River Styles and Stream Power Analysis Reveal the Diversity of Fluvial Morphology in a Philippine Tropical Catchment

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Abstract

Characterisation of hydromorphological attributes is crucial for effective river management. In the Philippines, such applications are usually solely based on water quantity and quality. This paper uses the River Styles Framework as an alternative template for identifying the diversity of river morphodynamics as a valuable input to river management. Eight distinct River Styles (river types) were identified in the Bislak catchment (586 km^2), north-west Luzon, indicating considerable geomorphic diversity within a relatively small catchment area. Three River Styles in Confined valley settings occupy 57% of the catchment area, another three in Partly-confined valley settings occupy 37%, and two in the remaining 6% are found in Laterally-unconfined valley settings. Five characteristic downstream patterns of River Styles were identified within the tributaries. We find that variation in channel slope for a given catchment area (i.e. total stream power) is insufficient to differentiate the type of river in a given reach. Hence, topographic analyses should be complemented with broader-framed, catchment-specific approaches to predict river character and behaviour. Geomorphologically-informed analyses can support management applications in the Philippines, explicitly incorporating understanding of river diversity and dynamics.

1. Introduction

Recognition of morphological diversity and understanding of river processes (dynamics) are essential for effective river management (Brierley and Fryirs, 2005, Gurnell et al., 2015, Rinaldi et al., 2016, Hohensinner et al., 2018). Differences between rivers are often contextualised at the reach scale (10^{-1}-10^{1} km; Belletti et al., 2017) where geomorphic structure and function are approximately uniform, determined by a set of boundary conditions within which the river operates (Frissell et al., 1986; Brierley and Fryirs, 2005; Wyrick and Pasternack, 2014). Imposed boundary conditions (e.g. geology, tectonics, and climate) influence the valley setting and topography of the landscape, while flux boundary conditions such as the interaction of water discharge and sediment transport induce reach-scale variability in morphodynamics (Brierley and Fryirs, 2005). Alterations to flux boundary conditions, including human-induced pressures and disruption to water and sediment flows, may irreversibly damage fluvial systems (Rhoads, 2020). Integrating principles from hydrology, geomorphology, and ecology strengthens the potential of river management applications (Brierley and Fryirs, 2008; Brierley et al., 2019), this requires detailed information of river morphological diversity across multiple spatiotemporal scales (Gurnell et al., 2016).

A range of classification schemes have been developed to assess river morphological diversity. Generally, these schemes seek to categorise reaches by grouping similar process and form characteristics. Classification schemes vary in their approach, the environment for which they were developed, and the spatiotemporal scales over which they are applied (Kondolf et al., 2003; Buffington and Montgomery, 2013). However, Kasprak et al. (2016) demonstrate that the underlying principles and premises of such geomorphological analyses are inherently consistent, with differing approaches generating similar outputs (i.e. maps). Classification based on hydrology and river geomorphology (hydromorphology) often provides a first step in the analysis of river systems (Fuller et al., 2013), and is a fundamental starting-point when integrating interdisciplinary components of analysis (e.g. Sear et al. 1995; Gilvear 1999; Kondolf et al. 2003; Downs and Gregory 2004; Brierley and Fryirs 2005, 2008; Meitzen et al. 2013; Tadaki et al. 2014; Rinaldi et al., 2016, Dallaire et al., 2019). Many river classification schemes were designed to improve scientific understanding, rather than with an explicit focus on river management (Rinaldi et al., 2016).

Spatially-hierarchical frameworks that support river management strategies, include those to maintain ecosystem functions (Dollar et al., 2007; Beechie et al., 2010), mitigate the effects of flood hazards (Rinaldi et al., 2013; 2015) and restore degraded rivers (Beechie et al., 2010). These frameworks use a nested spatial hierarchy to organise and structure complex river systems, wherein large-scale features (i.e. a river) are subdivided into sequentially smaller features (e.g. segment to river reach to geomorphic unit/s to microhabitat subsystems; Frissell et al., 1986). The River Styles Framework developed by Brierley and Fryirs (2005), incorporates spatially-hierarchical geomorphic analyses within a catchment-based approach to river management. Knowledge of the catchment (including what is happening both upstream and downstream of a site) is essential to contextualise local adjustment (Brierley and Fryirs, 2009), especially as disturbances may occur anytime and anywhere in a catchment (Gurnell et al., 2016). The River Styles Framework provides a set of consistent and generic procedures and guidelines for river assessment that can be locally or regionally adjusted to different situations. The framework has four stages. Stage One involves identifying and characterising River Styles. Stage Two uses geomorphic principles to assess evolution, and river condition, with recovery potential assessed in Stage Three. Target conditions and priorities are set in Stage Four to realise effective river management (Brierley and Fryirs, 2005).

Rivers in the Philippines are particularly dynamic, with fluctuating sediment supply driven by monsoon and typhoon related landslides, earthquakes, and volcanoes (Gran et al., 2011; Catane et al., 2012; Gob et al., 2016; Dingle et al., 2019). Additional pressures from anthropogenic activities include: flow alteration for fishing (Fig. 1e); dam construction, artificial alignment and confinement (Fig. 1a, h, i); gravel extraction (Fig. 1f); and floodplain use for agriculture (Fig. 1d) and recreational purposes (Fig. 1b, c). A major aspect of river management is in the containment of water and sediment by engineered structures (Fig. 1h). Water bodies (including rivers) in the country are classified based on water quality standards set by the Department of Environment and Natural Resources coupled with its intended use (DENR Administrative Order 2016-08). River basin management plans exist but only for the 18 major catchments (drainage area > 3000 km^2). Morphological attributes of rivers are infrequently addressed in these plans. Analyses of physiography, climate, geology, and land use lack fluvial geomorphological detail (i.e. stream network characteristics, geomorphic units, bed material, sediment, and flow regime). Consequently, gaps in hydromorphological understanding have resulted in local, reactive, and often incoherent management interventions such as misplaced dikes and river training measures that are expensive to build and maintain. Such structural interventions (e.g. Figure 1h) that impose a particular width and/or alignment on a channel not only modify water flow and sediment fluxes, they also restrict the capacity for adjustment, effectively ‘fighting’ against the prevailing river behaviour (Brierley and Fryirs, 2009). In light of the increasing magnitude and variability of river flows (Tolentino et al., 2016) and growing pressures on water supply from climate change and floodplain land use from agricultural and urban development (Eccles et al., 2019), such management responses increase problems for the future. Hence, geomorphologically-informed approaches to river management in the Philippines are critical.

2. Study Area

The Bislak Catchment, Ilocos Region, Luzon Island, Philippines (Fig. 2a) is 586 km^2 in area, with elevation from sea level to 1857 m (Fig. 2b) and slopes up to 71° (Fig. 2c). Most headwaters are bounded by the Luzon Central Cordillera (LCC) Mountain Range and the river network flows west towards the South China Sea. The Bislak River is a valuable resource for the local community; as a water source for domestic and agricultural purposes, a habitat for freshwater species, an economic resource for aggregate (i.e. sand and gravel) extraction, a food source, and a recreational and cultural amenity through the annual River Ritual. Almost half the population of the municipalities of Bacarra (15,937) and Vintar (15,753) reside on the Bislak River floodplains (Philippines Statistics Authority, 2015), in locations highly susceptible to flooding (Paringit and Pascua, 2017). In attempts to mitigate the flood and erosion hazards, hard engineering structures have been installed along the riverbanks in the downstream reach, and the riverbed is frequently dredged to reduce the effects of aggradation and increase channel conveyance.

