensure that management activities strive to rectify problems by focussing on underlying causes rather than their symptoms (e.g. bed processes are appraised prior to addressing bank erosion processes).

Stage Four of the River Styles Framework considers management applications. First, a vision of what is achievable (or desirable) is determined, striving to achieve the best-attainable catchment-wide river structure and function given the boundary conditions under which the river operates today. Due regard is given to the diversity of rivers, the identification of unique, rare or remnant river types, appraisal of reach condition, and recovery potential. Second, target conditions for any given reach are framed in relation to a catchment-scale vision, assessing the level of intervention that is required using appropriate measures. Catchment-framed rehabilitation plans strive to minimize off-site impacts, recognizing that treatment responses from one reach will inevitably impact upon reaches both upstream and downstream. A prioritization framework for management actions applies a conservation-first and recovery enhancement approach, emphasizing the maintenance of good-condition remnants and unique/rare reaches as the highest priority (FRYIRS; BRIERLEY, 2016). Protection of these areas makes sense in both environmental and economic terms. Degrading influences that may threaten the inherent value of these reaches are addressed as *strategic* priorities. Unless threatening processes are treated, recovery of

adjoining conservation or high recovery potential reaches may be compromised or require extreme, very expensive measures to rehabilitate, often with limited assurance that success will be achieved. Examples of strategic initiatives include management of headcuts in downstream reaches, or sediment slugs in upstream reaches. Next, emphasis is placed upon those reaches that have *high recovery potential* (helping the river to help itself). Improvements to river condition in high recovery potential reaches enhance prospects to address concerns in poor condition reaches over the longer term. These recovery enhancement initiatives build out from conservation reaches in the first instance; then work outwards from good condition reaches with high recovery potential that may be isolated in the catchment. Such reaches act as loci from which to work. Finally, concerns for *moderate* and *low recovery potential* reaches are addressed, recognizing explicitly that application of extensive and expensive rehabilitation techniques may yield limited success and that problems in these reaches can only be meaningfully managed when issues elsewhere in the catchment have been addressed. Critically, this approach to prioritisation can be directly linked to the level of intervention (and cost) involved in rehabilitation. Working with recovery is effective in both financial and environmental terms (FRYIRS *et al.*, 2018). Comprehensive monitoring programmes support ongoing (adaptive) learning (see BRIERLEY *et al.*, 2010), providing the evidence-base to assess the effectiveness of management actions (PALMER *et al.*, 2005).

While such scientific guidance may clash with social priorities and values, especially the quest for short-term, quick-fix solutions, not adopting such strategies and philosophies can harm long term prospects for environmental repair, as lack of success may reduce societal confidence in our capacity to promote more effective practices.

### **Prospective Use of the River Styles Framework to Support River Management Activities in the Macaé Catchment, Rio de Janeiro State**

Marçal *et al.* (2017) document an application of the River Styles Framework in the Macaé Catchment in Rio de Janeiro State. The river flows from steep hill country through rounded foothills to lowland terrain, draining a catchment area of 1800 km<sup>2</sup>. Lowland parts of the catchment have been subjected to a 'typical' Brazilian history of land use impacts post-colonization,

while headwater areas are relatively intact and are now protected in conservation zones. Marçal *et al.* (2017) show how post-colonial impacts have modified forms and rates of geomorphic river adjustment and the connectivity of process relationships in the catchment. Their study outlines how geographical and historical factors influence prospects for future management options through designation of 'moving targets' for management (BRIERLEY; FRYIRS, 2016). These possible future trajectories are based upon differing climate, land use and management scenarios. Building upon this work, this paper presents an overview of management applications that use core principles of the River Styles Framework:

1. Use a landscape template as an integrative platform.
2. Respect the inherent diversity of river forms and processes.
3. Work with variability, adjustment and change.
4. Know your catchment, understanding patterns of river types and tributary-trunk stream relationships.
5. Compare like with like in assessing geomorphic river condition.
6. Forecast prospective river futures to set moving targets for management based on appraisal of geomorphic recovery potential, as determined by the evolutionary trajectory of the river and catchment-scale sediment (dis)connectivity.
7. Apply a conservation-first and recovery enhancement ethos in the development of visionary yet realistically achievable management plans that have a clear evidence base for prioritization of actions.
8. Monitor and learn effectively using adaptive management principles.

#### **Principle 1 - Use a landscape template as an integrative platform**

As principles from geomorphology and hydrology are innately tied to ecological applications through complex suites of mutual interactions, a landscape platform provides a physical template to integrate understandings of ecosystem structure and function (e.g. JUNGWIRTH *et al.*, 2002; WIENS, 2002; BRIERLEY; FRYIRS, 2005, 2008). In simple terms, biodiversity is inherently linked to habitat availability and viability, and geodiversity directly shapes these relationships (e.g. CHESSMAN *et al.*, 2006; THOMSON *et al.*, 2001, 2004). Although ecosystem integrity is influenced by

many non-geomorphic factors, ecosystem potential will NOT be met unless geomorphic river forms and processes are appropriate for a given setting. When used effectively, an integrative physical template can be used to inform policy, planning and on-the-ground applications in a cross-scalar manner. Even more substantively, associated concerns for place draw upon links with socio-economic and cultural relations to river systems through shared understandings of biophysical-and-cultural landscapes (MOULD *et al.*, 2018; WILCOCK *et al.*, 2013).

Further work is required through collaborations with river engineers, aquatic ecologists and other practitioners to ensure that the landscape template for the Macaé Catchment documented by Marçal *et al.* (2017) underpins the development of a shared (integrative) information base for future decision-making. Most importantly, work with policy and planning personnel, and the local community, is required to enable and embed management success.

#### **Principle 2 - Respect the inherent diversity of river forms and processes**

Each catchment is unique because it is made up of patterns of interconnected river reaches, each of which may be distinctive in its own right (BRIERLEY *et al.*, 2013). Effective management builds upon key attributes of the character and behaviour of any given reach, and process linkages to other reaches. Concerns for diversity are manifest across a range of spatial scales, from particular landforms and habitats through to reach, catchment and ecoregion-scale applications.

The River Styles Framework applies an open-ended approach to river characterization, recognizing that there is no magic number of river types, and distinct forms and patterns may be found in a given setting. The distribution of River Styles in the Macaé Catchment is shown in Figure 2, along with six representative site locations that demonstrate the diversity of geomorphic units associated with different types of river (see FRYIRS *et al.*, 2019a). Significant differences in the presence and character of floodplains, the continuity (or absence) of a channel, and the assemblage of instream geomorphic units result in profound variability in habitat availability in these examples. Some reaches are heterogeneous, while others are relatively homogenous (e.g. the Laterally unconfined,

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discontinuous channel, swamp, fine grained versus Confined, bedrock margin-controlled, occasional floodplain pockets, boulder bed). Recognizing the inherent complexity or simplicity of river reaches and respecting what is ‘expected’ is a critical component of

‘working with nature’ (FRYIRS; BRIERLEY, 2009). Appraisals of river complexity should be tailored for the type of river under consideration, as ecosystems are adapted to the inherent geomorphic structure/habitat for different river types.

