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To plug-in or not to plug-in? Geomorphic analysis of rivers using the River Styles Framework in an era of big data acquisition and automation

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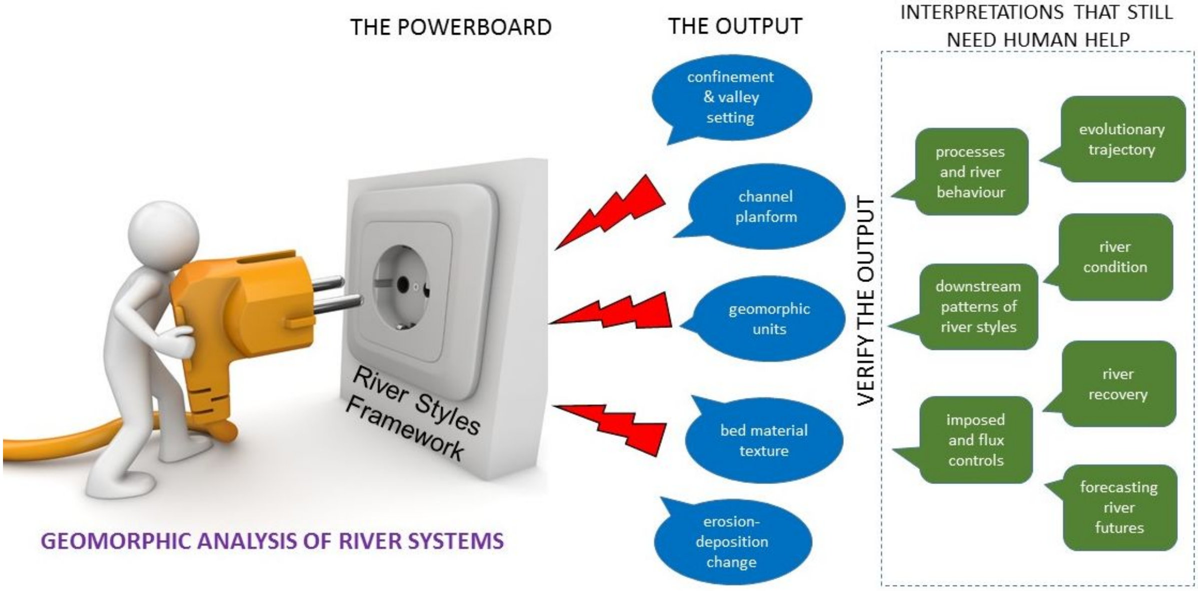

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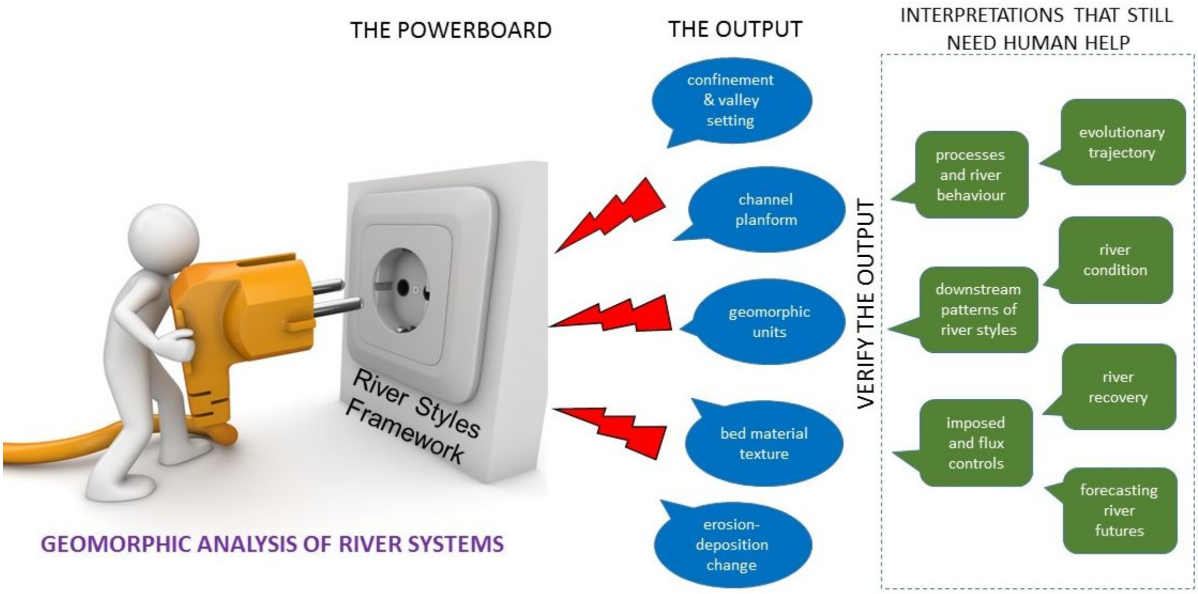
Abstract

In an era of big-data acquisition and semi-automation of geomorphic river surveys, it is timely to consider how to better integrate this into existing and widely used conceptual frameworks and approaches to analysis. We demonstrate how Stage 1 of the River Styles Framework, which entails identification and interpretation of river character and behaviour, patterns and controls, can be used as a 'powerboard' into which available, developing and future semi-automated tools and workflows can be plugged (or unplugged). Prospectively, such approaches will increase the efficiency and scope of analyses, providing unprecedented insights into the diversity of rivers and their morphodynamics. We appraise the role of human decision-making in conducting expert-manual analyses and interpretations. Genuine integration of big-data analytics, remote-sensing based tools for semi-automated river analysis with expert-manual interpretations including field insights, will be an essential ingredient to fully exploit emerging computational and remote sensing technologies to advance our understanding of river systems, to translate information into knowledge, and raise the standards of practice in river science and management.

Graphical/Visual Abstract and Caption



Use of emerging technology is transforming how we see riverscapes. Plugging-in tools and workflows to conceptual frameworks such as River Styles provides scaffolded and coherent datasets for use in river management. But, humans are not redundant! We are needed to choose the right tools for the job, interrogate and validate output(s), and make geomorphic and management interpretations of rivers.

Introduction

Geomorphology is an interpretative science, for which abductive reasoning underpins many analyses (Frodeman, 1995). Often, site- or system-specific attributes confound expectations in analyses of 'perfect landscapes' (Brierley et al., 2013; Cullum et al., 2017; Phillips, 2007). But, there are many different ways of reading the landscape. In geomorphic terms, simple differentiation can be made between remotely-sensed and field-based approaches to enquiry. Both approaches are vital; indeed, they are complementary. A revolution in practice in monitoring and measurement techniques is transforming data availability and approaches to analysis within earth and environmental sciences (Passalacqua et al., 2015; Piégay et al., 2015; Fryirs et al., 2018).

Within this context, geomorphologists have developed a deeper appreciation of the diversity of river types (**Figure 1**), the processes by which they are formed and reworked, their evolution and the impacts of human and climatic controls on their structure and function. These insights provide a representation of the physical template upon which a range of other environmental and social interactions occur (Brierley and Fryirs, 2008; Hawley, 2018; Jungwirth et al., 2002; Wiens, 2002). As such, these understandings have become an increasingly important input to river management and restoration in many parts of the world (e.g. Wohl et al., 2015; Gurnell et al., 2016; Sinha et al., 2017; Weber et al., 2018).

