



# Scale dependency in quantifications of the avulsion frequency of coastal rivers

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## ABSTRACT

Quantification of the frequency with which coastal-plain rivers avulse is important for elucidating autogenic dynamics and their role as controls on landscape change and stratigraphic architectures. An outstanding question exists, however, as to whether measures of avulsion frequency are inherently affected by the spatial and temporal scales at which they are evaluated, which has implications regarding our ability to make direct comparisons between different river systems or deltas. To address this problem, a quantitative analysis of the avulsion histories of 57 coastal-plain river systems is undertaken. Nine alternative measures of avulsion frequency are extracted. These are based on numbers of (i) avulsion events, (ii) active or abandoned channel courses, and (iii) delta lobes, all considered per unit time. Additional sets of avulsion-frequency proxies are established based on normalization of these numbers relative to the size of the area being studied, and to the number of distinct river systems that drain into that area. The sensitivity of these quantities to the spatial and temporal extent of study areas and time intervals, and their relationships with quantities describing the scale of the river systems, are assessed. All avulsion-frequency estimates demonstrate apparent negative relationships with the timespan over which they are determined; this may reflect global Holocene trends, or variations in resolution with the time window. Avulsion metrics that are not normalized by the planform extent of the study area do not show proportionality with the size of the study areas themselves, nor with the scale of the river systems; correspondingly, the spatio-temporal density of avulsion events tends to be higher for smaller rivers and associated study areas. This may be due to systematic variations in data resolution, to the influence of external controls that relate to the scale of deltas, or to inherent non-stationarity in the avulsion dynamics of lowland rivers, in association with forms of self-organization that do not vary with scale. Although non-normalized avulsion-frequency estimates do not scale with measures of river-system size, they are seen to correlate with progradation rates, which are themselves scaled to sediment discharge and catchment size. Practical considerations can be drawn on how avulsion frequency may be appropriately quantified to enable meaningful comparisons of the autogenic dynamics of coastal-plain rivers.

## 1. Introduction

Channel avulsion resulting in the diversion of a channelized sediment-transport pathway in favour of a new course is a common process of rivers, alluvial torrents and submarine channels (e.g., McCarthy et al., 1992; Field, 2001; Colombera and Bersezio, 2011; Jobe et al., 2020). Quantifications of the frequency with which channels avulse are crucial for research aiming to improve our understanding of (i) landscape change associated with channel morphodynamics, (ii) the role of autogenic mechanisms in governing the spatio-temporal variability in sediment distribution in sedimentary basins, and (iii) controls on the architecture of sedimentary successions (e.g., Bryant et al., 1995; Pelletier and Turcotte, 1997; Jerolmack and Mohrig, 2007; Gouw,

2008). However, the quantification of the frequency of avulsion events is not trivial. This quantification is commonly expressed in terms of interavulsion period, i.e., the lifespan of a channel, or its reciprocal value, the avulsion frequency (Törnqvist, 1994; Stouthamer and Berendsen, 2001; Törnqvist and Bridge, 2002; Slingerland and Smith, 2004). Yet, it can be surmised that these quantities depend on the spatial scale of the sample on which they are based (e.g., a reach of a certain length, a delta plain, an entire river system). In particular, these quantities depend on the total, cumulative channel length considered, which is itself a function of the extent of the area being evaluated and of the density of the channel network contained therein (cf. Stouthamer and Berendsen, 2007). This supposed dependency of avulsion frequencies on spatial scale has implications for the ability to make direct comparisons

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between different channelized systems. Equally, quantifications of the frequency of avulsion events may also vary depending on the temporal window over which they are determined. For datasets detailing Holocene avulsion histories, this may happen in part because of variations in avulsion frequency through time, in relation to temporal variations in the influence of geological controls, and in part because of the increased difficulty in resolving avulsion records as we consider progressively older episodes of river-system evolution. In considering the potential relationships between avulsion-frequency quantifications and the scales over which they are made, a question arises as to whether these quantities may be affected by factors whose importance is known to scale to the size of the sediment-routing system. For coastal-plain rivers, in particular, the scale of the fluvial system dictates characteristics such as the dominant sediment-delivery mechanisms, the streambed gradient, the extent of the backwater zone, and the rate at which the shoreline progrades (Milliman and Farnsworth, 2011; Blum et al., 2013; Aadland and Helland-Hansen, 2019). These factors can all influence the avulsion frequency of coastal channels, for instance by exerting controls on streambed aggradation and development of cross-channel gradient advantages (Jones and Schumm, 1999; Slingerland and Smith, 2004). On this basis, it can be hypothesized, for example, that larger river systems, typically associated with faster river-mouth progradation and gentler streambed gradient, may be prone to experience more frequent channel avulsions. At the same time, however, larger deltas may be characterized by less erodible delta-plain substrates, which may on the contrary offer increased resistance to channel diversions (cf. Edmonds and Slingerland, 2010). It is therefore of interest to establish whether some inherent scaling exists between avulsion frequencies and river-system scale. Given the particular set of scale-dependent variables that may control avulsion dynamics in lowland rivers, the focus of this work is specifically on fluvial systems that developed in relative proximity to the coast.

The aim of this work is to establish the degree to which avulsion-frequency metrics may depend on the temporal and spatial scales of investigation. Specific research questions are as follows. What quantification is needed to enable meaningful comparisons of avulsion frequencies relating to different river systems? If these metrics are seen to vary across spatio-temporal scales, what are the possible methodological and geological explanation of apparent variations? Given the inherent covariance of factors that are linked to river-system scale, and considering how these variables act to control river avulsion, is avulsion frequency intrinsically dependent on river-system size?

What this work does not aim to achieve is a comprehensive assessment of controls on avulsion frequencies, which are partly determined by factors that act independently of scale. Nevertheless, to understand whether potential dependency of avulsion frequency on scale is an apparent (i.e., due to methodological reasons) or true (i.e., due to geological reasons) phenomenon, we need to consider the role of potential geological controls that could cause it.

## 2. Data and methods

### 2.1. Original literature data

The dataset that underpins the quantifications presented in this work consists of qualitative documentations of the Holocene avulsion histories of 57 case studies of river deltas and alluvial coastal plains (Table 1; Fig. 1A). These examples were chosen based on the availability of suitable data documenting avulsion histories, channel activity and/or delta-lobe development over known temporal intervals. The case studies include both marginal-marine and marginal-lacustrine examples. Collectively, they cover a broad range of river-system scales (five orders of magnitude in drainage-basin area; Fig. 1B). The selected marginal-marine examples also developed under varied process regimes, i.e., they differ with respect to the relative importance of fluvial, wave and tidal processes in shaping their morphology and controlling their evolution (Fig. 1C); however, the dataset is characterized by a

predominance of river-dominated settings (28, compared to 17 wave-dominated ones and 3 tide-dominated ones), which may not be representative of deltaic systems globally (cf. Nienhuis et al., 2020). All the data are derived from open-source scientific literature (articles, dissertations, reports). The original studies documented the temporal evolution of lowland rivers through variable time spans of the Holocene. The planform evolutions of these river systems were characterized in terms of one or more of the following aspects: (i) courses of abandoned channels (palaeochannels), as well as presently active ones, (ii) location of avulsion sites and events, and/or (iii) position and extent of delta lobes. The occurrence of these features was variably determined on the basis of evidence available through historical maps or records (e.g., Bondesan et al., 1995; Mateo and Siringan, 2007), remote sensing (including satellite images, aerial photos, LiDAR or InSAR elevation data; e.g., Serrano Suarez, 2004; Phillips, 2012; Syvitski et al., 2013; Haghani and Leroy, 2020), and field investigations providing data on surface geomorphology and on the shallow subsurface geology (based on borehole and geophysical observations; e.g., Berendsen and Stoutamer, 2002; Fielding et al., 2006; El Bastawesy et al., 2017). The Holocene histories were reconstructed based on available temporal constraints: radiometric dates (e.g., Muñoz-Salinas et al., 2017), historical accounts (e.g., Holmes, 1968), archaeological evidence (e.g., Stanley et al., 2004), and historical maps, satellite images or aerial photos of known age (e.g., Karymbalis et al., 2016). Where multiple suitable data sources existed for the same case study, the datasets were integrated into a single reconstruction, if possible. Where discrepancies existed in the interpretations of Holocene histories based on different datasets available for the same case study, the interpretations that were considered were those supported by the most robust evidence and associated with higher-resolution data in terms of recognition of geological features and/or chronological constraints. Chronometric data were sourced from the wider literature, additional to the data sources on planform changes. All primary data sources are reported in Table 1.

### 2.2. Approaches to the quantification of avulsion frequency

Some alternative ways to quantify the frequency of river avulsion were considered, based on three fundamental quantities: (i) the number of avulsion events that occurred during a time interval, (ii) the number of channels that were active during a time interval, and which may or may not have been abandoned during that time (active channels and palaeochannels are collectively referred to as ‘channel threads’ hereafter), and (iii) the number of delta lobes that were active, and which may or may not have been abandoned, during a time interval (Fig. 2). For each case study, the time intervals considered for each quantification may differ, depending on the available records of each type of quantity. These numbers were determined over a study area of given size, typically the entire delta plain or the portion of a coastal plain that was active during the specified time (referred to as ‘study area’, hereafter). The size of the study areas is in part dictated by data coverage; hence, for each case study, the considered area may have differed for the three forms of quantification. In some cases, the defined study areas cover regions that are now located at considerable distance from the present-day coast: this is because study areas are defined to capture river reaches that developed in proximity of the shoreline in the past, and many of the studied examples have undergone extensive shoreline progradation over the timescales of interest.

The number of avulsion events considered includes both ‘full’ and ‘partial’ avulsions of reaches that lead to a river mouth; full avulsions consist of channel diversions that lead to the abandonment of a reach, whereas partial avulsions represent events that cause the establishment of a new course that coexists with the antecedent one (Slingerland and Smith, 2004). Events of levee break forming crevasse splays or subdeltas that are only active at high flow stage are not considered as avulsion events. Neck and chute cutoffs, which occur within the boundaries of channel belts, are not treated as avulsions. The avulsion events

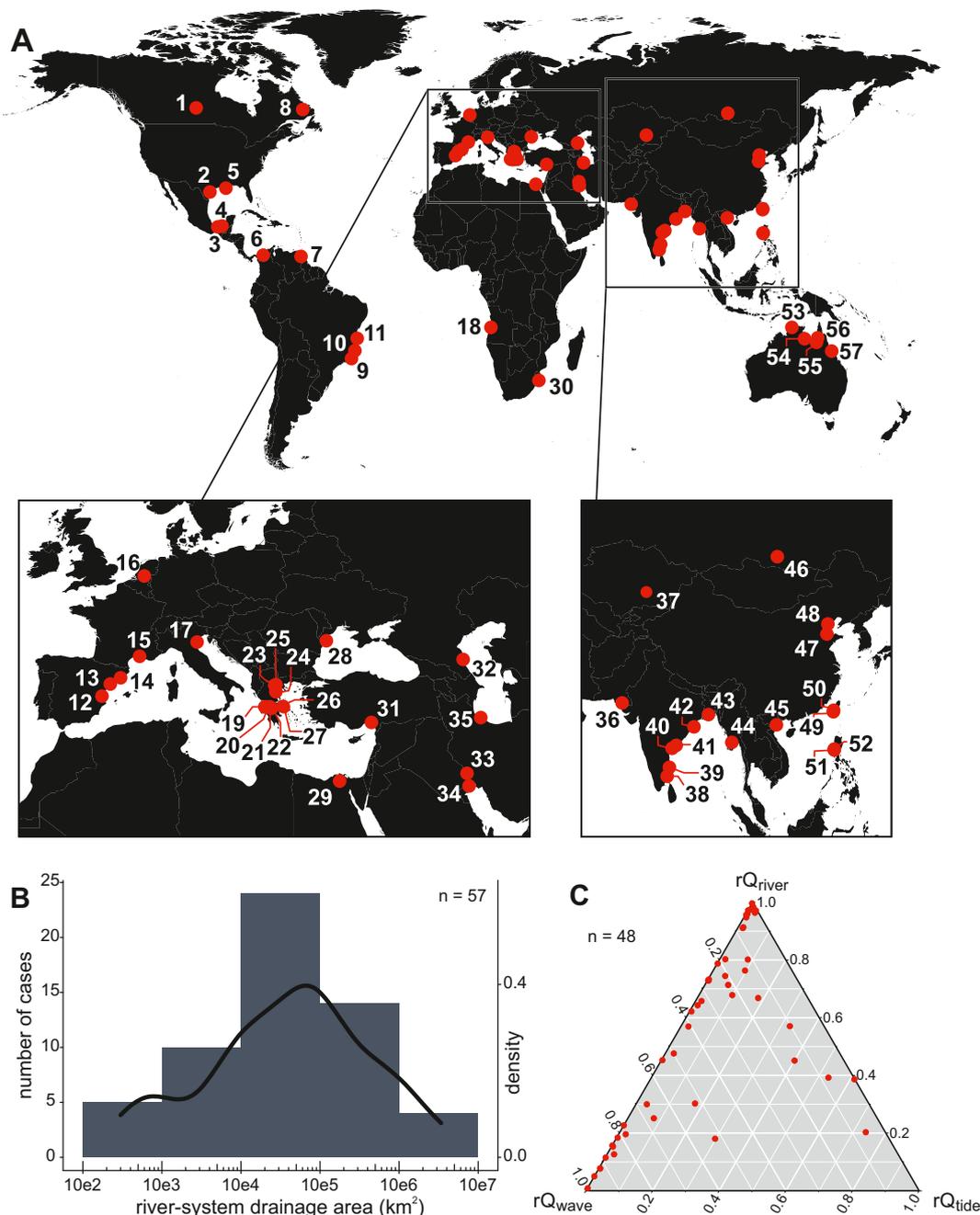
**Table 1**

Summary of the case-study coastal-plain river systems considered in this work, of the types of avulsion metrics extracted for each, and of the primary data sources. Ticks that appear in brackets indicate avulsion, channel-thread or delta-lobe records that are thought to be incomplete, and therefore examples that likely yield underestimated quantities.

