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Quasi-Universal Length Scale of River Anabranches

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Key Points:

- River anabranches show a characteristic length set by bankfull hydraulic geometry parameters of the main channel
- The anabranches length is unrelated to backwater length, thus marking a clear difference with respect to deltaic systems
- Field evidence is theoretically explained as the result of morphodynamic interaction between bifurcation and confluence nodes

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Looping patterns, where channels divide and reconnect further downstream, are widespread in natural rivers. Here, we build an extensive dataset of different gravel-bed and sand-bed rivers around the world encompassing a wide range of physiographic and sedimentological conditions. Field data show the existence of quasi-universal relations for the anabranches length when scaled with bankfull hydraulic geometry variables of the main upstream channel. The dimensionless length is found to be nearly slope-invariant, identifying a clear difference with respect to deltaic systems. This scaling relationship is explained by interpreting the dynamics of river loops as basically controlled by a two-way interaction between their constitutive elements, bifurcations and confluences. The identification of a quasi-universal length scale provides insight on the morphological evolution of multi-thread networks and constitutes a key information for the design of self-sustaining river restoration interventions.

Plain Language Summary River loops, where the water course splits into smaller branches that reconnect further downstream, are ubiquitous in natural environments. A deeper understanding of their spatial structure can greatly improve the effectiveness and sustainability of common practices in river restoration, where multiple channels are reactivated to recover the ecological functions of harmed riverine ecosystems. The analysis of many different rivers worldwide shows that the length of river loops is not randomly distributed but follows a characteristic law. In particular, the average length of bifurcating branches is found to be proportional to the hydraulic parameters (width, depth) of the main upstream channel, regardless of the specific climatic or geologic context. This relationship is explained in terms of the key physical mechanisms that control the distribution of water and sediment between the branches.

1. Introduction

Natural rivers often exhibit intertwined branches along their course. Channels divide along exposed depositional patches (i.e., bars), islands and ridges, and reconnect further downstream generating from a topological perspective a "loop" (Figures 1a and 1b). Over the last two centuries, the pervasive channelization and flow regulation of natural river corridors have strongly affected the overall functioning of river systems, especially in developed countries. In particular, a large number of pristine braided and anastomosing rivers experienced narrowing, which in most cases has led to a radical change in channel pattern, from multi-thread to single-thread morphology (Gurnell et al., 2009). The presence of multiple channels controls transport processes (e.g., dispersion of contaminants and recycling of nutrients), provides socio-economic benefits for human societies (e.g., flood protection and recreational activities) and valuable environments for aquatic and riparian communities (Brown, 1997; Gurnell & Petts, 2002; Tockner et al., 2006).

In the recent years, the restoration of pristine river loops through channel widening and opening of side channels (e.g., Habersack & Piégay, 2008; Rohde et al., 2005) has become a common practice in projects aimed at recovering geomorphological and ecological quality of harmed river ecosystems (Dufour & Piégay, 2009; Wilcock, 1997; Wohl et al., 2015). Therefore, there is an increasing need of knowledge about the morphodynamics of channel loops, including the identification of the main acting physical processes and the associated controlling factors. Specifically, there is a demand for specific information about the proper length scale for the design of these interventions and about the basic processes that could lead to a long term self-preservation without requiring intensive and regular maintenance (Riquier et al., 2017; Stoffers et al., 2021).

Bifurcations and confluences are key constitutive elements of looping patterns, whose dynamics is driven by factors of different nature, such as hydrological regime, sediment transport, and vegetation cover, acting on a hierarchy of spatial and temporal scales (Church, 2008). Complex natural phenomena typically manifest themselves