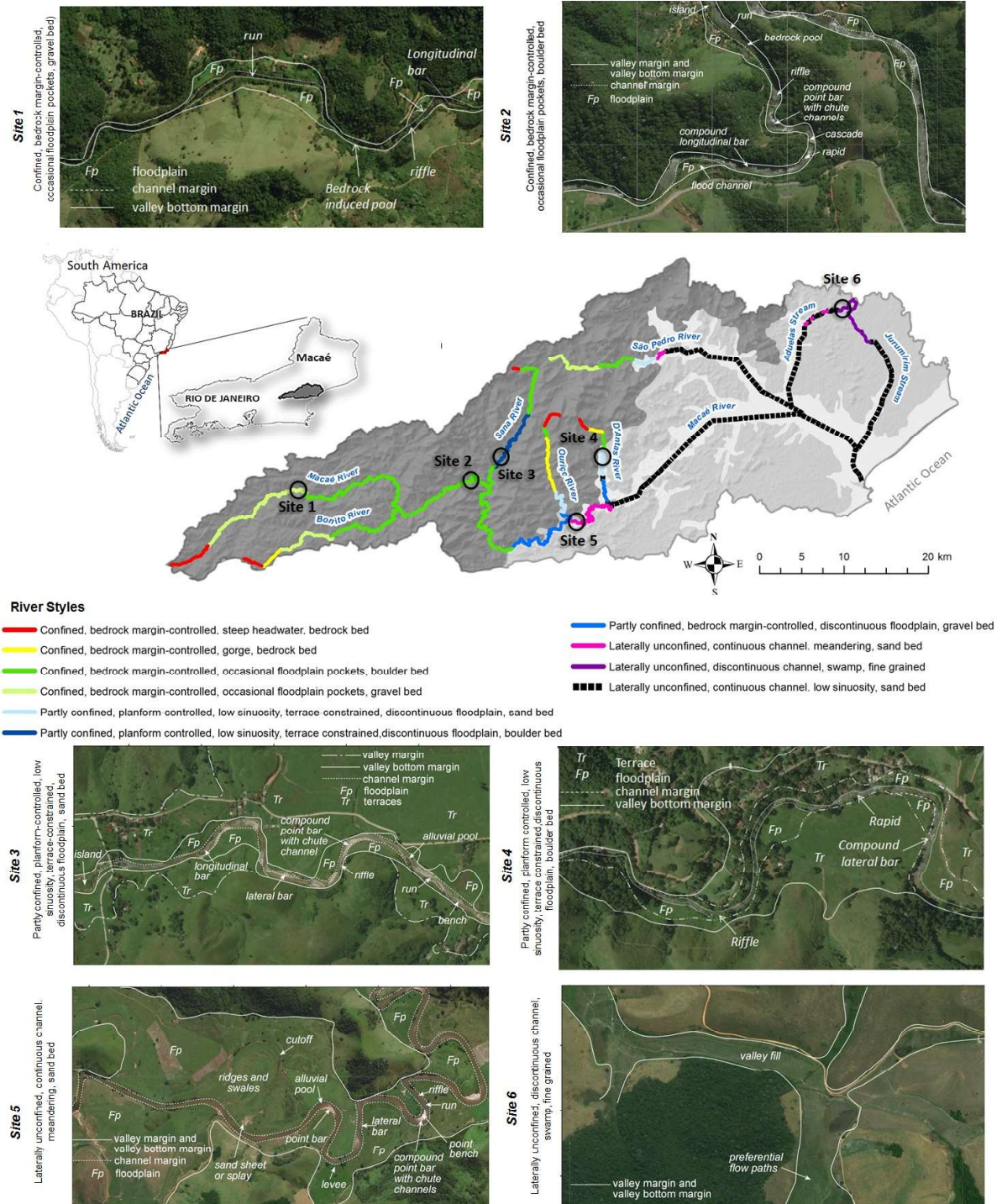


Figure 2 - The diversity of River Styles in the Macaé Catchment and examples of geomorphic maps for four of these River Styles. See Marçal et al. (2017) and Fryirs et al. (2019a) for further details.

### Principle 3 - Work with variability, adjustment and change

Effective management practices with a biodiversity focus work with the adjusting nature of the river (i.e. its range of behavior, which defines the dynamic physical habitat mosaic of a given reach), rather than aiming to fix a river in place (FRYIRS; BRIERLEY, 2009). Rivers are never static. In the River Styles Framework, a critical distinction is made between river behaviour and river change (BRIERLEY *et al.*, 2008). River behaviour refers to adjustments around a characteristic form for a given type of river. In contrast, river change refers to the adoption of a different type of river at a particular location (i.e. transition from one type of river with a given behavioural regime, to a different type of river with a different behavioural regime). Crossing a physical (abiotic) threshold limits prospects for geoecological recovery (e.g. BROOKS; BRIERLEY, 2004; CHESSMAN *et al.*, 2006; FRYIRS; BRIERLEY, 2001). If the physical structure of a river changes, so does everything else.

Each River Style varies in the ways in which it adjusts, the patterns of adjustment (i.e. the distribution of erosional and depositional processes) and the rate at which different adjustments take place. These characteristic behavioural traits are summarized to define the range of geomorphic behaviour for each River Style (i.e. its behavioural regime). Each type of river varies in terms of its capacity for adjustment (i.e. its range of variability) and the frequency of occurrence of formative flows (i.e. how the river adjusts at low flow, bankfull-stage events and during floods that go overbank). The frequency with which such events occur vary from reach to reach. Some rivers are relatively sensitive to adjustment, while others are quite resilient. Understanding a river's inherent capacity for adjustment in the vertical, lateral and wholesale dimensions, along with analysis of process-form associations of geomorphic units provides an interpretative basis to assess river behaviour and responses to disturbance events.

Appropriate understanding of the formative processes that create and rework the geomorphic structure of a river builds upon analysis of the assemblage of geomorphic units that make up the channel and floodplain compartments of a given river each. This provides a key interpretative tool to assess the role of flow events that

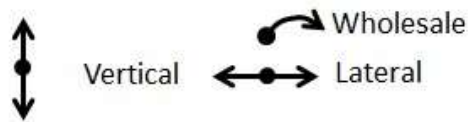
define the range of behaviour and the capacity for adjustment of a given reach. The morphodynamics of a reach determines the sediment regime, which in turn exerts a primary control upon ecological relationships (see WOHL *et al.*, 2015). As River Styles are often subjected to characteristic degradational tendencies, understanding process-based behaviour enables practitioners to:

1. Target key reach-based problems in a strategic manner, addressing the underlying causes of deterioration, rather than just the symptoms. All too often, engineering measures treated all rivers in the same way, using 'blanket' applications to 'fix' a river (e.g. SPINK *et al.*, 2009).
2. Interpret reach-scale responses to disturbance, determining the expected behaviour of a reach.
3. Identify benchmark reference reaches for differing River Styles that have an 'expected' range of character and behavior. This provides a realistic sense of the target conditions for management efforts, aiding meaningful transfer of understanding from one situation to another.
4. Determine appropriate forms and approaches to rehabilitation that are tailored to process-based understandings of the specific River Style under investigation.