ID	River system	N avulsion events	N channel threads	N delta lobes	Data sources
1	Saskatchewan upper delta	✓	✓		Morozova and Smith (1999, 2000)
2	San Antonio-Guadalupe	✓	✓	✓	Donaldson et al. (1970); McGowen et al. (1976); Weinstein and Junkin (1992); Phillips (2012)
3	Grijalva	✓	✓		von Nagy (2011); Nooren (2017)
4	Usumacinta	✓	✓		von Nagy (2011); Nooren (2017); Muñoz-Salinas et al. (2017)
5	Mississippi	(✓)	✓	✓	Welder (1955); Törnqvist et al. (1996); Roberts (1997); Chamberlain et al. (2018); Bhattacharya et al. (2019)
6	Sinú	✓	(✓)		Serrano Suarez (2004)
7	Orinoco	(✓)	(✓)		Van Andel (1967); Aslan et al. (2003)
8	Goose	✓		✓	Nijhuis (2013); Nijhuis et al. (2015)
9	Parafba do Sul		✓	(✓)	Martin et al. (1993); Da Rocha (2013); Ainsworth et al. (2019)
10	Doce		✓		Martin et al. (1993); Rossetti et al. (2015)
11	Jequitinhonha		✓	✓	Martin et al. (1993); Dominguez et al. (1981); Martin et al., 1993; Ainsworth et al. (2019)
12	Turia		✓		Ruiz-Pérez and Carmona (2019)
13	Ebro	✓	✓	✓	Somoza et al. (1998); Somoza and Rodríguez-Santalla (2014)
14	Llobregat		✓		Gàmez Torrent (2007)
15	Rhône	(✓)	✓	✓	Rey et al. (2009); Fanget et al. (2014); Provansal et al. (2015)
16	Rhine-Meuse	✓	✓		Berendsen and Stouthamer (2002); Stouthamer et al. (2011)
17	Po	✓	✓	✓	Bondesan et al. (1995); Mackey and Bridge (1995); Correggiari et al. (2005a, 2005b)
18	Catumbela		✓		Dinis et al. (2018)
19	Acheloos		✓		Piper and Panagos (1981); Vött et al. (2007a, 2007b)
20	Evinos		✓		Piper and Panagos (1981); Maroukian and Karymbalis (2004)
21	Mornos		✓		Karymbalis et al. (2007); Parcharidis et al. (2013)
22	Selinous		✓		Kontopoulos and Avramidis (2003); Koutsios et al. (2010)
23	Aliakmon		✓		Ghilardi (2007); Ghilardi et al. (2008); Styllas (2018)
24	Pinios		✓		Gaki-Papanastassiou et al. (2010); Karymbalis et al. (2016)
25	Axios		✓		Ghilardi (2007); Ghilardi et al. (2008)
26	Lilas	✓	✓	✓	Karymbalis et al. (2018)
27	Asopos	(✓)	✓	(✓)	Gaki-Papanastassiou et al. (2011); Gaki-Papanastassiou (pers. comm.)
28	Danube	(✓)	(✓)	✓	Vespremeanu-Stroe et al. (2017a, 2017b)
29	Nile		✓		Stanley and Warne (1993); Stanley et al. (2004); El Bastawesy et al. (2020)
30	Mfolozi	✓	✓		Grenfell et al. (2009)
31	Ceyhan-Seyhan	(✓)	✓	(✓)	Erol (2003); Ataol (2015); Rutishauser et al. (2017)
32	Sulak		✓	(✓)	Mikhailov et al. (2004, 2012)
33	Karkheh	(✓)	✓		Heyvaert et al. (2012)
34	Shatt-al-Arab		✓		Hussein (2011); Heyvaert and Walstra (2016); Al-Hamad et al. (2017)
35	Sefidrud	(✓)	✓	(✓)	Kazancı et al. (2004); Kazancı and Gulbabazadeh (2013); Haghani and Leroy (2020)
36	Indus		✓		Holmes (1968); Syvitski et al. (2013)
37	Ili		✓		Abdrasilov and Tulebaeva (1994); Deom et al. (2019)
38	Cauvery		✓		Ramasamy et al. (1991); Ramasamy et al. (2006); Singh et al. (2015)
39	Palar		✓		Ramasamy et al. (2006); Resmi et al. (2017)
40	Krishna		✓	✓	Nageswara Rao et al. (2020)
41	Godavari	✓	✓	✓	Nageswara Rao et al. (2015)
42	Mahanadi		✓		Mahalik et al. (1996); Maejima and Mahalik (2002); Dash et al. (2020)
43	Bengal (Ganges-Brahmaputra)		✓	(✓)	Allison et al. (2003); Sarker et al. (2013); Akter et al. (2016)
44	Irrawaddy	(✓)	✓	(✓)	Kravtsova et al. (2009); Giosan et al. (2018); Chen et al. (2020)
45	Red River (Song Hong)		(✓)	✓	Mathers and Zalasiewicz (1999); Tanabe et al. (2006); Cuong (2009); Funabiki et al. (2012)
46	Selenga	✓			Dong (2020)
47	Yellow River (Huanghe)	✓	✓	✓	van Gelder et al. (1994); Ganti et al. (2014); Wang et al. (2016); Zheng et al. (2017); Moodie et al. (2019)
48	Luanhe	(✓)	✓	(✓)	Wang et al. (1986); Cheng et al. (2020); He et al. (2020)
49	Tseng-wen	✓	✓		Chang and Chen (2001)
50	Pa-chang	✓	✓		Chang and Chen (2001)
51	Agno-Dagupan	(✓)	✓	✓	Mateo and Siringan (2007)
52	Bued-Patalan		✓	✓	Mateo and Siringan (2007)
53	Mary		✓		Mulrennan and Woodroffe (1998)
54	McArthur		✓		Woodroffe and Chappell (1993); Jones et al. (2003)
55	Gilbert		✓		Nanson et al. (1991); Jones et al. (2003)
56	Mitchell	✓	✓	(✓)	Lane et al. (2017)
57	Burdekin		✓	✓	Fielding et al. (2005a, 2005b, 2006)

considered in the quantification correspond to those that are significant enough to be recorded in the data sources (Table 1); as such, resulting metrics suffer from some subjectivity and are likely to represent conservative estimates. The number of avulsion events could be obtained for 28 of the 57 case studies; however, avulsion counts are thought to be accurate estimations of a true total number for 17 examples only.

The number of channel threads includes all the river courses leading to a river mouth that were active during the considered timespan, including those that may have been activated before. All throughgoing channel courses that are mapped and inferred to have been hydrologically connected to the river are included, regardless of their size. Inclusion of channels that may have already been active was done to

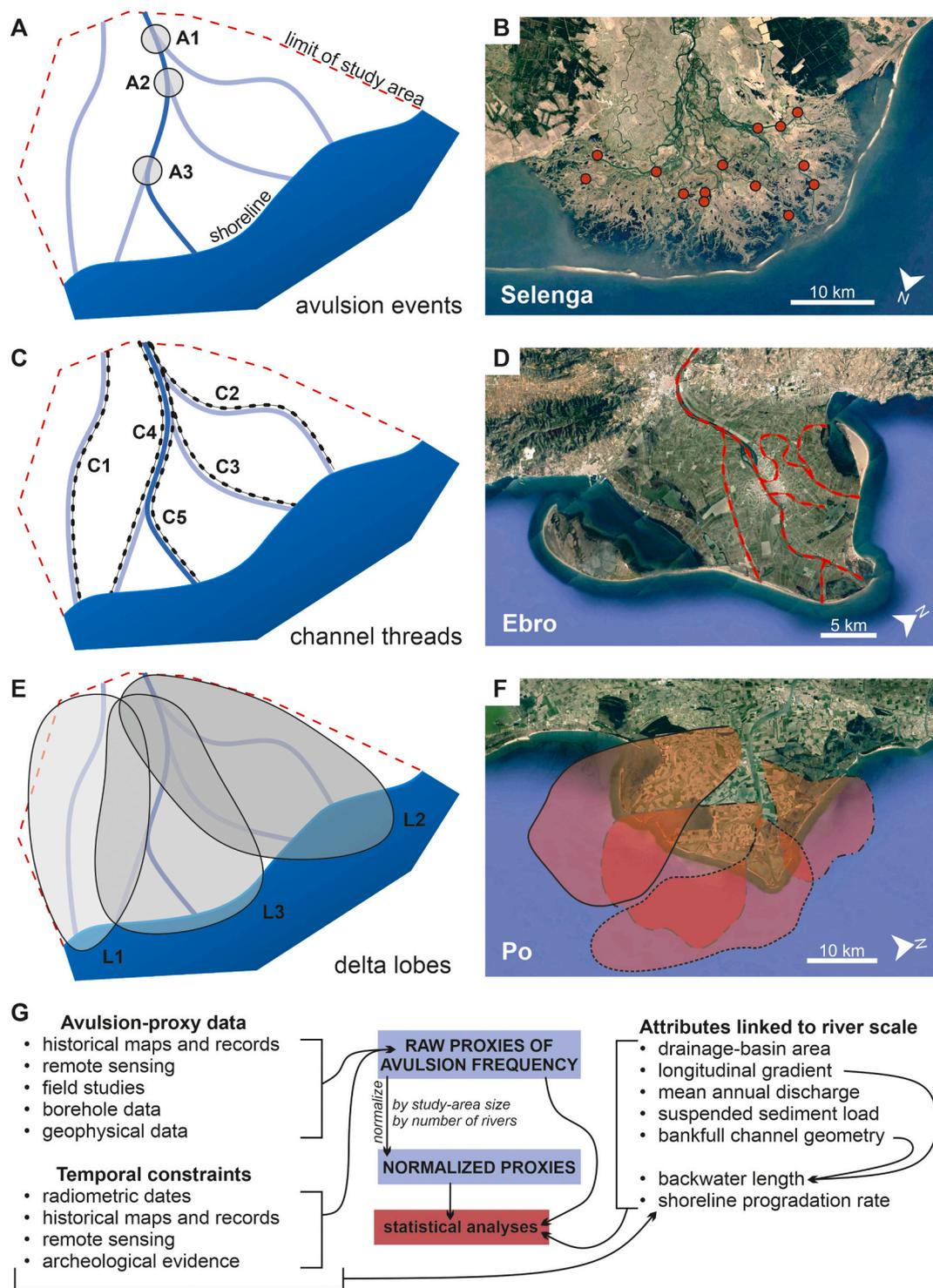


**Fig. 1.** (A) location map of the coastal-plain river systems considered in this study. (B) histogram and kernel density estimation of the distribution of drainage areas of river systems considered in this study; note the logarithmic scale in abscissa. (C) Ternary diagram illustrating the variability in process regime of marine deltas included in the study, expressed in terms of relative sediment flux ( $rQ$ ) associated with river, wave and tidal processes, based on data from [Nienhuis et al. \(2020\)](#). All presented data are included in the Supplementary Material.

broaden the temporal window of the observations as much as possible, as the exact timing of activation of older palaeochannels is in many cases unknown. However, this poses an issue in that the number of channel forms whose activation pre-dated the studied temporal interval may vary across the studied river systems. This quantity also includes channel threads that may have been established through avulsions that took place outside of the study area. Palaeochannels that are known to have been born from bifurcations around mouth bars at the coast, and which may have been incorporated into the delta plain following shoreline advance, have been excluded. As defined in this work, the term ‘channel thread’ is used to refer to individual distributary courses, which may take the form of channel belts with multiple channels: a braided channel belt is counted as one single ‘channel thread’. The number of

channel threads could be obtained for 54 of the 57 case studies, 51 of which are considered to have been characterized comprehensively.

The number of delta lobes quantifies the number of avulsions that are significant enough – in terms of magnitude of river-mouth relocation – to cause lobe switching. For the scopes of this work, a ‘delta lobe’ is defined as a three-dimensional sediment volume made of cogenetic delta-top, delta-front and prodelta deposits associated with a particular state of the drainage network that arose because of river avulsion (cf. [Colombera and Mountney, 2020](#), and references therein). Different diagnostic criteria may have been considered in the original data sources for the definition of delta lobes, such as the recognition of prodelta to delta-top facies successions, the lenticular three-dimensional shape of sediment accumulations, or some preserved seaward protrusion in



**Fig. 2.** Depiction of the features used to define the avulsion-frequency metrics used in this work: (A) idealized example of counted avulsion events and (B) their recognition in one of the case studies, the Selenga River delta (cf. Dong, 2020); (C) idealized example of counted channel threads and (D) their recognition in the Ebro River delta (cf. Somoza and Rodríguez-Santalla, 2014); (E) idealized example of counted delta lobes and (F) their recognition in the Po River delta (cf. Correggiari et al., 2005a); (G) flow-chart summarizing the adopted workflow and data types.

planform, related to abandoned river mouths. The chosen definition of a delta lobe can be applied at different scales to units that may even be nested hierarchically. The data were extracted relying on the application of the term ‘delta lobe’ by the authors of the original datasets; doing so means considering entities that are not necessarily comparable in terms of scale of development, but permits this category to be applied objectively. Accounts of delta lobes exist for 25 of the 57 case studies, but

numbers of delta lobes developed over a known length of time are only thought to be comprehensive for 16 of these.

The numbers of avulsion events, channel threads, and delta lobes per unit time are each considered as alternative proxies for channel avulsion frequencies. In addition, all these quantities are normalized relative to the planform extent of the study area considered for each. This permits determination of avulsion ‘density’, describing the number of avulsion

events, channel threads or delta lobes both per unit time and per unit area. The study area considered for this type of normalization corresponds to the coastal-plain area of interest covered by the river system up to the present day: i.e., currently drowned delta lobes are included, whereas any change in area due to coastal progradation is not quantified. These metrics are referred to as rates normalized by area, hereafter.

Some additional normalization has also been applied to the avulsion metrics of eight examples, representing the Holocene histories of coastal plains traversed by multiple coalescing river systems that joined intermittently. The quantities are normalized by the maximum number of river systems with distinct catchments known to have had independent drainage to the sea or lake at some point during the considered evolutionary histories; this value ranges from one, for the 49 examples not requiring normalization, to four. These metrics are referred to as rates normalized by area and river number, hereafter.

