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Review and outlook of river morphology expression

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ABSTRACT

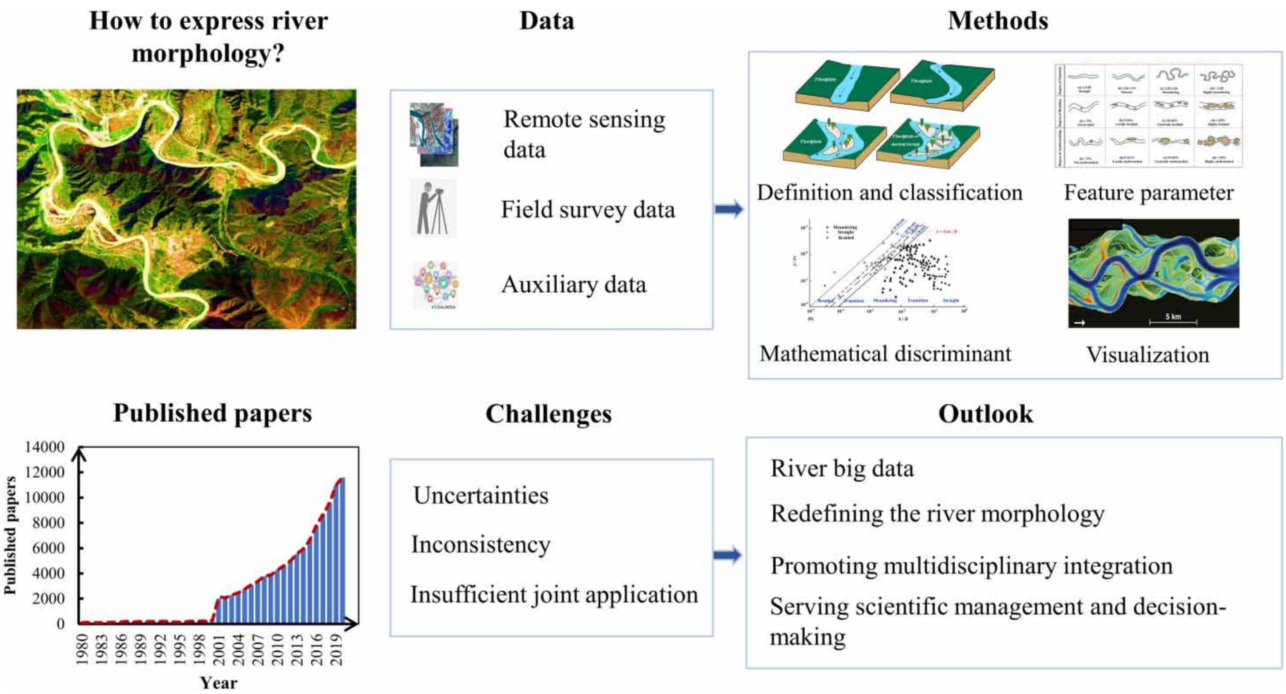
The morphological expression of rivers provides a primary medium for human understanding of river geomorphology and the transmission of geographical information. In an ever-changing environment, constantly updated river monitoring data and products offer considerable potential for an explicit expression of river morphological characteristics and associated processes. This paper reviewed the advances in river morphology expression and examines how the various approaches can be utilized to interpret changing geomorphic features of rivers. First, taking alluvial rivers as the research object, river morphology is classified into three types of expression data and four categories of expression models. Then, the limitations of current river morphology models, such as uncertainty, inconsistency, and poor joint application, are analyzed. Finally, four outlooks are offered for improving river morphology expression, including stimulating the expression of river morphology with big data of rivers, redefining different river types, promoting multidisciplinary and interdisciplinary integration, and serving scientific management and decision-making.

Key words: challenges, expression, outlook, river morphology

HIGHLIGHTS

- Constantly updated data and models offer great potential for expressing river morphology.
- The expression of river morphology faces the challenges of uncertainty, inconsistency, and insufficient joint application.
- Four outlooks are expected to enhance the future expression of river morphology.
- A systematic research framework for the morphological expression of rivers is recommended.

GRAPHICAL ABSTRACT



INTRODUCTION

As the fundamental connection between land and the ocean, the river is a crucial component of the global water and energy cycle (Wang *et al.* 2019). River morphology has been changing frequently over the last few decades due to climate change and anthropogenic factors (van Vliet *et al.* 2013; Grill *et al.* 2019). Particularly in ecologically fragile and densely populated areas, intensive human activity has severely affected and restricted the evolution of river morphology, and river ecology is facing increasing pressure (Tulbure *et al.* 2016; Yousefi *et al.* 2017; Zhang *et al.* 2019). In these areas, river morphology exhibits a high degree of nonlinearity and complexity (Agnihotri *et al.* 2020; Boota *et al.* 2021), and there is still no unified solution on how to accurately represent its morphological characteristics.

As rivers have formed under dissimilar incoming water, sediment, and riverbed boundary conditions (Eaton *et al.* 2010), river morphology poses a significant theoretical issue in river evolution. Since the concept of river channel morphology was offered by Leopold & Wolman (1957), the expression of morphological characteristics in rivers has begun to receive attention from different fields. For example, geomorphologists have proposed various classification systems and genesis hypotheses for river morphology (Rust 1978; Schumm 1985; Rosgen 1994; Xin *et al.* 2018). Scientists of hydraulics are interested in revealing the hydrological process of river formation (Crosato & Mosselman 2009). Sedimentologists and geologists have examined the distribution of sediment within the bend, bedforms within the channel, and sedimentary structures (Church 2006; Hohensinner *et al.* 2018). Several map experts have specialized in two-dimensional (2D) and three-dimensional (3D) map modeling, as well as river visualizations (Rhoads & Johnson 2018). In recent years, computer scientists have examined algorithms that recognize and detect river types automatically based on their morphological features (Li *et al.* 2014; Hou *et al.* 2020). Despite the significant contributions of these fields to the expression of river morphology, there is still a lack of a comprehensive review of research on the expression of river morphology in different disciplines, a systematic summary of the challenges, and some outlook for future research on river morphology. Meanwhile, with the advent of the era of big data on rivers and the requirements for digital river construction, it is urgently required to systematically re-examine the previous models and methods of river morphological expressions and to present practical solutions to further enhance human understanding of river geomorphology.

During the past few decades, constantly updated river data and significantly improved expression models of river morphology have provided opportunities for a comprehensive understanding of river morphology. The number of review articles related to river morphology is steadily increasing, such as summarizing the classification system (Tadaki *et al.* 2014), development conditions (Kleinhans 2010), influencing factors (Stecca *et al.* 2019), river diversion (Khaleghi & Surian 2019), river morphology transformation (Vayssière *et al.* 2020), and river management (Habersack *et al.* 2016; Zhang *et al.* 2018). These reviews, however, failed to consider the following significant issues. First, the existing definitions and classification of river morphology are unclear and, in particular, numerous terms in multi-flow rivers have not been sorted out comprehensively and systematically. Second, the progress of river morphology research has not been reviewed in a multidisciplinary way. Particularly, the visualization of river morphology in cartography and computer science has rarely been integrated with the representation of river morphology in traditional disciplines (e.g., geomorphology, hydrology, etc.). Third, the limited understanding of how rivers are expressed hinders the in-depth analysis of river morphology, the description of real geomorphological and environmental changes across rivers, and the revelation or explanation of underlying social, economic, and political issues.

To compensate for the lack of attention to the topic of river morphological expression in previous reviews, this paper focuses on the following three aspects: (i) summarizing existing data and methods of river morphological expression in various disciplines, (ii) analyzing the main challenges and limitations faced by various river morphological expression models and methods, and (iii) proposing future directions to promote a more comprehensive understanding of river morphology. Alluvial rivers have a large catchment area, and most of the river reaches are in natural or near-natural conditions. Therefore, this paper focuses on the morphological expression of alluvial rivers. It is expected that this paper will provide researchers with diverse perspectives on river morphology and call for cross-integrated research by multidisciplinary experts to jointly contribute to solving the problems faced by river morphological expression and promoting the development of river morphology.

OVERVIEW FRAMEWORK

Figure 1 shows an outline of the overview framework, including four sections: data, methods summary, limitations discussion, and future outlook.

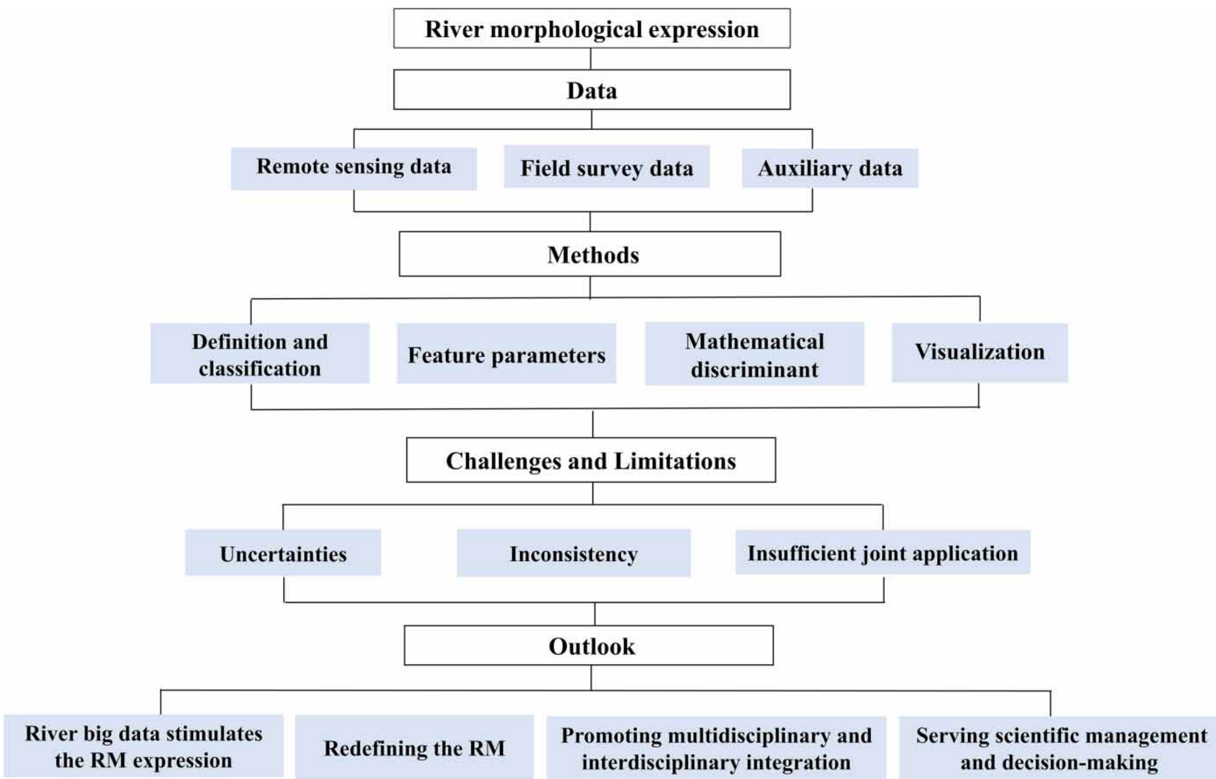


Figure 1 | Overview framework outline. RM is the abbreviation of river morphology.