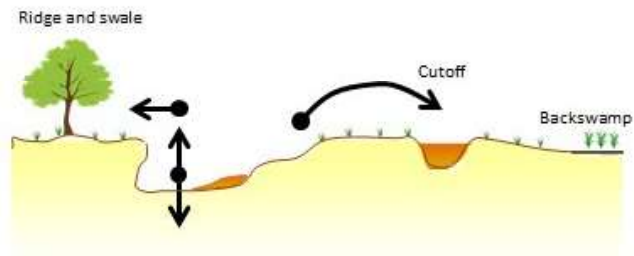
Forms and rates of geomorphic adjustment are shown for four different River Styles in Macaé Catchment in Figure 3. The fully alluvial reach (Figure 3a) has significant capacity to adjust in vertical, lateral and wholesale dimensions. This river is expected to erode or deposit along its bed and banks, to form and rework its floodplain, or experience a wholesale shift in channel position on the valley bottom (through either lateral migration or the creation of a cut-off). In contrast, the swamp situation shown in Figure 3b slowly accumulates sediment on the valley bottom through vertical accretion processes, yet it is prone to incision under exceptional circumstances (i.e. this is a cut-and-fill landscape). A bedrock valley margin and terrace constrain the capacity for geomorphic adjustment in the low sinuosity planform example shown in Figure 3c. Local lateral adjustment is possible adjacent to floodplain pockets, and the channel may adjust vertically. Finally, the confined reach (Figure 3d) has limited capacity for geomorphic adjustment because it is constrained by bedrock on the bed and banks. Adjustments are limited to local aggradation of coarse-grained bedload materials



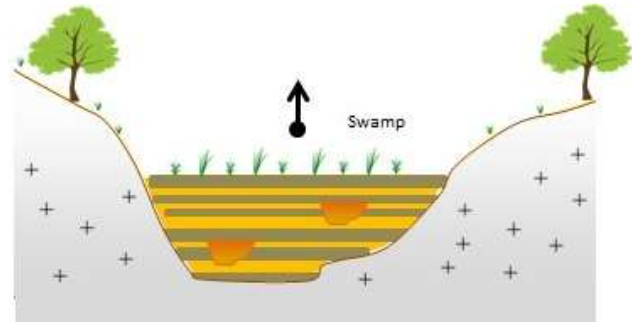
**Form of Adjustment**



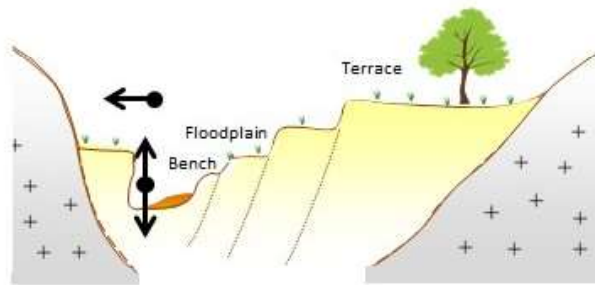
**(a)**  
Laterally unconfined,  
continuous channel,  
meandering, sand bed



**(b)**  
Laterally unconfined,  
discontinuous channel,  
swamp, fine grained



**(c)**  
Partly confined,  
planform controlled,  
low sinuosity, terrace constrained,  
discontinuous floodplain, sand bed



**(d)**  
Confined,  
bedrock margin-controlled,  
occasional floodplain pockets,  
boulder bed

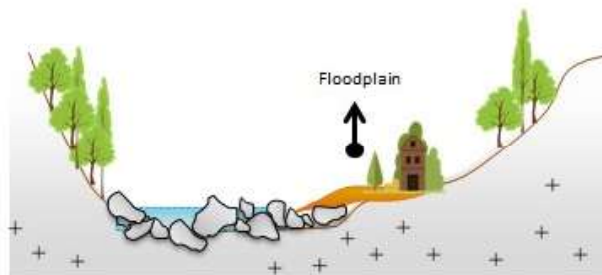


Figure 3 - Schematic diagrams showing capacity for adjustment for four River Styles from the Macaé Catchment.

and occasional accretion of small floodplain pockets.

Figure 4 shows a dramatic example of profound change in River Style along the lower course of the Macaé River. Creation of an artificial channelized reach transformed the remarkable diversity of a sand-bed meandering reach (similar to the river in Figure 2, Site 5 and Figure 3a) that contained riffles, pools

and numerous cut-off channels (ox-bow lakes or billabongs) and backswamps on the floodplain into a near-featureless channel trough with a continuous sand sheet. The over-enlarged channel is now functionally disconnected from the floodplain (MARÇAL *et al.*, 2017). Profound habitat loss and adjustments to aquatic ecosystem functionality accompanied these



Figure 4 - A channelized section of meandering sand bed river along the lower course of the Macaé River. This photograph picture was part of the collection from the now defunct agency DNOS (National Department of Construction and Sanitation; now part of the Municipal Public Archive Waldir Pinto de Carvalho (Campos dos Goytacazes, RJ).

geomorphic changes.

**Principle 4 - Know your catchment, understanding patterns of river types and tributary-trunk stream relationships**

Each river system has its own set of biophysical conditions, and its own history (and memory) of disturbance events. In planning and implementing any river rehabilitation activity, it is critical to relate position in the catchment to the pattern of river types and associated tributary-trunk stream relationships. In the River Styles Framework, these relations are analyzed and explained as patterns of river reaches along the longitudinal profile (BRIERLEY; FRYIRS, 2005). Marçal *et al.* (2017) and Fryirs *et al.* (2019a) present a fully processed analysis of downstream patterns and controls along the trunk stream of the Macaé River. Various tributary systems that feed into the Macaé have different patterns of river types along their course. Given variability in the sensitivity to geomorphic adjustment of these reaches, and differences in the connectivity relationships in each subcatchment, these tributaries have differing impacts upon the behaviour of the trunk stream (MARÇAL *et*

*al.*, 2017).

Figure 5 shows the downstream pattern of River Styles for two adjacent tributary systems – the Ouriço and D’Antas Rivers (located on Figure 2). The laterally-unconfined mid-lower catchment reaches along the D’Antas River are more prone to geomorphic adjustment than the more confined reaches that occur along the Ouriço River. The steeper longitudinal profile of the D’Antas likely results in more accentuated, geomorphologically effective flood flows that are able to rework the significant sediment stores along the wider valley. The D’Antas River has greater impact upon geocological attributes of the trunk stream than is evident at the Ouriço-Macaé confluence (see MARÇAL *et al.*, 2017). This reflects the greater capacity for geomorphic adjustment of the patterns of river reaches along D’Antas River, thereby resulting in significant sediment build-up at the D’Antas confluence (Figure 5E). There is no equivalent sediment accumulation at the Ouriço-Macaé confluence (Figure 5D).

