Geomorphic adjustment, sensitivity, and connectivity of the lower Mara River and its floodplain wetlands, Tanzania

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DECLARATION

This thesis comprises original research performed by Megan Gomes and has not previously been submitted for a degree or diploma at any university or institution. This thesis is being submitted to the University of Witwatersrand and to Macquarie University in accordance with the Cotutelle agreement, January 2021. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made in the thesis itself.

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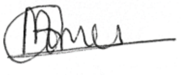
(Signed)  Date: 14/03/2023

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ABSTRACT

The Mara River in semiarid East Africa traverses one of the world's most important wilderness conservation regions. Like many other dryland rivers, the Mara sustains wetland and terrestrial ecosystems that provide essential ecosystem services to local human and wildlife populations. However, the hydrological and geomorphological diversity and complexity of dryland rivers, including the Mara, makes comprehensive understanding of their development and prediction of future biophysical changes difficult, representing major challenges in fluvial geomorphology and wetland management.

This thesis examines the key geomorphic controls that drive dryland river morphology and floodplain wetland formation, as well as the intrinsic processes that lead to channel and wetland adjustment, within the Mara system. Morphometric analysis based on satellite imagery mapping and discharge modelling is used to assess the valley-scale controls and hydrogeomorphic forms and processes of the river and its palaeochannels, as well as recent historical geomorphic adjustments (last 32 years) along the lower Mara River. The river and palaeochannels have marked downstream declines in channel capacity and changes in sinuosity due to declines in discharge and stream power, coincident with a reduction in valley confinement. While several large palaeochannels extended further downstream than the modern river, likely driven by higher-energy hydrological regimes in the past, the river now exhibits a nonequilibrium response to rapidly declining fluvial energy resulting in avulsions, channel diminution, and channel breakdown in the wetlands.

Geomorphic sensitivity analysis of the lower Mara River for the recent historical period indicates that the upper and lower reaches are 'Passive sensitive', the former with limited adjustments, the latter with numerous cut-offs and palaeochannels, and both reaches having low migration rates. In contrast, the middle reach is 'Fragile' with numerous lateral migration features, cut-offs, and higher migration rates. The lower reach appears to be close to a threshold and may switch to a Fragile state where avulsions become dominant, while the other reaches may be more resilient and maintain their present states. These complex geomorphic responses are likely related to spatiotemporal patterns of hydrogeomorphic connectivity in the catchment. Modelling of contributary hydrogeomorphic connectivity indicates that the upper catchment (source zone) is consistently well-connected and is responsible for the greatest inputs of water and sediment to the fluvial network. The middle

section (transfer zone) has lower and more variable seasonal, inter-annual and decadal connectivity, while the lowland reaches (deposition zone), where large floodplain wetlands occur, have relatively consistent, low connectivity. These trends are associated with downstream sedimentation resulting in river and wetland adjustments and avulsive behaviour.

Together, these findings provide novel insights into dryland river character and behaviour, as well as the valley- and catchment-scale conditions that contribute to geomorphic adjustments in internationally significant fluvial systems. Under increasing pressure from anthropogenic and climate change impacts the Mara River and its wetlands are likely to undergo future geomorphic changes, and thus an understanding of the biophysical controls, forms, and processes of river adjustment as well as states of sensitivity and patterns of connectivity are imperative for guiding conservation and management efforts.

DEDICATION

I dedicate this thesis to my parents, Carla, and Jose Gomes,
and my husband, Jason Donaldson.

Thank you for always believing in me.

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CHAPTER 1

Introduction, study rationale, aims and objectives, thesis overview

1 Introduction

Rivers and wetlands are highly complex and dynamic systems that are continuously evolving and shaping the Earth's surface. They are fundamentally important systems that provide numerous beneficial functions to humans and ecosystems, especially in climatically-variable and water-stressed drylands (Millennium Ecosystem Assessment, 2005). Despite the high socio-ecological value of dryland rivers and wetlands, they continue to be degraded as a result of anthropogenic modifications and other environmental pressures (Reis et al., 2017). Nevertheless, the hydrological and geomorphological variability of dryland fluvial systems across space and time makes comprehensive understanding of their development and prediction of future change difficult (Schumm, 2005), representing major challenges in managing and conserving these important fluvial systems.