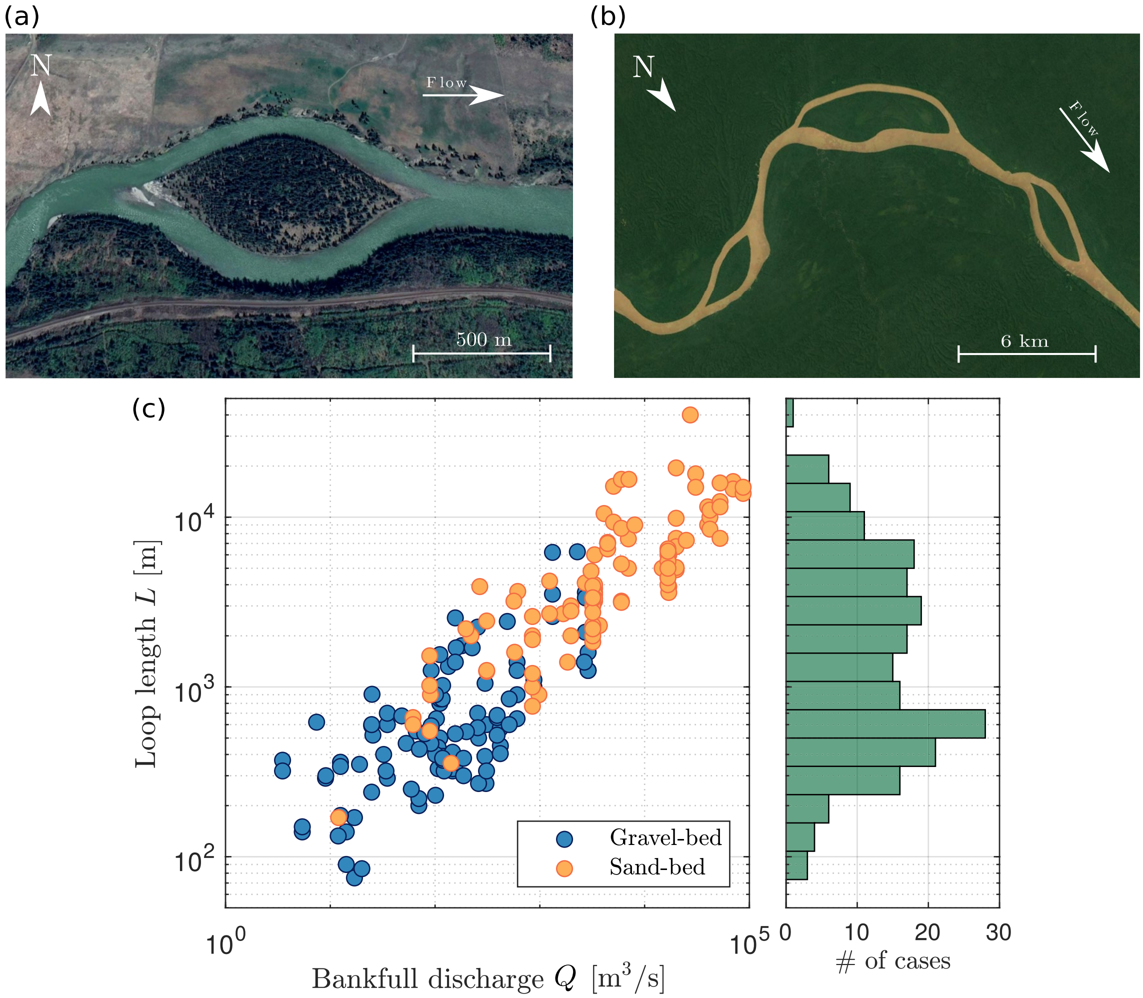

Figure 1. The diversified manifestation of river loops. Upper panels: examples of natural river loops: (a) Bow River, Alberta (Canada), 51°12′ N 114°37′ W; (b) Caquetá River (Colombia), 0°45′ S 72°01′ W. From Google Earth Digital Globe, 2021. Lower panel (c): loop length (L) against bankfull discharge (Q) for gravel-bed (blue circles) and sand-bed rivers (orange circles). The histogram represents the frequency distribution of the lumped dataset depending on the loop length.