The example shown in Figure 5 demonstrates the importance of not only assessing the behavioural

regime of a given type of river, but also analyzing the geomorphic processes that create and rework the river in relation to prevailing flow and sediment

fluxes that are determined by catchment scale relationships. Hence, each reach must be viewed in its catchment context. Hence the mantra: Know your

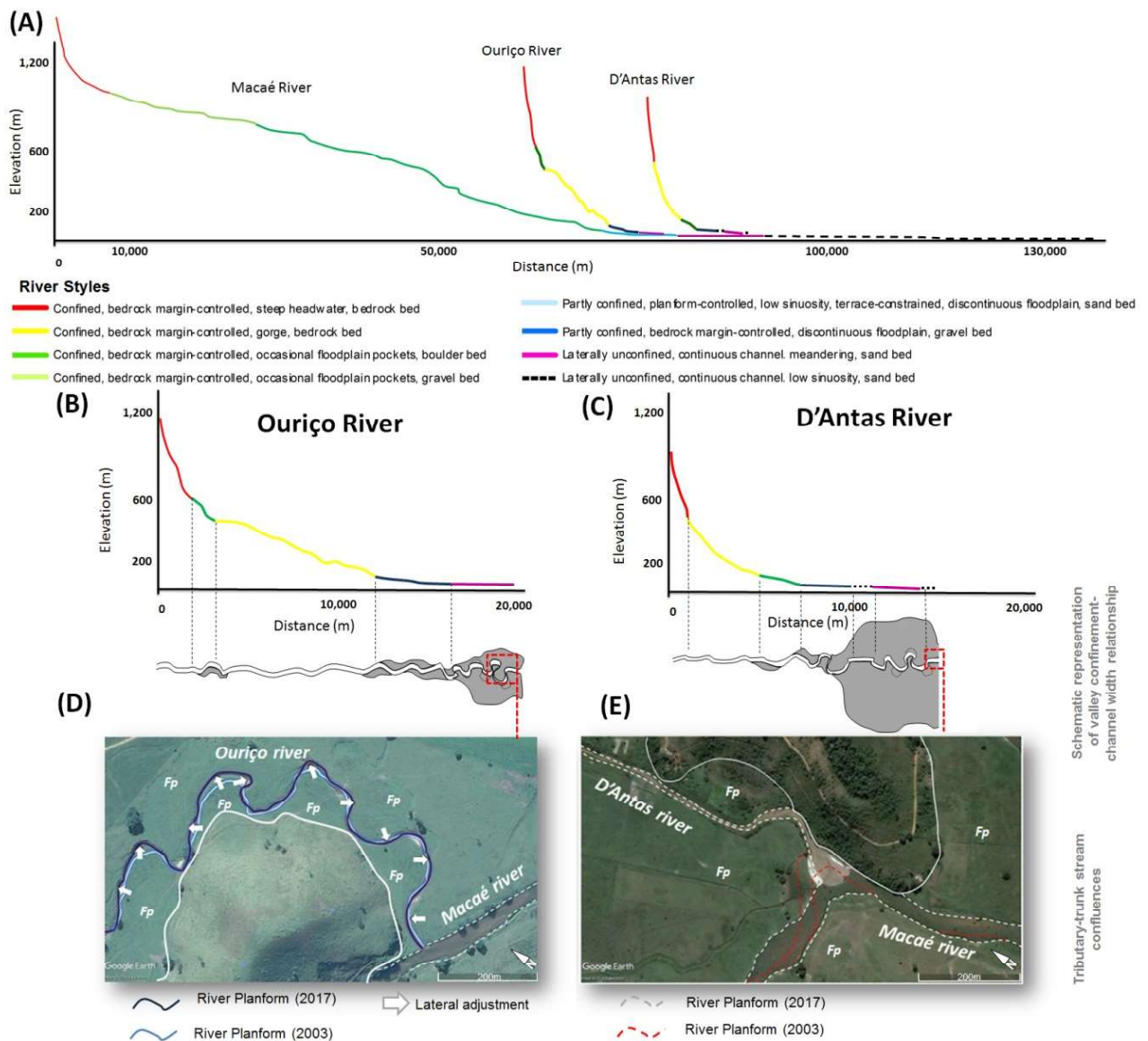


Figure 5 - Example of how different patterns of rivers and their variable sensitivity to adjustment create different tributary-trunk stream relations - Ouriço and D'Antas Subcatchments (see Marçal et al. (2017) for details).

catchment.

**Principle 5 - Compare like with like in assessing geomorphic river condition**

Given the range of geomorphic processes that create differing River Styles, effective management practices build upon process-based understandings of the type of river under consideration. This supports efforts to treat the causes, rather than the symptoms, of river adjustment. These considerations also underpin analyses of geomor-

phic river condition (see FRYIRS, 2015).

Using the examples shown in Figure 3, bank erosion is an important and expected process along concave banks of a laterally unconfined meandering river (Figure 3a) and the planform-controlled low sinuosity river (Figure 3c), but it is not an expected process in the other two examples. As sand is the most readily entrained material in river systems, the examples shown in Figures 3a and 3c have significant capacity to adjust,

but the former is far more sensitive than the latter. In both instances, bed stability is the key to prospective geomorphic adjustments. Limited space on the valley floor restricts the potential for the planform-controlled low sinuosity river to shift its position, while the meandering sand bed river may develop cut-off channels or in extreme instances it may avulse.

Appropriate measures of geomorphic river condition vary markedly for these four examples. Figure 3b has a homogeneous geomorphic structure, such that a good condition variant has a low diversity index (FRYIRS; BRIERLEY, 2009). In contrast, the three other examples are more heterogeneous and have higher diversity indices. This is especially the case of the meandering sand bed river (Figure 3a), where the floodplain compartment is a vital component of reach scale diversity. These are important considerations in determining appropriate management practices to protect or enhance the geomorphic condition of the river.

**Principle 6 - Forecast prospective river futures to set moving targets for management based on appraisal of geomorphic recovery potential, as determined by the evolutionary trajectory of the river and catchment-scale sediment (dis)connectivity**

Assessment of reach scale adjustments and biophysical linkages at the catchment scale provides fundamental information with which to interpret the trajectory of geomorphic river adjustment. This entails analysis of sediment (dis)connectivity between hillslope and valley floor processes, channels and floodplains, tributaries and trunk streams, and longitudinally from reach to reach (and interactions with coastal environments) (FRYIRS, 2013; FRYIRS *et al.*, 2007). Marçal *et al.* (2017) outline various future scenarios for the Macaé River system through foresighting exercises, framing 'moving targets' for management actions in relation to management choices: steady as she goes, a doomsday scenario based on continuation of a 'command and control' approach to river management, and an option for a geomorphologically-informed ecosystem approach to environmental management. As noted on Figure 5, any effort to forecast or predict geomorphic river futures is dependent upon reach scale attributes on the one hand (i.e. geomorphic character and behavior, and sensitivity to adjustment) and reach position in relation

to prevailing fluxes and threatening processes (such as a head cut or downstream translation of a sediment slug) on the other (i.e. the pattern of River Styles and their longitudinal connectivity are vital). Brierley and Fryirs (2009) refer to the design of river conservation and rehabilitation measures that build upon this premise as: "Don't Fight the Site." These insights help to determine 'what is realistically achievable' in managing the river. Meaningful visions for river conservation and rehabilitation give due regard to strategic sites that protect conservation priorities (e.g. rare or endangered species) while addressing threatening processes.