In recent decades there has been an increasing reliance on remote sensing datasets and geographical information systems (GIS) to inform the geomorphic analysis of river systems as the discipline transitions towards an era of big-data generation (Bizzi et al., 2016; Piégay et al., 2015; Passalacqua et al. 2015, Benda et al., 2016). Since the advent of Google Earth (GE; Tooth, 2006) in particular, and the provision of geospatial data by national environmental bodies for public use, the availability of free or low-cost remote sensing data has increased exponentially. Data derived from satellites (e.g. Dingle et al., 2019; Shean et al., 2016), manned and unmanned aerial vehicles (e.g. Dietrich, 2016; Jones et al., 2007;

Woodget et al., 2015), and on-ground scanners and sensors (e.g. Williams et al., 2014) are transforming not only our ability to analyse and quantify landscape characteristics, but to view landscapes in dimensions and detail like never before. Our capacity to work across scales is now unprecedented, making catchment-scale analyses of river systems (and associated management) a more tractable task. Following the availability of such datasets has come a wave of 'tool' and 'workflow' developments.

In parallel, recent decades have also seen the emergence of a number of riverscape interpretation frameworks; that document the geomorphic (or hydromorphic) context of a river system. These include classification and characterisation frameworks, nested hierarchical frameworks, and habitat assessment frameworks. (Belletti et al., 2015; Brierley & Fryirs, 2005; Fryirs et al., 2018; Gurnell et al., 2016; Kasprak et al., 2016). Typically these frameworks have, at their core, a conceptual structure and sequence of activities/steps that build layers of evidence, analysis and interpretation about riverscapes. Coherent, scaffolded information bases are used to explain and interpret landscape form, process, condition and trajectory. In many parts of the world, river management agencies have adopted such frameworks to aid in prioritisation, decision-making and on-ground conservation, restoration or rehabilitation activities (e.g. Brierley et al., 2011; Grabowski et al., 2014; Gurnell et al., 2016; Hawley, 2018). Tools and workflows can be plugged-in to these frameworks to help increase the efficiency and accuracy of geomorphic analysis of river systems.

This paper takes a step back from these rapidly developing practices to appraise the effectiveness with which emerging technologies and tools can (or cannot) be used to semi-automate various parts of these frameworks, to ensure that the tools are measuring the right things, and that the interpretations made using these data/tools can be verified on-the-ground. It is also timely to reflect on what tools are already available to plug-in to the process, what cannot yet be done, and where specific human decisions need to be made in the process.

The River Styles Framework (Brierley & Fryirs, 2005), and various complementary approaches that use and build upon similar core principles, have been widely adopted as a basis to perform coherent, catchment-specific geomorphic analyses of rivers that inform management applications (Belletti et al., 2017; Gurnell et al., 2016; Kasprak et al., 2016; Marcal et al., 2017; O'Brien et al., 2017; Rinaldi et al., 2015, 2017). The River Styles Framework has four stages; 1) catchment-wide baseline survey of river character, behaviour, patterns and controls, 2) catchment-framed assessment of river evolution and geomorphic river condition, 3) assessment of future trajectory of adjustment and geomorphic river recovery potential, and 4) catchment-framed vision building, and prioritisation of management efforts.

In this commentary, we use Stage 1 of the River Styles Framework, the identification and interpretation of river character and behaviour, patterns and controls, to highlight which parts of this analysis can (and cannot yet) be semi-automated. We outline some of the tools and workflows that are available to semi-automate analyses. Using the analogy of a powerboard, we demonstrate the need for a more integrated approach to analysis of rivers and provide a perspective on the importance of situating the River Styles Framework (and others like it) in an age of big-data. We also briefly discuss the potential for use of emerging technology to undertake analyses of river condition, trajectory and forecasting in Stages 2 and 3 of the River Styles Framework.

THE POWERBOARD AND ITS TOOLS: IDENTIFICATION AND INTERPRETATION OF RIVER CHARACTER AND BEHAVIOUR, PATTERNS AND CONTROLS IN STAGE 1 OF THE RIVER STYLES FRAMEWORK

Stage 1 of the River Styles Framework comprises two steps. Step 1 is analysis of river character and behaviour, and Step 2 is analysis of downstream patterns and controls.

Analysing and interpreting river character

Step 1 is used to identify, characterise and interpret the behaviour of river types across the spectrum of river diversity, some of which are displayed in **Figure 1**. To identify and characterise river types using the River Styles Framework four measures are used, set within a hierarchical approach to analysis (**Figure 2A**); valley setting, river planform, geomorphic units and bed material texture (Brierley & Fryirs, 2005).

The hierarchical structure of the Step 1 River Styles procedural tree means that as tools and workflows are developed or improved they can be plugged-in at a level to match the resolution of the data being used and the scale at which the analysis is being conducted (**Figure 2B**; Hiera et al., 2016; O'Brien et al., 2019). Conversely, if a tool or workflow becomes obsolete, superseded or no longer fit for purpose it can be unplugged or replaced in the approach. Additionally, if a tool is not yet available (or has been unplugged) then it is obvious to a user that the expert-manual approach to analysis is needed that employs traditional methods. This highlights the importance of having a conceptual framework and approach to analysis in place that can act as the 'powerboard' to underpin the geomorphic analysis of rivers.

In **Figure 2B**, each box matches a box in **Figure 2A**. **Table 1** provides links to, and key readings for, these and other available tools mentioned in the text. Yellow shading represents a socket where a tool or approach is currently available to undertake analysis. Blue shading is used where the data and technology are available for tool development. Green shading is used where an expert-manual approach to analysis is still required. This figure maps some of the tools and approaches that are already available, those that will come soon, and where a human is still needed for the foreseeable future. Even in instances where a tool exists, they occur on a spectrum from conceptual prototypes (only deployable or able to be plugged-in by the programmer who developed it) to operational research-grade tools (which work but require expertise to run), to more polished production-grade professional software (e.g. Geomorphic Change Detection (GCD)) (**Table 1**).

Table 1 Some of the available automated and semi-automated tools for the geomorphic analysis of rivers. Note: This is not intended to be an exhaustive list of all available tools, rather a guide to direct the reader to the tools identified in **Figures 2B** and **3**, and mentioned in the text. All websites were accessed 17/06/2019.

Tool	**Website or download page**	**Key related paper/s**
CONFINEMENT AND VALLEY SETTING		
Valley-Bottom Extraction Tool (V-BET)	http://rcat.riverscapes.xyz/Documentation/Version_1.0/VBET.html	Gilbert et al. (2016)
Valley Bottom Confinement Tool (VBCT)	http://confinement.riverscapes.xyz	Fryirs et al. (2016) O'Brien et al. (2019)
Fluvial Corridor Toolkit (FCT)	https://github.com/EVS-GIS/Fluvial-Corridor-Toolbox-ArcGIS	Roux et al. (2015)