2.1 Landscape units

Three morphostructural regions (landscape units) are identified in the Bislak Catchment: Steep Uplands, Rugged Hills and Lowland Plains (Fig. 2d). Steep Uplands which comprise headwater areas account for 59% of the catchment area (mean elevation 705 m). Rugged Hills, 36% of the catchment (mean elevation 170 m), are characterised by partly-confined valleys ranging from 25 to 1300 m in width. Only 5% of the catchment area is classified as Lowland Plains (mean elevation 20 m), where the river occupies an alluvial plain with continuous floodplain. Open forests and grasslands dominate the Steep Upland and Rugged Hills landscape units, while wooded grasslands are more abundant on moderate to lower slopes (Fig. 2e). Settlements and agriculture are concentrated on the Lowland Plains.

2.2 Climate

The Bislak Catchment has a Type I climate classified as having two distinct seasons, dry from November to April and wet from May to October (Coronas, 1920). Annual rainfall totals are high (Fig. 2b), and influenced by the Southwest Monsoon that advances from May to October, and the Northeast Monsoon from October to March. Mean annual rainfall (1969–2018) at the Laoag Synoptic Station (10.5 km southwest of Vintar) is 2019 mm, with the maximum monthly mean being 546 mm in August. An increasing average monthly rainfall was observed in the region from 1969 to 2018 (PAGASA). The International Best Track Archive for Climate Stewardship (IBTracs) shows that 83 tropical cyclones crossed within a 100 km radius of the Bislak Catchment from 1980–2019 (NOAA NCDC), most of these being from May to November. Recently, the Ilocos Region was placed under a state of calamity due to tropical cyclone impacts caused by Typhoon Ompong (Mangkhut; 2018) and Typhoon Ineng (Bailu; 2019).

2.3 Geology

Catchment geology is heterogenous, with thick sequences of sedimentary rock units and local exposures of intrusive and volcanic igneous rocks (Fig. 2f). The Steep Uplands are underlain by conglomerates, breccias, sandstones, and intrusive rocks of the Bangui and Bojeador Formations. Further downstream, less resistant sedimentary rocks belonging to the Pasuquin Limestone and Laoag Formation are exposed in the Rugged Hills. Recent alluvial deposits dominate the Lowland Plains. Northeast-trending lineaments along ridges in the upland areas reflect tectonic structures, mainly the Vigan-Aggao Fault (Philippine Institute of Volcanology and Seismology, 2008).

3. Methods

3.1 Topographic Analysis

Topographic analysis used a nationwide digital elevation model (DEM) acquired in 2013 and generated through airborne IfSAR technology, with 5 m spatial resolution (1 m root-mean-square error vertical accuracy; Grafil and Castro, 2014). TopoToolbox V2 was used to extract the stream network and calculate catchment areas using standard flow-routing algorithms (Schwanghart and Scherler, 2014). An upstream area threshold value (1 km^2) delineated the transition from debris flow-dominated channels to alluvial channels (Montgomery and Foufoula-Georgiou, 1993); only alluvial channels (> 1 km^2) were considered for analysis. Non-parametric quantile regression was applied to remove data artefacts and errors in longitudinal profiles (i.e. hydrological correction). Quantile carving along the central tendency of the stream network elevation data ($\tau = 0.5$) ensured downstream decreasing elevations (Schwanghart and Scherler, 2017). Because channel slope was variable over short distances, slope values were averaged over 0.2 km segment lengths (n = 1129). The mean elevation [m], mean slope [m/m], and median catchment area [km^2] were extracted for each segment length and exported to a stream network shapefile. The position of the stream network was validated against recent Google Earth imagery. Thematic maps for land cover, geology and faults were provided by the National Mapping and Resource Information Authority (NAMRIA), Mines and Geosciences Bureau (MGB), and Philippine Institute of Volcanology and Seismology (PHIVOLCS).

3.2 River Style identification

The procedural tree that underpins Stage One of the River Styles framework was used to identify different river types across the Bislak Catchment (Brierley and Fryirs, 2005; Fryirs and Brierley, 2018). The naming convention followed Fryirs and Brierley (2018). Segments of the river with similar confinement (position of the channel on the valley bottom), channel planform (continuity, number of channels, sinuosity), geomorphic unit assemblage, and bed material texture were classified into discrete reaches termed River Styles (Brierley and Fryirs, 2005; Khan and Fryirs, 2020). Each River Style represented a spatial unit with distinctive hydromorphological attributes. River Styles were identified from satellite and aerial image interpretation in Google Earth, viewed at the reach (~ 1:75,000 to 1:10,000) and unit scales (~ 1:5,000 to 1:500). Geomorphic attributes were ground-truthed and verified during field visits to accessible sites. The spatial distribution of River Styles was mapped and the longitudinal profiles for the major tributaries interpreted alongside the boundaries of landscape units, valley settings, geology, contemporary process zones, and sediment transport regimes. The approach enabled the identification of controls on the position and type of river across the catchment (Rhoads, 2020).

3.3 Stream power

Stream power is widely used as an indicator of the capacity of rivers to erode and transport sediment (Jain et al., 2006; Bizzi and Lerner, 2015). Total stream power is calculated as: $\Omega = \gamma QS$, where Ω [kg.m.s^{-3}] is total stream power, Q [m^3.s^{-1}] is discharge and S is reach slope. γ is the unit weight of water [kg.m^{-2}.s^{-2}] which is density (1 [kg/m^3]) x gravity (9.807 [m/s^2]). Q is a discharge that controls channel form, for which the bankfull discharge is often used (Petit et al., 2005). In landscape-scale studies, the relationship between catchment area, A, and Q often uses a catchment area-discharge relationship derived for the region. Using data from 14 gauges in NW Luzon (Irrigation Division: Philippines, 1924) collected in the early 20th Century, the 2-year discharge Q_2 was estimated using the R package fasstr (https://github.com/bcgov/fasstr), and related to catchment area as $Q_2 = 0.44A^{1.03}$ (n = 14; $R^2 = 0.93$; se = 0.25). The exponent is close to 1 (95% confidence interval 0.85–1.20), justifying substitution of A for Q_2 in the stream power equation $\Omega = \gamma AS$. For constant total stream power, catchment area and slope are thus inversely related, $A \propto S^{-1}$.

4. Results

4.1. River diversity

Eight River Styles are identified along 246 km of stream length (Table 1 and Fig. 3). River Styles in a Confined valley setting, where > 85% of either channel margin abuts the valley bottom margin, account for 57.1% of the stream length. The confined reaches located in upstream tributaries of the Steep Upland landscape unit, have a single-threaded, low sinuosity channel planform and bedrock or coarse bed material texture (boulder to cobble sized) with sculpted high-energy erosional geomorphic units. In confined reaches, there is limited capacity for the river to adjust laterally or vertically, except locally where isolated pockets of floodplain are present. River Styles in a Partly-confined valley setting, where 10–85% of either channel margin abuts the valley bottom margin, account for 36.5% of the stream length. These partly-confined reaches are mainly located on moderate slopes of tributaries in the Rugged Hills landscape unit, have one to two channels and a mixed bed material texture (boulder to sand-sized). Mid-channel and bank-attached depositional units occur more frequently in these reaches than in confined reaches upstream. The capacity for adjustment is moderate, particularly where discontinuous floodplain pockets are present, meaning that floodplain stripping and reworking can occur (enabling both lateral and vertical adjustment; Nanson, 1986). River Styles in the Laterally-unconfined valley setting account for only 6.3% of the stream length. These occur within the Lowland Plains landscape unit. The channel planform is predominantly multi-threaded with a mixed bed material texture (gravel to clay-sized). Geomorphic units in these reaches are products of short and long-term sediment accumulation such as compound islands and bars. Here, the capacity for lateral adjustment is greatest for these rivers, where the floodplain is continuous on both banks of the channel (Fig. 3). Several anthropogenic modifications (Fig. 1) designed to restrict lateral channel adjustment are present in the laterally unconfined river types.

Table 1
Distinguishing attributes of River Styles in the Bislak Catchment.

