Geomorphic River Sensitivity

Addressing spatio-temporal complexities of a "Perfect Landscape"

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Thesis submitted for the degree of Doctor of Philosophy, October 2020

She is ever shaping new forms:

What is, has never yet been;

What has been, comes not again.

Everything is new, and yet nought but the old.

- Goethe's reflections on Nature by T. H. Huxley (1869)

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ABSTRACT

The geomorphic sensitivity of a river is dependent on three key attributes: the mix of imposed and flux controls that govern the erosion-deposition dynamics occurring at any position in a catchment, system preconditioning that results from legacies of historical capacity for adjustment; and catchment scale sediment (dis)connectivity that controls the expression of geomorphic change in a catchment. This thesis uses these three geomorphic attributes to assess the geomorphic sensitivity of rivers across the case study Richmond River catchment, NSW, Australia. It also provides a package of remote sensing techniques and workflows for assessing geomorphic river sensitivity, that others can adapt and use in their own catchments.

In this digital era of publically available catchment wide datasets, access to high computational power and semi-automation, it is now possible to quantify the geomorphic attributes of a landscape and assess trends and patterns with a high level of confidence. In order to quantitatively assess the pattern and gradient of geomorphic river sensitivity across an entire catchment, along with field investigation, this research harnesses the information embedded within Digital Elevation Models and historical planform records. The work on geomorphic controls uses readily available remote sensing datasets to assess the mix of imposed and flux controls operating on different river types along longitudinal profiles. Univariate and bivariate statistics is used to assess relationships between controls, and the envelopes and gradient of controls that explain the variability and pattern of river types in a catchment. The research on historical capacity for adjustment tracks the geomorphic adjustment across the Richmond catchment since European colonisation and provides an approach to categorise the geomorphic sensitivity of rivers across a catchment. A method for assessing whether rivers are geomorphically Fragile, Active Sensitive, Passive Sensitive, Insensitive and Resistant is presented. The research on sediment (dis)connectivity assesses the role of system (de)coupling on network scale sediment flux to identify hostspots of channel adjustment. This thesis integrates this research on geomorphic controls, historical adjustment and sediment connectivity to assess the contemporary and future sensitivity of rivers in the Richmond catchment. In addition to this, technical papers and chapters provide novel GIS workflows for rapidly, semi-automating assessment of geomorphic attributes across a catchment using publically available datasets. Workflows have been built for the semi-automation of valley segment mapping across a catchment, and the semi-automation of quantification of imposed and flux controls across a catchment.

Statement of Originality

This thesis comprises the original research performed by the author, Sana Khan, and has not been submitted for higher degree at any other university or institution.

The introduction section of this thesis lists the individual contribution of fellow authors for the five data chapters that are published, or under review, or prepared for publication. Non-author contributions to the thesis are detailed in the acknowledgements section of each data chapter. The data sources are detailed in the methods sections of each data chapter.

Sana Khan

28 October, 2020

Acknowledgements

Firstly, I would like to take this opportunity to sincerely thank my amazing supervisor, Kirstie Fryirs, for thoroughly burnishing my research abilities. Through her in-depth knowledge of fluvial systems and pragmatic research skills, I have learned the subtle art of reading and interpreting the fluvial landscape, critically addressing any research problem at hand and I think I am finally getting the knack of the inevitable task of scientific writing. Her patient and selfless style of supervision had a major role in polishing my confidence and ability as a researcher. Kirstie, you have been an outstanding mentor and my role model. I have no regrets of leaving my PhD offer from the University of Oxford to undertake this project under your supervision.

I am sincerely thankful to the great group of research students at the Department of Earth and Environmental Sciences for wonderful support and encouragement throughout. I am particularly grateful to my geomorphology and remote sensing cohorts: Sam, Will, Rory, Brad, Simon and Zacc for all the research and technical discussions (plus quiet some banter on the side!). I am hugely grateful to Sara and Jonathan who volunteered to help with my fieldwork. Getting hands on all those river bed samples would have been super tough otherwise.

My associate supervisor, Tim Ralph provided timely advice and support throughout my PhD candidature that helped me navigate through uncertain time.

I am grateful to Simone Bizzi for collaboration on the sediment (dis)connectivity project and providing guidance throughout that part of my research work. Thanks for all the Zoom meetings at awkward Australian-Italian timings and pumping encouragement through my frustrations with coding. I would also like to thank Gary Brierley for invigorating discussions during Goulburn and ANZGG trips that helped me in channelising the ideas for my research project; and also for occasionally checking on me and pumping encouragement during tough times. I look forward to being mentored by both of you in my research career that lies ahead.

I also appreciate the encouragement and discussions with the academic staff in the department, particularly, Paul Hesse, Kerrie Tomkins, Kira Westaway and Scott Wilson.

Finally, I would like to thank my family for their unwavering love and encouragement throughout. You are my pillar of support that I cannot thank enough.

Chapter 1

Introduction

1. Introduction

Fluvial systems are a characteristic example of ‘The perfect landscape’ where the internal and external controls and the resultant degrees of freedom offer a contingent causality leading to multiple divergent geomorphic probabilities (Phillips, 2007). As a result, rivers can be geomorphically sensitive (or resilient) systems that create complex responses to processes operating at multiple spatial and temporal scales (Phillips, 2003; Schumm, 1973). Against this backdrop, anthropogenic activities within a river corridor together with climate change stressors can either accentuate or supress this complexity (Montgomery, 2008; Wohl, 2019). In the last few decades, there has been a shift towards managing rivers using strategies that ‘work with nature’, taking into account a river’s ‘expected’ or ‘natural’ character and behaviour, to determine what is realistically achievable in river rehabilitation and restoration (Bernhardt, 2005; Brierley and Fryirs, 2009, 2005; Darby and Thorne, 1996; Fausch et al., 2002; Fryirs et al., 2012; Fryirs, 2015; Malakoff, 2004; Montgomery, 2008; Montgomery and MacDonald, 2002; Wohl et al., 2012).

This thesis uses a suite of geomorphic principles to operationalise the analysis of river sensitivity across a hierarchy of spatial and temporal scales. Using the geomorphically diverse Richmond River catchment as a case study, this thesis aims to show how the concept of river sensitivity can be used to explain the spatio-temporal complexities of a ‘perfect landscape’. This thesis also provides a package of remote sensing techniques and workflows for analysing geomorphic river sensitivity, so others can adapt and use them in their own catchments.

1.1. Geomorphic river sensitivity

Brunsden and Thornes (1979) define landscape sensitivity “as the likelihood that a given change in the controls of a system will produce a sensible, recognisable and persistent response” (p. 476). This involves various aspects: the possibility of change, the propensity for change and the capacity of the system to withstand, absorb or adjust to that change (Chorley et al., 1984; Schumm, 1998; Downs and Gregory, 2014). Landscape complexities makes it challenging to practically approach the concept of river sensitivity and, very few advances have been made to apply this concept in practice (Fryirs, 2017; Lisenby et al., 2019; Preston et al., 2011; Thoms et a., 2018; Tooth, 2018; Wohl, 2014). As a result, geomorphic river sensitivity is a complex and poorly understood topic (Allison and Thomas, 1993; Fryirs, 2017).

To understand landscape complexities, Schumm and Lichty (1965) introduced the idea of considering controls on determining riverscape forms and processes at various spatial and temporal scales. Later, Haigh (1987) proposed that the concept of hierarchy can be used to analyse scalar linkages in geomorphology. These nested hierarchical approaches can be used as a basis for assessing river sensitivity at various spatio-temporal scales (Montgomery and MacDonald, 2002; Phillips, 2012; Rhoads, 2020).

Since rivers are a product of their landscape, they are often best studied at the catchment scale (Fryirs and Brierley, 2013). In many fields, including ecology, geomorphology and hydrology, there has been a unifying acceptance that river structure and function operates along a continuum (Fausch et al., 2002; Montgomery, 1999; Phillips, 2012; Vannote et al., 1980). The field of geomorphology in particular relies heavily on spatio-temporal scales to explain the dynamics of geomorphic forms and processes (Fryirs and Brierley, 2013; Rhoads, 2020). In fluvial geomorphology, spatial scales range from geomorphic unit scale to reach scale to catchment scale, and temporal scales range from days to millennia.

Geomorphic river adjustment is dynamic in nature, resulting in complex forms and processes (Rhoads, 2006; Schumm, 1973). Multiple fluvial processes operate at various spatio-temporal scales that govern river response to disturbance events and the resultant river behaviour (Lane and Richards, 1997). Three key aspects can be considered for understanding river sensitivity: (1) Catchment scale processes driven by flow and sediment dynamics (2) Attenuation or dampening of these processes as a result of geomorphic controls on net erosion and deposition (3) Landscape memory that preconditions the landscape to respond to geomorphic disturbances and produces various river responses and characteristic behaviour (Brierley, 2010). In direct or indirect ways, these three key aspects encapsulate a range of other core geomorphic principles such as thresholds (Bull, 1979; Schumm, 1973, 1969), complex response (Phillips, 2003; Schumm, 1973), fluvial forms and resultant geomorphic processes (Fryirs and Brierley, 2013; Leopold et al., 1964), system relaxation and lag times (Allen, 1974), causality (Schumm and Lichty, 1965), feedback mechanisms (Dean and Schmidt, 2011; King, 1970), relationship between magnitude-frequency of events (Wolman and Miller, 1960)and geomorphic effectiveness (Dean and Schmidt, 2013; Wolman and Gerson, 1978). Therefore, analysis of these three aspects provides a holistic logical basis for capturing catchment scale river sensitivity.

Fryirs (2017) proposed a conceptual framework to assess river sensitivity across multiple, hierarchical spatio-temporal scales using foundation principles in fluvial geomorphology. This thesis builds upon this framework and operationalises it to assess river sensitivity at landform (geomorphic unit), reach and catchment scales. Figure 1 illustrates the various forms of river sensitivity that can be analysed at these three spatial scales.

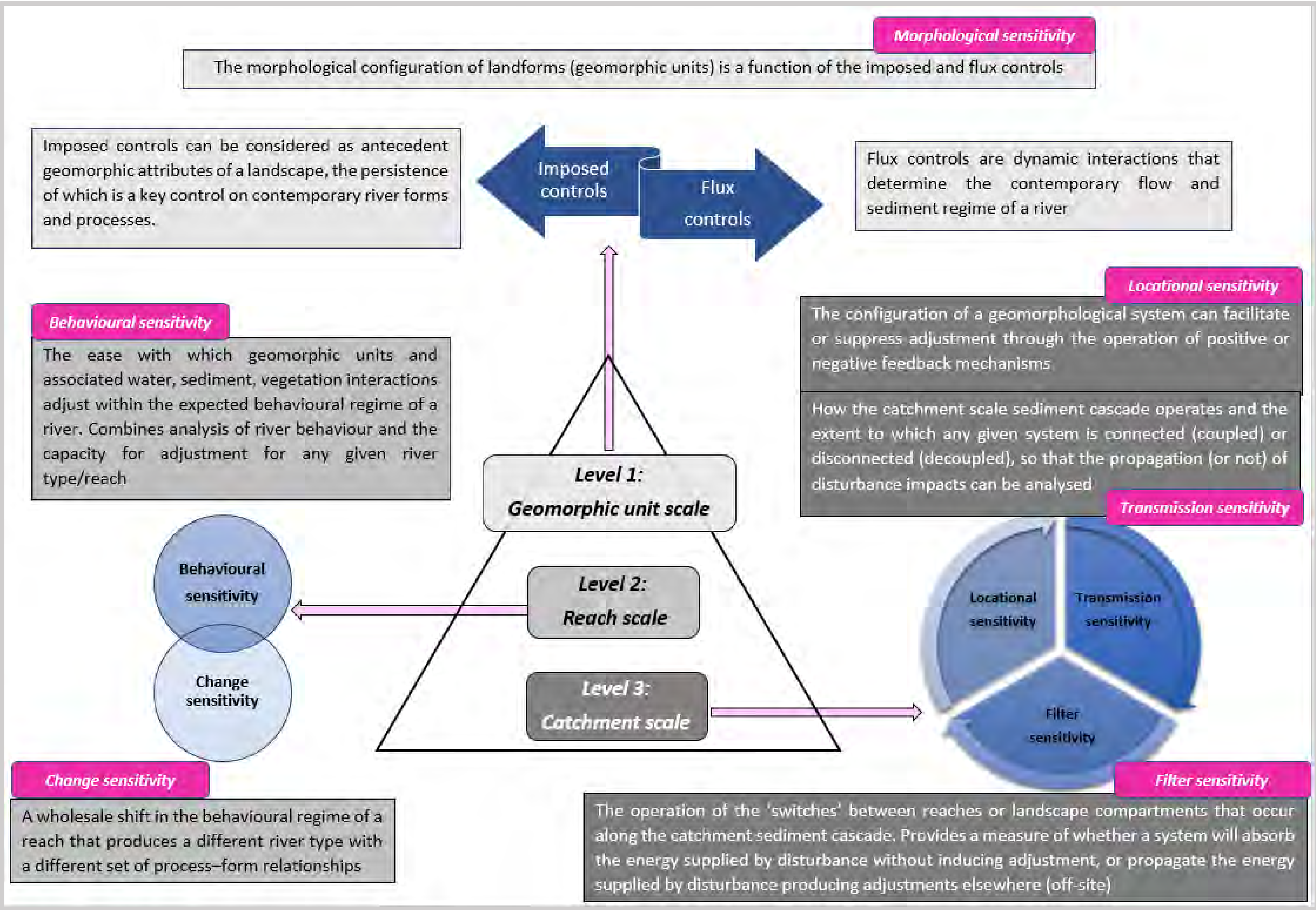

Figure 1 Various forms of river sensitivity that have been analysed in this thesis at three hierarchical spatial scales (based on defintions in Brunsden, 1993; Brunsden and Thornes, 1979; Downs and Gregory, 1995; Fryirs, 2017)

Level 1- Morphological sensitivity- At the landform scale, geomorphic units are created and reworked by an interplay between the imposed and flux controls (Church, 2006; Fryirs and Brierley, 2013). Geomorphic units are the building blocks of fluvial systems (Brierley and Fryirs, 2005; Carbonneau et al., 2012; Church, 2006; Fryirs and Brierley, 2013; Wheaton et al., 2015). Imposed controls are the antecedent geomorphic attributes of a landscape, the persistence of which is a key control on contemporary river forms and processes (Brierley, 2010; Brunsden and Thornes, 1979; Fryirs and Brierley, 2013; Phillips, 2001; Schumm and Lichty, 1965; Trofimov and Phillips, 1992). Imposed controls include valley width and slope. Flux controls are dynamic interactions that determine the contemporary flow and sediment regime of a river (Fryirs and Brierley, 2013). Based on internal system characteristics such as local gradient, bed material texture, available space for lateral and vertical adjustment; and external characteristics such as availability of discharge and sediment flux, a characteristic set of form-process associations results (Fryirs and Brierley, 2013; Rhoads, 2020). The downstream variability in these forms and processes creates contrasting process domains that determine the river diversity produced in any particular catchment (Buffington and Montgomery, 2013; Church, 2006; Kondolf, 1995; Kondolf et al., 2003; Montgomery, 1999; Schumm, 1985, 1981, 1977).

Level 2- Behavioural and change sensitivity- At the reach scale, various erosional and depositional processes operating both within-channel and on floodplains creates an assemblage of geomorphic units resulting into a characteristic behavioural regime (Brunsden, 1993; Fryirs and Brierley, 2013; Lane and Richards, 1997; Leopold et al., 1964). Natural and anthropogenic disturbances (as a result of changing water, sediment and vegetation interactions) may alter the behavioural regime of a reach (partially or wholesale) and alter this assemblage of geomorphic units resulting in adjustments within the contemporary behavioural regime of the river or wholesale river change (Baker and Costa, 1987; Brierley and Fryirs, 2005; Fryirs and Brierley, 2013; Phillips, 2014, 2009, 2003; Schumm, 1969). Tracking changes in the geomorphic unit assemblage at the reach scale over time can provide information on a river's capacity for adjustment as a result of changing controls (Fryirs et al., 2009; Lisenby and Fryirs, 2016; Scorpio et al., 2015; Wohl et al., 2012). Since not all rivers are influenced by a set of controls to the same extent, different rivers can respond to disturbance in different ways (Baker and Costa, 1987; Phillips, 2009, 2003; Schumm, 1969). Some might be more susceptible to adjustment; some may be resilient (Lisenby et al., 2019; Tooth, 2018).

Level 3- Locational, transmission and filter sensitivity- At catchment scale, the spatial configuration of reaches can facilitate or suppress adjustment via positive or negative feedback mechanisms i.e. position or location of the reach can have (or cannot have) an influence on the expression of geomorphic change in the catchment (Allen, 1974; Chappell, 1983; Fryirs, 2013; King, 1970). As a result of this locational sensitivity, the system can be coupled or decoupled such that the efficiency of routing of flow and sediment fluxes or transmission sensitivity can be variable. Depending on the (dis)connectivity between reaches, disturbance can propagate and manifest in various parts of the system (Bracken et al., 2015; Czuba and Foufoula-Georgiou, 2015; Fryirs, 2013). However, this degree of sediment (dis)connectivity can vary on the basis of sediment source, transfer and accumulation dynamics of a catchment and the position of blockages that may disrupt or filter the sediment cascade. The combination of locational, transmission and filter sensitivity governs if and where geomorphic change is expressed or suppressed within as system (Brunsden, 1993; Fryirs, 2013, 2017; Fryirs et al., 2007).

This thesis specifically focuses on the core geomorphic principles that determine landscape sensitivity over geomorphic timeframes. However, over relatively shorter timeframes, anthropogenic influence (Montgomery, 2008; Wohl, 2019) and vegetation characteristics

(Brierley et al., 2005; Wohl et al., 2012) can play a pivotal role in determining the trajectory of local reach scale landscape sensitivity. These can either accelerate or retard the overall landscape response to disturbance events. Chapter 5 of this thesis does a semi-quantitative assessment of landscape response to anthropogenic disturbances via alteration in riparian vegetation density as a result of post-European colonisation in the study area.

1.2. Geomorphic analysis of rivers in an era of big data acquisition and automation

Against the backdrop of accelerated anthropogenic alterations to river corridors, there is a growing need to manage fluvial systems at much broader spatial and temporal scales (Gilvear and Bryant, 2016). With the advent of Digital Elevation models (DEM) and satellite imagery, the geomorphic analysis of rivers can be undertaken at unprecedented scales and resolutions (Piégay et al., 2020).

A wealth of digital spatial datasets are available globally and regionally that can be used for the geomorphic analysis of river systems (Fryirs et al., 2019; Piégay et al., 2020). These include satellite imagery, aerial imagery, drone imagery and DEMs ranging from 90m to a few centimetre resolutions. Such datasets can be used for analysing and interpreting the riverscapes including landform scale assemblages, erosion-deposition dynamics of a reach (Darby et al., 2002; Konsoer et al., 2016; O'Brien et al., 2019; Wheaton et al., 2015, 2013; Williams et al., 2020; Zinger et al., 2011), tracking historical river forms and processes (temporal change at geomorphic unit scale) (Landwehr and Rhoads, 2003; Piégay et al., 2005; Scorpio et al., 2015; Simon et al., 2007; Zanoni et al., 2008), extracting channel characteristics (del Val et al., 2015; Roux et al., 2015; Schwanghart and Scherler, 2014; Zhao et al., 2019), modelling river processes and sediment flux at the network scale (Czuba and

Foufoula-Georgiou, 2015, 2014; Schmitt et al., 2018, 2016) and projecting future evolutionary trajectories (Lisenby et al., 2019; Stecca et al., 2019).

Further, easy availability of good computing resources supplemented by emerging high level programming languages with in-built libraries/packages of workflows and algorithms for complex statistical analysis has significantly enabled processing and interpretation of big data (Gibson and Hancock, 2020; Guillon et al., 2020; Rahmati et al., 2017; Shaeri Karimi et al., 2019). These resources also offer the ability to use multiple time slices, or different types of datasets to make the analysis reproducible (Roux et al., 2015). However, caution is needed when using automated remote sensing approaches and applying expert human judgement to the process. From choosing a well-tested tool or model for the job, to running the analysis, to verifying the output in-place in the field (Fryirs et al., 2019; Passalacqua et al., 2015; Piégay et al., 2005).

This thesis makes use of publically available remote sensing datasets and integrates this with the knowledge gained from field investigations to assess river sensitivity in the Richmond catchment at various spatio-temporal scales. Further, the methods used to assess river sensitivity have been provided as either new semi-automated tools or as generic workflows that integrate pre-existing open source models so that others can adapt and analyse river sensitivity in their own catchments.

1.3. The Richmond River Catchment

This section provides a very brief regional setting for the case study catchment. Further details are presented in the papers in the body of the thesis.

The Richmond River is located in the subtropical zone of the far North Coast of New South Wales (NSW). The river emerges from the Great Dividing Range on the slopes of the

McPherson Range and flows southeast into the Tasman Sea. The Richmond River drains a catchment area of 6858 km^2 and receives major flow contributions from its two major tributaries, Wilsons River and Bungawalbyn Creek (Figure 2). There is considerable variability in the streamflow of the Richmond system. The northern and central rivers of the catchment are free flowing and are perennial (Figure 2: 1, 2, 3 and 4). Although, there is high flow variability such that the bankfull stage can be ten times higher or even more than that at the low flow stage. In contrast, the southern rivers are either intermittent (Figure 2: 5 and 7) or ephemeral (Figure 2: 6 and 8) at low flow.

The Richmond River catchment was selected as the study area for this sensitivity analysis for two specific reasons: (1) the rich diversity in geomorphic river types and (2) availability of LiDAR DEM and historical planform records.

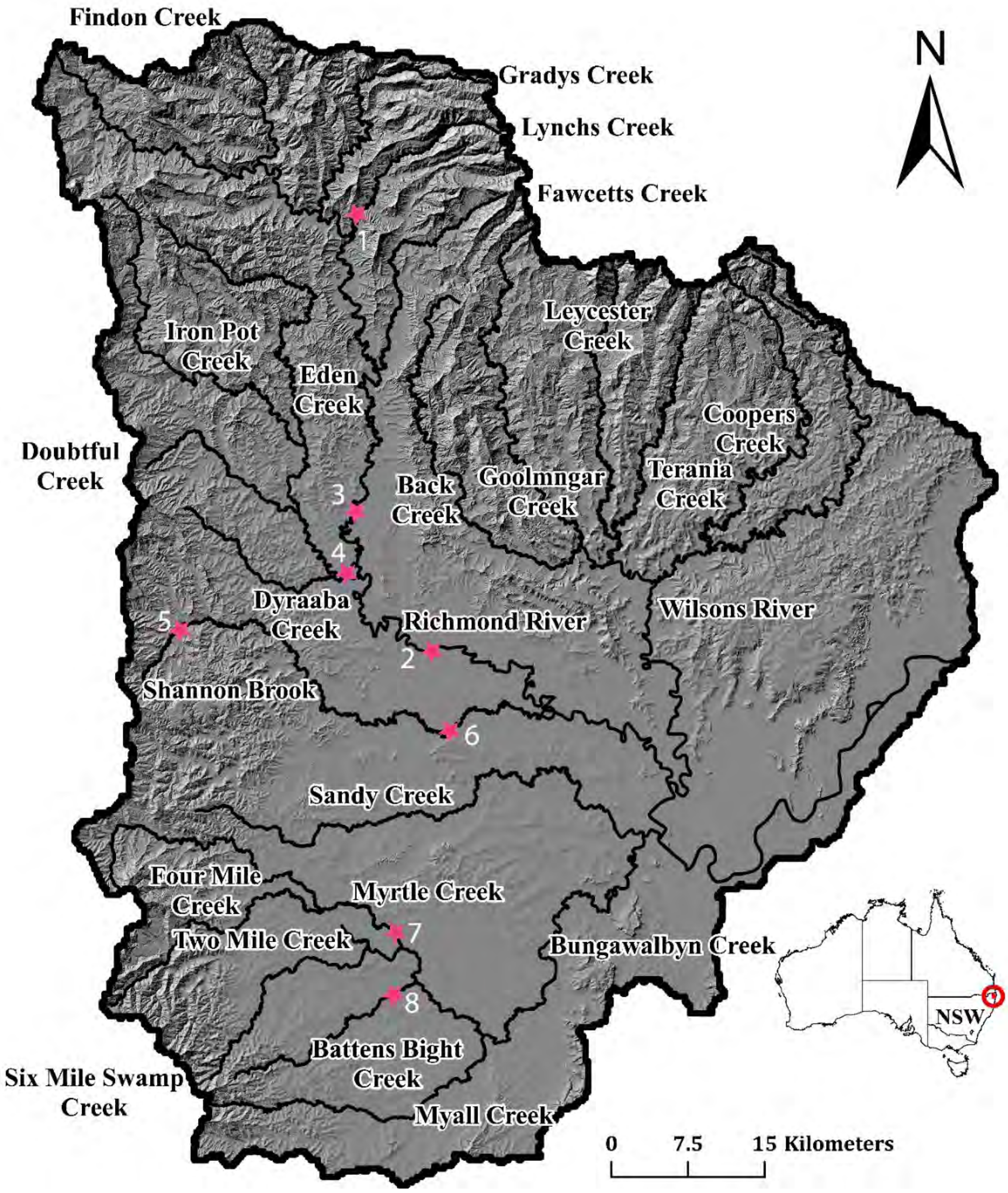

Figure 2 location of the Richmond River catchment and its tributaries. Field photographs at the right: (1) boulder bed river along Lynchs Creek (2) bedrock bed river at Casino along the Richmond River (3) gravel and sand bed river at MacDonals bridge along the Richmond River (4) sand bed river along Eden Creek (5) partially channelised pond along upstream Shannon Brook (6) sand bed river along dowsntream Shannon Brook (7) pond along Myrtle Creek (8) sand bed river along Battens Bight Creek


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There is significant variability in the lithology, topography and rainfall distribution throughout the Richmond catchment (Figure 3). The northern part of the catchment is comprised of young basalt geology that produces rugged hilly country with steep topography. The southern part of the catchment is comprised of relatively older underlying sandstone that produces gently rolling country with flat topography. This catchment experiences some of the highest rainfall in NSW and the streamflow is categorised as extreme late summer flows (Finlayson and McMahon, 1988). The rainfall is highest in the southern part of the catchment and decreases in the northern catchment.

Flood documentation extends back to 1857 and some of the largest floods on record occurred in 1861, 1945, 1954 and 1974. Following the catastrophic floods of 1954, the local community, state and local government implemented a number of flood mitigation efforts (https://rous.nsw.gov.au). The Bundjalung people are the traditional owners of the Richmond catchment. The mouth of the catchment was identified by the Europeans in 1828 and functioned as a major navigation port from the 1840s to the early twentieth century. Prior to the first land grants, deforestation for Cedar logging flourished across the catchment from 1842. The first large sawmill was built in 1865, the colonial sugar refinery started in 1881 and the first dairy cooperative was started in 1889 (Richmond River Historical Society). Currently, 48.4% of land use in the Richmond catchment comprises beef production, 41.2% by forestry, 4.3% by dairying, 3.6% by intensive agriculture, 1.7% by horticulture and 0.84% by urban areas (McKee et al., 2001).

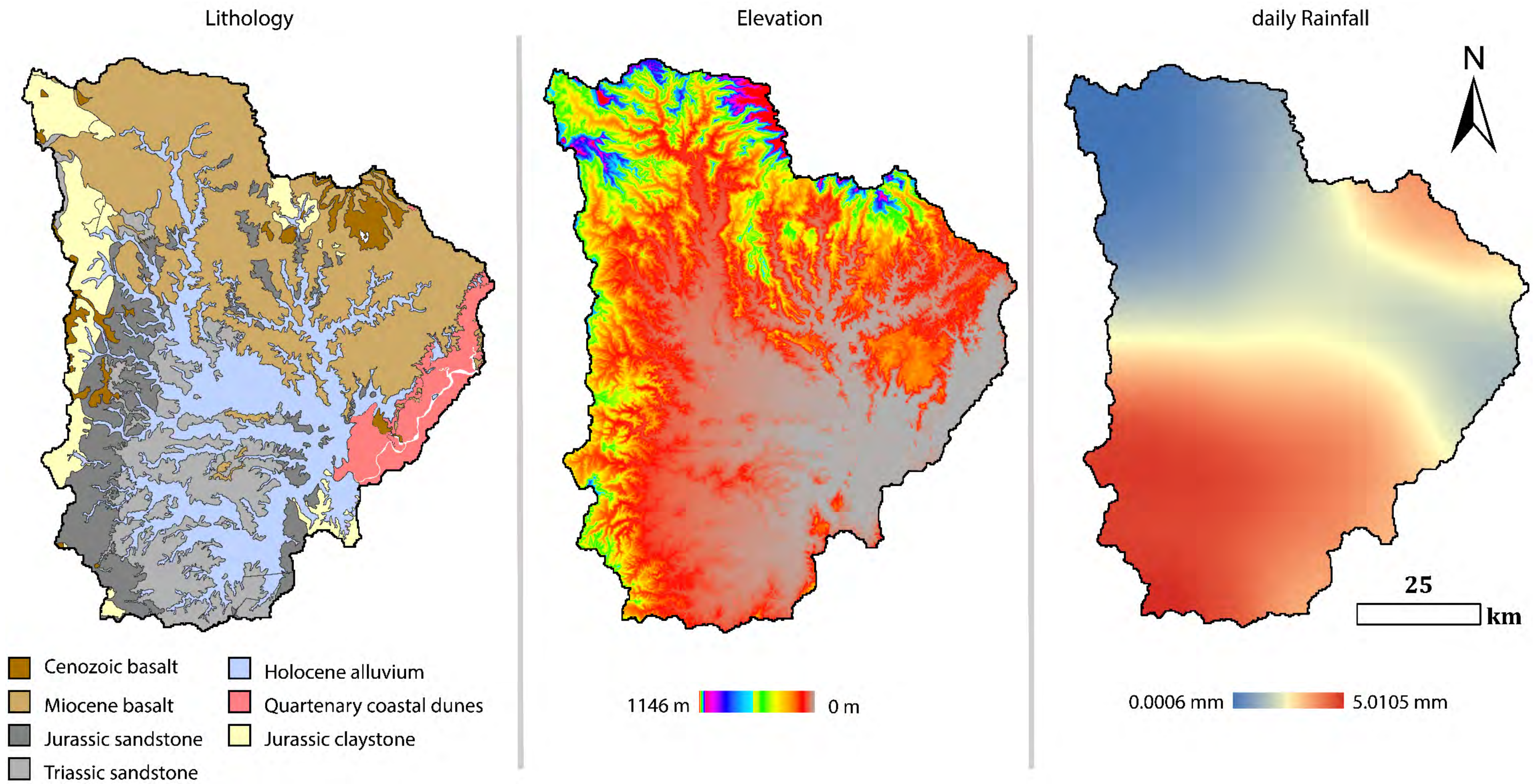

Figure 3 Lithology, elevation and rainfall variability across the Richmond catchment. Source: Geociences Australia

1.4. Thesis aims and structure

The overarching objective of this thesis is to determine the geomorphic sensitivity of rivers in the Richmond catchment at the landform scale, reach scale and catchment scale. This has been achieved using three key geomorphic attributes of a landscape: the mix of imposed and flux controls that govern the erosion-deposition dynamics occurring at any position in a catchment, system preconditioning that results from legacies of historical capacity for adjustment; and catchment scale sediment (dis)connectivity that governs the expression of geomorphic change in a catchment. In addition to this, this thesis also provides a package of remote sensing techniques and workflows for assessing geomorphic river sensitivity.