TerEx toolbox (terrace and floodplain mapping)	https://qcnr.usu.edu/labs/belmont_lab/resources	Clubb et al. (2017) Stout & Belmont (2014)
RIVER PLANFORM		
Fluvial Corridor Toolkit (FCT)	https://github.com/EVS-GIS/Fluvial-Corridor-Toolbox-ArcGIS	Roux et al. (2015)
Geomorphic Network and Analysis Toolkit (GNAT) Beaver Restoration Assessment Tool (BRAT)	http://gnat.riverscapes.xyz/ http://brat.riverscapes.xyz/	Macfarlane et al. (2017)
GEOMORPHIC UNITS		
Geomorphic Unit Tool (GUT)	http://gut.riverscapes.xyz/	Bangen et al. (2014) Wheaton et al. (2015)
Geomorphic Unit Survey (GUS)	https://reformrivers.eu/geomorphic-units-survey-and-classification-system-gus	Belletti et al. (2017)
Support Vector Machine classifier (SVMc)	Remote Sensing software e.g. eCognition http://www.ecognition.com/ , ORFEO https://www.orfeo-toolbox.org/	Belletti et al. (2017) Demarchi et al. (2016, 2017)
Hydrodynamic modelling	Variety of software are available e.g. SRH-2D https://www.usbr.gov/tsc/techreferences/computer%20software/models/srh2d/index.html	Wyrick & Pasternack (2016) Wyrick et al. (2014)
BED MATERIAL TEXTURE		
Digital Grain Size Project (DGSP)	https://dbuscombe-usgs.github.io/DGS_Project/	Buscombe (2013)
BASEGRAIN	https://basement.ethz.ch/download/tools/basegrain.html	Detert & Weitbrecht (2013)
Digital Gravelometer	http://www.sedimetrics.com/	Graham et al. (2005)
Topographic Analysis Tools (TAT), including ToPCAT	http://tat.riverscapes.xyz/	Brasington et al. (2012)
RIVER BEHAVIOUR		
Morphological change – Geomorphic Change Detection (GCD)	http://gcd.riverscapes.xyz/	Wheaton et al. (2010, 2013)
Channel Migration Toolbox	https://fortress.wa.gov/ecy/publications/SummaryPages/1406032.html	Legg et al. (2014)
Planform Statistics	https://repository.nced.umn.edu/browser.php?current=author&author=37&dataset_id=15	-
Measures of channel width and centreline (RivWidth, ChanGeom, RivMap, PyRIS)	RivWidth: http://uncglobalhydrology.org/rivwidth/ ChanGeom: https://www.burchfisher.com/data.html RivMap: http://live.ece.utexas.edu/research/rivamap/ https://www.mathworks.com/matlabcentral/fileexchange/58264-rivmap-river-morphodynamics-from-analysis-of-	Pavelsky & Smith (2008) Fisher et al. (2013) Isikdogan et al. (2017) Schwenk et al. (2017) Monegaglia et al. (2018)

	planforms PyRIS: https://github.com/fmonegaglia/pyris	
SCREAM	-	Rowland et al. (2018)
Google Earth Engine	https://earthengine.google.com/	Gorelick et al. (2017)
DOWNSTREAM PATTERNS OF RIVERS AND CONTROLS		
Longitudinal profile - ArcMap stacked profile tool	http://www.arcgis.com/index.html	-
Network Profiler Tool	https://riverscapes.github.io/NetworkProfiler/	-
Geospatial Modelling Environment	http://www.spatialecology.com/gme/	Beyer (2012)
Catchment area - ArcMap flow accumulation tool	http://www.arcgis.com/index.html	-
Gross stream power	http://brat.riverscapes.xyz/	Macfarlane et al. (2017)

Entry into the River Styles procedural tree occurs at a relatively coarse scale through identification of valley setting. The measure used to determine valley setting is lateral confinement of the channel. This entails analysis of the position of the channel relative to a valley bottom margin, and the extent to which either channel bank abuts that margin (see Fryirs et al., 2016; O'Brien et al., 2019 for methodology). Three valley settings cover the full spectrum of river diversity; confined, partly confined and laterally unconfined (**Figure 1**). Confined rivers have a channel that abuts the valley bottom margin along either bank along >85% of its length. Partly confined rivers have a channel that abuts the valley bottom margin along either bank along 10-85% of its length; with 10-50% differentiating margin-controlled rivers and 50-85% differentiating planform-controlled rivers (Fryirs & Brierley, 2010; Fryirs et al., 2016; O'Brien et al., 2019). Finally, laterally unconfined rivers have a channel that abuts the valley bottom margin along either bank along <10% of its length.

Thus, the entry point into the assessment of valley setting is mapping the valley bottom. Various tools have been developed that can be used to assist in the automation of mapping of valley bottoms across drainage networks (**Figures 2B, 3**). These include the Valley Bottom Extraction Tool (V-BET) (Gilbert et al., 2016), and the Fluvial Corridor Toolkit (FCT) (Roux et al., 2015). While these tools can be used to map valley bottoms across networks, to differentiate valley settings, measures of confinement are required. O'Brien et al. (2019) developed the Valley Bottom Confinement Tool (VBCT) that can map confining margins and calculate valley bottom confinement. However, the ability to systematically identify the type of margin control or constraint (e.g. bedrock hillslope, terraces, fan, anthropogenic feature) remains under development. Although Clubb et al. (2017) have demonstrated a method to identify floodplains and terraces from DEMs and output from the TerEx toolbox (Stout & Belmont, 2014) that can be edited by a user, interpretation of air photographs and virtual globe imagery (e.g. Google Earth, Bing Maps, ArcGIS, QGIS) are typically used as part of the expert-manual approach to complete this task. Differentiation of laterally unconfined rivers with continuous channels from those that are discontinuous watercourses (often with no channels), still requires an expert-manual approach. Data are available for which water detection tools are being developed to help identify the presence of a water channel (e.g. Demarchi et al., 2016; Fisher et al., 2013; Pavelsky et al., 2008; Smith et al., 2008). Topographic and morphometric analysis based on high resolution DEMs are also available to potentially detect channel and floodplain units (Heckmann et al., 2013; Stout et al., 2014). The differentiation of water, sediment and vegetation using spectral information, coupled with topographic analysis of available DEMs is showing promising signs for the semi-automated identification of types of margin control and other constraints, channel cross section features and floodplain units (Bizzi et al., 2018; Demarchi et al., 2017). While these advances have not yet specifically addressed the differentiation of channel margin features that is incorporated within the River Styles Framework, such tools and workflows are not far away and will likely be available in coming years.

For river types with continuous channels located in partly confined and laterally unconfined valley settings, river planform is the next measure used to differentiate among River Styles. This requires analysis of the three traditional measures of planform; the number of channels, channel sinuosity and lateral (in)stability (Schumm, 1977). Only some of these measures have been semi-automated (**Figures 2B, 3**). A standalone tool to calculate the number of channels or braiding intensity (Egozi and Ashmore, 2008) does exist but is incorporated as a by-product in research grade tools like the Geomorphic Network and Analysis Toolkit (GNAT) and Beaver Restoration Assessment Tool (BRAT). Plugging these tools into this framework may require purchase or development of a ‘plug converter’ in order for them to work in the required manner. Graph theory provides a promising approach to characterise multi-channel river networks (Connor-Streich et al., 2018; Marra et al., 2014). The Fluvial Corridor Toolkit (FCT) can be used to measure sinuosity. For lateral (in)stability, an 'expert-eye' is still useful for detecting evidence of channel adjustments from either air photographs and Google Earth, or in the field. Such evidence may include, for example, the presence of constraints on lateral channel adjustment (e.g. terraces or stopbanks), presence or absence of bank erosion, evidence of channel adjustment on the floodplain, etc. (see Fryirs & Brierley, 2013). Mapping the signs of lateral (in)stability cannot yet be semi-automated. It would require hyperspatial resolution and multi or hyper spectral sensors and ad-hoc calibrations (Marcus et al., 2003; Rowland et al., 2016) and the data required to do this are only available for selected reaches and not at a large-scale. Where tools are not available or could be developed in the future, the expert-manual approach can always be used to for undertake analysis of river planform – at least over smaller extents. For confined rivers, and laterally unconfined rivers with absent or discontinuous channels, river planform is not measured (see Brierley & Fryirs, 2005; Fryirs & Brierley, 2018).