Valley setting	River Style	% Stream Length	Channel planform	Geomorphic units	Bed material texture	Capacity for adjustment	Catchment area (km^2)	Elevation (m)	Slope (m/m)	Va wi (m
Confined (> 85% of either channel margin abuts valley bottom margin) Total stream length: 57.2%	Confined, Steep Headwater, Bedrock bed	27.8	Single thread, low sinuosity	Instream units: Waterfalls, cascades, rapids, bedrock pools, riffles, bedrock outcrops No floodplain	Bedrock, boulder, cobble	Laterally stable, vertically stable	< 45	185–1455	0.01–1.04	10
	Confined, Gorge, Boulder bed	23.6	Single thread, low sinuosity	Instream units Cascades, bedrock steps, riffles, pools No floodplain	Bedrock, boulder, cobble	Laterally stable; limited potential for vertical adjustment	2–115	140–780	0.008–0.24	15
	Confined, Occasional Floodplain Pockets, Boulder bed	5.8	Single thread, low sinuosity	Instream units: Rapids, pools, runs, boulder bars, benches, ledges Floodplain units: Terrace	Bedrock, boulder, cobble	Limited potential for lateral adjustment (floodplain pockets); limited potential for vertical adjustment	3–215	115–370	0.005–0.09	40 12
Partly-confined (10–85% of either channel margin abuts valley bottom margin) Total stream length: 36.5%	Partly-confined, Bedrock Margin-controlled Discontinuous Floodplain, Cobble bed	15.7	Single thread, valley aligned	Instream units: Pools, riffles, runs, compound bank-attached bars, mid-channel bars, benches, ledges Floodplain units: Terrace, chute channel	Bedrock, boulder, cobble, gravel, sand	Limited potential for lateral adjustment (floodplain); limited potential for vertical adjustment	10–255	75–210	0.002–0.03	11 42
	Partly-confined, Planform-controlled, Low Sinuosity Discontinuous Floodplain, Gravel bed	1.7	Single thread, low sinuosity	Instream: Pools, riffles, runs, compound bank-attached bars, mid-channel bars, benches, ledges Floodplain units: Terrace	Boulder, cobble, gravel, sand	Moderate potential for lateral adjustment (floodplain); moderate potential for vertical adjustment (floodplain stripping and reworking)	2–10	130–200	0.009–0.03	30 14
	Partly-confined, Planform-controlled Wandering, Discontinuous Floodplain, Cobble bed	19.1	Single thread, low sinuosity	Instream units: Pools, riffles, runs, benches, ledges Floodplain units: floodplain, terrace, floodchannels, chute channels	Boulder, cobble, gravel, sand	Moderate potential for lateral adjustment (floodplain); moderate potential for vertical adjustment (floodplain stripping and reworking)	20–550	25–100	0.002	80 20

Valley setting	River Style	% Stream Length	Channel planform	Geomorphic units	Bed material texture	Capacity for adjustment	Catchment area (km^2)	Elevation (m)	Slope (m/m)	Va wi (m
Laterally-unconfined (< 10% of either channel margin abuts valley bottom margin) Total stream length: 6.3%	Laterally-unconfined, Continuous Channel, Braided, Gravel bed	5.1	Multiple threads, low sinuosity	Instream units: Pools, riffles, runs, compound bank-attached bars, compound islands, benches, ledges Floodplain units: Paleochannel, chute channels, floodchannels	Cobble, gravel, sand	Large potential for lateral adjustment (floodplain; but more limited where anthropogenically confined); moderate potential for vertical adjustment (aggradation/degradation)	550–585	2–25	< 0.001–0.002	12 32
	Laterally-unconfined, Continuous Channel, Deltaic, Sand bed	1.2	Multiple threads, variable sinuosity	Instream units: Compound bank-attached bars, compound islands Floodplain units: Paleochannel, anabranches, floodchannels and floodrunners, backswamp, chute channel, levee	Gravel, sand, silt, clay	Moderate potential for lateral adjustment (floodplain more cohesive, but opportunities for avulsion); limited potential for vertical adjustment	> 585	0.2–2	< 0.001	> 2

4.2 Downstream patterns in River Styles

The distribution of downstream patterns (Fig. 4a) and processes along the river are presented by plotting the stream power against longitudinal profile-catchment area and annotating boundary conditions along the Bislak River (Fig. 5b). The sources of all tributaries in the Bislak Catchment are in the Steep Upland landscape unit, downstream of which they flow through confined valleys (Fig. 4a and 4c) and wider partly-confined valleys before joining the trunk stream (Bislak River). Five downstream patterns or sequences of River Styles occur in the catchment (Fig. 4b). Pattern 1 is the dominant downstream pattern, exhibited by 11 out of 17 major tributaries (Fig. 4c and 5a) and is found where tributaries pass through areas with similar catchment controls (i.e. steep slopes with similar geology). In Pattern 1, the downstream sequence of River Styles is: Steep Headwater, Gorge, and Occasional Floodplain Pockets found in the Confined valley setting; Bedrock Margin-controlled; Planform-controlled, Wandering, Discontinuous Floodplain found in Partly-confined valley setting; Continuous Channel, Braided; and finally, Continuous Channel, Deltaic found in the Laterally-unconfined valley setting. Two subsets arise from this pattern: Pattern 2 that passes through less resistant bedrock geology and does not contain Occasional Floodplain Pockets; and Pattern 3, a relatively short tributary that does not contain Gorges. Patterns 4 and 5 are only found in tributaries that initiate in the Steep Upland landscape unit but abruptly enter the Rugged Hills landscape unit as Partly-confined, Planform-controlled, Low Sinuosity, Discontinuous Floodplain. Pattern 4 exits to Bedrock Margin-controlled while Pattern 5 is set back in a Confined valley setting with Occasional Floodplain Pockets.

4.3 Differentiating river diversity with stream power

There is a general inverse relationship between slope and catchment area (Fig. 5a). Different River Styles occupy different regions of the plot, with confined River Styles occurring on steeper slopes than partly-confined River Styles. However, at any given catchment area, more than one River Style is encountered in both confined and partly-confined valley settings occurring at all catchment areas between 5 and 120 km^2 (Fig. 6a). This overlap between River Styles becomes more apparent when all data are plotted (Fig. 6b). The regression lines on Fig. 6b have gradients significantly less than the contours of constant stream power lines, and the gradient of all the data regression is -0.70 [± 0.03]. The significance of stream power is further emphasized when considering the slope-area data for individual river patterns (Fig. 6c; see Fig. 4 for pattern definitions). The relationship between slope and catchment area indicates the general topographic controls on river morphological diversity in the Bislak Catchment.

5. Discussion

5.1 River diversity and downstream patterns

Stage One of the River Styles Framework revealed the diversity of fluvial morphology in the Bislak Catchment. The identified River Styles operate under a combination of imposed boundary conditions (including landscape units, lithology, and valley-setting) which influences process zone distributions, interplaying with flux boundary conditions that affect stream power (as a function of slope and contributing catchment area).

In the Bislak Catchment, confined River Styles are characterised by small drainage areas, and steepest slopes (Fig. 6a). Initiating with a Steep Headwater River Style (Fig. 5), a change in lithology from metavolcanics to sedimentary bedrock results in transition to a Gorge River Style. With increasing catchment area and the channel slope remaining high (in the range 0.008–0.24 m/m; Table 1), the stream power gradually increases to a peak of 8340 W/m through the confined valley setting. Even though the stream power remains high (maximum 4305 W/m; Table 1), the storage potential is limited in Occasional Floodplain Pockets given the limited accommodation space in the valley bottom (Figs. 1b and 6c). Upon entering the Rugged Hills landscape unit, the valley confinement transitions to partly-confined and the channel slope is reduced (in the range 0.002–0.03 m/m; Table 1). With discontinuous floodplain, there is a switch to Bedrock Margin-controlled and Planform-controlled, Wandering, Discontinuous Floodplain River Styles. Stream power falls to a maximum of 2640 W/m and remains approximately consistent (as increases in discharge from tributary inputs are offset by downstream reductions in slope). At the downstream end of the Lowland Plain landscape unit, the stream power is reduced to < 2270 W/m because of the decrease in channel slope (in the range < 0.001–0.002 m/m; Table 1). These downstream patterns are also observed in other tropical catchments (Kuo and Brierley, 2013; Marcal et al., 2017; Nardini et al., 2020). Such catchment-based fluvial geomorphic understanding is essential for explaining local hydromorphological patterns and processes.

