Let's get connected: A new graph theory-based approach and toolbox for understanding braided river morphodynamics

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Abstract

Our understanding of braided river morphodynamics has improved significantly in recent years, however there are still large knowledge gaps relating to both long-term and event-based change in braided river morphologies. Furthermore, we still lack methods that can take full advantage of the increasing availability of remotely sensed datasets that are well suited to braided river research. Network analysis based on graph theory, the mathematics of networks, offers a largely unexplored toolbox that can be applied to remotely sensed data to quantify the structure and function of braided rivers across nearly the full range of spatio-temporal scales relevant to braided river evolution. In this paper, important commonalities between braided rivers and other types of complex network are described, providing a compelling argument for the wider uptake of complex network analysis methods in the study of braided rivers. We provide an overview of the extraction of graph representations of braided river networks from remotely sensed data and detail a suite of metrics for quantitative analysis of these networks. Application of these metrics as new tools for multi-scale characterisation of braided river planforms that improve upon traditional, spatially averaged approaches is discussed and potential approaches to network-based analysis of braided river dynamics are proposed, drawing on a range of different concepts from braided river research and other network sciences. Finally, the potential for using graph theory metrics to validate numerical models of braided rivers is discussed.

Graphical/Visual Abstract and Caption
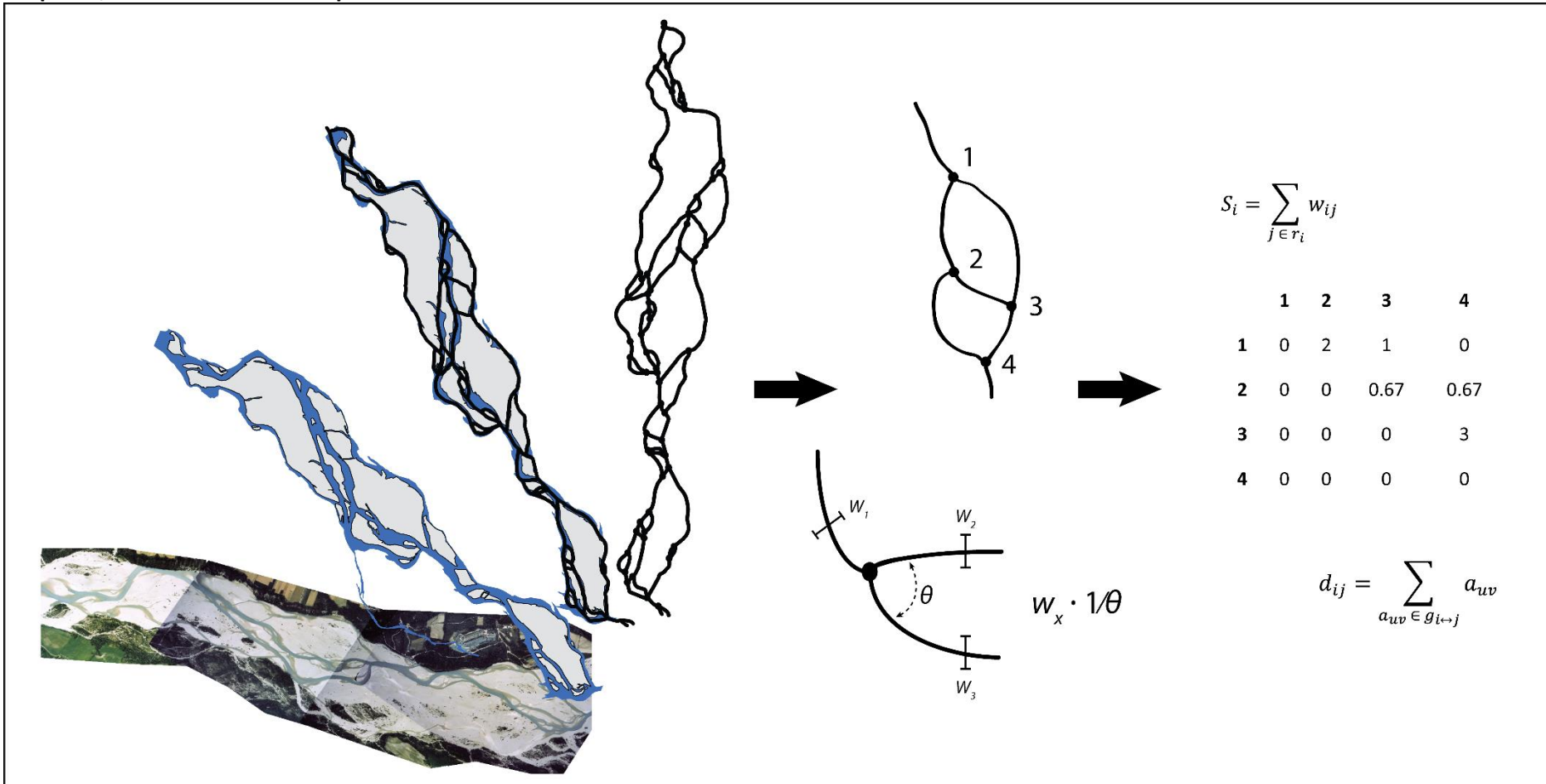
Braided river networks can be represented as weighted graphs, allowing the analysis of an array of different properties using graph theory.

1. INTRODUCTION

Braided rivers have a highly distinctive morphology that, when viewed from the air, appears as a complex network of interconnected channels that divide and converge around bars composed of sand or gravel (Figure 1). They are typically found in unconfined valley settings where the prevailing local geological, hydrological and geomorphological conditions result in large volumes of unconsolidated sediment, high stream powers that are capable of sustaining intense levels of bedload transport, and channel boundaries that are susceptible to erosion relative to the energy of the stream (Ashmore, 2013). These factors combine to make braided rivers one of the most dynamic and unpredictable Earth surface features, varying their morphology rapidly and dramatically via a suite of depositional (bar development) and erosional (bar dissection) processes that are most active under high flow conditions (Ashmore, 1991b; Ferguson, 1993).

These processes and their attendant variables are active across a huge range of spatio-temporal scales. Channel size exists in a hierarchy, from the main, first-order channels to higher order branching channels (Bristow & Best, 1993). Channel branching around bars creates the fundamental geomorphic unit in braided rivers: the bifurcation-confluence unit; an intrinsically unstable unit that evolves in response to interacting hydrodynamic and channel geometry variables (Ashworth, 1996; Bertoldi, 2012; Best & Roy, 1991; Kleinhans et al., 2013; Marra et al., 2014; Richardson & Thorne, 2001; Schuurman & Kleinhans, 2015; Thomas et al., 2011). At bar-scales, a suite of key "braiding mechanisms" both initiate and maintain braiding through bar-scale processes (Ashmore, 1991b; Wheaton et al., 2013), which may manifest as connections between upstream erosional processes and changing downstream morphologies through subsequent deposition and bar building (Ashworth, 1996; Ashworth et al., 2000). Migration of bedforms creates and alters the morphology of different bar types (Best et al., 2003; Sambrook Smith et al., 2006), whilst the migration of whole bars can affect planform evolution (Ashworth et al., 2011).

Above bar-scale, the spatio-temporal distribution of erosion, deposition and vegetation across reaches determines braided river morphologies. Vegetation stabilises bars and other floodplain surfaces against erosion and enhances deposition, affecting reach-scale topography (Bertoldi et al., 2011b, 2011a; Corenblit et al., 2014; Gran & Paola, 2001; Gurnell et al., 2001; Mardhiah et al., 2015; Rodrigues et al., 2007). The size of vegetated patches also affects channel planform, with many smaller patches associated with divergent flow pathways and a more complex channel network, whereas larger vegetated islands may focus flow into larger central channels from which smaller channels branch (Coulthard, 2005; Gran & Paola, 2001; Henshaw et al., 2013; Murray & Paola, 2003). The heterogeneous topography of braided river reaches thus steers flow and results in spatio-temporally variable sediment transport pathways that heavily influence reach-scale morphological evolution (Ashmore et al., 2011; Wheaton et al., 2013).

Beyond the reach-scale, width constraints on the floodplain's active area affects channel pattern, bed elevations and the rate of bar and island turnover (Fotherby, 2009; Garcia Lugo et al., 2015; Liébault et al., 2013; Zanoni et al., 2008) and the morphological evolution of braided river networks may follow trajectories of change that reflect varying boundary conditions related to climate, sediment supply, catchment land use and anthropogenic alterations to river channels (Belletti et al., 2015; Mueller & Pitlick, 2013; Ziliani & Surian, 2012). However, existing tools for studying braided river

morphological structure and behaviour through planform analysis do not account for the complex nature of these systems.

Traditional approaches to quantifying changes in braided river morphology at the scale of the channel network often utilise oblique/aerial photos or satellite images. Through-time and between-reach differences in braiding intensity have been investigated through the computation of indices based on the average number of individual channels across the river (e.g. Ashmore, 1991a; Howard et al., 1970; Luchi et al., 2007; Sarker & Thorne, 2006; Surian, 1999) or the total length of individual channels in a given reach length (e.g. Hong & Davies, 1979; Robertson-Rintoul & Richards, 1993). Relative levels of planform activity have been assessed through reach-averaged planimetric measurements of bank erosion and lateral shifts in the position of dominant channels (e.g. Bertoldi et al., 2010).

Figure 1: Looking upstream at the complex channel network of the braided Tagliamento River, Italy**.**

The deployment of these methods in studies of natural and experimental rivers has greatly enhanced our understanding of the control exerted by discharge and stream power on braiding intensity (Bertoldi et al., 2009b; Egozi & Ashmore, 2009; Robertson-Rintoul & Richards, 1993) and the morphological significance of floods of different magnitudes in braided rivers (Bertoldi et al., 2010), but they have several limitations. In addition to commonly reported issues such as their sensitivity to river stage and a lack of equivalence between different index types (Egozi & Ashmore, 2008), it is important to note that indices of braiding intensity only provide an aggregate measure of channel complexity, not morphological activity *per se*. As a result, they cannot be used to discriminate, for example, between braided reaches that experience no change between two points in time from those which are reconfigured extensively yet maintain the same number or length of channels. Similarly, reach-averaged values of channel migration obscure important geographical aspects of morphological change in braided rivers. Qualitative observations have demonstrated the importance of bifurcation evolution and avulsions as critical controls on the spatial configuration of braided

channel networks (e.g. Bertoldi et al., 2010; Egozi & Ashmore, 2009) but these cause-effect linkages cannot be captured using existing planimetric methods.