on a hierarchy of scales, often showing a fractal, scale-free geometry (Bak, 1996; Newman et al., 2006). Existence of scale-free behaviors is observed in channel networks (Dodds & Rothman, 2000; Rinaldo et al., 1998) and braided rivers (Ashmore, 2013; Paola & Foufoula-Georgiou, 2001; Sapozhnikov et al., 1998), leading to frame these systems as complex entities shaped by a multitude of nonlinear interactions among their constitutive elements. One could argue that channel loops may display an analogue scale-free character through the manifestation of a mosaic of lengths possibly resulting from a stochastic behavior, according to which bifurcating channels follow a sort of random walk before reconnecting downstream (Heller & Paola, 1996). Alternatively, one could imagine that a characteristic length scale may arise as the result of distinctive morphodynamic processes.

In this perspective, from the analysis of several local avulsions (i.e., the partial/full shifting of water course into two channels reconnecting further downstream) occurred in the Andean and Himalayan regions, Edmonds et al. (2016) observed the emergence of a preferential length scale set by the channel-belt width and thus substantially controlled by floodplain topography. Specifically, they found an avulsion spacing of the order of ten channel-belt widths. Other studies suggested that the spatial structure of river loops should reflect the nature of their formative mechanism, which can be grouped into two broad categories. First, it was argued that since flow splitting due to bars deposition is a key bifurcation-generating process, it is reasonable to relate the length-scale of bifurcation-confluence spacing in braided rivers to the initial wavelength of riffle-pool units, which is typically of the order of several times the main channel width (e.g., Ashmore, 2013; Bertoldi & Tubino, 2005; Parker, 1976). The same relation was suggested for single-thread streams when loops are generated by the deposition of mid-channel bars associated to width fluctuations (Ashworth, 1996; Hooke, 1986; Monegaglia et al., 2019; Repetto et al., 2002). Second, Jerolmack and Mohrig (2007) studied anabranches that were essentially generated by large scale avulsions, suggesting a correspondence between distributary deltas and anastomosing rivers, the latter constituted by a system of multiple channels often separated by vegetated islands (Nanson & Knighton, 1996). This line of thought gives support to a possible existing analogy between the spatial organization of looping patterns and river deltas. From this standpoint, several works (e.g., Chadwick et al., 2019; Chatanantavet et al., 2012; Jerolmack & Swenson, 2007) indicated that the distance between avulsion nodes and the shoreline in lowland deltas scales with the backwater length. The latter is defined as the distance over which, depending on flow conditions, the water surface exhibits a drawdown or a steepening (Lamb et al., 2012; Paola & Mohrig, 1996) set by a downstream standing body of water (e.g., lake, sea, or dam reservoirs) or a channel confluence (Ferguson, 2021; Meade et al., 1991; Ragno et al., 2021; Samuels, 1989).

In this work, we analyze how the length of anabranches varies among different river loops, building a dataset that covers a wide range of climatic and geologic environments (Section 2). We observe the existence of a clear relation between the length of connecting anabranches and the reach-averaged hydraulic geometry variables of the main channel, specifically bankfull width and bankfull flow depth, which is seemingly independent of the originating mechanism and of the specific hydrodynamics and sedimentological rivers properties (Section 3). A mechanistic justification of the emergent scaling is proposed in Section 4, where we also highlight how, differently from river deltas, looping patterns select a length of the anabranches that is slope-invariant. Finally, Section 5 is devoted to some concluding remarks.

2. Field Data

We considered 207 bifurcation-confluence units from a multitude of sand-bed and gravel-bed rivers worldwide (Figure S2 in Supporting Information S1), for which data on the hydrological and sedimentological variables (bankfull discharge Q, median grain size d_{50}) and reach-averaged hydraulic geometry (channel slope S, bankfull width W, and bankfull depth D) of the main channel were available (Text S1 in Supporting Information S1). In order to build a homogeneous dataset, we specifically focused on topologically simple loops as those occurring in single-thread channels when flow splits into two anabranches that reconnect further downstream. Therefore, the dataset does not comprise individual loops embedded in complex networks, such as braiding or anastomosing rivers, whose geometry may also variously depend on the overall network organization. Moreover, river deltas were deliberately excluded, as the downstream water surface elevation is constrained by the presence of the sea, which actively affects their dynamics potentially leading to different scaling laws, as discussed below.