Various stages of geomorphic adjustment in response to human disturbance can be identified for different types of river. Forms of adjustment along a degradation pathway, and subsequent transitions to a recovery pathway, are shown on the river recovery diagram for two River Styles in the Macaé Catchment on Figures 6 and 7. Along the lower Macaé River, sections of the laterally unconfined, meandering sand bed river have been irreversibly changed to a laterally unconfined low sinuosity river through artificial channelization (Figures 4 and 6). Some reaches continue to operate as a meandering sand bed river. Hence, the recovery diagram shown in Figure 6 is quite complicated, with various stages of adjustment evident, whether degradational or recovery stages (see figure caption for details). Given the significant geomorphic sensitivity of this kind of river, there is considerable difference in the range of 'condition' variants shown in Figure 6, and also the prospect that improvement in geomorphic river condition can be achieved. The key river management issue in this situation is to prevent damage before recovery prospects become limited (i.e. adoption of a precautionary approach to river management; prevention is cheaper and more effective than cure). Restoration is possible in remnant reaches of laterally unconfined, meandering sand bed river. However, further work is required to appraise the geomorphic sensitivity of laterally unconfined reaches upstream of the channelized section of the Macaé trunk stream. Initial analyses reveal limited instream adjustment and a low rate of lateral migration despite the sand bed conditions, limited riparian vegetation cover and significant floods in recent years. Also, the pulsed nature of sediment movement as sand sheets translate through the channelized reach, which results in recur-

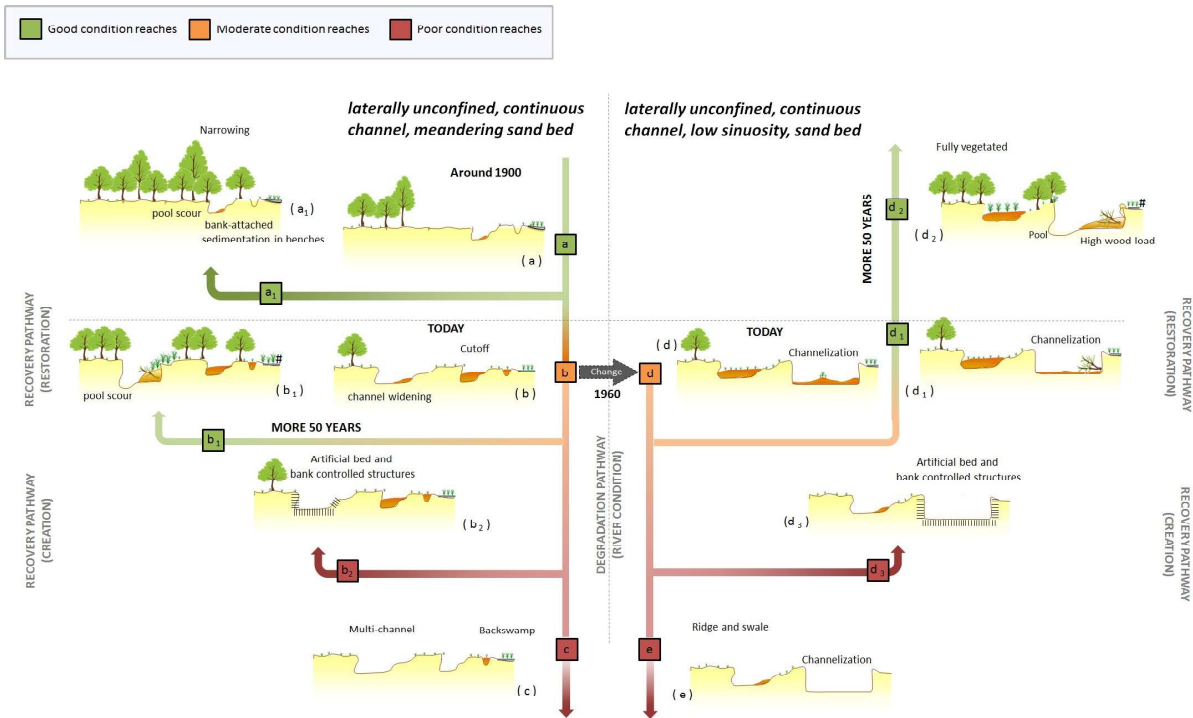


Figure 6 - Recovery diagram showing stages of geomorphic adjustment and prospective trajectories of adjustment for the laterally unconfined, continuous channel, meandering sand bed reaches of the Macaé River. Moving further away from the intact condition along the degradation pathway (stage a), the channel becomes larger and more disconnected from the floodplain, impacting on geomorphic river condition (from moderate condition at stage b to poor condition at stage c). This reduces prospects for geomorphic river recovery. Recovery along a restoration pathway is only possible after minimal disturbance (i.e. from stage a to stage a1). Channelization of the meandering sand bed river resulted in change to a different River Style (a low sinuosity sand bed river) with a different assemblage of geomorphic units and a different behavioral regime (stage d). Recovery of this river is marked by channel contraction and re-connection to the floodplain under geomorphologically effective management actions (improvement to a good geomorphic condition at stage d2), whereas further degradation is reflected in a habitat-poor oversized channel that is disconnected from its floodplain (stages d3 or e; both are considered to be poor condition variants).

rent rises and falls in bed level, is poorly understood.

A different evolutionary trajectory and range of management options based on recovery prospects is evident for the partly confined, planform controlled, low sinuosity, terrace-constrained, discontinuous floodplain, sand bed river shown in Figure 7. In this instance, degradation is reversible and recovery prospects are high. This reflects the relative resilience of this type of river, the fact that river change has not occurred, and fundamental transitions in flow/sediment flux have not transformed connectivity relationships in this part of the catchment.

**Principle 7 - Apply a conservation-first and recovery enhancement ethos in the development of visionary yet realistically achievable management plans that have a clear evidence base for prioritization of actions**

Biodiversity management implicitly entails an

understanding of what attributes we seek to protect and how we undertake their protection. Typically, policy applications for biodiversity management are applied at the *ecoregion* scale. In geodiversity terms, identification and protection of unique and/or rare river types is a first step in conservation and rehabilitation planning. Treatment of threatening processes that may impact on these values is a core component of proactive management.

In order to develop a coherent catchment management plan it is important to seek agreement on the key problems to be addressed. This requires appropriate insight that explains how a reach has achieved its current state. It pays to assess likely future condition if the river is left alone. If interventions are required, what treatments are recommended, and where/when should they be applied? Importantly, such measures should be framed and applied in ways that reflect interactions of biophysical process at the catchment-scale. This underpins the development and implementation of strategic and cost-effective approaches