Recent geomorphological research on dryland rivers and wetlands has focused on understanding the key hydrogeomorphic controls on river and wetland formation, the mechanisms by which these fluvial systems adjust, and the timescales over which these processes occur (e.g. Ralph and Hesse, 2010; Li et al., 2014; Hesse et al. 2018a, b; Larkin et al., 2017a, b, 2020a, b; Grenfell et al., 2022; Tooth et al., 2022). However, large areas of African dryland systems remain understudied, and research is required to explore how these systems fit into, or change, current dryland geomorphological theory. Research that focuses on rivers and wetlands in African dryland systems will develop our understanding of the full diversity of river and wetland types, as well as the processes and dynamics occurring in these poorly understood systems. This is imperative as dryland rivers and wetlands globally are critically important as they often provide the only surface water resource to sustain local human and wildlife populations in otherwise dry environments. However, these systems are under increasing threat from anthropogenic and climate change impacts which is compounded by the extreme climatic variability, strong seasonality, and annual rainfall deficits in dryland regions (Grenfell et al., 2022). Notably, Africa is expected to experience a substantial increase in population growth with the majority of the population concentrated around coastal and inland surface water and reliant to some degree on dryland rivers for resources, such as food and water (Millennium Ecosystem Assessment, 2005). Given the importance of rivers to dryland societies, particularly in developing countries, such as those in Africa, there is an urgent need to understand how anthropogenic (i.e. land-use) and climate change impacts (i.e. changing catchment hydrological conditions) will affect river sensitivity (i.e. capacity for river to adjust geomorphologically) and connectivity (i.e. hydrological and sediment transfer across the landscape). Such information is critical because the geomorphological response of rivers can significantly change ecosystem structure and function, and hence ecosystem service delivery.

A long-term perspective of dryland river development can be used to understand how these systems have changed in the recent past, and how they may respond in the future to anthropogenic and climate change impacts. Furthermore, a long-term context can improve understanding of the relationships between the key controls that influence thresholds of river behaviour (Larkin et al., 2017a, b). Key concepts, such as hydrological and sediment connectivity and landform sensitivity, can provide insights into the proclivity of a river to adjustment and reach threshold behaviour. An understanding of threshold responses to changing environmental factors is important when considering the future projections of increasing climatic variability and declining surface water availability in many drylands globally (Schewe et al., 2014; Cook et al., 2014; Pekel et al., 2016), as these trends may lead to profound changes in dryland river character and behaviour (Larkin et al., 2020b). As a contribution to understanding dryland fluvial systems in underrepresented regions of the world and how they may adjust in response to future climatic and anthropogenic impacts, this research focuses on the ecologically significant, semiarid Mara River and its floodplain wetlands in East Africa. The transboundary Mara River catchment shared between Tanzania and Kenya, is both regionally and globally important as it supports a local population of ~1.2 million people, as well as the annual migration of 2 million herbivores which is a major source of ecotourism for these countries.

In this context, this thesis examines the key geomorphic controls driving dryland river development and floodplain wetland formation in the Mara system. Understanding how this system has adjusted geomorphically in the past can provide insight into how it may respond to future climate change impacts. This thesis addresses four research questions:

1) What are the main geomorphic controls that influence river morphology and floodplain wetland formation in the Mara River system?
2) Which hydrogeomorphic processes drive river adjustment and landform sensitivity (i.e. natural range of variability) and define the overall character and behaviour of the Mara River and its floodplain wetlands?
3) How do patterns of hydrological and sediment connectivity and landform sensitivity affect the geomorphology of the Mara River system?

4) How will the Mara River respond to future changes in hydroclimatic or anthropogenic impacts?