Advances in geomatics and the development of methods for quantifying morphological change in three dimensions have partially addressed these issues. Modern techniques have eased the large-scale acquisition and processing of data for production of high-resolution digital elevation models (DEMs) of braided rivers with high accuracy (e.g. Brasington et al., 2012; Westoby et al., 2012; Williams et al., 2013), allowing identification of spatial patterns of post-flood erosion and deposition through DEM-differencing techniques capable of accounting for uncertainty (Brasington et al., 2003; Lane et al., 2003; Wheaton et al., 2010). The causal mechanisms of observed channel changes can then either be inferred through the identification of unique morphodynamic signatures, such as Ashmore's (1991b) "braiding mechanisms" and bank erosion (Wheaton et al., 2013), or field observations of bedload transport pathways and flow patterns (Williams et al., 2015). Nevertheless, the effort of field surveying means geographical and temporal coverage of existing models of morphological change in braided rivers are restricted.

The potential for new insights into the controls on braided river behaviour over broader spatial scales and longer time periods has been increased substantially by the recent revolution in Earth observation data. The public release of NASA's Landsat satellite image archive (Woodcock et al., 2008) and the launch of ESA's Sentinel missions (Berger et al., 2012) have provided scientists with a freely-accessible, global-scale dataset of multispectral satellite imagery with near-continual coverage at 30 m resolution or finer dating back to the early 1980s. Analysis using this dataset has demonstrated its capacity to provide temporally rich information on historical morphological changes in large braided rivers (Henshaw et al., 2013) but new metrics are required that can successfully characterise morphodynamic behaviour in a way that preserves spatial linkages between different parts of the channel network.

Graph theory, a branch of mathematics that is concerned with the structure and function of networks, offers a possible way forward. Graphs are mathematical representations of systems that comprise n nodes (or vertices) connected by m edges (or links/arcs) (Newman, 2010). Nodes can represent any physically- or process-based system component, while edges represent any kind of connection between nodes, which may be physical, statistical, temporal, behavioural, etc. (Heckmann et al., 2015). This data structure facilitates preservation and analysis of the intrinsic qualities of a system together with the pattern of connections that is crucial to determining how a system behaves, across multiple scales (Jordán & Scheuring, 2004; Newman, 2010). Such functionality has led to a growing interest in the application of graph theory and associated network methods to research in geomorphology (Heckmann et al., 2015) and the geosciences (Phillips et al., 2015). The geomorphic settings within which they have been applied is diverse, including glacial forelands (Andrews & Estabrook, 1971), sediment connectivity (Heckmann & Schwanghart, 2013), seismic networks (Abe & Suzuki, 2006), soil science (Phillips, 2011), prairie wetlands (Wright, 2010), hillslope hydrology (Masselink et al., 2016) and various fluvial and river delta environments (Marra et al., 2013; Passalacqua, 2017; Poulter et al., 2008; Tejedor et al., 2015b, 2015a; Werner, 1993). However, despite studies that have explicitly classified bifurcations and confluences as nodes in braided rivers (Kidová et al., 2016; Van Der Nat et al., 2002, 2003; Wheaton et al., 2013) and studies that have recognised topological linkages between nodes (Howard et al., 1970; Webb, 1995),

detailed topological analysis has, thus far, been limited to an innovative study by Marra et al. (2013) who used established network analysis measures to quantify the spatio-temporal importance of channels in the Jamuna River, Bangladesh.

A recent special edition of the journal Geomorphology focussed on connectivity and network thinking within the discipline (Wohl et al., 2017), though without examining these approaches in relation to braided rivers. In this paper, we seek to make the case for a much wider adoption of network methods in braided river research. We begin by examining the characteristics of braided channels from a network perspective, highlighting commonalities with other systems and phenomena, in order to define a set of universal properties. We provide an overview of methods for extracting graphs of braided rivers from remotely sensed imagery and then identify and describe a collection of graph theory metrics that are particularly well suited to the study of these graphs. Finally, we explore how this toolbox of methods could be used to address key gaps in knowledge.

2. BRAIDED RIVERS AS NETWORKS

Graph representations of systems as networks of nodes, connected by edges and described mathematically by an accompanying adjacency matrix (Newman, 2010), can be intuitively applied to the planform structure of a typical braided river network (e.g. Marra et al., 2013; Figure 2b). Bifurcations and confluences are represented as numbered nodes and connecting channels represent edges. Pairs of nodes can be connected by more than one edge (e.g. where a channel splits around a medial bar or island) and all edges are necessarily unidirectional (i.e. traversed downstream) due to the nature of water and sediment flux in rivers. In the adjacency matrix, positive numbers denote the presence of a directed edge or edges between two nodes ("from" nodes identified by row number, "to" nodes identified by column number) and zero values are used in the absence of a connection. In most natural systems, it is unusual for all connections to have equal significance. This can be represented in a graph by applying weights to nodal connections to reflect their properties (Barrat et al., 2004; Newman, 2010). Edge weights in the example shown in Figure 2b are based on an arbitrary, equal division of flow at each node, but more physically meaningful weights can be applied in braided channel networks. For example, Marra et al. (2013) propose the use of channel width (as a proxy for discharge) and the inverse of channel length (as a proxy for channel slope) due to their association with sediment transport capacity.

In addition to being directed, all braided river networks have a number of other common properties. Firstly, they are inherently spatial in their nature, with nodes embedded in two- or three-dimensional space. Spatial embedding alters concepts related to paths, which are measured by geodesic distance in non-spatial networks, but have additional properties of route distance and Euclidean distance between nodes in spatial networks (see box 1; Barthélemy, 2011). This has important implications for the topological properties of braided systems, with the probability of direct links between two neighbouring nodes declining with distance. Secondly, braided river networks can be considered to be acyclic in that they contain no self-edges (edges that connect a node to itself) or directed cycles (closed loops of directed edges that start and finish at the same node; Newman, 2010). For the practical purpose of computing potentially useful cycle-related metrics (see Section 4), the directionality of edges can be removed, but most graphical representations will reflect the true nature of flow and sediment routing through braided reaches. Finally, all graphs of braided river

networks are characteristically planar, meaning they can be drawn on a plane without having any edges cross and nodes are present wherever two edges intersect (Barthélemy, 2011; Cardillo et al., 2006; Newman, 2010).
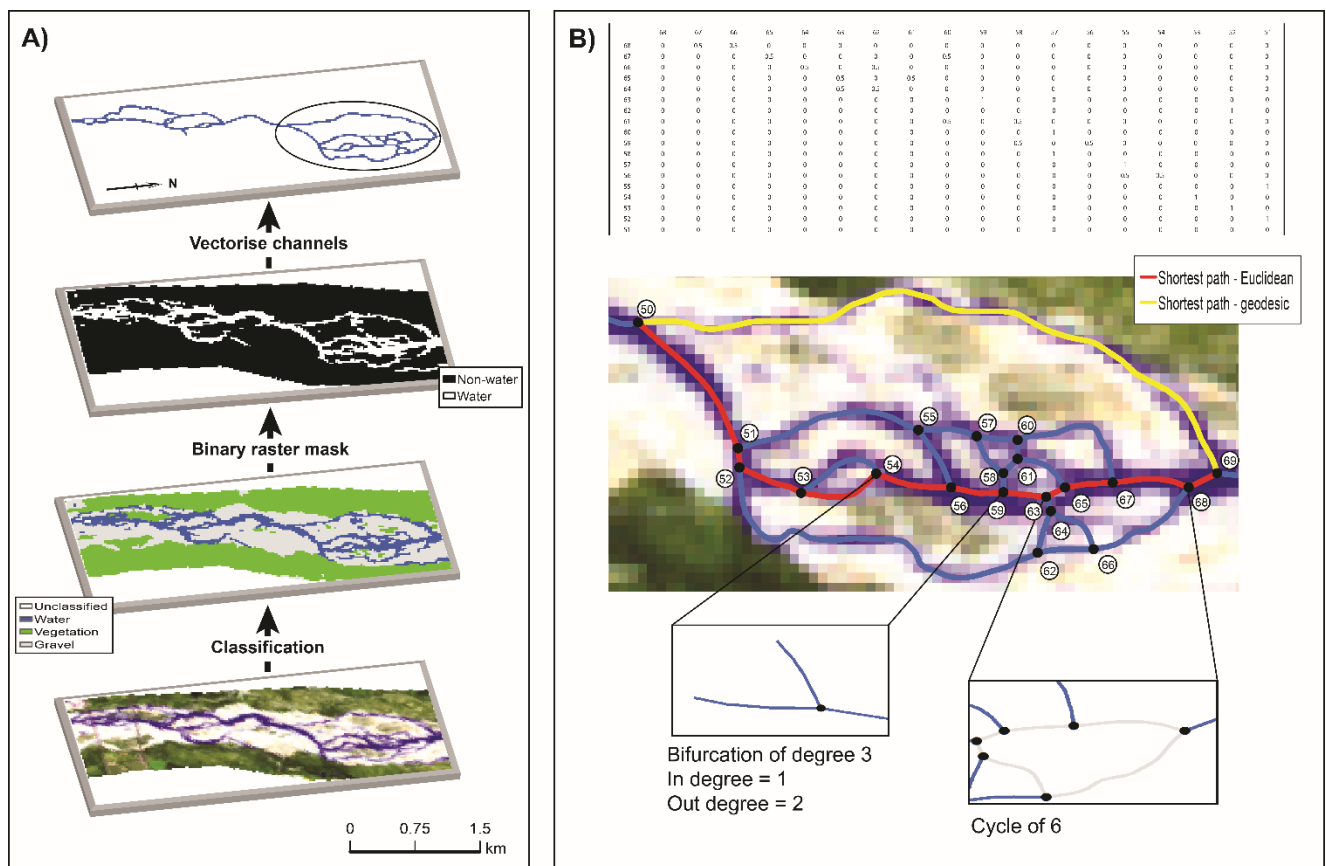
Figure 2: A) Overview of the image processing workflow applied to derive a braided river graph from a raw satellite image. The area in the ellipse is expanded in B). B) Close-up of the graph for a small subnetwork (middle), with an extract of the associated adjacency matrix (top). Node numbers reflect their position in the wider network and decrease in a streamwise direction, indicating flow direction. The adjacency matrix could not be included in full and is weighted to reflect an equal division of flow at each node. The close-up also highlights two types of shortest path, Euclidean and geodesic (see text) and the boxes (bottom) visually describe the graph theory metrics of node degree and cycles (cycle shown as grey channels; see text for descriptions).