### 2.3. Ancillary data and associated quantifications

Ancillary data have been collected to constrain variables that describe the river systems and that are known to scale with their size. Among these, the variables considered in this study are: (i) river-system drainage-basin areas, (ii) average river water-surface gradients across the study areas; (iii) mean annual water discharges as based on observations from gauging stations located near the upstream end of the study area (data from the *Global Runoff Data Centre*, from the primary data sources of Table 1, and from the wider scientific literature: Begg, 1978; Poulos and Chronis, 1997; Fytianos et al., 2002; Kao and Milliman, 2008; Milliman and Farnsworth, 2011; Cohen et al., 2013; Efstratiadis et al., 2014; Pueppke et al., 2018; Skoulikidis et al., 2018; Nienhuis et al., 2020), (iv) suspended sediment loads (data from the primary data sources of Table 1 and from the literature: Ashmore and Day, 1988; Poulos and Chronis, 1997; Rivera, 1997; Erkens et al., 2006; Syvitski and Saito, 2007; Kettner and Syvitski, 2008; Rustomji, 2010; Bernardes et al., 2012; Milliman and Farnsworth, 2011; Potemkina, 2011; Cohen et al., 2013; Duskayev et al., 2020), (v) empirical estimations of bankfull width and mean bankfull depth at the upstream end of the study area, as provided by Andreadis et al. (2013). Where available, data on water discharge and sediment load have been used that relate to times prior to the construction of dams, which may have significantly altered these quantities.

Shoreline progradation rates are calculated as increases in coastal-plain area per unit shoreline width per unit time; these rates are computed based on temporal constraints available in the scientific literature, and over a timescale of equivalent order of magnitude to that of one or more of the avulsion-frequency proxies computed for each case study.

Backwater lengths are estimated as the ratio between flow depth at the upstream end of the study area and the water-surface gradient across the study area, which is considered to be a reasonable approximation of the streambed gradient (cf. Paola, 2000). Alternative quantifications of backwater lengths are computed according to three different approaches based on (i) mean bankfull depth (Andreadis et al., 2013), (ii) a characteristic flow depth based on mean yearly discharge and bankfull width (cf. Lamb et al., 2012), and (iii) a characteristic flow depth determined from the mean discharge of the wettest month and bankfull width (cf. Chatanantavet et al., 2012; Lamb et al., 2012; Ganti et al., 2016a). Results of the application of the three approaches have been compared with each other, as well as with other estimations of backwater lengths for the same coastal rivers (Jerolmack, 2009; Chatanantavet et al., 2012; Ganti et al., 2016b; Hartley et al., 2017). This was done to establish the sensibility of the quantifications. As the three chosen approaches yield similar results, for scopes of data presentation, only backwater-length estimations based on inferred mean bankfull depths are presented, since these could be constrained for the largest number of case studies (N = 50).

### 2.4. Dataset limitations

Each of the chosen alternative approaches to the quantification of avulsion frequency suffers from some issues. All the metrics may be affected by some degree of human regulation of the river systems, especially in the form of controls on river drainage and efforts for preventing river avulsions, which might have varied across the case studies, as well as through time and spatially in each. This reflects the scarcity of detailed and extended records of avulsion histories of persistently pristine coastal-plain river systems on which to perform a study of this type. Known artificial diversions (and resulting channels) are not treated as avulsions (or products thereof), but a detailed record of human intervention may be lacking for the earliest times of river histories. The only forms of quantification of avulsion frequency that are potentially precise are those based on the number of avulsion events; yet these are unlikely to be accurate in practice due to the fragmentary nature of historical records, especially over millennial timescales. The adoption of the number of channel threads as a proxy for avulsion frequency is subject to several notable problems. The number of channel threads could include a count of palaeochannels whose inception was related to artificial diversions that were not documented as such. The same number fails to quantify re-occupational avulsion events (i.e., the avulsive reoccupation of previously abandoned reaches; Aslan et al., 2005; Reitz et al., 2010; Stouthamer et al., 2011; Reitz and Jerolmack, 2012). It may also include examples of distributary channels whose inception was not due to avulsion, such as for example groundwater-fed channels, or distributary channels that originated from bifurcations around mouth bars (Edmonds and Slingerland, 2007; Hoyal and Sheets, 2009). It also considers particular forms of avulsion ‘by annexation’ (sensu Slingerland and Smith, 2004), such as where groundwater-fed tributaries propagate upstream to intersect other channel reaches, or where tidal channels extend updip to achieve connection with fluvial drainage (cf. Mulrennan and Woodroffe, 1998). The number of delta lobes may underestimate avulsion frequency significantly, as the distinction of delta lobes may depend on the amount of lateral offset of a river and its mouth, which is controlled in part by the variable rates of accommodation generation in the nearshore (e.g., Restrepo and Cantera, 2013). Additionally, the term ‘delta lobe’ may be applied to parts of deltas that themselves are known to have experienced multiple avulsions (e.g., Kazanci and Gulbabazadeh, 2013) or to have been traversed by multiple (palaeo)channels (e.g., Karymbalis et al., 2018; Dong, 2020). Also, the timing of lobe development may be offset relative to the timing of creation of its feeder channel, as lobe growth may be related to variations in the partitioning of discharge and sediment load across multiple distributaries (cf. Vespereanu-Stroe et al., 2017a).

Data on the relative timing of avulsion events of known location, or of the inception of palaeochannels of known location, are not recorded, since these facts are only known for few examples (e.g., Stouthamer et al., 2011; Somoza and Rodríguez-Santalla, 2014). This limits the types of analyses that can be undertaken with the current dataset.

Some river-system variables (bankfull hydraulic geometry, backwater length) represent estimations based on proxy datasets. The variables that characterize the river systems may only reflect present-day or recent conditions; these may not approximate those of pristine natural states, and/or are unlikely to be representative of the entire Holocene timespan over which avulsion metrics have been determined.

The selected case studies are not representative of all types of channel networks seen in coastal-plain river systems. In particular, a bias is likely to exist because studies of avulsion dynamics may focus preferentially on markedly avulsive river systems. Examples for which avulsions are undocumented in the Holocene record (e.g., Mekong, Tamura et al., 2012; Yangtze, Chen and Stanley, 1995) have necessarily been excluded.

The dataset is heterogeneous in terms of the size of the considered study areas relative to the coastal domain. In some cases, the apex of a delta can be identified on the basis of the recognition of topographic

slope breaks, alluvial-valley outlets or persistent avulsion nodes (cf. Stouthamer and Berendsen, 2000; Syvitski et al., 2013; Nooren et al., 2017); in these cases, the extent of the delta sets the size of the study area, provided that the spatial coverage of avulsion-proxy data extends to the delta apex. In the absence of delta apices, the selection of an upstream boundary for areas of interest is necessarily somewhat arbitrary, and placed in such way that the study areas may extend beyond present-day coastal regions. The study areas outline portions of the river systems that have developed relatively near the shoreline at some point in time, but which may now occur far upstream of the coast, where avulsion dynamics may differ. By taking this approach, avulsion events that have occurred in these settings are included in the study. Defining study areas dynamically, so as to track the regressive evolution of the systems, would enable improved analyses; however, this approach is rendered difficult in practice by the limited temporal resolution of avulsion events and palaeoshoreline positions.

### 2.5. Statistical analyses

An assessment is made of relationships between the different avulsion-frequency proxies, between avulsion metrics and the temporal and spatial scales over which they have been determined, and between avulsion metrics and variables describing properties of the river system that are known to reflect its scale. The sign and magnitude of correlations have been quantified by Pearson or Spearman correlation coefficients of the variables or by Pearson correlation coefficients of their corresponding logarithmic transformations. *t*-tests and Welch's one-way ANOVA have been applied to assess statistical significance of differences in mean values of variables across two or more groups of observations, respectively. Normality in data distributions has been tested by Shapiro-Wilk tests. Logarithmic variable transformations have been applied to account for deviations from normality and homoscedasticity in data distributions, to ensure that the assumptions for the use of parametric statistical tests are met; *t*-tests and ANOVA have been applied to log-transformed variables where needed. Statistical significance of both correlations and statistical tests is quantified by *p*-values; outcomes are stated as significant for  $\alpha = 0.05$ . Datasets that are considered as representing relatively complete records of avulsion histories (Table 1), based on what is reported in the data sources and on critical analysis of the broader literature on the same case studies, are labelled as being of 'higher quality'; these are considered separately from the entire data pools in some of the analyses.

## 3. Results

### 3.1. Avulsion metrics and data quality

Some differences are seen in the distributions of avulsion metrics across classes of data quality that reflect the completeness of the associated records (Table 1); yet, these differences are not systematic across the three alternative avulsion-frequency proxies (also termed avulsion 'rates' hereafter for the sake of brevity). Rates based on the number of avulsion events are lower on average for datasets flagged as being of lower quality (Fig. 3a, b). For rates based on counts, mean values are  $34.2 \text{ kyr}^{-1}$  ( $N = 17$ ) and  $2.8 \text{ kyr}^{-1}$  ( $N = 11$ ), and standard deviations are equal to  $101.3 \text{ kyr}^{-1}$  and  $3.2 \text{ kyr}^{-1}$ , for higher and lower-quality datasets respectively; a two-sample *t*-test conducted on log-transformed values of these variables indicates that the difference in mean is statistically significant (*T*-value = 2.15, *p*-value = 0.041, degrees of freedom [d.f.] = 26). For rates normalized by area and river number, mean values are  $0.063 \text{ kyr}^{-1}\text{km}^{-2}$  and  $0.042 \text{ kyr}^{-1}\text{km}^{-2}$ , and standard deviations are  $0.162 \text{ kyr}^{-1}\text{km}^{-2}$  and  $0.104 \text{ kyr}^{-1}\text{km}^{-2}$ , for high and low-quality datasets respectively; however, a two-sample *t*-test on log-transformed values of these variables indicates that mean values do not vary significantly (*T* = 1.51, *p* = 0.152, d.f. = 26). Low- and high-quality avulsion-event datasets cover temporal durations that are on average 2.78 kyr

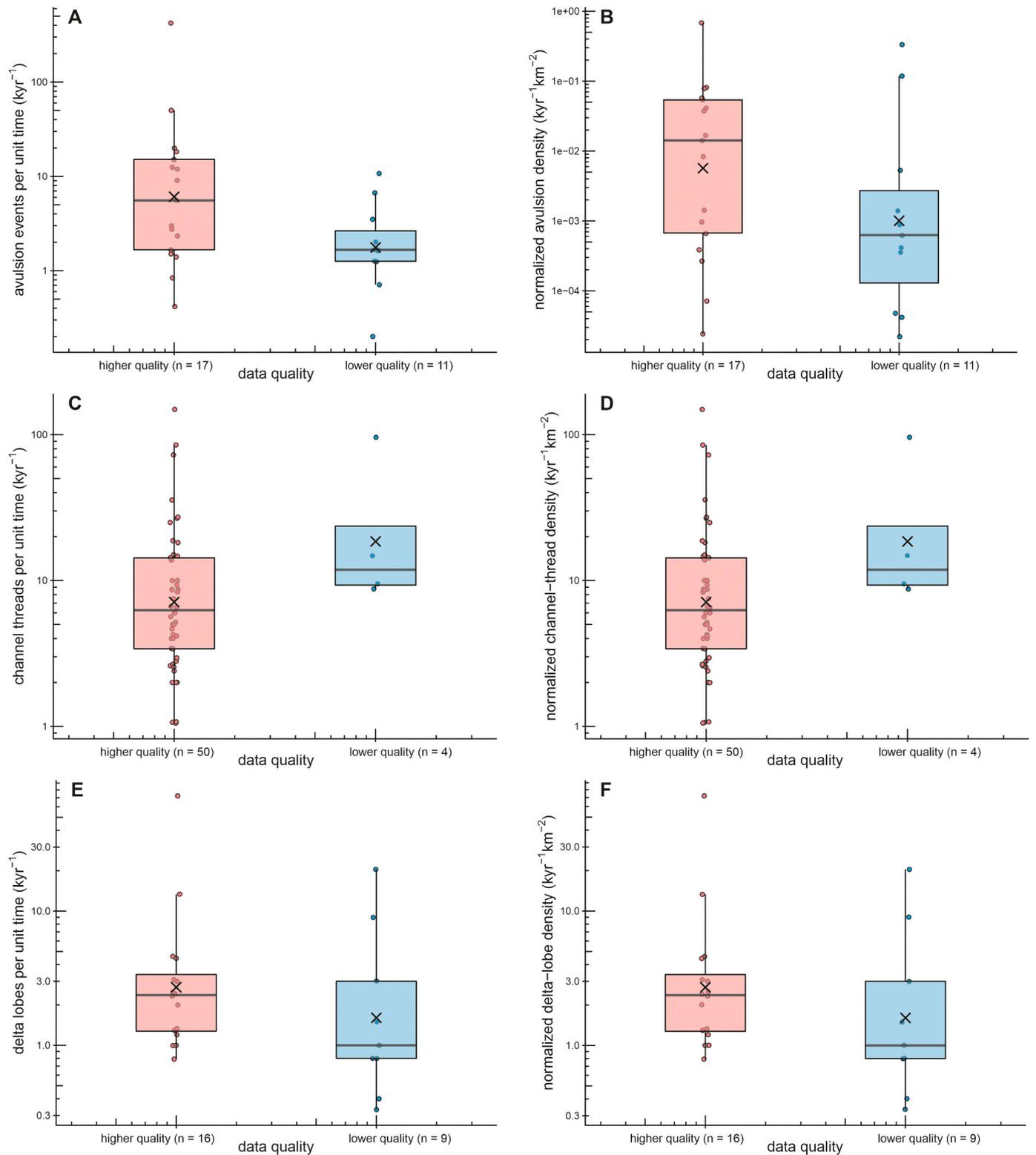
and 2.85 kyr, respectively. Rates based on the number of channel threads, instead, are lower on average for datasets classified as 'higher quality' (Fig. 3c, d). For rates based on counts, mean values are  $14.3 \text{ kyr}^{-1}$  ( $N = 50$ ) and  $32.2 \text{ kyr}^{-1}$  ( $N = 4$ ), and standard deviations are equal to  $25.1 \text{ kyr}^{-1}$  and  $42.5 \text{ kyr}^{-1}$ , for high and low-quality datasets respectively; the difference in mean values is not statistically significant (two-sample *t*-test of log-transformed values: *T* =  $-1.69$ , *p* = 0.098, d.f. = 52). Corresponding rates normalized by area and river number have mean values of  $0.077 \text{ kyr}^{-1}\text{km}^{-2}$  and  $0.156 \text{ kyr}^{-1}\text{km}^{-2}$ , and standard deviations of  $0.193 \text{ kyr}^{-1}\text{km}^{-2}$  and  $0.311 \text{ kyr}^{-1}\text{km}^{-2}$ , for high and low-quality datasets respectively; the difference in mean values is not statistically significant (two-sample *t*-test of log-transformed values *T* = 0.31, *p* = 0.760, d.f. = 52). Low- and high-quality channel-thread datasets cover on average 2.81 kyr and 3.38 kyr, respectively. Rates based on delta-lobe counts are higher on average for higher-quality datasets, only for rates that are not normalized (Fig. 3e): mean values of these rates are  $7.26 \text{ kyr}^{-1}$  ( $N = 16$ ) and  $4.14 \text{ kyr}^{-1}$  ( $N = 9$ ), and standard deviations are equal to  $17.51 \text{ kyr}^{-1}$  and  $6.68 \text{ kyr}^{-1}$ , for high and low-quality datasets respectively; the difference in mean values is not statistically significant (two-sample *t*-test of log-transformed values: *T* = 1.02, *p* = 0.317, d.f. = 23). Instead, corresponding rates normalized by area and river number (Fig. 3f) have mean values of  $0.017 \text{ kyr}^{-1}\text{km}^{-2}$  and  $0.073 \text{ kyr}^{-1}\text{km}^{-2}$ , and standard deviations of  $0.027 \text{ kyr}^{-1}\text{km}^{-2}$  and  $0.156 \text{ kyr}^{-1}\text{km}^{-2}$ , for high and low-quality datasets respectively; again, means do not differ significantly (two-sample *t*-test of log-transformed values *T* = 0.54, *p* = 0.493, d.f. = 23). Low- and high-quality delta-lobe datasets have average time windows of 4.02 kyr and 3.60 kyr, respectively.