The thesis has five aims and comprises of three data chapters and two technical chapters. All chapters are set out as publications that are either published, under review or in preparation for submission to international journals. The final discussion chapter critically assesses the concept of geomorphic river sensitivity and how it can be measured and assessed using publicly available, remotely sensed datasets. Table 1 lists the thesis aims and sequentially links them to the thesis chapters.

Table 1 Relationship between thesis aims and associated chapters

S.No.	Thesis aims	Chapter number and title
1	To explain controls on geomorphic river diversity across the study catchment	2- Geomorphic controls
2	To provide GIS workflows to semi-automate the analysis of valley bottom extent, valley segmentation and to calculate imposed and flux controls across the study catchment using publically available datasets	3- Valley bottom extraction and segmentation 4- Semi-automating the catchment scale calculation of controls
3	To track post-colonisation geomorphic capacity for adjustment across the study catchment as a basis for developing a method for assessing river sensitivity	5- Tracking post-colonisation geomorphic river capacity for adjustment
4	To provide a workflow for the calculation of historical behavioural and change sensitivity across the study catchment to determine whether rivers are geomorphically Fragile, Active Sensitive, Passive Sensitive, Insensitive and Resistant, and to map this across the catchment	5- Tracking post-colonisation geomorphic river capacity for adjustment
5	To analyse the pattern of sediment (dis)connectivity across the study catchment as a basis to assess the role of system (de)coupling on network scale sediment flux in identifying hotspots of channel adjustment	6- Sediment (dis)connectivity

1.5. Author contributions

Here, the aims of the thesis are related to the chapters in a sequential order and the contribution of each individual author is specified

1.5.1. Geomorphic controls

Khan, S., Fryirs, K., Ralph, T. J. Geomorphic controls on the diversity and patterns of fluvial forms along longitudinal profiles. CATENA, in press.

The chapter titled ‘Geomorphic controls on the diversity and patterns of fluvial forms along longitudinal profiles’ is currently under review in the journal CATENA.

This chapter measures and statistically assesses the network scale mix of imposed and flux controls occurring along longitudinal profiles of various shape to explain the diversity, pattern and sequence of river types at different positions in a catchment.
This is used to analyse the imposed controls of slope and valley bottom width and the flux controls of bed material size and gross stream power for five river types, ranging from confined continuous rivers in headwaters to laterally unconfined discontinuous rivers in lowland plains. The results suggest that slope and gross stream power are strong, positively correlated controls on all river types, but act most strongly on rivers with continuous channels. In contrast, bed material size is a dominant control on rivers with discontinuous channels. Slope and gross stream power are also critical for determining the downstream pattern of river types along longitudinal profiles. This work demonstrates that an understanding the mix and patterns of controls operating along longitudinal profiles can be used to explain the variability and pattern of river types we see in the landscape.

Intellectual contribution- Sana Khan (65%), Kirstie Fryirs (25%), Tim Ralph (10%)

Data collection, analysis and interpretation- Sana Khan (85%), Kirstie Fryirs (10%), Tim Ralph (5%)

Manuscript preparation- Sana Khan (65 %), Kirstie Fryirs (30%), Tim Ralph (5%)

1.5.2. Valley bottom extraction and segmentation

Khan, S., Fryirs, K., 2020 Application of globally available, coarse resolution Digital Elevation Models for delineating valley bottom segments of varying length across a catchment. Earth Surface Processes and Landforms, *https://doi.org/10.1002/esp.4930*

This chapter titled ‘Application of globally available, coarse resolution Digital Elevation Models for delineating valley bottom segments of varying length across a catchment’ is published in the journal Earth Surface Processes and Landforms.

This chapter first presents an approach for delineating valley bottom extent across a large catchment using only publicly available, coarse-resolution DEM input. We assess the sensitivity of results to variable DEM resolution and find that coarse-resolution datasets (90m resolution) provide superior results. Also, the results show that LiDAR-derived DEMs produce more realistic results than satellite-derived DEMs across the full range of topographic settings tested. Satellite-derived DEMs perform more effectively in moderate topographic settings, but fail to capture the subtleties of valley bottom extent in mild gradient, low-lying topography and in narrow headwater reaches. Second, this chapter presents a semi-automated technique within ArcGIS for delineating valley bottom segments using DEM-derived network scale metrics of valley bottom width and slope. This study uses an unsupervised machine-learning technique based on the k-means clustering algorithm to solve a conundrum in GIS-based geomorphic analysis of rivers: the delineation of valley bottom segments of variable length. The delineation of valley bottom segments provides a coarse-scale entry point into automated geomorphic analysis and characterisation of river systems.

Intellectual contribution- Sana Khan (85%), Kirstie Fryirs (15%)

Data collection, analysis and interpretation- Sana Khan (95 %), Kirstie Fryirs (5%)

Manuscript preparation- Sana Khan (80%), Kirstie Fryirs (20 %)

1.5.3. Semi-automating the catchment scale calculation of controls

Khan, S., Fryirs, K., Shumack, S. Semi-automating the calculation of catchment scale geomorphic controls on river diversity using publically available datasets. CATENA, in press.

This chapter titled ‘Semi-automating the calculation of catchment scale geomorphic controls on river diversity using publically available datasets’ is currently in press in the journal CATENA.

This chapter presents a semi-automated GIS approach to quickly and accurately extract catchment scale geomorphic controls: slope, gross stream power, valley bottom width and bed material texture along a drainage network. To enable rapid application of this approach, workflow is provided for the calculation of elevation, slope, contributing catchment area and gross stream power embedded within ArcGIS toolkit, ArcGIS ModelBuilder and Python script as supplementary data. This study also presents an approach for disaggregating the drainage network and deciding on the most appropriate reach length over which to calculate slope based on catchment topography. One finding is that it is important to investigate DEM quality prior to use, select an appropriate flow accumulation algorithm, and validate the drainage network output using aerial imagery prior to use.

Intellectual contribution- Sana Khan (85%), Kirstie Fryirs (5%), Sam Schumack (10 %)

Data collection, analysis and interpretation- Sana Khan (90 %), Kirstie Fryirs (5%), Sam Schumack (5%)

Manuscript preparation- Sana Khan (85%), Kirstie Fryirs (10%), Sam Schumack (5%)

1.5.4. Tracking post colonisation geomorphic river capacity for adjustment

Khan, S., Fryirs, K., 2020. An approach for assessing geomorphic river sensitivity across a catchment based on analysis of historical capacity for adjustment. Geomorphology 359, 107135. https://doi.org/10.1016/j.geomorph.2020.107135

This chapter titled ‘An approach for assessing geomorphic river sensitivity across a catchment based on analysis of historical capacity for adjustment’ is published in the journal Geomorphology.

This chapter tracks the history of geomorphic river adjustment in the Richmond catchment from the time of European colonisation in the mid-late nineteenth century. The study develops an approach, called the ‘Behavioural sensitivity logical tree’ that can be applied to assess and quantify reach scale behavioural sensitivity, defined as the ease with which geomorphic units and associated water, sediment and vegetation interactions adjust within the expected behavioural regime. The results are then used to categorise rivers as Fragile, Active sensitive, Passive sensitive, Insensitive and Resistant.

Fragile rivers have a behavioural sensitivity > 75% and have the propensity to undergo wholesale river change such that a new river type and behavioural regime is created.

Active sensitive rivers have a behavioural sensitivity ranging from 50%–75% and have the ability to re-configure within their contemporary behavioural regime. The behavioural sensitivity of Passive sensitive rivers lies between 20%–50%. These rivers have the ability to maintain their behavioural regime and withstand adjustment. Insensitive rivers have a behavioural sensitivity ranging from5%–20%. They do not readily adjust and may contain significant antecedent elements that limit geomorphic adjustment. Resistant rivers have a behavioural sensitivity < 5% and because of the imposed geological setting cannot readily adjust. This study further discusses the evolutionary nature of behavioural sensitivity itself and how rivers can dynamically evolve and shift to a different sensitivity category over time in response to different forms of direct and indirect disturbances.

Intellectual contribution- Sana Khan (70%), Kirstie Fryirs (30%)

Data collection, analysis and interpretation- Sana Khan (85%), Kirstie Fryirs (15%)

Manuscript preparation- Sana Khan (55 %), Kirstie Fryirs (45%)

1.5.5. Sediment (dis)connectivity

Khan, S., Fryirs, K., Bizzi, S. In preparation. Tracking sediment (dis)connectivity across a river network to identify hotspots of potential geomorphic adjustment.

This chapter titled ‘Tracking sediment (dis)connectivity across a river network to identify hotspots of potential geomorphic adjustment’ has been prepared for submission to an international journal.

This chapter assesses the catchment scale pattern of sediment (dis)connectivity in the Richmond River catchment to identify hotspots of potential geomorphic adjustment. For cross-catchment analysis, spatial variability in effective catchment area and sedimentary buffer is assessed for interpreting the causes and consequences of system coupling-decoupling. An overall pattern shows that two distinct zones exists in the Richmond system: the disconnected or decoupled SW Richmond catchment and the connected or coupled NE Richmond catchment. Contextualisation of the system coupling-decoupling using locational-transmission-filter sensitivity show that during geomorphically effective events, the highly coupled NE Richmond catchment is relatively resilient to adjustment whereas the SW catchment is susceptible to onsite and offsite adjustment. The network scale pattern of sediment fluxes is used to identify potential locations of geomorphic activity (or hotspots) during geomorphically effective events and for identification of possible controls on geomorphic activity and sensitivity across the catchment. The results show that the major controls on sediment dynamics of the Richmond system are the locations of sediment stores within discontinuous water courses, transient sediment storages units within sand bed rivers, tributary confluence, junction of contrasting geomorphic rive types and floodplain pockets within partly confined planform controlled valley settings.

Intellectual contribution- Sana Khan (60%), Simone Bizzi (30%), Kirstie Fryirs (10%)

Data collection, analysis and interpretation- Sana Khan (85 %), Simone Bizzi (10%), Kirstie Fryirs (5%)

Manuscript preparation- Sana Khan (90%), Simone Bizzi (0%), Kirstie Fryirs (10%)

1.6. References

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Chapter 2

Geomorphic controls

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Khan, S., Fryirs, K. A., & Ralph, T. J. (2021). Geomorphic controls on the diversity and patterns of fluvial forms along longitudinal profiles. *Catena*, *203*, 1-15. [105329].

Access to the published version: https://doi.org/10.1016/j.catena.2021.105329

Chapter 3

Valley bottom extraction and segmentation

Pages 97-112 of this thesis have been removed as they contain published material. Please refer to the following citation for details of the article contained in these pages.

Khan, S., & Fryirs, K. A. (2020). Application of globally available, coarse resolution digital elevation models for delineating valley bottom segments of varying length across a catchment. Earth Surface Processes and Landforms, 45(12), 2788-2803.

Access to the published version: https://doi.org/10.1002/esp.4930

Chapter 4

Semi-automating the catchment scale calculation of controls

Pages 115-137 of this thesis have been removed due to copyright restriction. Please refer to the following citation for details of the article contained in these pages.

Khan, S., Fryirs, K. A., & Shumack, S. (2021). Semi-automating the calculation of catchment scale geomorphic controls on river diversity using publically available datasets. Catena, 203, 1-8. [105354].

Access to the published version: https://doi.org/10.1016/j.catena.2021.105354

Chapter 5

Tracking post-colonisation geomorphic river capacity for adjustment

Khan, S., & Fryirs, K. (2020). An approach for assessing geomorphic river sensitivity across a catchment based on analysis of historical capacity for adjustment. *Geomorphology*, *359*, [107135].

DOI: https://doi.org/10.1016/j.geomorph.2020.107135

Geomorphology 359 (2020) 107135

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

An approach for assessing geomorphic river sensitivity across a catchment based on analysis of historical capacity for adjustment

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ARTICLE INFO

Article history:
Received 6 December 2019
Received in revised form 28 February 2020
Accepted 29 February 2020
Available online 03 March 2020

Keywords:
Catastrophic floods
River management
River restoration
Forecasting
Post colonisation
Human disturbance

ABSTRACT

Contemporary river forms and processes can be heavily influenced by the legacies of anthropogenic disturbances to river systems. Knowledge of the historical range of river adjustment can be used to develop an understanding of a river's 'expected' character and behaviour. Drawing upon the case study of Richmond River Catchment, New South Wales, Australia, we track the history of geomorphic river adjustment from the time of European colonisation in the mid-late nineteenth century. We use this study to develop an approach, called the '*Behavioural sensitivity logical tree*' that can be applied to assess and quantify reach scale behavioural sensitivity, defined as the ease with which geomorphic units and associated water, sediment and vegetation interactions adjust within the expected behavioural regime. We use the results to categorise rivers as *Fragile*, *Active sensitive*, *Passive sensitive*, *Insensitive* and *Resistant*.

Fragile rivers have a behavioural sensitivity >75% and have the propensity to undergo wholesale river change such that a new river type and behavioural regime is created. Active sensitive rivers have a behavioural sensitivity ranging from 50%–75% and have the ability to re-configure within their contemporary behavioural regime. The behavioural sensitivity of Passive sensitive rivers lies between 20%–50%. These rivers have the ability to maintain their behavioural regime and withstand adjustment. Insensitive rivers have a behavioural sensitivity ranging from 5%–20%. They do not readily adjust and may contain significant antecedent elements that limit geomorphic adjustment. Resistant rivers have a behavioural sensitivity <5% and because of the imposed geological setting cannot readily adjust. We further discuss the evolutionary nature of behavioural sensitivity itself and how rivers can dynamically evolve and shift to a different sensitivity category over time in response to different forms of direct and indirect disturbances.

1. Introduction

In an era of degrading and depleting water resources, amplified by global climate change and increase in human population, management of freshwater resources is a high priority (Qin et al., 2019; Vorosmarty, 2000). Given the ubiquitous human impact on the fluvial landscape, the persisting legacies of anthropogenic alterations can considerably influence contemporary river forms and processes (Walter and Merritts, 2008; Wohl, 2019). Against this omnipresent backdrop, has been a growing need to understand a river's 'expected' or 'natural' character and behaviour, particularly in the context of determining what is realistically achievable in river rehabilitation and restoration (Bernhardt, 2005; Fryirs et al., 2015, 2012; Malakoff, 2004; Wohl et al., 2012). Moreover, lessons learned from the past have taught us that "it pays to do the painstaking work of historical sleuthing" (Montgomery, 2008; p. 282) even in areas thought to define benchmarks in understanding. Such work situates understandings about contemporary river response within an historical context and provides the basis for forecasting possible future responses to a range of disturbance events (Brierley and Fryirs, 2016; Downs and Gregory, 2014; Fitzpatrick and Knox, 2000; Fryirs et al., 2012; Gregory and Lewin, 2015; Lane, 2013; Wohl, 2017; Wohl et al., 2012).

One key concept that can be used is river sensitivity (Fryirs, 2017). Various studies have been conducted that assess river sensitivity at multiple spatial and temporal scales and geomorphologists have used a range of terminology to describe complex river responses to disturbance events: event sensitivity, degrees of instability, resilience, non-resilience, sensitive, robust, hypersensitive, over-relaxed and insensitive (Allison and Thomas, 1993; Brunsden and Thornes, 1979; Buckley, 1991; Chorley et al., 1984; Crozier, 1986; Downs and Gregory, 2014, 1995; Fitzpatrick and Knox, 2000; Fryirs et al., 2015, 2009; Fryirs, 2017; Fuller et al., 2019; Gordon et al., 2001; Graf, 1982, 1979; Piégay et al., 2018; Quine and Brown, 1999; Reid and Brierley, 2015; Schumm, 1998, 1988, 1985, 1976; Thomas, 2001; Thoms et al., 2018; Tooth, 2018). Schumm (1985) identified sensitivity as one of the seven reasons for geological uncertainty because of the variable spatial response of different landscape compartments to similar magnitude disturbance events. However, despite providing solid foundations for

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https://doi.org/10.1016/j.geomorph.2020.107135
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the conceptualisation of river sensitivity, these studies do not provide a consistent approach to assess reach-scale sensitivity that can be applied and mapped across a catchment (Fryirs, 2017). Furthermore, the lack of a clear and consistent approach for the analysis and measurement of river sensitivity inhibits comparison of the quantum of adjustment across catchments or regions.

Brunsden and Thornes (1979) define the sensitivity of a landscape to change "as the likelihood that a given change in the controls of a system will produce a sensible, recognisable and persistent response" (p. 476). This involves various aspects: the possibility of change, the propensity for change and the capacity of the system to withstand, absorb or adjust to that change (Chorley et al., 1984; Schumm, 1998; Downs and Gregory, 2014; Thoms et al., 2018; Tooth, 2018). However, geomorphic river adjustment is dynamic in nature, both spatially and temporally, resulting in complex forms and processes (Schumm, 1973). To make sense of this complexity and to provide guidance on ways to conceptualise and analyse it, Fryirs and Brierley (2013) make a clear distinction between river behaviour and river change. River behaviour is defined as "adjustments to river morphology induced by a range of erosional and depositional mechanisms by which water moulds, reworks and reshapes fluvial landforms, producing characteristic assemblages of landforms at the reach scale" (Brierley and Fryirs, 2005, p. 143). River behaviour reflects ongoing geomorphic adjustments over timeframes in which flux boundary conditions (i.e., flow and sediment regimes, and vegetation interactions) remain relatively uniform, such that a reach retains a characteristic set of process–form relationships (Fryirs and Brierley, 2013; Lane and Richards, 1997; Leopold et al., 1964). Lewin (1977) calls this the autogenic regime of a river. Therefore, each river type functions within a behavioural regime such that the interaction between flow, sediment and vegetation produces characteristic landforms or geomorphic units (Brierley and Fryirs, 2005; Fryirs and Brierley, 2013). Within this behavioural regime, a mix of erosional and depositional processes regularly moulds, reworks and reshapes these landforms and a reach experiences characteristic forms of adjustment that produce a set (or assemblage) of geomorphic units (Brunsden, 1993; Fryirs and Brierley, 2013; Lisenby and Fryirs, 2016). The forms and ease of adjustment that take place define a river's inherent behavioural sensitivity (Brunsden and Thornes, 1979; Fryirs, 2017). Because different river types have different capacity to adjust there is a gradation of behavioural sensitivity that occurs across the spectrum of river diversity. However, when subjected to a singular episodic disturbance event or a series of disturbance events (Baker and Costa, 1987; Phillips, 2009, 2003), the behavioural regime of some rivers (particularly those that are threshold-driven) can undergo wholesale shift such that a geomorphic 'metamorphosis'(Schumm, 1969), 'state transition' (Phillips, 2014) or 'river change' (Brierley and Fryirs, 2005; Fryirs

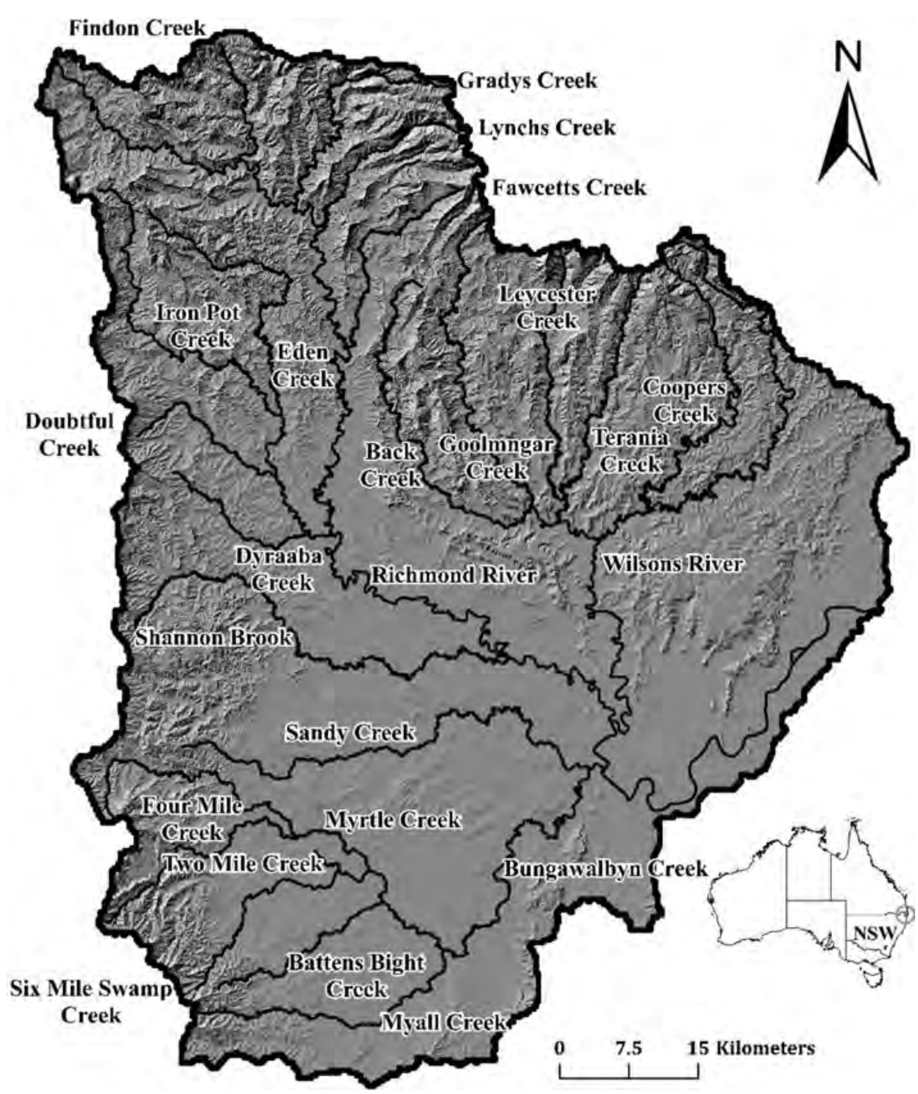


Fig. 1. Location of the Richmond catchment and its major tributaries.

and Brierley, 2013) occurs. This changes the river to a different type with a new set of process-form relationships (Fryirs et al., 2012; Fryirs and Brierley, 2013). Such rivers are change-sensitive (Fryirs, 2017).

One way to assess a river's behavioural or change sensitivity is to characterise and track geomorphic forms of adjustment over the historical record or a pre-defined timeframe of reference (Lisenby and Fryirs, 2016). Such work is variously called analysis of response gradients (Fryirs et al., 2009), historical range of variability (Wohl et al., 2012), expected capacity for adjustment (Fryirs et al., 2012), and evolutionary trajectory (Brierley and Fryirs, 2016; Scorpio et al., 2015). When the behavioural and/or change sensitivity of each river type is analysed across a catchment, the spatial pattern of sensitivity can be assessed and hotspots of sensitivity identified.

Tracking behaviour and change over time introduces the idea that a river's behavioural sensitivity is not static in time, but can dynamically evolve such that some rivers can become more sensitive to future disturbances, others may become more resilient (Downs and Gregory, 2014; Fryirs, 2017; Schumm, 1998). Such analyses provide the foundations for extension work to examine the geomorphic effectiveness of different disturbance events on sensitivity (Costa and O'Connor, 1995; Fryirs et al., 2015), the analysis of threshold conditions under which change occurs (Bull, 1979; Chappell, 1983; Schumm, 1979), the role of pre-conditioning and antecedence on contemporary forms and processes (Crozier, 1999; Phillips, 2006; Trofimov and Phillips, 1992), and reaction, relaxation and the recovery times following disturbance (Allen, 1974; Chappell, 1983). Such foundation understanding is required for geomorphological forecasting of likely event sensitivity to a range of possible future disturbances (Crozier, 1999; Fryirs, 2017).

Although advances have been made in the understanding of geomorphic river sensitivity, there are very few documented applications of the concept in practice (Fryirs, 2017; Lisenby et al., 2019; Preston et al., 2011; Tooth, 2018; Wohl, 2014). Viewing behavioural and change sensitivity as set out in this paper provides a basis for developing an analytical approach that can be used to assess river sensitivity in both space and over time. In this paper, we develop an approach for assessing river sensitivity called the '*Behavioural sensitivity logical tree*'. We then apply this approach across the Richmond River Catchment, New South Wales, Australia. We track forms of geomorphic adjustment of the fluvial system since European colonisation in the mid-late nineteenth century. We use the output to categorise reaches across the catchment as Fragile, Active sensitive, Passive sensitive, Insensitive and Resistant, providing a snapshot of contemporary hotspots of sensitivity. We then discuss the evolutionary nature of behavioural sensitivity and how the approach can be used elsewhere.

2. Regional setting

The Richmond River is located in the subtropical zone of the far North Coast of New South Wales (NSW). The river emerges from the Great Dividing Range on the slopes of the McPherson Range and flows southeast into the Tasman Sea. The Richmond River drains a catchment area of 6858 km^2 and receives major flow contributions from its two major tributaries, Wilsons River and Bungawalbyn Creek (Fig. 1). The northern part of the catchment is comprised of young basalt geology that produces rugged hilly country with steep topography. The southern part of the catchment is comprised of relatively older underlying sandstone that produces gently rolling country with flat topography. This catchment experiences some of the highest rainfall in NSW and the streamflow is categorised as extreme late summer flows (Finlayson and McMahon, 1988). Flood documentation extends back to 1857 and some of the largest floods on record occurred in 1861, 1945, 1954 and 1974. Following the catastrophic floods of 1954, the local community, state and local government implemented a number of flood mitigation efforts (https://rous.nsw.gov.au).

The Bundjalung people are the traditional owners of the Richmond catchment. The mouth of the catchment was identified by the Europeans in 1828 and functioned as a major navigation port from the 1840s to the early twentieth century. Prior to the first land grants, deforestation for Cedar logging flourished across the catchment from 1842. The first large sawmill was built in 1865, the colonial sugar refinery started in 1881 and the first dairy cooperative was started in 1889 (Richmond River Historical Society). Currently, 48.4% of land use in the Richmond catchment comprises beef production, 41.2% by forestry, 4.3% by dairying, 3.6% by intensive agriculture, 1.7% by horticulture and 0.84% by urban areas (McKee et al., 2001).

3. Methods

3.1. Data acquisition and processing

To analyse the behavioural sensitivity of rivers, *a logical tree* was developed (Fig. 2). The data used include Digital Elevation Models (DEM), satellite imagery, historical planform records and historical streamflow datasets. The 2-m spatial resolution LiDAR DEM tiles were obtained from the Elevation and Depth Foundation Spatial Data website (https://elevation.fsdf.org.au/) and mosaicked in ArcMap 10.5 to produce a catchment scale DEM and hillshade raster. SAGA GIS was used for generating multiple flow direction flow accumulation, which was further used in ArcMap to delineate the streamline shapefile of all the rivers in the Richmond catchment. This streamline shapefile was validated using the country wide hydrology dataset available from Geosciences Australia (https://www.ga.gov.au/) and 50-cm resolution satellite imagery available from Sixmaps (https://maps.six.nsw.gov.au/). The DEM and streamline shapefile were used to generate longitudinal profiles for all the rivers along which historical mapping took place.

The *first step of the logical tree* involves selection of the representative reaches on the basis of the downstream pattern of river types along longitudinal profiles (Fig. 3). Stage 1 of the River Styles Framework (Brierley and Fryirs, 2005; Fryirs and Brierley, 2018) was used to identify the range of river types occurring in the Richmond catchment (Table 1 and Fig. 3). This analysis was undertaken using desktop and field-based investigation. Each river type was identified using hillshade raster and satellite imagery on the basis of confinement (position of the channel within the valley setting), channel planform characteristics (channel continuity, number of channels, sinuosity), geomorphic unit assemblage and bed material texture. All River Styles and their attributes were verified in the field. On the basis of valley confinement, rivers were categorised as confined where >85% of either channel margin abuts a valley bottom margin, partly confined bedrock margin controlled where 50–85% of either channel margin abuts a valley bottom margin, partly confined planform margin controlled where 10–50% of either channel margin abuts a valley bottom margin and laterally unconfined where <10% of either channel margin abuts a valley bottom margin (sensu Fryirs et al., 2016; O'Brien et al., 2019). Given the number of meandering variants of rivers found in the Richmond catchment, sinuosity became an important factor for differentiation. If the sinuosity of the channel was between 1.06 and 1.30, the reach was characterised as a low sinuosity river. If the sinuosity of the channel was >1.30 without evidence of paleo cut-offs on the floodplain, the reach was characterised as a sinuous river. If the sinuosity was >1.30 and paleo cut-offs were present, the reach was characterised as a meandering river. If there were multiple cut-offs observed, then the reach was characterised as a cut-off river. For the cut-off rivers with a high propensity of chute cut-offs, the reach was further differentiated as an active cut-off river. This contrasts with passive cut-off rivers where the cut-offs are isolated on the floodplain.