DATA AND METHODS IN RIVER MORPHOLOGICAL EXPRESSION

Data

The objective of this section is to proffer an overview of major datasets in the river morphology expression collected through a variety of monitoring techniques, including remote sensing data, field survey data, and auxiliary data.

According to Belletti *et al.* (2015), remote sensing data accounted for 73% of river morphology monitoring, which provides reliable data for determining the dimensionality and depth of the river morphological expression. A series of remote sensing images are gradually being applied to river morphology, including high-resolution datasets (SPOT-5, Google, Sentinel-2, GF-1,2) (Obida *et al.* 2019; Xia 2019; Lu *et al.* 2020), low- and medium-resolution datasets (e.g., MODIS; Landsat) (Miller *et al.* 2014; Yamazaki *et al.* 2015; Hou *et al.* 2020; Ogilvie *et al.* 2020), hyperspectral remote sensing imagery (Liu & Bo 2015), radar data (e.g., Sentinel-1, GF-3) (Mersel *et al.* 2013; Mitidieri *et al.* 2016), historical images (e.g., CORONA) (Spada *et al.* 2018), topographic data (e.g., digital elevation models, DEM) (Bjerklie 2007; Lehner *et al.* 2008; James *et al.* 2012), etc. The specific river remote sensing data are shown in Table 1.

The measured data are utilized to simulate and verify the river morphology with high accuracy. Field measurements, hydrological station monitoring, and questionnaire surveys are the fundamental methods of obtaining data on river morphology (Belletti *et al.* 2015). At present, mainstream classification discriminant criteria, as well as thresholds, are based on measurements. Auxiliary data serve as data supplement, data enhancement, and accuracy verification tools (Lallias-Tacon *et al.* 2016; Magliulo *et al.* 2016). Representative datasets are shown in Table 2.

Methods

Figure 2(a) summarizes the research related to river morphology from 1980 to 2020. It is found that the number of published papers on river morphology has gradually increased since 2001, especially from 2015 to 2020, with an average annual increase of 936 papers. The CiteSpace software has been utilized to analyze the keyword frequency of the papers in Web

Table 1 | The list of major river datasets and key features of remote sensing data

Satellite/ sensor	Dataset type	Accessibility	Spectral bands	Available period	Spatial resolution	Representative dataset	Utilization and advantages
MODIS	1–2 days	MODIS web	Multi-band (36)	1999	250/500/ 1,000 m	Land cover data	High update frequency, great value for real-time monitoring.
Landsat	16 days/ time-series dataset	Free USGS	Multi-band (4,7,8,11)	1972	30/15 m	Land surface water dataset/ land use data	Reflect on the characteristics of long time-series river morphology.
CORONA images	Annual	Part free USGS	Black and White (BW) images	The 1960s–1970s	2.8 m	River historical data	Reveal the historical morphology and evolution of rivers.
Google Earth	/	Not free		2005	1.5 m	Land surface water dataset	Search, location, accuracy comparison, verification, etc.
Sentinel	5 days	Free Copernicus Hub website	Multi-band (13)	2A:2015 2B:2017	10/20/ 60 m	/	Meet high-resolution monitoring needs.
GF-1	4/2 days	Not free	Multi-band (9)	2013	8/16 m	/	
GF-2	5 days	Not free	Multi-band (5)	2014	1/4 m	/	
SAR	Daily dataset	Part free	Microwave frequencies	1978		/	Independent from weather and illumination conditions.
DEM	/	Free USGS	/	1890s	12.5/30/ 90 m	Slope dataset; aspect dataset	Support for hydrological characterization of rivers in the basin.

Table 2 | Representative measurement datasets and auxiliary datasets

	Dataset	Sub-dataset	Year
Measurement datasets	Field measurement	Leopold & Wolman (1957), Hey & Thorne (1986), Van den Berg (1995), Wang *et al.* (2005)	/
	Hydrological station		/
	Questionnaire survey	/	/
Auxiliary datasets	Geo-located social media data	Weibo, WeChat, Twitter	Real time
	Statistical yearbooks	Yellow River Yearbook; Yangtze River Yearbook, etc.	Yearly
	Website data	China Environmental bulletin data; Ministry of water resources monitoring and forecasting data	1989
	Bulletin data	Bulletin of the national water conservancy survey; Bulletin of Chinese river sediment; a monthly report of groundwater dynamics; Bulletin of water conservancy informatization; etc.	Yearly; monthly
	Historical topographic maps		
	Historical photos		

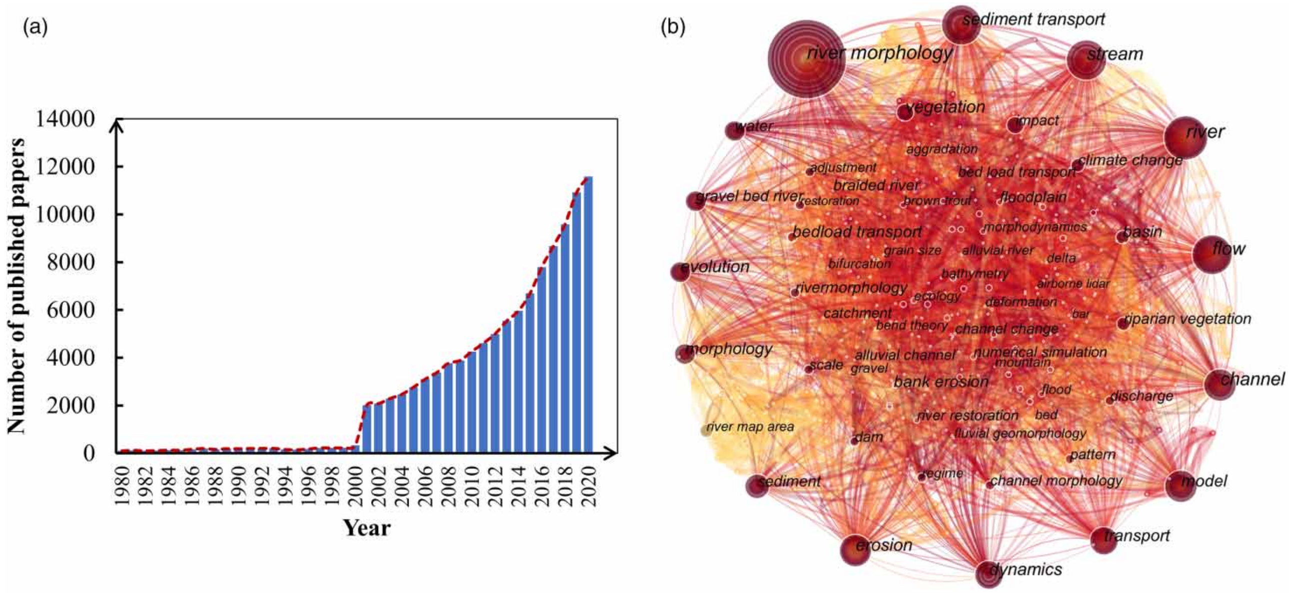


Figure 2 | Related research on river morphology statistics. (a) The number of published papers on river morphology from 1980 to 2020. (b) Knowledge graph of keywords used in river morphology research. The search was conducted using the WOS with the search conditions set as: (TI=(*river morphology * OR * river morphology * OR * river form* OR * river type*) AND LANGUAGE: (English) AND DOCUMENT TYPE: (Articles OR Review Articles)).

of Science (WOS) to decide the hot topics of river morphology research (Figure 2(b)). The top frequency ranking takes into consideration river classification (gravel-bed river, braided river), morphology (channel morphology, dynamics), cause (stream, flow), evolution (sediment transport), map (river map area), and other factors. In this paper, we outlined these research hotspots into four types of models to express the river morphology, including the definition and classification, the feature parameter extraction, the mathematical discriminant, and the river morphology visualization, and then summarize the advances for each model separately.

Definition and classification of river morphology

Classifying and defining river morphology is the first step for humans to understand and quantify the characteristics of rivers. Several classification and nomenclature systems have already been used for rivers and channels, including single channel and multiple channel networks (Table 3). Figure 3 is a schematic diagram of dissimilar river morphologies. However, those river types were ill-defined, leading to confusion in the terms utilized to describe multichannel networks (North *et al.* 2007). For example, Bridge (2003) reserved the term 'anastomosing' for the networks of channels carved into areas of the floodplain, as well as the 'braiding' networks that were formed from accretionary islands within the flow field (Figure 3(e)). Nanson & Gibling (2003, 2004) provided a definition of anabranching systems that includes the subset 'anastomosing' (Figure 3(f)). According to Mayhew (2009), the anastomosed channel is different from the branch channel, which can further split into its distribution, but this contradicts Jackson's original definition (Jackson 1834). By the end of the 20th century, a common theme emerged, using 'anastomosing' to describe relatively stable channel networks with non-submerged islands and 'braiding' to describe unstable channels with bars whose networks are mostly formed by either predominantly erosion (e.g., avulsion) or by flow split of accretionary islands classified as 'anabranching' (Figure 3(g)).