The relationship between slope and catchment area shows the potential to determine the downstream pattern of River Styles in the Bislak Catchment (Fig. 6). Stream power analysis indicates the general topographic controls on the distribution of River Styles within the catchment. However, the overlap (variation in slope) between River Styles for a given catchment area (e.g. between confined and partly-confined River Styles, Fig. 6) suggests that stream power alone is insufficient to differentiate and predict river character. To fully appraise the morphological diversity, a hierarchical approach such as the River Styles Framework can complement topographic analyses to understand river character and behaviour. In the Bislak Catchment, patterns of River Styles reflect geologic controls upon valley setting alongside determinants of flow energy expressed as stream power, including analysis of discharge sediment supply, and vegetation controls (Buffington, 2012).

5.2 Translation of River Styles principles to guide river management

The diversity of River Styles has revealed differences in river character and behaviour in the Bislak Catchment. Bespoke management strategies will be required to work with the local river character, behaviour, and capacity for adjustment. It is contended that the principles introduced in this paper are required to support sustainable river management across the Philippines. Table 2 outlines several key principles of the River Styles Framework (column 1) that are translated to a simplified understanding (column 2) and can support sustainable river management practices (column 3). Indeed, we argue that effective river management cannot be reliably conducted independent from geomorphic insights into catchment-scale patterns of river character and behaviour.

Table 2
River Styles principles that support the understanding of fluvial geomorphology and guide sustainable river management in the Bislak Catchment and more widely in the Philippines.

River Styles principles	Translated to a simplified understanding of:	Implemented to guide river management through:
Capacity for adjustment	● Whether the river can adjust laterally, vertically, or both. ● Where the river is likely to adjust i.e. the spatial distribution of bank erosion. ● Where the river is confined and less able (or unable) to adjust. ● Where sediments will be deposited (aggrade) or eroded (degrade) in the channel. ● Whether the channel can shift (migrate, avulse) and where this might occur.	● Land-use planning (e.g. where not to build infrastructure or developments). ● Identification of hazardous buffer zones (flood- and erosion-risk). ● Providing 'erodible corridors', 'space to move', and/or 'channel migration zones' guided by a working with nature principle. ● Strategic placement of necessary river control structures.
River diversity	● Recognizing the diverse types of river, with various rates of adjustment, and behaviour. ● Distinct characteristics and hydromorphological attributes. ● Whether the reach is sensitive or resilient.	● Which reaches (parts of the river) should be prioritized for catchment action planning (e.g. for conservation value), or to maintain sediment sources to prevent downstream degradation. ● Different types of reach require different types of interventions.
Identifying geomorphic units	● The presence of diverse geomorphic units signifies the types of river styles. ● Indicates how the river behaves. ● Differentiates erosional or depositional features.	● Understanding where different habitats are located (e.g. fishing) and recreational areas. ● Areas for sustainable gravel extraction .
Pattern of rivers	● Whether the pattern is unique or similar to other patterns in the catchment. ● Whether the boundaries between River Styles are gradual or distinct (abrupt).	● How sensitive different reaches are to pattern transitions due to changes in water or sediment supply, from upstream management decisions and climate change impacts (i.e. connectivity and offsite impacts).
Position in catchment and controls	● Whether the reach is a source zone, transfer zone or accumulation zone. ● Whether the reach is situated in a low, moderate, or high energy environment. ● Possible geologic and tectonic influences.	● Policies for extractive activities. ● Identification of geomorphic hazards (e.g. landslides, debris flows). ● Floodplain zonation.
Tributary-trunk relationships (connectivity)	● Relative fluxes of water and sediment discharge from different parts of the catchment. ● Downstream changes in grain size and thus roughness and water depth during high flows.	● Land-use planning in vicinity of confluences.
Know your catchment	● Regional settings and location influences the differences between catchments.	● Locally-appropriated management options, including socio-economic considerations and indigenous practices.
Nested hierarchical approach	● Range of analyses and approaches that can be undertaken in different scales. Top-down approach on controls on character and behaviour while bottom-up approach on interpretation of the character and behaviour.	● Coordination of management approaches from different local and national government agencies.

The Bislak River serves a range of functions for the community (Fig. 1, b - f). Neglecting the principles of fluvial geomorphology can lead to reactive management, exemplified by expensive and unsustainable attempts to control the river in addressing hydrometeorological risks (Fig. 1g). In the Bislak Catchment, river management has involved construction of multiple structures including flood defences, embankments, gabion walls, and flow deflectors (Fig. 1, a,h,i). The structures are frequently damaged and require regular repair following high-magnitude flows. The effects of the structures on the geomorphology of the river are often left unaccounted for, but may negatively affect flow patterns and sediment flux (Brierley et al., 2011). Disregarding the principles of fluvial geomorphology often leads to mismanagement of a river, posing threats to the ecosystem the river is supporting (Brierley, 2008).

By translating the principles of Stage One of the River Styles Framework to the management of the Bislak Catchment (and Philippine rivers more widely), it would be possible to identify whether a particular reach is sensitive or resilient to natural and anthropogenic influences and to assess the offsite effects of interventions. Although physical processes and principles which control river form are universal, catchment properties and anthropogenic history mean that the outcomes of these principles will not always be the same and such differences are critical for effective management (Brierley et al., 2013). These principles provide an entry point for hydromorphological information to be incorporated into river basin management and catchment action plans. Subsequent stages of the River Styles Framework, focusing on river evolution and the assessment of geomorphic condition as a basis to predict future trajectories and trends, are essential in understanding river recovery towards better river management/practice through crafting responsive policies for various river projects including but not limited to: sustainable river gravel quarrying plans; upstream intervention for flood mitigation; and river use management.

6. Conclusions

Sustainable river management cannot be conducted independent of geomorphic insight into both the character and behaviour of rivers. Eight distinct River Styles are identified in the Bislak Catchment with Confined (57%) and Partly-confined (37%) River Styles dominating the stream network by length. Examining the downstream sequences of River Styles, a similar downstream pattern was exhibited by 11 out of 17 major tributaries, where tributaries pass through similar catchment controls (i.e. steep slopes with homogenous geology). Variation in channel slope for a given catchment area (i.e. total stream power) is insufficient to differentiate the type of river in a given reach. The guiding principles of the River Styles Framework regarding reading the landscape, working with nature, and knowing your catchment by respecting the diversity and the different patterns of rivers at the catchment scale (Brierley and Fryirs, 2005) are starting points for developing catchment-scale visions and moving towards geomorphologically-informed, sustainable river management.

Declarations

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Competing interests

The authors declare that they have no competing interests

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Availability of data and materials

Following review, all GIS dataset will be made available through the NERC data repository.

Author contributions following CRediT

Conceptualization - PT, RB, TH, RW, KF, GB. Methodology - PT, JP, EG, RB, TH, RW, KF, GB. Software - PT, JP, EG, RB, TH. Formal analysis - RB, TH. Investigation - PT, JP, EG, RB, TH. Resources - KF, GB. Writing - Original Draft - PT, JP, EG, RB, TH. Writing - Review & Editing - RW, KF, GB, CD. Visualization - PT, RB. Supervision - RW, CD. Project administration - PT, RW, CD. Funding acquisition - PT, RW, GB.