The wiring of complex networks can appear random, but their topological properties are a consequence of network evolution, fundamental design principles and limitations (Maslov et al., 2004). As such, complex networks ranging from neural pathways in the brain, to transport links and food webs, have shown similarities in functional and structural patterning that have been identified using graph theory-based metrics. Many of these networks also share common topological features with braided river channels. For example, structural connections in brain networks form around a highly connected, central "rich-club" backbone (Binicewicz et al., 2016; van den Heuvel et al., 2012). Anatomically, this is more costly than alternative configurations, e.g. a larger number of shorter connections. However, although the neural "rich-club" pathways represent a relatively small element of the total wiring length of the brain, they carry a disproportionately large amount of information

flow due to their enhanced topological efficiency, enabling faster, higher-level cognitive activity (Alexander-Bloch et al., 2013; Nicosia et al., 2013; van den Heuvel et al., 2012). This type of configuration, where a distinct dominant branch or branches from which secondary channels divide off, linking distal areas of the network, is commonly observed in braided rivers (Ashmore, 2013). This pattern emerges as a result of 1) topographic asymmetry and instability of bifurcations which, in turn, results in an unequal division of discharge and sediment transport that propagates downstream following the most efficient pathway (Bertoldi et al., 2009; Schuurman & Kleinhans, 2015); and 2) non-linear relationships between shear stress and sediment transport rates (Church, 2006; Dade, 2000), such that small changes in discharge and slope can generate large changes in sediment transport rate along different pathways.

Road networks also tend to form around central backbones of major highways, from which secondary roads branch off (de Arruda et al., 2016). The topology of road networks is heavily influenced by spatial constraint, in particular planarity (Barthélemy, 2011; Cardillo et al., 2006). Spatial planar networks have important characteristics that limit, for example, the number of connections to a single node (Cardillo et al., 2006; Lämmer et al., 2006), thereby placing particular importance on certain types of junctions in road networks (Strano et al., 2012). This is also true of braided channel networks, with bifurcations comprising a single incoming channel and two outgoing channels, and confluences usually comprising two (but occasionally more) incoming channels and a single outgoing channel (Ashmore, 2013). Road networks incorporating T-junctions provide a direct topological analogue to the majority of bifurcations and confluences in braided rivers (Figure 2b).

Box 1: Key terms

Topology: The interrelations and arrangement of components in a network that result in patterns of connections.

Nodes: Discrete network components that can represent either tangible, physical things within a system or properties/processes. Also referred to as vertices.

Edges: Connections between nodes that transfer "information" through a network. Also referred to as links and arcs.

Degree: The number of edges that connect to a node.

Graph order: The total number of nodes in a graph.

Geodesic distance: The number of edges on a path between two nodes.

Euclidean distance: The straight-line, or "as-the-crow-flies", distance between two points on a two-dimensional plane (Euclidean space).

Route distance: The sum of physical edge lengths on a path between two nodes, often referred to as a measure of the physical length of the shortest geodesic path between nodes.

Spatial network: A network where network elements have a defined position in 2- or 3-D space.

Planar network: A type of spatial network where a node is formed every time edges intersect.

The pattern of structural (physical) connectivity is an important control of function in many types of network, however system behaviour can also depend on the degree of synchronicity between clusters, or modules, of nodes (Cabral et al., 2011). For example, synchronicity of electrical activity in brains has found functional connections between modules that act as a key control on pathological brain dynamics (Chavez et al., 2010), with this analytical approach recently being proposed as a means to map functional connectivity in hydrological systems (Rinderer et al., 2018). Modules are abstractions of sub-networks of neurons and intriguingly, it appears that the morphological structure of these modules can determine the degree of synchronicity and thus functional connectivity, rather than any direct linkage between them (Nicosia et al., 2013). In braided rivers, this is analogous to non-proximal reaches that possess similar morphological configurations displaying similar behavioural responses to stimuli such as flood events of a given magnitude, changes in sediment supply or channel management (e.g. Surian & Rinaldi, 2003).

The structural and functional similarities braided rivers share with the complex networks presented above indicates that graph theory-based metrics applied in other fields should be both transferable and, potentially, useful. However, when selecting measures and determining how they should be applied, it is also important to consider some of the differences between braided rivers and other forms of complex networks. Some of these are relatively subtle. For example, transport networks generally facilitate the efficient transfer of people between places, with their movement governed, in part, by the spatial extent and properties of different network elements (Tang et al., 2016). People drive on roads, not through buildings or fields, and any given road can only accommodate a certain number of cars. Likewise, material transfers through braided river networks are also governed, to a certain degree, by the spatial properties of network elements, from the micro-scale morphology of individual channels, through the meso-scale positions of channels within the braidplain, to the macro-scale morphological configuration of the entire braidplain. However, the spatial properties of braided river networks are far less constrained than those of road networks. The spatial constraints imposed on single junctions (nodes) and roads (edges), for example, limits their capacity to evolve, regardless of the traffic flow they receive. By contrast, in braided rivers the morphology of a bifurcation/confluence (node) or channel (edge) adjusts to the flow of water and sediment it receives, with subsequent effects on the wider braided network.

Other differences between types of complex networks and braided rivers are more striking. Networks ranging from the climate to the internet have been shown to demonstrate small-world or scale-free characteristics (Abe & Suzuki, 2006; Beauguitte & Ducruet, 2011; Bullmore et al., 2009; Faloutsos et al., 1999; Kühnert et al., 2006; Sen et al., 2003; Tsonis et al., 2006). Small-world networks (SWNs) are characterised by topologies that facilitate efficient information transfer between densely interconnected sub-networks through a relatively small number of long-range connections between pairs of nodes, evidenced by high values of the *clustering coefficient* and low shortest path lengths (see section 4.2; Watts & Strogatz, 1998). Scale-free networks (SFNs) are characterised by node degree distributions that follow scale-free power-law decay, i.e. there are many nodes with few connections and few nodes with many connections (Barabási & Albert, 1999). This network property results from new nodes preferentially attaching to nodes that already have many connections. However, the development of SWN and/or SFN topologies are restricted when a network is both spatial and planar (Barthélemy, 2011; Beauguitte & Ducruet, 2011; Cardillo et al., 2006). As braided

rivers are spatial planar networks, certain graph theory-based metrics, for example the *clustering coefficient* (see section 4), used to characterise/discriminate between SWNs and SFNs are unlikely to be applicable in this context. Furthermore, in most braided rivers, pathways diverge and converge before eventual convergence of all paths on a single outlet node. This property will affect the transferability of certain measures designed for use with "tree" networks, which are reliant on either the convergence of multiple pathways (e.g. drainage networks; Rodriguez-Iturbe et al., 1994) or largely divergent pathways (e.g. river deltas; Passalacqua, 2017; Passalacqua et al., 2013; Tejedor et al., 2015a, 2015b).

3.   FROM IMAGERY TO GRAPHS: HOW TO EXTRACT A BRAIDED RIVER NETWORK FOR ANALYSIS?

In order to treat a braided river as a graph, a topological representation of the network must first be extracted. There are four broad steps required to extract a braided river network for graph analysis:

1) Image pre-processing;
2) Image classification;
3) Skeletonise and vectorise classified images;
4) Construct graph models using dedicated software.

Each of these steps encompasses a wide array of separate image processing and manipulation techniques, which it is beyond the scope of this paper to discuss in detail. A synopsis of the processing applied to Landsat Surface Reflectance (SR) data (Masek et al., 2006) to extract graph representations of a medium sized braided river is given below and shown visually in figure 2a. It should also be noted that if using, for example, Landsat SR data that is already atmospherically corrected, the pre-processing step may not be necessary.

Once a pre-processed image has been obtained, this image should be classified to isolate the land covers of interest. In the case of braided rivers, these are active channels (water), vegetation and bare gravel. The array of available classification techniques is multifarious and interested readers are directed to Lu & Weng (2007) or Phiri & Morgenroth (2017; Landsat-specific) for summaries. Classification using object-based image analysis (OBIA) techniques has been recognised as (generally) providing more accurate results than traditional, pixel-based approaches (Phiri & Morgenroth, 2017), with a consistent upsurge in applications in Geographic Information Science (Blaschke et al., 2014). OBIA techniques have been applied in the eCognition Developer OBIA software (Trimble Inc., Sunnyvale, USA) to create a fast and accurate classification routine for the classification of water, gravel and vegetation (Figure 2a).

After classifying a remotely sensed image, the channel network is skeletonised, turning a classified water raster into a set of channel centrelines in vector format. The author has developed a simple workflow using geoprocessing tools available in ArcGIS (ESRI Inc., Redlands, USA) that converts a

binary raster mask of the channel network, e.g. water cells = 1, all other cells = 0, to channel centrelines (Figure 2a). To not over represent channels disconnected by falling stage, channel centrelines connected at both ends are restricted to areas of visibly contiguous water pixels. Disconnection should be represented by "dangling" channels with a node of degree 1 (see box 1). This workflow requires some manual correction to remove artefacts created during vectorisation of the input raster. A further issue exists in determining the direction of flow along an edge. Ideally, a digital elevation model (DEM) would be used to assess the local channel slope and thus flow direction, however there is a paucity of DEMs available at sufficiently high spatial and temporal resolution for most braided rivers. In the present case, it is possible to unambiguously determine the direction of flow based on the overall directional trend of the river and the angles at bifurcations. Once edge direction has been assigned, channel centrelines are converted to the ArcGIS Coverage data format (ESRI Inc., 2016), allowing extraction of network topology in the form of an edge list. Free sources of remotely sensed data and software for conducting graph analysis are detailed in Box 2.