The oldest and longest flow stage record for the Richmond River was obtained from the Rouse County Council website (https://rous.nsw.gov.au). Lismore flood stage data recording moderate to major flood peaks from the 1870s to present was the longest record available. For reconstructing the history of geomorphic river adjustment, three types of historical planform records were used: aerial imagery, parish maps and the first surveyor notebooks. Digital copies of the parish maps of the entire catchment dating back to the 1890s were obtained from the NSW Land Registry Services (in Sydney) to extend the sequence back to early surveys of the area after European settlement. Hard copies of the 1940s aerial photographs were viewed at the National Library of Australia (in Canberra) and scanned at 1200 dots per inch resolution. Electronic copies of aerial imagery from the 1950s to 2009 were obtained from the NSW State Spatial Services (in Bathurst). Because of the vast spatial coverage of the study area, the aerial imagery encompassed multiple time slices for different

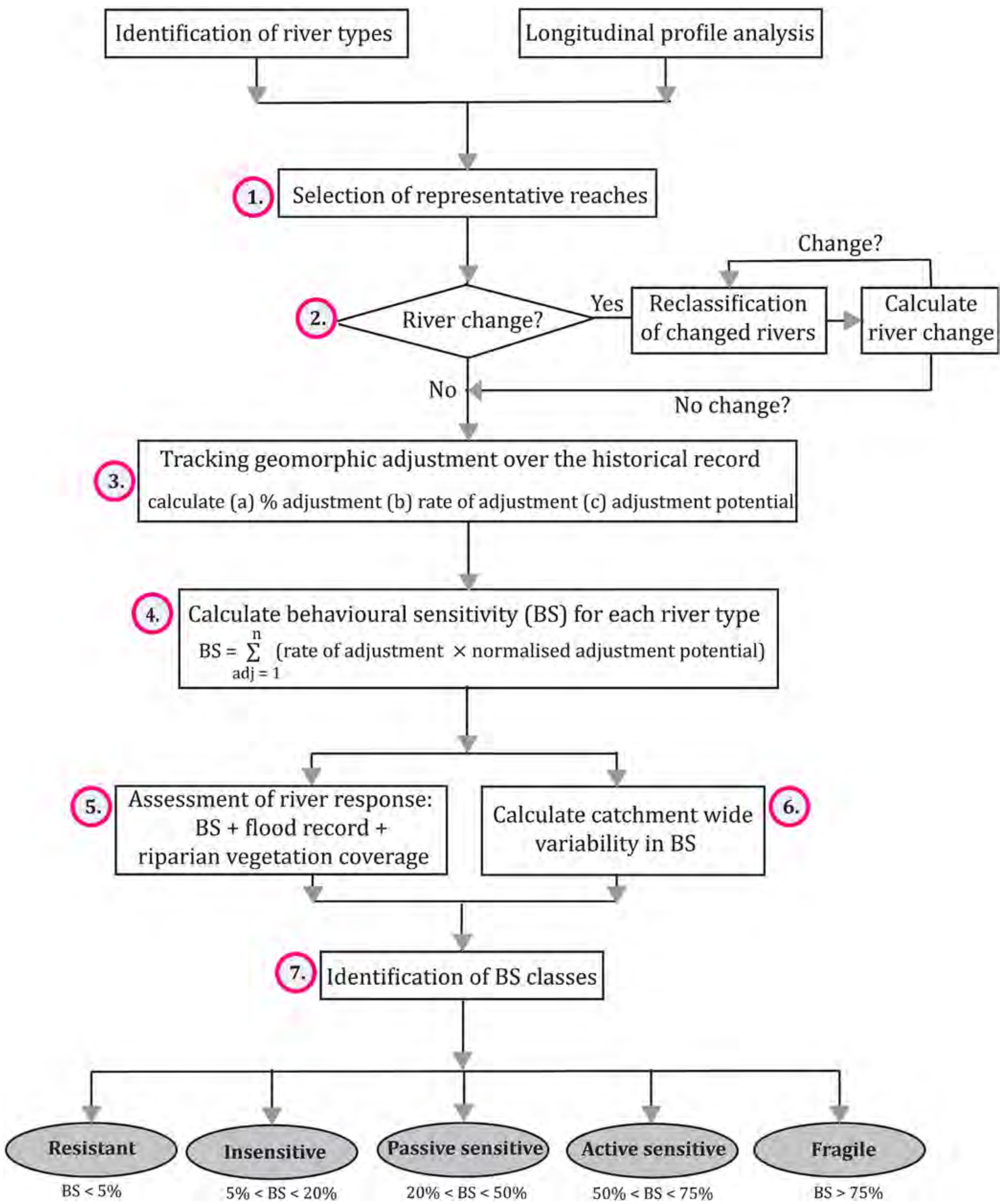


Fig. 2. Logical tree showing the geomorphic river change and geomorphic behavioural sensitivity (BS) approach used in this study.

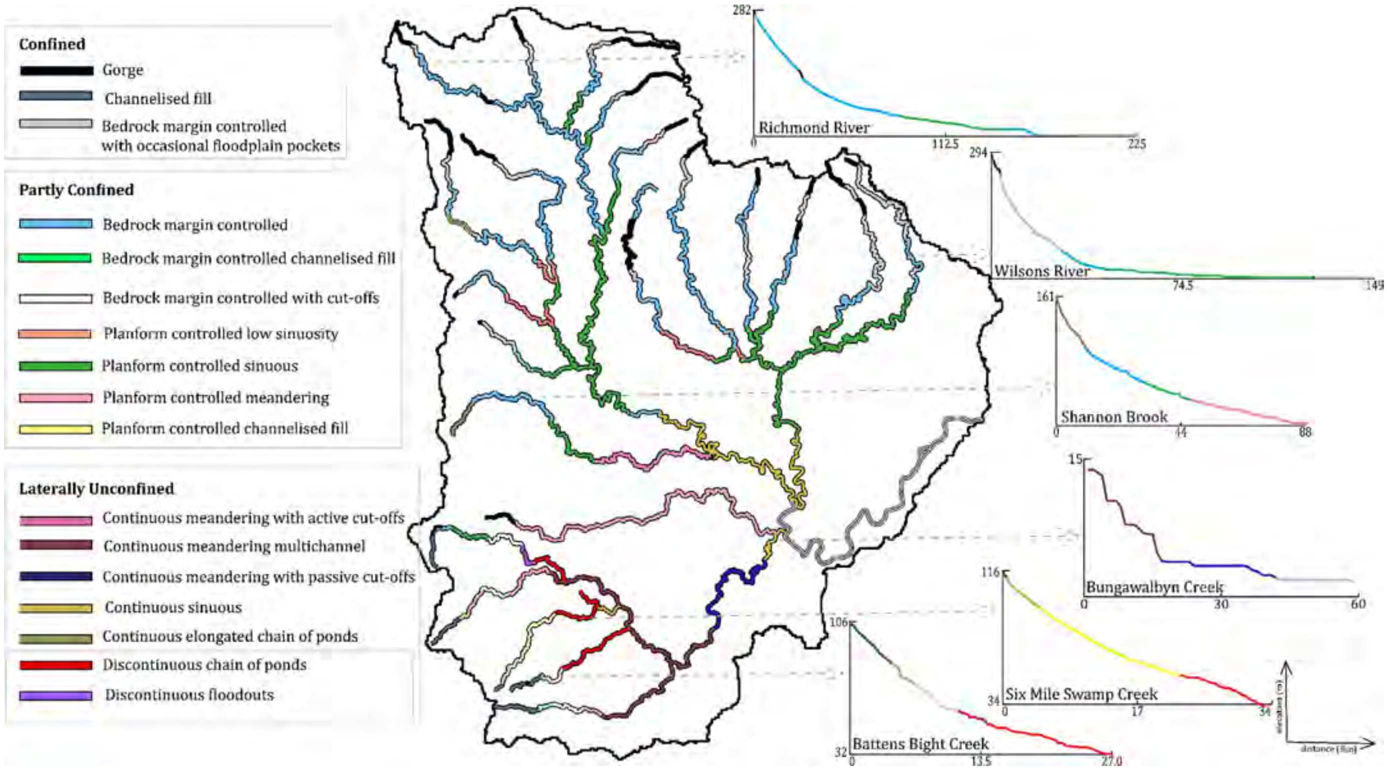


Fig. 3. River Styles identified in the Richmond catchment and the longitudinal profiles of the streams analysed.

administrative boundaries, i.e., the catchment-wide imagery was not uniformly available for all the years. Further historical information was obtained from the Surveyor General's survey books from 1878 that were viewed in the NSW State Archives (in Kingswood). These books contain information on vegetation distribution and type, river configuration and the presence or absence of features such as pools, riffles, etc. The aerial photographs and parish maps were orthorectified and digitised in ArcMap. The resolution of the aerial imagery and maps was variable; therefore, digitisation was performed at a scale ranging from 1:3000 to 1:6000.

3.2. Measurement of change and behavioural sensitivity

The *second step of the logical tree* is used for rivers that have undergone wholesale river change. If wholesale river change was observed, Stage 1 River Styles analysis was reiterated for each time slice and river change was recorded in the stream shapefile attribute table. At each iteration, river change was calculated as the ratio of stream length undergoing wholesale change to the total reach length:

$$\%River\ change = \frac{(Total\ length\ of\ stream\ undergoing\ wholesale\ change)}{(Total\ stream\ length)} \times 100 \qquad (1)$$

The *third step of the logical tree* (Fig. 2) is used to track the decadal geomorphic adjustments along the stream network. First, the length of reach affected by each form of geomorphic adjustment for each river type in each decadal time slice was recorded in the stream shapefile attribute table (ΔL). The oldest available record, the Surveyor General's survey book from the year 1878 described some of the planform, geomorphic and vegetation characteristics of the rivers. Given that the survey notebooks and parish maps only contain coarse-level information, only channel planform adjustments such as channelisation, occurrence of cut-offs, bend adjustments and channel straightening could be discerned from these records.

For each time slice, the type and spatial extent of each form of adjustment was used to calculate the decadal percentage of stream length that experienced adjustment for each reach of each river type:

$$\%adjustment = \frac{\Delta L}{L} \times 100 \qquad (2)$$

Second, the rate of adjustment was calculated by dividing Eq. (2) by the number of times the adjustment was recorded or the adjustment frequency between time slices:

$$rate\ of adjustment = \frac{\%adjustment}{adjustment\ frequency\ (years)} \qquad (3)$$

Third, the adjustment potential of each form of geomorphic adjustment was calculated by multiplying the length affected by that adjustment (ΔL) with the probability of adjustment for all the time slices, where the probability of adjustment is the inverse of the number of times that particular adjustment was recorded (Eq. (4)). This adjustment potential quantifies the relative extent to which various forms of adjustments alter a reach. The values of adjustment potential were normalised between 0 and 1.

$$adjustment\ potential\ (P) = (\Delta L \times probablity\ of\ adjustment) \qquad (4)$$

The *fourth step of the logical tree* is used to calculate the behavioural sensitivity for each river type (that underwent adjustment within its behavioural regime) using the rate of adjustment and the normalised adjustment potential calculated using Eqs. (3) and (4). For this, the value of normalised adjustment potential was multiplied by the rate of adjustment of each form of adjustment across the entire period of record and aggregated to calculate the behavioural sensitivity of each river type (Eq. (5)). Thus, behavioural sensitivity of a river type is a function of the reach length affected by geomorphic adjustment and the potential for that form of adjustment to geomorphically alter a reach.

$$behavioural\ sensitivity = \sum_{adj=1}^{n}(rate\ of\ adjustment \times normalised\ P)\ (5)$$

The *fifth step of the logical tree* is used to assess the timing of river response by determining the extent to which river adjustment or change coincides with the timing of changes in riparian vegetation coverage or flood events. Changes in riparian vegetation coverage were qualitatively assessed using a visual estimate of the change in vegetation density occurring in the riparian zone of each stream between each time slice. These changes in the riparian vegetation coverage were recorded either as decrease, slight increase, increase or major increase.

The *sixth step of the logical tree* is the derivation of catchment scale behavioural sensitivity. Because reaches falling within the same River Style function within a specific behavioural regime, the value of the behavioural sensitivity calculated for each sample of the River Style was uniformly assigned to all the remaining reach samples of that River Style.

The *seventh and the final step* of the logical tree is the identification of distinct classes of river response and their ranges of behavioural sensitivity. Five behavioural sensitivity classes emerged for the Richmond River system analysis: *Resistant* (BS < 5%), *Insensitive* (BS = 5–20%), *Passive sensitive* (BS = 20–50%), *Active sensitive* (BS = 50–75%) and *Fragile* (BS > 75%).

4. Results

4.1. River types and geomorphic forms of adjustment in the Richmond catchment

Table 1 outlines the geomorphic attributes of rivers in the Richmond catchment categorised using Stage 1 of the River Styles Framework. There are 17 different River Styles in the catchment that occur along several different downstream patterns (Fig. 3). The NE catchment consists of Wilsons River and its tributaries, the Richmond trunk stream and its upstream tributaries that are characterised by continuous single channels throughout. The longitudinal profiles of these channels consist of localised knickpoints that coincide with bedrock outcrops at changes in lithology (Richmond River and Wilsons River in Fig. 3). This contrasts to the rivers in the SW that are dominated by discontinuous water courses and multi-channel systems. The knickpoints along the longitudinal profiles record the history of river incision (Bungawalbyn Creek, Six Mile Swamp Creek and Battens Bight Creek in Fig. 3). Shannon Brook lies between the NE and SW catchment and exhibits a mix of characteristics of both the NE and SW systems (Fig. 3).

Almost all the streams of the catchment include a confined gorge in the headwaters that is characterised by steep slopes and very narrow valleys. It is followed by confined, bedrock margin controlled rivers within slightly wider valleys where occasional floodplain pockets can form. Farther downstream, the pattern of river varies in different regions of the catchment. In the NE, the rivers form partly confined

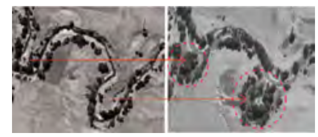
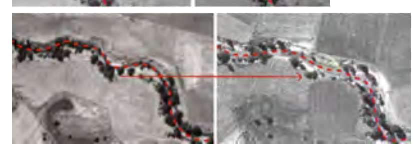
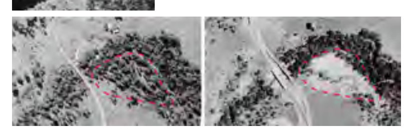
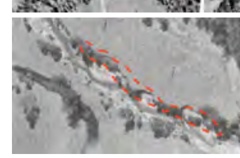
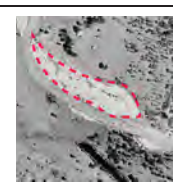
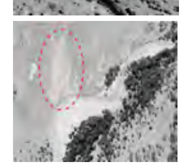
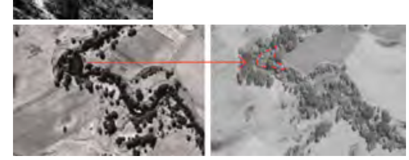
Table 1
Geomorphic characteristics of River Styles identified in the Richmond Catchment.

Valley setting	River style	River characteristics
Confined (>85% of either channel margin abuts valley bottom)	Confined gorge	Very steep gradient, no floodplain, bedrock steps, pools and riffles, cascades. Bed material is mainly bedrock with boulder, gravel and sand
	Confined channelised fill	Very steep gradient, occasional floodplain. Channel incised through valley fill. Bedrock steps, pools and riffles, cascades. Bed material is bedrock and coarse sand
	Confined bedrock margin controlled with occasional floodplain pockets	Steep gradient, occasional pockets of floodplain that are dominated by bedrock outcrops, pools and riffles. Bed material is mainly bedrock with boulder and sand
Partly confined (10–85% of either channel margin abuts valley bottom)	Partly confined bedrock margin controlled	Medium gradient, discontinuous floodplain, bedrock outcrops, benches, point bars, pools and riffles. Bed material is bedrock and coarse sand
	Partly confined bedrock margin controlled channelised fill	Medium gradient, discontinuous floodplain. Channel incised through valley fill. Benches, lateral bars and bedrock outcrops. Bed material is bedrock and coarse sand
	Partly confined bedrock margin controlled with cut-offs	Medium gradient, discontinuous floodplain, bedrock confined channel meandering on sand bed, multiple cut-offs, point bars and benches. Bed material is bedrock and coarse sand
	Partly confined planform controlled low sinuosity	Medium gradient, discontinuous floodplain, low sinuosity channel with sinuosity <1.06, lateral bars, benches and ledges. Bed material is medium to coarse sand
	Partly confined planform controlled sinuous	Medium gradient, discontinuous floodplain, sinuous channel with sinuosity from 1.06 to 1.30, point bars, benches and ledges. Bed material is medium to coarse sand
	Partly confined planform controlled meandering	Medium gradient, discontinuous floodplain, meandering channel with sinuosity >1.31, cut-offs, flood runners, point bars and benches. Bed material is medium to coarse sand
	Partly confined planform controlled channelised fill	Medium gradient, discontinuous floodplain, continuous channel incised through valley fill. Sand sheets, sand slug, benches, lateral bars and bedrock outcrops. Bed material is medium to coarse sand
Laterally unconfined (<10% of either channel margin abuts valley bottom, or channel is discontinuous/absent)	Laterally unconfined continuous meandering with active cut-offs	Continuous, tortuous meandering channel with multiple active chute cut-offs, flood runners, benches, point bars, sand slug, ridges and swales. Bed material is medium to coarse sand
	Laterally unconfined continuous meandering multichannel	Continuous meandering multi-channel with ill-defined banks, benches, flood runners, mid channel and point bars. Bed material is medium to coarse sand
	Laterally unconfined continuous meandering with passive cut-offs	Continuous tortuous channel with multiple isolated cut-offs, flood runners, ridges and swales, benches, ledges, sand slug and fine-grained sculpted point bars. Bed material is medium to fine sand
	Laterally unconfined continuous sinuous	Continuous sinuous channel with bank attached benches, ledges and point bars. Fine bed material with clay and silt
	Laterally unconfined continuous elongated chain of ponds	Incised elongated ellipsoidal ponds with gullied connecting channels between ponds that connects the flow during medium to high stage events. Ledges, sand slug and sand sheets. Bed material in ponds is medium to coarse sand and is gravels, fine to coarse sand in connecting gullies
	Laterally unconfined discontinuous chain of ponds	Ellipsoidal ponds separated by swampy preferential flow path. Pond bed material is medium to coarse sand
	Laterally unconfined discontinuous floodouts	Discontinuous channel separated by sand-based floodouts on floodplain or intact valley fill

variants with deep and narrow cross sections and channels of low to medium sinuosity planform. In the most downstream parts of these systems, the rivers transition to laterally unconfined rivers with both low sinuosity and meandering planform. In the SW, the rivers have highly variable cross section and planform attributes. In the downstream parts of this catchment, the rivers occur in wide alluvial plains and contain both discontinuous watercourses (chain of ponds, swamps and floodouts) and laterally unconfined multichannel and meandering single channels with cut-offs. The upstream reaches of Shannon Brook consist of elongated chain of ponds representing degraded discontinuous water courses followed by partly confined variants of continuous channel that transition into laterally unconfined valleys with continuous meandering channels and active cut-offs.

From the historical analysis, ten forms of geomorphic adjustment were identified within two broad categories: erosional and depositional (Table 2). Erosional forms of adjustment include chute cut-off

Table 2
Erosional and depositional forms of geomorphic adjustment identified along rivers in the Richmond catchment.

Erosional forms of adjustment	
Chute cut-off (C) Formed at high flow stage when a meander bend is cut-off via chute channel formation. A reduction in channel sinuosity results.	
Bend adjustment (Bn): bend expansion, translation, rotation and extension Occurs at high flow stages when the river erodes a bank (usually the concave bank) and the channel bend expands at the bend or shifts laterally.	
Channel straightening (Cs) Occurs at high flow stage when flow takes a more direct path down-valley. Bend cut-offs, incision and knickpoint retreat or reoccupation of palaeochannels may all be responsible for channel straightening. A reduction in channel sinuosity results.	
Incision (I) Occurs at moderate and high flow stages with sufficient energy to cut down vertically through a channel bed or valley fill. A knickpoint may form that retreats upstream. Sediment supply increases and channel straightening can result.	
Floodplain stripping (Fp) Removal of sections of floodplain at high flow stages. Common in partly confined valleys where overbank flows with sufficient energy scour and remove whole sections of floodplain.	
Ledges (L) Formed by expansion of the macro channel via scour of pre-existing floodplain. Usually flat topped and stepped bank attached features.	
Depositional forms of adjustment	
Sediment slug (SS) Occurs when there is an oversupply of sediment to a channel and the capacity-limit of the receiving channel is exceeded. Sediment slugs moves downstream as a pulse.	
Sand sheet (Sh) Formed when flow is dispersed over the floodplain and loses its transport capacity. Sediment splays onto the proximal floodplain.	
Bars (Br) Formed by deposition of sediment in the channel during low to medium flow stages.	
Benches (B) Formed by channel contraction via vertical accretion of sediment during moderate flood events. Usually flat topped and stepped bank attached features. Create compound channels.	

formation, bend adjustments (bend expansion, translation, rotation and extension), channel straightening, incision, floodplain stripping and ledge formation. Sediment is often reworked to produce transient depositional units like sand slugs and sand sheets or forms relatively permanent depositional geomorphic units like bars and benches.

When analysed across the catchment, certain adjustments are more common and affect a significant reach length whereas others are more localised (Fig. 4). Chute cut-offs and floodplain stripping occur along localised sections of bends and have the lowest adjustment potential. Ledges, bars, benches and sediment slugs have moderate adjustment potential. More transient sand sheets have high adjustment potential and can occur along large sections of river. More permanent erosional forms of adjustment such as incision, bend adjustment and channel straightening occur over extensive reach length, hence have the highest adjustment potential.

4.2. Historical river change and river behaviour in the Richmond catchment

Drastic river change was observed in several rivers in the SW Richmond catchment (Figs. 5 and 6). From 1890s to 2009, several discontinuous water courses along Six Mile Swamp Creek and Battens Bight Creek were transformed to continuous channels. As a result of this irreversible change, the reaches adjusted to a new process regime. In the Surveyor General's book of 1878, Six Mile Swamp Creek was labelled as Six Mile Water Holes ('W.H.'), indicating that the contemporary reaches with continuous channels had been a discontinuous chain of ponds at that time. The 1890s parish maps also show the entire Six Mile Swamp Creek (Fig. 5) and Battens Bight Creek systems as a series of 'W.H.' on a swampy floodplain. Comparison between the parish maps and first available aerial imagery in 1955 showed that the chain of ponds system was either (1) channelised via headcut initiation or (2) undergoing incision and widening of a preferential flow path producing a longitudinal elongation of the ponds that subsequently channelised into continuous channels. For both types of channelisation mechanisms, the most sensitive areas to disturbance were in the highest elevation reaches with high potential energy generated on relatively steep slopes. For the type 1 initiation, once the channelisation commenced, headcuts travelled in the upstream direction (Fig. 5a). This resulted in a cascading effect that resulted in floodout formation and channelisation of downstream reaches (Fig. 5b).

Fig. 6 shows the decadal river change alongside the flow record and observed vegetation change for Six Mile Swamp Creek and Battens Bight Creek. Bar graphs show for each decade the percentage of reach length affected by different forms of adjustment. The cumulative percent adjustment for each form of adjustment occurring for each river type was used along with the values of normalised adjustment potential to calculate the net behavioural sensitivity of each river type. The values of behavioural sensitivity for various river types are noted in the legend for each River Style (Fig. 6).

The most dramatic phase of river change coincided with the extreme floods of 1931, 1945, 1948 and 1954. During this phase, 55.4% of Six Mile Swamp Creek and 44.3% of Battens Bight Creek was transformed into

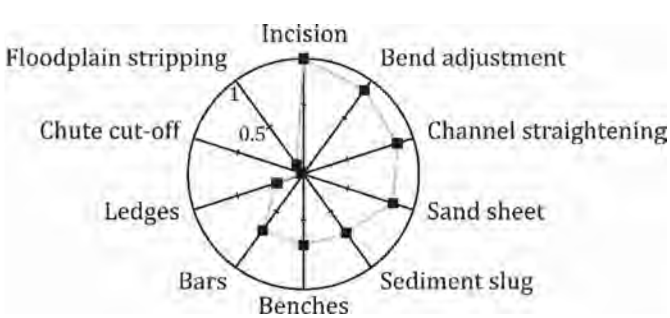


Fig. 4. Normalised adjustment potential (P) calculated for various forms of geomorphic adjustment identified along rivers in the Richmond catchment.

partly confined and laterally unconfined channelised fills. Between 1955 and 1964, 13.8% of Six Mile Swamp Creek underwent river change dominated by erosional forms of adjustments: incision, channel expansion by ledge formation, straightening with only minor deposition via instream sand slugs, floodplain sand sheets and bars. This time slice was punctuated by three major flood events in 1956, 1962 and 1963 and significant reduction in riparian vegetation coverage. By contrast, during this period, no wholesale change nor change in riparian vegetation coverage was recorded along Battens Bight Creek. Only local erosional and depositional forms of adjustments occurred during the 1950s and 1960s flood events. Between 1964 and 1979, the extent of river change along Six Mile Swamp Creek was reduced to 7.4%, but along Battens Bight Creek it increased to 20.3%. Bench formation started along the channels of both systems. This time slice experienced multiple flood events and an increase in riparian vegetation coverage was observed along Six Mile Swamp Creek with a slight increase along Battens Bight Creek. In the next decade (1979–1988), the chain of ponds became fully channelised resulting in 22.7% river change along Six Mile Swamp Creek and 5.5% river change along Battens Bight Creek. This decade was punctuated by five major flood events and the riparian vegetation coverage moderately increased along Battens Bight Creek and significantly increased along Six Mile Swamp Creek. The occurrence of bench formation and a transition to dominantly depositional forms of adjustment were observed from this period onwards. Between 1988 and 1994, the headcut continued to travel upstream along Six Mile Swamp Creek to form the laterally confined channelised fill resulting in a further 5.9% river change in this system. No further change was noted along Battens Bight Creek. Only a single flood event occurred in 1989 and the riparian vegetation coverage had significantly increased along both channels. Between 1994 and 2009, no further river change was observed along Six Mile Swamp Creek, however, a 9.5% change was observed along Battens Bight Creek as the headcut travelled into the headwater regions.

Historical imagery for the upstream reaches of Shannon Brook was only available from 1960s onwards. At this time, the system consisted of elongated chain of ponds. This likely represents a geomorphically degraded chain of ponds that had been experiencing channelisation prior to the 1960s. Between 1960s and 1970s, vegetation coverage increased and the only visible adjustment for these elongated chain of ponds was the formation of benches in connecting channels. Post 1970s, no further adjustments were observed for these upstream reaches of Shannon Brook.

In contrast to the SW rivers, the rivers in the NE part of the Richmond catchment did not undergo wholesale river change but have been adjusting within their behavioural regime. Fig. 7 shows the decadal river change alongside the flow record and observed vegetation change for Shannon Brook and the Wilsons River. The net behavioural sensitivity of each river type is noted in the legend for each River Style. In the downstream section of Shannon Brook, along the laterally unconfined continuous meandering reaches with active cut-offs, numerous erosional and depositional forms of adjustment were noted during the study period (Fig. 7a). Between 1890s and 1940s, around 50% of reach length was affected by various forms of bend adjustment. No vegetation data could be confidently discerned from the parish maps, but the flow stage record in this period shows the occurrence of multiple flood events. The 1940s imagery of Shannon Brook shows almost no riparian vegetation, and only a small increase in the next decade. Flood events occurred in 1945, 1948, 1954 and 1956. In the 1940s and 1950s, around 20% of reach length experienced erosional forms of adjustment that caused lateral realignment of channel position on the valley bottom via chute cut-off, bend adjustment and channel straightening. Further, around 22% of channel length experienced depositional forms of adjustment via sand slugs, sand sheet, bars and benches. During the 1950s and 1960s, the pattern of adjustment shifted towards predominantly deposition with the formation of benches along 45% of river length and only 4% erosion via chute cut-offs, channel straightening and floodplain

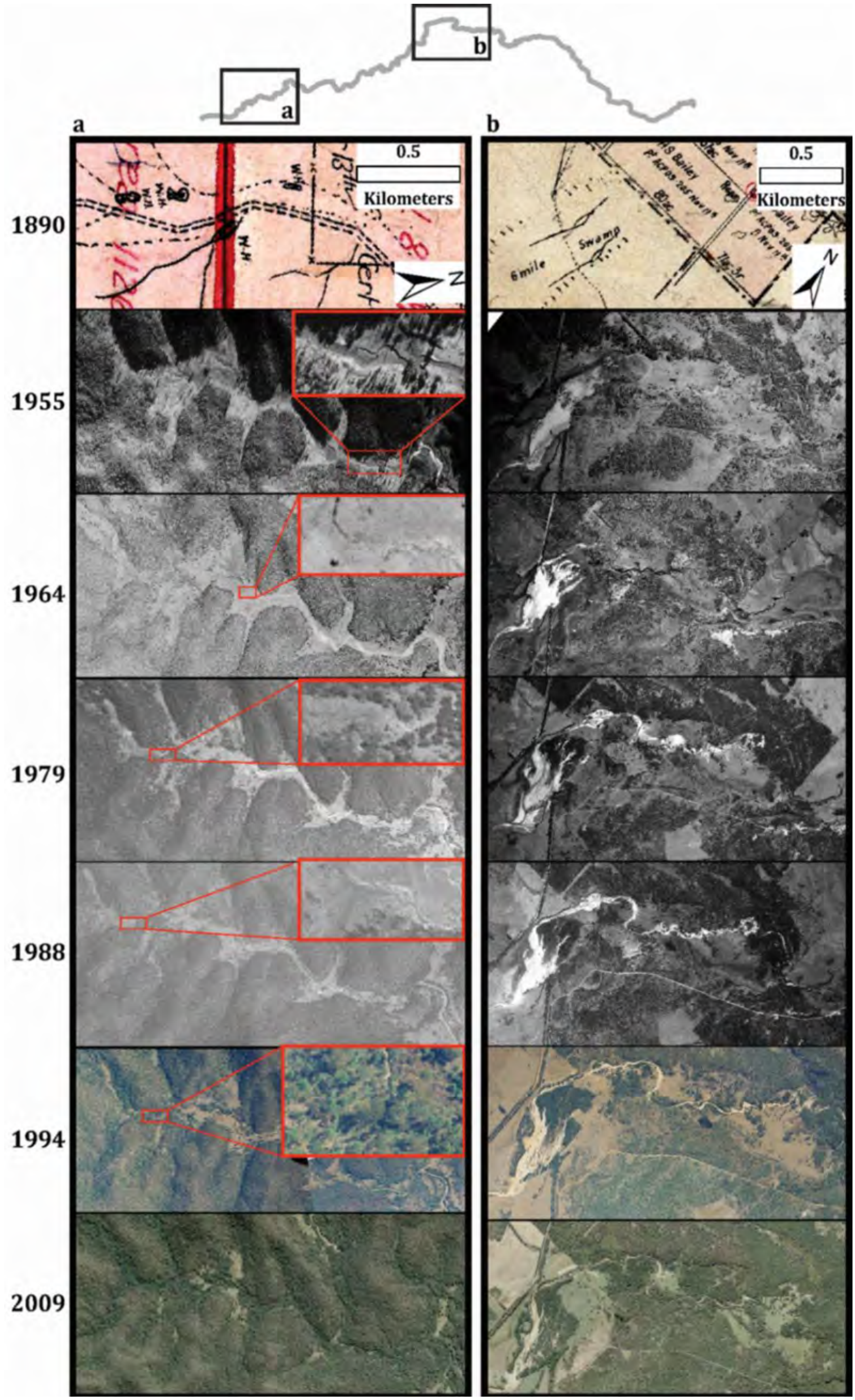


Fig. 5. Historical time slices showing the sequence of river change along Six Mile Swamp Creek. The parish map of 1890s in column (a) marks the location of chain of ponds labelled as water holes or 'W.H.'. The historical imagery in column (a) from 1955 to 2009 marks the decadal location of headcut (inset zoomed figures) and subsequent channelisation. The parish maps of 1890s in column (b) marks the location of chain of ponds along the reach. The historical imagery in column (b) from 1955 to 2009 shows floodout, sand slug formation, channel expansion and subsequent bench formation post channelisation.