References

1. Beechie TJ, Sear DA, Olden JD, Pess GR, Buffington JM, Moir H, Roni P, Pollock MM (2010) Process-based principles for restoring river ecosystems. Bioscience 60:209–222
2. Belletti B, Rinaldi M, Bussettini M, Comiti F, Gurnell AM, Mao L, Nardi L, Vezza P (2017) Characterising physical habitats and fluvial hydromorphology: A new system for the survey and classification of river geomorphic units. Geomorphology 283:143–157. doi:10.1016/j.geomorph.2017.01.032
3. Biron PM, Buffin-Belanger T, Masse S (2018) The need for river management and stream restoration practices to integrate hydrogeomorphology. Can Geogr 62(2):288–295. doi:10.1111/cag.12407
4. Bizzi S, Lerner DN (2015) The use of stream power as an indicator of channel sensitivity to erosion and deposition processes. River Res Applic 31:16–27. doi:10.1002/rra.2717
5. Bollati IM, 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. doi:/10.1016/j.geomorph.2014.06.007
6. Brierley GJ, Fryirs K (2000) River styles, a geomorphic approach to catchment characterization: implications for river rehabilitation in Bega catchment, New South Wales. Australia Environ Manage 25:661–679. doi:10.1007/s002670010052
7. Brierley GJ, Fryirs K, Outhet D, Massey C (2002) Application of the River Styles framework as a basis for river management in New South Wales, Australia. Applied Geography 22(1):91–122. doi:0.1016/S0143-6228(01)00016-9
8. Brierley GJ, Fryirs KA (2005) Geomorphology and river management: applications of the river styles framework. Blackwell, Malden
9. Brierley GJ (2008) Geomorphology and river management. Kemanusiaan The Asian Journal of Humanities. 15–26
10. Brierley GJ, Fryirs KA, Hillman M (2008) River futures. In: Brierley GJ, Fryirs KA (eds) River futures: an integrative scientific approach to river repair (Science and practice of ecological restoration). Island Press, Washington DC, pp 273–283

11. Brierley GJ, Fryirs KA (2009) Don't Fight the Site: Three Geomorphic Considerations in Catchment-Scale River Rehabilitation Planning. Environmental Management 43:1201–1218. doi.org/10.1007/s00267-008-9266-4
12. Brierley GJ, Fryirs KA, Cook N, Outhet D, Raine A, Parsons L, Healey M (2011) Geomorphology in action: Linking policy with on-the-ground actions through applications of the River Styles framework. Appl Geogr 31(3):1132–1143. doi:10.1016/j.apgeog.2011.03.002
13. Brierley GJ, Fryirs KA, dos Santos Marçal M, Lima R (2019) The use of the River Styles framework as a tool to 'work with nature' in managing rivers in Brazil: Examples from the Macaé catchment. J Rev Bras Geomorfol 20 dx. doi:10.20502/rbg.v20i4.1559
14. Buffington JM (2012) Changes in channel morphology over human time scales. In: Church M, Biron PM, Roy AG (eds). Gravel-Bed Rivers: Processes, Tools, Environments. Chichester, UK: Wiley. 32:435–463. doi:10.1002/9781119952497
15. Buffington JM, Montgomery DR (2013) Geomorphic classification of rivers. In: Shroder J, Wohl E (eds). Treatise on Geomorphology 9:730–767. doi:10.1016/B978-0-12-374739-6.00263-3
16. Dallaire CO, Lehner B, Sayre R, Thieme M (2019) A multidisciplinary framework to derive global river reach classifications at high spatial resolution. Environ Res Lett 14(2). doi:10.1088/1748-9326/aad8e9
17. Department of Environment and Natural Resources – Environment Management Bureau (2016) Water Quality Guidelines and General Effluent Standards. https://pab.emb.gov.ph/wp-content/uploads/2017/07/DAO-2016-08-WQG-and-GES.pdf. Accessed 20 Jun 2020
18. Dollar ESJ, James CS, Rogers KH, Thoms MC (2007) A framework for interdisciplinary understanding of rivers as ecosystems. Geomorphology 89(1–2):147–162. doi:org/10.1016/j.geomorph.2006.07.022
19. Dingle EH, Paringit EC, Tolentino PLM, Williams RD, Hoey TB, Barrett B, Long H, Smiley C, Stott E (2019) Decadal-scale morphological adjustment of a lowland tropical river. Geomorphology 333:30–42. doi:10.1016/j.geomorph.2019.01.022
20. Eccles R, Zhang H, Hamilton D (2019) A review of the effects of climate change on riverine flooding in subtropical and tropical regions. Journal of Water Climate Change 10(4):687–707. doi:10.2166/wcc.2019.175
21. Frissell CA, Liss WJ, Warren CE, Hurley MD (1986) A hierarchical framework for stream habitat classification: Viewing streams in a watershed context. Environ Manage 10:199–214. doi:10.1007/BF01867358
22. Fryirs K, Brierley G (2018) What's in a name? A naming convention for geomorphic river types using the River Styles framework. PLOS ONE 13(9). doi:10.1371/journal.pone.0201909
23. Fuller I, Reid H, Brierley G (2013) Methods in geomorphology: Investigating river channel form. In: Shroder J (eic), Switzer AD, Kennedy DM (eds). Treatise on Geomorphology 14:73–91. doi:10.1016/B978-0-12-374739-6.00374-2
24. Grafil L, Castro O (2014) Acquisition of IfSAR for the production of nationwide DEM and ORI for the Philippines under the Unified Mapping Project. Infomapper 21:12–13, 40–43
25. Gurnell AM, Rinaldi M, Belletti B, Bizzi S, Blamauer B, Braca G, Buijse AD, Bussettini M, Camenen B, Comiti F, Demarchi L, García de Jalón D, González del Tánago M, Grabowski RC, Gunn DM, Habersack H, Hendriks D, Henshaw AJ, Klösch M, Lastoria B, Latapie A, Marcinkowski P, Martínez-Fernández V, Mosselman E, Mountford JO, Nardi L, Okruszko T, O'Hare MT, Palma M, Percopo C, Surian N, van de Bund W, Weissteiner C, Ziliani L (2015) A multi-scale hierarchical framework for developing understanding of river behaviour to support river management. Aquatic Sciences: research across boundaries 78:1–16. doi.org10.1007/s00027-015-0424-5
26. Hohensinner S, Hauer C, Muhar S (2018) River morphology, channelization, and habitat Restoration. In: Schmutz S, Sendzimir J (eds) Riverine Ecosystem Management. Aquatic Ecology Series, vol 8. Springer, Cham. doi.org/10.1007/978-3-319-73250-3_3
27. Irrigation Division: Philippines (1924) Surface Water Supply of the Philippine Islands 1908–1922: Volume I-IV: Division of Irrigation: Bureau of Public Works. Bureau of Printing, Manila
28. Jain V, Preston N, Fryirs KA, Brierley GJ (2006) Comparative assessment of three approaches for deriving stream power plots along long profiles in the upper Hunter River catchment, New South Wales, Australia. Geomorphology 74:297–317. doi.org/10.1016/j.geomorph.2005.08.012
29. Kasprak A, Hough-Snee N, Beechie T (2016) The blurred line between form and process: a comparison of stream channel classification frameworks. PLoS One 11(3). doi.org/10.1371/journal.pone.0150293
30. Kondolf GM, Montgomery DR, Piegay H, Schmitt L (2003) Geomorphic classification of rivers and streams. In: Kondolf GM, Piegay H (eds) Tools in fluvial geomorphology. Wiley, Chichester, pp 171–204
31. Mines and Geosciences Bureau (MGB) (2010) Geology and mineral resources of the Philippines, 2nd edn. Mines and Geosciences Bureau, Manila
32. Montgomery DR, Foufoula-Georgiou E (1993) Channel network source representation using digital elevation models. Water Resour Res 29(12):3925–3934. doi.org/10.1029/93WR02463
33. Nanson GC (1986) Episodes of vertical accretion and catastrophic stripping: a model of disequilibrium floodplain development. Geol Soc Am Bull 97:1467–1475
34. Nardini A, Yepez S, Zuniga L, Gualtieri C, Bejarano MD (2020) A computer-aided approach for River Styles-inspired characterization of large basins: The Magdalena River (Colombia). Water 12:1147. doi.org/10.3390/w12041147
35. National Mapping and Resource Information Authority (NAMRIA). National Land Cover Mapping. http://www.namria.gov.ph/download.ph. Accessed 17 December 2019
36. Paringit EC, Pascua C (eds) (2017) LiDAR Surveys and Flood Mapping of Bacarra River. University of the Philippines Training Center for Applied Geodesy and Photogrammetry, Quezon City, p 250
37. Philippine, Atmospheric, Geophysical and Astronomical Services Administration (PAGASA) http://bagong.pagasa.dost.gov.ph/climate/climate-data. Accessed 16 December 2019