Feature parameter extraction

Feature parameter extraction is a crucial transition from qualitative to quantitative analysis of river morphology. Studies have developed numerous parameters for (1) quantifying channel geometry using geometric attributes such as length and width

Table 3 | Existing definition and main characteristics of river morphology

River types	Definition	Channel features	Representative
Straight	Relatively straight channel	Single	Leopold & Wolman (1957) Schumm (1968) Rust (1978)
Meandering	Channel bending	Single	
Braiding/braided	Channel networks of bars or islands	Single or multiple	
Anabranching/anabranched	Relatively stable channel networks with bars or non-flooding islands	Multiple	Nanson & Gibling (2003, 2004)
Anastomosing/anastomosed	Multiple channel systems have major secondary channels that separate and rejoin the main channel to form a network	Multiple	Bridge (2003)
Wandering	A transitional channel from single channels to fully braided channels	Multiple	Carson (1984), Burge (2005), Carling *et al.* (2014)

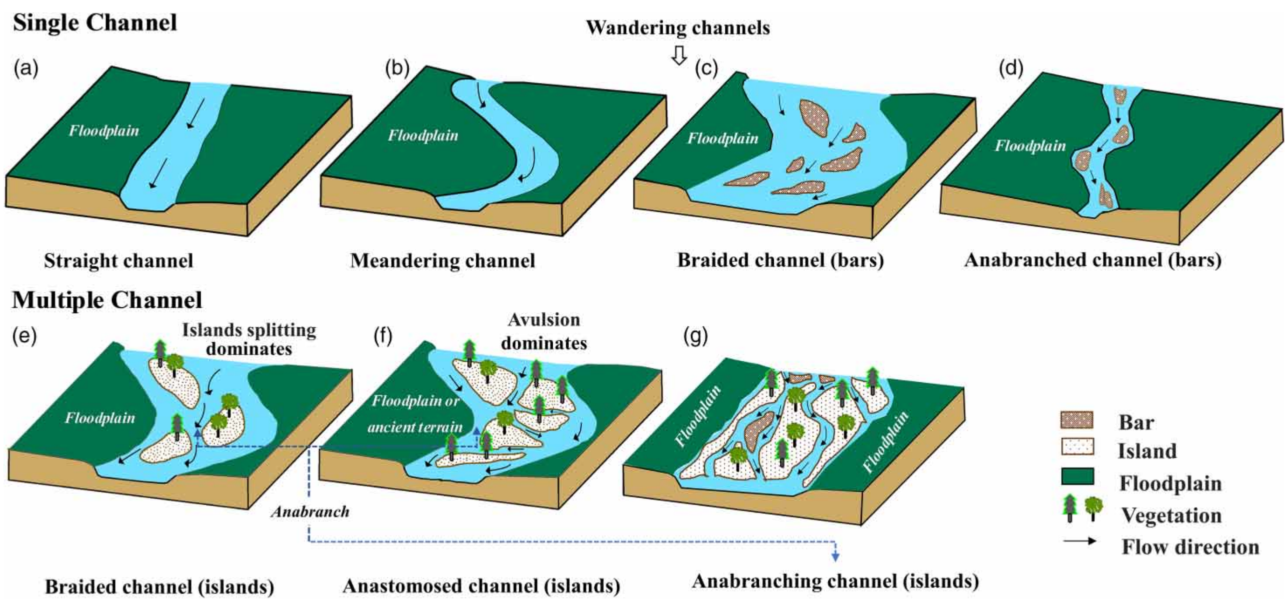


Figure 3 | Schematic diagram of river classification. Detailed explanations of the river types in (a)–(g) can be found in Appendix A.

(Haron *et al.* 2019). (2) Defining the detailed types of the channel, such as the sinuosity index, which can be utilized to define the straight, sinuous, meandering, and extremely meandering channels (Figure 4) (Tiwari *et al.* 2016). A braided river can be described by the percentage of the channel length divided by islands or bars. Then two types of braided channels (bars and islands braided) are classified based on braiding intensity and the number of islands or bars (Bertoldi *et al.* 2009). In anabranching channels, its width is greater than three times the water width at average discharge (Brice & Blodgett 1978). It is the percentage of a reach length occupied by large islands that determines the degree of anabranching. (3) Evaluating the variability of the rivers over time, such as bars carrying very small sand and gravel loads migrating through the channel (Monegaglia *et al.* 2018) (Figure 5(a)), coarse sediment moving through the channel as alternate bars (Figure 5(b)), a meandering channel cutoff at their necks (Figure 5(c)) or chute (Figure 5(d)), meander shift, and bank erosion (Figure 5(e)), islands migrating through the channel, and then avulsion occurrence (Nicoll & Hickin 2010) (Figure 5(f)). (4) Expressing the

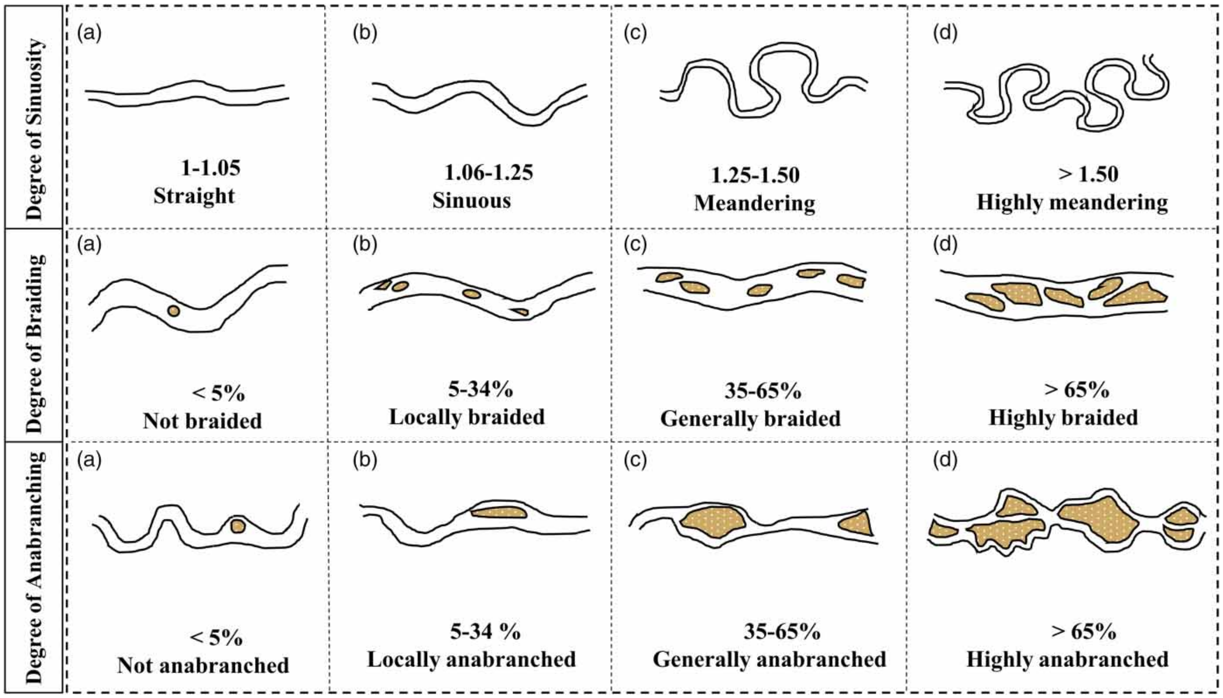


Figure 4 | Definition of channel morphology based on feature parameters (Brice & Blodgett 1978).

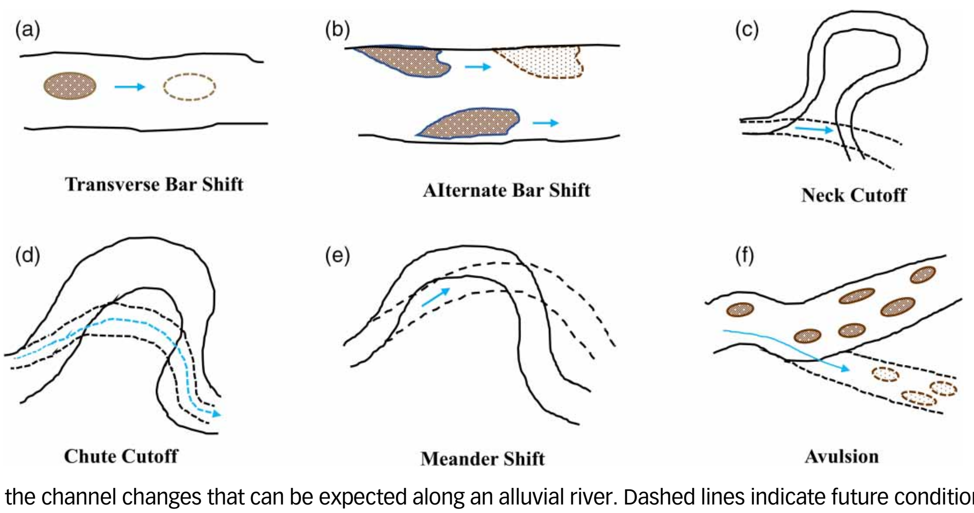


Figure 5 | Some of the channel changes that can be expected along an alluvial river. Dashed lines indicate future conditions (Schumm 1985).

complexity of the channel morphology by the structural indices, such as the fractal dimensions (Shen *et al.* 2011; David *et al.* 2013), the distribution of islands (Crosato & Mosselman 2009), the landscape morphology index (Stecca *et al.* 2019), and the hydrological morphology index (Rinaldi *et al.* 2015), etc. Typical parameters for quantifying the morphological characteristics of the river are shown in Table 4.