### 3.2. Relationships between avulsion-frequency proxies

Relationships between the three alternative avulsion metrics have been determined to assess the consistency with which they may quantify avulsion frequency and act as proxies for each other. All avulsion metrics are considered as (i) counts per unit time, and as corresponding counts normalized (ii) by area and (iii) by area and number of river systems; hence, nine avulsion metrics are considered overall. The data are presented in Fig. 4, and correlations are reported in Table 2. Positive and statistically significant correlations are seen between any pair of the three metrics having the same form of normalization, or between their log-transformed equivalent (Fig. 4, Table 2). In general, as expected, river systems for which more frequent avulsion events are recorded tend to be associated with larger numbers of delta lobes and channel threads per unit time; the numbers of channel threads and delta lobes per unit time also tend to correlate positively.

### 3.3. Avulsion metrics and spatial scales

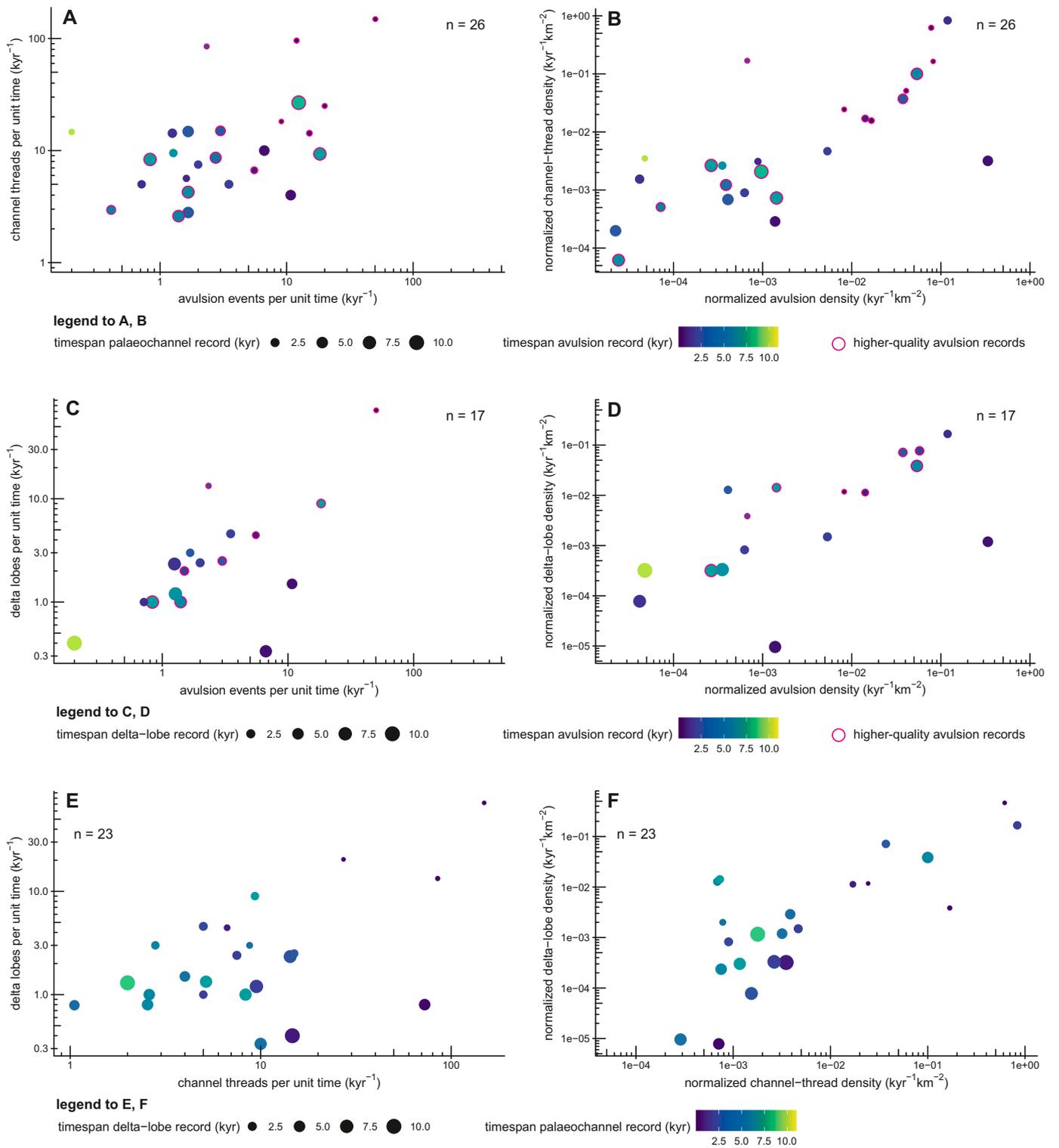
Relationships between the alternative avulsion metrics and the size of the study area over which these metrics have been computed have been determined. This analysis provides an assessment of whether the density of avulsion events in coastal-plain river systems varies as a function of spatial scale, on the assumption that the size of the study area is directly proportional to the size of the drainage network that can experience avulsion events. In turn, the results of this analysis can help establish the way in which these metrics can be applied to compare the avulsion histories of different river systems and to study controls on river avulsion. The data are presented in Fig. 5, and correlations are reported in Table 3. If the spatio-temporal density of avulsion events was independent of river-system size, we would expect some positive correlation between non-normalized avulsion metrics and study-area sizes. On the contrary, however, no significant correlations are seen between study-area size and the numbers per unit time of avulsions, channel threads, or delta lobes, or between their log-transformed equivalents. In view of this, necessarily, negative correlations emerge between the size of the study areas and normalized rates, since these rates are computed



**Fig. 3.** Distributions in avulsion metrics across case studies grouped by data quality, for: number of avulsion events per unit time (A), and corresponding rates normalized by area and river number (B); number of channel threads per unit time (C), and corresponding rates normalized by area and river number (D); number of delta lobes per unit time (E), and corresponding rates normalized by area and river number (F). Spots represent individual examples. Boxplots report interquartile ranges as boxes, mean values as crosses and median values as bars.

with the study-area size as denominator. Negative correlations between log-transformed study-area size and normalized rates are statistically significant. In general, the spatio-temporal densities of avulsion events, channel threads and delta lobes appear to vary with the size of the study

area; conversely, avulsion-frequency proxies do not increase systematically as a function of the size of the area being studied.



**Fig. 4.** Scatterplots showing relationships between alternative avulsion-frequency metrics: number of channel threads per unit time vs number of avulsion events per unit time (A), and corresponding rates normalized by area and river number (B); number of delta lobes per unit time vs number of avulsion events per unit time (C), and corresponding rates normalized by area and river number (D); number of delta lobes per unit time vs number of channel threads per unit time (E), and corresponding rates normalized by area and river number (F). The size and colour of the spots indicate the timescale over which the avulsion metrics shown in ordinate and abscissa, respectively, have been computed. Higher-quality records of numbers of avulsion events are indicated with magenta circles (see Table 1).

**Table 2**

Pearson correlation coefficients (R) and *p*-values quantifying relationships between the alternative avulsion-frequency metrics, based on different types of normalization, and separately presented for the entire dataset and data from higher-quality records (see Table 1). 'A' indicates rates based on number of avulsion events per unit time; 'C' indicates rates based on number of channel threads per unit time; 'L' indicates rates based on number of delta lobes per unit time. Correlations presented in brackets refer to log-transformed variables. 'N' indicates the number of observations.

	Normalization	Higher-quality records only	All dataset
A vs C	none	$R = 0.753, p = 0.002, N = 14$ ( $R = 0.649, p = 0.012$ )	$R = 0.716, p < 0.001, N = 26$ ( $R = 0.505, p = 0.008$ )
	by area	$R = 0.654, p = 0.011, N = 14$ ( $R = 0.803, p = 0.001$ )	$R = 0.312, p = 0.121, N = 26$ ( $R = 0.719, p < 0.001$ )
	by area and river number	$R = 0.626, p = 0.017, N = 14$ ( $R = 0.825, p < 0.001$ )	$R = 0.312, p = 0.121, N = 26$ ( $R = 0.752, p < 0.001$ )
A vs L	none	$R = 0.986, p < 0.001, N = 7$ ( $R = 0.889, p = 0.007$ )	$R = 0.951, p < 0.001, N = 16$ ( $R = 0.727, p = 0.001$ )
	by area	$R = 0.874, p = 0.010, N = 7$ ( $R = 0.949, p = 0.001$ )	$R = 0.966, p < 0.001, N = 16$ ( $R = 0.779, p < 0.001$ )
	by area and river number	$R = 0.874, p = 0.010, N = 7$ ( $R = 0.949, p = 0.001$ )	$R = 0.966, p < 0.001, N = 16$ ( $R = 0.766, p = 0.001$ )
C vs L	none	$R = 0.931, p < 0.001, N = 12$ ( $R = 0.872, p < 0.001$ )	$R = 0.838, p < 0.001, N = 22$ ( $R = 0.542, p = 0.009$ )
	by area	$R = 0.427, p = 0.166, N = 12$ ( $R = 0.810, p = 0.001$ )	$R = 0.797, p < 0.001, N = 22$ ( $R = 0.769, p < 0.001$ )
	by area and river number	$R = 0.266, p = 0.403, N = 12$ ( $R = 0.791, p = 0.002$ )	$R = 0.794, p < 0.001, N = 22$ ( $R = 0.756, p < 0.001$ )

### 3.4. Avulsion metrics and timescales

An assessment is made of relationships that may exist between the alternative avulsion metrics and the length of time over which they have been computed. This provides a quantification of how avulsion-frequency proxies may vary as a function of their associated time window, either because of geological factors whose influence on coastal river avulsion may have changed through the Holocene, or because of the way the data resolution of avulsion histories may decrease going back in time. The outcomes of this analysis can help inform comparisons of avulsion histories of different river systems and assessments of potential controls on river avulsion. The data are presented in Fig. 6, and correlations are reported in Table 4. Negative, moderate to strong correlations are seen between log-transformed values of the different avulsion metrics and the timespan on which they are calculated; these correlations are statistically significant when based on the entire available dataset (Fig. 6, Table 4). In general, data relating to shorter time windows tend to yield larger values in the different proxies for avulsion frequency.

When considering relationships between avulsion-frequency metrics and timescale, in view of the results presented earlier (Fig. 5, Table 3), it is useful to determine the possible covariance of temporal and spatial scales of the considered samples. This may arise, for example, because the full extent of each study area reflects in part the amount of shoreline progradation that took place during the studied avulsion history, which is itself a function of the time window being considered. However, only weak positive correlations are seen between study-area size and the timespan of each avulsion metric (for log-transformed data; avulsion events: Pearson  $R = 0.292, p = 0.176$ ; channel threads:  $R = 0.286, p = 0.03$ ; delta lobes:  $R = 0.262, p = 0.206$ ).