The resulting dataset spans a wide range of scales: water discharge ranges from 3.5 to 70,000 $m^3 s^{-1}$, channel slope passes from 4.7% of coarse steep mountain streams to 0.002% of gentle lowland rivers, channel width varies between 6.4 m and 2000 m, and channel depth goes from 0.19 to 34.6 m. On the basis of the median grain size, which varies from 0.01 to 216 mm, the dataset was divided into two subsets: gravel-bed (here defined as having median grain size $d_{50} > 2$ mm) and sand-bed rivers ($d_{50} \leq 2$ mm). This distinction is convenient as alluvial rivers tend to naturally separate into two main classes that are approximately representatives of different sediment transport modality (e.g., Dade & Friend, 1998; Dunne & Jerolmack, 2018; Parker et al., 2002): bedload-dominated gravel-bed rivers and suspended-dominated sand-bed rivers. Conversely, we did not distinguish channel loops on the basis of their respective originating process, so that loops formed by chute cut-off of a river bend, avulsion, central bar deposition, and other possibles mechanisms, were all included in the dataset.

River loops were identified through satellite imagery, even including those systems where one of the two branches was inactive over years. The loop length (L) was calculated as the mean length of the two anabranches measured along the channels axis (Figure S3 in Supporting Information S1). To avoid including river loops simply formed by isolated vegetation patches or localized sediment deposits, we deliberately excluded from our analysis those loops that were shorter than approximately four times the bankfull width, which roughly coincides with the typical length scale of mid-channel bars (Ashworth, 1996; Fujita, 1989; Hundey & Ashmore, 2009; Jang & Shimizu, 2005).