2 Background

2.1 Dryland rivers and wetlands

‘Drylands’ is a collective term used to describe the subhumid, semiarid, arid and hyperarid regions of the world that cover ~45% of the Earth’s land surface (Fig 1.1) (Millennium Ecosystem Assessment, 2005; Tooth, 2013). Globally drylands are classified according to an Aridity Index (AI), defined as the ratio between mean annual precipitation (MAP) and potential evapotranspiration (UNEP, 1992). Drylands are areas where AI is <0.65 and are characterised by overall surface water deficits resulting from low but highly variable precipitation, high evapotranspiration, and sparse, unevenly distributed vegetation cover (Millennium Ecosystem Assessment, 2005). Despite hydrological constraints, many of the world’s extensive dryland regions host a diverse range of perennial, seasonal and ephemeral river, and wetland systems which play an important role in landscape dynamics and exert a strong influence on resource use by humans (Tooth and McCarthy, 2007; Tooth et al., 2015). Given their presence in otherwise dry environments, dryland rivers and wetlands are recognised as hotspots of ecosystem service delivery (Tooth et al., 2015), including provisioning services (e.g. food, water, and building materials), regulating services (e.g. flood attenuation, water quality improvement, maintenance of soil fertility, and potential carbon storage), supporting services (e.g. nutrient cycling, removal of toxins, and hotspots of biodiversity) and cultural services (e.g. recreation/ecotourism and spiritual experience) (Millennium Ecosystem Assessment, 2005; Zedler and Kercher, 2005; Mitchell, 2013). Nevertheless, dryland river hydrology and geomorphology are still poorly understood in comparison to rivers in more temperate-humid regions (Tooth, 2013), even though they support more than two billion people, 90% of which live in developing countries, and depend on these rivers to some degree for resources (Reynolds et al., 2007).

Drylands persist across a wide range of climatic, physiographic, geological, and vegetative settings. As such, dryland rivers are the product of their environment and are highly diverse and variable in terms of their character and behaviour (i.e. forms and processes) (Tooth and Nanson, 2011; Tooth, 2013). River character describes the physical structure of a river (i.e. channel pattern, planform, and cross-sectional morphology), while river behaviour describes the suite of internal processes (i.e. adjustments) responsible for producing the characteristic morphology and planform of the river (Brierley and Fryirs, 2005). Therefore, dryland river diversity reflects the range of conditions in which they operate across, for example differing flow regimes (e.g. ephemeral, intermittent, perennial), substrate characteristics (e.g. bedrock, alluvial, mixed bedrock-alluvial), and riparian vegetation associations (e.g. non-vegetated, woody vegetation, herbaceous vegetation) (Tooth and Nanson, 2011), and these various combinations of environmental factors result in different river types (e.g. braided, single channel, meandering, multiple anastomosing, distributary channels). For instance, some dryland rivers exhibit perennial or seasonal flow regimes that are maintained by more humid settings and are characterised by a single, sinuous throughgoing channel, such as the Klip River in eastern South Africa (Fig. 1.1) (Tooth et al., 2007; Tooth, 2013). Whereas other rivers have intermittent or ephemeral flow regimes that are maintained by local rainfall–runoff events and are characterised by a straight channel that undergoes dramatic downstream declines in discharge and channel size, leading to unchannelised terminal floodouts, for example, the Sandover-Bundy River, central Australia (Tooth et al., 2000). In some cases rivers flow from more humid headwaters into dry lowlands, and as a result they experience gradual declines in discharge, stream power and channel capacity downstream, eventually breaking down into unchanneled wetlands or floodouts, before re-establishing a channel further downstream, for example the Macquarie Marshes in southeastern Australia (Fig. 1.1) (Ralph and Hesse, 2010). Overall, the diversity of river types and their physical characteristics (i.e. single channel versus unchanneled wetlands, or discontinuous channel segments), which are defined by their character and behaviour, largely influence ecosystem structure and functioning and thus the range and quality of ecosystem services provided by the river (Kotze et al., 2009).