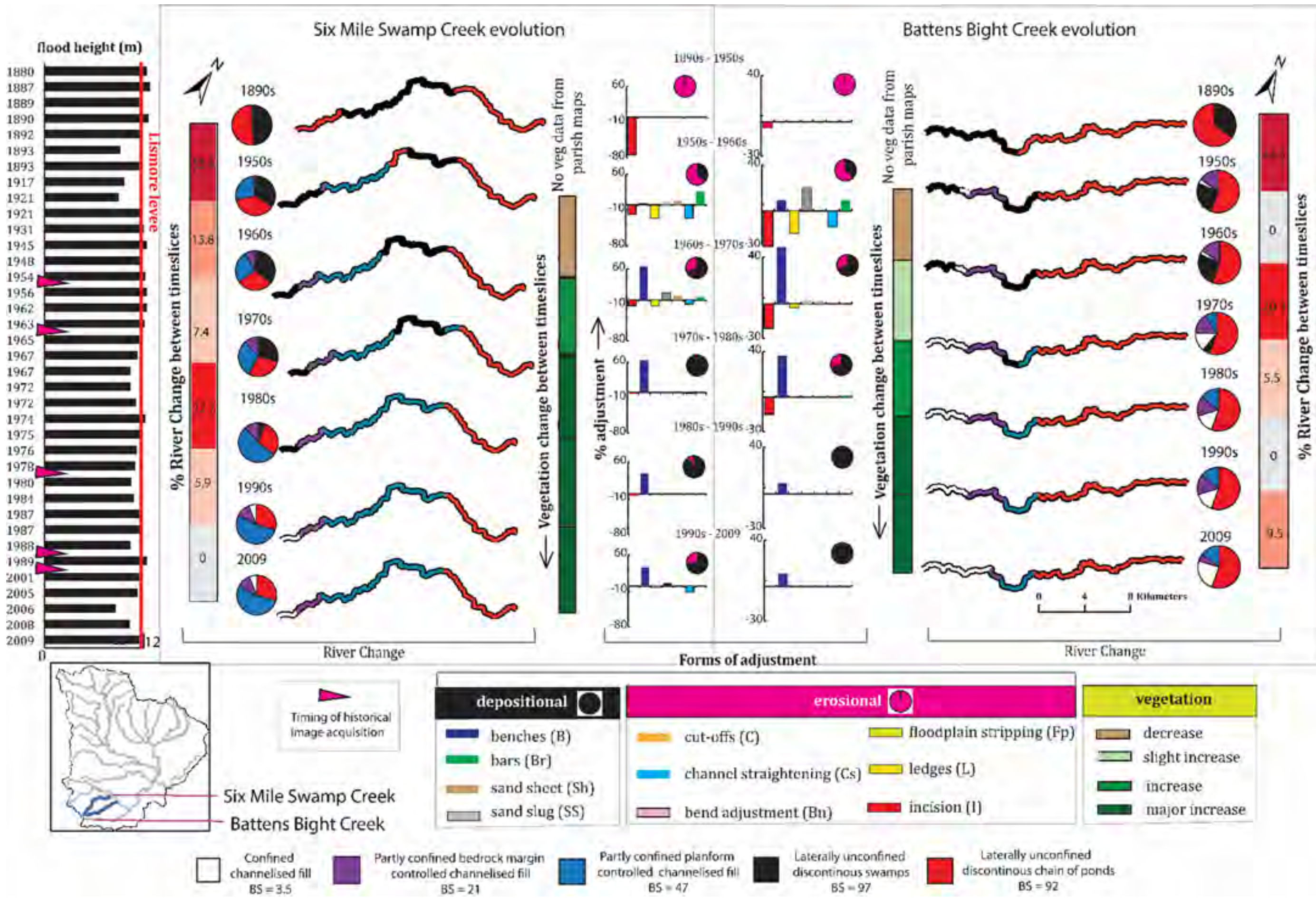


Fig. 6. River change in Six Mile Swamp Creek and Battens Bight Creek. The flood history bar graph records all the major floods from 1880 and marks the timing of image acquisition. Percentage river change is recorded in the intensity plot next to the stream shapefile and pie graphs document the proportion of each type of river in the corresponding time slices analysed. Qualitative riparian vegetation coverage change estimates from 1950s onwards is represented by the intensity plots. The decadal percentage adjustment caused by various forms of geomorphic adjustment is recorded in the bar graph such that the depositional forms of adjustment are shown above the x-axis and erosional forms of adjustment are shown below the x-axis. The percentage adjustment has been used along with the adjustment potential to calculate gross behavioural sensitivity (BS) of each river type.

stripping. Three major flood events (1962, 1963, 1965) occurred in these decades. Riparian vegetation had moderately increased. In the 1960s and 1970s, around 20% of reach length experienced deposition via bench formation and only 2% of reach length experienced erosion via bend adjustment. Floods occurred in 1967, 1972 and 1974 and the riparian vegetation coverage was observed to have significantly increased. From the 1970s onwards, the riparian vegetation coverage remained fairly consistent, and only around 2% of reach length underwent adjustment.

The upstream partly confined planform controlled sinuous reaches of Shannon Brook, which underwent relatively fewer geomorphic adjustments than their downstream counterparts. No adjustments were noted from the 1890s to the 1940s. In the 1940s and 1950s, 8% of reach length was affected by erosional forms of adjustment that caused channel straightening and floodplain stripping and around 12% of reach length was affected by deposition via the formation of benches. A slight increase in vegetation was noted during this time frame. Floods occurred in 1945, 1948, 1954 and 1956. In the 1950s to 1980s, the only observable adjustment was the formation of benches. No further adjustment was noted after the 1980s and riparian vegetation coverage remained consistent. Farther upstream along Shannon Brook, in the partly confined bedrock margin controlled reaches, the 1960s onwards shows predominantly depositional adjustment via formation of benches. In the 1960s and 1970s, around 50% of river length experienced channel contraction through bench formation. In the 1980s, around 15% of channel length was affected by bench formation. No further adjustments were noted after the 1980s.

Along the Wilsons River, relatively fewer adjustments were noted. The only adjustments occurred in the 1940s and1950s, which coincided with the floods of 1945, 1948, 1954 and 1956 and sparse riparian vegetation coverage. In the most downstream laterally unconfined continuous sinuous reaches, no forms of geomorphic adjustments were noted from the 1890s onwards. Farther upstream, in the partly confined planform controlled sinuous reaches, around 2% of stream length was affected by deposition through instream sand slugs and erosion via a single chute cut-off. Around 5% of the partly confined bedrock margin controlled reaches were affected by instream sand slug deposition. Further, in the confined bedrock margin controlled with occasional floodplain pockets reaches, around 6.8% of channel length was affected by sand slug and 1% by erosion via floodplain stripping. Along the confined gorge reaches that form the headwaters of the Wilsons River, no visible geomorphic adjustments were noted over the entire period of record.

4.3. Catchment wide variability in behavioural and change sensitivity

In the Richmond catchment, the behavioural sensitivity of reaches that underwent river change was >75%. Fig. 8 shows the catchment wide pattern of behavioural sensitivity. Red marks the location of reaches that have experienced wholesale river change since the 1890s.

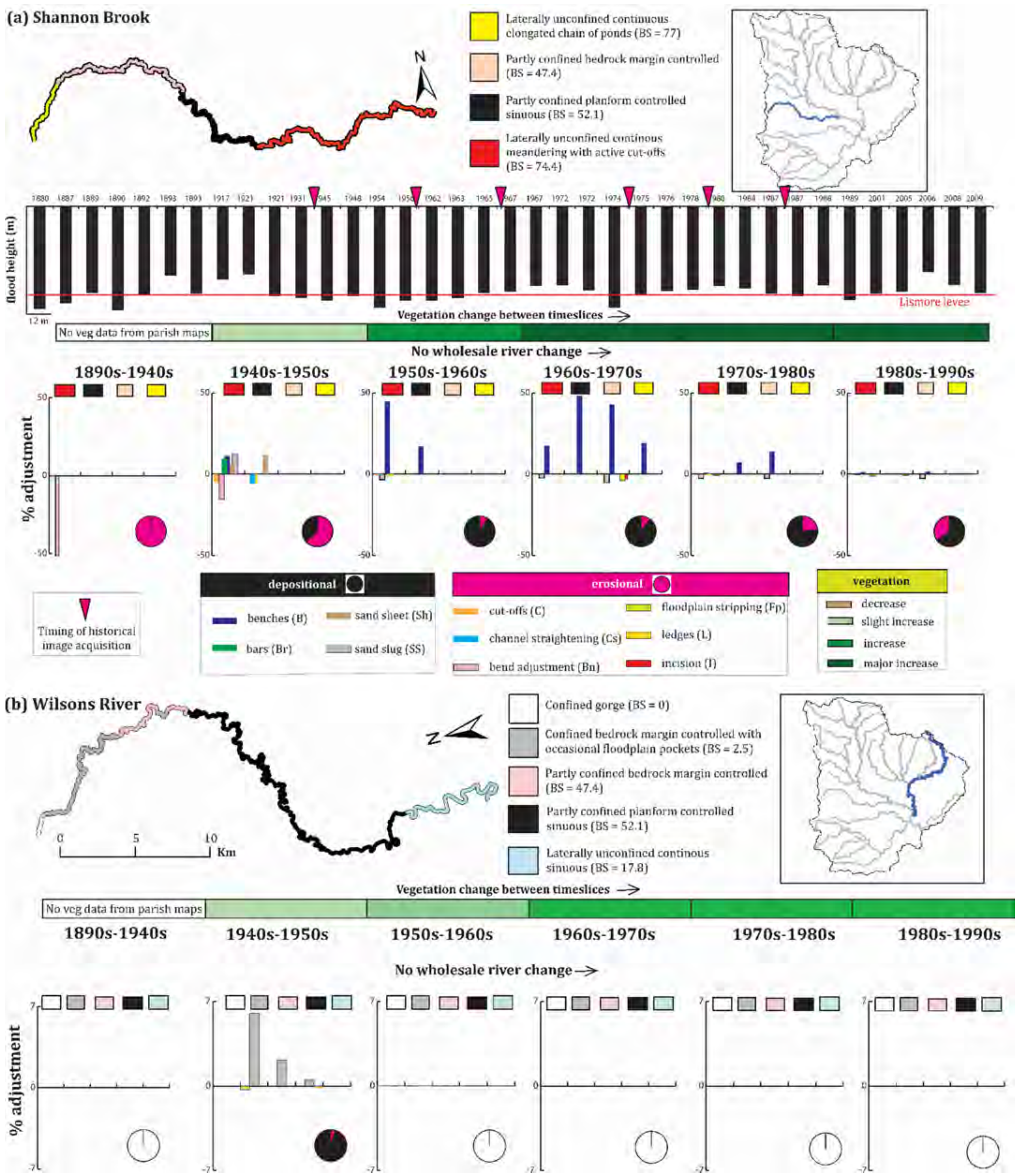


Fig. 7. River adjustment for (a) Shannon Brook and (b) Wilsons River from 1890s to 1990s. The flood history bar graph records all the major floods from 1880 and the timing of image acquisition. Qualitative riparian vegetation coverage change estimates from 1940s onwards is represented by the intensity plots. The decadal percentage adjustment caused by various forms of geomorphic adjustment is recorded in the bar graph such that the depositional forms of adjustment are shown above the x-axis and erosional forms of adjustment are shown below the x-axis. No wholesale change was recorded hence river change is not marked in these diagrams. The percentage adjustment has been used along with the adjustment potential to calculate gross behavioural sensitivity (BS) of each river type.

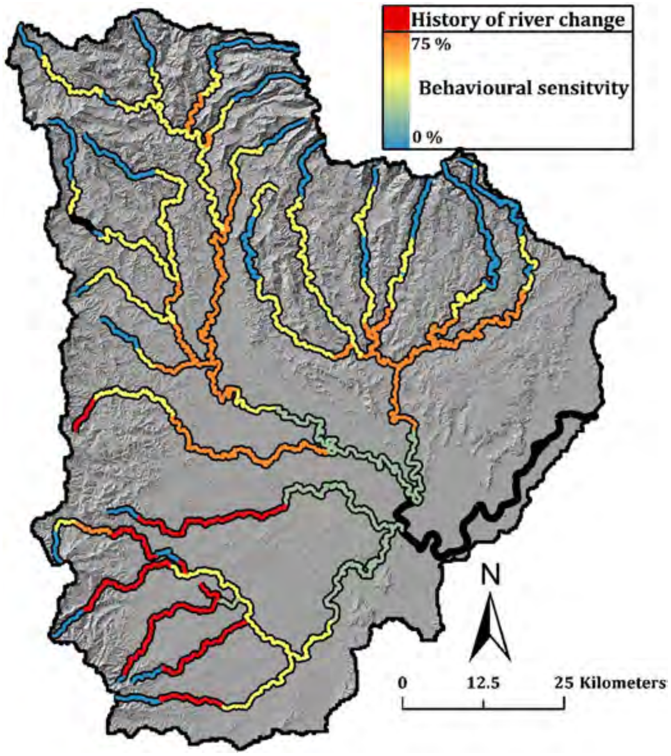


Fig. 8. Catchment wide variability in behavioural sensitivity and change for rivers in the Richmond catchment. The reaches marked in black were not analysed as these represent location of dam and tidal influence. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

However, the range and rate of adjustment, as well as the river responses in other parts of the catchment, has been highly variable. Along Shannon Brook, the laterally unconfined meandering reaches with active cut-offs have very high behavioural sensitivity at about 70%. These reaches have the capacity to undergo significant geomorphic adjustment in the vertical, lateral and longitudinal dimensions. Reach reconfiguration via erosional forms of adjustments such as chute cut-off and bend adjustment; and via depositional forms of adjustment such as sand slug, sand sheet, bars and benches have occurred. The partly confined planform controlled sinuous and low sinuosity reaches found in the mid-catchment sections of the Richmond River, Wilsons River and their northern tributaries have high to medium behavioural sensitivity of between 45 and 55%. These reaches have limited capacity to adjust because of imposed confinement (10–50% of either channel margin abuts the valley bottom margin). These reaches adjust via localised channel straightening, sand sheet and sand slug deposition, and the formation of benches. Rivers with high to medium behavioural sensitivity tend to have bed material texture comprised of coarse sand or fine gravel and occur on medium slopes in a laterally unconfined to partly confined planform controlled valley setting.

Farther upstream, the partly confined bedrock margin controlled rivers have intermediate behavioural sensitivity of around 40%. These reaches have localised capacity for adjustment along the discontinuous floodplains via localised chute cut-offs, minor bend adjustment, incision, floodplain stripping and the formation of ledges and benches along channel banks. These coarse sand and gravel bed rivers occur on medium to steep slopes in bedrock margin controlled valleys (50–85% of either channel margin abuts the valley bottom margin). The laterally unconfined continuous meandering rivers with passive cut-offs and laterally unconfined continuous meandering multi-channel rivers in the SW sub-catchment have low behavioural sensitivity of between 20%–50%. These rivers tend to have bed material texture comprised of medium to fine sand and occur on mild slopes. Laterally unconfined sinuous rivers have lowest behavioural sensitivity of between 5%–20%. These rivers are characterised by very low slope and have fine-grained bed material texture. Almost no behavioural sensitivity was noted for the confined rivers that occur in the upstream sections of all streams in the Richmond catchment. They are characterised by steep slopes and channel bed materials dominated by bedrock, boulders and cobbles.

5. Discussion

5.1. Assessing the behavioural sensitivity of rivers

The historical analysis of rivers in the Richmond catchment has not only provided an understanding of the spatial pattern of post-colonisation geomorphic adjustment, but has also provided an opportunity to develop an approach for assessing behavioural and change sensitivity at the reach scale. The approach has also been used to map behavioural sensitivity across a catchment, allowing for the analysis of spatial patterns of sensitivity and identification of 'hotspots' of geomorphic activity (Newson, 2010).

As adjustment is an integral component of river character and behaviour, analysis of the history of river adjustment can be used to differentiate reaches on the basis of their sensitivity to adjust (Allison and Thomas, 1993). In the Richmond catchment, different river types exhibit variable types and extents of erosional and depositional forms of adjustment. This produces a gradation of behavioural sensitivity (Fig. 9). Five distinct classes of behavioural sensitivity have emerged from our analysis: *Fragile*, *Active sensitive*, *Passive sensitive*, *Insensitive* and *Resistant*.

The versatile nature of the workflow in the *Behavioural sensitivity logical tree* provides a robust approach for quantitatively segregating the behavioural and change sensitivity of river reaches within a catchment. We note, however, that the quantitative ranges of behavioural sensitivity we have identified for the Richmond system may not be universally applicable. When applied to other case studies, it is important that a user determines whether these ranges are suitable for the type and extent of adjustments occurring in their system, and if not, redefine the ranges for each class.

The five classes of behavioural sensitivity identified in the Richmond system have been mapped across the catchment (Fig. 9) and positioned along hypothetical longitudinal profiles (Fig. 10). Because river behaviour in the SW of the catchment is starkly different to that in the NE of the catchment, two hypothetical longitudinal profiles are produced to explain the patterns of variability in river sensitivity (Fig. 10). Further, the radar plots in Fig. 10 quantify the forms of adjustments experienced by different river types. A significantly higher quantum of geomorphic adjustment is experienced by rivers in the SW compared to those in the NE (Fig. 10).

5.1.1. Fragile river: has propensity to undergo wholesale river change

Some rivers are hypersensitive such that they are susceptible to disproportionately high geomorphic adjustment (Quine and Brown, 1999). When subjected to natural or human induced disturbances, these rivers have the ability to produce a catastrophic response by undergoing dramatic geomorphic adjustments such as channel widening (Schumm, 1988; Downs and Gregory, 2014), or incision and channel straightening (Brookes, 1987). Here, we define Fragile rivers as those that have significant capacity to adjust with the propensity to undergo wholesale change (i.e., from one river type to another) (Fryirs et al., 2012; Fryirs, 2017; Petts, 1979; Schumm, 1969).

Several rivers in the SW Richmond catchment have already undergone wholesale river change and now operate as a different river type with a new behavioural regime (Fig. 10). Change along these rivers was initiated with knickpoint erosion into formerly discontinuous watercourses. The high percentage of erosional forms of adjustment that occurred along these rivers indicates the disproportionately high quantum of geomorphic work done by these rivers (see radial plots in Fig. 10). The primary forms of geomorphic adjustment were incision, channel expansion and ledge formation, bend adjustment and

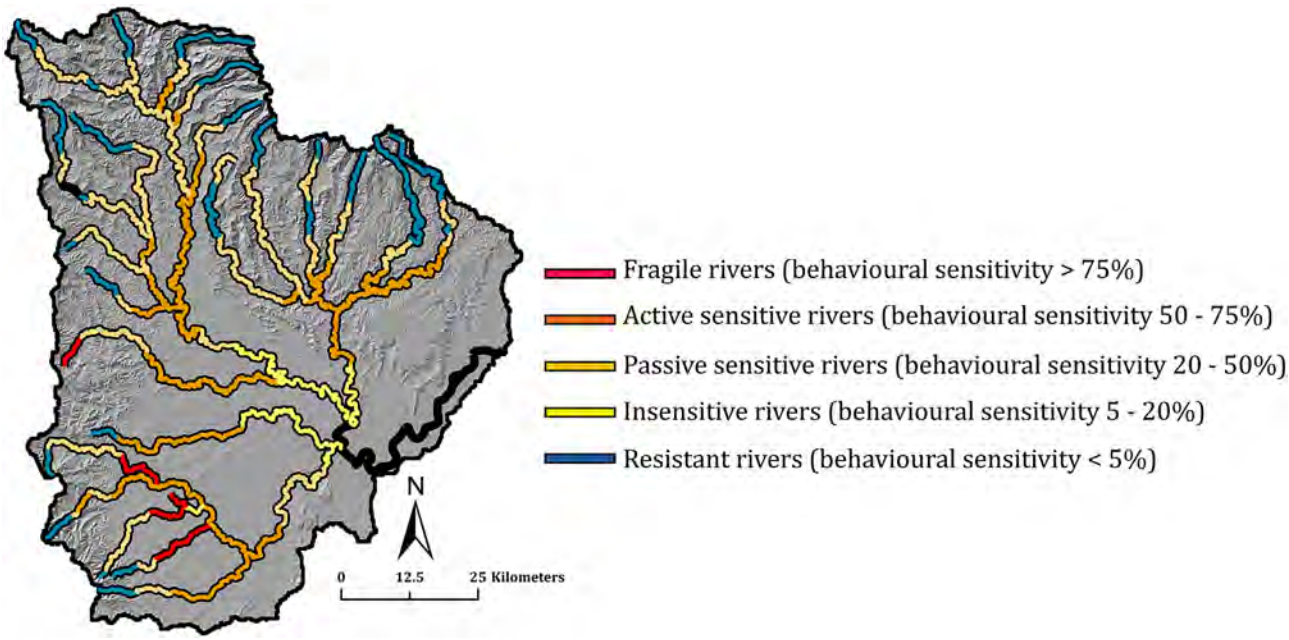


Fig. 9. The distribution of Fragile, Active sensitive, Passive sensitive Insensitive and Resistant rivers in the Richmond catchment. The reaches marked in black were not analysed as these represent location of dam and tidal influence.

floodplain stripping. The eroded sand was deposited in the form of an instream sand slug, floodplain sand sheets, bars and benches (Fig. 10) (Brookes, 1987; Simon, 1989).

In locations where incision occurred mid-catchment, floodouts were formed as 'alluvial fans' or splays on intact valley fill surfaces downstream (c.f, Fryirs and Brierley, 1999; Johnston and Brierley, 2006). Wholesale river change occurred most notably for the chain of ponds rivers that were initially transformed into elongate chain of ponds and eventually channelised fills with continuous channels. From upstream to downstream, incision produced confined channelised fill, partly confined bedrock margin controlled channelised fill, partly confined bedrock margin controlled with cut-offs, partly confined planform controlled channelised fill, laterally unconfined discontinuous floodouts and laterally unconfined elongated chain of ponds river types. These

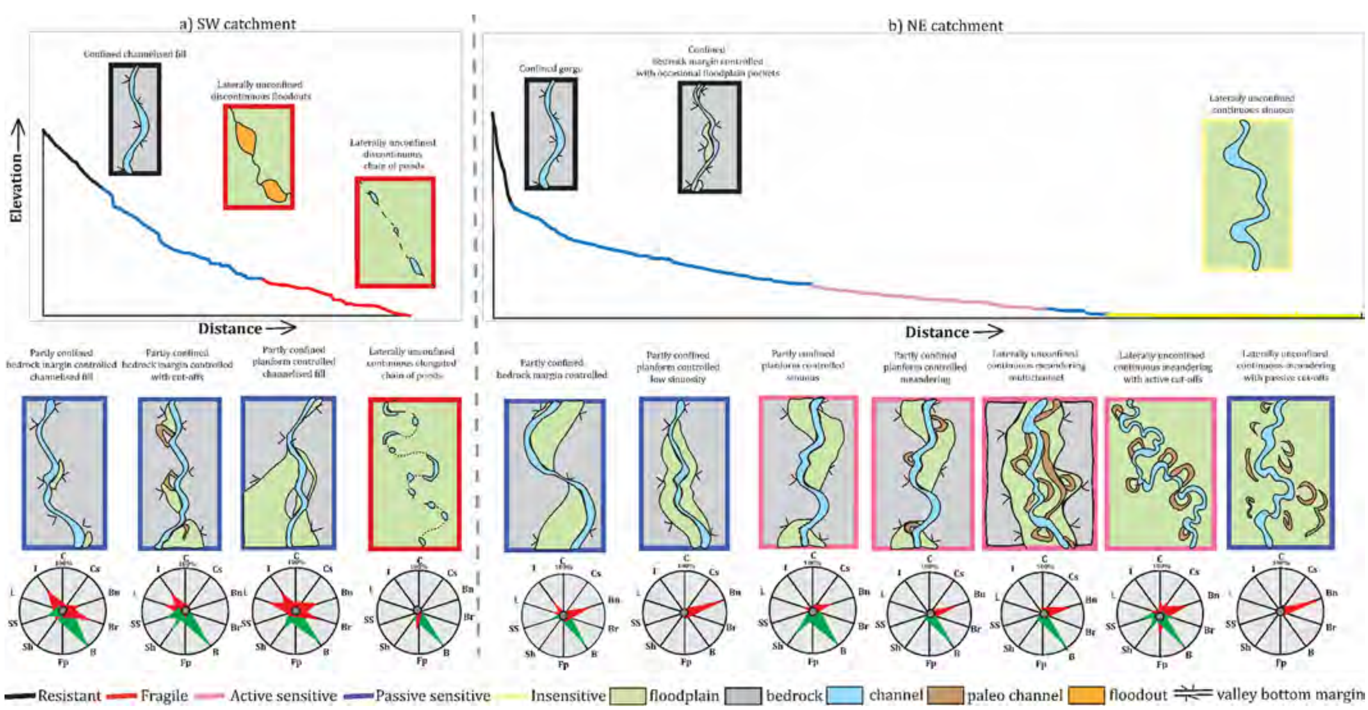


Fig. 10. Schematic representation of the downstream pattern and sensitivity of River Styles identified in the SW and NE of the Richmond Catchment. The River Styles that have not undergone adjustment since 1890s are shown above the hypothetical longitudinal profile and the River Styles that have undergone adjustment since 1890s are shown below the longitudinal profile. The percent normalised adjustment rate for each form of adjustment is plotted in the radar plots under the River Style planform schematics. Abbreviations: C - chute cut-offs, I - incision, Bn - bend adjustment, B - benches, SS - sand slug, Sh - sand sheet, L - ledges, Fp - floodplain stripping, Cs - channel straightening, Br - Bars. The erosional forms of adjustment are represented in red and depositional forms of adjustment are represented in green. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

rivers are now either Passive sensitive or Resistant (see Figs. 9 and 10). Remnant intact chain of ponds, elongated chain of ponds and floodout river types in the SW catchment are currently considered to be Fragile (Figs. 9 and 10). These are the rivers that are most prone to change if disturbances are severe enough to trigger a wholesale shift in the geomorphic characteristics and behaviour of the river.

5.1.2. Active sensitive river: able to re-configure by adjusting within its behavioural regime

Some rivers have the capacity to adjust within their behavioural regime via reinforcing positive feedback mechanisms, such that one adjustment produces a secondary, auto-catalytic response (Brunsden and Thornes, 1979; Schumm, 1976; Twidale, 1976). These rivers are classed as Active sensitive. Active sensitive rivers have the ability to progressively adjust and then undergo abrupt adjustment (Schumm, 1988; Downs and Gregory, 2014). An example is channel realignment such as meander growth leading to meander cut-off. Tooth (2018) defined a specific category of system (non)resilience where the landscape has the capacity to adjust, re-organise and evolve to a more stable configuration. Fryirs (2017) noted that such systems experience an expanded capacity for adjustment, but the core structural and functional attributes of the river are not modified. Some Active sensitive rivers have the propensity to undergo wholesale river change, some do not. However, all periodically adjust and are quite active within their contemporary behavioural regime. The identification of sequences of primary, secondary and tertiary geomorphic adjustment that often occurs for Active sensitive rivers is called a response gradient (Fryirs et al., 2009).

In the Richmond catchment, Active sensitive rivers are found in the areas that are characterised by medium slopes, medium sand to coarse gravel bed material and moderate valley bottom width. These Active sensitive rivers are often laterally unconfined meandering reaches (both with active cut-offs and multi-channels) and partly confined planform controlled meandering and sinuous reaches (Fig. 9). Active sensitive rivers in the Richmond catchment exhibit a wide capacity for adjustment through erosional forms such as chute cut-off, bend adjustment, channel straightening and ledge formation; as well as depositional forms such as sand sheets, sand slugs, bars and benches (see radar plots in Fig. 10). For the Richmond system, depending on the river type, three key sets of adjustments define the behavioural sensitivity of these rivers. First, these reaches are susceptible to re-configuration via erosional forms of adjustments such as chute cut-offs, bend adjustment and channel straightening. These adjustments tend to re-align or re-configure the macro channel towards a straighter planform as reach sinuosity is altered. In the Richmond catchment, these adjustments tend to occur during periods of low vegetation coverage that coincide with medium to large flood events (Fig. 7). These reaches then experience a secondary set of erosional adjustments such as channel incision, channel expansion through ledge formation and floodplain stripping. These adjustments increase channel capacity, destabilise banks and augment sediment supply to downstream reaches. Where these forms of adjustment occur along extensive sections of river, a tertiary set of adjustments can occur, with the formation of depositional forms of adjustment such as sand sheets and sand slugs. During periods of increased riparian vegetation coverage, these sand sheets and sand slugs can be reworked within a decade to form distinct bars and bank attached benches. The formation of benches acts to reduce the channel capacity and is often considered a key indicator of geomorphic river recovery (Brierley and Fryirs, 2005; Mould and Fryirs, 2018).

5.1.3. Passive sensitive river: able to withstand adjustment within its behavioural regime

Unlike Fragile and Active sensitive reaches that have a wide capacity for adjustment, Passive sensitive rivers undergo only transient adjustment and a narrower set of secondary and tertiary adjustments such that the system has the ability to recover from disturbance. These rivers experience a limited range of geomorphic adjustments and adjust progressively (Schumm, 1988; Downs and Gregory, 2014). This is often because of the influence of internal resistance in the system; whether channel or boundary (Knighton, 1999). In most cases, the contemporary channel may be set within a much larger macrochannel of variable capacity with limited space to adjust (Fryirs et al., 2009, 2015; Hoyle et al., 2008). This imparts an event resilience to the system such that the river undergoes only localised geomorphic adjustment during high magnitude events that would elsewhere produce significant geomorphic activity (Costa and O'Connor, 1995; Crozier, 1999; Fryirs et al., 2015; Lisenby and Fryirs, 2016; Magilligan et al., 2015; Miller, 1990; Wolman and Gerson, 1978). Such rivers can be considered an event dependent 'hotspot' (Downs and Gregory, 2014; Schumm, 1988).

In the Richmond catchment, Passive sensitive rivers tend to occur in the mid-catchment locations, are characterised by a coarse-grained macrochannel in partly confined valleys or a fine-grained macrochannel in laterally unconfined valleys. In the NE of the catchment, the Passive sensitive rivers are the laterally unconfined meandering reaches with passive cut-offs, partly confined planform controlled low sinuosity reaches and partly confined bedrock margin controlled reaches. Radial plots in Fig. 10 show the relatively narrow range of adjustments for these river types: erosional adjustment via localised bend adjustment and vertical incision; and depositional adjustment via sand sheets, sand slugs and benches. In the SW of the catchment, Passive sensitive rives are those that previously experienced wholesale river change. In the Richmond catchment, where river change has occurred from previous chain of ponds and floodout river types, a range of continuous incised channelised fills have been created that now experience very different forms of geomorphic adjustment. Most of the geomorphic adjustments now occur within the incised 'macrochannel'. These 'new' river types have shifted from Fragile to the Passive sensitive class. These examples demonstrate that over time, a river's behavioural sensitivity can shift, particularly if river change has occurred.