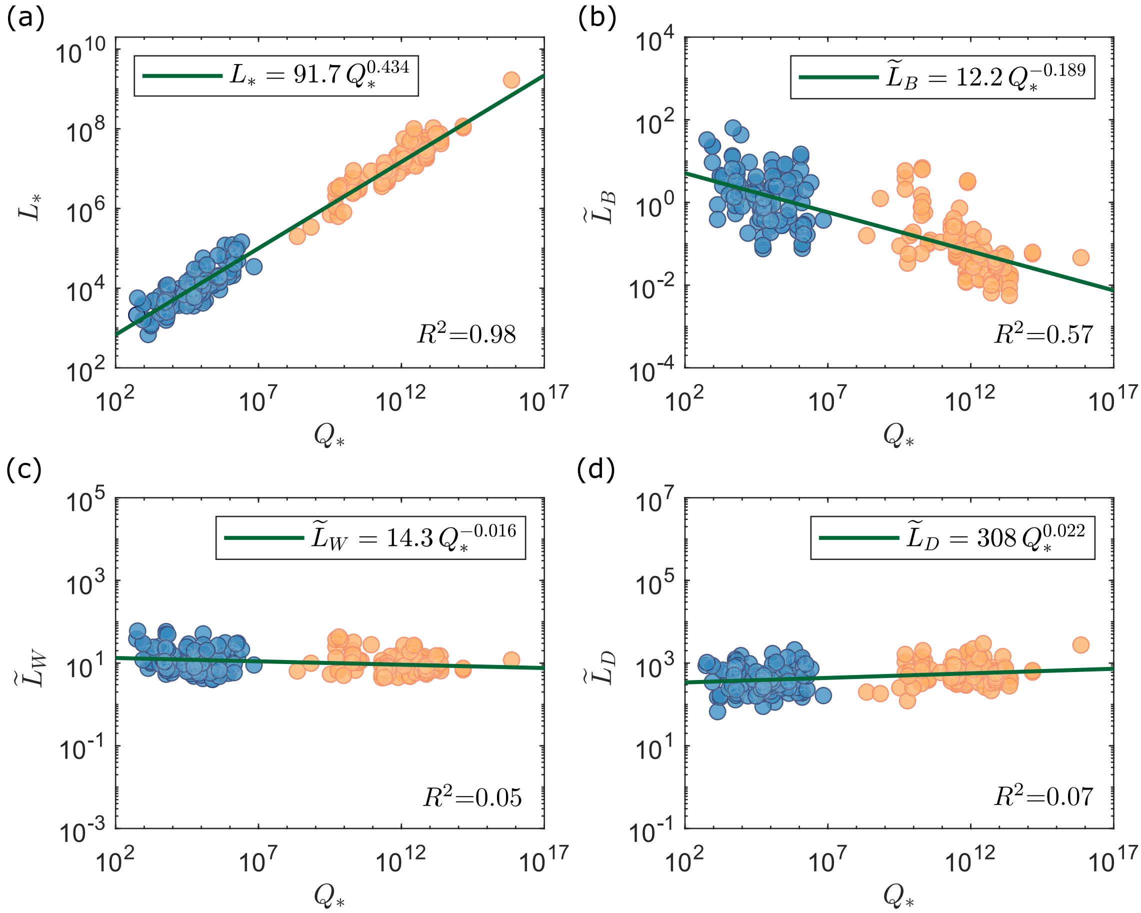

Figure 2. Dependence of the dimensionless loop lengths $\left(L_*, \tilde{L}_B, \tilde{L}_W, \tilde{L}_D\right)$ on the dimensionless discharge Q_*. The following scaling lengths are employed: (a) median grain size (d_{50}); (b) backwater length (B); (c) bankfull width (W) and (d) bankfull flow depth (D) of the main channel. Blue and orange circles indicate gravel- and sand-bed rivers, respectively. The green line indicates the least squares regression on the lumped dataset, with R^2 denoting the associated coefficient of determination.

3. The Manifestation of a Quasi-Universal Length Scale

The analysis of the dataset described in Section 2 displays a large variability of the loop length, which encompasses a range of values spanning over four order of magnitudes (Figure 1c). These values are longer for large rivers, showing a clear increasing trend with the bankfull discharge for both the gravel- and the sand-bed subset. The question therefore arises whether there is a relationship between loop length and some specific reference quantities. We pursue this aim by introducing a set of suitable dimensionless parameters. A dimensionless formulation has two main advantages: first, it allows to reduce the number of arguments to which the problem depends on; second, an appropriate choice of scaling variables allows to underline the physics behind the observed trend of length variations in natural river loops (Barenblatt, 1996).

In general, following the lead of studies dealing with alluvial hydraulic geometry (e.g., Métivier et al., 2017; Parker et al., 2007; Phillips et al., 2022), a first-order analysis can be performed by scaling the loop length L with the median grain size of bed material d_{50}. The variation of the dimensionless length $L_* = L/d_{50}$ is then described in terms of a dimensionless bankfull discharge $Q_* = Q/\sqrt{g\, d_{50}^5}$, with g the gravity acceleration. Results show how gravel- and sand-bed rivers subset separate into two distinct clusters, encompassing values of L_* that spans over eight orders of magnitude (Figure 2a). Despite the presence of a certain degree of scatter, L_* follows a clear power-law trend with Q_*, with a substantial collapse of data on the regression line $L_* \propto Q_*^{0.434}$. The scaling relation existent between L_* and Q_* is indicative of a more profound property of loop length when compared against flow discharge, namely its self-similarity, that is, an invariance with respect to Q_* or, in other words, the constancy of the ratio between L and a suitable scaling length.