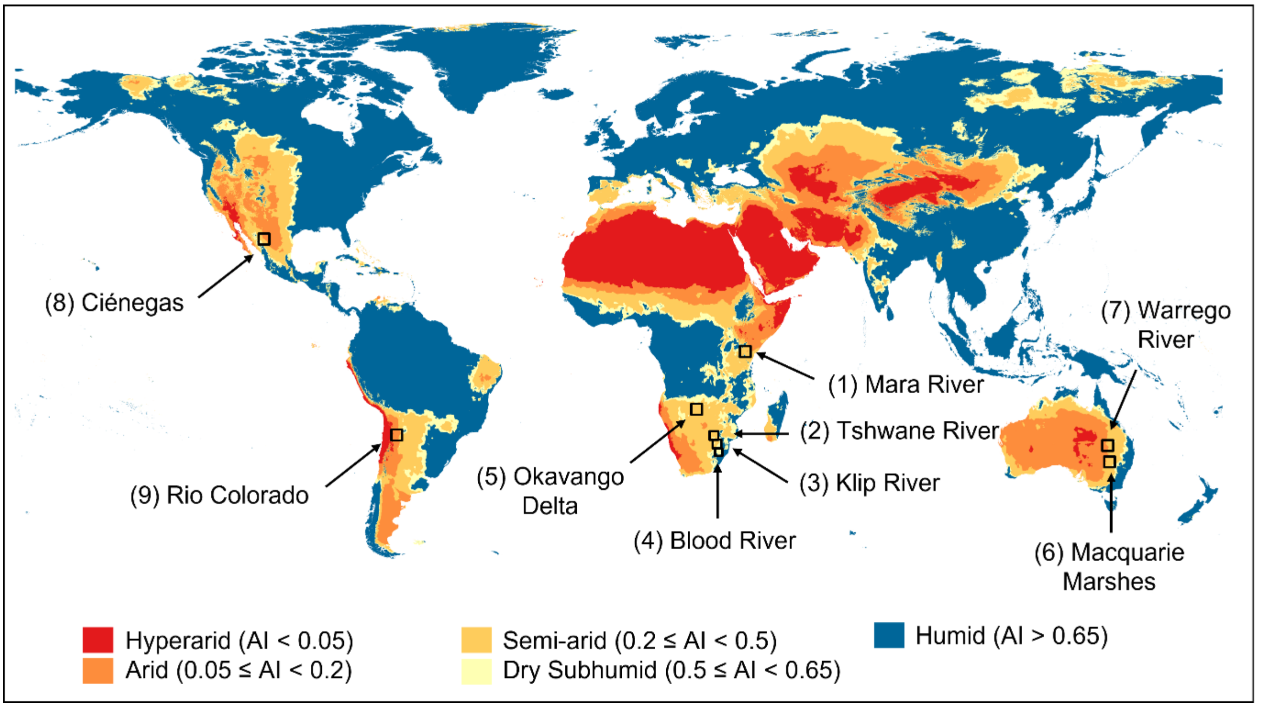


Figure 1.1. Extent of the world's drylands. Sub-categories and aridity index (AI) defined by the United Nations Convention to Combat Desertification (UNCCD). Source: UNEP-WCMC, 2018. The different dryland fluvial systems highlighted in this figure are discussed in Table 5.2 in the discussion section of this thesis.

2.2 Extrinsic and intrinsic controls

The character and behaviour of dryland rivers develop in response to both intrinsic processes of adjustment and extrinsic forces. Extrinsic forces operate over long-timescales and set the boundary conditions within which the system operates (Fryirs et al., 2012). Examples of extrinsic forces, include climate-induced hydrological regime shifts (Hesse et al., 2018a, b), base-level change resulting from tectonic activity (Holbrook and Schumm, 1999) or anthropogenic-induced habitat degradation (Kingsford, 2000). These external forces have an overarching control on the environmental parameters of a system (e.g. flow regime, slope, sediment load), and largely define the natural range of variability. Within these boundary conditions, intrinsic processes related to the balance between discharge, slope, and sediment supply, drive river adjustment and development within this range of variability (Tooth et al., 2007; Larkin et al., 2017a). For example, the amount and frequency of water available to transport the supplied sediment is controlled by extrinsic characteristics of the catchment, whereas the intrinsic processes of adjustment determine how efficiently the river transports the supplied water and sediment towards its base level (Nanson and Huang, 2008).

However, dryland rivers are dynamic, self-adjusting systems and their complex, non-linear response to extrinsic forcings and intrinsic processes of adjustment makes it difficult to isolate the relative importance of these controls in driving changes in river character and behaviour. Geoproxies, such as palaeochannels preserved on floodplains, provide some of the key records of past morphological and hydrological change and can offer insights into the role of stable or changing extrinsic and intrinsic controls that drive fluvial character and behaviour (Page et al., 2009; Kemp and Rhodes, 2010; Hesse et al., 2018a; Larkin et al., 2020a). To understand this complexity and disentangle the relative importance of these controls, the interdependent geomorphic concepts of threshold responses (Schumm, 1979), landform sensitivity (Brunsden and Thornes, 1979) and landscape connectivity (Walling, 1983) can be used.