Recent work has proposed automated methods for delineating river networks from satellite imagery without computing topology (Isikdogan et al., 2015; Monegaglia et al., 2018) and computing braided river networks with topology (Kleinhans et al., 2017). The latter method requires topographic data as an input. A robust, automatable method for channel network extraction will be required to facilitate rigorous network analysis of braided rivers globally. The method detailed by the author is simple, having the advantage of being applicable by non-experts in remote sensing and computer science and allowing the extraction of braided river topologies with only a satellite image as input.

4.   GRAPH THEORY-BASED METRICS FOR THE ANALYSIS OF BRAIDED CHANNEL NETWORKS

The following sections outline a toolbox of potentially useful graph theory-based metrics that offer scope to quantify the character of braided rivers. This list is not exhaustive (for various metrics not included here see Hernandez & Van Mieghem (2011), Newman (2010), Rubinov & Sporns (2010), but note the array of available metrics is extensive). The following selection was guided by the preceding discussion of the characteristic features of braided channel networks, with metrics chosen and organised by relevance to the scale at which the metric is applied (from local to reach/global) and the nature of the network property described by the metric. Note that certain metrics that are not relevant to braided river topologies but are widely used in other network studies have been included to reinforce the above comments on the transferability of metrics.

It should also be noted that network elements can be weighted to account for the properties of nodes and edges. Graph theory metrics calculated on weighted graphs are subsequently weighted, which can modify the equations (Rubinov & Sporns, 2010). The unweighted versions of metrics are presented below, with the exception of *strength*, for which edge weights are integral. The choice of node and edge weights in braided rivers will depend on the source of data from which a graph is

derived. For graphs derived from satellite and aerial imagery, weights will be 2-D geometric variables, e.g. channel width, length etc., or parameters such as vegetated area, due to its effect on erosion and deposition (Corenblit et al., 2014). The choice of edge weights will reflect both the specifics of research questions and the availability of weighting data.

4.1. Local-scale metrics

4.1.1. Basic metrics

The simplest way of describing the character and significance of a given node in a network is by examining the number of edges that are connected to it (Rubinov & Sporns, 2010). This property is known as node degree (k_i)

$$k_i = \sum_{j \in N} a_{ij}$$

(1)

where N is the set of all nodes in the network and a_{ij} is the connectivity between nodes i and j. $a_{ij} = 1$ when edge (i,j) occurs and 0 otherwise. In directed networks, degree can be decomposed to in-degree, the number of ingoing edges to a node, and out-degree, the number of outgoing edges (Figure 2b; Newman, 2010). Degree is an intuitively important measure of a node's connectedness that is often analysed in a global sense by looking at its probability distribution, often termed the degree distribution (e.g. Barabási & Albert, 1999). Degree could be a useful tool in identifying particular morphological features, for example disconnected channels where $k_i = 1$, or confluence-bifurcation meeting points where $k_i = 4$. In weighted networks, a simple extension of degree is node *strength* (S_i; de Arruda et al., 2016) with the *strength* for each node i as

$$S_i = \sum_{j \in r_i} w_{ij}$$

(2)

Where r_i is the set of neighbours of i and w_{ij} is the weight of the edge connecting i to j. This metric will represent the spatial distribution of whichever morphological variable is used to weight edges.

Similarly, the number of triangles around a node i is a fundamental structural property of most networks (Rubinov & Sporns, 2010)

$$t_i = \frac{1}{2} \sum_{j,h \in N} a_{ij} a_{ih} a_{jh}$$

(3)

where a represents connectivity between node pairs (i,j), (i,h) and (j,h). This metric is integral to measuring segregation of a network into subnetworks (Rubinov & Sporns, 2010). The slender, chain-like and directed nature of braided river networks (Marra et al., 2013) will limit the utility of t_i, even if the network is treated as undirected for the purpose of calculating structural metrics.

Box 2: Datasets and software to support graph analysis of braided rivers

Datasets:

Table B1 lists sources of remotely sensed data. All sources of satellite data are freely available through either the USGS' Earth Explorer portal (USGS, 2017) for Landsat (note other portals exist but this is the largest repository (Phiri & Morgenroth, 2017)), the ESA Copernicus Open Access Data Hub (ESA, 2017) for Sentinel data or by request for SPOT data (ESA, 2018).

Table B1: Sources of remotely sensed data. Repeat coverage refers to time between surveys of the same area of the Earth's surface.

Platform	Sensor type	Spatial resolution (m)	Timespan (yrs)	Repeat coverage (days)
Landsat 4-8	Multispectral	15-30	35	16
Sentinel 1	Radar	20	3	6
Sentinel 2 + 3	Multispectral	10-60	2	5
SPOT	Multispectral	1.5-20	32	≥26
Aerial	Various, e.g. optical, radar, LiDAR	Metre to sub-metre	Variable	Variable

Graph analysis software:

The following open-source software packages for graph analysis have been identified:

- *Igraph* (Csárdi & Nepusz, 2006) – A package of network analysis tools that can be coded in R, Python or C/C++ languages.
- *Rgraphviz* (Hansen et al., 2017) – A package for graph visualisation in R Statistics (R Core Team, 2017).
- *Gephi* (Bastian et al., 2009) – Graphical user interface (GUI)-based graph visualisation and analysis platform. Analysis uses pre-programmed metrics. Visualisations are not suited to braided river planforms.

This list is not exhaustive and is intended to provide a flavour of available tools for graph analysis of braided river networks. GUI-based platforms, such as Gephi (Bastian et al., 2009), take edge lists as inputs and can be used to easily compute a limited number of graph theory metrics. More flexibility is afforded by software such as igraph (Csárdi & Nepusz, 2006), which provides packages/libraries to compute an array of different metrics and can provide outputs for remapping to braided river visualisations in GIS.

4.1.2. Metrics of centrality

Metrics of centrality are more complex and can be used to quantify the role of individual nodes or edges in facilitating interaction between regions of networks and fostering resilience to disturbance (Rubinov & Sporns, 2010). *Betweenness centrality* (*BC*) is perhaps the most well used centrality metric, having been applied to networks as diverse as roads (Lämmer et al., 2006), prairie wetlands (Wright, 2010), artificial drainage networks (Poulter et al., 2008) and, indeed, braided rivers (Marra et al., 2013). A node *i* has high *BC* if it is on many shortest paths between a pair of nodes

$$BC_i = \frac{1}{(n-1)(n-2)} \sum_{\substack{h,j \in N \\ h \neq j, \ h \neq i, \ j \neq i}} \frac{\rho_{hj}(i)}{\rho_{hj}} \qquad (4)$$

where ρ_{hj} is the number of shortest paths between nodes *h* and *j*, and $\rho_{hj}(i)$ is the number of shortest paths between these nodes that cross *i*. The first term in the equation normalises a node's *BC* to account for the number of nodes in network (Freeman, 1977). Node *BC* can be generalised to edges, with *edge betweenness centrality* (*eBC*) measuring the number of shortest paths between pairs of nodes that run along an edge (Girvan & Newman, 2002). Marra et al's (2013) application of weighted *BC*, using channel width and length as edge weights (see above), found that channels on the Jamuna River with high *BC* showed little variation in spatial position through time, being deemed morphodynamically more important to the network based both on size and high levels of connectivity to other channels.

BC and other centrality metrics quantify an abstract property of network topology, namely the role of a node in shortest paths between other nodes (Freeman, 1977). These metrics are based on geodesic paths and thus do not account for space. Combining Euclidean distance between node pairs and the sum of "physical" edge lengths on shortest geodesic paths between a pair of nodes led to the formulation of *straightness centrality* $C^s(i)$ (Barthélemy, 2011)

$$C^s(i) = \frac{1}{N-1} \sum_{j \neq i} \frac{d_E(i,j)}{d_R(i,j)} \qquad (5)$$

where $d_E(i, j)$ is the Euclidean distance between nodes *i* and *j*, and $d_R (i, j)$ is the route distance on the shortest path between *i* and *j*. Developed in the study of spatial networks, $C^s(i)$ provides a measure of the tortuosity of all shortest paths that cross node *i*. As the value of the metric approaches one, these paths become increasingly straight. Furthermore, by restricting *i* and *j* to adjacent nodes (connected by a single edge), the ratio $d_E(i, j)/d_R(i, j)$ provides a measure of the sinuosity of all single channels in a braided river network. High sinuosity is generally associated with lower channel slope, as straighter channels tend to follow paths of steeper slope, thus having greater stream power (Knighton, 1998; van den Berg, 1995). $C^s(i)$ and its single channel derivative can provide a detailed characterisation of sinuosity in braided rivers

and are deemed an improvement on classic sinuosity indices that produce a single value of sinuosity for an often arbitrarily defined reach length (Egozi & Ashmore, 2008).

4.1.3. Network motifs and cycles

Motifs are small, characteristic patterns of nodes and edges that repeat in different parts of the network (Binicewicz et al., 2016). Functional motifs are a measure of these patterns (Rubinov & Sporns, 2010) which have been used to show that nodes representing different brain areas participated more strongly in certain patterns of connection (Binicewicz et al., 2016). Whilst not explicitly using graph theory, a very similar approach has also been applied to the classification of landforms, using patterns of elevation change (Jasiewicz & Stepinski, 2013). "Path motifs" have also been used to show that certain ordered sequences of nodes exist in brains to facilitate communication between less well connected "local" nodes by routing information transfer through highly connected "rich-club" nodes that form the network's central backbone (van den Heuvel et al., 2012). It is not clear whether subnetworks in braided rivers will show enough variation in their patterns of connections to calculate functional motifs. However, existence of these patterns would suggest a degree of local self-organization driven by the interaction between large-scale forcing variables, such as discharge and sediment supply, and more localised factors relating to the morphology of the braidplain.