The next step in the procedural tree entails identification of geomorphic units (landforms that are the building blocks of rivers; Belletti et al., 2017; Brierley & Fryirs, 2005; Fryirs & Brierley, 2013; Wheaton et al., 2015). This is the key diagnostic indicator used to differentiate river types, and is used to interpret process and river behaviour in subsequent steps of Stage 1. Instream and floodplain geomorphic units are pieced together (like a jigsaw) to characterise the assemblage of geomorphic units that comprise a river type. Various tools have been developed to semi-automate the mapping of geomorphic units (**Figures 2B, 3**). At a coarse, macro-scale water channel, unvegetated sediment bars, sparsely vegetated units and floodplain units can be mapped and identified using a support vector machine classifier (SVMc) and the Geomorphic Unit Survey (GUS) (Belletti et al., 2017; Demarchi et al., 2016, 2017). At a finer scale, hyperspatial information derived from multi or hyper spectral bands from UAV mounted sensors (Rivas Casado, 2017; Woodget et al., 2017), and hydrodynamic modelling and depth-velocity relationships, have been used to map geomorphic units (Wyrick & Pasternack, 2016; Wyrick et al., 2014). The shape/morphology of different surfaces (i.e. concave, convex and planar surfaces) can be mapped along reaches using the Geomorphic Unit Tool (GUT) (Bangen et al., 2014; Wheaton et al., 2015). While these tools produce useful results, work is still required to develop an approach that produces consistent and robust outputs across a range of different river types. The primary limitation is the availability of high-resolution hyperspatial and/or topographic data across a large enough range of replicates across the full range of river diversity that can be used to train the classifiers to accurately map and identify shapes and morphologies (Wheaton et al. 2017). GUT has been used to apply a fluvial taxonomy to identify -in-channel geomorphic units systematically (Brierley & Fryirs, 2005; Fryirs & Brierley, 2013; Wheaton et al., 2015), but is not yet operational for floodplain geomorphic units. Moreover, the in-channel unit differentiation works much better if an expert-manual delineation of thalwegs is provided as an input as this allows for proper identification of riffles. This level of interpretation still requires the expert-manual approach. However, given the increase availability of hyperspatial data, mostly from UAS (drone) that generate spectral but also topographic information (DEM), and the opportunity offered by novel deep learning algorithms, this task is likely going to represent an active and fruitful research topic in the coming years.

Finally, analysis of bed material texture is used to further differentiate river types at the finest scale of resolution in the hierarchy. The tools that have been developed to analyse bed material grain size have, to date, focussed primarily on gravel-bed rivers (**Figures 2B, 3, Table 1**). Approaches have focused either upon grain size mapping from aerial imagery or from hyperscale DEMs. A variety of photosieving methods have been developed to analyse digital grain size distributions by analysing photograph image texture using semivariograms (Verdú et al., 2005), autocorrelation (Rubin, 2004) and the identification of individual grains (e.g. BASEGRAIN, Detert & Weitbrecht, 2013; Digital Gravelometer Graham et al., 2012). Bed material texture is mapped from hyperscale DEMs by developing relationships between topographic roughness and grain-size (Pearson et al., 2017; Reid et al., 2019). For example, the Digital Grain Size Project (DGSP) (Buscombe, 2013) and Topographic Analysis tools (TAT) such as ToPCAT (Brasington et al., 2012). It is nowadays a standard procedure to derive, from UAV imagery acquisitions, sediment distribution information (Carbonneau et al., 2018). Some of these methods have been developed to calculate grain size across large areas using airborne imagery (Carbonneau et al., 2004, 2012). However, all these tools still require fieldwork for calibration and validation of the output. Tools for differentiating grain size classes such as bedrock, boulder, sand and fine-grained bed material textures with easily available data (such as globally available satellite data) have not yet been developed, due to limitations associated with the spatial resolution of imagery, but given the increasing availability of multiple spectral bands, orbital grain size mapping represents an open research challenge.

Fryirs and Brierley (2018) used the River Styles procedural tree as a basis for designing a naming convention for geomorphic river types. This convention uses the same principles of scaffolding and entry-exit (plug-in or unplug) to develop names; both verbose and abbreviated. While the convention has not yet been converted into an automated procedure, the potential exists for feature classes and options sets to be built into such a platform to produce River Styles names for consistent use in any setting.

Analysing and interpreting river behaviour

In the River Styles Framework process-form associations are used to interpret the mix of erosion and deposition processes that make up a river reach (Fryirs & Brierley, 2013). By correctly mapping and identifying geomorphic units that make up a river reach, a geomorphologist can infer the process or processes by which each geomorphic unit was formed and reworked. The assemblage (or package) of geomorphic units that make up a reach is used to interpret river behaviour, defined as "adjustments to river morphology induced by a range of erosional and depositional mechanisms by which water moulds, reworks and reshapes fluvial landforms, producing characteristic assemblages of landforms at the reach scale" (p. 143, Brierley & Fryirs, 2005).

For analysis and interpretation of process and river behaviour another set of tools and skill-sets are required (e.g. **Table 1**). To date, this step is at the forefront of remote sensing applied to river geomorphic analysis (Marcus & Fonstad, 2010) and semi- or full-automation procedures are being explored. For example, multi-temporal aerial photography and satellite imagery are available to undertake analysis of lateral channel dynamics for rivers with notable geomorphic adjustments. Horizontal scales of detection are a function of imagery resolution; for example, LANDSAT, Sentinel-2, PlanetScope and Worldview3 satellites have resolutions of 30, 10, 3-4 and 0.31 m respectively. The unprecedented frequency of data acquisitions mean that there is potential to track geomorphic adjustments daily or sub-weekly. A number of tools have been developed to measure planform statistics

(Cantelli et al., 2019), channel width and centrelines from imagery, such as RivWidth (Pavelsky & Smith, 2008), ChanGeom (Fisher et al., 2013) and RivMap (Isikdogan et al., 2017). PyRIS (Monegaglia et al., 2018) improves upon the broken multi-channel connectivity in multi-channel networks offered by RivaMap and discriminates between main and secondary channels. These tools provided the foundation for the development of semi-automated to automated tools for multi-temporal analysis of planform change and historical instability, which are available in the Channel Migration Toolbox (CMT; Legg et al., 2014), SCREAM (Rowland et al., 2018), RivMap (Schwenk et al., 2017) and PyRIS (Monegaglia et al., 2018). PyRIS can be considered as fully automated since it includes algorithms to automatically delineate river masks but CMT requires a centreline and SCREAM and RivMap require binary masks of river channels. Google Earth Engine (Gorelick et al., 2017) is likely to enable spatial and temporal upscaling of existing tools.

For the analysis of morphologic change, Geomorphic Change Detection (GCD) provides a helpful tool/workflow to aid interpretations (Wheaton et al., 2010, 2013). This approach uses sequential sets of high-resolution point data to map and quantify areas of erosion and deposition along river reaches (see **Figure 4**). This, combined with geomorphic unit maps provides the foundation data to make interpretations of process and behaviour. However, as **Figure 4** highlights, an expert-manual approach is still needed to translate erosion-deposition dynamics and match this with the geomorphic units that are being formed and reworked to then categorise the processes (and by extension, behaviour) and map areas of adjustment or change (Wheaton et al., 2013; Williams et al., 2015).

Analysing downstream patterns and controls

Any analysis of river character and behaviour should be placed within a catchment-scale context (Brierley & Fryirs, 2009; Gurnell et al., 2016). Knowing the position of a reach within its catchment and the pattern of reaches that occur along any drainage line sets context, and aids interpretation of the mix of imposed and flux controls that determine why that type of river occurs where it does and why that pattern of river types occurs (Brierley & Fryirs, 2005). When conducted across a catchment, analysis of tributary-trunk stream relationships is possible. By extension, and in latter stages of the River Styles Framework, this baseline set of information is also used to interpret sediment (dis)connectivity patterns and dynamics, make forecasts about the sensitivity of different river reaches to disturbance, and to assess the recovery potential of any given river reach in a catchment (see Fryirs & Brierley, 2001, 2016; Fryirs et al., 2007).