38. Philippine Institute of Volcanology and Seismology (PHIVOLCS) Distribution of active faults and trenches in the Philippines map (2008) https://gisweb.phivolcs.dost.gov.ph/gisweb/geomatics-services-request Accessed 26 November 2018
39. Rhoads B (2020) River Dynamics: Geomorphology to support management. Cambridge University Press, Cambridge. doi:10.1017/9781108164108
40. Retamar AE, Guba G, Lopez GV, Paler HB, Javier J, Garcia FCC, Badong-Carlos J, Capito J, MOsquerra IC, de Paz M, Yabut JJ (2017) HydroMet: Deployment of a large scale nationwide hydrometeorological sensor network for flood warning and monitoring. IEEE Global Humanitarian Technology Conference (GHTC), San Jose, CA. 19–22 October 2017
41. Rinaldi M, Gurnell A, González del Tánago M, Bussettini M, Hendriks D (2016) Classification of river morphology and hydrology to support management and restoration. Aquat Sci 78:17–33. doi.org/10.1007/s00027-015-0438-z
42. Rinaldi M, Surian N, Comiti F, Bussettini M (2013) A method for the assessment and analysis of the hydromorphological condition of Italian streams: the morphological quality index (MQI). Geomorphology 180–181:96–108. doi.org/10.1016/j.geomorph.2012.09.009
43. Rinaldi M, Surian N, Comiti F, Bussettini M (2015) A methodological framework for hydromorphological assessment, analysis and monitoring (IDRAIM) aimed at promoting integrate driver management. Geomorphology. doi:10.1016/j.geomorph.2015.05.010
44. Schwanghart W, Scherler D (2014) TopoToolbox 2 – MATLAB-based software for topographic analysis and modeling in Earth surface sciences. Earth Surf Dyn 2:1–7. doi.org/10.5194/esurf-2-1-2014
45. Schwanghart W, Scherler D (2017) Bumps in river profiles: uncertainty assessment and smoothing using quantile regression techniques. Earth Surf Dyn 5:821–839. doi.org/10.5194/esurf-5-821-2017
46. Tolentino PLM, Poortinga A, Kanamaru H, Keesstra S, Maroulis J, David CPC, Ritsema CJ (2016) Projected impact of climate change on hydrological regimes in the Philippines. PLoS ONE 11(10). //doi.org/10.1371/journal.pone.0163941

Figures

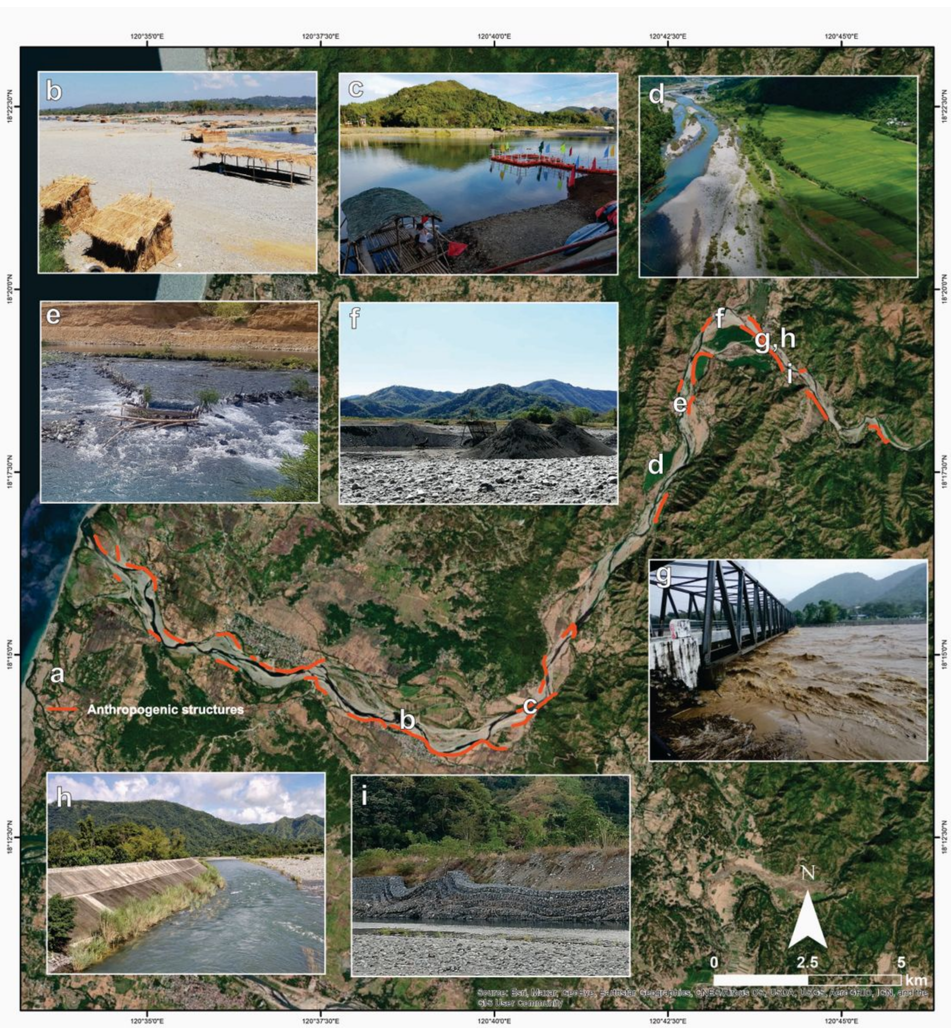

Figure 1

(a) Anthropogenic impacts on the geomorphology of the Bislak Catchment, including flood and erosion structures. Anthropogenic structures include: (b) summer huts built on sediment bars; (c) old Vintar Dam turned into a recreational area; (d) floodplains utilised for agriculture; (e) instream fish traps on a riffle; (f) mounds of quarried sediments; (g) flow infrastructure interactions during Typhoon Ineng in 2019; (h) concrete dikes downstream of Tamdagan Bridge; and

(i) gabion failure upstream of Tamdagan Bridge.In this study, Stage One of the River Styles Framework is applied to appraise topographic controls upon river morphological diversity in the Bislak Catchment, Philippines. Through topographic analysis of a recent digital elevation model (DEM), interpretation of satellite and aerial imagery, and ground-truthing, we identify distinct River Styles within the catchment. Then, using stream power as a measure of the capacity of rivers to erode and transport sediment, we evaluate whether a simple stream power model can be used to predict patterns in River Styles. By characterising the hydromorphological attributes of the Bislak Catchment, we provide a geomorphologically-informed and place-based understanding of river character and behaviour, which is essential for effective river management.