Patterns that should be identifiable in braided river networks are cycles (closed loops of edges that start and finish at the same node). These have been used in the study of road networks as a means of showing differences in road layout that exist between urban areas (Cardillo et al., 2006). Specifically, a cycle of four, for example, indicates a typical "block", such as those associated with road networks designed on a grid system. Indeed, Cardillo et al. (2006) found that American cities (which are often built on grid systems) tended to have the greatest proportion of cycles of four in the sample of cities analysed. Cycles are a less sophisticated metric than functional motifs, but as they consist of closed patterns, they will be present in braided river networks. The directionality of the network will need to be removed in order to permit their identification, but the metric should enable identification of bar types of varying complexity (compare the cycle of 2 between nodes 54-53 and the cycle of 6 in the expanded box in Figure 2b).

4.2. Reach/global-scale metrics

4.2.1. Metrics of integration

Integration describes the capacity of different regions of a network to communicate rapidly with one another based around the concept of paths (Rubinov & Sporns, 2010). Shorter, more direct paths between pairs of nodes will, in general, facilitate more efficient transfer of information between these nodes. Employed in studies of both spatial and non-spatial networks, shortest path length d_{ij} is a descriptor of geodesic distance, in terms of number of nodes a_{uv} on a shortest path $g_{i\leftrightarrow j}$ between a node pair ij (Latora & Marchiori, 2001)

$$d_{ij} = \sum_{a_{uv} \in g_{i \leftrightarrow j}} a_{uv} \tag{6}$$

The characteristic path length of a network can be calculated by averaging the shortest path lengths between all pairs of nodes (e.g. Watts & Strogatz, 1998). In spatial networks, $d_R(i, j)$ defines the physical length of this path (Barthélemy, 2011).

Latora & Marchiori (2001) analysed networks using the metric *efficiency* (ϵ_{ij}). *Efficiency* of communication between two nodes *i* and *j* is defined as inversely proportional to the shortest path (d_{ij}) between these nodes. The average *efficiency* of a graph **G** is defined as

$$E(\mathbf{G}) = \frac{\sum_{i \neq j \in \mathbf{G}} \epsilon_{ij}}{N(N-1)} = \frac{1}{N(N-1)} \sum_{i \neq j \in \mathbf{G}} \frac{1}{d_{ij}} \tag{7}$$

$E(\mathbf{G})$ measures the *global efficiency* of the graph (E_{glob}). *Local efficiency* E_{loc} is defined as the average efficiency of subgraphs $\mathbf{G_i}$ of a node *i*

$$E_{loc} = 1/N \sum_{i \in \mathbf{G}} E(\mathbf{G_i}) \tag{8}$$

Applied to braided rivers, these metrics describe complexity at either the reach- or network-scale. Low values of E_{glob} or E_{loc} indicate a reach or network that is heavily bifurcating. Most bifurcations in braided systems are asymmetrical, with one distributary becoming dominant and causing a possible destabilisation of the bifurcation (Ashworth, 1996; Schuurman et al., 2016). Consequently, low efficiency network configurations may tend towards small-scale instability related to the dynamics at single bifurcations, whereas high efficiency networks may be more stable but with a greater probability of large-scale morphological change propagating from a point of disturbance.

Analysing sub-networks within river delta channel networks, Tejedor et al. (2015a, 2015b) defined *resistance distance* (*RD*), based on the theory of electrical circuits. Instead of focusing on the shortest path between a pair of nodes, *RD* quantifies the number of disjoint paths, paths not containing the same edges, between a node pair. As *RD* increases, so do the number of disjoint paths between a pair of nodes. Braided rivers exhibit longitudinal fluctuations in the number of parallel channels (Figure 2), which should manifest as subnetworks with varying *RD*. Simply looking at *RD* at a snapshot in time would give a variable describing the complexity of a reach at that time. However, multi-temporal analysis may provide insight into how this important aspect of a braided channel network varies in response to different stimuli, such as changes in flow or sediment supply.

4.2.2. Metrics of segregation

These metrics describe the presence of densely interconnected groups of nodes (Rubinov & Sporns, 2010). The clustering coefficient of the network (C) is one of the most widely used measures of segregation. Networks with a high C and low $\langle d_{ij}\rangle$ are classed as small-world (see section 2; Sen et al., 2003; Watts & Strogatz, 1998). C is not well suited to planar graphs but the meshedness coefficient M is a promising alternative (Buhl et al., 2004)

$$M = \frac{F}{F_{max}} \qquad (9)$$

where F is the number of internal faces, regions of a planar graph bounded by edges, and F_{max} is the number of internal faces in the maximally connected version of the same graph, e.g. the version of the graph where each node is connected to as many neighbours as possible without breaking planarity. For any planar graph, F and F_{max} can be defined as (Buhl et al., 2004)

$$F = m - n + 1 \qquad (10)$$

$$F_{max} = 2n - 6 \qquad (11)$$

where m and n are the number of edges and nodes in the graph. Cardillo et al. (2006) used M to assess the structure of urban road networks, with low values (≤ 0.1) of M being more tree-like and networks tending towards a regular lattice as M approaches 1. Variation in M in braided rivers would show network-scale fluctuations in complexity, with higher values being associated with rivers that that maximise possible connections between nodes.

4.2.3. Metrics to assess network sensitivity

Sensitivity is of paramount importance in networks such as infrastructure (Jenelius, 2009; Scott et al., 2006; Sullivan et al., 2010), supply (Herrera et al., 2016; Kim et al., 2015; Wagner & Neshat, 2010) and the internet (Newman, 2010). Approaches to sensitivity often utilise degree distributions. For example, SFN degree distributions (Barabási & Albert, 1999) result in networks that are sensitive to targeted attacks on high k nodes, but relatively insensitve to random attacks with higher probability of affecting low k, poorly connected nodes (Newman, 2010). Given that k is expected to have a limited range in braided rivers, examination of degree distributions in isolation is unlikely to provide much insight on network sensitivity. However, other measures designed to quantify the relative abundance of particular features based on k may be more instructive. For example, studying road networks, Strano et al. (2012) defined r_N

$$r_N = \frac{N_1 + N_3}{\sum_{k \neq 2} N_k} \qquad (12)$$

here N_k is the sum of nodes of degree k, thus measuring the relative abundance of dead ends (N_1) and T-junctions (N_3) in the network. Strano et al. (2012) did not consider nodes with $k = 2$, as they are not proper road junctions. Adapting this metric to consider only nodes of either in- or out-degree = 2 quantifies the number of either bifurcations or confluences in the sample of nodes of N_k. Weighting a directed version of r_N with, for example, bifurcation angle may

quantify the relative abundance of morphological features prone to instability, e.g. high-angle bifurcations (Bertoldi, 2012).

5.   APPLICATIONS OF GRAPH THEORY TO BRAIDED RIVER RESEARCH

5.1. Graph theory: a new framework for the morphological characterisation of braided rivers

The manifold elements and processes active in braided rivers result in their complex and spatially variable planform, which is inadequately described by spatially averaged braiding indices. Graph representations of braided rivers allow characterisation of braided planforms across the near full range of morphological unit scales. Above (section 4), we have highlighted a range of metrics that allow analysis across this range of scales. Metrics applicable to network-scale characterisation of braided rivers include E_{glob} (eq 7) and M (eq 9-11). It is possible that limitations placed on node degree in braided rivers may limit the variability of these metrics, which has been seen for E_{glob} on a small ensemble of braided river graphs (unpublished data). However, further exploration of larger graph ensembles is needed to confirm whether these metrics provide a broad discriminator between different types of braided river.

A simple example of reach-scale planform characterisation of three reaches using graph theory is shown in Figure 3. Graph metrics were calculated using the R (R Core Team, 2017) package *igraph* (Csárdi & Nepusz, 2006). These reaches have similar total braiding index (BI_T) values, being 4.8, 3 and 4.3 for reaches A-C, respectively. BI_T was defined in accordance with Egozi and Ashmore (2008). *eBC*, normalised by the product of the number of upstream and downstream edges to account for the position of an edge in the network (Marra et al., 2013), shows a similar spatial pattern in all three reaches, with the highest centrality edges on a path on the right-hand margin of the active tract. The second highest *eBC* path is established to the left-hand margin of the active tract and tracks the largest channel through each reach. In reaches B and C, the largest channel is substantially larger than the channels on the highest *eBC* path, reflecting 1) the need to weight metrics to account for physical properties of the network; 2) the interaction between channels on the highest *eBC* path and small channels that are dissecting compound bars in the middle of the braidplain. Similarly, in reach A, the high *eBC* of the right-hand path is driven by a complex of chute channels dissecting a compound bar that are forced to re-converge on the right-hand path by a flow constriction at the downstream end of this reach. Bifurcation angles have been plotted onto nodes in Figure 3 and show a broad pattern of lower values on the two most central paths (with the lowest largely on main channel bifurcations). The highest values are associated with small channels in the central braidplain. This fits with the general relationship between bifurcation angles and bifurcation stability, whereby higher bifurcation angles are less stable and may subsequently result in the closure of one of the channel branches (Bertoldi, 2012), which is more likely to occur on small chute channels. This example shows that, relative to a

traditional total braiding index, a simple application of a path-based graph theory metric provides a notably greater amount of quantitative information on the planform character of these reaches.

At the scale of single nodes, the changing spatial distribution of different *strength* nodes (de Arruda et al., 2016) will show how the physical properties of channels vary at discrete locations across the braidplain. Reformulation of r_N (Strano et al., 2012) to analyse in- and out-degree on weighted networks would characterise the relative abundance of either bifurcations or confluences that have certain properties. Methods have also been proposed for deltas that use upstream channel properties to make probabilistic estimates of water or sediment flux routing to downstream neighbour nodes (Tejedor et al., 2015b), though this method is fraught with large assumptions on flux routing controls. Characterisation of single network elements can likewise be applied to edges. The topological importance of single edges could be assessed using *eBC* (Girvan & Newman, 2002) to show areas where channel closure may disconnect part of a network. A similar approach has been applied to Norwegian road networks to ascertain edges (roads) at risk of closure from debris flows and the subsequent cost (in route distance) of the next shortest path between disconnected nodes (Meyer et al., 2015). Edges may also be declared "homogenous" if the nodes connected to them share properties (Del Vicario et al., 2016). The spatial distribution of "homogenous" edges would help to characterise areas of the braidplain that show local changes in physical properties.