Mathematical discriminant

There are three fundamental mathematical expressions of river morphology: graph, mathematical statistics, and fuzzy mathematics. In the early years, Leopold & Wolman (1957) were the first to employ a graphic method to determine threshold conditions of disparate river types. To distinguish between braided and meandering rivers, he drew a double logarithmic coordinate diagram between the gradient of the flat beach and the discharge of the river (Figure 6(a)). After that, the concepts of the Froude number (Parker 1976) and river power (Van den Berg 1995) were proposed to derive the threshold conditions for the single channels (straight, meandering) and braided rivers (Figure 6(b),(c)) based on measured data. Nevertheless,

Table 4 | River morphological characteristic parameters

Application	Parameters	Definition	Formula	References
Geometric attributes	length/L	The arc length between two nodes on the curve.	/	
	Channel width/W	The vertical distance between the banks of the river.	/	
Definition and classification	Sinuosity/S	The ratio of channel length to valley length or valley slope to channel slope.	L_c/L_v S_c/S_v	
	Braid index/B_i	The ratio of the number of rivers in braided reaches to the number of effective rivers excluding braided reaches.	$B_i=N_z/N_y$	
	Branching coefficient/R_b	The ratio of the number of rivers of grade N_u to the number of rivers of grade N_{u+1}.	$R_b=N_u/N_{u+1}$	
	Normalized braid wavelength (N.wave)	(Main channel length/total number of channel nodes)/main channel width (node=confluence or diffluence)		Ashmore (2001)
Alteration and migration	Meander migration index	Treating each meander as a polygon and the location of the centroid of each polygon is calculated and compared with the same meander over the years.	$\mathrm{MMI}=\sqrt{(x_{i+1}-x_i)^2+(y_{i+1}-y_i)^2}$	Shahrood *et al.* (2020)
	Centerline migration index	Measuring the migrations of the river centerline in each year and compare it against that in the reference year.	$\mathrm{ACM}=\frac{\sum_{i=1}^{n}(\lvert L_{2i}\rvert-\lvert L_{1i}\rvert)}{n}$ $\mathrm{RCM}=\frac{\mathrm{ACM}}{\mathrm{Year}_{m+1}}-\mathrm{Year}_m$	
	Bar migration rates	The location of the centroid of each bar is calculated and compared with the same bar over the years.	$L=S_{c,i+1}-S_{c,i}$	Monegaglia *et al.* (2018)
Measure the complexity	Fractal dimension/D_c	The dimension of a small cube with side length r and its number $N_{(r)}$.	$D_c=-\lim_{r\to o}\frac{\log N(r)}{\log r}$	Shen *et al.* (2011)
	Shape index/S	Reflect the shape of the river by the ratio of the area to the square of the long axis.	$S=A/L^2$	

Note: Detailed explanations of the parameters in every formula can be found in Appendix A.

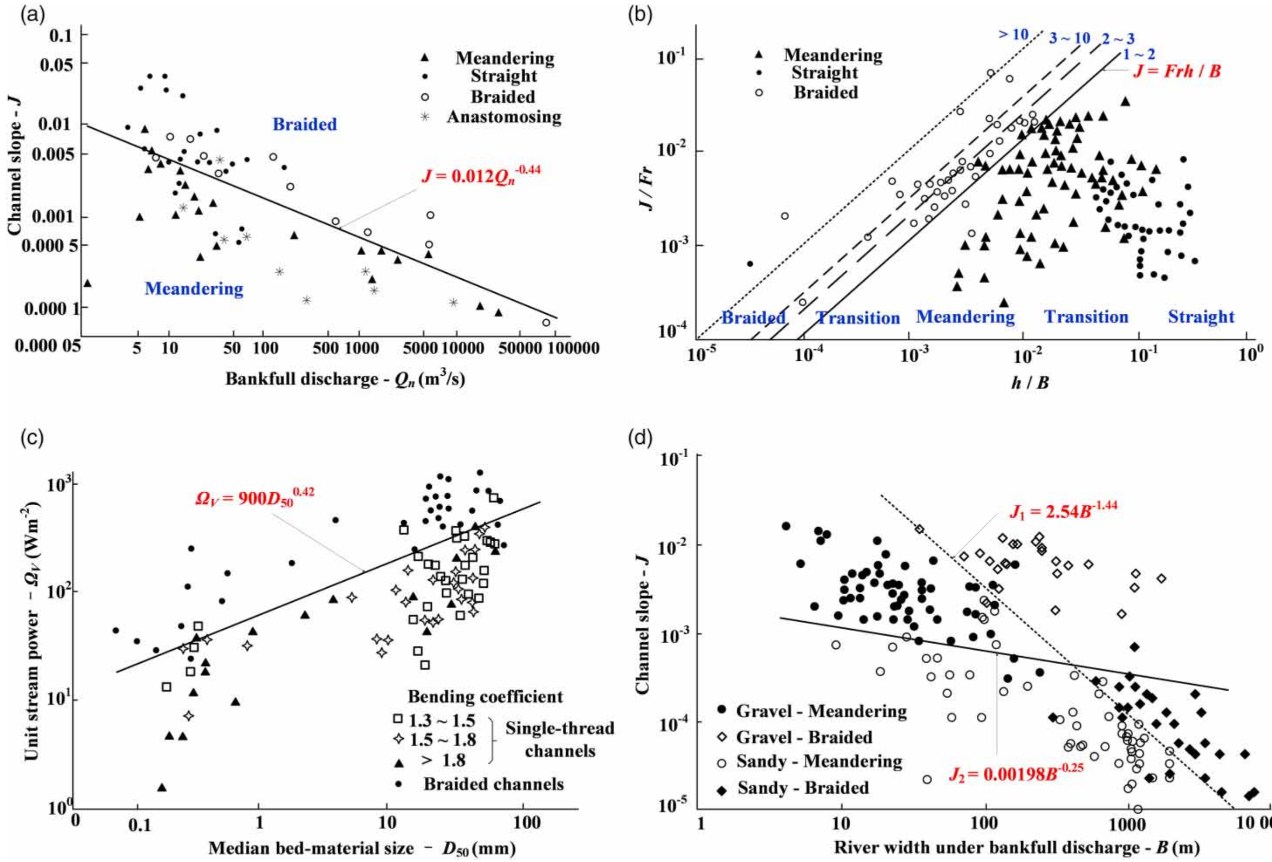


Figure 6 | The threshold diagrams of divergent river types. Detailed explanations of the parameters in (a)–(d) can be found in Appendix A.

Lewin & Brewer (2001) argued that Van den Berg's parameters were too simple to represent all factors that affected river formation with a simple power-particle size scatter plot. According to Xu (2004), Leopold's method is also criticized because it cannot be utilized for river-type thresholds for sandy or gravelly riverbeds (Figure 6(d)).

The goal of mathematical statistics is to establish the functions between river types and flow activity. Three types of functions were derived, and the first is designed to describe rivers from their components by equations, such as the median grain size in the bed sediment (Carson 1984). The second point is to determine the thresholds of different river types based on the river formation theory and analysis method (Alexeevsky & Chalov 2015). For example, river morphology is linked to river activity by integrating resistance coefficients to produce discriminant curves (i.e., resistance thresholds) that characterize river morphology (Xin *et al.* 2018). Furthermore, a stream power method (Van den Berg 1995; Petit *et al.* 2005) and logistic analysis (Bledsoe & Watson 2001) were proposed to establish the discriminant to distinguish river patterns, as well as a bar theory (Kleinhans 2010; Kleinhans & Van den Berg 2011), stability theory (Parker 1976), and a nonlinear evolution model (Bai & Wang 2014). A third method is to calculate the relationship between multiple parameters to determine the river types, such as the discriminant method based on a generalization of the well-known Darcy–Weisbach equation (Song & Bai 2015).

Some scholars, however, believe that precise thresholds between river morphology do not exist (Zieliński & Widera 2020). It appears that the transformation between river morphology occurs gradually, and mathematical statistics cannot be utilized to represent river morphology. For example, Shi (2009) argued that river morphology undergoes a continuous transformation from quantitative to qualitative change, with no clear dividing line between the two. Thereafter, a comprehensive set of fuzzy clustering methods was developed for the classification and discrimination of river morphology.

River morphology visualization

River visualization is a tool for acquiring river spatial information, as well as a language for transmitting and expressing the river morphology. Graphic expression, map expression, and 3D visualization are the three fundamental visual expressions of river morphology (Bettinger *et al.* 2020).

An effective way to convey information about river morphology is to employ appropriate symbols corresponding to the morphological characteristics of the river (Lisitskii 2016). In the symbol library and comparison table of the river, the focus is principally on the design of visual variables of river symbols (Chen & Willett 2016), the design of river symbol structures (Otto *et al.* 2011), and symbol editors for visualizing rivers (Gustavsson *et al.* 2006). As a result, the cartographic symbols for national fundamental scale maps (FGDC 2006; GB/T 2017) (Figure 7) and industry graphic standards (e.g., GIS symbol library) related to water have been formulated to standardize the expression of rivers.

Through visual symbols, colors, and messaging, maps present information on the morphology and location of the river at a scale suitable for the intended audience (Bettinger *et al.* 2020). A river is one of the fundamental elements of a map and is generally represented on a map by a line or an area, depending on the scale at which the river is mapped (Figure 8(a)). For example, at larger scales, it is possible to reveal the details of river morphology, but at smaller scales, river morphology is simplified. Accordingly, displaying the spatial relationships of river morphology at disparate scales is one of the cores of map visualization (Leng *et al.* 2017) (Figure 8(b)). For map synthesis, a series of river morphology elements are gradually proposed for scale auto-conversion algorithms (Li 2007; Yan *et al.* 2019). Moreover, maps, with their rigorous mathematical foundation, can carry out corresponding measurements and analyses (Nass *et al.* 2011). Thus, the maps of the dissimilar periods record the morphological characteristics of the rivers and proffer valuable information for the study of their evolution.