5.1.4. Insensitive river: slowly responding, antecedence controlled

The contemporary behaviour of some rivers is controlled by conditions set in the past, i.e., antecedence, which have 'set' the system to its contemporary capacity and position (Dean and Schmidt, 2011; Fryirs et al., 2015; Phillips, 2009, 2007; Thorne et al., 1996; Ziliani and Surian, 2012). Because of the persistence of relief and/or landforms, these systems have been termed 'over-relaxed' or 'over-adjusted' slowly responding systems (Brunsden, 2001; Brunsden and Thornes, 1979; Crickmay, 1959). These Insensitive rivers continue to develop and adjust along the same trajectory even under changing (or changed) boundary conditions (Brunsden, 2001). Such rivers were referred to by Chorley and Kennedy (1971) as a palimpsest. The most obvious forms of antecedence that occur along rivers are the presence of terraces formed under a past climate and flow regime, or the presence of ancient low relief, fine-grained floodplains (Fagan and Nanson, 2004). The presence of such landforms demonstrates a simple, lagged, stabilising response that dampens contemporary geomorphic adjustments to disturbance (Brunsden and Thornes, 1979).

In the Richmond catchment, Insensitive river types occur along the Richmond trunk stream and along the lower Wilsons River and Bungawalbyn Creek (Fig. 9). They are high order, very low slope, laterally unconfined reaches set within extensive fine-grained cohesive floodplains. Even during phases of low riparian vegetation coverage, intense human disturbance and during large catastrophic floods, these reaches have experienced minimal geomorphic adjustment over the historical record (Fig. 10).

5.1.5. Resistant river: able to resist adjustment

Certain landscapes remain largely unaffected by climatic and land use controls and have the capacity to persist for very long periods of time. Geological controls often override both climatic and anthropogenic controls on river response (Gupta et al., 1999). These rivers contain significant barriers to change (sensu Brunsden, 2001) such that the impulse of change generated during high magnitude, or high intensity disturbance events is either modified, diffused or stored in the system and little or no geomorphic response occurs (Fuller et al., 2019; Phillips, 2009).

The confined rivers in the headwater of the Richmond catchment (Fig. 9) have very limited or no capacity to undergo significant geomorphic adjustment in response to disturbance events and are classified as Resistant rivers. These reaches are characterised by steep slopes, are bedrock confined and have bedrock and boulder bed material texture. The confined gorge and confined bedrock margin controlled with occasional floodplain pockets river types have not experienced any visible forms of geomorphic adjustment since colonisation and are therefore considered to be Resistant rivers (Fig. 10).

5.2. Evolutionary nature of behavioural sensitivity: importance for future forecasting

Not only is there 'natural' variability in the spatial patterns of behavioural and change sensitivity in catchments, there are also temporal changes in the behavioural and change sensitivity of rivers. Brunsden (2001) emphasised that ambiguity in the understanding of sensitivity largely arises because of the evolutionary nature of landscape sensitivity itself. Some large events can precondition a system to a threshold-breaching disturbance that leads to rare or unusual forms of change and dramatic switches in river sensitivity (Schumm, 1973). In other cases, more gradual changes in sensitivity can occur as the mix of intrinsic and extrinsic controls that govern the geomorphological 'life cycle' of the fluvial system adjust (Ellery et al., 2016; Tooth, 2018).

In the Richmond catchment, post-colonisation human disturbance has accentuated the variable capacity of rivers to adjust their sensitivity. Some rivers have become more sensitive, some have become more resistant, while some have maintained their sensitivity or resistance over time. For example, rivers in the SW of the Richmond catchment, the formerly Fragile chain of ponds, have switched to Resistant and Passive sensitive river types or have changed to a different type of Fragile river (Fig. 10).

Mapping the distribution of river sensitivity can provide a useful guide for planning and management (Brunsden, 2001). Understanding historical river behaviour can aid in contextualising the contemporary river behaviour and be further used as the foundation from which to project future trajectories of river adjustments under a range of scenarios, whether they be changing climate or river management scenarios. The behavioural sensitivity logical tree developed in this paper provides one such approach with which these analyses can occur.

6. Conclusion

Tracking river adjustment for rivers in the Richmond catchment since the time of European colonisation in the mid-late nineteenth century has provided a dataset with which to assess the historical range of variability of geomorphic adjustment for different types of rivers in the catchment. This has been used to develop an approach, called the '*Behavioural sensitivity logical tree*', which can be applied to assess and quantify reach scale behavioural sensitivity. Such analyses can be used to classify rivers as *Fragile*, *Active sensitive*, *Passive sensitive*, *Insensitive* and *Resistant* and map them across a catchment. This case study further demonstrates the evolutionary nature of behavioural sensitivity itself as certain rivers have the capacity to dynamically evolve and shift to a different sensitivity category in response to different forms of direct and indirect disturbances. The analysis of behavioural sensitivity can be used for developing awareness of a river's 'expected' or 'natural' character and behaviour. Against the backdrop of changing climate and ongoing human disturbance to rivers, this sets a basis for forecasting the future sensitivity of rivers.

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.

Acknowledgements

We thank Quentin Slade of National Library of Australia, Tracie Walker of NSW Department of Finance, Services and Innovation and Debbie Pickett of NSW Land Registry Services for help sourcing historical aerial photographs and parish maps in the archives. We thank Tim Ralph and Gary Brierley for discussions on this topic. Sana Khan is supported by a Commonwealth Government International Research Training Program (iRTP) scholarship and Macquarie University Higher Degree Research Funds. We thank the editor Scott Lecce and the reviewers Avijit Gupta and Ian Fuller for review comments which have improved this paper.

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Chapter 6

Sediment (dis)connectivity

Tracking sediment (dis)connectivity across a river network to identify hotspots of potential geomorphic adjustment

1. Introduction

Rivers are essentially a network of conduits that transport the fluxes of flow, sediment and energy through a catchment (Bracken et al., 2015; Fryirs, 2013; Wohl, 2017, 2014; Wohl et al., 2018). In fluvial geomorphology, this network is commonly related to a 'conveyor belt' that transports the fluxes of flow and sediment in the downstream direction (Ferguson, 1981). However, the transport of fluxes is not spatially and temporally uniform across a catchment. While some parts of a catchment might be strongly connected or coupled such that they can transmit the fluxes efficient in the downstream direction via 'smooth conveyor belt', others might be disconnected or decoupled such that the fluxes are transmitted downstream in an intermittent fashion via 'jerky conveyor belt' (Ferguson, 1981). As a result, some parts of a catchment can be geomorphically sensitive to disturbance events, while others can be resilient to adjustment. Moreover, since fluvial systems operate at a catchment scale, this downstream routing of fluxes can propagate onsite as well as offsite geomorphic adjustment (Fryirs and Brierley, 2013). As a result, within a catchment, a gradient of sediment (dis)connectivity can occur.

Three aspects can be considered while analysing the catchment scale pattern of sediment (dis)connectivity: (1) landscape configuration that facilitates or restricts adjustment (2) degree to which the cascades along the river network are connected or disconnected, and (3) the hillslope-channel coupling-decoupling created by the presence/absence of sediment stores that absorb or propagate the available energy producing off-site adjustment. *Locational sensitivity* determines if the geomorphic configuration of reaches within a catchment can facilitate or suppress adjustment via positive or negative feedback mechanisms (Allen, 1974; Brunsdern 1993; Chappell, 1983; King, 1970; Fryirs, 2013, 2017). *Transmission sensitivity* governs the strength of linkages within a sediment cascade and determines the extent to which a system is connected or disconnected and hence the propensity of the geomorphic system to propagate disturbance in the downstream direction (Fryirs, 2017). Furthermore, configuration of antecedent sediment stores between the hillslope and channel can filter the effect of geomorphic activity within the system, called *filter sensitivity* (Brunsden, 1993; Fryirs, 2013, 2017; Fryirs et al., 2007b). These elements can act as 'switches' that attenuate or suppress the signal of geomorphic change either by absorbing the energy produced during a disturbance event or transmitting the energy downstream and hence producing offsite adjustment (Fryirs, 2013; Fryirs et al., 2007b, 2007a). The trio of this locational-transmission-filter sensitivity within a system determines where, how and when the expression of geomorphic change can be expressed in the system (Fryirs, 2017). Depending upon the landscape characteristics, the order and prominence of this trio locational-transmission-filter sensitivity can vary considerably.

Sub-catchment scale pattern of sediment (dis)connectivity can be assessed by studying the physical links between hillslope and channel as this determines the degree to which a system is sedimentologically connected or disconnected from the source zone (Fryirs et al., 2007a; Jain and Tandon, 2010). Hillslope-channel (dis)connectivity can be a result of the buffering elements that impede direct sediment transfer from hillslope to channel via sediment storage within geomorphic features such as floodplains, swamp, trapped tributary fills, levee, fan and lakes (Brunsden, 1993; Fryirs, 2013; Hoffmann, 2015; Kelsey et al., 1987; Phillips, 2003; Phillips et al., 2007). The catchment scale variability in hillslope-channel (dis)connectivity can be assessed by mapping these 'buffers' and the proportion of the catchment that is directly connected to the river network, called as 'effective catchment area' (Fryirs, 2013; Fryirs et al., 2007a).

Analysis of catchment scale (dis)connectivity can provide information on how the disturbance can or cannot propagate along the fluvial network (Baartman et al., 2013; Bennett et al., 2013; Bracken et al., 2015; Cavalli et al., 2013; Czuba and Foufoula-Georgiou, 2014; Fryirs, 2013; Jain and

Tandon, 2010; Phillips et al., 2020; Santangelo et al., 2013; Wohl et al., 2018). This in turn can aid identification of hotspots of geomorphic adjustment in a catchment (Czuba and Foufoula-Georgiou, 2015; Schmitt et al., 2016). Assessment of the pattern of network scale fluxes can be further used to analyse the controls on the sediment dynamics of river reaches. Since the strength of linkages is a function of the geomorphic template (Harvey, 2002; Lisenby and Fryirs, 2016; Rice, 1999, 1998), the causes and consequences of the pattern of system (dis)connectivity can be used to address management questions such as: Does the river operates within its expected behavioural regime within a specific temporal scale? What might be the causes of sediment deposition or erosion in a particular reach? Will an onsite or offsite disturbance propagate geomorphic adjustment within a specific reach of interest? What changes in the land management activities or climate can aggravate or suppress healthy geomorphic river behaviour?

This study aims to assess the gradient of sediment (dis)connectivity in the Richmond River catchment, New South Wales, Australia. For this, the effective catchment area and buffer analysis is performed across the catchment for analysing the system coupling-decoupling. This is used to understand the patterns and potential consequences of locational, filter and transmission sensitivity across a catchment. Further, network scale metrics of sediment dynamics is simulated under a geomorphically effective event to identify potential hotspots of channel adjustment.

2. Methodology

Three datasets: LiDAR DEM, geomorphic map and historical flow records were acquired from open access sources and bed material surveys and samples were taken during field investigation (Table 1).

Table 1 Data type and source of acquisition

No.	Data type	Source
1	5 m resolution LiDAR DEM (raster)	Australian Government Elevation and Depth - Foundation Spatial Data website (http://elevation.fsdf.org.au/)
2	Geomorphic map (vector shapefile)	NSW Government Sharing and Enabling Environmental Data (SEED) website (https://www.seed.nsw.gov.au/)
3	Historical flow data (1968 to 2018 years)	WaterNSW website (https://www.waternsw.com.au/)
4	Bed material texture or grain size	Field investigation

A discharge-area relationship for the Richmond catchment was extrapolated from this historical flow dataset using Log-Pearson Type III statistical analysis (Khan et al. subm.). The 10 year return interval streamflow has been observed to produce geomorphically effective floods (that is, floods resulting in geomorphic adjustment) in similar coastal river settings (Lisenby and Fryirs, 2016). Therefore, the 10 year return interval discharge-area relationship was used to calculate continuous streamflow in the Richmond catchment.

$$10\ year\ return\ interval\ Q = 8.2667 \times A^{0.662}$$

Bed material size surveys and samples were collected in the field during low flow conditions in August 2019 from 25 locations across the catchment (Figure 1). To gain the most realistic estimate of the bed material size variability, sampling was conducted over lateral, longitudinal and mid-channel bars as these features represent the most transient geomorphic units. Depending upon the variability in grain size and site accessibility, representative bed material samples were collected at each site. For reaches dominated by fines and sands, three to five samples of approximately 0.5 to 1 kg were collected in sample bags. For reaches dominated by pebbles and cobbles, grain size was measured using the Wolman Pebble count method (Bevenger and King, 1995). These counts were conducted longitudinally along the bars using zig-zag sampling method. For this, at regular intervals along the zig-zag tape, the intermediate axis of each grain size was measured. Each survey had approximately 80-120 pebble counts. For inaccessible locations (e.g. gorges), bed material size was estimated using photographs and aerial imagery. The sediment samples were then processed in the Macquarie University soil laboratory to estimate the grain size variability. Dry sieving was performed at 1 phi intervals and a sediment distribution plot used for calculating D16, D50 and D84 grain size.

On the basis of lateral confinement, channel (dis)continuity and degree of sinuosity, Khan and Fryirs 2020 characterised the Richmond rivers into 17 river styles. For the network scale analysis of sediment (dis)connectivity, the coarse scale valley bottom confinement, channel (dis)continuity and bed material texture were used to aggregate the river styles into eight river types. These are (i) confined bedrock and boulder bed (ii) partly confined bedrock margin controlled bedrock, bolder, gravel and sand bed (iii) partly confined bedrock margin controlled sand bed (iv) partly confined planform controlled gravel and sand bed (v) partly confined planform controlled sand bed (vi) laterally unconfined continuous sand, silt and clay bed (vii) laterally unconfined continuous sand bed and (viii) laterally unconfined discontinuous sand bed. The rivers in the north are dominated by confined and partly confined rivers that drain over relatively high relief, basalt lithology (Figure 1). Rivers in the S-W of the catchment are dominated by laterally unconfined continuous and laterally unconfined discontinuous reaches that drain over low relief, sandstone lithology (Figure 1).

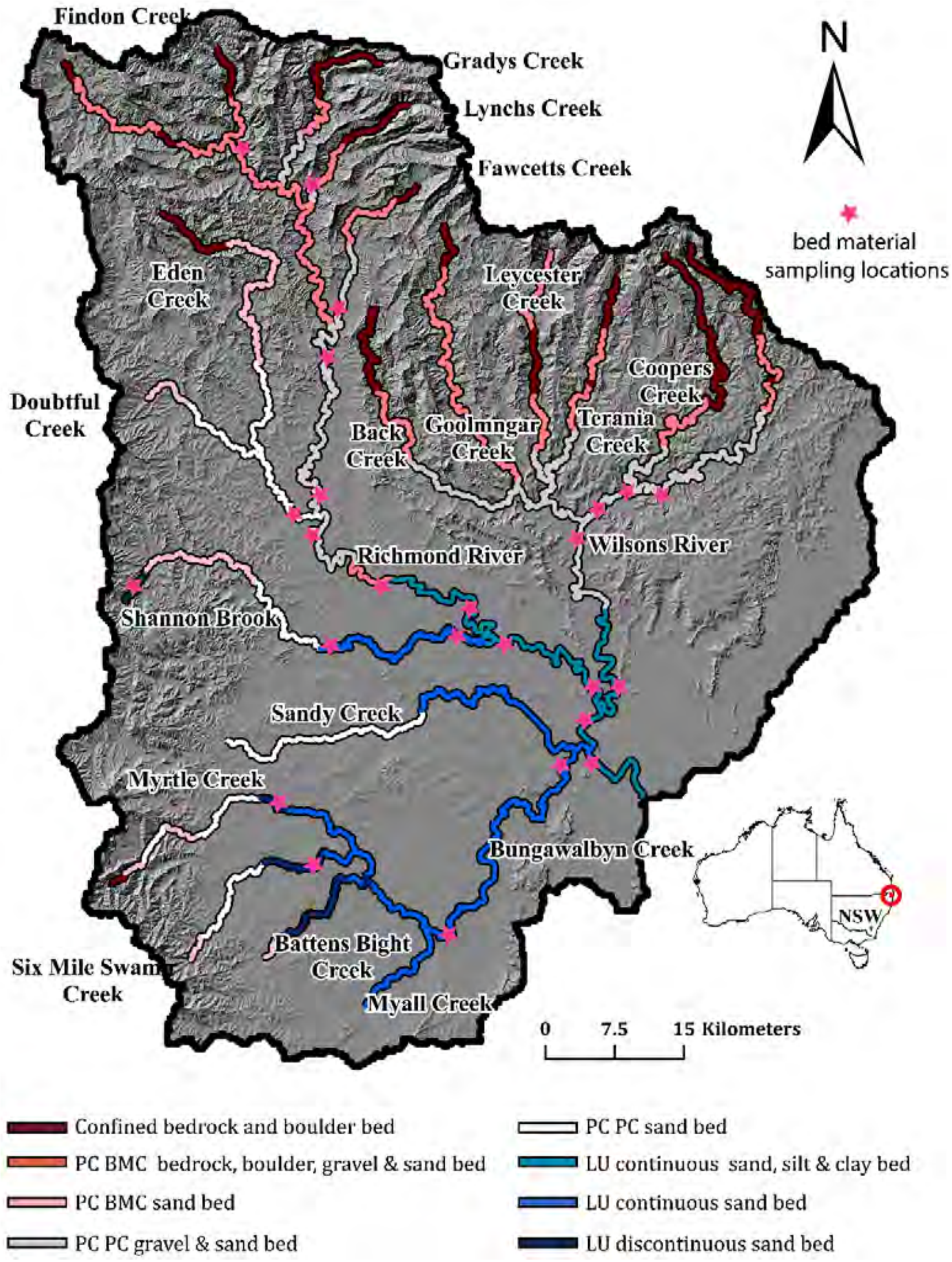

Figure 1 Location of the Richmond catchment and its tributaries. River diversity is colour coded in the drainage network and the bed material sampling locations are marked by pink stars. Abbreviations: PC BMC- Partly confined bedrock margin controlled, PC PC- Partly confined planform controlled

The cross-catchment analysis of sediment coupling-decoupling (i.e. (dis)connectivity) was performed within ArcMap 10.5.1 by mapping sedimentary buffers and effective catchment area for each sub-catchment (Fryirs et al., 2007b). Firstly, the tributary sub-catchment areas and the drainage network was delineated using a Multiple Flow Direction (MFD) flow accumulation model in SAGA GIS (Conrad, 2006) and ArcHydro toolbox imported into ArcMap (Maidment and Morehouse, 2002). Further, the geomorphic map was used for identifying and mapping sedimentary buffers across the catchment using the methodology in Fryirs et al. (2007b) and Lisenby and Fryirs (2017). Buffers are the geomorphic features that impede sediment movement from hillslope to channels, thus governing the extend of hillslope-channel coupling-decoupling (Fryirs et al., 2007; Fryirs, 2013). The geomorphic map of the catchment was used to identify and group the specific landforms that act as sedimentary buffers: floodplain, swamp, alluvial fan, levee, trapped tributary fills and lakes (natural and artificial). The 5-meter resolution LiDAR DEM was resampled to 30 m resolution for calculating effective catchment area (ECA) (c.f. Fryirs et al., 2007a; Lisenby and Fryirs, 2017). ECA is the proportion of the tributary sub-catchment area that has significant gradient and is connected to the trunk stream and can therefore contribute sediment to that trunk stream. The GIS workflow of Lisenby and Fryirs (2017) was used for mapping ECA using a 2º slope threshold. The proportion of buffer extend and ECA within each tributary sub-catchment was used to assess the variability of coupling-decoupling across the catchment.

To quantify potential fluxes of sediment along the drainage network, network scale sediment cascades were modelled/simulated using the CASCADE (CAtchment Sediment Connectivity And DElivery) modelling framework (Schmitt et al., 2016). CASCADE integrates the principle of graph theory with the empirical sediment transport formulas to simulate the sediment transport dynamics between sources and sinks. This modelling was performed within a MATLAB interface using functionalities of CASCADE toolbox and Topo toolbox (Schwanghart and Scherler, 2014; Tangi et al., 2019). The detailed methodology for CASCADE model set up and simulation steps is discussed elsewhere (Tangi et al., 2019). Here a brief description of the model set up for the Richmond catchment is provided.

To define the drainage network, a series of connected nodes and edges needs to be built. Here, the DEM and reach segment length input was used. This created a connected graph network representing the drainage network with information of latitude and longitude of each node and reach specific slope. This network was then imported within ArcGIS for impregnating the reaches with local geomorphic information - discharge, bankfull channel width, D16, D50 and D84 of the bed material size, estimate of channel bed Manning's n, estimate of floodplain Manning's n, sand depth within the channel bed and an estimate of transport limitation parameter (representing entrainment potential) (Tangi et al., 2019). The Manning's n value was estimated using field investigation and aerial imagery. After supplementing the drainage network with the geomorphic attributes, the GIS shapefile was imported into the MATLAB interface and the CACADE model was applied to calculate bankfull channel depth (corresponding to the input bankfull channel width) in each reach segment using Manning's equation. Further, sediment dynamics was simulated using an empirical sediment transport formula. Since the bed load in the Richmond system is a combination of both gravel and sand, the Wilcock and Crowe (2003) equation was used to calculate the sediment transport capacity of each reach segment. The reach scale pattern of resultant entrained, transported and deposited sediment was critically assessed by using the expert knowledge of the geomorphology of the Richmond system. To obtain more realistic results, further simulations were performed by tweaking the transport limitation parameter and grain size distribution on the basis of expert judgement.

The transport limitation parameter in CASCADE allows the user to limit for each reach the potential for sediment supply to the network from the river bed (Tangi et al., 2019). The value of this parameter ranges from 0 to 1 such that 0 indicates reaches where no sediment can be entrained via local bed erosion and 1 represent reaches where local erosion can be equal to the total transport capacity of the reaches. Since no sediment is expected to be entrained in high energy bedrock confined gorge settings, the transport capacity in those reaches was set to 0. Similarly, confined bedrock margin controlled reaches with occasional floodplain pockets were assigned transport capacity of 0.2. In partly confined bedrock margin controlled reaches of the NE, transport capacity was set to 0.4. In laterally unconfined continuous reaches in NE, the value was set to 0.6. In the remaining partly confined reaches, transport capacity was set to 0.8. In laterally unconfined continuous and discontinuous rivers, the transport capacity was set to 1.

Further, since bed material sampling was performed only at limited representative locations, there were certain reaches along the network where an estimate of bed material size fractions (i.e. D16, D50 and D84) needed to be manually interpreted and assigned on the basis of expert judgment. The first CASCADE simulation was performed by assigning a similar grain size distribution to reaches falling within the same river style category and on the basis of the proximity of the un-sampled reaches to the sampled reaches. For further simulations, this grain size variability was altered on the basis of expert judgment. This expert judgment was mainly based upon two criteria: (i) interpretation from aerial imagery and (ii) visual information acquired from geomorphically similar reaches that could not be sampled or surveyed in the field due to site inaccessibility.

Once a satisfactory pattern of modelled entrained, transported and deposited sediment captured the expected erosional and depositional patterns of reaches, the results were exported and further analysed to understand sediment flux dynamics.

3. Results

3.1. Distribution of tributary effective catchment area and sedimentary buffering in the Richmond catchment

The geographic location of each tributary sub-catchment significantly influences the extent of effective catchment area (ECA) and sedimentary buffering within the basin. Figure 2 shows that within each tributary sub-catchment, ECA is significantly higher in upstream reaches and progressively decreases in the downstream direction. However, the significantly steeper NE sub-catchment contains relatively higher proportion of ECA when compared to the low lying, flat gradient southern sub-catchment. Inversely, the proportion as well as the variety of sedimentary buffers increases in the downstream direction. The SW sub-catchment is highly buffered with a diverse set of buffering units. The NE sub-catchments are relatively less buffered with a smaller variety of buffering units.

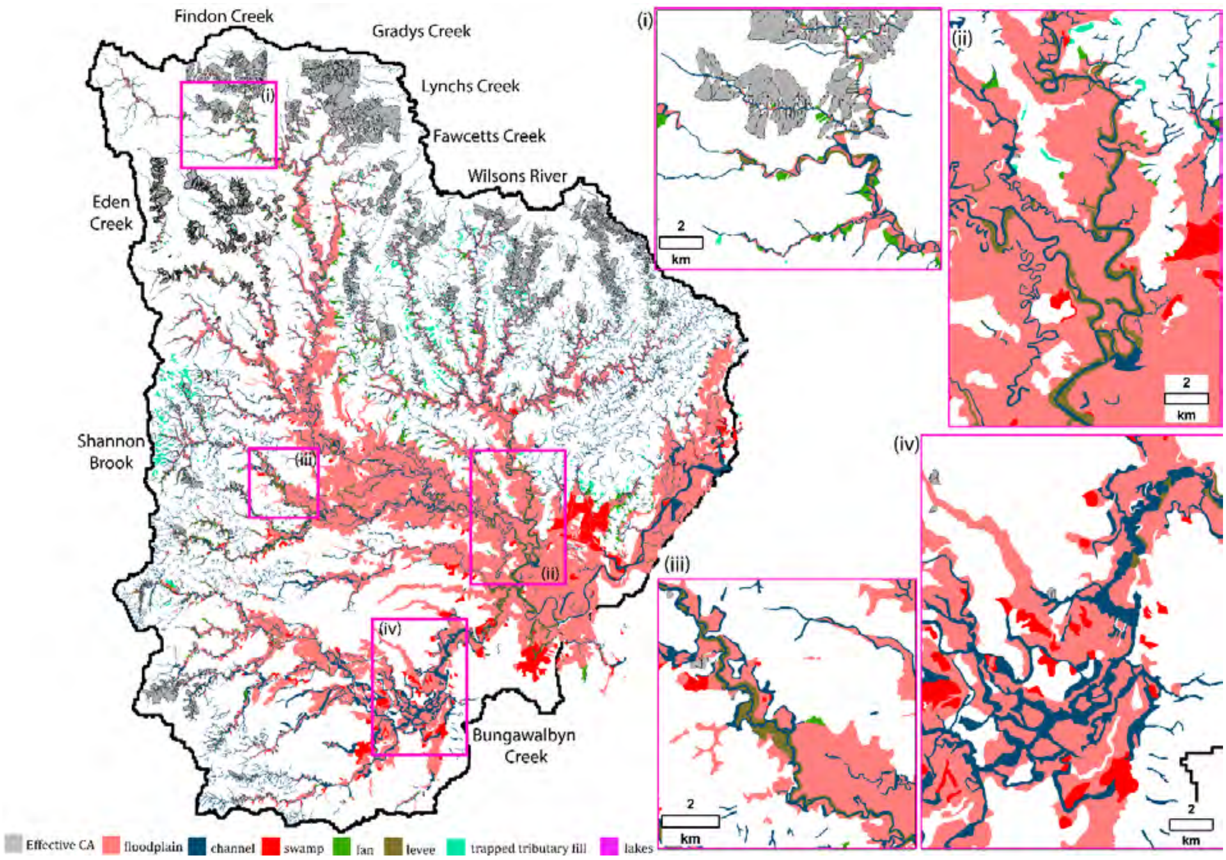

Figure 2 Spatial distribution of the effective catchment area (ECA) and buffers throughout the Richmond catchment

Figure 3a quantifies the total and effective catchment area within each tributary sub catchment and Figure 3b shows the comparison between the proportion of ECA within each tributary sub-catchment. Larger catchment area does not imply that the proportion of ECA will also be large. The mild gradient Bungawalbyn sub-catchment in the SW of the Richmond catchment has the lowest proportion of ECA. In contrast, the more mountainous tributaries in the NE have the smallest sub-catchment area but the highest proportion of ECA as a result of dominance of steep slopes throughout. Overall, the proportion of ECA is highest in the Lynchs catchment followed by Gradys, Findon, Fawcetts, Wilsons, Eden, Shannon and Bungawalbyn sub-catchment.

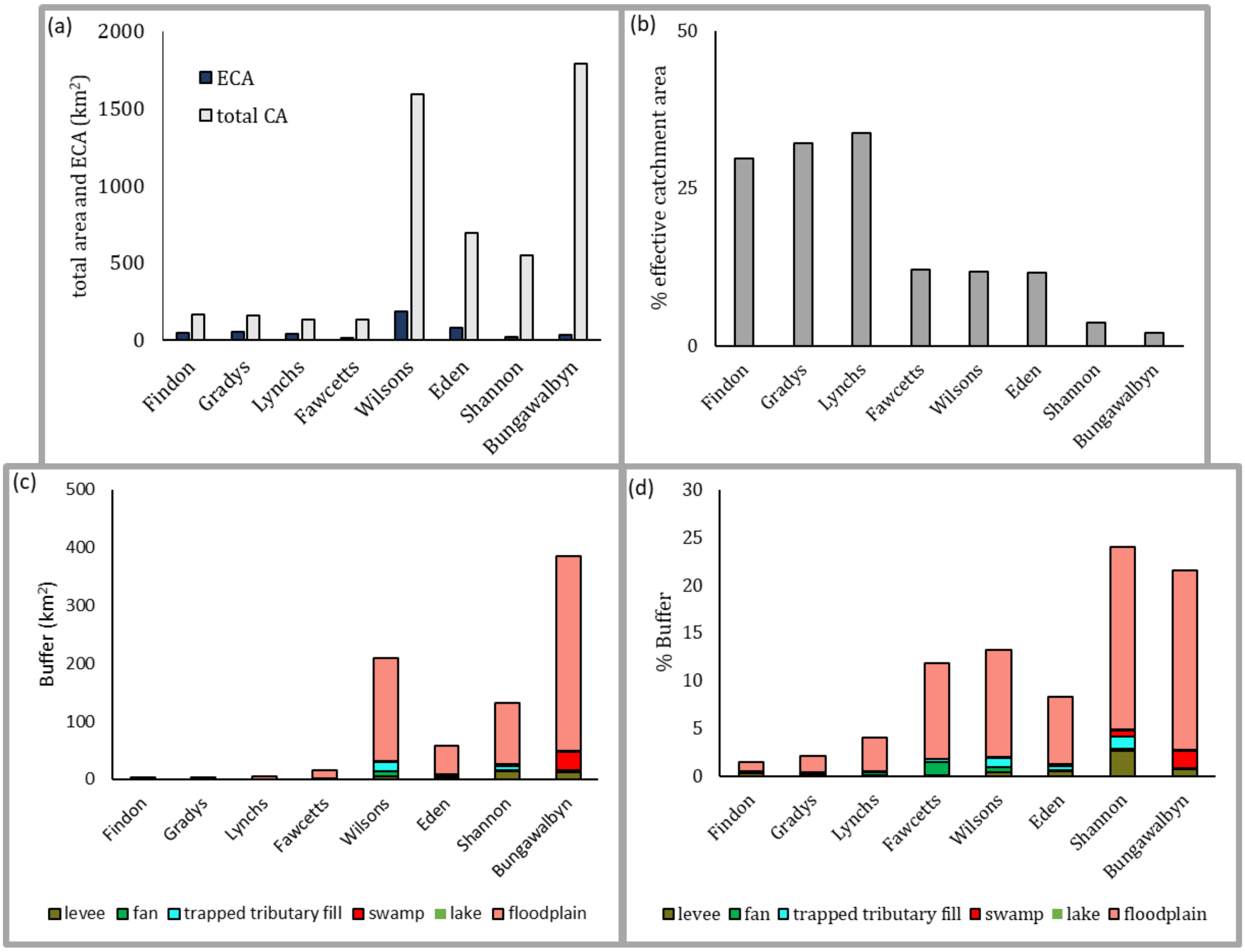

Figure 3 Comparison between the distribution of effective catchment area (ECA) and buffers within each tributary sub-catchment of the Richmond Rive system

The proportion and variety of sedimentary buffers are much higher in the southern Richmond catchment when compared to the northern part (Figure 3c and d). In the Findon, Gradys and Lynchs Creek, the more mountainous tributaries of the northern Richmond catchment, the proportion of sedimentary buffer is only 1.5, 2.1 and 4%, of which the major contribution is from the intermitted floodplain pockets and fan. In the Fawcetts, Wilsons and Eden Creek, the proportion of sedimentary buffer is 11.9, 13.2 and 8.3%, of which the major contribution is from floodplain and trapped tributary fills. The highest proportion of sedimentary buffer is in the Shannon Brook and the Bungawalbyn Creek subcatchment at 24 and 21.6%, of which the major contribution is from floodplain, levee, swamps and trapped tributary fill.