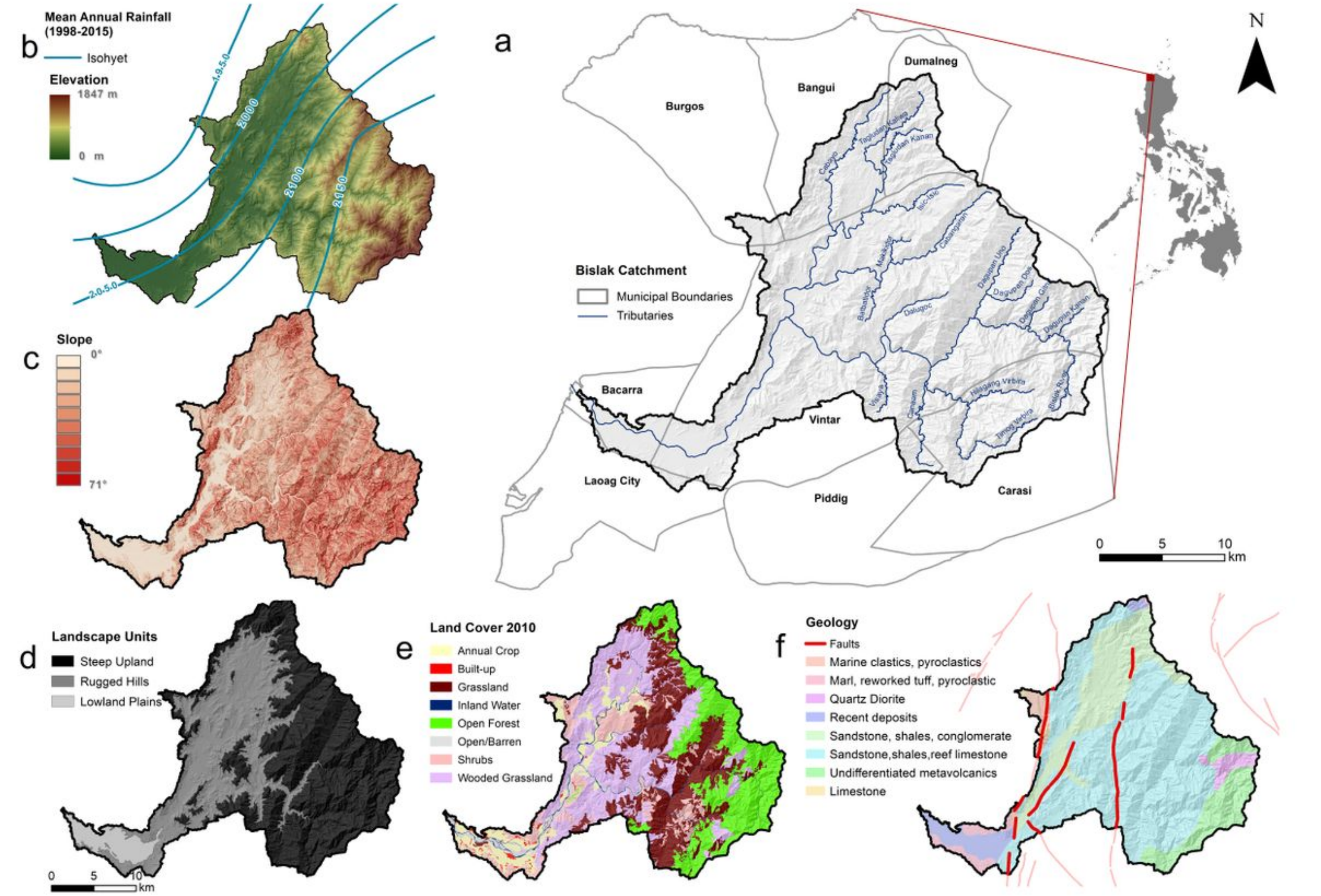

Figure 2

Regional and catchment setting maps: (a) location map of the Bislak Catchment; (b) elevation and isohyet of rainfall distribution; (c) slope; (d) distribution of landscape units; (e) land cover (NAMRIA, 2010); and, (f) geology and fault map (PHIVOLCS, 2008; MGB, 2010; NAMRIA, 2010).

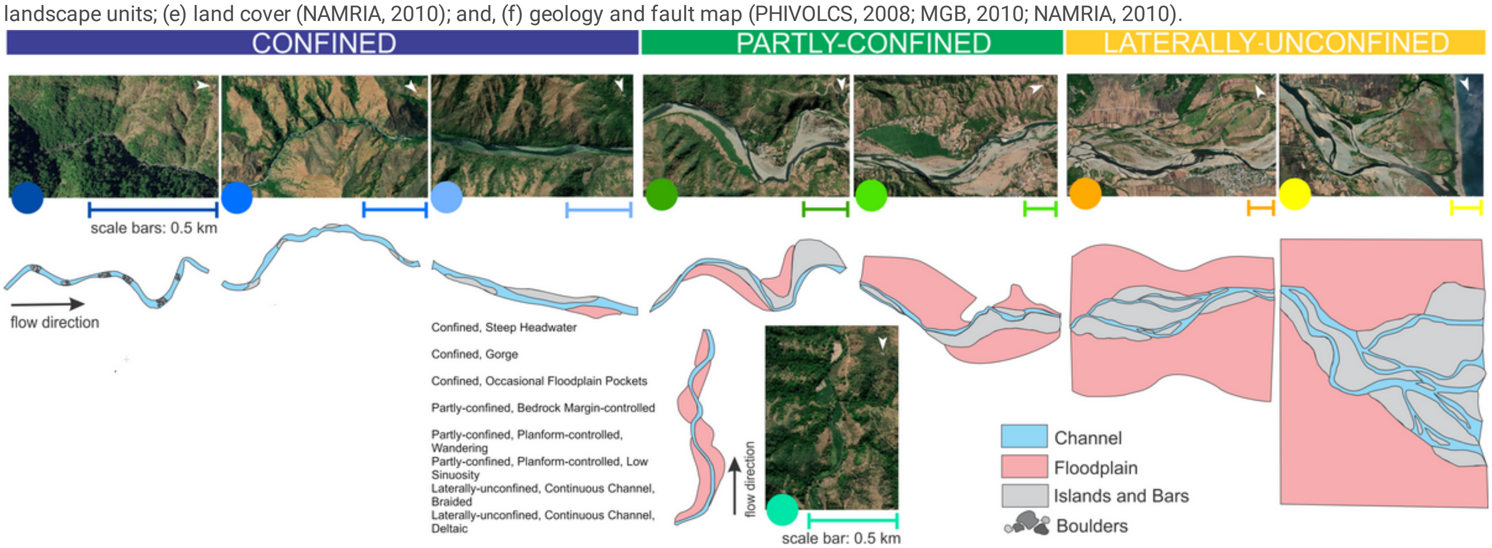

Figure 3

River morphological diversity in the Bislak Catchment. Flow direction in the catchment is generally from east to west. Planform diagrams and aerial photos of the eight River Styles are arranged in a downstream sequence from left to right.