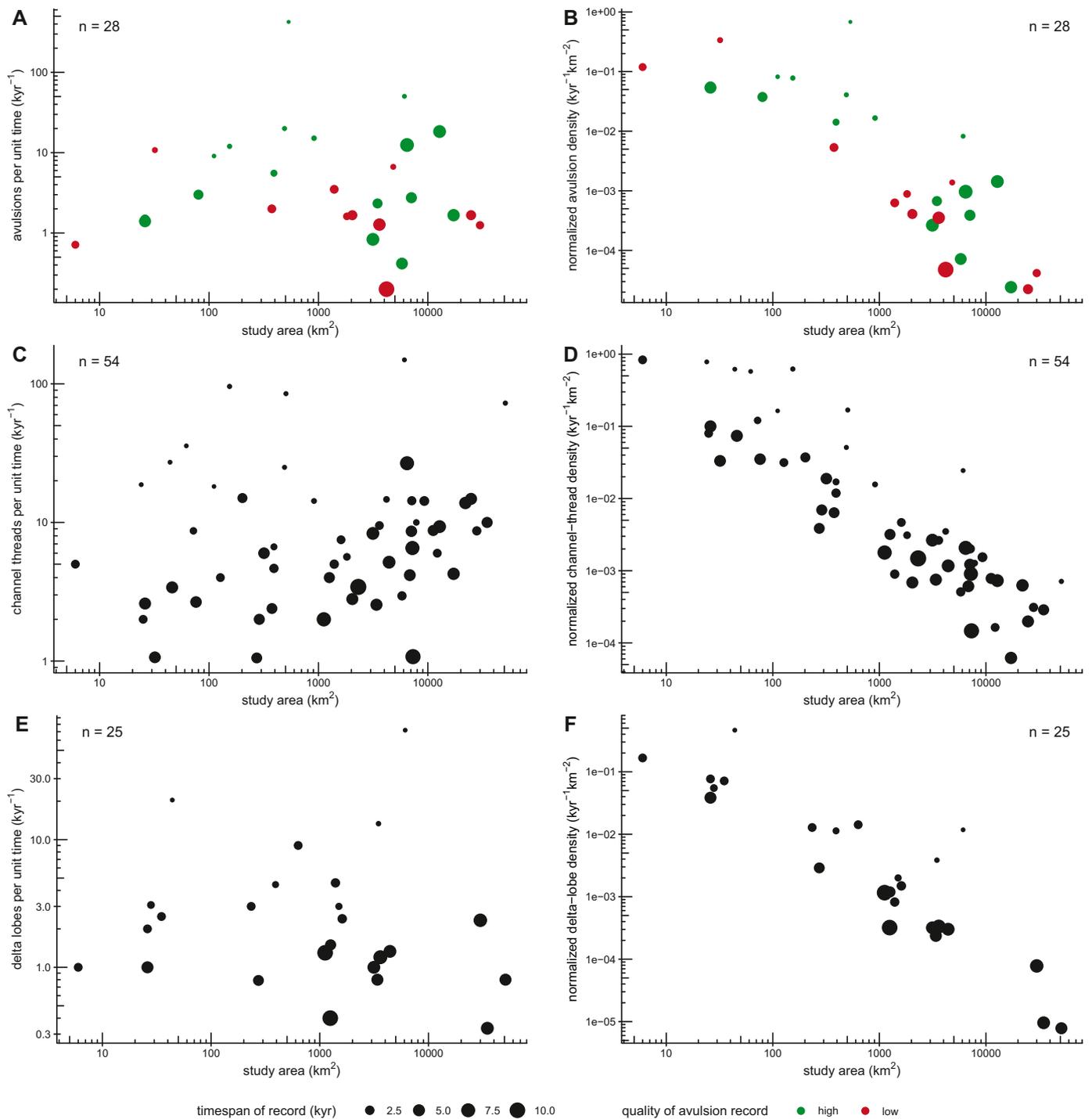
### 3.5. Avulsion metrics and river-system scale

An assessment is made of relationships that may exist between avulsion metrics and the size of the river systems, and which may arise because of natural controls on avulsion frequency that are inherently related to scale. Particular consideration is given to attributes of the river system that are known to scale to its size and to act as potential controls on avulsion dynamics: the longstream gradient, the shoreline progradation rate, and the backwater length. The gradient advantages that drive channel avulsion may be expected to be more readily generated by channel-ridge aggradation on alluvial plains where the longitudinal gradient is lower (Slingerland and Smith, 2004), since a stronger

contrast between cross-stream and longstream gradients is generated for the same amount of aggradation. Where the river mouth progrades more rapidly, a faster lengthening of the longitudinal profile of the river is associated with a more rapid decrease in longstream gradient, and is expected to be paralleled by faster streambed aggradation; this can again favour the superelevation of channels and the generation of gradient advantages (Jones and Schumm, 1999; Swenson, 2005). Also, avulsion nodes may be expected to be preferentially concentrated near the upstream end of the backwater zone (cf. Chatanantavet et al., 2012); hence, spatial non-uniformity in the distribution of avulsion sites over the study area may reflect: (i) the size of the backwater zone relative to that of the study area over which avulsion metrics are evaluated; and (ii) the magnitude in downdip shift in the backwater limit associated with shoreline progradation and coastal-plain aggradation. The following additional variables are considered as measures of river-system size: the drainage-basin area, the mean yearly water discharge, and the suspended-sediment load. The data are presented in Figs. 7–9 and Supplementary Figs. S1 and S2; correlations are reported in Fig. 10.

As a preliminary analysis, relationships between the size of the study areas and the size of the river systems are determined for all three avulsion metrics. Positive correlations are seen between log-transformed values of the size of the study areas and the drainage-basin areas of the corresponding river systems (for avulsion events: Pearson  $R = 0.784, p < 0.001$ ; for channel threads:  $R = 0.805, p < 0.001$ ; for delta lobes:  $R = 0.793, p < 0.001$ ). In the studied deltaic systems, the extension of the study area typically corresponds to the size of the delta; these results therefore reflect the intuition that larger rivers build larger deltas. This must be taken into account in the evaluation of the following results, in light of how avulsion metrics are influenced by the spatial scale over which they are computed (Fig. 5, Table 3).

In the selected case studies, as expected, drainage-basin areas correlate inversely with coastal-plain gradients (for log-transformed values: Pearson  $R = -0.799, p < 0.001$ ) and directly with mean annual discharges (for log-transformed values:  $R = 0.837, p < 0.001$ ). No significant relationship is observed between drainage-basin areas and any of the avulsion-frequency metrics based on counts per unit time; moderate negative correlations are seen between the log-transformed values of catchment areas and those of normalized counts per unit time of avulsions ( $R = -0.522, p < 0.001$ ), channel threads ( $R = -0.658, p < 0.001$ ) and delta lobes ( $R = -0.706, p < 0.001$ ) (Fig. 7, Supplementary Fig. S1). A significant, albeit weak, relationship with mean water discharge is seen for the number of channel threads per unit time (for log-transformed values:  $R = 0.308, p = 0.025$ ); no relationship is



**Fig. 5.** Scatterplots showing relationships between the different avulsion-frequency metrics and the size of the area over which they have been determined, for: number of avulsion events per unit time (A), and corresponding rates normalized by area and river number (B); number of channel threads per unit time (C), and corresponding normalized rates (D); number of delta lobes per unit time (E), and corresponding normalized rates (F). The size of the spots indicates the timescale over which the avulsion metrics have been computed. In A and B, the colour of the spots indicates the quality of the data on number of avulsion events (see Table 1).

seen for corresponding metrics based on avulsion events or delta lobes. Negative relationships are seen between water discharge and normalized metrics based on avulsion events (for log-transformed values:  $R = -0.602$ ,  $p = 0.001$ ), channel threads (for log-transformed values:  $R = -0.613$ ,  $p < 0.001$ ) and delta lobes (for log-transformed values:  $R = -0.769$ ,  $p < 0.001$ ) (Fig. 7, Supplementary Fig. S2). Similarly, a modest but statistically significant negative relationship is seen between the number of channel threads per unit time and the average coastal-plain gradient (for log-transformed values:  $R = -0.341$ ,  $p = 0.012$ ),

whereas no relationship is seen for corresponding rates based on numbers of avulsions or delta lobes (Fig. 7). Positive relationships are seen between the average gradient and normalized metrics based on avulsion events (for log-transformed values:  $R = 0.647$ ,  $p < 0.001$ ), channel threads (for log-transformed values:  $R = 0.532$ ,  $p < 0.001$ ) and delta lobes (for log-transformed values:  $R = 0.598$ ,  $p < 0.001$ ) (Fig. 7).

In the chosen case studies, shoreline progradation rates have been evaluated over different timescales, covering three orders of magnitude. Therefore, these rates may plausibly be affected by the Sadler effect, i.e.,

**Table 3**

Pearson correlation coefficients (R) and *p*-values quantifying relationships between avulsion-frequency metrics and the size of the area over which they have been determined, based on different types of normalization, and separately presented for the entire dataset and data from higher-quality records (see Table 1). 'A' indicates rates based on number of avulsion events per unit time; 'C' indicates rates based on number of channel threads per unit time; 'L' indicates rates based on number of delta lobes per unit time. Correlations presented in brackets refer to log-transformed variables. 'N' indicates the number of observations.

	Normalization	Higher-quality records only	All dataset
A vs area	None	$R = -0.158, p = 0.546, N = 17$ ( $R = 0.020, p = 0.941$ )	$R = -0.120, p = 0.543, N = 28$ ( $R = -0.062, p = 0.756$ )
	by area	$R = -0.277, p = 0.283, N = 17$ ( $R = -0.785, p < 0.001$ )	$R = -0.246, p = 0.207, N = 28$ ( $R = -0.837, p < 0.001$ )
	by area and river number	$R = -0.277, p = 0.282, N = 17$ ( $R = -0.792, p < 0.001$ )	$R = -0.246, p = 0.207, N = 28$ ( $R = -0.839, p < 0.001$ )
C vs area	none	$R = 0.222, p = 0.122, N = 50$ ( $R = 0.203, p = 0.157$ )	$R = 0.158, p = 0.254, N = 54$ ( $R = 0.168, p = 0.224$ )
	by area	$R = -0.228, p = 0.112, N = 50$ ( $R = -0.888, p < 0.001$ )	$R = -0.248, p = 0.071, N = 54$ ( $R = -0.886, p < 0.001$ )
	by area and river number	$R = -0.226, p = 0.115, N = 50$ ( $R = -0.887, p < 0.001$ )	$R = -0.246, p = 0.073, N = 54$ ( $R = -0.887, p < 0.001$ )
L vs area	none	$R = 0.090, p = 0.740, N = 16$ ( $R = 0.264, p = 0.323$ )	$R = -0.060, p = 0.775, N = 25$ ( $R = -0.102, p = 0.626$ )
	by area	$R = -0.287, p = 0.281, N = 16$ ( $R = -0.870, p < 0.001$ )	$R = -0.194, p = 0.354, N = 25$ ( $R = -0.902, p < 0.001$ )
	by area and river number	$R = -0.298, p = 0.262, N = 16$ ( $R = -0.864, p < 0.001$ )	$R = -0.184, p = 0.378, N = 25$ ( $R = -0.901, p < 0.001$ )

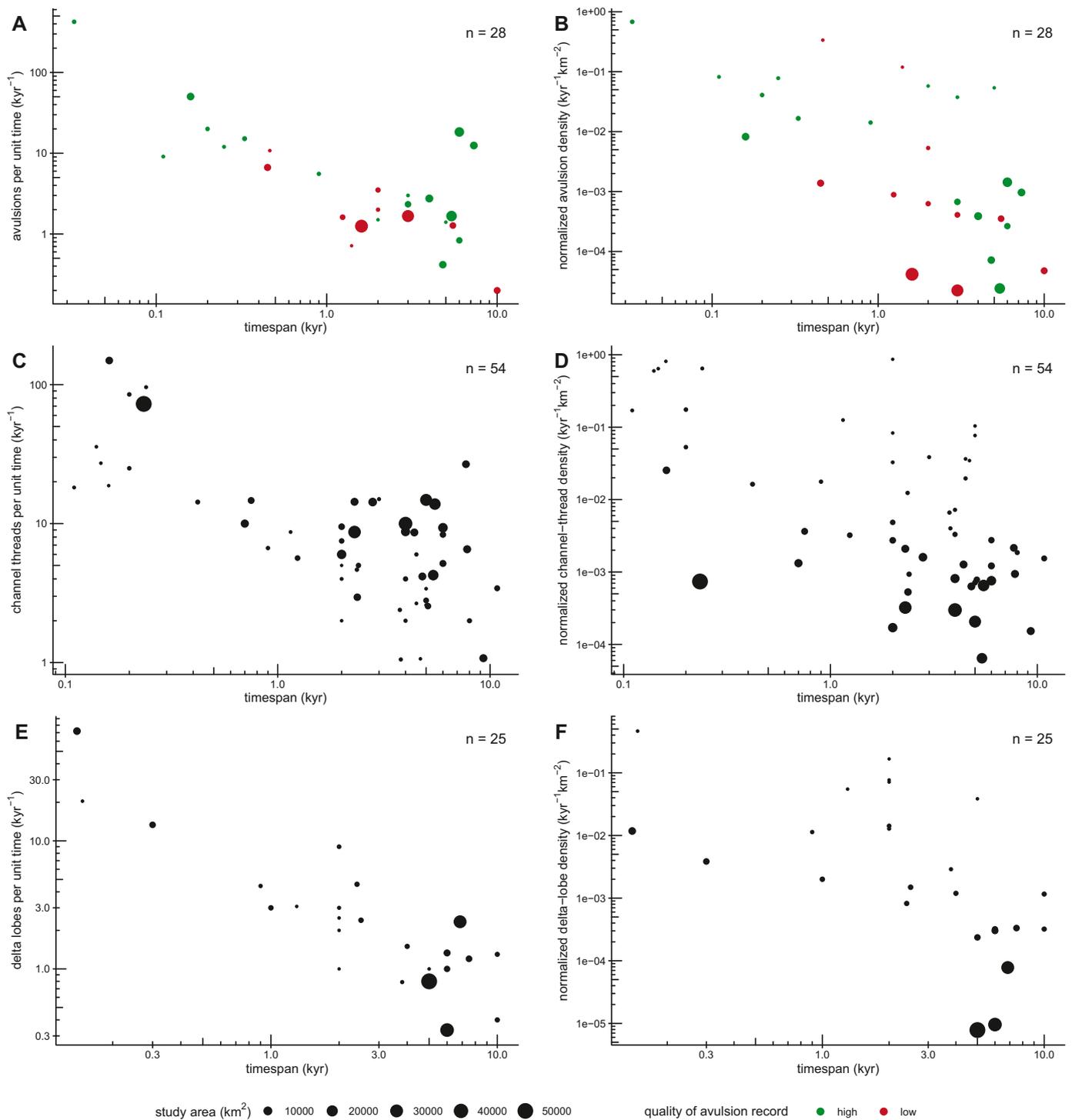
by timescale dependency due to the fact that local shoreline accretion is unsteady and the average length of interruptions in sedimentation may increase with the length of time being considered (Sadler, 1981; Sadler and Jerolmack, 2015). Indeed, log-transformed values of progradation rates and the times over which they have been evaluated demonstrate some negative correlation (Pearson  $R = -0.607; p < 0.001$ ). Nevertheless, progradation rates are still more strongly correlated to the rates of sediment supply, through a positive relationship between log-transformed values of progradation rates and total suspended solids in the studied rivers ( $R = 0.675; p < 0.001$ ). In addition, positive relationships are seen between log-transformed values of progradation rates and both catchment size ( $R = 0.577; p < 0.001$ ) and mean annual discharge ( $R = 0.583; p < 0.001$ ). With regard to the avulsion metrics, statistically significant positive correlations are seen between progradation rates and the counts per unit time of both channel threads (for log-transformed values:  $R = 0.760; p < 0.001$ ) and delta lobes (for log-transformed values:  $R = 0.526; p = 0.017$ ); correlation with the number of avulsion events per unit time is also positive, but modest and not significant (for log-transformed values:  $R = 0.303; p = 0.271$ ) (Fig. 8). In spite of positive scaling between progradation rates and study-area sizes (for log-transformed values:  $R = 0.477; p = 0.004; N = 35$ ), no relationships are seen between progradation rates and normalized avulsion metrics (Fig. 8).