Whilst graph theory can be applied to multi-scale characterisation of braided river morphologies, it may also have the potential to quantitatively define reaches. The reach is one of the key spatial units in braided river studies, but is often defined arbitrarily (e.g. Ashmore et al., 2011; Fotherby, 2009; Henshaw et al., 2013; Liébault et al., 2013). Topological metrics may provide a quantitative means to segment a braided river into reaches. *NN(h)* defines the average size of a neighbourhood (number of nodes) of *h* hops (along edges) from a given node (Faloutsos et al., 1999). For a low *h*, *NN(h)* should scale with network complexity, which fluctuates along the length of a braided river (compare the reach in the ellipse in Figure 2a with the area downstream). Calculating *NN(h)* for subsamples of nodes in a downstream direction should capture this fluctuating complexity, which may also serve as a basis for defining reach boundaries. Combining *NN(h)* with sequence zonation algorithms that use longitudinal variation in input parameters to define boundaries in a sequence (Parker et al., 2012) could provide a quantitative method for defining reaches on braided rivers.

5.2. Network-based dynamical approaches to braided river research

5.2.1. Braided rivers as dynamic systems: some prospects and challenges

Morphodynamic responses of geomorphic systems result from both antecedent conditions and the present dynamics of variables that drive a system's evolution (Bracken & Croke, 2007; Lane & Richards, 1997; Phillips, 2015). Braided rivers are one of the most dynamic types of geomorphic system on Earth, undergoing rapid morphological evolution over the course of a single large flood that can thoroughly rearrange network structure and braidplain morphology (Ashmore, 2013; Belletti et al., 2015; Bertoldi et al., 2010). The evolution of a braided system is broadly driven by the interplay between sediment supply, discharge and vegetation (Bertoldi et al., 2010; Charlton, 2010; Gurnell et al., 2001), with the feedback between these variables resulting in a characteristic morphological state. Vegetated island turnover illustrates this interaction. Islands in a large braided river have been observed to persist for, at most, ~25 years, with variation in island area exhibiting strong cyclicity linked to the timing and frequency of high flow events (Kollmann et al., 1999; Van Der Nat et al., 2003; Zanoni et al., 2008). Zanoni et al. (2008) also found that this cyclicity was imposed on underlying trends of varying braidplain width, which they attributed to variation in catchment-scale sediment inputs and gravel mining. Thus, braided river morphologies evolve in response to present dynamics, for example the interaction of single flood events with vegetation, which are imposed onto longer term evolutionary trajectories governed by antecedent conditions and changing large-scale boundary conditions, such as climate, catchment land-use and sediment supply (Mueller & Pitlick, 2013; Ziliani & Surian, 2012).

The often flood-driven nature of braided river morphodynamics creates considerable problems for their study. Inundation of the braidplain during flood events decreases network complexity and increases morphodynamic activity (Ashmore et al., 2011; Bertoldi, Ashmore, & Tubino, 2009; Van Der Nat et al., 2002). Thus, we are left with something akin to Labov's (1972) "observer's paradox": when a braided river is at its most outspoken, it is also at its least observable!   Network analysis of remotely sensed data may help to get around this problem. It is important to note the stage-dependence of braided river network complexity, which is greatest at intermediate stages when most channels are connected and higher bar surfaces are not inundated (Van Der Nat et al., 2002, 2003). This will have considerable effects on certain graph theory metrics. Pattern-based metrics, such as *motifs* and *cycles*, will vary considerably with stage, likely showing minimal variation at high stage when few bars are exposed. Similarly, path-based metrics that assess alternate paths on subnetworks, e.g. *RD*, will likely show maxima at intermediate stage when the number of wetted channels is also at a maximum.
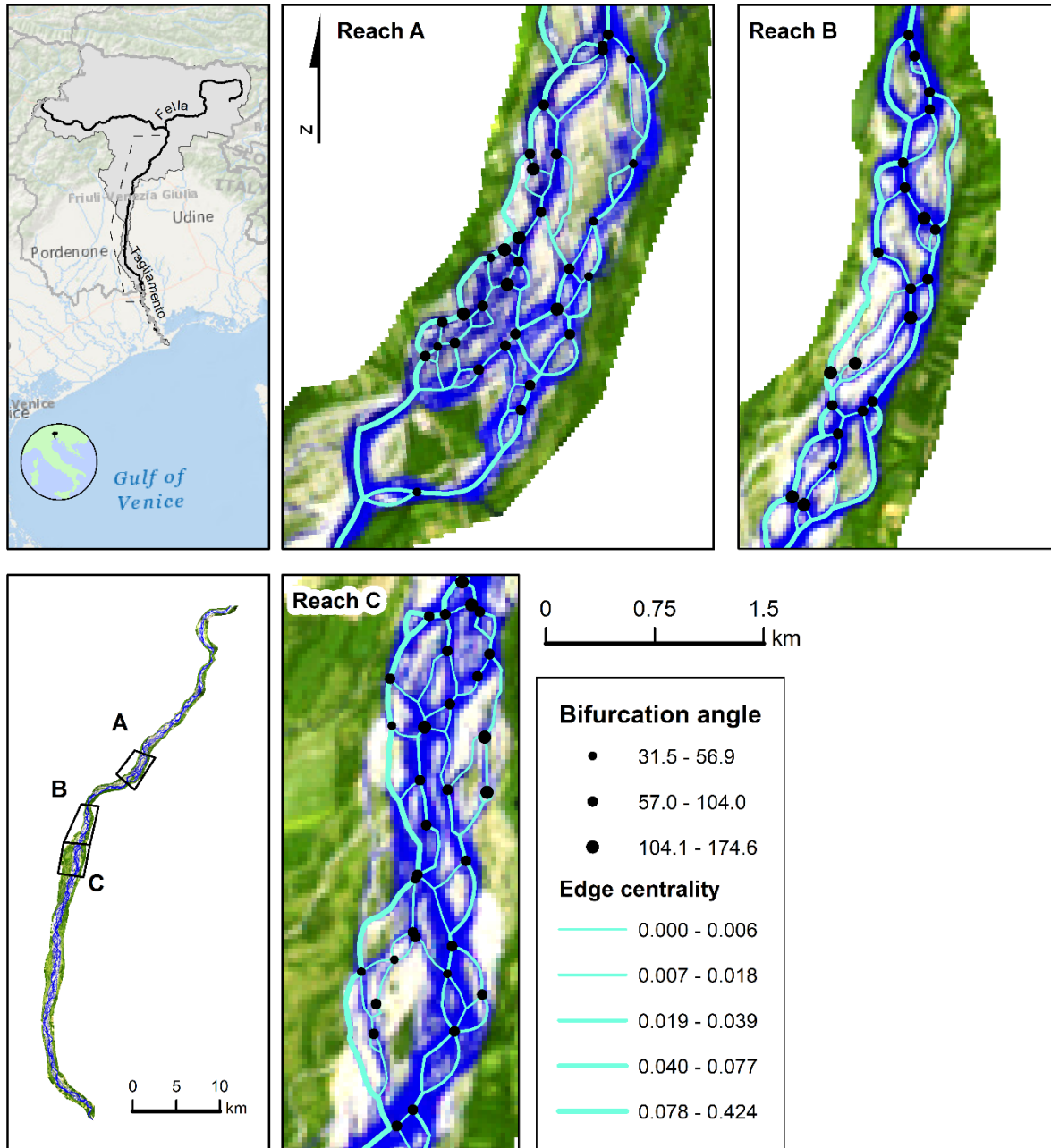
Figure 3: Maps of unweighted, normalised *edge betweenness centrality* and bifurcation angle (°) between the downstream channel centrelines at each node for three reaches, A-C, on the River Tagliamento, Italy. Graphs for this analysis were derived from a Landsat 5 TM scene captured on 20/06/2011, which is shown, clipped to the braidplain extent, in the bottom left panel. The dashed line in the top left panel shows the location of this section of the river. Flow is from north to south.

Whilst stage-dependent network complexity undoubtedly causes problems for network analyses, it may also present opportunities. Where temporally rich datasets provide imagery over the course of a flood event, mapping the channel network and how its topology evolves

with rising stage may allow inference of 3-D properties from 2-D analysis. For example, $C^s(i)$-type metrics may indicate the order in which channels of different slope magnitudes begin to convey flow. The temporal frequency for such analyses would likely come from aerial surveys or fixed position cameras (e.g. Bertoldi, 2012; Bertoldi et al., 2010). These survey methods also avoid the inherent issue of cloud cover in satellite imagery around the time of floods. Multispectral satellite imagery does, however, provide temporal depth. Datasets such as Landsat, which spans 35 years with global, 16-day repeat coverage enable multi-temporal analysis of the evolution of braided river networks (Henshaw et al., 2013). Again, it is important to recognise the limitations of braided river network analysis using satellite data. The entire network structure of braided rivers may be reset during large floods (Belletti et al., 2015; Bertoldi et al., 2010) and the length of time between cloud-free imagery can exceed the temporal persistence of single nodes and small bars. Although network elements will be georeferenced, it is unwise to try and track all but the largest of channels and bars over periods of variable hydrological conditions or without high temporal resolution observations.

The limitations posed by remote sensing datasets can be overcome with numerical models, which provide the ability to "observe" the unobservable, outputting detailed changes in morphometric variables and sediment transport rates across the model domain (Church & Ferguson, 2015; Nicholas, 2000; Schuurman & Kleinhans, 2015; Ziliani et al., 2013). Network analysis of numerical models could use sediment transport data to weight nodes and edges, a similar approach to which has been taken in tributary networks, with results highlighting hotspots of geomorphic change (Czuba & Foufoula-Georgiou, 2014, 2015). Applying these weights to *BC*, for example, would show channels that are central to the network from both a topological and process-based perspective.