3.2. Distribution of modelled sediment fluxes across the Richmond River network

The final CASCADE model output produced network scale metrics of sediment flux entrained, transported and deposited in each reach. This output is used to analyse trends in downstream distribution of sediment flux in various river types and in contrasting geographic locations.

Sediment flux entrained is the total sediment entrained in each reach by the newly formed cascade in that reach. Depending upon the availability of transport capacity and the ability of bed material to be entrained within the reach of interest, sediment can or cannot be entrained. The river network in Figure 4a illustrates the quantum of sediment flux entrained in each reach during the occurrence of a 10 year return interval flood. In general, the sand bed rivers in the west experience significant more entrainment (illustrated by higher proportion of red, orange and yellow shades) when compared to the rivers in the NE (illustrated by higher proportion of blue shade). These fluxes were related to the eight river types identified previously to compare the amount of sediment flux entrained along different geomorphic river types in the catchment (Boxplots in Figure 4b). The highest sediment flux is entrained in the laterally unconfined discontinuous and continuous sand bed rivers in the Bungawalbyn and Shannon sub-catchments located in the SW of the Richmond catchment. This implies that during geomorphically effective events, these rivers have the highest capacity to entrain sediment in the system and hence have the capacity to undergo geomorphic adjustment. The second highest sediment flux is entrained along the partly confined planform and bedrock margin controlled sandy rivers in the Bungawalbyn, Eden and Shannon sub-catchments of the western Richmond catchment. Significant amount of sediment is also entrained within the partly confined planform controlled rivers in the NE Richmond catchment. Negligible sediment is entrained from the bedrock and boulder dominated confined and partly confined bedrock margin controlled reaches in the NE catchment and fine silt-clay bed laterally unconfined continuous reaches near the river mouth. Further comparison between the rivers in the NE Richmond catchment (including Richmond trunk stream), rivers in the Bungawlbyn Creek sub-catchment, Eden Creek sub-catchment and Shannon Brook sub-catchment reveal that in total, the highest sediment flux occurs in the Bungawalbyn Creek sub-catchment, followed by Eden Creek and Shannon Brook sub-catchments respectively. In comparison, negligible sediment is released from the rivers in NE Richmond catchment (Figure 4c).

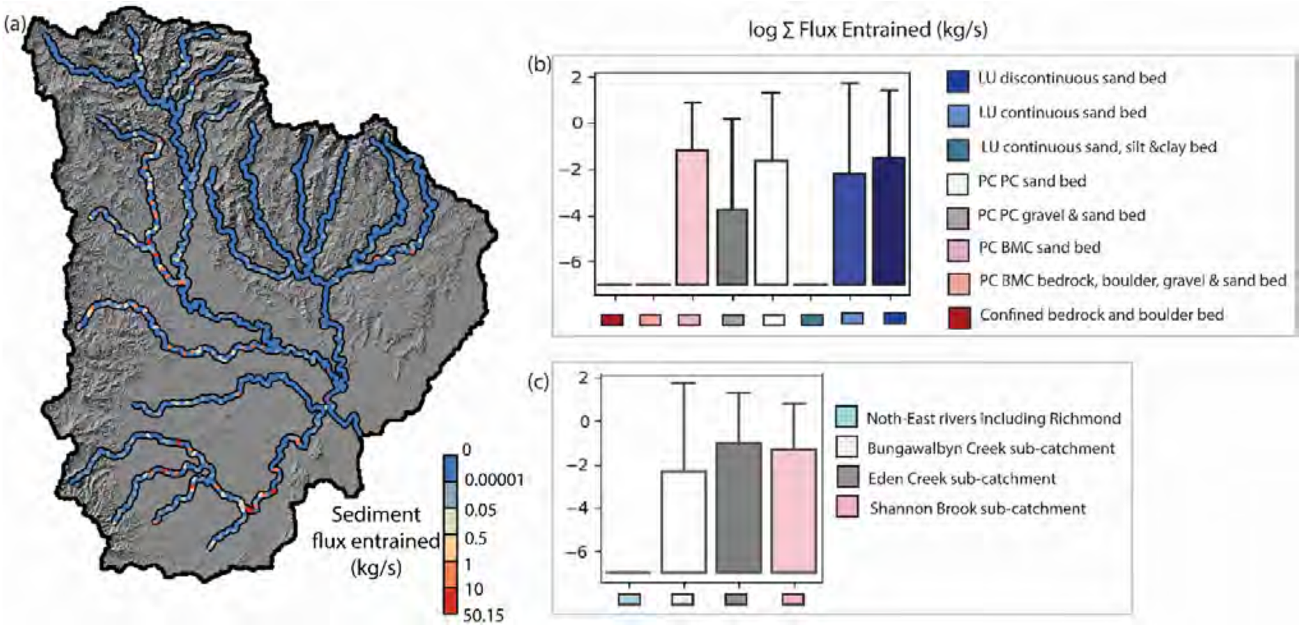

Figure 4 (a) Network scale distribution of sediment flux entrained within the Richmond River network (b) Boxplots showing the summation of sediment flux entrained within each river type identified (c) Boxplots showing the summation of sediment flux entrained within N-E Richmond catchment, Bungawalbyn sub-catchment, Eden Creek sub-catchment and Shannon Brook sub-catchment

Sediment flux transported is the total sediment transported through each reach by all the cascades passing through it. Depending upon the transport capacity of the reach and the availability of sediment (function of sediment entrained within that specific reach and the reaches upstream to it), bed material can (or cannot) be transported. Figure 5a illustrates the quantum of sediment flux transported in each reach during a simulated 10 year return interval flood. Significant similarities and also some notable differences can be visually identified between the entrained and transported maps (Figure 4a and Figure 5a). Similar to the pattern of entrainment, the sand bed rivers in the west transport significant amount of sediment (illustrated by higher proportion of red, orange and yellow shades) when compared to the rivers in the NE Richmond catchment (illustrated by higher proportion of blue shade). The most obvious difference is that, in the partly confined reaches, a significant amount of sediment is transported when compared to the sediment entrained (comparatively higher proportion of yellow and orange shades in the mid-stream reaches). Upon comparing the transported flux between various river types (Figure 5b), it is found that the highest sediment is transported within laterally unconfined discontinuous and continuous sand bed rivers in the SW followed by the partly confined rivers throughout the Richmond catchment. Some sediment is also transported by the headwater confined reaches and the laterally unconfined continuous reaches near the river mouth. The highest sediment is transported by the reaches in the Bungwalbyn sub-catchment followed by the Eden creek, Shannon Brook and then the NE Richmond catchment (Figure 5c).

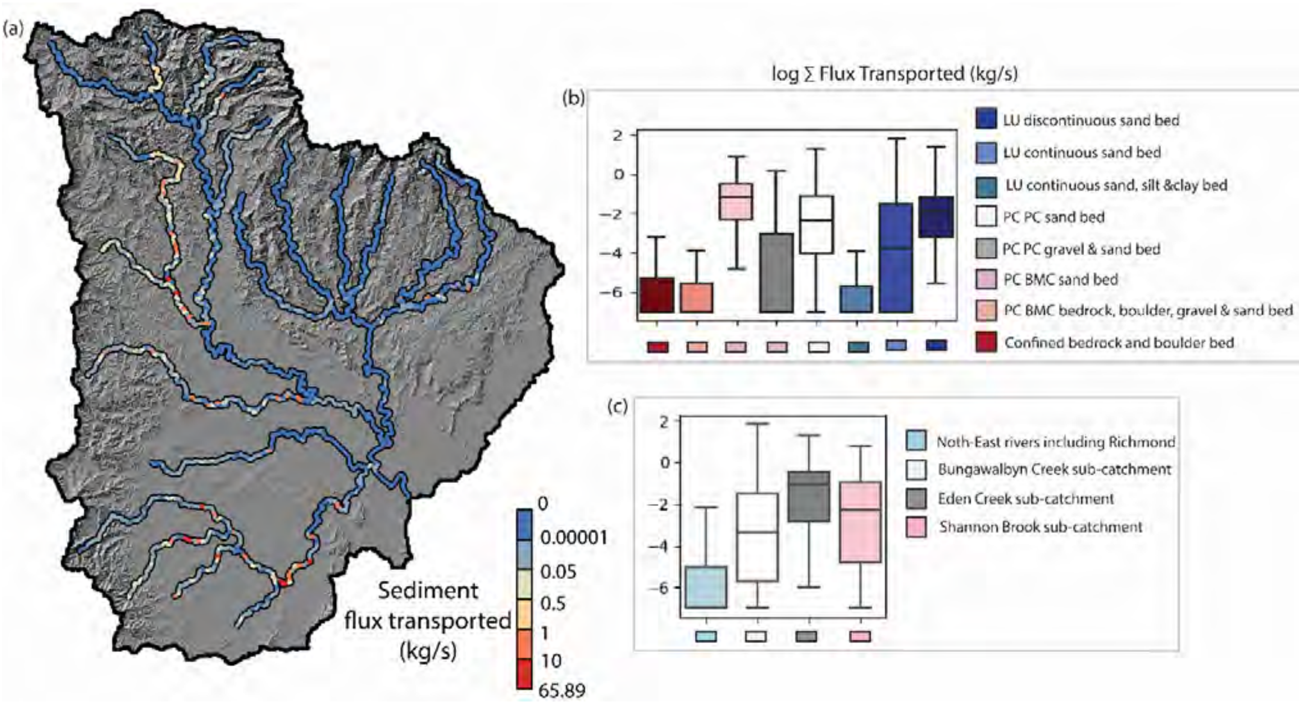

Figure 5 (a) Network scale distribution of sediment flux transported within the Richmond River network (b) Boxplots showing the summation of sediment flux transported within each river type identified (c) Boxplots showing the summation of sediment flux transported within N-E Richmond catchment, Bungawalbyn sub-catchment, Eden Creek sub-catchment and Shannon Brook sub-catchment

Sediment flux deposited is the total sediment deposited in each reach by all the cascades passing through it. Depending upon the sediment entrained as well as the transport capacity of the upstream reaches, the sediment entrained from upstream reaches can be transported and then deposited in any specific reach. Figure 6a illustrates that like the pattern of the entrained and transported sediment fluxes, a higher volume of sediment is deposited in the sand bed rivers of the western Richmond catchment when compared to the NE catchment. The boxplots in Figure 6b show that the highest deposition occurs in the laterally unconfined continuous and discontinuous sand bed rivers in the SW followed by the partly confined planform controlled reaches and partly confined bedrock margin controlled sand bed reaches. Negligible sediment is deposited within the partly confined bedrock margin controlled rivers that are dominated by bedrock and boulder, headwater confined and laterally unconfined continuous reaches near the river mouth during geomorphically effective events. The highest deposition of sediment takes place in the rivers in the Bungawalbyn sub-catchment, followed by Eden Creek, Shannon Brook and then the rivers in the NE Richmond catchment.

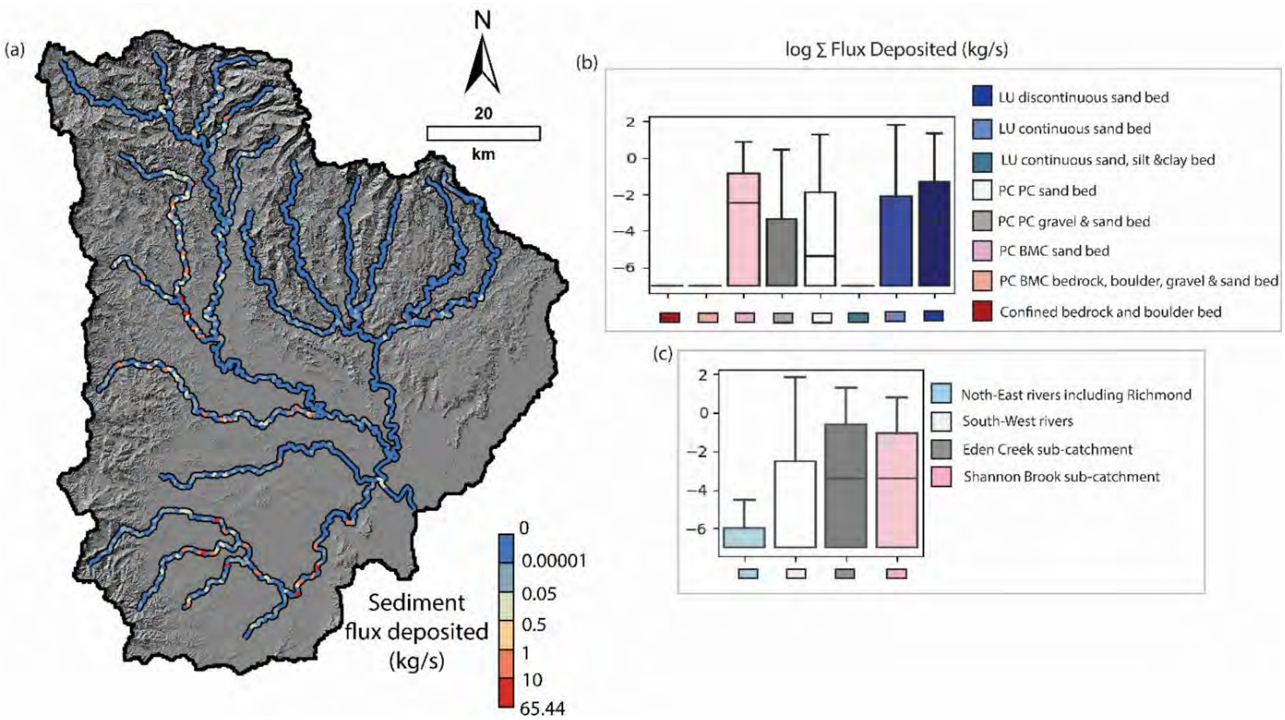

Figure 6 (a) Network scale distribution of sediment flux deposited within the Richmond River network (b) Boxplots showing the summation of sediment flux deposited within each river type identified (c) Boxplots showing the summation of sediment flux deposited within N-E Richmond catchment, Bungawalbyn sub-catchment, Eden Creek sub-catchment and Shannon Brook sub-catchment

The Kernel density plots in Figure 7 show the comparison between the transported and deposited sediment flux in the rivers in (i) NE Richmond catchment (ii) Bungawalbyn Creek sub-catchment (iii) Eden Creek sub-catchment and (iv) Shannon Brook sub-catchment. Rivers in the NE Richmond catchment transport a higher proportion of sediment when compared to the net sediment deposited in those reaches. Contrastingly, the rivers in the Bungawalbyn sub-catchment deposit more sediment when compared to the net sediment transported in those reaches. In both the Shannon Brook and the Eden Creek sub-catchments, the proportion of sediment transported is higher than the proportion of sediment deposited.

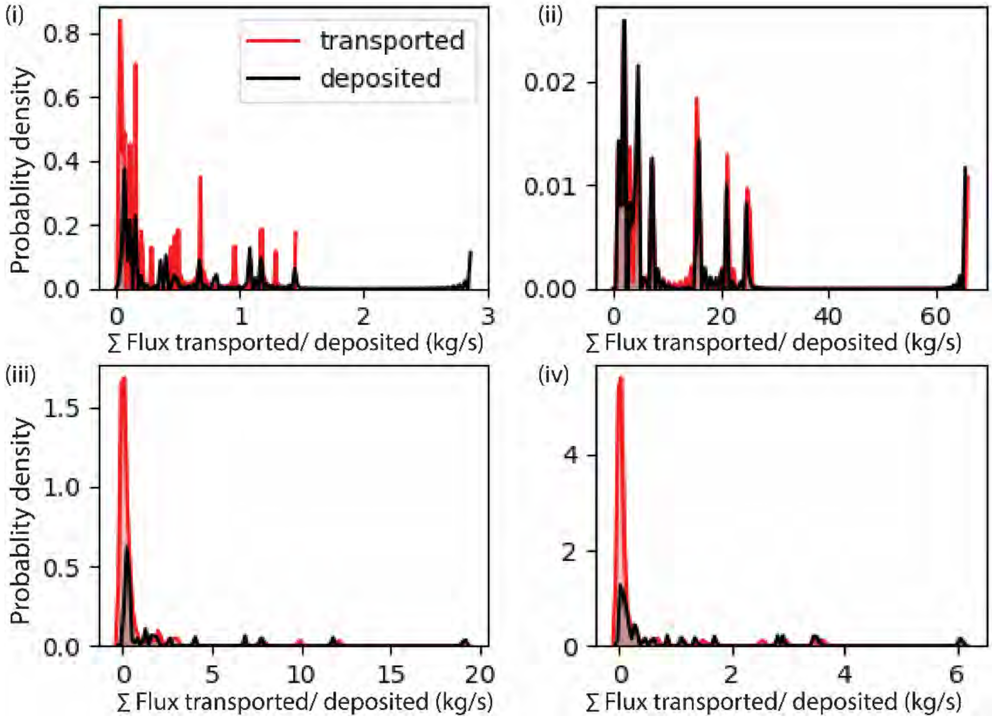

Figure 7 Kernel density plots comparing the transported (red) and deposited (black) sediment fluxes between the rivers in (i) N-E Richmond catchment (ii) Bungawalbyn Creek sub-catchment (iii) Eden Creek sub-catchment and (iv) Shannon Brook sub-catchment

4.3 Identification of distinct downstream patterns of variability in modelled sediment transport

The above network scale analysis provided information on the catchment wide variability in sediment fluxes and highlighted the contrasting sediment dynamics within different geomorphic river types that occur in different geographic locations. In order to understand the controls on the reach scale variability in sediment fluxes within different rivers in contrasting geographic settings, representative rivers were selected and analysed in detail.

From the mild gradient, sand dominated southern Bungawalbyn sub-catchment, the downstream variability in sediment fluxes was analysed along the Six Mile Swamp Creek and Myrtle+Bunagwalbyn Creek. The Six Mile Swamp Creek is a lower order sand bed stream with a mixture of continuous and discontinuous water courses. Figure 8 shows the pattern of entrained, transported and deposited fluxes along with the river types of the Six Mile Swamp Creek. During a geomorphically effective event (represented by 10 year return interval flood in this case), a significant amount of sediment can get entrained from the discontinuous chain of ponds river types that then gets transported and deposited in nearby downstream reaches. Therefore, the major control on sediment dynamics of such rivers is the availability of sediment stores within these discontinuous sand bed water courses.

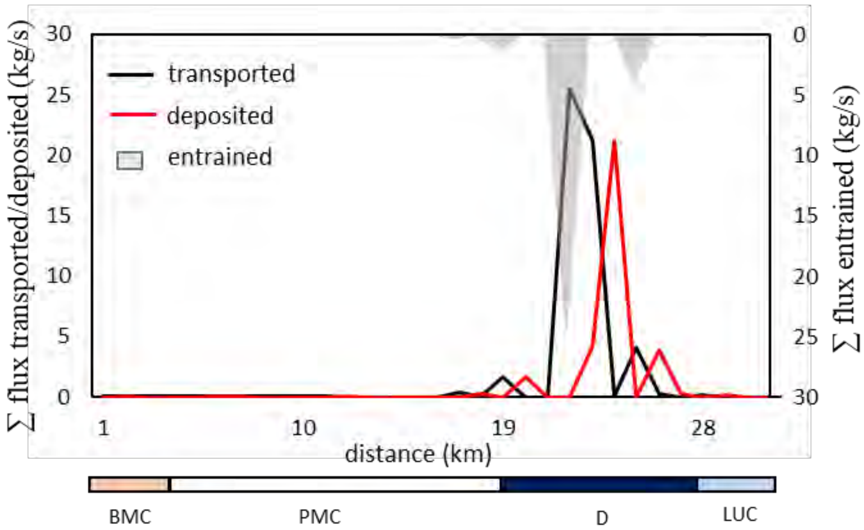

Figure 8 The downstream patterns of variability in sediment transport along the Six Mile Swamp Creek. The color codes below marks the boundary of different river types. Abbreviations: BMC- partly confined bedrock margin controlled sand bed river, PMC- partly confined planform controlled sand bed river, D- laterally unconfined discontinuous sand bed river and LUC- laterally unconfined continuous sand bed river

The Myrtle+Bungawalbyn Creek is the longest river in the Bungawalbyn sub-catchment that connects a number of continuous and discontinuous sand bed streams. The pink arrows in Figure 9 marks the location of tributary input to this river. The pattern of sediment peaks along Myrtle+Bungawalbyn Creek shows that major sediment dynamics occurs at (i) tributary confluence (ii) discontinuous water courses and (iii) at the junction of two river types. This suggests that during high flood events, there is potential for major geomorphic adjustment to occur at these specific locations.

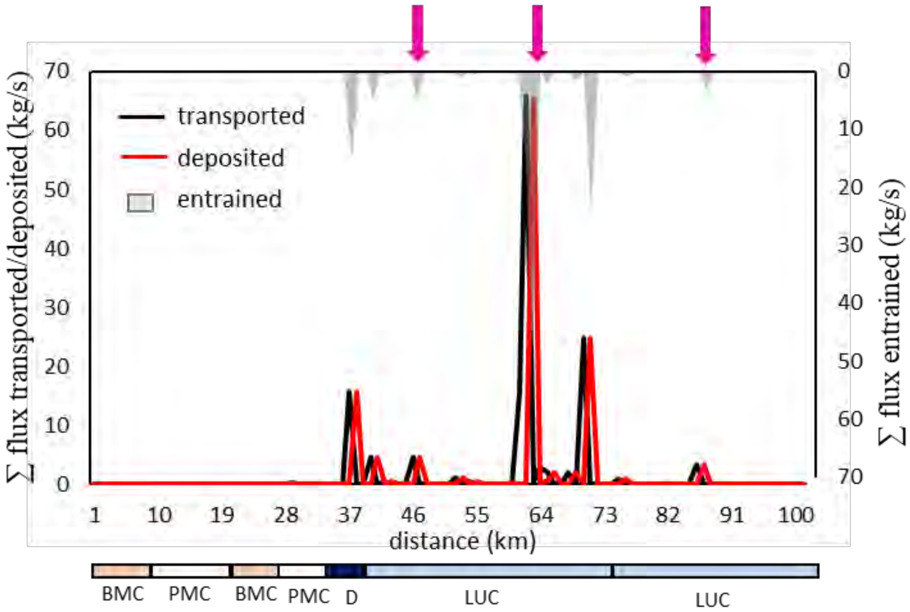

Figure 9 The downstream patterns of variability in sediment transport along the Myrtle+Bungawalbyn Creek. The pink arrows marks the tributary confluence. The color codes below marks the boundary of different river types. Abbreviations: BMC- partly confined bedrock margin controlled sand bed river, PMC- partly confined planform controlled sand bed river, D- laterally unconfined discontinuous sand bed river and LUC- laterally unconfined continuous sand bed river

The Richmond trunk stream receives discharge and sediment input from the geomorphically diverse NE and SW tributaries. The concentration of shaded inverse grey peaks in partly confined planform controlled reaches (Figure 10) highlight that the majority of sediment entrainment along the Richmond River occurs from floodplain pockets within these reaches. The distribution of red peaks suggests that the majority of sediment transportation along Richmond trunk stream occurs at the tributary junction (coincident with the pink arrows). The inset plot shows the amount of sediment transported by the Richmond River downstream of its confluence with the Eden Creek. This suggests that the major control of sediment dynamics during geomorphically effective events in the Richmond River is (i) tributary confluences and (ii) transport dynamics within partly confined planform controlled floodplain pockets reaches.

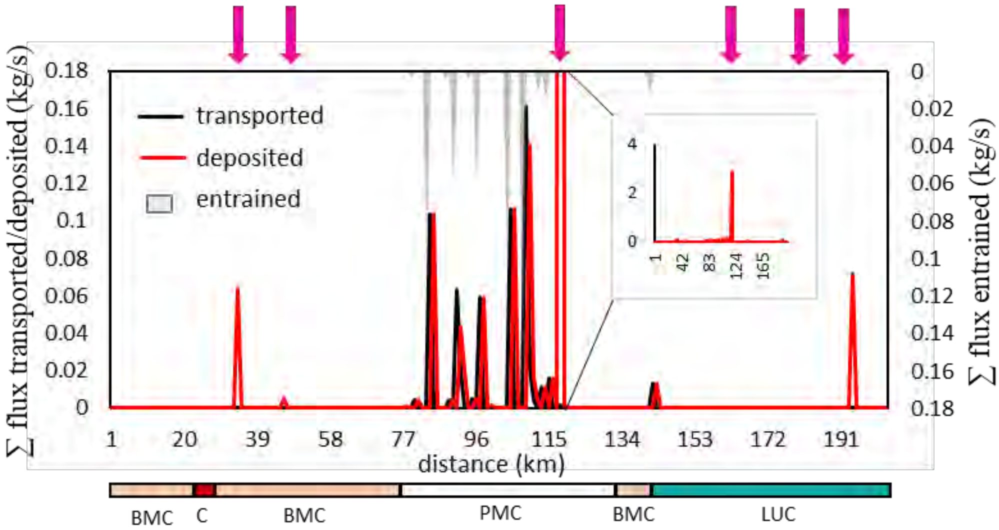

Figure 10 The downstream patterns of variability in sediment transport along the Richmond River. The pink arrows marks the tributary confluence. The color codes below marks the boundary of different river types. Abbreviations: BMC- partly confined bedrock margin controlled boulder, gravel and sand bed river, C- confined bedrock and boulder river PMC- partly confined planform controlled gravel and sand bed river, LUC- laterally unconfined continuous sand, silt and clay bed

Similar to the Richmond trunk stream, the major control of sediment dynamics during geomorphically effective events in the Eden Creek is (i) tributary confluences and (ii) transport dynamics within partly confined floodplain pockets reaches.

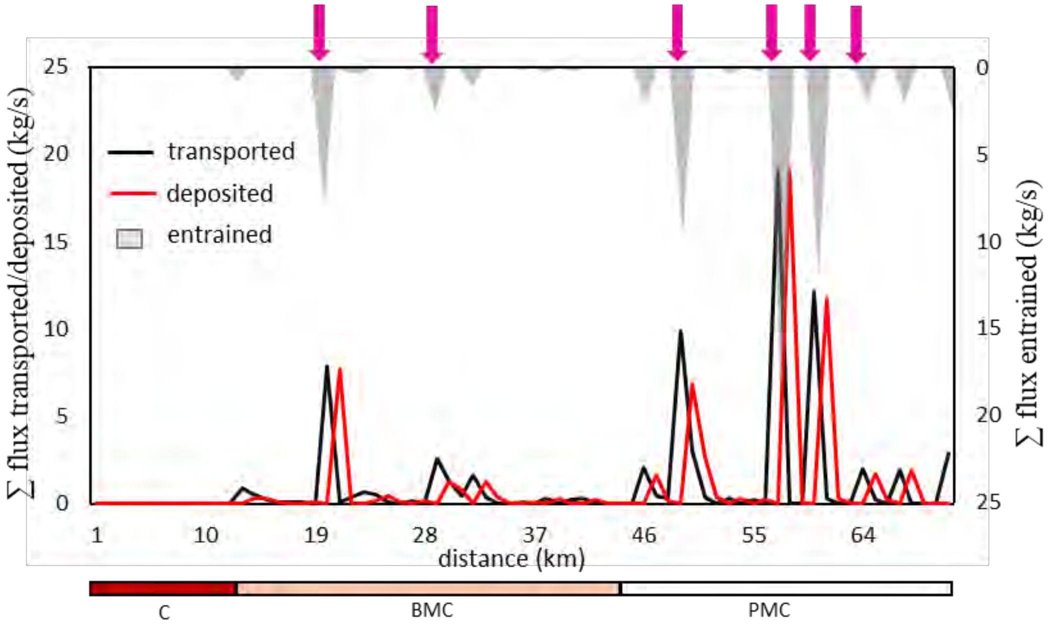

Figure 11 The downstream patterns of variability in sediment transport along the Eden creek. The pink arrows marks the tributary confluence. The color codes below marks the boundary of different river types. Abbreviations: BMC- partly confined bedrock margin controlled sand bed river, C- confined bedrock and boulder river, PMC- partly confined planform controlled sand bed river

The Shannon Brook lies in the middle of the western Richmond catchment initiates with discontinuous water courses in the headwaters and has sand bed partly confined and laterally unconfined rivers downstream. During geomorphically effective events, active sediment transport is observed throughout the river length. Significant sediment dynamics is observed at the locations of (i) discontinuous water courses (ii) tributary confluences (iii) partly confined planform controlled floodplain pockets reaches and (iv) laterally unconfined sand bed reaches.