Positive correlations are seen between log-transformed values of backwater length and those of both mean annual discharge (Pearson  $R = 0.928, p < 0.001$ ) and catchment area ( $R = 0.883, p < 0.001$ ). These relationships are expected, given how the size of a river's backwater zone is scaled to the size of the river system (cf. Blum et al., 2013): estimations of backwater length used in these analyses are based on ratios between estimated mean bankfull depths and average coastal-plain gradients, and may carry significant error (see Section 2.3).

The dip extent of the backwater zone of each river system ( $L_b$ ) is considered relative to the dip length of the study area ( $l$ ) and the estimated amount of coastal-plain progradation that occurred during the timespan of interest (here termed 'progradation distance';  $D$ ). By assuming, simplistically, that the progradation rate was constant throughout the duration of the characterized avulsion history, the progradation distance is approximated as the product of said rate and the timespan over which each avulsion metric is estimated. Using these quantities, observations are divided into three groups based on (i) whether the dip length of the study area is larger than the backwater length ( $l > L_b$ ), and (ii) on whether the sum of the backwater length and the progradation distance over the timescale of the avulsion metric in

question is larger than the downdip extent of the study area ( $[D + L_b] > l$ ). This grouping is undertaken to attempt discrimination of examples that can be inferred to embody one of the following situations: (i) a backwater limit permanently within the study area ( $[D + L_b] < l$ ); (ii) a backwater limit transitioning from outside to inside the study area ( $[D + L_b] > l$  and  $L_b < l$ ); or (iii) a backwater limit permanently outside of the study area ( $L_b > l$ ). Given the difficulty in constraining values of progradation distance, the dataset associated with each of these groups is, in some cases, very limited in size. Nevertheless, an assessment of differences in the alternative avulsion metrics across the three groups is attempted. Results indicate that values of mean and standard deviation of the avulsion metrics do not vary systematically across the three groups for the three proxies (Table 5). Avulsion-frequency metrics based on numbers of avulsion events are highest on average for examples for which the backwater limit is inferred to have been located outside the study area, and smallest for examples for which the limit is inferred to have been always inside. Metrics based on numbers of channel threads are on average highest for case studies for which the backwater limit is inferred to have transitioned from outside to inside the study area, and smallest for those for which the limit is inferred to have been permanently inside. Metrics based on the number of delta lobes are on average highest for examples for which the backwater limit is inferred to have transitioned inside the study area, and smallest for examples for which the limit is inferred to have been permanently outside. Thus, differences in these metrics are not manifested consistently among the three groups. Furthermore, when tested by means of Welch's one-way ANOVA, the means of the considered avulsion metrics do not differ in a statistically significant manner across the three case-study groups for any of the three avulsion metrics; this may however reflect the small sample sizes (Table 5).

Bivariate analyses indicate that no significant correlations are seen between the estimated backwater length and proxies for avulsion frequency based on the number of avulsion events per unit time (for log-transformed values: Pearson  $R = -0.212, p = 0.332$ ), the number of channel threads per unit time (for log-transformed values:  $R = 0.214, p = 0.145$ ), or the number of delta lobes per unit time (for log-transformed values:  $R = -0.093, p = 0.689$ ) (Fig. 9). As expected, given these results, backwater lengths yield modest to moderate negative correlations with normalized rates based on avulsion events (for log-transformed values:  $R = -0.506, p = 0.014$ ), channel threads (for log-transformed values:  $R = -0.283, p = 0.051$ ), and delta lobes (for log-transformed values:  $R = -0.500, p = 0.021$ ) (Fig. 9); these relationships likely reflect covariance between river-system size, study-area size, and backwater length



**Fig. 6.** Scatterplots showing relationships between the different avulsion-frequency metrics and the length of time over which they have been determined, for: number of avulsion events per unit time (A), and corresponding rates normalized by area and river number (B); number of channel threads per unit time (C), and corresponding normalized rates (D); number of delta lobes per unit time (E), and corresponding normalized rates (F). The size of the spots indicates the size of the study area over which the avulsion metrics have been computed. In A and B, the colour of the spots indicates the quality of the data on number of avulsion events (see Table 1).

(Fig. 10).

Overall, factors that quantify the size of the river systems tend to exhibit monotonic relationships with normalized proxies for avulsion frequency, due to covariance between these factors and the size of deltas and of the relative study areas on which normalizations are made; these relationships are expressed consistently across the alternative normalized avulsion proxies (Fig. 10). A notable exception to this is observed in

the lack of consistently negative correlations between normalized avulsion metrics and progradation rates, in spite of progradation rates being scaled to the rate of sediment delivery and to catchment size; this reflects the positive correlations between progradation rates and avulsion-frequency metrics that are not normalized by study-area size (Fig. 10).

**Table 4**

Pearson correlation coefficients (R) and *p*-values quantifying relationships between avulsion-frequency metrics and the length of time over which they have been determined, based on different types of normalization, and separately presented for the entire dataset and data from higher-quality records (see Table 1). 'A' indicates rates based on number of avulsion events per unit time; 'C' indicates rates based on number of channel threads per unit time; 'L' indicates rates based on number of delta lobes per unit time. Correlations presented in brackets refer to log-transformed variables. 'N' indicates the number of observations.

	Normalization	Higher-quality records only	All dataset
A vs time	none	$R = -0.331, p = 0.194, N = 17$ ( $R = -0.762, p < 0.001$ )	$R = -0.251, p = 0.198, N = 28$ ( $R = -0.761, p < 0.001$ )
	by area	$R = -0.374, p = 0.139, N = 17$ ( $R = -0.720, p < 0.001$ )	$R = -0.349, p = 0.069, N = 28$ ( $R = -0.668, p < 0.001$ )
	by area and river number	$R = -0.375, p = 0.138, N = 17$ ( $R = -0.719, p < 0.001$ )	$R = -0.349, p = 0.069, N = 28$ ( $R = -0.669, p < 0.001$ )
C vs time	none	$R = -0.400, p = 0.004, N = 50$ ( $R = -0.712, p < 0.001$ )	$R = -0.424, p = 0.001, N = 54$ ( $R = -0.710, p < 0.001$ )
	by area	$R = -0.364, p = 0.009, N = 50$ ( $R = -0.577, p < 0.001$ )	$R = -0.394, p = 0.003, N = 54$ ( $R = -0.609, p < 0.001$ )
	by area and river number	$R = -0.363, p = 0.010, N = 50$ ( $R = 0.565, p < 0.001$ )	$R = -0.393, p = 0.003, N = 54$ ( $R = -0.598, p < 0.001$ )
L vs time	none	$R = -0.398, p = 0.127, N = 16$ ( $R = 0.900, p < 0.001$ )	$R = -0.416, p = 0.039, N = 25$ ( $R = -0.880, p < 0.001$ )
	by area	$R = -0.342, p = 0.194, N = 16$ ( $R = -0.469, p = 0.067$ )	$R = -0.382, p = 0.060, N = 25$ ( $R = -0.606, p = 0.001$ )
	by area and river number	$R = -0.328, p = 0.215, N = 16$ ( $R = -0.469, p = 0.067$ )	$R = -0.365, p = 0.073, N = 25$ ( $R = -0.601, p = 0.001$ )

## 4. Discussion

Here we discuss the significance of the findings presented above by considering how quantifications of river avulsions are affected by the temporal and spatial scales at which they are determined. We then draw practical implications that may be of use to future studies on river avulsion frequency. Before doing this, we must stress that all observed relationships between the studied avulsion metrics and measures of scale exhibit important scatter: this is expected, since the frequency of channel avulsion is controlled by factors whose importance is not systematically dependent on spatial or temporal scales, such as tectonics (e.g., Reitz et al., 2015), presence of compactable peat substrates (van Asselen et al., 2009), and wave- or tide-driven channel stabilization (cf. Swenson, 2005; Rossi et al., 2016), for example.

### 4.1. Avulsion frequency and temporal scales

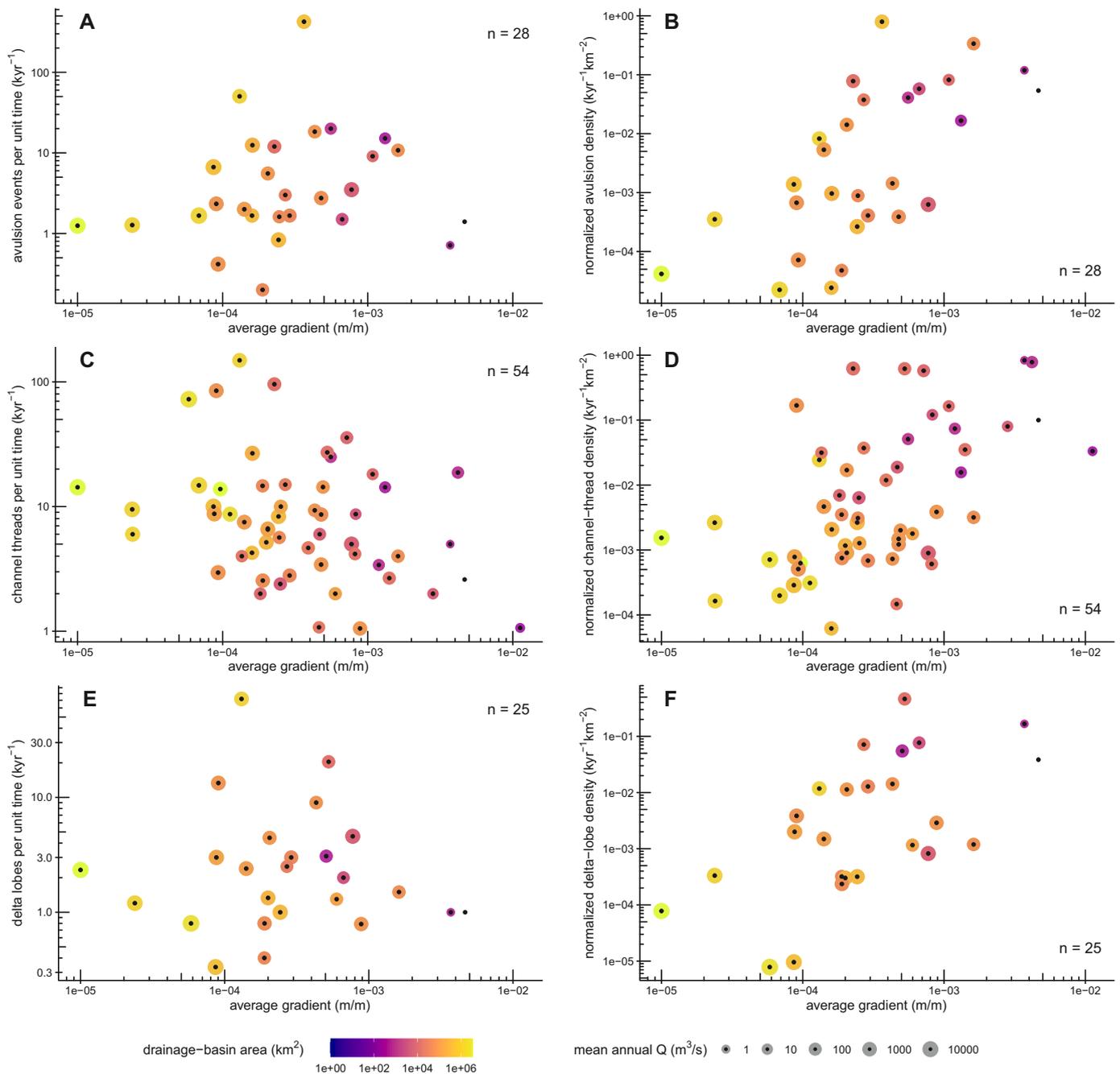
Relationships between measures quantifying the frequency of river avulsion and the length of time over which those frequencies are extracted (Fig. 6, Table 4) can be explained by both methodological and geological reasons. A methodological explanation lies in the decreasing resolution of historical, sedimentary and geomorphic records with the age of the events, forms or deposits that they document, due to variations in preservation and data granularity. Alternatively, the same trends may be the result of temporal variations in environmental controls through the Holocene. Since the time windows of almost all datasets are anchored to the present day, apparent trends with time scale may actually represent a record of trends in avulsion dynamics through time. These trends could themselves be linked to temporal changes in sediment supply, water discharge, base level, or marine process regime, through their influences on coastal-plain aggradation, shoreline progradation and river hydrodynamics.

Among these factors, the rate of base-level change is perhaps the one that is invoked most commonly as a control on river avulsion, but the way in which relative sea-level changes affect avulsion dynamics is not fully understood. The prevalent view is that the rate of relative sea-level rise may control avulsion frequency by enhancing streambed aggradation, causing the avulsion period to decrease for faster rates of rise (cf. Jerolmack, 2009; Chadwick et al., 2020). Temporal trends in channel-belt avulsion frequency of the Rhine-Meuse delta, for example, have been linked to variations in the rate of sea-level rise accordingly (Stouthamer and Berendsen, 2007; Stouthamer et al., 2011). The negative trends between avulsion-frequency proxies and time length

observed across the considered marginal-marine examples cannot however be explained in terms of a direct relationship between rates of eustatic change and avulsion frequency, given the progressive slowdown in the rate of eustatic sea-level rise through the Holocene (Fleming et al., 1998; Smith et al., 2011; Mörner, 2013; Lambeck et al., 2014). It is nonetheless recognized that avulsions may even become more frequent during slower rates of rise in base level, and that channel super-elevation may even be facilitated by relative sea-level falls in some cases (cf. Nijhuis et al., 2015; Lane et al., 2017). The alternative view that an inverse relationship between avulsion frequency and rates of sea-level rise may emerge is corroborated by results of numerical models, demonstrating how in effect sea-level rise may result in distributed and locally reduced channel aggradation, which can hinder the development of avulsion set-up conditions (Moran et al., 2017). Hence, the possibility that the results of our analyses reflect a global record of variations in rates of eustatic change through the Holocene cannot be discounted.