In Stage 1, Step 2 of the River Styles Framework, analysis of downstream patterns and controls on rivers is undertaken using longitudinal profiles as the key tool for analysis and visualisation (Brierley & Fryirs, 2005; Church, 1992; Jain et al., 2008; O'Brien et al., 2017). The analysis starts with differentiation of river courses that have similar patterns from those that are distinct, undertaken by plotting the downstream pattern of river types under the longitudinal profile (**Figure 5**). The analysis of controls is then conducted by stack-plotting the sequence of imposed and flux controls. Imposed controls are those that are landscape-scale attributes that are set over geomorphic timeframes (Brierley and Fryirs 2005; Fryirs et al., 2012). They include slope (i.e. the longitudinal profile), catchment area, valley setting (i.e. valley bottom confinement) and landscape unit (i.e. areas of uniform topography such as tablelands, rounded hills, escarpments). Sometimes geology and geological boundaries are added as another imposed control. Flux controls are those that adjust over geomorphic timeframes and in this analysis include the longitudinal pattern of gross stream power, and analysis of the sediment regime (whether the reach is bedload, mixed-load or suspended load dominated) and the contemporary process zone (i.e. whether the reach is acting as a source, transfer or accumulation zone) (Brierley & Fryirs 2005; Fryirs et al., 2012). Using this set of information, an interpretation is made of the mix of controls on the character and behaviour of each river type.

Some parts of this analysis can already be fully automated, particularly the imposed controls (**Figure 5; Table 1**). The production of longitudinal profiles, catchment area and gross stream power plots can be produced throughout networks using standardised GIS procedures. For example, longitudinal profile generation can be automated using the ArcMap stacked profile tool, the Geospatial Modelling Environment of Beyer (2012), the Network Profiler Tool (NPT) or GNAT (**Table 1**). Catchment area can be automated using the ArcMap flow accumulation tool. In terms of flux controls, gross stream power requires data extraction from a DEM coupled with catchment-area discharge (CA-Q) relationships (Bizzi & Lerner, 2015; Jain et al., 2008; O'Brien et al., 2017) or as part of BRAT (**Table 1**; Macfarlane et al., 2017). The analysis of River Styles and valley bottom confinement (valley setting) is plugged-in from Stage 1, Step 1 of the River Styles Framework. The analysis of landscape units can be semi-automated by processing a DEM using *ad-hoc* GIS procedures or relying on existing toolboxes (e.g., FCT) and then analysing and plotting the outputs using data analytic software linked to GIS environments such as R, or Python. The interpretation of contemporary process zone and sediment transport regime still needs to be undertaken using the expert-manual approach.

POTENTIAL EXTENSIONS INTO STAGES 2 AND 3 OF THE RIVER STYLES FRAMEWORK

In the River Styles Framework, catchment-wide appraisals of river character, behaviour and pattern conducted in Stage 1 provide the foundations for systematic analyses of geomorphic river condition and recovery potential in Stages 2 and 3, prior to considering management applications in Stage 4 (Fryirs, 2015; Fryirs & Brierley, 2016). These determinations build upon catchment-wide analysis of river evolution and changing connectivity relationships (Fryirs et al., 2007; Fryirs 2013). This includes analysis of river responses to disturbance events and changes to prevailing fluxes, alongside predictions of prospective river futures based upon analyses of the evolutionary trajectory of the river (see Brierley & Fryirs, 2009, 2016; Fryirs et al., 2009). With rapidly emerging datasets, analytical and modelling approaches, such analyses can be integrated with, and build upon, historical (decadal) studies of channel adjustment (Bizzi et al., 2018). These appraisals are readily facilitated by analysis of satellite imagery (e.g. Connor-Streich et al., 2018; Isikdogan et al., 2017; Leduc et al., 2019; Monegaglia et al., 2018) and derived quantitative assessment of the pattern/extent of channel adjustment on the one hand, or using geomorphic change detection (GCD) techniques on the other (e.g. Marteau et al., 2017; Pasternack & Wyrick, 2017; Rowland et al., 2016; Schaffrath et al., 2015; Wheaton et al., 2010, 2013). Such planimetric analyses support greater insight into trajectories of river adjustment (e.g. Horton et al., 2017; Lammers & Bledsoe, 2018; Suizi & Nanson, 2018). With estimates of bank height, time-series of aerial photographs can be used to estimate bank erosion volumes over decadal timescales (Spiekermann et al., 2017). Such work is now directly utilised in analysis of flood risk where delineation of areas of floodplain inundation and erosion hotspots are used to define ‘erodible corridors’, ‘space to move’ and ‘event-scale morphodynamic corridors’ (Piégay et al., 2005; Rinaldi et al., 2015; Croke et al., 2016).

Moreover, if historic aerial images are of sufficient image resolution and overlap, quantitative three-dimensional analyses of river geomorphic adjustment and condition are achievable (Bakker & Lane, 2017). Remote sensing technology now allows us to generate objective and robust information at a large scale, across regions and river networks. Large scale datasets with (virtually) continuous data at the network scale are already being used to characterise how river channels adjust and evolve in response to geological, climatic and anthropogenic controls. This includes analysis of lag and legacy effects and the ways and rates at which responses to disturbance events are conveyed through river systems as sediment pulses (e.g. Czuba & Foufoula-Georgiou, 2014; Schmitt et al., 2017; Tunnicliffe et al., 2018). It also includes the development of tools to map and quantify riparian vegetation and wood loading, recruitment potential and accumulation that can be used to make interpretations on the mediating role of vegetation and wood on river adjustment and condition (e.g. RCAT – Riparian Condition Assessment Tool in Macfarlane et al. (2017) and Wood Restoration Assessment Tool in Wheaton et al. (2019)).

In addition, important conceptual advances have accompanied the significant growth in high resolution, increasingly frequently-acquired datasets. Together, insight from spatially distributed observations and numerical predictions of sediment transport rates and volumes shed light on fluvial morphodynamics and can inform river management decision making (Frings & Ten Brinke, 2018). For example, Czuba et al. (2015) predict the distribution and role of network structure as a control upon geomorphic hotspots at tributary confluences, while Schmitt et al. (2016) and Tangi et al. (subm) develop a predictive tool called CASCADE (http://cascademodel.org/), to appraise changing connectivity relationships in river systems. Williams et al. (2016) use a two-dimensional numerical model to predict changes to braided river morphodynamics at the event scale. Collectively, these various analyses present greatly enhanced capacity to quantify and predict changes to bedload transport rates in river systems and associated morphodynamic responses during floods (e.g. Czuba et al., 2017; Downs et al., 2018; Reid et al., 2019; Schmitt et al., 2018a, b; Vaughan et al., 2017). By extension, these novel applications open the way to develop or extend existing frameworks to be capable of running various climate and anthropogenic scenarios to forecast the range of future channel trajectories.

Prospectively, these various developments will engender profound transformations in practice in river science and management, providing insight into the dynamic physical habitat mosaic of each river system. Rather than considering reaches as types, quantitative analysis of river character, behaviour and pattern will allow each river to ‘speak for itself’ over the time period for which data are available (Brierley, 2019). Catchment-specific data on morphodynamics and evolutionary trajectories present enhanced predictive capability to support foresighting exercises.

IS A HUMAN STILL NEEDED TO UNDERTAKE GEOMORPHIC ANALYSIS OF RIVERSCAPES?