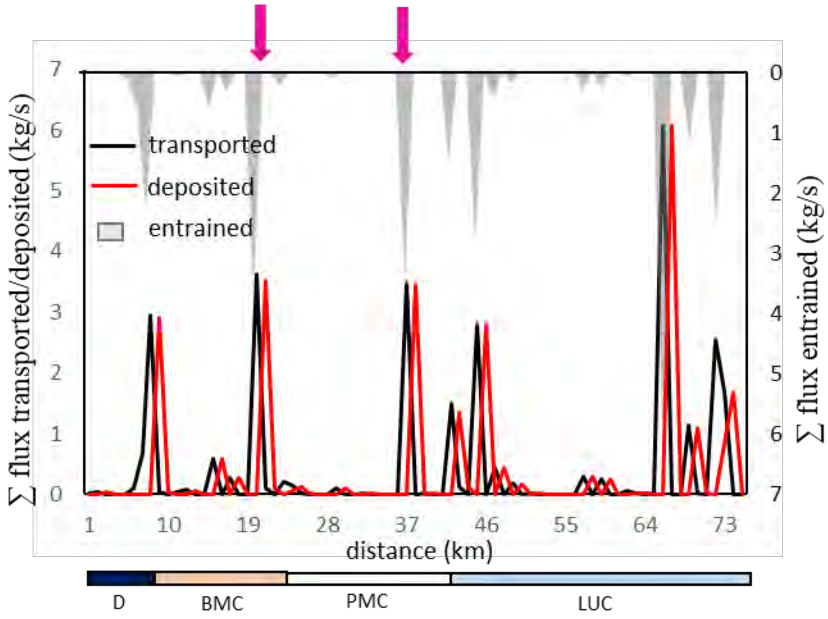

Figure 12 The downstream patterns of variability in sediment transport along the Shannon Brook. The pink arrows marks the tributary confluence. The color codes below marks the boundary of different river types. Abbreviations: BMC- partly confined bedrock margin controlled sand bed river, PMC- partly confined planform controlled sand bed river, D- laterally unconfined discontinuous sand bed river and LUC- laterally unconfined continuous sand bed river

Lynchs Creek is a short mountain tributary in the northern Richmond catchment. The major control on the sediment dynamics of this rivers is the junction of two different geomorphic river types. Figure 13 shows that the majority of entrainment, transportation and deposition of sediment occurs when the river changes from confined to partly confined bedrock margin controlled and then to partly confined planform margin controlled river type.

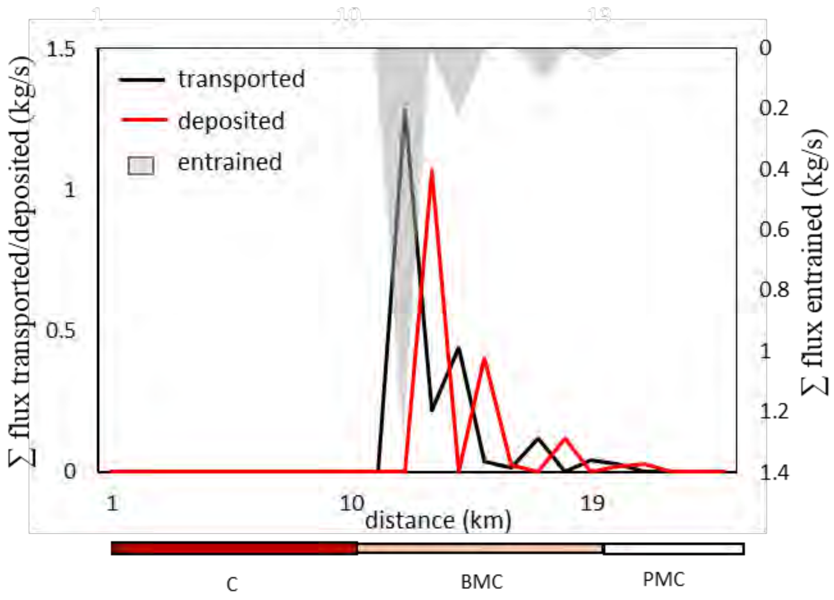

Figure 13 The downstream patterns of variability in sediment transport along the Lynchs creek. The pink arrows marks the tributary confluence. The color codes below marks the boundary of different river types. Abbreviations: BMC- partly confined bedrock margin controlled boulder, gravel and sand bed river, C- confined bedrock and boulder river, PMC- partly confined planform controlled gravel and sand bed river

4. Discussion

4.1.Interpreting the causes and consequences of sediment (dis)connectivity

This analysis of catchment scale variability in sediment coupling-decoupling and network scale distribution of sediment fluxes in the Richmond catchment has provided information on the gradient of sediment (dis)connectivity in this system. An overall pattern shows that two very distinct zones exists in the Richmond system: the disconnected or decoupled SW Richmond catchment and the connected or coupled NE Richmond catchment (Figure 14).

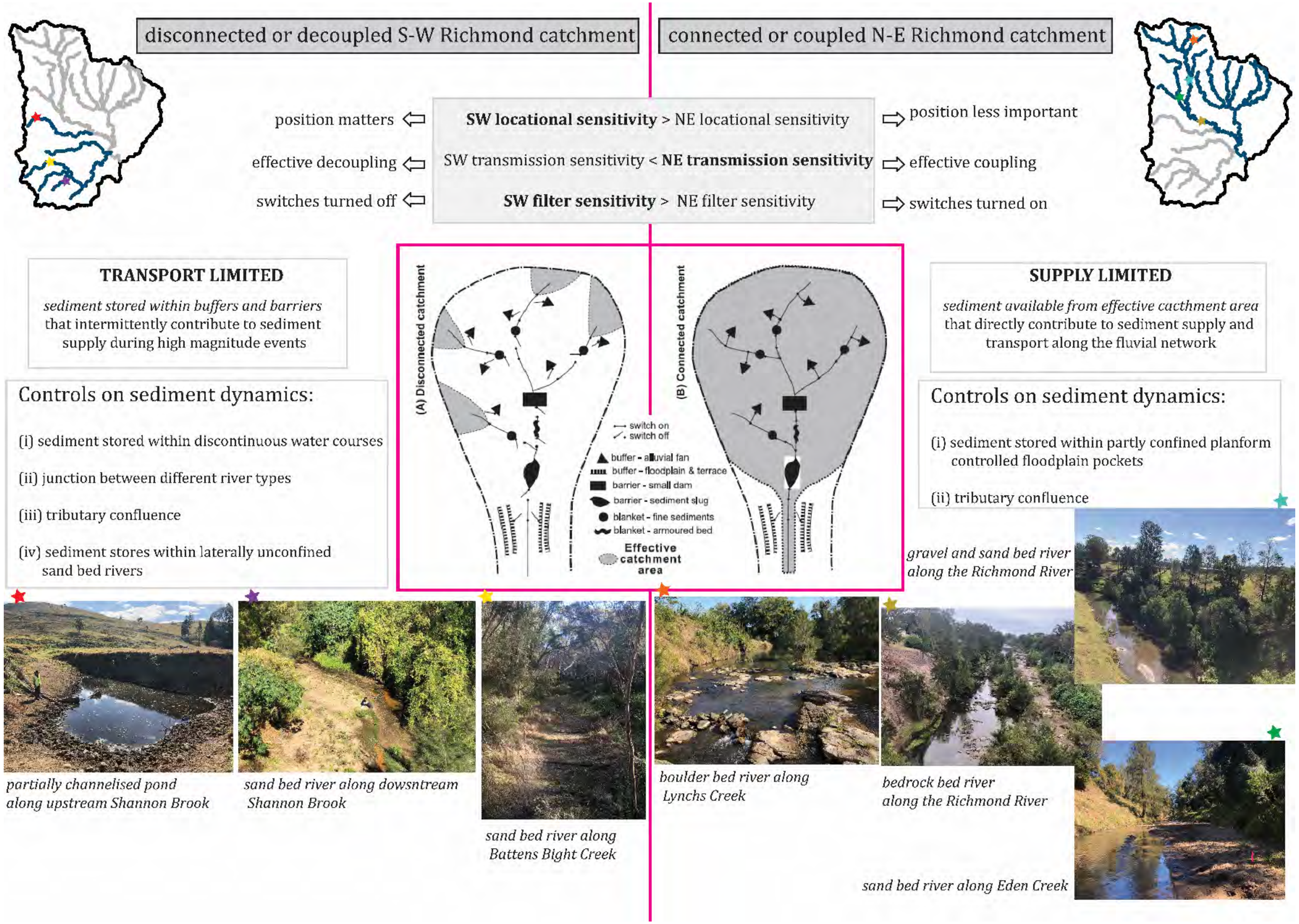

Figure 14 The disconnected or decoupled S-W Richmond catchment and the connected or coupled N-E Richmond catchment. The conceptual diagram in the middle is taken from Fryirs, 2017

Due to very mild gradient and hillslope-channel decoupling via antecedent sediment stores, the SW catchment has negligible ECA and extensive sedimentary buffers that impede direct contribution of sediment supply and transport along the fluvial network. The majority of sediment is stored within these extensive buffers and barriers (e.g. Fryirs et al., 2007b). These buffers and barriers are likely only breached (or activated) and supply sediment during geomorphically effective events. As a result of this decoupling, the rivers in the SW catchment have low transmission sensitivity but high locational sensitivity i.e. the position of the reaches within the catchment plays a dominant role in determining the potential for geomorphic adjustment during geomorphically effective events (Brunsden, 1993; Fryirs, 2017; Lisenby and Fryirs, 2016). This can trigger positive or negative feedback mechanisms that determine if the system can accentuate or attenuate geomorphic adjustment locally and in the downstream direction (Allen, 1974; Chappell, 1983; King, 1970; Fryirs, 2013). The location of antecedent sediment stores i.e. the buffers and barriers acts as ‘off-switches’ between landscape compartments that filter the river response to disturbance events either by absorbing the energy supplied during the disturbance event without resulting into adjustment, or propagating the energy and producing adjustment elsewhere (Brunsden, 1993; Fryirs, 2013, 2017; Fryirs et al., 2007b).

These SW Richmond Rivers form a transport limited system that is choked with medium to fine sand along the channel bed but has very low energy to transport that sediment (see field photographs in Figure 14). However, these rivers are event sensitive (Crozier, 1999; Fryirs, 2017) and threshold driven (Bull, 1979; Chappell, 1983; Schumm, 1973). The antecedent condition of the landscape or the system preconditioning by past geomorphic events heavily influences the trajectory of river response in these reaches (Allison and Thomas, 1993; Baartman et al., 2013; Brierley, 2010; Brierley and Fryirs, 2016; Schumm, 1985). This is because during geomorphically effective events, these rivers have the potential to mobilise this sediment at the hotspots of high locational sensitivity and produce onsite or offsite geomorphic adjustment. As a result, these rivers act like a 'jerky conveyor belt' that gets activated during high magnitude events (Ferguson, 1981).

In contrast, the rivers in the NE Richmond catchment have steep slopes and relatively high hillslope-channel coupling. This results in a relatively higher proportion of effective catchment area that directly contributes to unimpeded sediment supply and transport along the fluvial network. A relatively lower proportion of sediment buffering along the sediment cascade implies higher lateral connectivity and an absence of sediment storage units except within floodplain pockets. Therefore, these rivers have high transmission sensitivity and low locational sensitivity, implying that the position or configuration of reaches within the catchment does not play a prominent role in river response and adjustment during geomorphically effective events as these reaches have the capacity to efficiently propagate energy in the downstream direction (Brunsden, 1993; Fryirs, 2017). The filter sensitivity in this system is very low as most of the switches are 'turned on' such that the reaches promptly transmit the fluxes of flow and sediment (Fryirs, 2013). This implies that these reaches have a lower propensity to produce geomorphic adjustment except at specific hotspots.

Therefore, rivers in the NE of the Richmond catchment are essentially a supply limited system that have high energy and transport capacity but are sediment starved and therefore have very limited capacity to undergo geomorphic adjustment (see field photographs in Figure 14). As a result, even during extreme flood events, hardly any geomorphic adjustment and change can be expected to occur. Hence, these rivers rather act like a 'smooth conveyor belt' that efficiently propagate fluxes in downstream direction.

4.2. Linking the network scale pattern of sediment fluxes to geomorphically sensitive reaches for identifying hotspots of geomorphic adjustment

In the last couple of decades, a number of conceptual and empirical studies on sediment (dis)connectivity have emerged that have enhanced our ability to understand and interpret the sediment cascade of a catchment (Baartman et al., 2013; Fryirs et al., 2007a, 2007b; Sinha et al., 2019; Wohl, 2017; Wohl et al., 2017). While most studies have addressed this issue at the catchment scale (Cavalli et al., 2013; Fryirs et al., 2007c; Lisenby and Fryirs, 2016), a handful of these studies have approached it at a network scale (Czuba and Foufoula-Georgiou, 2015, 2014; Kondolf et al., 2018; Schmitt et al., 2018, 2016). Furthermore, a few of these studies have used this concept to identify trends and patterns of geomorphic adjustment and change in a catchment.

Analysis of the Richmond catchment has been used to specifically address two aspects (i) using the network scale pattern of sediment dynamics to identify potential locations of geomorphic activity (or hotspots) during geomorphically effective events (ii) identification of possible controls on geomorphic activity and sensitivity across the catchment.

Analysis has highlighted the variable nature of sediment (dis)connectivity in different geomorphic river types. This emphasises the remarkable influence of geomorphic configuration of the landscape on the nature of sediment (dis)connectivity in rivers (Brierley et al., 2006; Fryirs, 2017; Jain and Tandon, 2010; Phillips et al., 2020; Sutfin and Wohl, 2019). Not all river types exhibit similar magnitude and variability in sediment entrainment, deposition and transportation during flow events of different magnitude, frequency and effectiveness. Moreover, different rivers are driven by different controlling mechanisms that produce variable sediment dynamics in different geomorphic river types.

During geomorphically effective events in the Richmond catchment, sediment dynamics are particularly accentuated in the laterally unconfined discontinuous water courses. Highest amount of sediment gets entrained and further mobilised in these rivers, suggesting that these reaches are potential hotspots of geomorphic adjustment in the catchment. Locational sensitivity is a key control on these reaches driven by the position of transient sediment storage units such as sediment slugs, sand bars and un-vegetated benches that acts as off-switches that attenuate signal of geomorphic adjustment during low-medium flow stages. However, these sediment stores can be switched-on during geomorphically effective events and instigate adjustment onsite and/or offsite. These results coincided with the behavioural sensitivity analysis in the Richmond catchment where these discontinuous water courses were classified as fragile rivers such that they have the propensity to undergo wholesale dramatic river change during extreme events (Khan and Fryirs, 2020).

Next on the gradient are the laterally unconfined continuous sand bed rivers that also entrain and mobilise sediment during geomorphically effective flows. The key control on the locational sensitivity of these reaches are the loose sediment stores available on the sand bed in the form of sand slugs and sand bars that are easily mobilised and propagate geomorphic adjustment. These results coincide with the behavioural sensitivity results where these reaches were classified as active sensitive rivers as they have the ability to re-configure on the floodplain via lateral migration and maintain their contemporary behavioural regime (Khan and Fryirs, 2020).

Next on the gradient are the partly confined planform controlled sand bed rivers, partly confined bedrock margin controlled sand bed rivers and the partly confined planform controlled gravel and sand bed rivers. Some sediment can get entrained and transported downstream from these reaches, resulting in localised geomorphic adjustment. The control on the locational sensitivity of these reaches are the floodplain pockets that can be eroded and mobilised during geomorphically effective events. These results align with the behavioural sensitivity results where these reaches were classified as passive sensitive rivers because they have the capacity to adjust within a macro channel but maintain their overall behavioural regime and withstand permanent adjustment (Khan and Fryirs, 2020).

In comparison, the confined boulder and bedrock rivers, partly confined bedrock margin controlled bedrock, bolder, gravel and sand bed rivers and the laterally unconfined continuous sand, silt and clay bed rivers hardly experience any significant sediment dynamics. This suggest that these rivers are not prone to any significant geomorphic adjustment. These results also coincide with the behavioural sensitivity results where these reaches were classified as resistant and insensitive rivers as they either do not have the capacity to adjust due to the dominance of imposed controls such as bedrock and boulders or fine cohesive bed material that acts as an antecedent control on the capacity for adjustment (Khan and Fryirs, 2020).

Apart from this influence of these varying attributes of the geomorphic river diversity on sediment dynamics, further magnification of sediment dynamics in Richmond Rivers were observed at the locations of tributary confluences and junctions between different river types, specifically at junctions of laterally unconfined and partly confined reaches. This implies that (dis)connectivity can become exacerbated at junctions that separate different process domains (Brunsden, 1993; Harvey, 2002; Montgomery, 1999; Rice, 1999, 1998). These locations can act as hotspots of geomorphic adjustment as these junctions marks the position of integration of geomorphically diverse reaches. At tributary confluence, integration of the tributary with the trunk stream results in changes in transport of discharge, sediment and energy that can propagate geomorphic adjustment, especially during geomorphically effective events.

These results strongly suggest that the concept of sediment (dis)connectivity can be used to better understand the multi-faceted concept of landscape sensitivity and to understanding and identify areas in catchments where geomorphic adjustments occur (or are likely to occur) at different scales (Bracken et al., 2015; Fryirs et al., 2007c; Fryirs and Brierley, 2013; Wohl, 2017; Wohl et al., 2018). Such studies provide a robust platform for identifying the pattern and controls on sediment dynamics of different river types with implications for identifying the hotspots of geomorphic adjustment (Czuba and Foufoula-Georgiou, 2015).

5. Conclusion

The analysis of sediment (dis)connectivity in the Richmond catchment has highlighted the gradient of sediment coupling-decoupling across the catchment and provided information of the locations of the occurrence of hotspots of geomorphic adjustment along the river network. The highly coupled NE Richmond catchment emerges as relatively resilient to adjustment during geomorphically effective events whereas the SW catchment is susceptible to onsite and offsite adjustment during geomorphically effective events. The major controls on sediment dynamics of this system are the locations of sediment stores within discontinuous water courses, transient sediment storages units within sand bed rivers, tributary confluence, junction of contrasting geomorphic rive types and floodplain pockets within partly confined planform controlled valley settings.

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Chapter 7

Discussion

7. Discussion and thesis conclusion

7.1. Thesis overview

The overarching objective of this thesis has been to assess geomorphic river sensitivity of different river types in the Richmond River catchment and provide a package of remote sensing techniques for assessing river sensitivity that others can adapt and use in their own catchment. To fulfil this objective, this thesis has five aims that frame the analysis of river sensitivity. Three key geomorphic attributes of a landscape are considered. This discussion will firstly consider these three geomorphic attributes in an integrated way to investigate how they function together to ascertain geomorphic sensitivity of a fluvial system. In subsequent sections each geomorphic attribute will be discussed and situated within an international context so as to underpin the contribution of this research to the field of fluvial geomorphology.

Understanding the continuum of process domains (Fryirs and Brierley, 2013; Montgomery, Buffington, 1998; Montgomery, 1999; Montgomery and MacDonald, 2002), their spatial and temporal hierarchy (Bisson et al., 2006; de Boer, 1992; Gurnell et al., 2016) and the integrated nature of geomorphic forms and processes is important for understanding fluvial dynamics and change (Brierley and Fryirs, 2005; Rhoads, 2020, 1999; Rhoads and Thorn, 1993; Simon et al., 2007). This can be used to answer questions such as: Why a certain river type occurs where it does in a catchment and what controls its occurrence? How do different types of river adjust under natural or anthropogenic disturbance? How can an onsite or offsite disturbance affect a specific reach i.e. how connected or disconnected is a certain river to its floodplain and other reaches upstream/downstream? This thesis demonstrates that the concept of river sensitivity is capable of answering these important questions by assessing three key geomorphic attributes of a landscape: geomorphic controls, system preconditioning as a result of historical geomorphic adjustment and sediment (dis)connectivity.

Figure 1 conceptualises the interrelationships between these three geomorphic attributes by showing that while most components operate independent of each other (non overlapping circles), in fluvial systems there are significant interactions between attributes that need to be considered to assess river sensitivity.

River diversity is a key attribute (Figure 1). Therefore, identification of geomorphic river type is an important first step for understanding the structure and function of a river (Bisson et al., 2006; Fryirs and Brierley, 2013; Montgomery, Buffington, 1998; Simon et al., 2007). The shape of longitudinal profiles of rivers provide a strong proxy for understanding the geomorphic history of a catchment (Roy and Sinha, 2017; Sinha and Parker, 1996; Snow and Slingerland, 1987). The pattern of river types and their position (and associated slope) on the longitudinal profile is a key control on why certain rivers occur where they do and how sensitive they are to on-site or off-site disturbances (Figure 1). Furthermore, since geomorphic processes are a result of erosion and deposition dynamics along the fluvial corridor, bed material size plays an important role in determining the contemporary sediment flux dynamics that control the extent and nature of system (de)coupling (Figure 1).

This thesis investigates the mix of *geomorphic controls* operating on the fluvial system to determine the sensitivity of any given river or river type to adjustment. This is considered as a mix of network scale imposed controls such as slope and valley bottom width, and flux controls such as stream power and bed material size (Fryirs and Brierley, 2013; Khan et al. in review (Chapter 2)). Analysing *historical geomorphic adjustment* provides a basis for determining system preconditioning as a result of historical disturbances. This is done by tracking the historical capacity for adjustment and developing a method to calculate behavioural and change sensitivity across the network (Fryirs, 2017; Fryirs and Brierley, 2013; Khan and Fryirs, 2020a (Chapter 5)). The extent of *sediment (dis)connectivity* is analysed by considering the effective catchment area of a catchment, the position of blockages (buffers) and network scale analysis to simulate the operation of the catchment sediment cascade (Czuba and Foufoula-Georgiou, 2015; Fryirs et al., 2007; Fryirs and Brierley, 2013; Schmitt et al., 2016; Khan et al. in preparation (Chapter 6)).

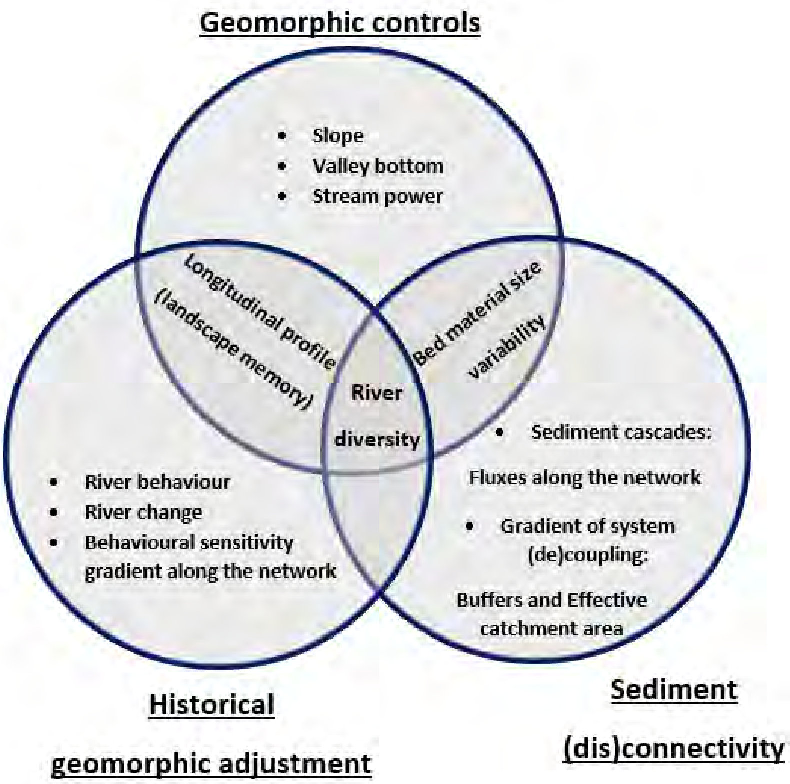

Figure 1 Conceptual venn diagram showing the interrelationships between the components of each of the three geomorphic attributes discussed in this thesis: geomorphic controls, historical geomorphic adjustment and sediment (dis)connectivity

Table 1 sets out the five aims of this thesis relative to the research approach used and the corresponding thesis chapters. *Firstly*, this thesis assessed the types of rivers that occur in the Richmond catchment and analysed their position along longitudinal profiles and the mix of controls operating on them (see Chapter 2, Khan et al., in review). For this, imposed controls that do not change over geomorphic timeframes and produce the environmental setting in which a river functions; and flux controls that represent the dynamic interactions between flow and sediment (Church 1996; Fryirs and Brierley, 2013) were calculated across the Richmond network using LiDAR DEM and historical discharge record. Statistical analysis was performed at univariate, bivariate and multivariate levels to determine the envelopes of controls, strength of controls and the dominance of controls on each river type and this was used to explain the resulting pattern of river types along the longitudinal profiles. This study provides clarity on the morphological characteristics of the Richmond catchment, the controlling factors on geomorphic river diversity and paves the way for further understand of the geomorphic processes operating at the reach and catchment scale. *Secondly*, this thesis developed easy-to-use semi-objective workflows for creating a valley bottom polygon, valley bottom segmentation and semi-automating the calculation of the network scale geomorphic controls. This work is presented in Chapter 3 and 4, (Khan and Fryirs 2020b; Khan et al., in review). *Thirdly,* this thesis tracked the historical capacity for adjustment of rivers in the Richmond catchment since European colonisation. For this, surveyor general's notebooks, parish maps and historical aerial imagery for each decade from the 1890s onwards were used. This work is presented in Chapter 5 (Khan and Fryirs 2020a). *Fourthly,* the historical analysis was used to develop a workflow called a behavioural sensitivity logical tree for calculating behavioural sensitivity and change sensitivity. This workflow is presented in Chapter 5 (Khan and Fryirs 2020a). This paper also presents a scheme for classifying rivers as geomorphically Fragile, Active Sensitive, Passive Sensitive, Insensitive and Resistant. Finally, this thesis approached the *fifth* aim by simulating the sediment cascade of the catchment. It used a combination of the effective catchment area and buffer analysis of Fryirs et al. (2007) and the CASCADE model of Schmidt et al. (2016) to determine the role of system (dis)connectivity on network scale sediment flux and potential for geomorphic change at different positions within the catchment. This is used to identify hotspots of channel adjustment. This work is presented in Chapter 6.

Table 1 Relationship between thesis aims, research approach and associated chapters

Thesis aims	Research approach	Chapter no.
To explain controls on geomorphic river diversity across the study catchment	• Visually assess the network scale pattern of imposed and flux controls • Statistically analyse the univariate and bivariate relationships between a range of imposed and flux controls; identify the envelopes of key controls within which the different river types are formed; and assess the relative strength of each control to determine those that are dominant and have significant effects on the spectrum of river types in the catchment. • Situate the imposed and flux controls along longitudinal profiles of different shape identified to describe the gradient of controls influencing the patterns of river diversity identified in this system.	**2**
To provide GIS workflows to semi-automate the analysis of valley bottom extent, valley segmentation and to calculate imposed and flux controls across the study catchment using publically available datasets	• Provide a quick and easy-to-use semi-objective approach for creating a valley bottom polygon using publicly available DEM input. • To assess the accuracy and precision of different DEM sources and optimum DEM resolution for valley bottom extraction across a catchment using this approach. • Demonstrate the application of an unsupervised machine-learning technique using k-means clustering to delineate and map network-scale valley bottom segments of variable length. • Provide GIS approach to quickly and accurately extract catchment scale geomorphic controls on river diversity: slope, gross stream power, valley bottom width and bed material texture along the drainage network using publically available datasets • Provide the workflow for calculating these controls embedded within an ArcGIS toolkit, ArcGIS ModelBuilder and Python script.	**3 & 4**
To track post-colonisation geomorphic capacity for adjustment across the study catchment as a basis for developing a method for assessing river sensitivity	• Track historical adjustment since European colonisation in the Richmond catchment using surveyor general's notebooks, parish maps and decadal aerial imagery • Relate various forms of adjustment observed in different river types to	**5**

	corresponding flood regime and riparian vegetation density	
To provide a workflow for the calculation of historical behavioural and change sensitivity across the study catchment to determine whether rivers are geomorphically Fragile, Active Sensitive, Passive Sensitive, Insensitive and Resistant, and to map this across the catchment	• Provide workflow for calculation of historical behavioural and change sensitivity across the catchment • Provide an approach, called the 'Behavioural sensitivity logical tree' that can be applied to assess and quantify reach scale behavioural sensitivity	**5**
To analyse the pattern of sediment (dis)connectivity across the study catchment as a basis to assess the role of system (de)coupling on network scale sediment flux in identifying hotspots of channel adjustment	• Analyse the distribution of effective catchment area and buffers to assess the variability in subcatchment (de)coupling • Quantify the cascades of entrained, transported and deposited sediment fluxes across the river network	**6**

7.2. River sensitivity: A unifying principle of fluvial geomorphology

Rivers, like any other natural environmental settings are complex, nested, hierarchical systems that offer non-linear and spatially variable response to disturbances of varying magnitude and frequency (Phillips, 2010, 2009, 2007, 2006, 2003; Schumm, 1979, 1973). This is because river response is a complex result of the internal characteristics and external forcings operating on the system that has the capacity to alter the geomorphic structure at scales ranging from the local to the catchment and over timeframes ranging from days to millennia (Rhoads, 2020). Therefore, in order to unravel the spatio-temporal nature of river sensitivity in any catchment of interest, it is important to solve these geomorphic complexities in a hierarchical manner. However, river sensitivity is a complex and poorly understood topic (Allison and Thomas, 1993; Brunsden and Thornes, 1979; Fryirs, 2017). Although numerous studies have been conducted in fluvial geomorphology, most have been conceptual and do not provide methodologies for assessing river sensitivity in practice (Brunsden, 2001; Fuller et al., 2019; Piégay et al., 2018; Thoms et al., 2018; Tooth, 2018).

The concept of river sensitivity as presented in this thesis brings together a suite of geomorphic principles and remote sensing tools to provide a systematic and logical basis for geomorphologists to know their catchment (Brierley and Fryirs, 2005; Fryirs and Brierley, 2013). This provides the basis for operationalising the "standardised definitions of sensitivity" (Downs and Gregory, 1995; p. 168) to enable analytical assessment of this lost foundational concept in fluvial geomorphology (Fryirs, 2017).

This thesis has used a hierarchical framework to assess geomorphic river sensitivity across three scales; the landform scale, the reach scale and the catchment scale. This forms the basis for interlinking the trio of morphological sensitivity; behavioural and change sensitivity and; locational, filter and transmission sensitivity (Figure 2).