The natural next question follows: what is the proper scaling length that leads to self-similarity? To answer this question, we consider two alternative approaches. First, following the suggested idea of an existent analogy between branching patterns in fluvial environments and river deltas (Jerolmack & Mohrig, 2007), we consider the backwater length

$$B = \frac{D}{S}\left(1 - Fr^2\right), \qquad Fr = \frac{Q}{W\sqrt{gD^3}}, \tag{1}$$

as scaling quantity $\left(\tilde{L}_B = L/B\right)$, with Fr the Froude number. Second, we consider the possible relation between loop length and reach-averaged hydraulic geometry of the main channel, namely the bankfull width W and bankfull flow depth D. As a consequence, we introduce the two scaling lengths $\tilde{L}_W = L/W$ and $\tilde{L}_D = L/D$.

Figure 2b shows that $\tilde{L}_B$ again follows a power-law trend with Q_*. A systematic decrease of $\tilde{L}_B$ over five orders of magnitude is observed, which suggests that the backwater length is not the proper scaling length that we are looking for. Differently, a nearly constant value of the dimensionless loop length when scaled with reach-averaged hydraulic geometry quantities, is shown across the entire spectrum of Q_* (Figures 2c and 2d). Regression for $\tilde{L}_W$ and $\tilde{L}_D$ applied to each subset does not reveal any substantial difference between gravel- and sand-bed rivers. In this case, the functional relation among dimensionless parameters can be considered as nearly constant as it is essentially independent of Q_*. This configures a "complete similarity" (Barenblatt, 1996), in which an appropriate combination of the governing parameters allows for eliminating the dependence on some dimensionless group (i.e., Q_*). Comparatively, the above-presented scaled quantities L_* and $\tilde{L}_B$ lead to an "incomplete similarity," in the sense that such scalings are not sufficient to rule out the dependence from Q_*.

Yet, it is worth noting that parameters D and W can be both considered as "quasi-universal" length scales, since these quantities allow to explain most of the variability observed among a wide range of conditions, despite the discernible deviation from this universality (hence the prefix "quasi") arising from several factors that are not considered in the analysis. For example, geometry and hydraulic characteristics of the bifurcates, the density and type of riparian vegetation (if present), possible geological constraints (e.g., the degree of confinement of the floodplain), or the properties of bank material, are likely to influence the proposed relations.

4. Discussion

The analysis of our dataset shows the existence of quasi-universal relations for the loop length in rivers, regardless of the specific originating process leading to establishment of the intertwining structure and independently of external factors such as physiographic, hydrological and sedimentological conditions of the single rivers. Specifically, our analysis shows the existence of a complete similarity of the scaled lengths $\tilde{L}_W$ and $\tilde{L}_D$, which suggests that the spacing of river loops directly scales with bankfull hydraulic geometry variables of the main channel.

A possible mechanistic justification to the above scaling relations is provided by the outcomes of the recent theoretical work by Ragno et al. (2021), who introduced a mathematical model for studying the coupled evolution of bifurcations and confluences in an idealized river loop. Their derivation is founded on the idea of a morphodynamic interaction between the two constitutive elements of the loop. Most river bifurcations tend to unevenly distribute water and sediment fluxes toward the downstream anabranches (e.g., Bolla Pittaluga, Coco, & Kleinhans, 2015; Redolfi et al., 2019); the downstream confluence is not passively subject to the incoming fluxes because stream collision produce variations of the free surface elevation (Figure S1 in Supporting Information S1). These variations at the confluence node can exert an upstream influence, providing a feedback that tends to stabilize the bifurcation. Therefore, river loops are found to be essentially governed by a two-way morphodynamic interaction between bifurcation and confluence nodes, which mutually exchange information along the connecting anabranches depending on their length. Specifically, the intensity of this effect turns out to depend on the length L through the "interaction parameter" Λ, defined as:

$$\Lambda := \left(\frac{L}{D\,c^2}\right)^{-1}, \tag{2}$$

where c is the dimensionless Chézy coefficient (i.e., the ratio between the mean flow velocity and the friction velocity). Equation 2 shows explicitly the direct link between Λ and the previously defined scaled length $\tilde{L}_D$