In addition to map expression, 3D visualization technology can show river morphology more visually and intuitively. The 3D visualization technology is principally based on digital image processing technology and computer graphics. It can present the river data and results obtained from scientific calculations in a 3D format, realizing real-time simulation and dynamic interaction of river morphology. The 3D visualization technique is more intuitive and realistic, following people's habit of perceiving river morphology, which is therefore gradually becoming a key research direction in digital river basins, especially in morphodynamic modeling and river management. 3D visualization of rivers includes 3D description and representation methods (Döllner & Buchholz 2005), the design and realization of 3D symbol libraries (Sun *et al.* 2013), and 3D dynamic simulation (Mao *et al.* 2019). In addition, simulation of co-evolution of river and floodplain within contrasting models is suitable for investigating contrasting fluvial styles (Nicholas 2013) (Figure 9). Accordingly, a series of river visualization tools have been developed, including but not limited to Velocity Mapping Toolbox (Parsons *et al.* 2013), Rivervis (Mao *et al.* 2019), and Google Earth Engine (Li *et al.* 2021).

CHALLENGES AND LIMITATIONS OF RIVER MORPHOLOGY EXPRESSION

Although extensive studies have been conducted on river morphology to perceive the changes in river geomorphology, the current application of river morphology still faces challenges due to the limitations of data and methods. The fundamental limitations and challenges are summarized in Figure 10.

Uncertainties in river morphology expression

First, uncertainty exists in the conceptualization of river morphology. Although various terms have been proposed to describe channel types for many years, a consistent nomenclature has emerged, leading to overlapping and sometimes conflicting usage of terms (Alexeevsky *et al.* 2013). While many scholars have attempted to formulate a systematic classification system based on aspects such as river planform (Schumm 1985), formation process (Carling *et al.* 2014), sedimentation (Kleinhans *et al.* 2012), structure (Nikora 1991), discharge, and velocity (Xin *et al.* 2018), it does not seem to achieve the desired effect. Carling *et al.* (2014) proposed a solution that advocates river scientists to research and agree on a common method to describe the planar morphology of selected river channels, which can distinguish the systems consistently within an existing or current typology. Nevertheless, there is no relevant activity information available. It is time to resolve the conceptualization problem of river morphology research, which has undergone several decades of modern research.

Second, river-type thresholds have always been controversial. Researchers have noticed that river morphology is not discrete, but constantly changing. For example, the Sagavanirktok River in northern Alaska (Bridge & Lunt 2006) and the Waimakariri River on the South Island of New Zealand (Ethridge 2011) have both braided rivers and meandering rivers in the same gorge section. In addition, common river morphology can undergo mutations (Xiao *et al.* 2020). A lot of experimentation and methods are still required to determine the thresholds of river types.

Moreover, there are some uncertainties in the expressed scale of river morphology (Hundey & Ashmore 2009), such as system-scale (or larger-scale), reach-scale (or small-scale), and microscale (Schumm 1985), which depends on both the size of the river and the part of the fluvial system under consideration. The reach-scale of the river is one of the most frequently

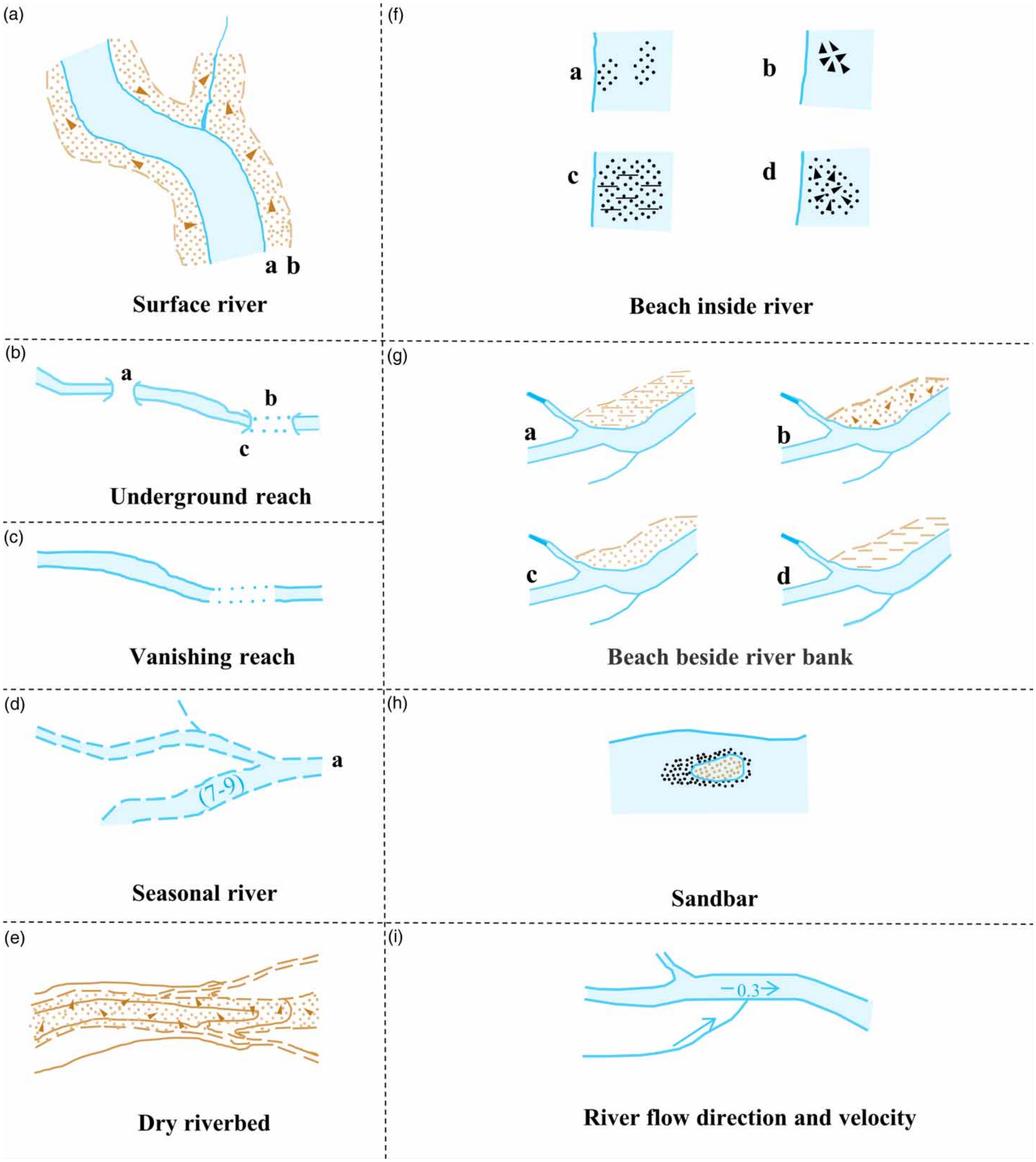


Figure 7 | Cartographic symbols for national basic scale maps of the river system (1:500, 1:1,000, and 1:2,000). Detailed explanations of the labels in (a)–(f) can be found in Appendix A.

used scales to express the morphological characteristics of rivers, and contrasting definitions and segmentation methods have emerged, such as based on expert judgment (Rinaldi *et al.* 2013), geomorphological characteristics (Liu *et al.* 2021) (Figure 11(a)), hydrometric sections (Xia *et al.* 2014) (Figure 11(b)), cartographic units (Grill *et al.* 2019) (Figure 11(c)), and physical segment (e.g., grids or equal length) (Saleh *et al.* 2013; Bora & Goswami 2021) (Figure 11(d)). A variety of river classification schemes have emerged accordingly. Nevertheless, these segmentation approaches are based on

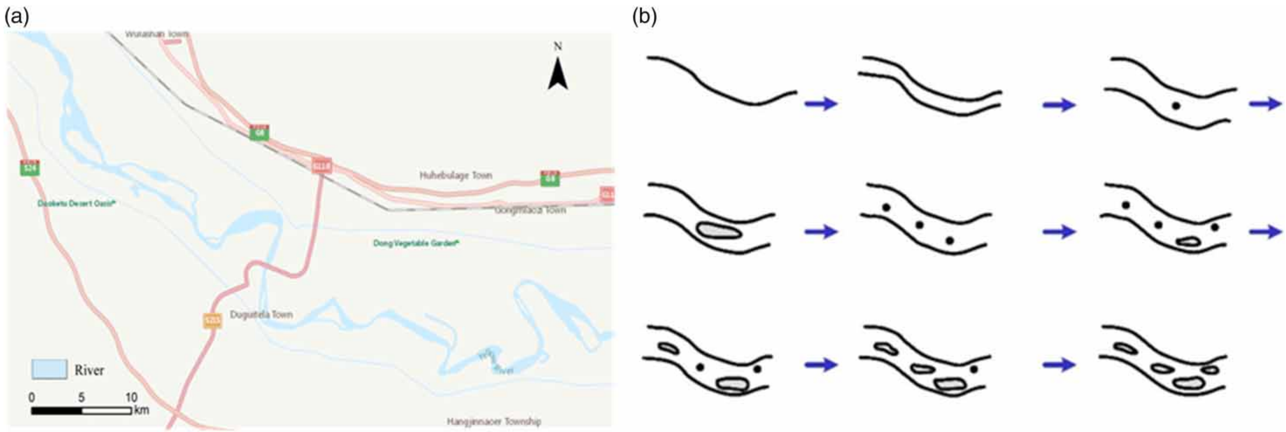


Figure 8 | (a) Example of river representation on a map. (b) As the representation scale gradually increases, the river boundary gradually changes from a single-line to a double-line river, river bars from nothing to point, then to polygon (Leng *et al.* 2017).