**Partly confined, planform controlled, low sinuosity, terrace constrained, discontinuous floodplain, sand bed**

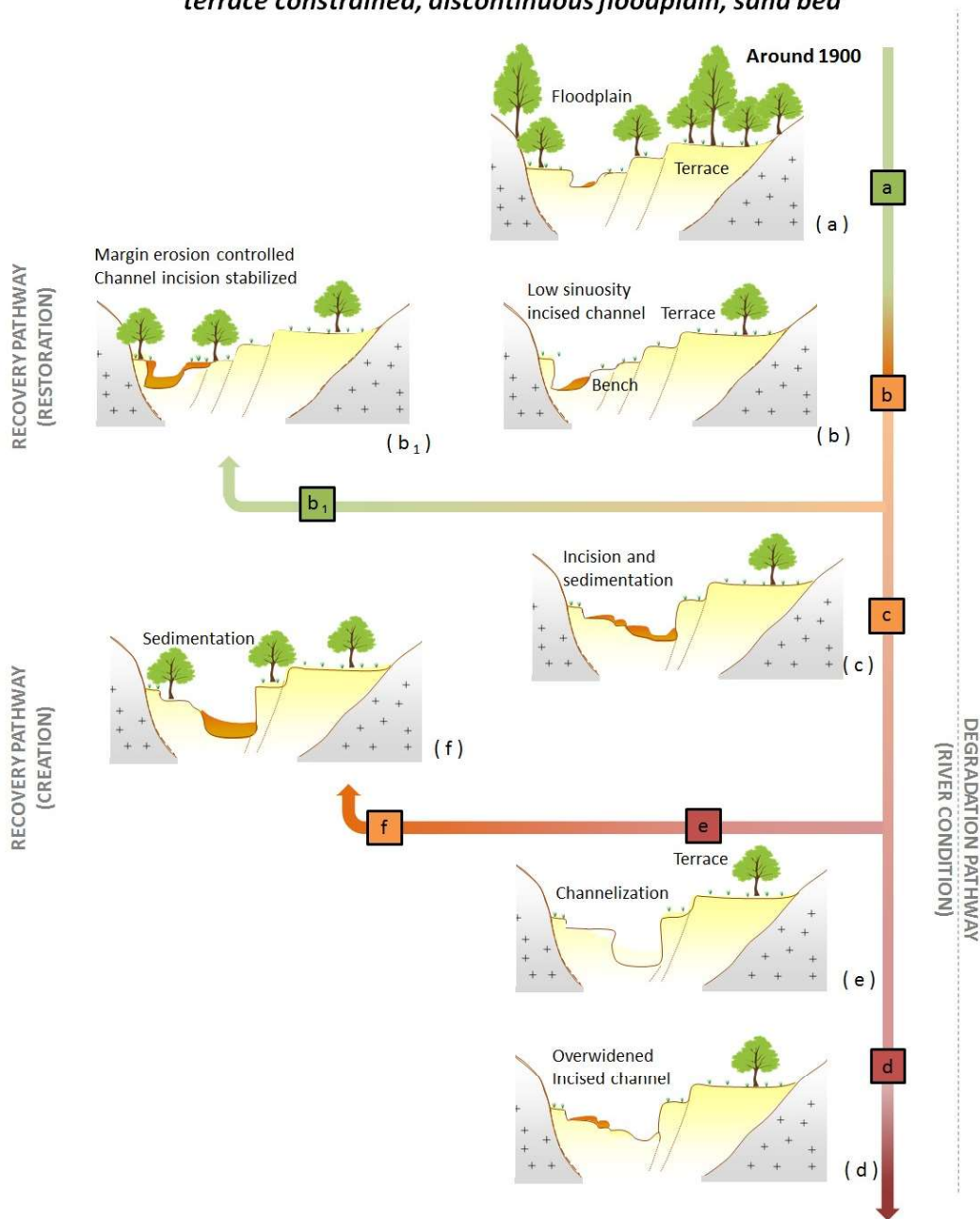


Figure 7 - Recovery diagram for Partly confined, planform controlled, low sinuosity, terrace constrained, discontinuous floodplain, sand bed river. Degradation from an intact state (stage a) to a moderate condition reach associated with degradational influences (stage b) is characterized by channel expansion, with prospect for bench sedimentation and return to a good condition variant if recovery occurs (stage b1). However, if degradation continues, and the channel deepens further and increases further in size, the potential for recovery is reduced and the reach has a poor geomorphic condition (stages c and e). The further down the degradation pathway the reach proceeds, the lesser the prospects for recovery. Hence, it is recommended that a transition to a recovery pathway is adopted as soon as possible (indicated by improvement to a moderate condition reach in stage f).

to prioritize management actions, striving to maximize benefits while minimizing negative off-site impacts.

Application of a conservation-first ethos as part

of the River Styles Framework can be used to identify what should be protected. This entails determination of good condition reaches and associated habitat values before they are lost. Then, it is important to determine

where recovery is possible (and likely), so that management efforts can help the river system to self-heal as a part of proactive catchment management plans (FRYIRS; BRIERLEY, 2016; FRYIRS *et al.*, 2018). Process-based analyses of river character, behavior, patterns and evolutionary traits (i.e. recovery prospects) provide fundamental guidance in determining what is realistically achievable in management terms.

Application of geomorphic recovery principles to inform river management options in the Macaé Catchment is shown in Figure 8 (based on MARÇAL *et al.*, 2017). In this instance, upstream reaches have high recovery

potential and given their good geomorphic condition they are designated as conservation priorities. These confined upland valleys help to maintain the sediment balance of the basin as a whole, as landslides are common in the extensive source zone, and the river has significant capacity to flush sediments downstream in this longitudinally connected system. Managing prospective issues at source is an important consideration in a geomorphologically-informed management plan. Beyond this zone, mid-catchment reaches with high recovery potential are considered a high priority for rehabilitation (see FRYIRS; BRIERLEY, 2016). However, coincident with the D’Antas confluence,