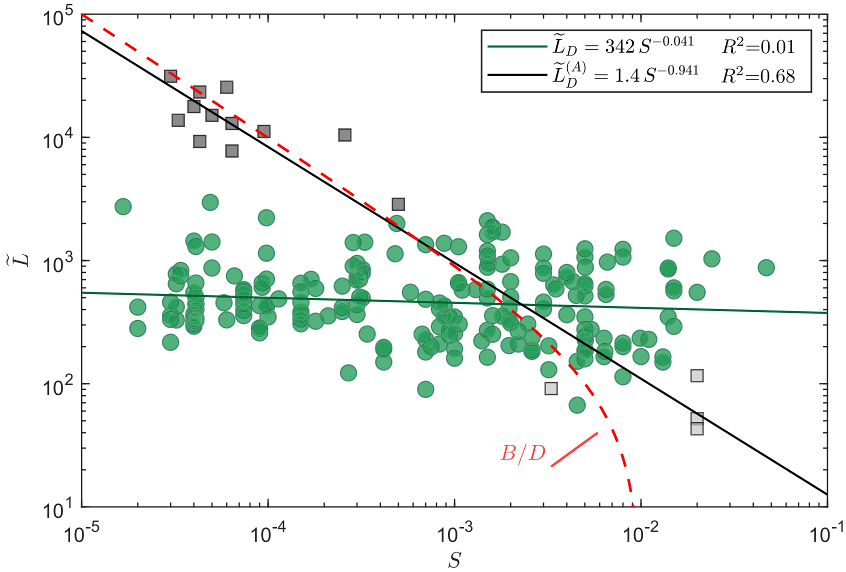

Figure 3. The different scaling of fluvial looping patterns and deltaic systems. Observed loop length in rivers (green circles) and avulsion length in river-dominated deltas (gray squares), scaled with the bankfull depth $(\tilde{L}_D, \tilde{L}_D^{(A)})$ and plotted against the channel slope (S). Solid lines indicates the best-fitting power-laws for the two datasets, the dashed line represents the scaled backwater length B/D, obtained from Equation 1. Dark and light squares denote field and experimental data (Text S1 in Supporting Information S1), respectively.

derived from field data. Since values of the Chézy coefficient are relatively constant in both gravel- and sand-bed rivers, with $c \sim 10$ (Parker et al., 2007; Wilkerson & Parker, 2011), Equation 2 implies that $\Lambda \propto 1/\tilde{L}_D$. Field data shown in Figure 2d yields values of the interaction parameter of the order of 10^{-1} to 10^{0} (Figure S4a in Supporting Information S1), which turns out to coincide with the range of Λ values needed to produce a significant interaction between the bifurcation and the confluence as suggested by the theory of Ragno et al. (2021).

A second important outcome emerging both from field data and theory is the almost slope-independence of $\tilde{L}_D$ (Figure 3), which allows us to definitely reject the hypothesis that loop spacing is somehow controlled by the backwater length. Specifically, the theory shows that the interaction parameter Λ, and consequently $\tilde{L}_D$ (Equation 2), is almost independent of channel slope as the result of a compensation between the Froude-dependent hydrodynamic effect generated by stream collision at the confluence and consequent slope-dependent backwater effect exerted on the upstream bifurcation (see Text S2 in Supporting Information S1).

A direct consequence of the slope-invariant behavior of looping patterns is the independence of scaled length $\tilde{L}_D$ from the Froude number, which derives from the fact that S and Fr are directly related by the uniform flow relation $Fr^2 = S\, c^2$. This can be noticed in Figure S4b in Supporting Information S1, the latter showing the weak dependence of the scaled length with the Froude number. In purely two-dimensional contexts, the Froude number has a prominent role unless all spatial variations are much longer than the backwater length (Paola, 2000). For example, the importance of Froude number can be observed in contexts like the study of equilibrium state achieved during auto-retreat due to base-level rise (Wu et al., 2020), bed waves propagation (Lanzoni et al., 2006), river-tides interaction (Bolla Pittaluga, Tambroni, et al., 2015; Ragno et al., 2020), classical theory of open-channel flows in a fixed-bed formulation (Chanson, 2004), and in the design of distorted physical models (Paola et al., 2009; Peakall et al., 1996). However, the weak effect of the Froude number has been also observed in various three-dimensional morphodynamic processes, including the formation of river bars and the planform evolution of meandering channels (Redolfi et al., 2021; Seminara, 2006; Wilkinson et al., 2008).