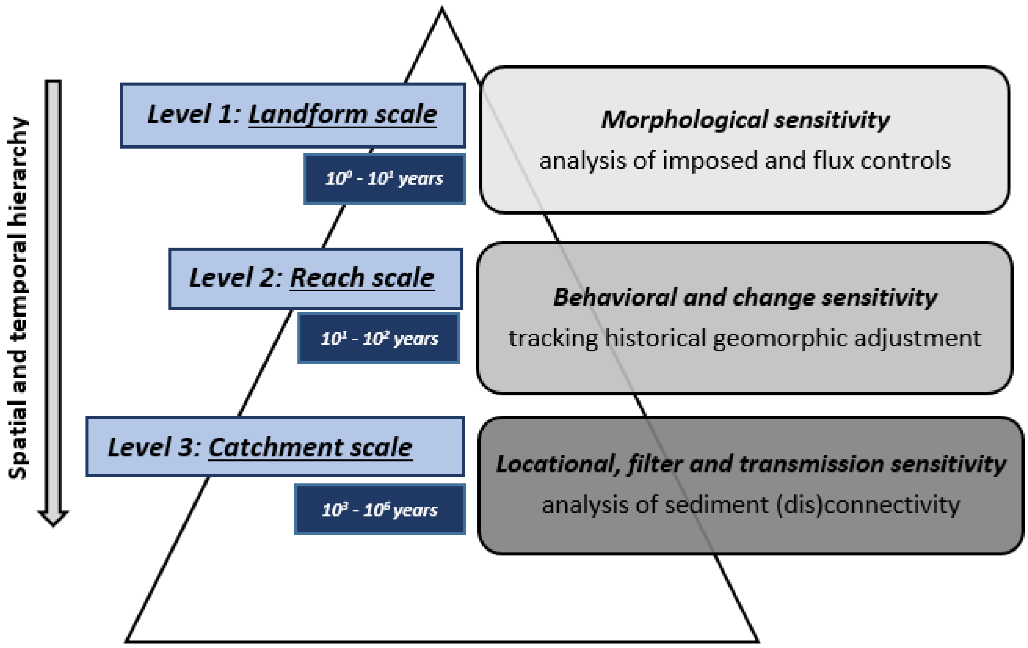

Figure 2 Nested hierarchical framework for assessing river sentivity as underpinned by this thesis. The three levels show the spatial and temporal scales that can be used addressed river sensitivity

Level 1 is *morphological sensitivity* that operates at *landform scale*. At this scale, geomorphic units are formed and reworked over temporal scales ranging from days to decades (Fryirs and

Brierley, 2013). To address river sensitivity at this scale, static and dynamic controlling conditions are assessed (i.e. imposed and flux controls) to identify the relationships and the dominant controls on geomorphic river diversity and patterns that eventuate (Montgomery, 1999; Phillips, 2010). Imposed controls encapsulate the antecedent characteristics of the landscape, the persistence of which is a key control on contemporary river forms and processes (Brierley, 2010; Brunsden and Thornes, 1979; Phillips, 2001; Schumm and Lichty, 1965; Trofimov and Phillips, 1992). Imposed controls determine the relief, slope and valley morphology (width and confinement) within which rivers are formed and adjust (Fryirs and Brierley, 2013). For example, geological controls such as lithology influence landscape elevation and relief (i.e. slope), and long-term landscape evolution determines the drainage pattern, the shape of longitudinal profiles, and the width and alignment of valleys within which rivers are (or are not) confined (Fryirs and Brierley, 2010, 2013; Sonam and Jain, 2018; Strahler, 1964). Flux controls represent the contemporary fluxes operating at reach scale as a result of the combination of internally and externally derived influences and include stream power available to derive geomorphic change and bed material texture that determines the ability of the channel bed to adjust (Brierley and Fryirs, 2005; Czuba and Foufoula-Georgiou, 2015; Darby and Thorne, 1996; Lane, 1955; Rhoads, 2020, 1987; Sinha et al., 2019; Wheaton et al., 2013). Therefore, to understand the functioning of geomorphic systems it is important to coherently analyse both these internally and externally derived influences (Downs, 1995; Fryirs and Brierley, 2013; Lisenby and Fryirs, 2016).

Level 2 is *behavioural and change sensitivity* that operates at the *reach scale*. A reach is defined as a section of river along which controlling conditions are sufficiently uniform such that the river maintains a near consistent geomorphic unit assemblage at temporal scales ranging from years to centuries (Fryirs, 2017; Fryirs and Brierley, 2013). To assess river sensitivity at this scale, river behaviour and river change is analysed. River behaviour is the ease with which geomorphic units and associated water, sediment, vegetation interactions adjust within the expected behavioural regime of a river (Fryirs and Brierley, 2013; Lane and Richards, 1997; Leopold, 1964). Lewin, (1977) calls this the autogenic regime of a river. This combines the analysis of characteristic forms and processes and the temporal variability in the capacity for adjustment by tracking the various erosional and depositional forms of geomorphic adjustment via identification of changes in geomorphic unit assemblage. However, when subjected to a singular episodic disturbance event or a series of disturbance events (Baker and Costa, 1987; Landwehr and Rhoads, 2003; Phillips, 2009, 2003), the behavioural regime of some rivers (particularly those that are threshold-driven) can undergo wholesale shift resulting in geomorphic 'metamorphosis' (Schumm, 1969), 'state transition' (Phillips, 2014) or 'river change' (Brierley and Fryirs, 2005; Fryirs and Brierley, 2013). River change is a wholesale shift in the behavioural regime of a reach that produces a different river type with a different set of process–form relationships.

Level 3 is *locational, transmission and filter sensitivity* that operates at *catchment scale* and at temporal scale of centuries to millennia. At this scale, the configuration and strength of linkages in a catchment determine the propagation of sediment fluxes which govern the propensity of geomorphic change as a result of sediment (dis)connectivity (Fryirs, 2013; 2017, 2015; Surian et al., 2009; Bracken et al., 2015; Brunsden, 2001; Brunsden and Thornes, 1979). Locational sensitivity is the spatial configuration of the reaches within a catchment that determines the ability of the geomorphic system to facilitate or suppress adjustment via positive or negative feedback mechanisms (Brunsden, 1993; Fryirs, 2017; King, 1970). If the system is highly connected, then the landscape configuration does not play a dominant role in determining the expression of geomorphic change. In this case, the transmission sensitivity is higher than the locational sensitivity (Fryirs, 2017). That is, if the system is highly coupled, the position of reaches has negligible influence on the pattern and propagation of disturbance (Harvey, 2002). In disconnected systems, decoupling of various landscape compartments produces a buffering capacity that operates like 'off-switches' that filter the geomorphic response of the system

(Fryirs et al., 2007a, 2007b). If the filter sensitivity is high, then the system absorbs the energy produced during disturbance events without inducing adjustment or propagating the energy elsewhere to produce adjustment. During geomorphically effective events, these ‘off-switches’ can be ‘turned-on’ such that they intermittently contribute to the sediment cascades along the fluvial network (Fryirs, 2013). Such rivers have high locational and filter sensitivity but low transmission sensitivity as the configuration of reaches within the catchment, and the position of ‘switches’ acts as a key control on the spatio-temporal dynamics of system coupling-decoupling (Harvey, 2002).

In the Richmond catchment, the morphological variability in the imposed and flux controls plays a significant role in producing the resultant river diversity and downstream river patterns (see Chapter 2). The envelopes of controls for confined, partly confined, laterally unconfined continuous and laterally unconfined discontinuous river types demonstrate that these different river types do operate within distinct set of controlling conditions. Imposed controls significantly influences confined river reaches, and bed material size (a flux control) heavily influence the laterally unconfined discontinuous reaches. The partly confined and laterally unconfined continuous reaches are influenced by both imposed and flux controls, although the influence of imposed controls is slightly heavier in the partly confined reaches as compared to the laterally unconfined continuous reaches. Contrasting longitudinal profiles further accentuated the distinctness between rivers draining highly variable topography. The northern rivers have highly concave profiles while the southern rivers have relatively convex shapes.

While the study of geomorphic controls elucidates on the morphological sensitivity of the system via variability in the imposed and flux controls on the geomorphic river diversity, it does not provide information on reach scale behavioural and change sensitivity. To understand behavioural and change sensitivity it is essential to undertake historical analysis and use this to assess the nature of geomorphic adjustments over time (Fryirs et al., 2015, 2009; Landwehr and

Rhoads, 2003; Scorpio et al., 2015; Simon et al., 2007; Surian et al., 2009; Urban and Rhoads, 2003). Such analysis of historical river behaviour can be used to further analyse the thresholds responsible for river adjustment/change (Bull, 1979; Larkin et al., 2020; Magilligan, 1992; Phillips, 2006; Schumm, 1979) and the geomorphic effectiveness of the flood events (Dean and Schmidt, 2013; Lisenby et al., 2018; Magilligan et al., 1998) and the role of natural and anthropogenic disturbance. Not all rivers respond to a certain magnitude and frequency event in a similar manner. While some rivers may be extremely sensitive to a certain disturbance event, others might be resilient to the same disturbance (Tooth, 2018). This is because of very variable geomorphic and possibly variable local controls (vegetation, land use characteristics etc.) operating on different river types. Therefore, a long term record of historical river adjustment of a certain river type can inform the variable river behaviour of that river (Landwehr and Rhoads, 2003; Urban and Rhoads, 2003). Generating a catchment wide record of such historical river behaviour can provide a perspective of spatial variability in behavioural sensitivity of different river types (Fryirs et al., 2009).

The analysis of historical river adjustment in the Richmond catchment highlighted the variable capacity for adjustment for different river types and identified a gradient of river sensitivity (see Chapter 5). The confined headwater reaches in the Richmond catchment are resistant to geomorphic adjustment as they do not have the capacity to adjust due to the dominance of imposed controls. The partly confined reaches in this system are passive sensitive because they have the capacity to adjust within a macro channel but maintain their overall behavioural regime and withstand permanent adjustment. The downstream laterally unconfined rivers are geomorphically insensitive. Fine cohesive bed material acts as an antecedent control on the capacity for adjustment. The mid catchment laterally unconfined rivers are active sensitive because they have the ability to re-configure on the floodplain via lateral migration and maintain their contemporary behavioural regime.

In contrast, the discontinuous water courses are geomorphically fragile as they have the propensity to undergo wholesale river change to a new river type with a new behavioural regime. However, not all discontinuous rivers reacted to disturbance in a similar manner i.e. divergence of geomorphic forms and processes was observed (Chorley, 1962; Phillips, 2014, 2007, 2006). Most of the laterally unconfined discontinuous rivers were gradually transformed into a spectrum of continuous river types with very different behavioural regime. In the remaining discontinuous reaches that were not channelised, landscape persistence (Brunsden, 1993) is such that a significant geomorphically effective event (Costa and O’Connor, 1995; Lisenby et al., 2018) is needed to breach the system threshold (Magilligan, 1992) and shift the contemporary natural capacity for adjustment towards river change (Fryirs, 2017; Fryirs and Brierley, 2013).

The geomorphic sensitivity of a river can change over time. Tracking behaviour and change implies that a river's behavioural sensitivity is not static in time, but can dynamically evolve such that some rivers can become more sensitive to future disturbances, others may become more resilient (Brunsden, 2001; Downs and Gregory, 1995; Fryirs, 2017; Schumm, 1998, 1973; Tooth, 2018). In the Richmond catchment, resistant and insensitive rivers that are mainly confined and partly confined have not changed their sensitivity since European colonisation (Figure 4 a and e). These rivers contain significant antecedent elements such as bedrock confinement (in headwater reaches) and cohesive clay bed material (near the catchment mouth) that inhibit geomorphic adjustment and change. In contrast, the discontinuous sand bed rivers are fragile (Figure 4 b). With natural and anthropogenic disturbances post European colonisation, these reaches experienced an accelerated river evolution such that they become either resistant, active or passive sensitive rivers. The remnant discontinuous water courses in the Richmond are the last remaining geomorphically fragile reaches in the catchment. The mid-catchment continuous rivers that are active or passive sensitive have the capacity to adjust within their behavioural regime but with geomorphically effective disturbance, could evolve into a different category of sensitivity (Figure 4 c and d). Such analyses provide the foundations for extension work to examine the geomorphic effectiveness of different disturbance events on sensitivity (Costa and O'Connor, 1995; Fryirs et al., 2015), the analysis of threshold conditions under which change occurs (Bull, 1979; Chappell, 1983; Schumm, 1979), the role of pre-conditioning and antecedence on contemporary forms and processes (Crozier, 1999; Phillips, 2006; Trofimov and Phillips, 1992), and reaction, relaxation and the recovery times following disturbance (Allen, 1974; Chappell, 1983).

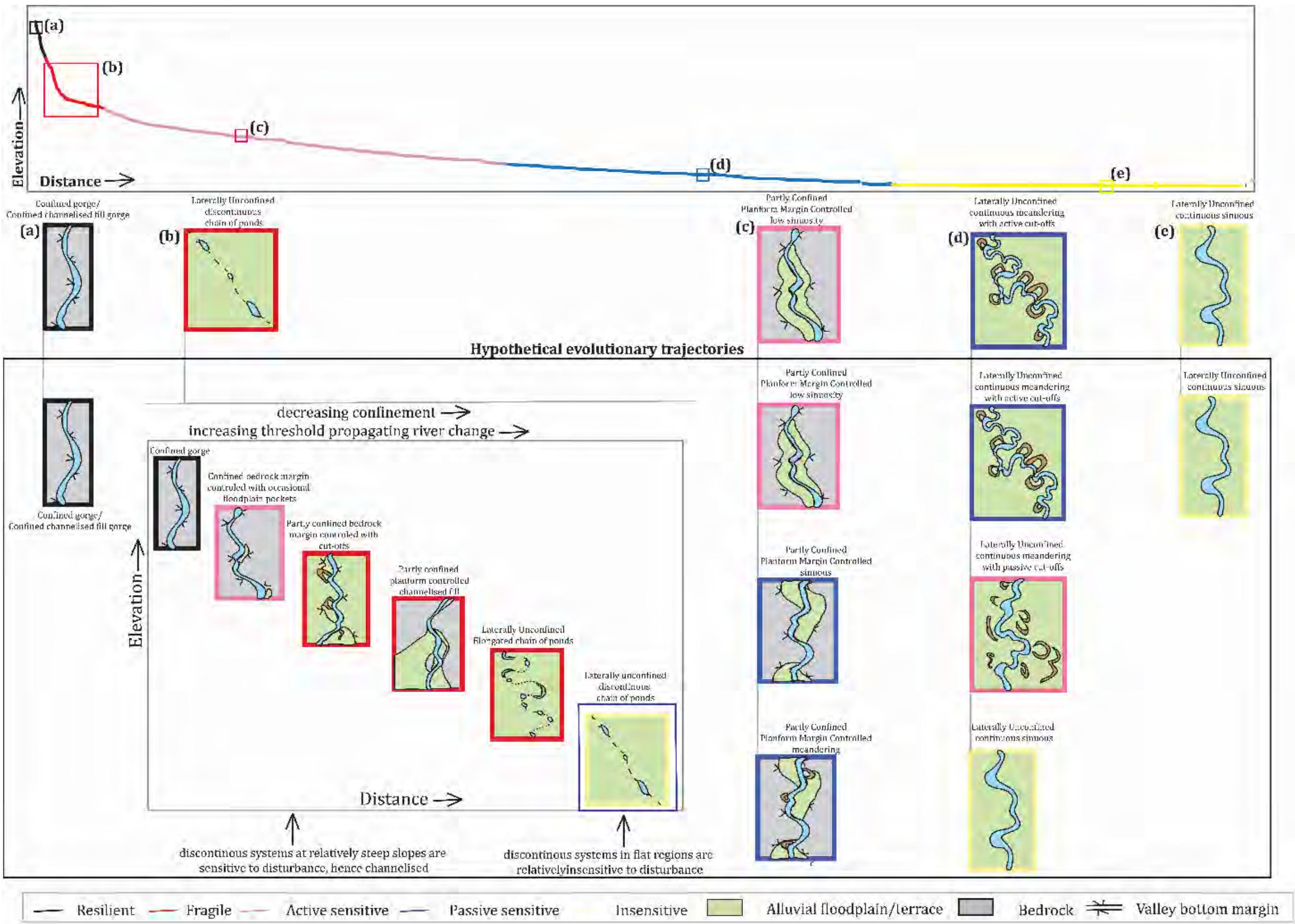

Figure 3 Hypothetical evolutionary trajectories of rivers in the Richmond catchment

While the analysis of morphological and behavioural sensitivity provides a robust geomorphic perspective for 'knowing the catchment', to fully understanding catchment scale processes, it is imperative to understand catchment scale synchronisation (Phillips, 2012) between sub-catchments and reaches. This can be achieved by placing each reach within its catchment context to better understand the extent to which sediment fluxes and (dis)connectivity might enhance or suppress geomorphic adjustment (Fryirs, 2013; 2017, 2015; Surian et al., 2009; Bracken et al., 2015; Brunsden, 2001; Brunsden and Thornes, 1979). This encapsulates other geomorphic concepts such as locational resistance (Brunsden, 1993) and positive and negative feedback mechanisms (King, 1970).

Sediment (dis)connectivity governs the degree of system coupling-decoupling and the resultant expression of geomorphic change in the system (Harvey, 2002). To assess sediment dynamics in a catchment, three key components are involved: (1) sediment availability and supply, (2) sediment size and texture and (3) sediment transferability and flux. The degree to which a system is coupled-decoupled can amplify or attenuate the signal of geomorphic change along different types of rivers (Baartman et al., 2013; Brunsden and Thornes, 1979; Hooke, 2003; Phillips, 2003; Brunsden, 1993; Fryirs et al., 2007; Harvey, 2002; Montgomery, 1999).

The Richmond catchment comprises of two very distinct sub-systems (see Chapter 6). The NE Richmond catchment is strongly connected or coupled whereas the SW part of the catchment is disconnected or decoupled. Due to very mild slopes and hillslope-channel decoupling, the SW Richmond catchment has negligible effective catchment area that can provide regularly sediment supply along the network. Rather, the sediment sources in this system are the sedimentary buffers and barriers that are activated during geomorphically effective events and release pulses of sediment intermittently. As a result, this transport limited system has high locational and filter sensitivity but low transmission sensitivity as the configuration of reaches within the catchment and the position of buffers is the key control on system coupling-decoupling. The steep slopes and strong hillslope-channel coupling in the NE Richmond catchment makes this system strongly connected. Here, the effective catchment area directly contributes to sediment supply and transport along the fluvial network. This supply limited system has high transmission sensitivity and negligible locational and filter sensitivity. The network scale modelling suggests that the locations of hotspots of river adjustment in the SW system are the sediment stores within discontinuous water courses, at the junctions between two different rive types, and at tributary confluences and where transient sediment storage units (mainly sand bars and slugs) occur along laterally unconfined sand bed rivers. In contrast, the major locations of hotspots in the NE system are the tributary confluence and sediment stores within floodplain pockets of partly confined planform controlled reaches. Therefore, understanding sediment (dis)connectivity dynamics in a catchment can be used to assess where, and to what extent, geomorphic adjustment or change is likely to occur in a catchment (Czuba and Foufoula-Georgiou, 2015, 2014; Schmitt et al., 2016).

7.3. Virtual rivers: Harnessing remote sensing technology and processing toolkits to analyse river sensitivity

In this digital era of publically available large spatial datasets, access to high computational power and semi-automation of geostatistical analysis using high-level programming languages, it is now possible to quantify the geomorphic attributes of a landscape and assess trends and patterns with a high level of confidence (Fryirs et al., 2019; Passalacqua et al., 2015; Piégay et al., 2020; Tarolli, 2014). Significant progress has been made in the geomorphic analysis of rivers using a range of remotely sensed platforms (Cavalli et al., 2013; Guillon et al., 2020; Khan and Fryirs, 2020a, 2020b; Piégay et al., 2005; Schmitt et al., 2016; Tangi et al., 2019; Wheaton et al., 2015, 2013). The commonly used remotely sensed datasets used in fluvial geomorphology include historical planform records (maps, aerial imagery and satellite imagery), digital elevation models (DEMs) and contemporary imagery acquired via satellite, airborne and drone sensors.

Moreover, easy access to high computing facilities has made the analysis of big datasets possible at large spatial scale (Gibson and Hancock, 2020; Guillon et al., 2020; Khan and Fryirs, 2020b;

Shaeri Karimi et al., 2019). In addition, semi-automation via geostatistical analysis using high-level programming languages such as MATLAB, PYTHON and R has enabled the reproducibility of such analysis at multiple locations or other study areas and improved the quality assurance and quality control of outputs.

For *landform scale* analysis of *morphological sensitivity*, coarse and high resolution DEMs can be used to characterise rivers and assess forms of adjustment. Coarse resolution DEMs are widely used to extract first level geomorphic characteristics at the catchment scale such as drainage network, valley bottom extent; the elevation variability along the river profile (i.e. longitudinal or long profile); reach scale cross section metrics such as channel width and depth, valley width and depth. Particularly, the global availability of 30m and 90m satellite derived DEMs have accelerated coarse scale remote sensing studies worldwide since 2000 (Passalacqua et al., 2015; Tarolli, 2014; Zhang et al., 2019). The advent of meter resolution LiDAR DEM has opened up possibilities for extracting second level landform scale geomorphic characteristics such as lateral confinement and stream power (Jain et al., 2006; O'Brien et al., 2019). Further, the global availability of 10m resolution TandemX data provides a middle ground between these two commonly used datasets, however, high cost of this data source restricts its popularity in academic projects (Zhang et al., 2019).

For *reach scal*e analysis of *behavioural and change sensitivity*, archival aerial and satellite imagery can be used for tracking historical river adjustment, especially to study anthropogenic impacts on river forms and processes. These historical planform records are a treasure trove for geomorphologists as these archives provide a glimpse into past river character (Bizzi and Lerner, 2015; Fryirs et al., 2009; Khan and Fryirs, 2020a; Landwehr and Rhoads, 2003; Piégay et al., 2005; Reid and Brierley, 2015; Roy and Sinha, 2018; Scorpio et al., 2015; Surian et al., 2009; Thorne et al., 1996; Urban and Rhoads, 2003; Wheaton et al., 2013). The historical analysis of river adjustment in the Richmond catchment since European colonisation used a range of these remotely sensed datasets including digitised historical aerial photographs, digitised parish maps and Google Earth imagery to assess historical river adjustment and develop a method for classifying rivers into sensitivity classes - Fragile, Active sensitive, Passive sensitive, Insensitive and Resistant rivers (Chapter 5). Such historical records have been widely used for conceptualisation of possible trajectories for future river adjustment (Brierley and Fryirs, 2016; Fryirs and Brierley, 2016; Lisenby et al., 2019; Mould and Fryirs, 2018; Piégay et al., 2005; Surian et al., 2009).

This task of traditional ‘historical sleuthing’ is a very important step in its own regard (Montgomery, 2008) as it enables the geomorphologist to revisit the past and situate contemporary forms and processes in an evolutionary context (Fryirs et al., 2012, 2009; Wohl et al., 2012). However, it is the advent of DEMs that have revolutionised the analysis of fluvial systems. DEMs provide ‘a digital laboratory’ that records the topographic variability of a landscape which can be used to analyse catchment scale geomorphic attributes with a high level of precision. On the basis of spatial resolution (raster cell size) supplemented by other input parameters/layers, multi-level information with a high level of confidence can be extracted from DEMs (Figure 5). Recently, very fine resolution DEM acquisition via drone sensors have enabled repeated topographic surveys (aerial or drone based) for use in tracking erosional and depositional changes in reach scale sediment budgets (Carbonneau et al., 2012, 2020; Wheaton et al., 2015, 2013). However, there is a temporal limitation associated with such geomorphic change detection as river adjustment can only be tracked from the time of availability of a DEM. Working in a landscape such as Australia, it is often the case that little or no geomorphic change has occurred during this digital era, meaning many analyses still require the use of traditional methods.

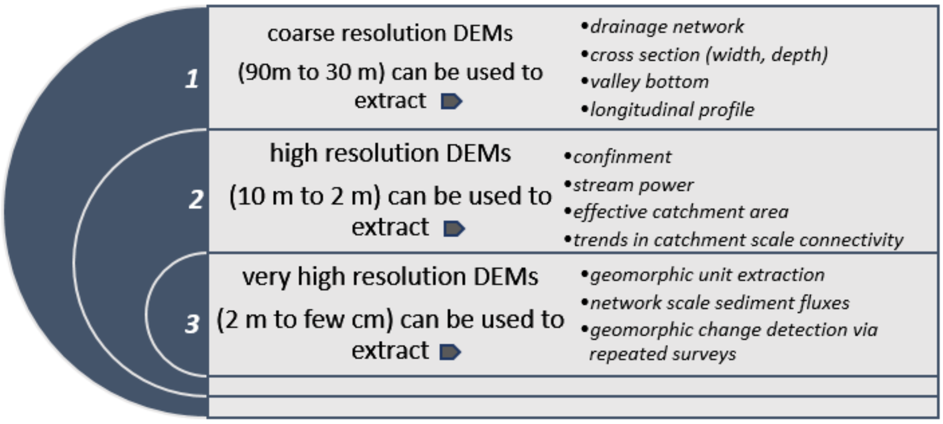

Figure 4 A conceptual framework showing the three levels of geomorphic attributes that can be modelled using DEMs of variable resolution. Only few key attributes are noted

For *catchment scale* analysis of *locational sensitivity*, high and very high resolution LiDAR DEMs are popularly used for analysing trends in spatial sediment (dis)connectivity via assessment of system coupling-decoupling and simulating network scale metrics of sediment fluxes (Cavalli et al., 2013; Czuba and Foufoula-Georgiou, 2015; Fryirs et al., 2007b; Jain et al., 2006; O'Brien et al., 2019; Schmitt et al., 2016; Tangi et al., 2019). In this thesis, CASCADE model was tested and used to help understand the sediment (dis)connectivity of the Richmond catchment and by extension how to use such analyses and models to make preliminary interpretations of locational, transmission and filter sensitivity.

The easy availability of datasets does not necessarily imply its usefulness for geomorphic analysis of rivers. Careful consideration needs to be given to the research objective and then use the technology and data to fulfil the objective. For this, cautious pre-planning needs to be given to the questions being asked and whether the data is of sufficient quality to answer that question (Boulton and Stokes, 2018; Hancock et al., 2020; Lisenby and Fryirs, 2017; O'Brien et al., 2019; Passalacqua et al., 2015; Sørensen and Seibert, 2007; Tarolli, 2014; Wheaton et al., 2013). Chapter 4 of this thesis emphasised the importance of reconnaissance of the input datasets to suit the task at hand. Almost always, there is some error associated with the raw DEM and it is very useful to perform preliminary analysis (Deng et al., 2007; Thompson et al., 2001; Vaze et al., 2010; Wheaton et al., 2009; Wolock and Price, 1994; Wu et al., 2008) and verify the results using basemaps such as satellite imagery and hillslope raster to test the validity of the results (Colombo et al., 2007). Also, while the modelled results might be accurate in certain topographic settings, it might not be the case throughout the study area, especially if the topography is highly variable (Khan and Fryirs, 2020b; Lisenby and Fryirs, 2017; Tarolli, 2014). For example, the drainage network obtained via D8 flow accumulation algorithm accurately mapped the river network in steep and moderate topographic setting in the Richmond catchment, however, failed to capture the river network in relatively flat low lying southern sub catchment. Rather, the Multiple Flow direction algorithm accurately captured the drainage network throughout the Richmond catchment (see Chapter 4). The availability of computational power and time is also a factor as more accurate workflows are computationally more demanding than simpler workflows. Therefore, decisions need to be made on the basis of research question and expected outcomes, time availability, available computational power and the expected resolution of the research output.

Furthermore, the finest resolution DEM available is not always the best choice for all types of geomorphic analysis. Recently, several studies have emphasised that for certain catchment scale studies (i.e. studies conducted at large spatial scale), coarse resolution DEMs are still incredibly useful and perform better than fine resolution DEMs. Therefore decisions need to be made about the most appropriate resolution needed to answer the question being asked to achieve optimum results (Boulton and Stokes, 2018; Colombo et al., 2007; Deng et al., 2007; Khan and Fryirs, 2020b; Lisenby and Fryirs, 2017; Yang et al., 2014). For example, in development of the valley bottom extraction workflow presented in Chapter 3 of this thesis it was found that the delineation of valley bottom extent using fine resolution DEMs was detecting metre-scale topographic disturbances (i.e. micro landforms in the floodplain topography) which resulted in significant localised inconsistencies in the output, making it challenging to obtain a clean valley bottom for the entire catchment. However, for studies aiming for more detailed reach scale studies, fine resolution LiDAR would definitely provide more accurate and precise information. Moreover, although LiDAR-derived DEMs capture the topography more accurately as compared to the satellite-derived DEMs, the globally available satellite-derived DEMs can still be used for geomorphic analysis if it is recognised that they produce less accurate results in certain topographic settings (Khan and Fryirs, 2020b; Zhang et al., 2019) (see Chapter 3). While modelling approaches are incredibly useful for deriving new layers of large scale information that cannot be easily produced manually, all output needs to be closely integrated with manual expert judgement and knowledge of the study area (i.e. field work interpretation) (Fryirs et al., 2019; Piégay et al., 2020).

Further, advances in physical based numerical modelling has enabled evaluation of channel dynamics at scales ranging from local cross sections to individual reaches (Brasington et al., 2003; Darby et al., 2002; Darby and Thorne, 1996; Pasternack et al., 2004, 2004; Wheaton et al., 2013). In the last couple of decades, a number of hydrological and landscape evolution models have emerged that have enabled estimation of catchment scale sediment dynamics (Coulthard et al., 2013, 2012; Gibson and Hancock, 2020; Lazar et al., 2010; Luzio et al., 2002). These models have been widely used for simulating contemporary landscape processes and forecasting future sediment budgets with changing climate and land management scenarios (Darby et al., 2015; Khan et al., 2018; Rahman et al., 2018). Further research can aim to incorporate the analysis of river sensitivity into these models to explore the evolutionary trajectories of river sensitivity at various spatio-temporal scales in any given setting.

7.4. Conclusion

In this thesis, the concept of river sensitivity has been assessed at three spatial scales: landform scale-morphological sensitivity, reach scale-behavioural and change sensitivity and catchment scale-locational, transmission and filter sensitivity. This work incorporates an understanding of system preconditioning via analysis of historical river adjustment, analysis of geomorphic controls on river morphology and sediment (dis)connectivity; and encapsulates other geomorphic concepts such as antecedence, geomorphic effectiveness, landscape memory, preconditioning, degrees of freedom and filter sensitivity. Until now most of these concepts have remained conceptual and have not been operationalised. This thesis uses remote sensing approaches as well as traditional methods such as fieldwork interpretation alongside manual expert judgment to assess and quantify geomorphic river sensitivity in a large geomorphically diverse catchment. In this digital era of big data, landscape modelling and automation, remote sensing approaches are a very valuable tool for the geomorphic analysis of rivers. However, caution needs to be applied to ensure that the gaps are filled accurately (requiring expert knowledge of the study area) and that outputs are verified in the field. This is particularly important if the findings of modelling or remotely sensed analysed are used in river management practice.

The understanding of river sensitivity in the Richmond catchment has provided answers to important questions such as: How can a river adjust? Where can a river change? How can future flooding result in onsite or offsite adjustment of a river? How can various land management changes impact a river onsite or offsite? Which rivers in a catchment are fragile? While this thesis has elucidated the historical and contemporary geomorphic sensitivity of the Richmond catchment, there is room for strengthening the understanding of river sensitivity by incorporating other concepts such as thresholds of erosion and deposition, transient controls on geomorphic river adjustment such as wood loading, anthropogenic alterations along the river network and landuse changes. Future research can strive to incorporate these additional understandings with the existing knowledge of the Richmond system to project trajectories of future river behaviour with changing climate and land management scenarios so the findings can be used to better understand the river forms and processes occurring in this system, and ultimately be used to inform river management.

7.5. References

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