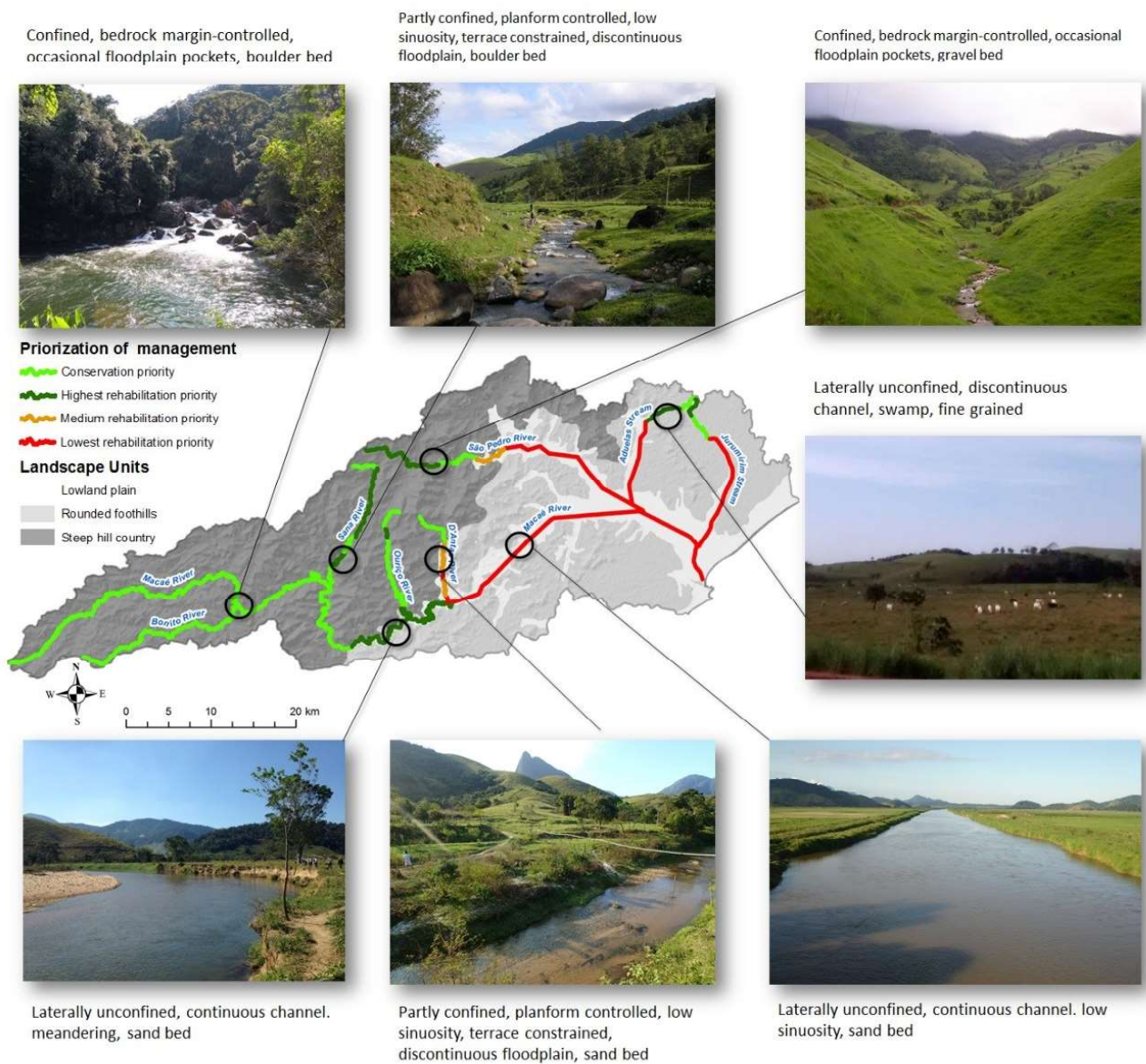


Figure 8 - Application of the River Styles prioritization framework and decision tree for management actions for the Macaé catchment (based on Marçal *et al.*, 2017).

as noted on Figure 5, there is a transition to a low priority reach in downstream areas because prospects for recovery are greatly reduced in this section of river.

Two additional examples of conservation and/or rehabilitation prospects and priorities have been identified in the Macaé Catchment. Given extensive floodplain habitat, reintegrating flows and functional habitat in cut-off channels and backswamps could make

a strategic management initiative along parts of the lowland reach. In their appraisal of moving targets for the Macaé River, Marçal *et al.* (2017) consider this an option for geomorphologically-effective approaches to river management (see also OPPERMAN *et al.*, 2009).

As an immediate priority measure, Figure 9 shows the distribution of remaining lower order swamps and discontinuous watercourses in the Macaé Catchment.

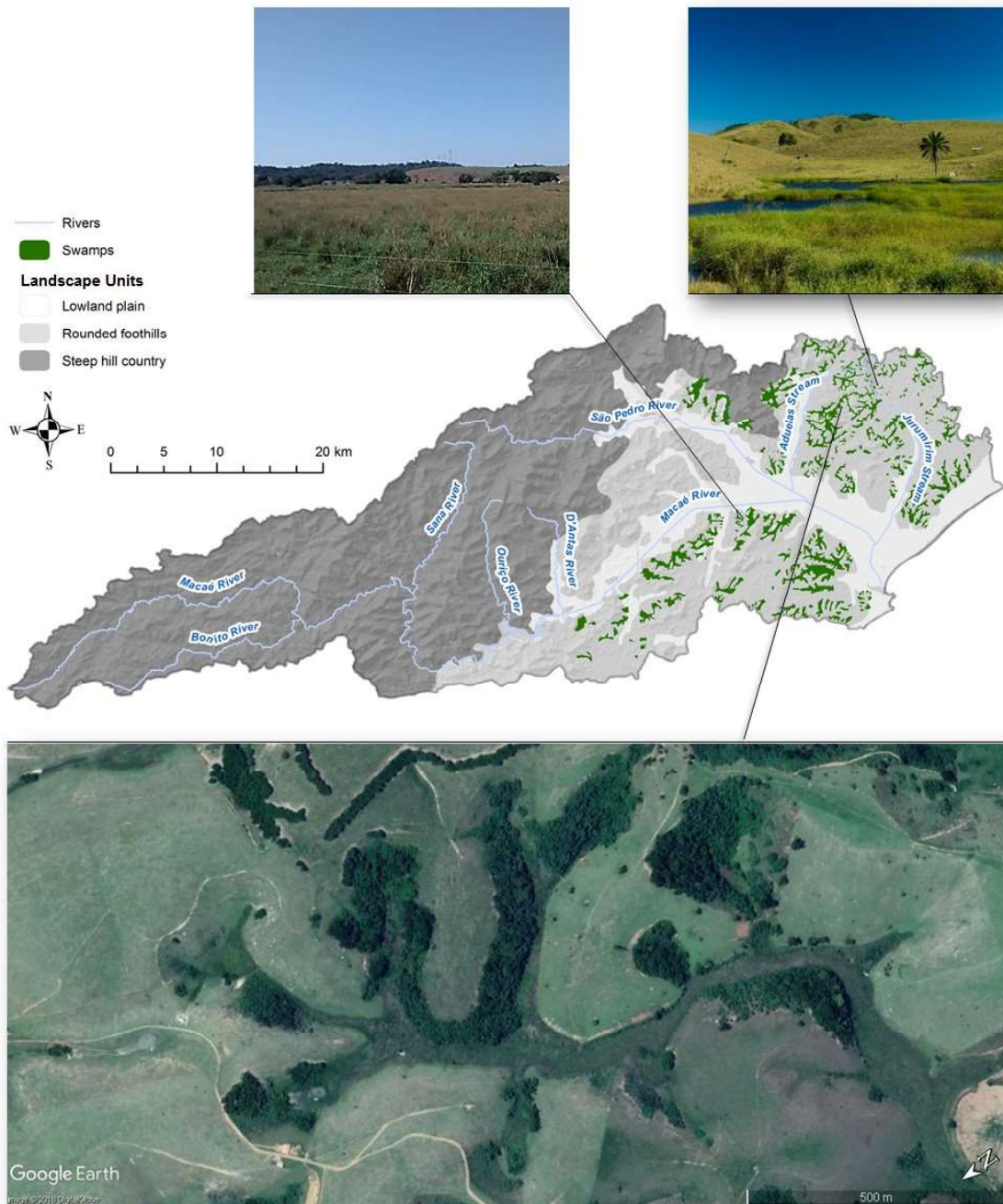


Figure 9 - Distribution of laterally unconfined, discontinuous channel, swamps that would receive a strategic conservation and rehabilitation priority in the Macaé Catchment.



Given their fundamental role as sponges and filters in the landscape, these areas are identified as conservation priorities.

**Principle 8 - Monitor and learn effectively using adaptive management principles**

Adaptive management practices adopt a learning approach, whereby management is viewed as an experiment in which effective monitoring supports efforts to learn effectively from experiences, whether positive or otherwise. Effective use of monitoring data allows agencies and decision makers to respond and adapt quickly to risks and opportunities, refine management interventions and develop an evidence-base for what works and what does not (BRIERLEY *et al.*, 2010; FRYIRS *et al.*, 2018). Given inherent complexities and uncertainties, adaptability and flexibility are important components in the design and implementation of catchment management plans.

**Discussion and Concluding Comment**

A paradigm shift in approaches to land and water management is required in Brazil, viewing rivers as much more than a flowing body of water (cf., BRIER-

LEY, 2019). Other components of the physical, biotic and anthropic environment need to be integrated with analyses of flow (SOFFIATI, 2013; TUCCI, 2013). This paper has shown how appraisal of geomorphic river diversity, patterns and evolutionary trajectory is required to support sustainable management practices. This transition in practice makes sense not only in socio-cultural and environmental terms, it also makes economic sense, reducing costs of ongoing river maintenance programs (cf., BUFFIN-BELANGER *et al.*, 2015).