A further result highlighted in Figure 3 is the clear difference between the spatial scaling of river looping patterns and deltaic systems. In lowland river-dominated deltas (i.e., deltas in which the magnitude of marine processes like waves and tides is minimal) the avulsion length $L^{(A)}$, defined as the distance upstream of the shoreline where avulsions preferentially occur (e.g., Chadwick et al., 2019), is known to be mainly controlled by the characteristic length of the backwater profiles (e.g., Chatanantavet et al., 2012; Jerolmack & Swenson, 2007). The reanalysis of avulsion data we retrieved from the literature (Text S1 in Supporting Information S1), shows that scaling the length $L^{(A)}$ with the bankfull depth leads indeed to a clear difference with respect to river loops, with values of $\tilde{L}^{(A)} = L^{(A)}/D$ markedly decreasing with channel slope. This dependence essentially follows the backwater length.

From a physical point of view, the difference between river loops and deltaic systems can be explained by considering that the suggested mechanism of compensation does not hold in cases when the downstream effect is "externally imposed" by variations of the sea level, or due to variations of the flow discharge. Ultimately, the difference between the two kinds of scaling relations can be attributed to the fact that the backwater length represents the scale at which gravitational and frictional forces become comparable, while the length c^2D represents the relation between inertial and frictional forces (e.g., Canestrelli et al., 2014). As a consequence, the scaling quantity c^2D also plays an important role in determining the spacing of bar-pools units and meander bends (Camporeale et al., 2005; Ikeda et al., 1981; Mosselman et al., 2006; Parker & Johannesson, 1989; Struiksma et al., 1985), which in turn reflects in the confluence-bifurcation spacing in braided rivers (Ashmore, 2013; Hundey & Ashmore, 2009).

Finally, in this study we did not consider braided rivers, due to the difficulty to obtain reliable data for individual channel loops within the complex network of channels. However, the suggested scaling may generally hold for any multi-thread systems, including braided and anastomosing rivers. Ordinary regression of data in Figure 1c yields to the power-law $L = 65\ Q^{0.48}$, showing a striking analogy with comparable results obtained by Ashmore (2001) from the analysis of the so-called "braid wavelength" (or link-length) in a series of field braided reaches, in which the mean downstream spacing of confluences is found to be equal to $L^{(C)} = 52\ Q^{0.45}$, a trend further confirmed in a series of successive laboratory investigations (Bertoldi et al., 2009; Hundey & Ashmore, 2009).

5. Conclusions

The consistency between observed and theoretically predicted values of $\tilde{L}_D$ suggests that river loops may organize themselves by selecting a spatial scale that is not randomly distributed, but it is basically controlled by a morphodynamic two-way interaction between the bifurcation and confluence nodes. The stabilizing effect induced by this interaction may allow river loops to survive in the long term, escaping from the abandonment or complete filling of one of the two anabranches. In this sense, the observed quasi-universality might not result from an adaptation of the individual loops toward optimal conditions, but rather from a sort of Darwinian process according to which the loop population is regulated by a natural selection of the more stable individuals. Therefore, results of this work provide a key information for the design of effective and self-sustaining river restoration and river engineering interventions aimed at creating and re-activating pristine channel loops, and gives further insights into the study of the spatial organization of braided and anastomosing rivers.

Data Availability Statement

We made the entire dataset publicly available at https://doi.org/10.5281/zenodo.6901398.

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