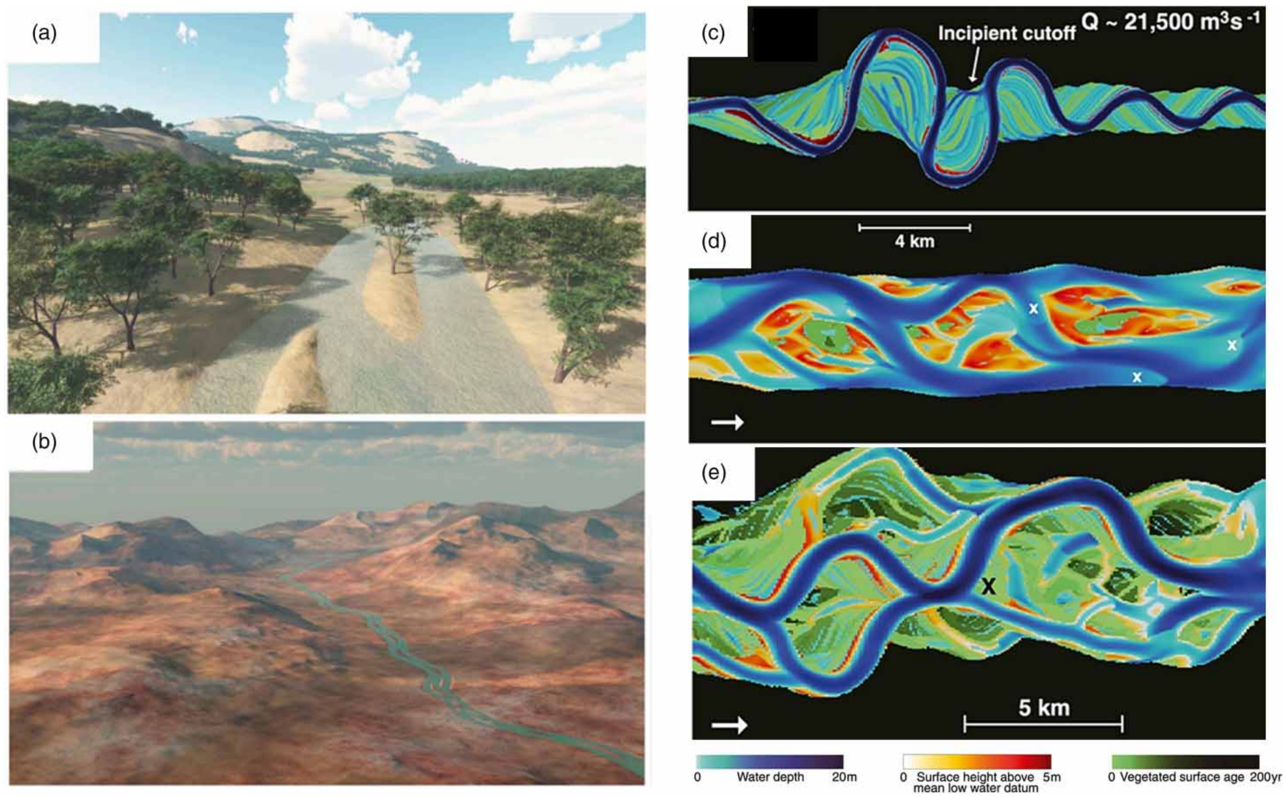


Figure 9 | Examples of river morphology simulation models. (a), (b) The procedural modeling for braided channels based on Genevaux *et al.* (2013) and Brown & Pasternack (2019). (c)–(e) Simulated channel morphology for meandering, braided, and anabranching channels and its evolution for 80, 150, and 250 yr, respectively, from Nicholas (2013).

pragmatism, with less consideration of the principles of river typology. Therefore, the results of river typology segmentation are inaccurate, and there is even a tendency to destroy their spatial structure.

Inconsistency between the river morphology expressions and the actual rivers

River morphology expression models are essential to accurately represent or reproduce actual rivers. Inconsistency between existing river morphology expressions and real rivers is influenced by factors such as monitoring data, expressed models, and

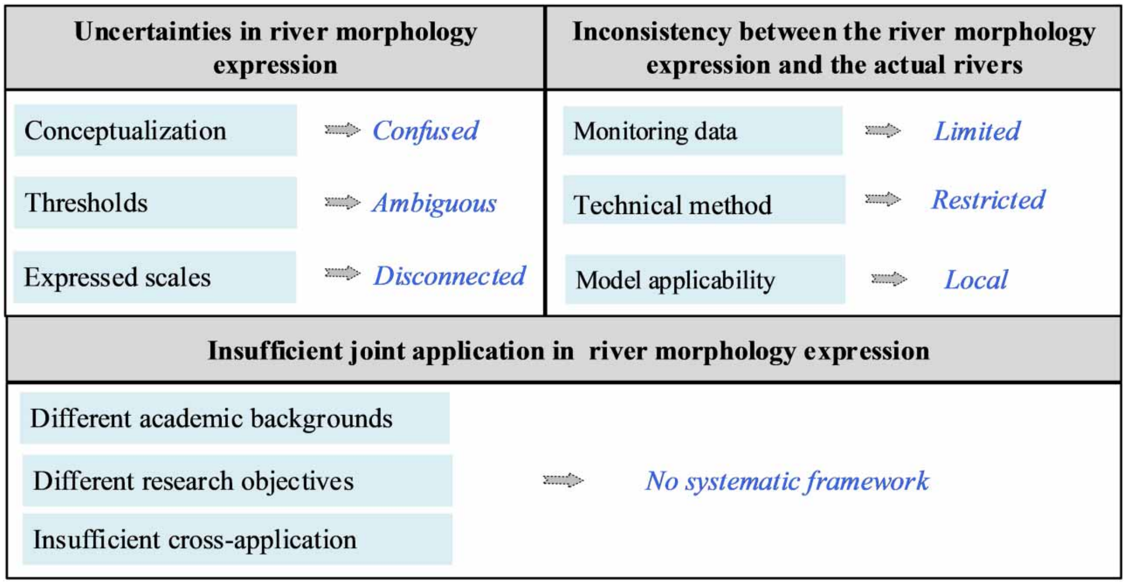


Figure 10 | Current challenges and limitations of river morphology.

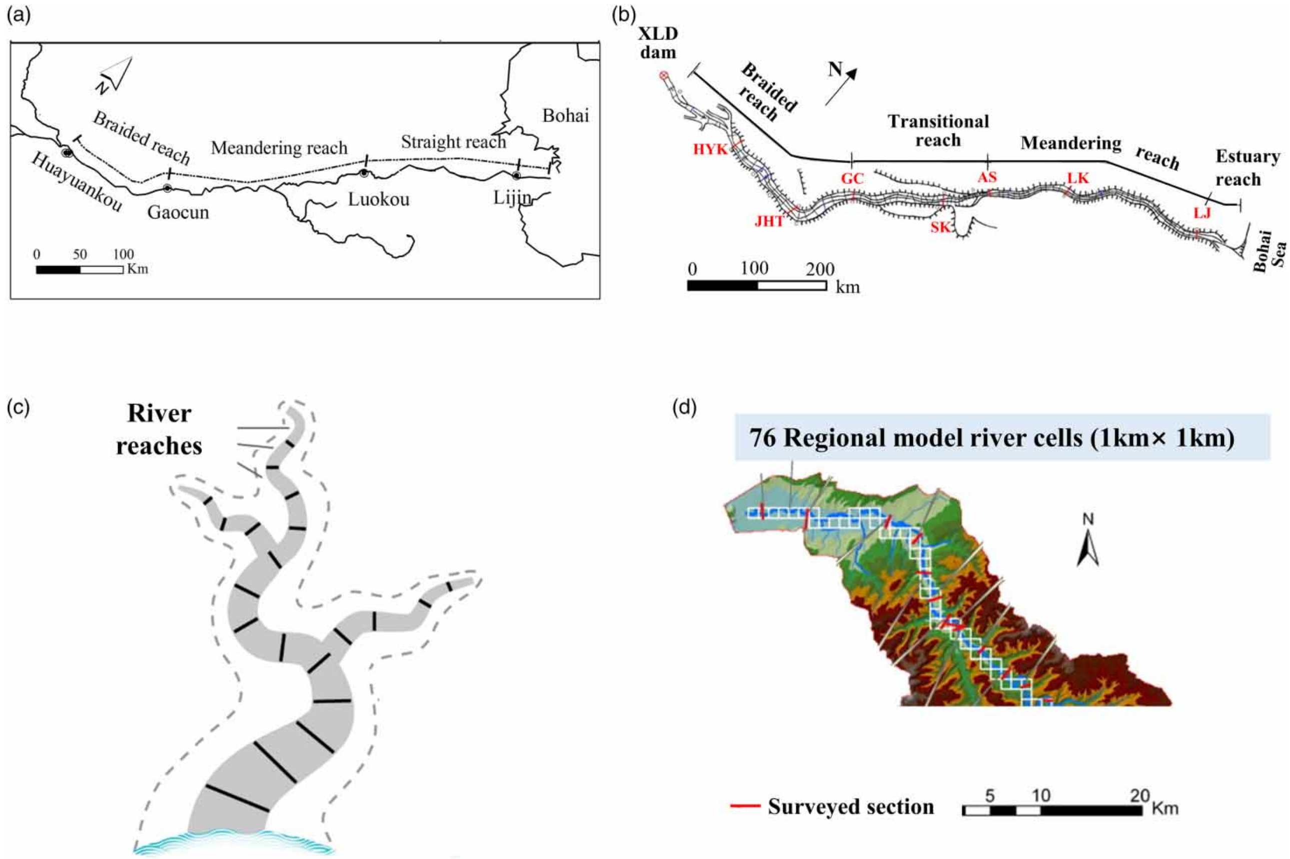


Figure 11 | Different definitions and segmentation methods of '*River reach*'. Detailed explanations of (a)–(d) can be found in Appendix A.

its transferability. First, inconsistency in model simulations may be caused by limited ground observations and their poor spatiotemporal expressions (Liu & Mishra 2017; Khaki *et al.* 2019). Present studies have focused on the validation and calibration of river morphology expression models using measured and auxiliary data (Rowland *et al.* 2016; Isikdogan *et al.* 2017;

Shahrood *et al.* 2020). However, there are exceptional difficulties and uncertainties in model calibration and prediction in rivers that are extremely influenced by human factors (Hartanto *et al.* 2017; Xiong *et al.* 2019), which affect the expression of actual river morphology.