2.2.1 Geomorphic river responses

Geomorphic river responses are the physical adjustments to fluvial landforms (e.g. river channels, floodplains, terraces, sediment bars and benches) that are driven by extrinsic forces (e.g. natural and/or anthropogenic disturbance events) and ultimately structured by internal system dynamics (Phillips, 2009). Geomorphic responses have been categorised into various erosional and depositional forms of adjustment (e.g. Brierley and Fryirs, 2005; Fryirs et al., 2009). In the absence of extrinsic forcing, intrinsic geomorphic thresholds are responsible for river adjustments and define river behaviour (Schumm, 1979; Wohl, 2011). Geomorphic thresholds refer to the erosional and depositional processes that are inherent in the development of a landscape, such that an external force is not required for a threshold to be exceeded. For instance, river channel diminution and sediment aggradation resulting from downstream declines in fluvial energy can promote avulsions – the relocation of the channel to a new position on the floodplain. The types of intrinsic geomorphic threshold responses and the rate at which they occur define the natural (or historic) range of variability of a system (Wohl, 2011; Fryirs et al., 2012). In other words, rivers undergo continual adjustments within a natural range (defined by its boundary conditions) but maintain a characteristic set of landform-process relationships, such that river type remains unchanged despite intrinsic variability and complex geomorphic response (Fryirs et al., 2012). However, if an extrinsic geomorphic threshold is crossed (Schumm, 1979; Phillips, 2009) the river can undergo a shift in river character and behaviour, such that ‘metamorphosis’ (Schumm, 1969), or ‘river change’ occurs (Fryirs and Brierley, 2013). Extrinsic geomorphic thresholds are crossed when the environmental variables of a system are altered, for instance sustained decreases in flow and/or sediment supply induced by climate-driven changes to the hydrological regime. The crossing of an extrinsic threshold results in a change in river type as landform-process relationships are altered and intrinsic processes are redefined under different environmental parameters. A good example of this is evident in the Warrego River in Australia, where extrinsically controlled hydroclimatic change (i.e. declines in flow during the late Holocene) resulted in a transformation of river type from meandering channels to the modern single thread, anabranching, and distributary channels (Larkin et al., 2020a).

Intrinsic processes and related geomorphic threshold responses adjust channel form to maintain water and sediment transport in the system. These internal processes have been described as self-organised behaviour that leads to rivers generally becoming more stable and energy efficient (Phillips, 2006; Nanson and Huang, 2017). Within the boundary conditions of a catchment, alluvial rivers can self-organise or self-adjust to maximise flow efficiency and stability (Nanson and Huang, 2008). For instance, in response to an excess or deficit of energy in a system, rivers adjust to either expend or conserve the energy to maintain bed and bank stability. As such, higher energy settings with steeper slopes typically result in rivers with increased rates of lateral activity (e.g. meandering, laterally active) which acts to dissipate energy by reducing the channel gradient and increasing frictional losses, whereas lower energy settings with more gradual slopes result in channel straightening (e.g. sinuous and straight, laterally inactive) which acts to conserve energy by increasing the channel gradient for a given slope, and reducing frictional losses at bends (Kleinhans and van den Berg, 2011; Nanson and Huang, 2017). In the lower Tshwane River in northern South Africa (Fig. 1.1), for example, Larkin et al. (2017a) demonstrated that downstream declines in flows resulted in a transition from a larger, meandering channel (energy surplus) to a narrower, straighter channel (energy deficit) in an effort to maximise flow efficiency. Therefore, in some rivers (e.g. the Klip and Tshwane Rivers), these adjustments act to maintain sediment throughput (lateral meander migration and eventual cut-off), resulting in an equilibrium river response and a continuous, throughgoing channel (Tooth et al., 2002; Larkin et al., 2017a), whereas, in other rivers (e.g. the Macquarie, Blood, and Okavango Rivers), sediment throughput is not maintained, and sediment deposition and channel aggradation occur resulting in a nonequilibrium river response and discontinuous channel (Tooth and McCarthy, 2004; Ralph and Hesse, 2010; Tooth et al., 2014) (Fig. 1.1).