5.2.2. Network approaches to studying braided river dynamics

Few networks are static and concepts and behavioural analogies arising from studies of network dynamics in different fields may stimulate dynamic approaches to braided river research. In human brain networks, resting-state oscillation of electrical signals (Cabral et al., 2011) are analogous to the constant, small-scale morphological adjustments that occur in braided rivers during periods of lower, yet competent, flows (Bertoldi et al., 2010). These small-scale adjustments may be part of the evolution of a braided network towards a self-organised critical state (Sapozhnikov & Foufoula-Georgiou, 1997, 1999), priming the system for a certain response to a stimulus, e.g. a large flood. Figure 4 illustrates this idea, showing the change in *eBC* on a single reach of a medium-sized, gravel-bed braided river after a series of high flow events which exceeded the discharge threshold (~150 m^3 s^{-1}) for sediment movement and included one near-bankfull flood, corresponding to a discharge of ~1700 m^3 s^{-1} and a return period of up to three years (Bertoldi et al., 2010). A period of low flows covered the two months up to Figure 4a. BI_T is very similar between dates, however the network structure and position of both central, high *eBC* channels and branching, lower *eBC*

channels and the bifurcation angles associated with both has shifted, reflecting a shift in the loci of bar dissection and avulsive processes from the right-side of the braidplain to the left (Figure 4). Interestingly, as seen in Figure 3, the highest *eBC* channels did not correspond with the physically largest channels visible in the original Landsat image. Given that responses to stimuli in complex, natural systems are often mediated by the propagation of a stimulus through a network's nodes (Bar-Yam & Epstein, 2004), it will be interesting to see whether the unweighted topology of braided rivers has any relationship with the response of the system over longer time-series and if system responses are better represented by weighted topologies. How to analyse dynamics using topological relations is an open question, to which some ideas are offered below.

Time-series analysis of braided river topologies is likely to be a key tool in probing responses to stimuli and long-term evolutionary trajectories. Methods based around the analysis of fractals have used time-series data to show that braided rivers scale dynamically, e.g. the evolution of network elements can be scaled in time such that rates of evolution are the same for elements across different spatial scales (Sapozhnikov & Foufoula-Georgiou, 1997). Sapozhnikov & Foufoula-Georgiou (1997) note that dynamic scaling is indicative of a system at a critical state and that in order to assess whether a braided river has established self-organised criticality, it would be necessary to track parameters that affect critical behaviour, for example slope. $C^s(i)$-type (Barthélemy, 2011) sinuosity metrics may provide a surrogate for slope (see section 4), at scales ranging from single channels to the whole network. Combining analysis of dynamic scaling and $C^s(i)$-type metrics may provide a means to show whether a braided system is in a critical state and how it might react to further forcing. Responses to forcing also depend on antecedent conditions, with braided river evolution suggested to occur along trajectories (Ziliani & Surian, 2012). Autoregressive modelling of graph theory metrics, whereby the value (y_t) of a time-series at time *t* is modelled as a function of previous values ($y_{t-1}...y_{t-n}$; Harvey & Clifford, 2009) could investigate the presence of such trajectories. Cross-correlation analysis, which has shown time-dependent correlations between morphodynamic variables in a flume environment (Ashmore, 1991a), may also provide insight into relationships between graph theory metrics over time. Given that morphological instabilities can propagate downstream in braided rivers (Ashmore, 1987; Schuurman et al., 2016; Takagi et al., 2007), cross-correlation of, for example, reach-averaged *cycles* may show how different reach configurations propagate downstream over time, or show the periodicity with which a reach returns to a certain configuration.
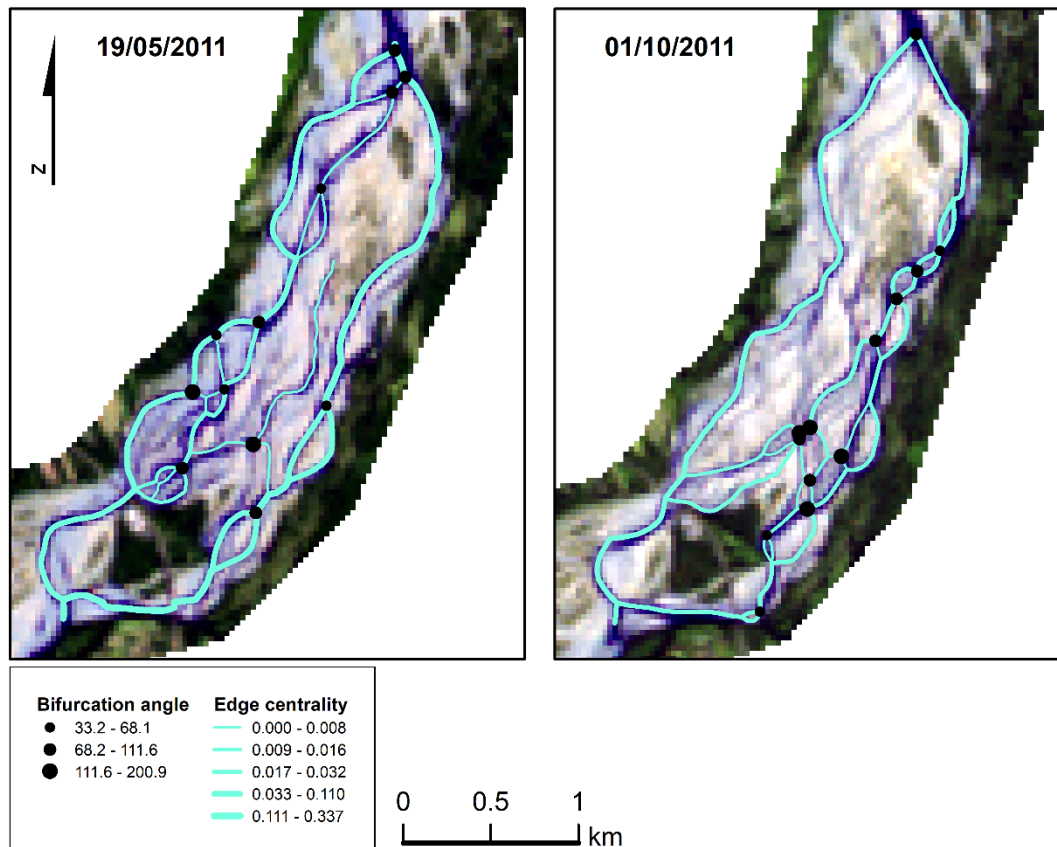
Figure 4: Maps of unweighted, normalised *edge betweeness centrality* and bifurcation angle (°) for reach A (see Figure 3) on two dates separated by a series of different flood events, including one bankfull event, on the River Tagliamento. Total braiding index (BI_T; Egozi & Ashmore, 2008) values are 3.3 and 2.9 for the 19/05/11 and 01/10/11, respectively. Graphs for this analysis were derived from Landsat 5 TM scenes. Both scenes were captured at low stage and flow is from north to south.

Propagation of certain reach configurations could also be thought of in terms of continuation in what Thibaud et al. (2013) refer to as filial relations. This concept is based on ancestry and descendance between entities. An entity is a geomorphic feature, identified by one or more attributes that distinguish it from others present at the same time. If an entity persists from one timestep to the next, it perpetuates its identity. Changes to an entity may derive descendants, possibly by amalgamation with other entities. These two modes of filiation are termed "continuation" and "derivation" (Thibaud et al., 2013). In braided rivers, entities could be defined by reaches, or sub-reach-scale *motifs* or paths, with their identities defined by attributes such as graph theory metrics and physical properties. Setting thresholds for change in the attributes of an entity shows continuation of the entity, or derivation. Analysis of the continuation or derivation of entities is performed in the lens of variables that drive morphodynamics (floods, sediment input etc.). Thus, filiations could provide a framework to assess the risk of morphodynamic change in response to driving variables at the reach-scale and, the aforementioned problems with tracking nodes and edges notwithstanding, at sub-reach scales.

Unlike remote sensing or field-based datasets of braided rivers, network elements can be tracked in numerical models of braided rivers and application of detailed morphometric or rate-based model outputs will improve the capacity for weighting graphs derived from these models. Subsequently, time-series or filiation analyses could be extended to smaller spatio-temporal scales. The detailed representation of morphodynamic processes in numerical models may also enable agent-based modelling (ABM), whereby nodes (agents) are in one of various states, represented by a suite of different physical and graph theoretical metrics, and changes to these states occur based on dynamical rules or the state of neighbouring nodes (Barrat et al., 2013). Dynamical rules could be developed through present knowledge of braided river processes. An ABM then probes the relative importance of different processes by iteratively changing rules to increase or decrease the importance of certain processes, with the response of the ABM checked against that of the numerical model. Barrat et al. (2013) note that difficulties in discriminating the effects of assumptions or parameters in ABMs grows with the number of parameters used. Given the spatial and temporal complexity of even a single braided river process, for example sediment transport (Ashworth & Ferguson, 1986; Kasprak et al., 2015; Nicholas, 2000), there will be limitations on how detailed an ABM of a braided river could be, but ABMs may provide new insight into how certain parameters and processes affect braided river dynamics.

5.3. Does my model talk the talk *and* walk the walk? Graph theoretical approaches to numerical model validation

There has been considerable development in numerical modelling of braided rivers, with models now able to generate realistic braided morphologies of large braided rivers (Engelund & Skovgaard, 1973; Murray & Paola, 1994, 2003; Schuurman et al., 2016; Williams et al., 2016; Yang et al., 2015). However, simplifying assumptions are inevitable, for example applying uniform roughness coefficients across the model domain or simplifying the effects of vegetation (Church & Ferguson, 2015). As such, datasets from natural systems are needed against which to validate the output of numerical models. There is, however, a lack of both laboratory and natural datasets that can be used to support model development (Williams et al., 2016). Datasets that do exist for natural systems, either remote sensing planform-based or field-based, often only cover short time intervals or are of low temporal resolution for repeat surveys. Further limitations are placed on using planform-based datasets due to the low discriminatory power of classic methods, e.g. braiding indices, used to characterise such data (see above).