The second inconsistency is caused by the river expression method. Modeling of fluvial morphology focuses on developing, calibrating, and validating models against real-world conditions. Some models do aim to achieve as much realism as possible in river morphology, while others aim to simplify methods (Brown & Pasternack 2019). Accordingly, it is not possible to accurately express the actual river morphology based on expression models alone.

In addition, existing expression models of river morphology are often applicable only to specific areas, and no general model has been reported that can integrate the expression of river morphology in different regions, which leads to inconsistencies between the application of the model and actual conditions.

Insufficient joint application in river morphology expressions

River morphology is expressed by individuals with expertise in geomorphology, hydrology, computer science, earth science, etc., for a variety of purposes. Currently, the diversity of academic backgrounds and purposes has led to inherent conflicts in the reality of river morphology (Brown & Pasternack 2019). For example, while geomorphologists may be able to define river types and develop corresponding quantitative indicators in a scientific context, it is impossible to map or visualize rivers in this background. Computer scientists can build surface and 3D models of river morphology using the latest technology, but may not be able to classify and extract river morphology without training due to a lack of knowledge of the river's constituent structures (Smelik *et al.* 2014). Although joint research has been conducted between some models, such as establishing the mapping relationship between river descriptive language and automatically generating map symbols based on semantic descriptions (Kuhn 2013), researchers in different disciplines do not always share the same expected outcomes (Gurnell *et al.* 2016). Moreover, the application of some new morphological feature extraction methods (e.g., machine learning/deep learning) and geographic expression techniques (e.g., virtual geographic environments, geographic augmented reality, and geographic hypermedia) in the field of river morphological expression is lagging. Therefore, it is difficult to effectively address river morphology in one or several ways without an integrated multidisciplinary systematic framework.

AN OUTLOOK FOR RIVER MORPHOLOGICAL EXPRESSION

According to the current challenges and limitations of river morphology in expression models, three key outlooks are recommended in Figure 12.

Big data of rivers stimulate the expression of river morphology

According to the list of Earth Observation Satellites (Rom *et al.* 2015), more than 20 organizations have deployed more than 170 earth observation satellites worldwide. Over 150 satellites will be launched for earth observation in the next 10 yr (Ji & Brown 2017). The era of big data of rivers has undoubtedly arrived (Balti *et al.* 2020). For the past, present, and even the future, long-term, and consistent river datasets are an urgent requirement for continuous and consistent monitoring of rivers on a regional to global scale. By integrating river observations with geo-located data (Peterson 2013), multi-spectral/sourced remote sensing, field data, and social media data, river morphology will be better expressed (Zhao *et al.* 2019). Beside validating the information extracted from river observations, we can understand whether river morphology interacts with ground features and human activities, such as river dynamics derived from socio-media data, by integrating other relevant data. In addition, field data obtained through site-specific analysis can be used to explore the anomalous dynamics of river geomorphology and reveal their drivers. Thus, this multi-source dataset should be utilized more for monitoring river changes, identifying river morphology, and exploring their potential causes.

Redefining the river morphology

In response to the confusing and inconsistent terminology in the current definition of river types, we propose to redefine river morphology in terms of river planform. Typically, channel networks appear visually distinct, but are self-affine, a concept also known as 'scale invariance' (Foufoula-Georgiou & Sapozhnikov 2001), such as braided rivers that are statistically indistinguishable under proper magnification or contraction (Figure 13). In view of this, we suggest that river reaches with the same topology and composition can be considered as river morphological units regardless of the specific spatial scale. The River Morphology Unit (RMU) is the smallest visual perception space unit in the river, with clear morphological attributes, and is also the basic unit carrying multi-source information. The river planform is selected as the basis for river classification, and the river type can

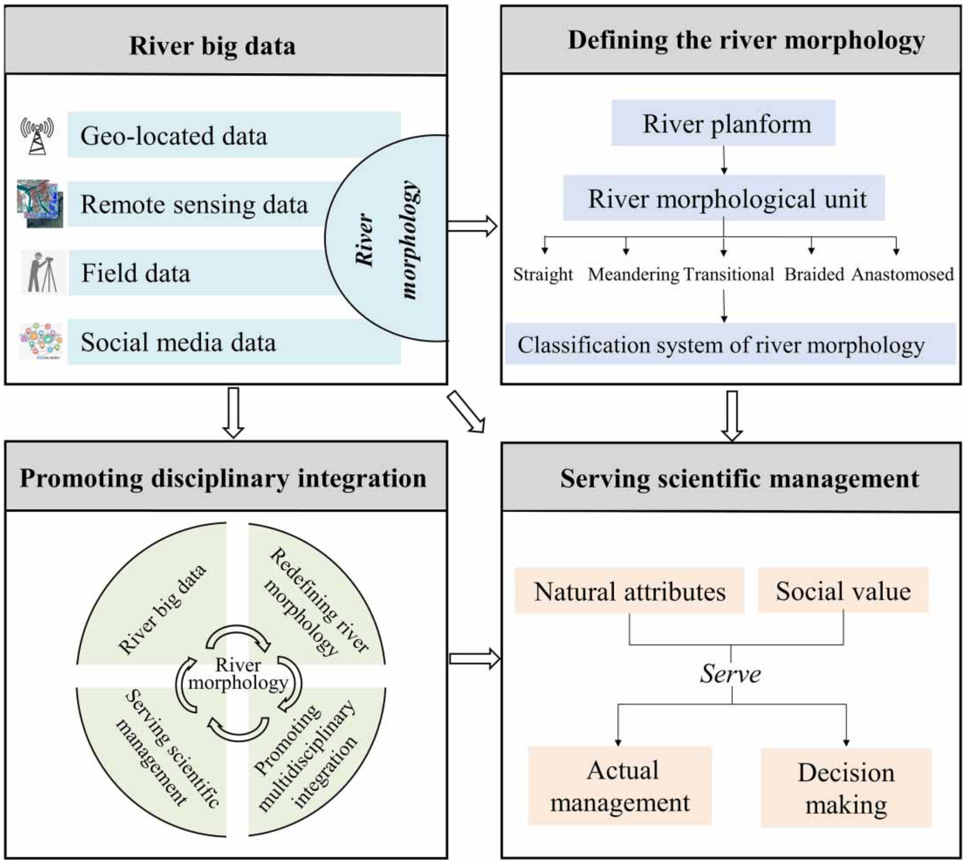


Figure 12 | A prospective framework for the expression of river morphology.

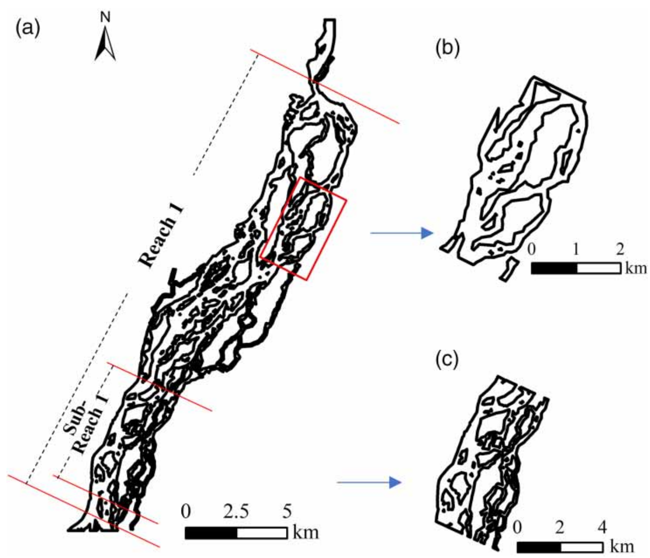


Figure 13 | Illustration of anisotropic scaling in the morphology of a braided river. (a) A reach of the Yellow River in China. (b) A small part of the river was enlarged by stretching its horizontal axis and vertical axis. (c) A sub-reach of the river. The stretched small part and the sub-reach of the river look statistically similar to the original larger part.

be classified on different levels according to the need for detail in the expression. In Figure 14, RMUs are defined as five fundamental types in the first level, 10 types in the second level, and other attribute information in the third level.

Taking RMU as the research object may possess several advantages. First, each river unit corresponds to a defined river type, which eliminates mixed river types caused by physical or artificial segmentation of scale (Makaske 2001). In addition, RMU can provide insights into the underlying mechanisms that lead to the formation of rivers. By examining the geological, structural, and tectonic history of many river catchments, it is possible to determine whether visually different styles differ in their formation and maintenance processes. Furthermore, if the RMU is quantified, a concise statistical description of the planform geometry and evolution of a river can be generated. It is possible to express a river by its spatial sequence of RMUs and to determine its evolution law from statistics of RMU quantity and spatial position change over time (Figure 15).