The geomorphic analysis of rivers will never be fully-automated. While significant progress has been made to develop tools and workflows that can help make the process more efficient, scaleable and less-qualitative, much of what has been developed to date can only assist an expert to undertake analyses and interpretations and has occurred independent of an integrating platform or framework to plug into. In 2019, we suggest that the field is still situated in an expert-manual approach for the analysis of riverscapes.

We recognise that some of the tools noted in this paper will not yet perform well in some settings, largely due to insufficient data resolution, or the need for a new tool to be developed (e.g. high-energy mountain streams or lower order confined rivers). However, in coming years it is highly likely that as emerging technologies and data resolution improve, and processing speeds increase, much of the initial, baseline survey of rivers will become semi- or fully-automated, and new plug-in tools will be available to undertake, at least, a first filter of the types, distribution and behavioural attributes of rivers we see in our landscapes (e.g. Demarchi et al., 2017; O’Brien et al., 2019). The potential roll out of such tools across networks (and regions) is a partial reality.

Currently, to take the next step and analyse process and behaviour, an expert is required to interpret erosion-deposition or change detection outputs and to place this analysis in a spatial and temporal context (e.g. **Figure 4**). It is likely that in the coming years remote sensing derived products, tools, analysis procedures will be used not only in Stage 1 but also Stages 2 and 3 of the River Styles Framework allowing the characterisation of historical condition and trajectories, and the prediction of future ones for use in analysis of river condition and recovery potential.

There will always be a fundamental need for the results of such work to be contextualised and interpreted by an expert. In many cases, there will also be a need for experts to field-verify and validate the approximations derived using such models. A geomorphologist is required to check that what is produced through the semi- or fully-automated process makes sense on-the-ground. This is particularly important when outputs are used by environmental management agencies and local communities to make decisions about prioritisation, resourcing and on-ground rehabilitation activities. If the output does not make sense in their 'place' then the likely uptake and utility of such products will be limited to the academic arena.

In essence, a human is still needed in many parts of the process and this will continue to be the case into the foreseeable future. Humans are still needed to:

- continue to develop new tools and approaches to analysis of big data;
- carefully choose a coherent, scaffolded framework or approach to plug the tool into;
- have the conceptual grounding and training to ask the right questions;
- collect the right data, measure the right things, at the right spatial and temporal scales to answer the questions;
- choose the right tool or workflow for the job;
- carefully consider whether current data and tools are 'good enough' for some analyses (or choose to use traditional methods);
- interrogate and interpret the output (check its validity in the field);
- manage datasets and their storage;
- make resourcing and conservation or rehabilitation decisions; and
- undertake place-based, community integrated, river management on-the-ground.

A delicate balance needs to be struck in moving the geomorphic analysis of rivers forward in light of this technology and big-data revolution. As a discipline we cannot allow the technology to drive the questions and outputs, but we do need to use the latest technology and big-data to answer questions of significance, whether scientific or managerial. We call on the geomorphology community to carefully consider how we might work more collaboratively to share tools and findings on the usability, validity and veracity of available (and new) tools in moves to support the democratisation of knowledge. Open Access libraries (e.g. Community Surface Dynamics Modeling System (CSDMS): https://csdms.colorado.edu/, Open Topography: http://opentopography.org; and Riverscapes Consortium http://www.riverscapes.xyz) are slowly emerging and provide avenues for valuable collaboration across both research and practitioner communities. Platforms for big data analysis of geospatial data like Google Earth Engine or CSDMS allow many of these algorithms to be scaled up to catchment-wide, regional and national extents.

The River Styles Framework is one of several coherent, conceptual frameworks to analysis and interpretation of rivers into which the right tools can be plugged to automate the process. Our capacity to develop and integrate such tools into this (and other) frameworks as part of collaborative research and development is an exciting challenge for the fluvial geomorphology and river management community going forward into the 21st Century.

CONCLUDING COMMENT

Emerging technologies present enormous promise to allow each river to ‘speak for itself’, as place-based data provide insight not only into how a river looks, but more importantly how it adjusts, behaves and changes and its associated evolutionary traits. Prospectively, transformative understandings of river morphodynamics, their relations to formative processes, and their associated magnitude, frequency, duration and sequence will soon be in-hand for all rivers, everywhere.

An appropriate conceptual and operational framework is required to organise information and interpretations in a logical and coherent manner in conducting geomorphologically-informed approaches to river management. Such catchment-specific applications need to ask the right questions, rather than being overwhelmed by available data. The River Styles Framework provides an approach into which tools can be plugged-in to develop understandings of controls upon river character, behaviour, patterns and evolutionary trajectory.

Such data-driven evidence offers prospect to develop scientific and managerial frameworks that reflect place-based insights into the character and behaviour of a river, rather than applying classification frameworks that impose an interpretation of how and why a river adjusts in the way that it does. Building upon such opportunities and insights, information bases and analytical frameworks are likely to be used more as an analytical tool, rather than a point of departure in geomorphic analyses of river systems.

In recent years, various tools have been developed to identify and characterise geomorphic river types across basins in a semi-automated manner, thereby providing a coherent synthesis of geomorphic information to support applications in river science and management. Many powerful tools are already in-hand, others are in-development, and some will not be available for some time. However, technology on its own will not provide all the answers. An expert-manual approach will always be required to guide parts of the process, complemented by field-based interpretations of river character and behaviour, patterns and controls, and evolutionary traits.

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Figure captions

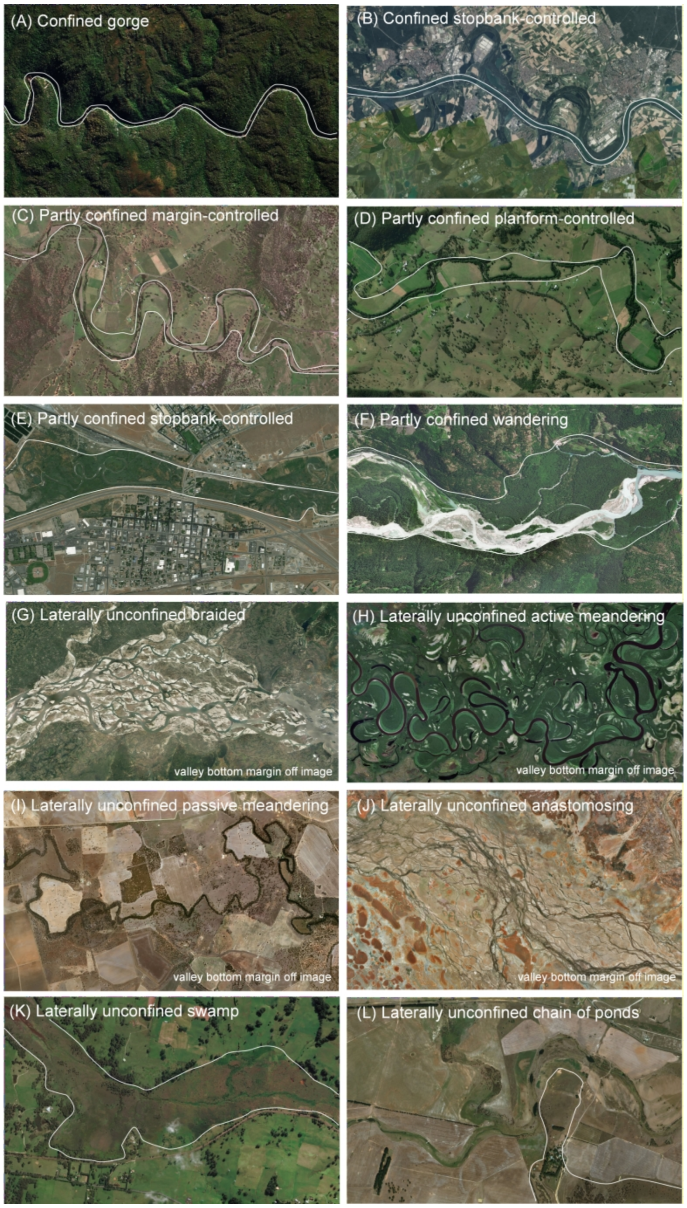
Figure 1: Examples of geomorphic river diversity. Valley bottom margin noted as white lines. For definitions and methods see Fryirs et al. (2016), Fryirs and Brierley (2018) and O'Brien et al. (2019). (A) Franklin River, Australia; (B) Rhein River, Germany; (C) Pages River, Australia; (D) Williams River, Australia; I Humboldt River, USA; (F) Squamish River, Canada; (G) Brahmaputra River, Bangladesh; (H) Nowitna River, Alaska; (I) Macquarie River, Australia; (J) Cooper Creek, Australia; (K) Wingecaribee River, Australia; (L) Mulwaree Ponds, Australia. Basemaps produced with ArcGIS® software by Esri. Sources: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community. For approaches to identification and naming of these examples see Fryirs and Brierley (2018).