It is also recognized that avulsion frequency should scale with the rates of shoreline progradation, in light of the control operated by river-mouth lengthening and the associated shift in the river longitudinal profile on streambed aggradation and gradient reduction; this can cause channel super-elevation and the generation of cross-floodplain gradient advantages (Jones and Schumm, 1999; Swenson, 2005; Ratliff et al., 2018). Moreover, channel-mouth progradation can be intimately associated with mouth-bar deposition, which can drive channel aggradation through a morphodynamic backwater effect (Hoyal and Sheets, 2009). However, a tendency of globally increasing shoreline progradation rates through the Holocene, which would explain the results, is at odd with the notion that several of the studied examples have experienced a progressive reduction in sediment supply since the early Holocene (cf. Goodbred Jr and Kuehl, 2000), and with the expected role of autogenic deceleration in progradation during delta growth (Muto and Steel, 1992). The examples used in this study for which time-lapse palaeo-shoreline reconstructions are available show that – when averaged over the timescales of interest – the rates of progradation typically varied to a limited degree and not systematically, demonstrating a progressive deceleration in shoreline progradation through the considered time-spans (e.g., Correggiari et al., 2005b; Fanget et al., 2014; Nooren et al., 2017; Pennington et al., 2017; Zheng et al., 2017; Chen et al., 2020; Nageswara Rao et al., 2020) or only modest acceleration (e.g., Nageswara Rao et al., 2015). It seems therefore unlikely that the observed timescale dependency of avulsion-frequency metrics could reflect temporal variations in progradation rates.

Other natural controls may be at play, such as climate-related factors

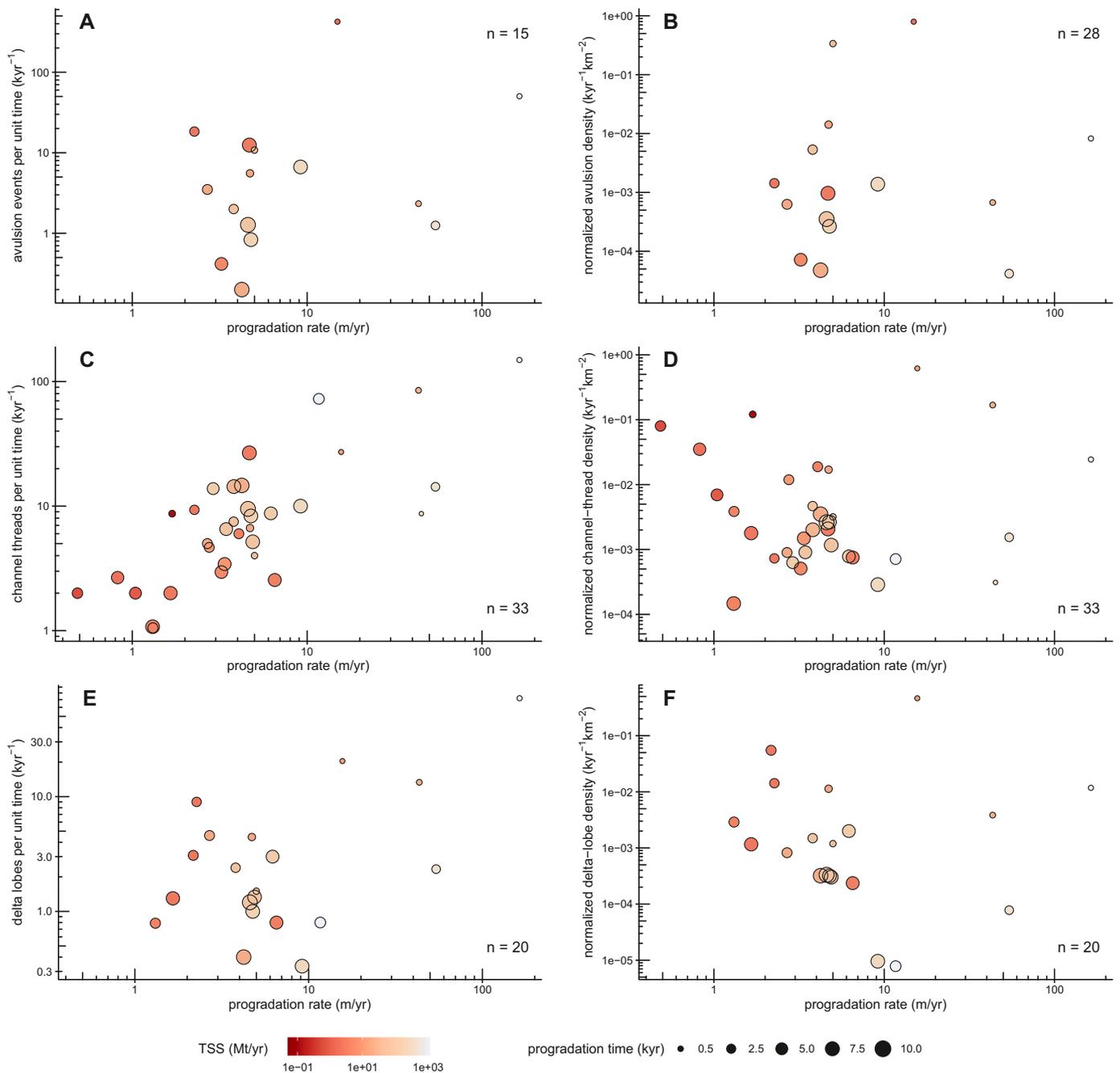


**Fig. 7.** Scatterplots showing relationships between the different avulsion-frequency metrics and the average gradient of the river system over the study area, for: number of avulsion events per unit time (A), and corresponding rates normalized by area and river number (B); number of channel threads per unit time (C), and corresponding normalized rates (D); number of delta lobes per unit time (E), and corresponding normalized rates (F). The size of the spots indicates the mean annual discharge, whereas their colour indicates the drainage-basin area; these two variables are plotted against avulsion-frequency metrics in [Supplementary Figs. S1 and S2](#).

affecting rates of sediment delivery and stream power, which themselves control river mobility. Although it is likely that significant spatial variability in the influence of these factors should mask any global Holocene trend, an assessment of their importance requires separate analyses of their relationships with avulsion-frequency metrics, to be undertaken on examples for which these variables can be constrained.

Anthropogenic factors may also provide a partial explanation of the results. However, a timescale dependency of avulsion frequency is unlikely to be a result of unrecognized human modifications to river drainage networks. Known artificial channel diversions are excluded from our quantifications, and the number of undocumented channel

relocations – which may have been mistreated as avulsions in this study – is expected to increase for more ancient times, which are more likely to lack historical records. It is possible that human engineering of drainage networks could cause water and sediment rerouting in a manner that would affect the avulsion potential of upstream or downstream reaches, but the way in which this could determine temporal trends observed globally cannot be foreseen. Human controls on sediment delivery and water discharge, meanwhile, are known to have varied geographically and through time in both magnitude and direction ([Shi et al., 2002](#); [Oldfield and Dearing, 2003](#); [Erkens et al., 2006](#); [Syvitski and Kettner, 2011](#); [Walling, 2011](#)). An assessment of the possible role of



**Fig. 8.** Scatterplots showing relationships between the different avulsion-frequency metrics and the average shoreline progradation rate of the studied coastal plain, for: number of avulsion events per unit time (A), and corresponding rates normalized by area and river number (B); number of channel threads per unit time (C), and corresponding normalized rates (D); number of delta lobes per unit time (E), and corresponding normalized rates (F). The size of the spots indicates the length of time over which the progradation rates have been determined, whereas their colour indicates the total suspended solids (TSS) of the river.

anthropogenic influences on the observed trend requires further analysis, which will rely crucially on the ability to constrain variables describing human pressures on the fluvial systems.

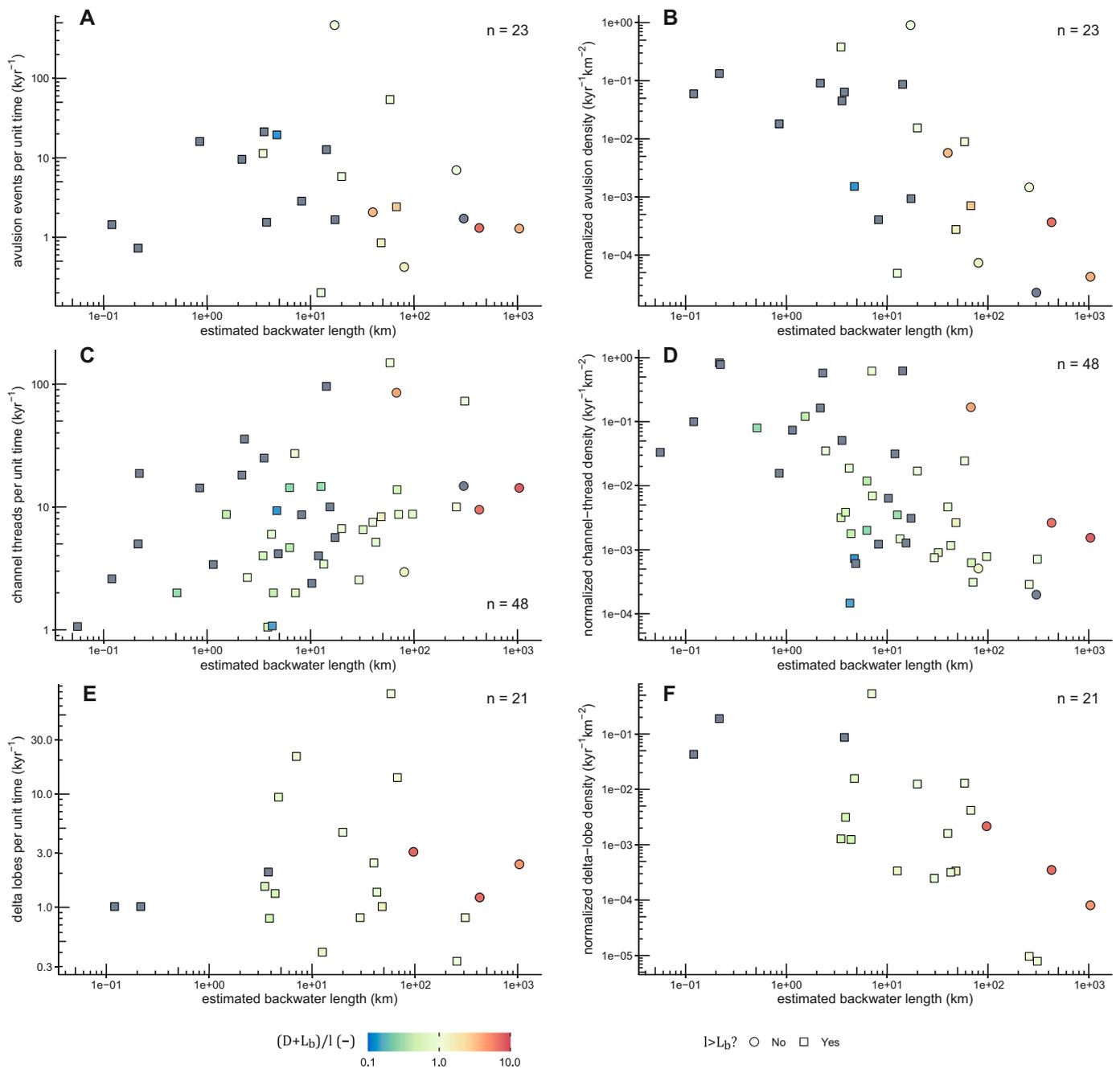
The lack of definitive evidence in support of controls by eustatic sea-level rise, shoreline progradation or human intervention may favour a methodological reason, but a conclusive explanation of the dependency of avulsion-frequency metrics on the time over which they are computed is elusive. To elucidate possible factors affecting the temporal variability in avulsion-frequency metrics, more analysis is needed on datasets including the timing of events, palaeochannel activation, and delta-lobe inception: due to paucity of chronometric constraints, this is in most cases not achievable for the chosen datasets, some of which do not even

afford the establishment of a complete relative chronology.

#### 4.2. Avulsion frequency and spatial scales

Unlike with temporal scales, clear trends between study-area size and avulsion metrics based on simple counts of events, channel threads or delta lobes per unit time do not emerge. There are alternative explanations of the fact that non-normalized avulsion-frequency metrics do not vary with spatial scale, and, implicitly, of the fact that inverse correlations between study-area size and normalized proxies are seen.