Figure 10 shows how systematic, geographic analyses could support zoning, planning and management activities as part of Basin Plans. Catchment-specific analyses help to understand how and why rivers operate in the way that they do, determining the magnitudes and frequencies of geomorphologically effective flows that shape channel geometry and channel-floodplain interactions, the distribution of hydraulic forces and associated habitats along river courses, and sediment transport conditions. Collectively, these factors exert a fundamental control upon the ecological diversity of a river. Process-based analyses aid determination of realistic options in evaluating prospective river futures, supporting determination of targeted, cost-effective

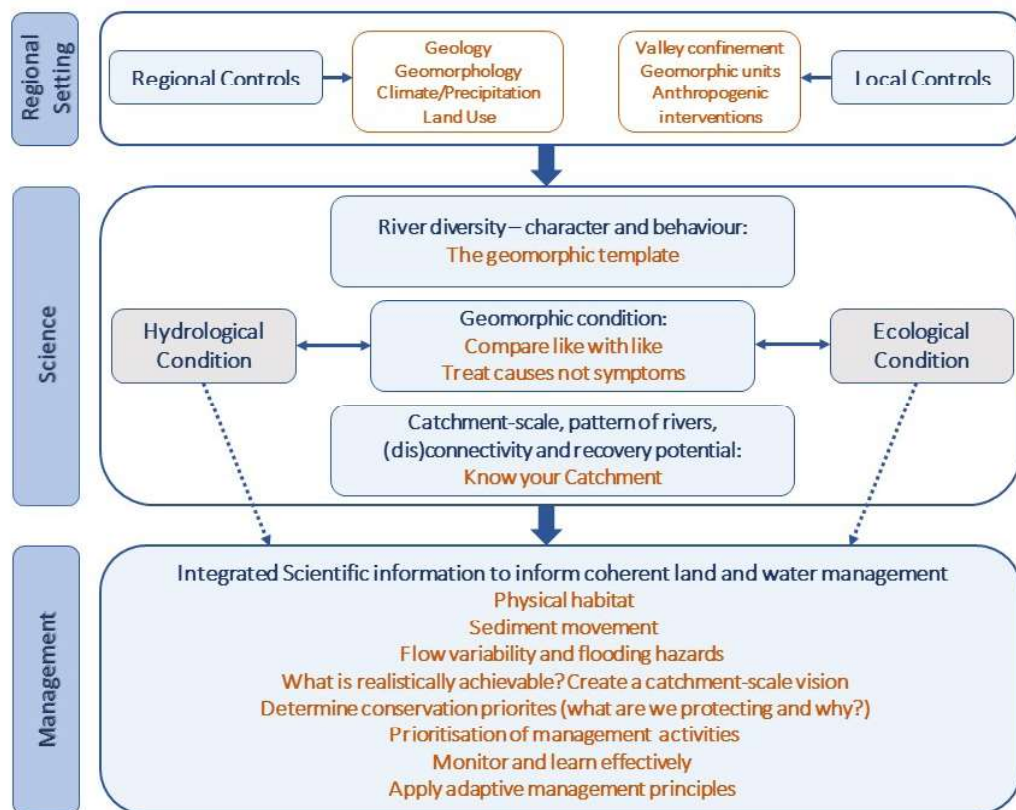


Figure 10 - Incorporating fluvial geomorphology as a coherent scientific platform to inform land and water management in Brazil.

management actions. Strategies and solutions need to be ‘fit for purpose’; after all, each river is a living entity in its own right (EVERARD; POWELL, 2002).

These assertions highlight the importance of context: recognizing, explaining and managing rivers on the basis of how they adjust and evolve, their similarities and differences to each other, and meaningful transfer of understandings and lessons learnt from management applications in one situation to another (BRIERLEY *et al.*, 2013). As outlined on Figure 10, the geology, geomorphology, soils and climate of an area influence land use potential and the ways in which landscapes and rivers can support various human activities. At any given location, local factors may be important controls upon socio-economic and cultural interactions with the river: does the river have floodplains and rich alluvial soils; are there fish and other food stocks in the river; what flood/drought and sedimentation hazards occur in that area; how does the legacy of past human activities affect the ways in which the river works today; what future character and behaviour is possible (realistically achievable)? Understanding of these regional and local scale factors is required to “Know Your Catchment”. Effective approaches to resource and environmental management directly link land and water management programmes (BRIERLEY *et al.*, 2011).

The second box on Figure 10 presents an overview of the primary geomorphic considerations that must be incorporated into a scientific appraisal of a river system. Essentially, these components represent the first three stages of the River Styles Framework (Figure 1; BRIERLEY; FRYIRS, 2005). In Figure 10, these attributes are considered alongside flow considerations (water quantity and quality) and ecological conditions (flora and fauna) to present a coherent scientific platform to inform management applications. Mika *et al.* (2010) present a conceptual model that shows how these various considerations can be brought together to develop an integrative approach to assess the evolutionary trajectory of a river. Finally, the third box on Figure 10 shows how management tasks undertaken as part of stage four of the River Styles Framework can be applied using the various principles outlined in this paper.

All too often, river management activities emphasize reactive concerns to particular problems, wherein recurrent emergencies represent a form of crisis management. Appropriately informed and locally-owned catchment action plans are required to underpin proactive management. In framing these efforts, it is important to

learn from past mistakes. Many path dependencies set by over-engineered rivers not only impact negatively on the geoecological functionality of a river, they are also extremely costly to revoke, yet ongoing maintenance costs may be exceedingly high. Failure to intervene in these situations is likely to undermine community confidence in management decision-making in the long-term.

Coherent baseline information is required to underpin logical, rational and evidence-based management actions. An open and just approach to decision-making determines what we seek to protect and repair, how to go about it, and prioritization of actions. These are vital components of proactive river management. Given inherent uncertainties about the future, it is important to incorporate future variability into management plans through articulation of ‘moving targets’ that are framed as flexible, open-ended and dynamic goals (BRIERLEY; FRYIRS, 2016). Multi-purpose applications create greater ‘buffering capacity’ in hazard management, while also addressing concerns for a range of biophysical, environmental, economic, cultural, recreational and aesthetic values (e.g. BUFFIN-BÉLANGER *et al.*, 2015; PIÉGAY *et al.*, 2005). These catchment-specific endeavors are shaped by the present condition of the river system, its inherent capacity for recovery (i.e. its resilience), policy and governance frameworks, economic and/or political will and community aspirations.

Building upon the carefully documented case study reported by Marçal *et al.* (2017), this study has shown that there is significant potential for geomorphologically-framed management actions in the Macaé Catchment in Rio de Janeiro State. While development of such information bases is time-consuming and requires an appropriate level of professional training in geomorphology, emerging technologies are providing increasingly high resolution data at lower (or zero) cost, and moves are underway to develop a cohort of appropriately skilled practitioners (FRYIRS *et al.*, 2019a).

Participation, stewardship, engagement, ownership and effective partnerships are integral components of land and water management. Enabling and supportive governance frameworks link top-down (policy) and bottom up (community) measures in productive and generative ways, linking what is biophysically possible with what is socially desirable/acceptable. Like litter campaigns, collective action is required now, rather than waiting for someone else to ‘fix’ a problem. Management efforts to maintain or enhance the health of environmental systems

are likely to be compromised unless society genuinely supports what is being done. Essentially, this is a lifestyle choice: Healthy rivers are products of healthy societies.

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