Nonequilibrium river responses characterise many dryland rivers that lose much of their energy downstream (Tooth and McCarthy, 2007). In these cases, downstream declines in discharge and stream power result in excessive sedimentation which primes the channels for avulsions and can lead to abandoned palaeochannels. These internal threshold responses can act to improve flow efficiency at certain places, such as in newly formed avulsion channels (Nanson and Huang, 2008), but ultimately if nonequilibrium conditions are dominant then there is insufficient energy to maintain sediment throughput, resulting in channel discontinuity and channel breakdown where water and sediment are spread over adjacent alluvial surfaces in a floodout (e.g. the Sandover, Sandover–Bundey and Woodforde Rivers in Australia; Tooth, 1999). The timescales in which these intrinsic threshold responses and feedbacks are considered is also important as channels that may be discontinuous over shorter timescales (years, decades) may be continuous over longer timescales (millennia). For example, over the short term, the Blood River in South Africa exhibited an incisional, headcutting channel that reformed at the downstream end of the floodout, while it is possible that over the longer term this channel may re-establish a continuous channel through the floodout zone (Fig. 1.1) (Tooth et al., 2014). Importantly, while intrinsic processes and threshold responses are responsible for driving ongoing river adjustments and development, extrinsic forces ultimately exert a long-term control on these processes and thus influence the overall character and behaviour of a river.

2.2.2 River sensitivity

The complex geomorphic response of fluvial systems to intrinsic and extrinsic thresholds is dependent on the varying sensitivity of landforms to disturbances (Schumm, 1979; Phillips, 2003; Fryirs, 2017). The concept of sensitivity describes the ease with which landforms respond or adjust to environmental disturbances, where more sensitive landforms have a greater capacity to adjust (e.g. an alluvial reach in an unconfined valley) compared to less sensitive or resilient landforms that have a limited capacity to adjust (e.g. a bedrock reach in a confined valley). 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). The response of the system involves various aspects, including 1) the possibility of change – adjustments will occur when the magnitude of a disturbance exceeds the system’s ability to resist the disturbance; 2) the propensity for change – adjustments depend on the proximity of the system to a threshold or tipping point; and 3) the capacity to withstand change – the ability of the system to absorb or adjust to and recover from disturbance (Downs and Gregory, 1995; Thoms et al., 2018; Tooth, 2018). The sensitivity of a river can be assessed by quantifying geomorphic adjustments over historical time periods. By tracking geomorphic adjustments over time, the historical range of variability or expected capacity for adjustment can be defined and used to assess the spatiotemporal distribution of landform sensitivity, as well as highlight the potential ‘drivers of change’ within a catchment (Wohl, 2011; Fryirs et al., 2012; Reid and Brierley, 2015). Numerous studies have recognised the importance of river sensitivity in understanding complex river responses to disturbance events (Brunsden and Thornes, 1979; Schumm, 1979; Downs and Gregory, 2004; Reid and Brierley, 2015; Fryirs, 2017; Thoms et al., 2018; Tooth, 2018), however, a systematic and consistent approach to assess and measure geomorphic river sensitivity is lacking. Although few studies have addressed this by conducting historical quantitative analysis of channel adjustments (e.g. Lisenby and Fryirs, 2016; Joyce et al., 2020; Khan and Fryirs, 2020), these studies are limited and a broader application of these methods to other regions, particularly in dryland systems is necessary.

An important factor influencing landform sensitivity is the antecedent conditions or pre-conditioning of a reach for adjustment (Phillips, 2006). In other words the pre-event ability of a system to respond will determine the post-event geomorphic response. For instance, the ability of a system to respond to a geomorphic effective event (e.g. large floods) will depend on the proximity of the system to a threshold (e.g. avulsion) (Wolman and Miller, 1960; Schumm, 1979). In addition, the sensitivity of a system will also influence how it recovers after a disturbance event which in turn affects how it will respond to subsequent future disturbances (Phillips and Van Dyke, 2016). Therefore, the sensitivity of a system influences its ability to respond and will subsequently control the geomorphic effectiveness of any disturbance event (Wolman and Miller, 1960). These conditions highlight the notion that a river's behavioural sensitivity is not static in time and can dynamically evolve, such that some rivers may become more sensitive to future disturbances while others may become more resilient and stable (Brunsden and Thornes, 1979; Downs and Gregory, 2004). An understanding of the changes in the spatiotemporal distribution of river sensitivity is necessary for forecasting the likely event sensitivity of a river to a range of possible future disturbances (Fryirs, 2017) and for identifying regions that require management interventions.