By representing natural braided rivers as a graph, much of their inherent complexity is assimilated into the graph's nodes and edges, whilst still representing the structure and behaviour of the network. Graph theory could, therefore, offer a novel approach to validating numerical models of braided river morphodynamics. The temporal depth and resolution of satellite imagery provides datasets at spatial and temporal scales that capture both long-term and event-based morphodynamic responses in braided rivers. With datasets that can assess network change before and after discrete events *and* network behaviour of natural systems

through time, it would also be possible to closely examine the behaviour of a numerical model.

Adapting graph theory as a tool to better understand model sensitivity and the mechanistic behaviour of models could take various approaches that utilise graph theory metrics to quantify properties of natural systems and use them as novel sources of reference data. Global properties of the network quantified with, for example, E_{glob} (Equation (7)), M (Equation (9)-(11)) or average BC (Equation (4)) account for a variety of different structural properties of the network (see section 4) that cannot be captured using traditional braiding indices. Deriving these global network metrics for natural systems over time and before and after flood events would provide an overall measure of how modelled braided rivers replicate the structure of their natural counterparts. At smaller scales, both processes and forms may show spatial scaling in braided rivers (Ashmore, 2013; Kasprak et al., 2015; Reitz et al., 2014; Sapozhnikov & Foufoula-Georgiou, 1996). If it is found that, for example, channel length correlates with BC or that nodes of a given BC have a typical spacing within the network, then these could be used as model validation parameters by assessing whether a model recreates the same spatial scaling of network metrics seen in natural systems.

Alternative approaches to scaling in network research often utilise scale in the frequency or probability distribution of a metric (Barabási & Albert, 1999; Beygelzimer et al., 2005; Chen et al., 2002). Initial analysis of the distributions of eBC for braided river graphs at low, medium and high discharge appear to show patterns in their frequency distributions (Figure 5). Lower discharge seems to be associated with heavier tailed distributions. Visual assessment of BC maps for the Jamuna River (Marra et al., 2013) suggest a similar pattern may be seen in these data, reflecting what is likely the effect of a relatively high number of more central channels at low flow, which diminishes at higher flows as more channels and new paths become active. Whilst more analysis is needed to confirm this relationship, it indicates that the distribution of BC, or other metrics, may have typical scaling for a given discharge in a natural river. Thus, the scaling of metric distributions in natural rivers could provide a reference against which to test a similarly parameterised model.

There is also potential for validating internal behavioural responses in models using graph theory. Schuurman et al. (2016) found that bifurcation instabilities cascaded downstream in their model of a large, sand-bed braided river. With graph datasets of natural systems at sufficient temporal resolution, tracking metrics such as r_N (Equation (12)) through time and space in both real and modelled rivers may show the propagation of these instabilities and whether the spatio-temporal properties of modelled propagation are corroborated by real-world observations. This would provide a dynamic measure of whether numerical models of braided rivers match the behaviours seen in modelled systems.
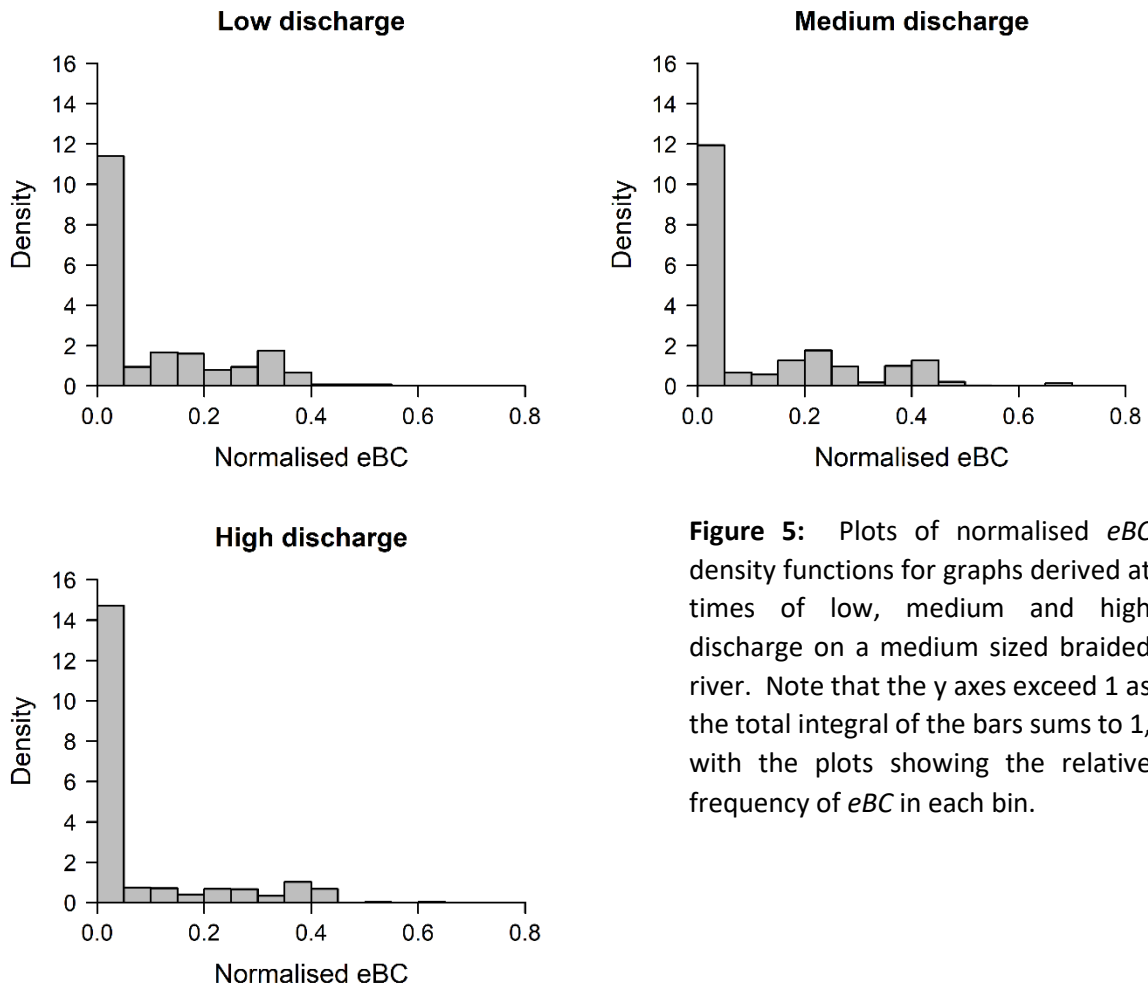
Low discharge

Medium discharge

High discharge

Figure 5: Plots of normalised *eBC* density functions for graphs derived at times of low, medium and high discharge on a medium sized braided river. Note that the y axes exceed 1 as the total integral of the bars sums to 1, with the plots showing the relative frequency of *eBC* in each bin.

6.   SUMMARY

Network analysis is a key tool for understanding the behaviour of natural and anthropogenic systems in a wide range of disciplines. This paper sought to highlight how the topologies of braided river networks have striking similarities with networks as diverse as roads and brains, providing a rationale for the application of network analysis to braided river geomorphology. Our study of network analyses across a range of disciplines has identified a suite of graph theory metrics that may be of relevance to braided river morphodynamics. These metrics are applicable at nearly the full range of scales relevant to braided river processes and can also account for connectivity between geomorphic units within braided river networks. The *raison d'être* for network analysis of braided river systems can be pleasingly summarised by Boulding (1956: p. 207), who described the knowledge attained from systems approaches as "like, shall we say, the 'knowhow' of the gene as compared with the knowhow of the biologist."

Marra et al. (2013) have shown the potential of network analysis for studying braided river morphodynamics. To date, this is the only example of research applying network methods and graph theory to braided rivers, despite a recent upsurge in geoscientific applications (Czuba & Foufoula-Georgiou, 2015; Heckmann et al., 2015; Heckmann & Schwanghart, 2013;

Masselink et al., 2016; Passalacqua, 2017; Phillips, 2011; Phillips et al., 2015; Poulter et al., 2008; Tejedor et al., 2015a, 2015b; Wright, 2010). The graph theory toolbox presented herein provides a suite of new metrics that can describe a multitude of topological properties, how these topological properties are affected by physical properties and new ways of showing the spatial distributions of these physical properties. Taken together, this toolbox provides a powerful new approach to quantitative descriptions of braided river morphologies, which can be linked to morphodynamic processes. There will be many approaches to graph theory-based analysis of braided river morphodynamics, of which some ideas have been offered here. Time-series analysis of braided river graphs is likely to be pivotal, whilst more experimental approaches, e.g. ABMs, could be facilitated by numerical modelling. Dynamical studies of network behaviour is growing field in network research (Boccaletti et al., 2006), which may produce exciting possibilities for braided river studies. And graph theory could provide metrics that can test the response of numerical models of braided rivers, assessing whether the gross-scale structure and function of a modelled braided river matches its natural counterpart.

There is exciting theoretical potential in the application of network analysis to braided rivers that is supported by the recent increase in availability of temporally rich and relatively high-resolution satellite imagery such as Landsat (Roy et al., 2014), providing a means to generate multi-temporal network datasets of medium to large braided rivers, globally. We have provided an overview of a simple procedure for extracting braided river graphs, but there is now a question of how to refine this process to provide robust, repeatable and automated data collection. Developments in 3-D survey technologies, such as Structure-from-Motion (Smith et al., 2015; Westoby et al., 2012) and satellite-based stereo-photogrammetry (Noh & Howat, 2015), also provide new datasets that could be used to weight network elements, allowing graph theory metrics to have greater physical relevance.

With the availability of datasets for network analysis of braided rivers, there is also the question of which metrics will actually be interpretable from a geomorphic perspective? This review has aimed at a theoretical overview of possible interpretations of graph theory metrics in the context of braided river morphodynamics. It is now down to thorough testing to look for statistical patterns in metrics and their relationships with drivers of braided river behaviour and the behaviours themselves. This review and the approaches described herein are interdisciplinary. It is hoped that through collaboration with researchers in other network disciplines and with those taking field- and modelling-based approaches to braided river research, we can develop novel insights into the structure and function of braided rivers and how these may relate to other networks.

Acknowledgments

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