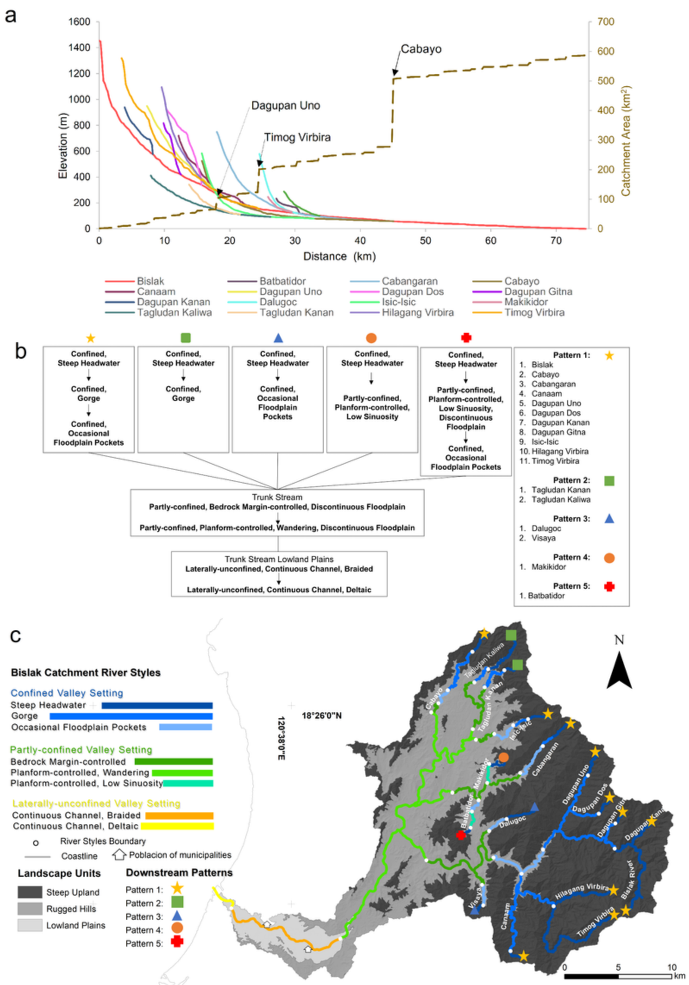

Figure 4

Downstream patterns of River Styles in the Bislak Catchment. (a) Longitudinal profiles of the tributaries of the Bislak River. (b) Flow diagram of downstream patterns in the catchment and list of tributaries exhibiting each pattern. (c) Distribution of downstream patterns across the catchment.

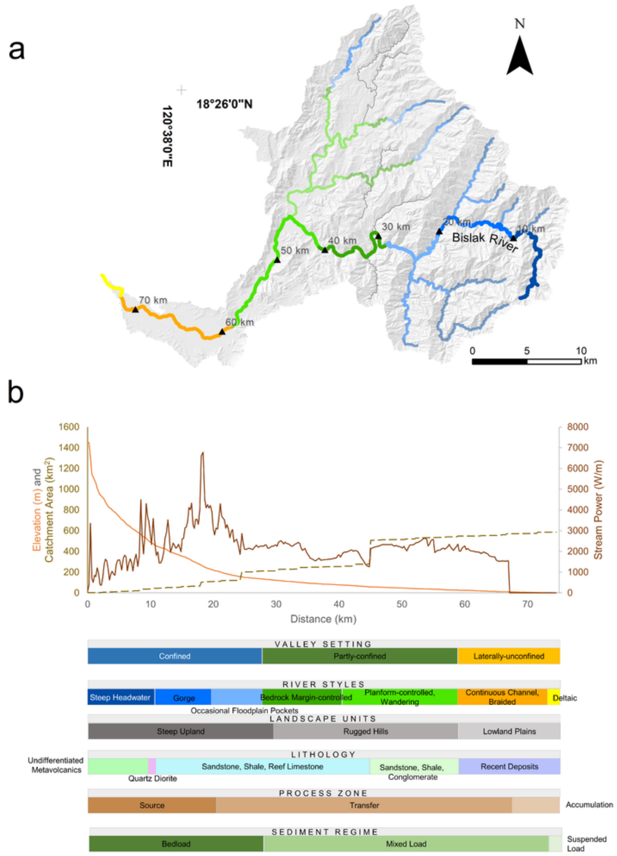

Figure 5

(a) Distribution of Pattern 1 rivers in the Bislak Catchment. The trunk stream (Bislak River) is represented by thicker lines with markers to show the distance from the channel head to the outlet. Pattern 2-5 rivers are shown in grey. (b) Stream power against longitudinal profile-catchment area for the Bislak River (annotated with boundary conditions).

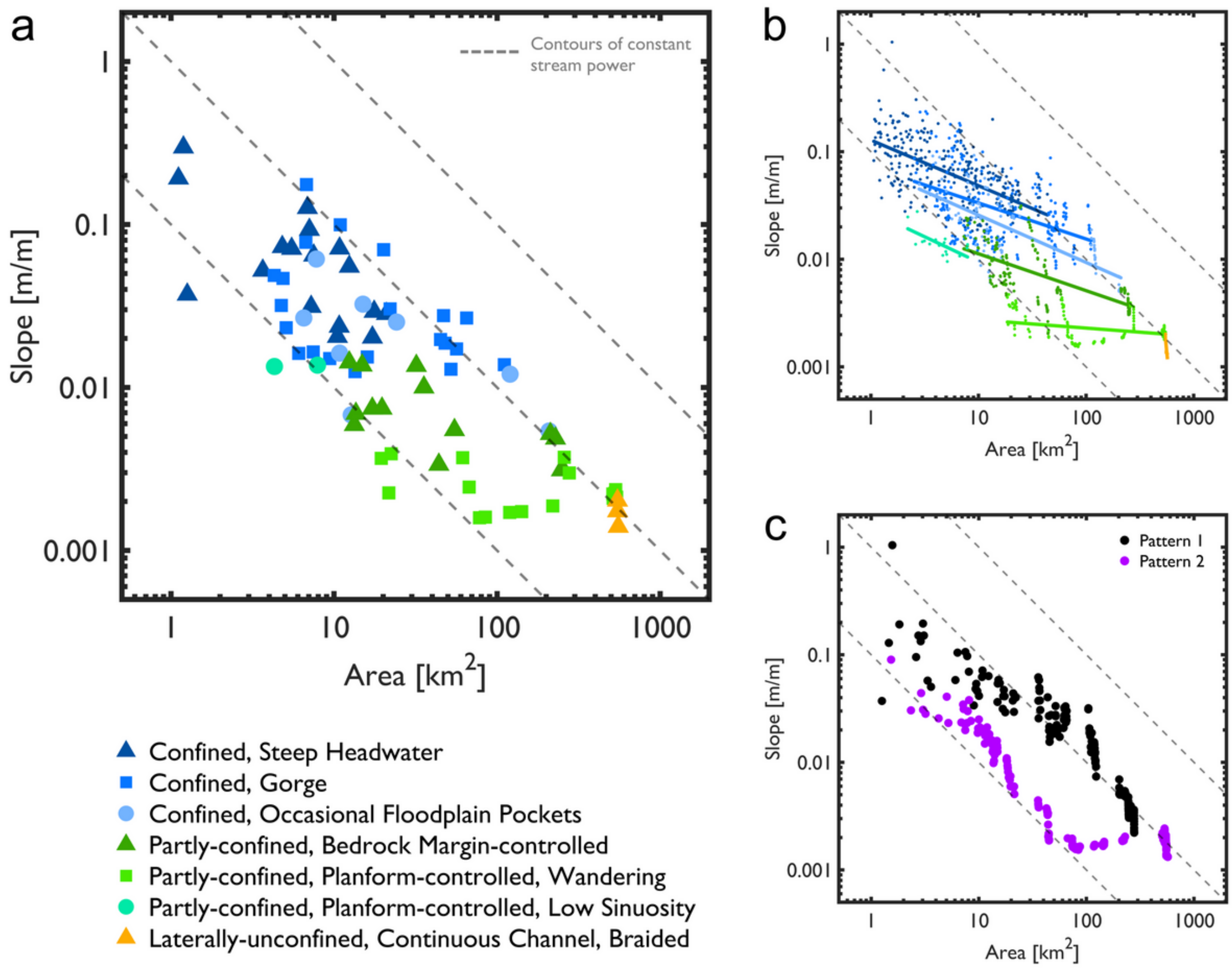

Figure 6

Slope-catchment area relationships grouped by River Style: (a) values extracted at 2.5 km intervals along the stream network (n = 89); (b) values averaged over 0.2 km segment lengths (n = 1129), coloured lines are log-log regressions; and, (c) comparisons between downstream Pattern 1 and Pattern 2. Dashed lines are contours of constant stream power (S α Q-1, see text for details)