2.2.3 Landscape connectivity

Landscape connectivity is another key control on the complexity and (un)predictability of geomorphic river responses to disturbance events (Brunsden, 2001; Lisenby et al., 2017). Landscape connectivity encapsulates hydrological and sediment connectivity and can be defined as the routing of water and sediment through interconnected landscape units (i.e. drainage basins, hillslopes, floodplains, wetlands) from a source to a sink (Okin et al., 2015;

Wohl et al., 2019). Both natural and anthropogenic features can alter the natural landscape processes and either increase or decrease connectivity with subsequent effects on water and sediment transfer processes (Fryirs et al., 2007). Within river catchments, the spatiotemporal dynamics of connectivity are controlled by climatic factors (e.g. rainfall duration and intensity) and mediated by catchment characteristics (e.g. slope, relief, and elevation), channel characteristics (e.g. slope, stream network density, valley confinement), and vegetation (e.g. land-use changes). In connected (coupled) catchments, sediment is conveyed efficiently through the system from the headwater source zone to the basin outlet. The efficiency of sediment transfer depends on the biophysical linkages and geomorphic processes operating at different positions in the catchment (i.e. longitudinal, lateral, and vertical connectivity) (Brunsden and Thornes, 1979; Heckmann and Schwanghart, 2013). For instance, hillslope-channel and channel-floodplain couplings (lateral linkages) drive sediment delivery to the channel network (e.g. Benda and Dunne, 1997); whereas tributary-trunk stream couplings (longitudinal linkages) dictate the ability of the channel network to transfer sediment along its length (e.g. Hooke, 2003); and surface-sub-surface couplings (vertical linkages) drive water, sediment, and nutrients between the channel and hyporheic zone (Fryirs, 2013). Conversely, in disconnected (decoupled) catchments, sediment transfer between upstream sediment sources and downstream lowland sinks can be disrupted by natural barriers (e.g. valley constrictions), buffers (e.g. alluvial fans and floodplains), or blankets (e.g. floodplain sediment sheets) that impede and decouple lateral, longitudinal, and vertical linkages (Fryirs et al., 2007a). In decoupled catchments sediment is stored (e.g. at the base of hillslopes) until landscape connectivity is re-established (Cavalli et al., 2013; Fryirs, 2013), resulting in inefficient sediment transport to the channel network (e.g. Dedkov and Mozzherin, 1996) or lagged effects of downstream sediment conveyance (e.g. Benda and Dunne, 1997). For instance, decoupling of tributary and channel linkages occur when sediments are trapped behind floodplain pockets at confluences or in tributary fills (Brierley and Fryirs, 1999). In addition, anthropogenic interventions can decrease connectivity and thus affect sediment conveyance, for example, dams, levees, and elevated roads may hinder sediment movement downstream (e.g. Kumar et al., 2014). While these structures have positive socio-economic and biophysical impacts, such as through water provision and economic development, they also affect the catchment negatively by influencing natural ecological and geomorphological processes, such as limiting fish migration, impacting downstream channel morphology, and reducing ecosystem service delivery (Sandercock and Hooke, 2011; van der Waal and Rowntree, 2018). These various forms of (de)coupling serve to (dis)connect large parts of a catchment from the fluvial corridor, influencing the effective catchment area contributing unobstructed sediment downstream. Understanding the dynamics of landscape connectivity is crucial for guiding effective management and conservation efforts in a catchment (Lexartza-Artza and Wainwright, 2009).