Promoting multidisciplinary and interdisciplinary integration

The promotion of multidisciplinary and interdisciplinary research on river morphology is significant to explore its expressive potential. According to the statistics of the WOS journals publishing river morphology, several disciplines have achieved research achievements in river morphology (Figure 16). In addition to interdisciplinary studies with traditional geology, biology, water resources, etc., the study of river morphology has been closely integrated with ecology and environmental science in recent years, which indicates that cross-discipline has become an unstoppable trend. However, we should also note that there are relatively few applications of advanced technologies such as artificial intelligence in river morphological expression in recent years. It is worth considering how to strengthen interdisciplinary research with computer science, cartography, and other disciplines in the future. Consequently, we suggest that multiple disciplines work together to establish a

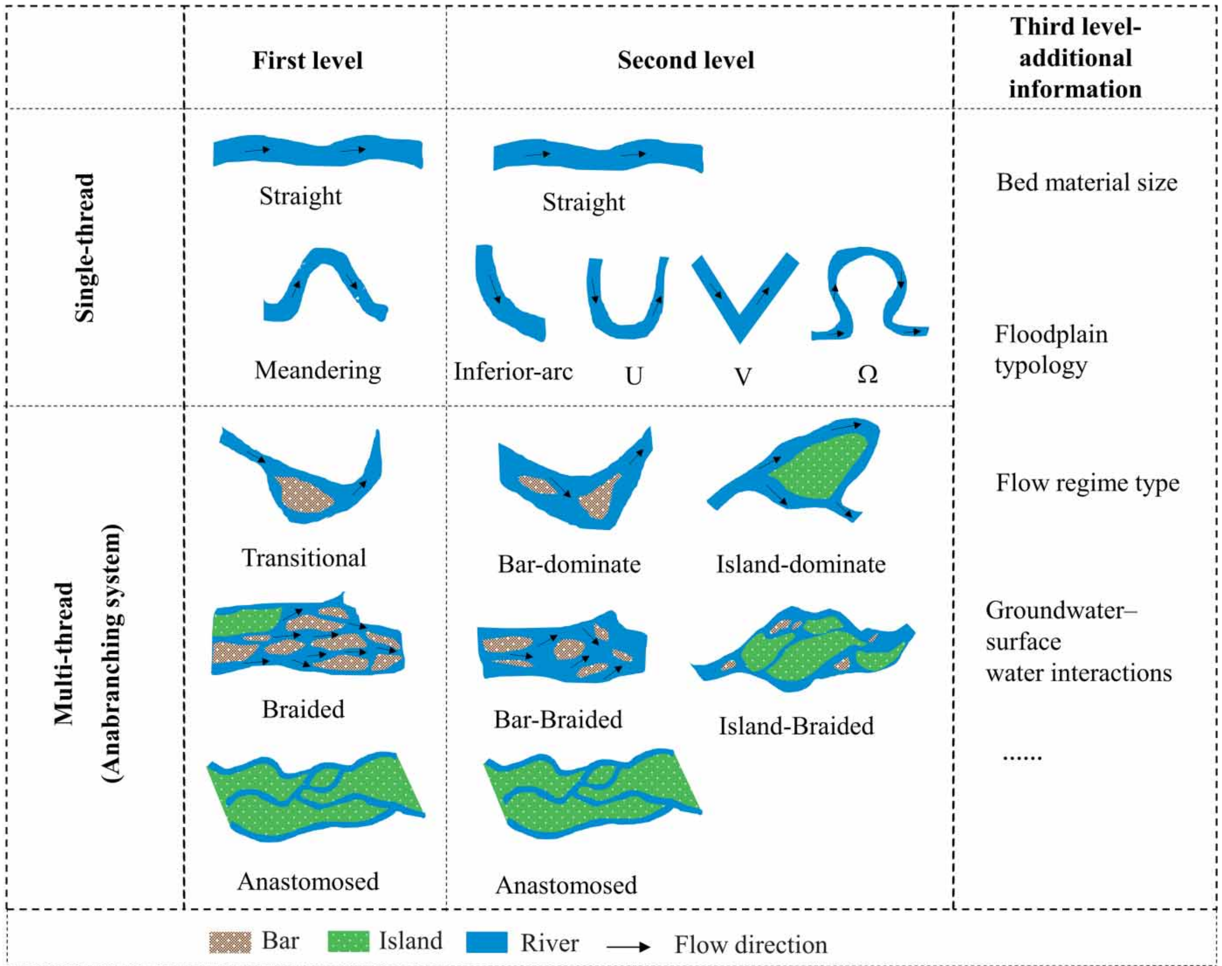


Figure 14 | Classification and definition framework based on the RMU.

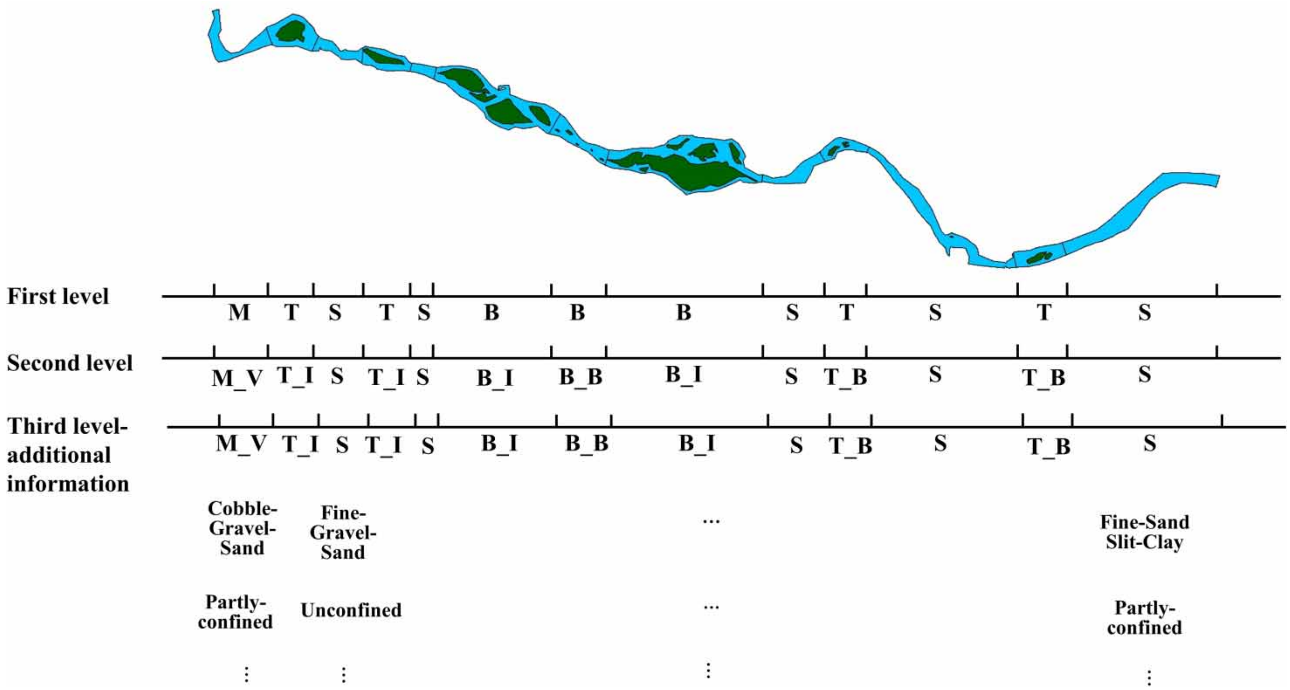


Figure 15 | Spatial sequence of RMUs (a section of the Middle Yellow River in 2020).

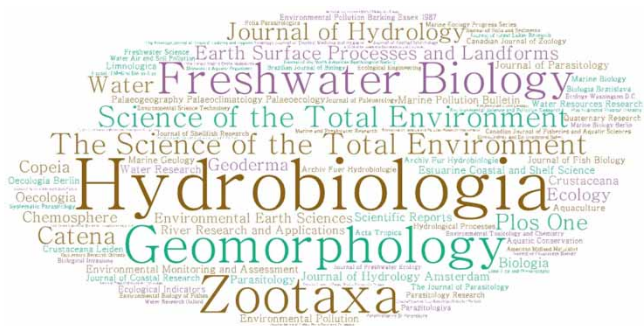


Figure 16 | A word cloud map of journals published on the topic of river morphology in the WOS between 1990 and 2020.

relatively standardized and systematic research framework in which multidisciplinary researchers can contribute to advancing the expression of river morphology by learning from each other.

River morphology expression serving scientific management and decision-making

Beside their natural attributes, rivers also have social value, such as their service functions (Luo *et al.* 2020). River landscape ecosystem services are a paramount part of the benefits that humans derive from nature (Hale *et al.* 2019). It is worth investigating whether different river morphologies can supply differential landscape ecological services. In addition, river morphological expression models are expected to contribute to practical management and decision-making. A systematic expression model of river morphology should be able to perform a variety of functions such as the description of river morphology, change detection, quantitative evaluation, cause analysis, and management decision-making. Consequently, there is still a long way to go to establish a comprehensive expression model that can meet the multi-level, multi-objective, and cross-domain realities. To reach the balance and unity of natural and social functions of the river, much more work still needs to be done.

CONCLUSIONS

In this review, we summarized the research progress of river morphology expression, which contributes to the perception, characterization, and quantification of morphological characteristics in river geomorphology on earth from a current perspective. River data products, specifically remote sensing data, are continually updated and improved, providing abundant and reliable support for river morphological expression. Furthermore, expression models for four types of river morphology, including river classification, parameter quantification, mathematical theory, and visual expression, exceptionally contribute to our understanding of river landforms. Because of unresolved technical problems in data production and processing, uncertainty and inconsistencies among models, an insufficient amount of joint application, and differences between disciplines, there are still challenges in the systematic expression of river morphology, which hinder further applications of river morphology to better understand river variability. To obtain accurate and valuable information on rivers, we suggest adding current data sources in the process of improving the quality of existing data, especially at the advent of the era of big river data. Moreover, based on the analysis of the topological structure and constituent elements of rivers, the idea of redefining and classifying river morphology with RMU is proposed, hoping to proffer a reference for formulating a unified river morphology classification scheme. In conclusion, future river morphology researchers should aim to create a comprehensive expression system that can integrate multidisciplinary knowledge and can serve river management and intelligent decision-making.

AUTHOR CONTRIBUTIONS

Z.L. conceived the idea, planned the scope, produced a draft manuscript, oversaw the production of subsequent revisions and the final manuscript. C.Y. conceived and directed the overall research project, provided the funding support, developed the methodology and supervised the article. M.W.B. contributed the literature and revised the paper.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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