Figure 2 Stage 1, Step 1 of the River Styles Framework as a powerboard into which semi-automated tools for analysis can be plugged or un-plugged (denoted by the yellow shading with three-point power socket) where data and technology are available for tool development (blue shading), and where an expert-manual approach is still needed (green shading). Note: relative proportions of colour in each box are not significant. (A) from Brierley and Fryirs (2005) and Fryirs and Brierley (2018). (B) V-BET = Valley-Bottom Extraction Tool, VBCT = Valley Bottom Confinement Tool, FCT = Fluvial Corridor Toolkit, API = aerial photograph interpretation, GE = Google Earth, SVMc = support vector machine classifier, GUT = Geomorphic Unit Tool, GUS = Geomorphic Unit Survey. The category 'H-res DEM' (High resolution Digital Elevation Model) includes use of LiDAR and Structure from Motion (SfM) as two available geomatics technologies. The category 'satellite' refers to both planimetric imagery and derived DEMs. **Table 1** provides links to, and key readings for, these available tools.

Figure 3 (A) Plug-in options available to aid production of (B) Example outputs that can be used to characterise river types. **Table 1** provides links to, and key readings for, these available tools.

Figure 4 Example of Geomorphic Change Detection (GCD) output overlayed with expert-manual interpretation of processes and types of adjustment. (A) Wheaton et al. (2013) and (B) Williams et al. (2015).

Figure 5 (A) Plug-in options available to aid production of (B) Stacked-longitudinal profile plots for analysis of downstream patterns and controls on river character and behaviour. The example used is the Middle Fork John Day, USA (modified from O'Brien et al. 2017). **Table 1** provides links to, and key readings for these available tools.



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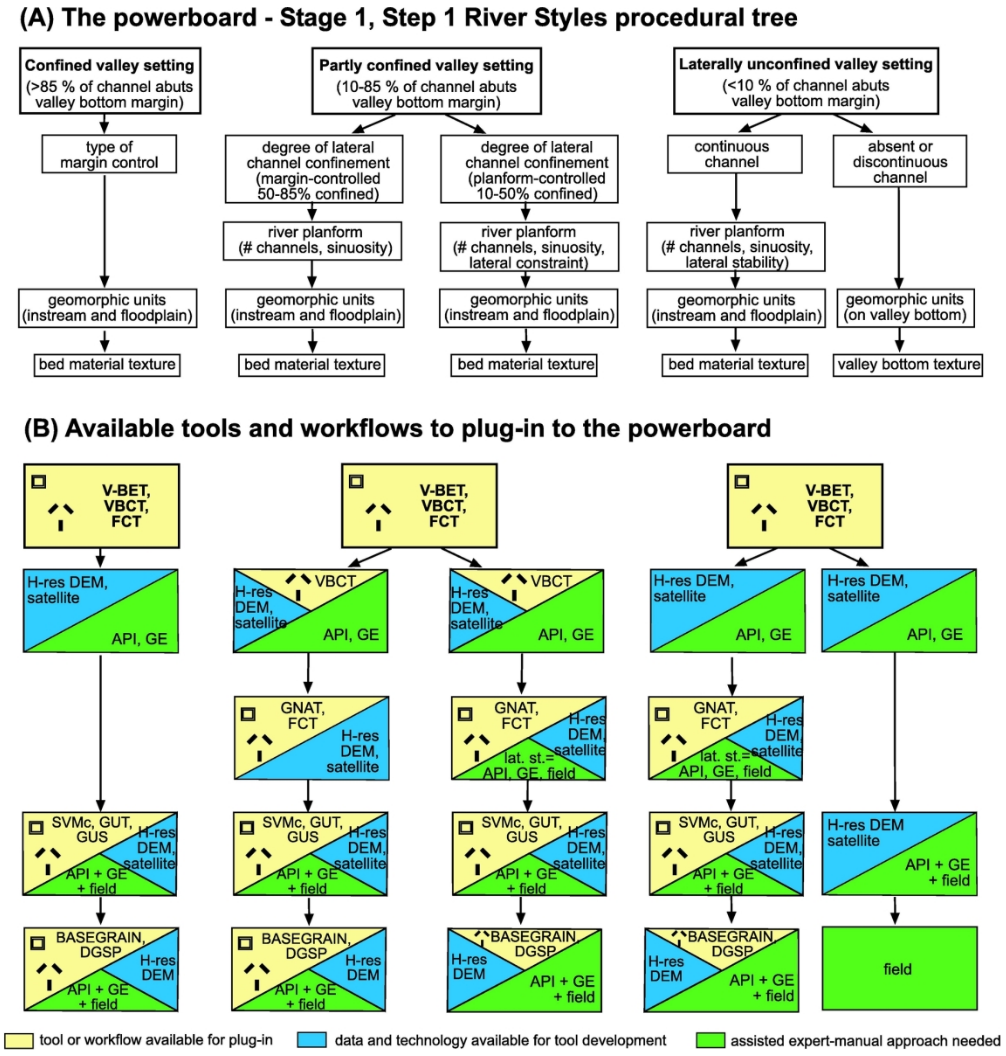