These observations may arise from variability in data quality, whereby smaller-scale studies may afford higher resolution in the

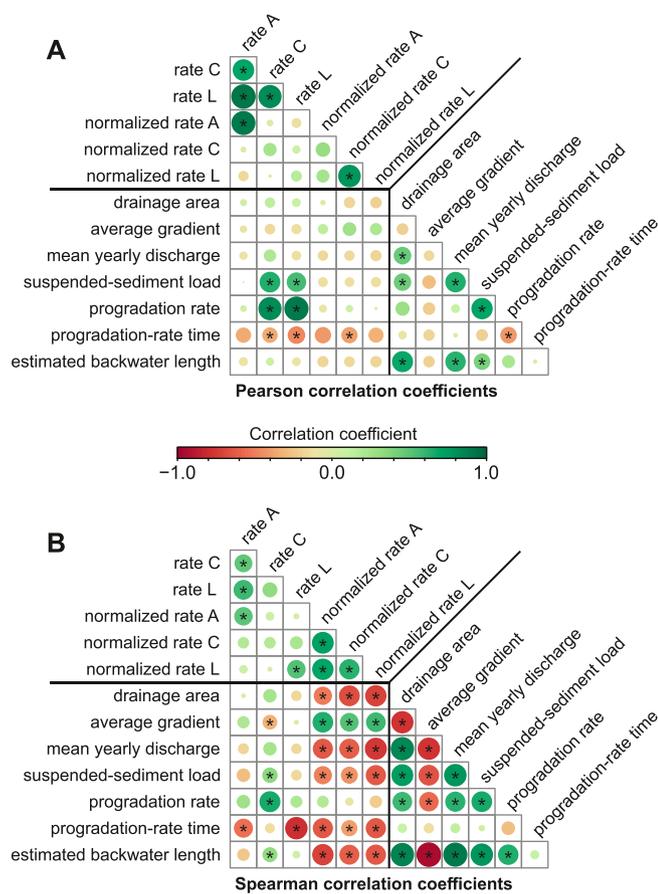


**Fig. 9.** Scatterplots showing relationships between the different avulsion-frequency metrics and the estimated backwater length of the river systems, for: number of avulsion events per unit time (A), and corresponding rates normalized by area and river number (B); number of channel threads per unit time (C), and corresponding normalized rates (D); number of delta lobes per unit time (E), and corresponding normalized rates (F). The shape of the spots indicates whether the downdip extent of the study area ( $l$ ) is larger than the backwater length ( $L_b$ ), whereas their colour reflects a factor equal to the sum of progradation distance (over the timescale of the avulsion metric in question; D) and backwater length divided by the downdip extent of the study area. This ratio is used to discriminate examples that can be inferred to have had (i) a backwater limit permanently within the study area (ratio  $> 1$ ), (ii) a backwater limit transitioning inside the study area (ratio  $< 1$  and  $l > L_b$ ) and (iii) a backwater limit permanently outside of the study area (ratio  $< 1$  and  $l < L_b$ ). Grey symbols indicate examples for which a progradation distance could not be estimated.

definition of avulsion events and drainage networks. We can expect, for example, that a palaeochannel of a certain size that may be mapped on a small fan delta could go unrecognized if occurring on the delta of a large continental-scale river. Nevertheless, based on our classification of datasets on their expected completeness of record, which flags low-quality datasets known as yielding underestimations of avulsion rates, it appears that inherent data variability may not be a major factor in this case. Differences in avulsion-frequency metrics between examples that

are classified as lower versus higher quality are limited in magnitude and not consistent across all proxies (Fig. 3).

It can alternatively be hypothesized that the inverse proportionality between normalized avulsion rates and study-area size reflects possible correlation between study-area size and the timespan of record (e.g., because longer avulsion histories may be associated with more extensive coastal-plain progradation, resulting in larger coastal-plain areas of interest); yet, no significant relationship is seen between these two



**Fig. 10.** Heatmaps of correlation matrices quantifying correlation between avulsion-frequency metrics and characteristics of the river systems, by means of Pearson (A) and Spearman (B) correlation coefficients; asterisks denote significant correlations ( $p < 0.05$ ). A: avulsion events per unit time; C: channel threads per unit time; L: delta lobes per unit time. Normalized rates are based on normalization by area and river number.

variables.

In view of this, the lack of relationships between the size of the study areas and the magnitude of the avulsion proxies (and, implicitly, the inverse relations between study-area sizes and normalized avulsion proxies) may indicate that smaller coastal river systems tend to record more frequent avulsions relative to the size of their drainage network. One of the objectives of this work was to determine whether the avulsion frequency of a channel network scales with its extent or with quantities that describe river system size, in relation to potential geological controls on river morphodynamics that are known to vary with scale (cf. Powell et al., 2012; Moran et al., 2017). This does not seem to be the

case, overall, if avulsion-frequency proxies that are not normalized are considered. Avulsion metrics based on numbers of events, channel threads or delta lobes do not correlate with explicit measures of river-system size, such as drainage area or mean annual discharge. Correspondingly, normalized avulsion-frequency metrics exhibit negative correlations with the same descriptors of fluvial-system scale, which reflect how the size of the study areas (by which the metrics are normalized) is an indirect measure of the size of the river system.

It is possible that this is observed because of spatial non-stationarity in river avulsions on coastal plains, and this is an explanation that aligns with current understanding of the roles of certain geological controls and autogenic dynamics in determining how avulsions operate through lowland channel networks. In particular, avulsions are commonly clustered around avulsion nodes, which may be preferentially located in the proximity of delta apices, because of controls by backwater effects or basin and floodplain topography (Chatanantavet et al., 2012; Hartley et al., 2017; Ratliff et al., 2021). Conversely, channel avulsions may be relatively less common along more distal reaches subject to streambed erosion due to water-surface drawdown hydrodynamics, operating over areas that are also proportional to river-system size (Chatanantavet et al., 2012; Lamb et al., 2012). If most study areas include persistent nodes where avulsions preferentially occur, like those observed at delta apices, and if the number of nodes in a delta and the associated tempo of nodal avulsion are independent of the size of the river system (with which study areas tend to be scaled), considering a study area that extends further downstream of those nodes may result in a variation in counted features (events, channel threads, delta lobes) that is not proportional to the increase in area. It is recognized for example that the size of delta lobes tends to be scaled to the backwater length (Ganti et al., 2016a; Moodie et al., 2019), and hence to river-system size and to the size of the delta itself; this notion is consistent with the presented quantifications of delta-lobe switching frequency. In relation to the supposed importance of backwater hydrodynamics as a cause for non-stationarity in the location of avulsion occurrence, it is also useful to consider the coverage of the study areas relative to the backwater lengths of their associated rivers. In this work, the spatial variability in avulsion frequency that may be linked to backwater processes is only considered by means of some crude analysis, by considering the size and amount of shift of the backwater zone relative to the size of the study area, as a way to determine whether avulsion-frequency metrics may differ within backwater reaches characterized by non-uniform river flow. Results of this analysis indicate that avulsion rates associated with examples inferred to have had a backwater limit permanently outside of the study area are not systematically lower, which would instead be expected if avulsions were less likely in the downstream portion of the backwater zone (Chatanantavet et al., 2012). It must be recognized, however, that the location at which avulsion nodes may preferentially develop along backwater reaches is not well understood. Current research suggests that this location may not coincide with the upstream portion of the backwater zone, and that it may be determined in part by other factors, such as discharge variability and progradation history

**Table 5**

Variations in mean and standard deviations of avulsion metrics across groups of case studies defined on the basis of the relative extent of backwater length, progradation distance and study-area dip length; statistical significance in the difference between mean values across the three groups is determined by means of Welch's one-way ANOVA applied to log-transformed quantities. L: study-area dip length; L<sub>b</sub>: backwater length; D: progradation distance; SD: standard deviation; A: avulsion events per unit time; C: channel threads per unit time; L: delta lobes per unit time. Normalized rates are based on normalization by area and river number.

	(D + L <sub>b</sub> ) < 1			(D + L <sub>b</sub> ) > 1, L <sub>b</sub> < 1			L <sub>b</sub> > 1			ANOVA
	mean	SD	N	mean	SD	N	mean	SD	N	
Rate A (kyr <sup>-1</sup> )	9.3	9.1	2	14.0	20.7	5	72.6	172.3	6	F[2, 2.63] = 0.10, p = 0.905
Normalized rate A (kyr <sup>-1</sup> km <sup>-2</sup> )	0.74 × 10 <sup>-3</sup>	0.98 × 10 <sup>-3</sup>	2	0.072	0.066	5	0.13	0.32	6	F[2, 3.56] = 0.93, p = 0.473
Rate C (kyr <sup>-1</sup> )	9.2	15.2	21	34.8	56.5	6	27.9	38.3	4	F[2, 6.20] = 2.49, p = 0.160
Normalized rate C (kyr <sup>-1</sup> km <sup>-2</sup> )	0.014	0.031	21	0.111	0.249	6	0.043	0.083	4	F[2, 6.01] = 0.63, p = 0.566
Rate L (kyr <sup>-1</sup> )	2.45	3.22	6	12.78	23.26	9	2.18	0.91	3	F[2, 9.40] = 0.41, p = 0.673
Normalized rate L (kyr <sup>-1</sup> km <sup>-2</sup> )	0.33 × 10 <sup>-2</sup>	0.54 × 10 <sup>-2</sup>	6	0.055	0.153	9	0.80 × 10 <sup>-3</sup>	0.10 × 10 <sup>-2</sup>	3	F[2, 6.65] = 0.55, p = 0.600

(Ganti et al., 2016a, 2016b; Moodie et al., 2019; Brooke et al., 2020; Chadwick et al., 2020). To elucidate how backwater processes may have controlled the avulsion histories of Holocene deltas, additional analysis is needed; this would need to leverage on chronometric constraints for both avulsion sites and palaeoshorelines to allow the determination of avulsion lengths (sensu Ganti et al., 2016b).

The absence of correlation between study-area size and avulsion-frequency metrics may alternatively reflect the fact that smaller rivers are inherently more avulsive – in proportion to the extent of their drainage networks – because of the role of external factors that vary with scale. This idea might clash with current understanding of certain controls on avulsion set-up conditions, notably with the fact that smaller river systems tend to be characterized by steeper streamwise gradients, or by slower river-mouth progradation (Aadland and Helland-Hansen, 2019). Yet, the importance of certain upstream or intrabasinal controls on avulsion triggers and/or preconditions may vary systematically with the scale of the river system. It is possible, for example, that smaller deltas experience floods that are relatively more conducive to channel avulsion, or exhibit substrate characteristics or dominant morphodynamic behaviours that make their channels more susceptible to diversion. It is known for example that rivers with catchments that are on average smaller tend to be characterized by higher variability in daily water discharge within a year, by higher sediment delivery rates in proportion to their discharge, and by suspended-sediment flux concentrated over comparatively shorter durations (Walling, 1983; Meybeck et al., 2003; Hansford et al., 2020). Some of the studied fan deltas with small, high-relief catchments may have been subject to avulsions driven by channel chocking caused by mass flows (cf. Karymbalis et al., 2010). By contrast, the largest, suspended-load-dominated river systems may be characterized by increased fractions of cohesive sediment in levees and overbank areas, which can stabilize channels and inhibit river avulsion (cf. Edmonds and Slingerland, 2010; Caldwell and Edmonds, 2014). Additionally, in the chosen dataset, several of the smaller river systems tend to be associated with catchments and basins located in tectonically active areas (e.g., river systems of Greece, Taiwan, Philippines), where the influence of seismic triggers to avulsion (e.g., local surface deformation, levee liquefaction, groundwater expulsion; cf. Quigley and Duffy, 2020) can be expected to be higher. To establish whether our observations are determined by any of these potential controls, further analyses need to be undertaken in which these factors are expressly considered.

On account of the lack of correlation between study-area size and ‘pure’ avulsion frequency metrics, and given the relationships between progradation rates, sediment-supply rates, and river-system size, the observed correlations between progradation rates and avulsion-frequency estimations based on channel-thread or delta-lobe counts may be interpreted to support the view that an increase in avulsion frequency may result from faster shoreline progradation (Jones and Schumm, 1999; Swenson, 2005). More rapid progradation does not correspond to higher spatio-temporal density of avulsion events, but this does not necessarily challenge this interpretation, since the size of a study area reflects the scale of the river system, with which avulsion-density metrics correlate negatively overall. Also, any relationships between avulsion metrics and progradation rates may be obfuscated by how some of the studied systems may have undergone progradation under partially forced regressive conditions (e.g., Kazanci et al., 2004; Nijhuis et al., 2015). Nevertheless, any inference of how rates of channel-mouth progradation and associated drivers may control avulsion frequency is not strongly supported by data on avulsion-event counts. It must also be considered that higher progradation and sediment-supply rates may be linked to enhanced mouth-bar growth, and hence to a larger number of bifurcations around mouth bars, from which some of the mapped palaeochannels may have evolved.

In summary, whether relationships between normalized avulsion-frequency metrics and the scale over which they are determined represent apparent trends due to methodological limitations, or a record of

how the behaviour of avulsive channel networks changes in relation to factors that vary with the scale of the river system, cannot be established with confidence solely on the basis of the presented analyses.

#### 4.3. Practical implications

If we trust that data quality does not have a major effect on the adopted metrics, relationships between measures of avulsion frequency and the size of the study area over which they are determined provide guidance on the application of these metrics for comparisons of different fluvial systems. A hypothesis was made that – to facilitate comparisons between different river systems – rates may need to be normalized by the area over which they have been considered, based on the argument that the size of the study area is proportional to the size of the channel network, such that a larger cumulative length of channel threads that can avulse is sampled. The findings of this work indicate that measures of channel-avulsion frequency may not scale proportionally with the planform extent of the area over which they are evaluated, if the size of that area (e.g., extent of a delta plain) is directly related to the size of the river system. It is also observed that, expectedly, avulsion statistics vary as function of the time window over which they are determined. Hence, quantifications of avulsion frequency or interavulsion period do not seem meaningful in absence of some specification of the temporal and spatial scales over which they have been determined. These considerations should be born in mind when comparing avulsion-frequency proxies of different coastal-plain river systems and over different scales. In attempting to quantify avulsion frequency in a way that enables meaningful comparisons, it is recommended that (i) uncertainties associated with apparent scale dependency are recognized, (ii) alternative integrative approaches are adopted (i.e., simultaneous consideration of raw and normalized avulsion statistics), and (iii) scales of the spatial and temporal samples are explicitly reported.

#### 5. Conclusions

An analysis has been conducted of the avulsion histories of 57 coastal-plain river systems, which have been quantified by means of metrics based on numbers of avulsion events, channel threads and delta lobes; these quantifications have been made with consideration of the size of the study areas and of the number of separate rivers traversing them.

These metrics vary with temporal and spatial scales in ways that may be due to both geological and methodological reasons, such as non-uniformity in the way controlling factors operate in space and time, or variations in the resolution of avulsion records with their temporal and spatial extent. Proxies for coastal-plain river avulsion frequency tend to decrease in magnitude as the time window over which they are evaluated increases, likely because of Holocene trends in the importance of avulsion drivers or due to a decrease in the completeness of older avulsion records. Non-normalized avulsion-frequency metrics are not directly related to the size of the area over which they are determined, indicating that smaller deltas tend to record more frequent avulsions in proportion to the extent of their channel networks. This may be an apparent trend due to variations in resolution with the scale of investigation; it may otherwise represent a true emerging characteristic of river deltas, due to non-stationarity in channel avulsion, or to factors acting as avulsion triggers or enablers whose importance varies in relation with river-system scale (e.g., variability in water and sediment discharge, substrate stability).

Measures of the spatio-temporal density of avulsion events in coastal-plain fluvial systems vary in relation to spatial and temporal scales, and this has implications on how we quantify and compare the avulsion frequency of lowland rivers.

## Data statement

A file containing data employed in this paper is included as supplementary material, along with explanation of the data fields.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.earscirev.2022.104043>.

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