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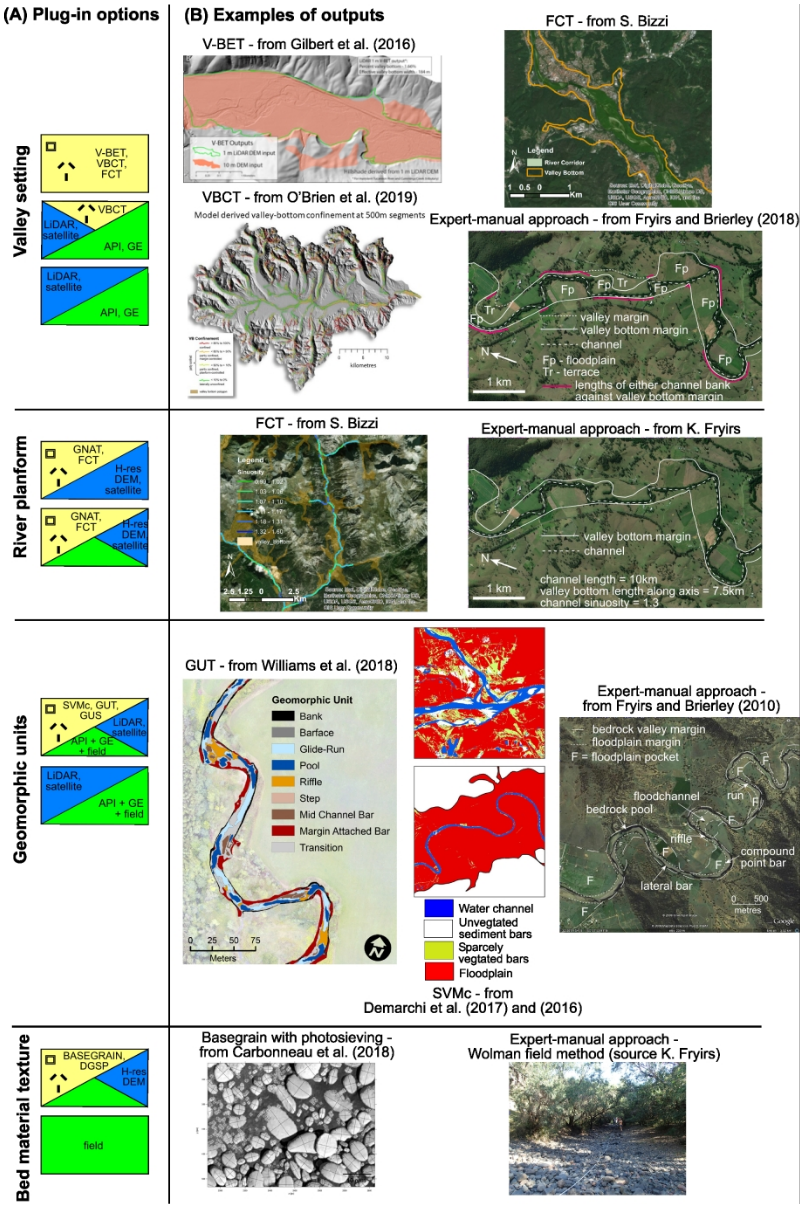

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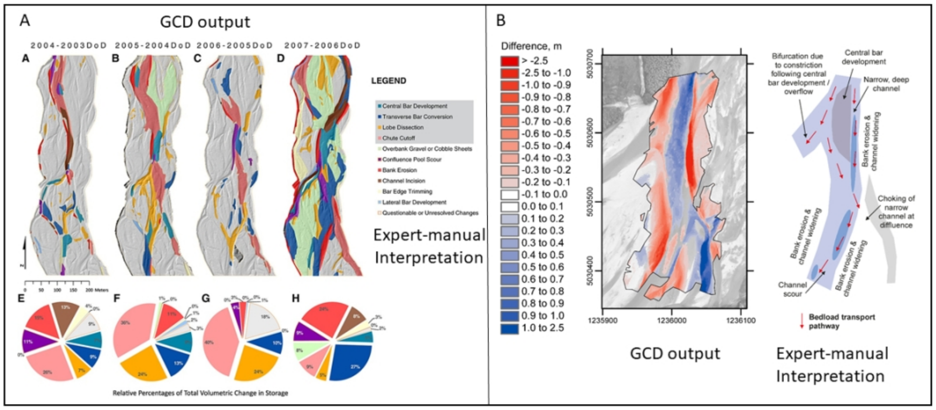

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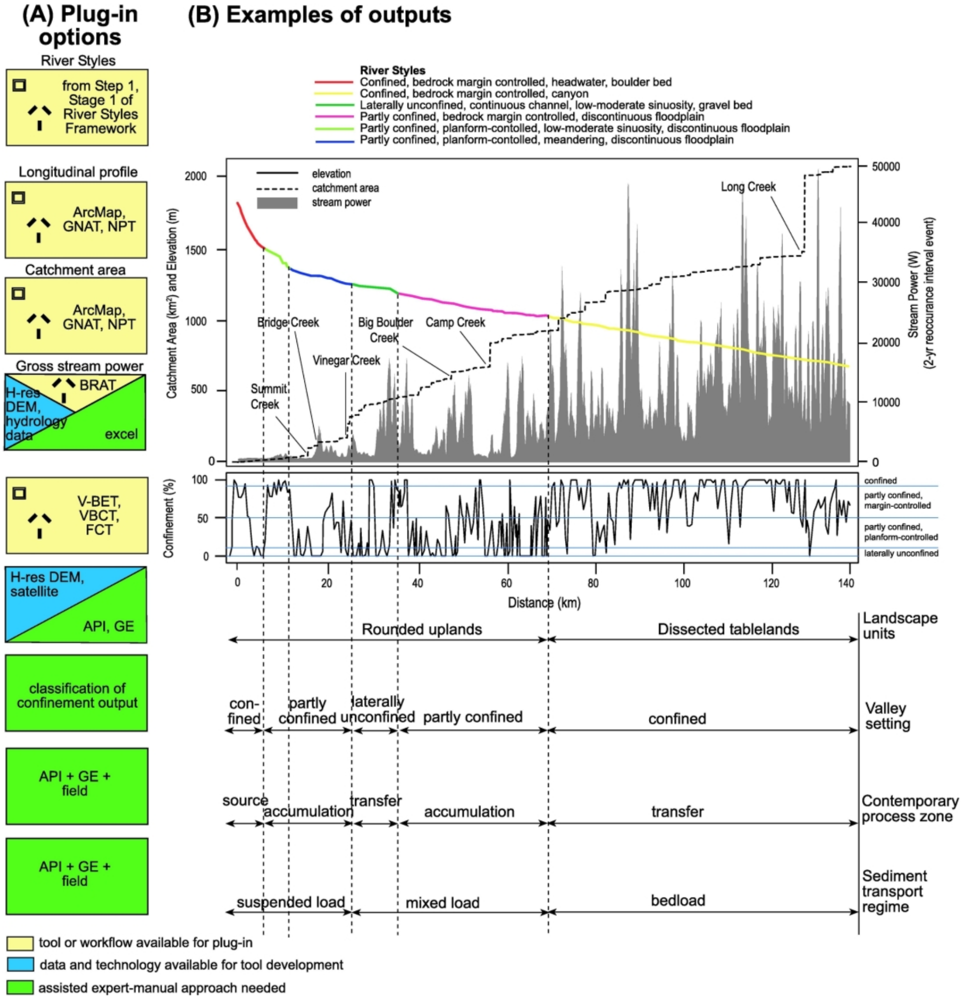

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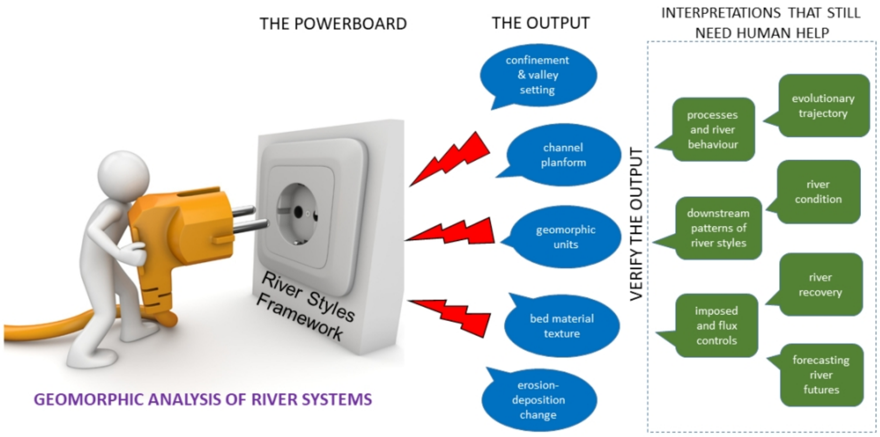

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