The spatial and temporal variability of (dis)connectivity patterns exerts a primary control upon the efficiency with which responses to disturbance are propagated through a catchment (Brierley et al., 2006; Fryirs, 2013; Bracken et al., 2015). In highly connected or coupled catchments, responses to disturbances are efficiently propagated downstream, for example, several sub-basins in the upper Kosi basin in India are well connected and sediment mobilised due to land use and land cover change is efficiently transported to the main channel and further downstream (Mishra et al., 2019). Whereas in disconnected catchments, responses are lagged, for instance, disturbances that mobilise sediment from hillslopes may be stored at the base, producing lagged responses where sediment transfer to the channel occurs over decadal scales as the sediment deposits are slowly reworked (e.g. Fryirs et al., 2007a). Moreover, the degree to which a catchment is connected, and responses are propagated (i.e. sediment transferability) governs the form, severity, and distribution of geomorphic adjustments farther downstream. This in turn influences the sensitivity and recovery potential of a system following disturbance (e.g. Thomas, 2001; Poeppl et al., 2017; Lisenby, 2019).

Overall, the geomorphic concepts of landform sensitivity and landscape connectivity represent the integration of flow regime, sediment availability, vegetation, and anthropogenic impacts as controls on how readily a river channel can adjust. These concepts are thus well suited to assess the ability of different regions in the catchment to respond to disturbance and predict how reach-scale adjustments may influence responses further downstream along the channel network (Downs and Gregory, 2004; Fryirs et al., 2009). Therefore, the spatiotemporal variability of landform sensitivity and landscape connectivity exerts a substantial control on the ability of a river to geomorphologically adjust to disturbance events, which makes these concepts useful to interpret past and present river behaviour and establish possible scenarios of river adjustments in the future (Czuba and Foufoula-Georgiou, 2015; Fryirs, 2017). This is important as the geomorphological response of rivers can dramatically change ecosystem structure and function, and hence ecosystem service delivery. Despite these concepts proving useful for understanding river processes and forms, they are rarely considered in river management and conservation strategies.

2.3 Future trajectories of dryland rivers and wetlands and management implications

Drylands are critically important systems to society, yet extremely vulnerable to climate change. Climate projections indicate that hotter, drier conditions will continue to intensify across drylands globally (i.e. increased temperatures and more variable rainfall) (Cook et al., 2014), likely resulting in the global expansion and further desiccation and degradation of dryland areas (Feng and Fu, 2013). These projected trends have been attributed to the compounded effects of population increase, land use changes, and increasing climatic variability (e.g. increasing temperatures and declining precipitation) (IPCC, 2022). Warmer temperatures are expected to increase evapotranspiration rates, and thus even if regions do not experience a net reduction in rainfall, they will likely experience higher overall aridity (Cook et al., 2014). Although some tropical regions are expected to receive higher annual rainfall totals, inter-annual variability is expected to increase (Milly et al., 2005). These projected increases in aridity and high variability in rainfall are expected to magnify surface water shortages in many drylands (Dore, 2005; Schewe et al., 2014). Moreover, the increasing pressure on water usage will likely exacerbate these shortages consequently impacting the hydrology of dryland river catchments with knock on effects on surface water availability, flow regimes and ecosystem service delivery (Reynolds et al., 2007; Bregoli et al., 2019; Grenfell et al., 2022).

There is considerable uncertainty associated with climate model projections and it is difficult to accurately predict future rainfall patterns. However, in general, climate models agree that globally drylands will experience increasing water scarcity and reduced streamflow in the coming decades (Milly et al., 2005; Schewe et al., 2014; Gosling and Arnell, 2016). Knowledge of how anthropogenic and climate change impacts will affect the geomorphology of dryland rivers globally and within Africa is essential for water-resource allocation planning and land-use management in these regions (e.g. Reynolds et al., 2007). Although dryland rivers have been the focus of many conservation strategies and policies, efforts to preserve and manage dryland rivers are often hampered by incomplete scientific information and understanding. Therefore, a deeper understanding of the geomorphic controls and processes driving river adjustment, sensitivity and connectivity is imperative for effectively managing and conserving these fundamentally important systems.

3 Study site

This thesis focuses on a large, sub-equatorial dryland river catchment in a data deficient region of the world. The Mara River catchment in East Africa (Fig. 1.2) is of significant ecological importance as it hosts the internationally recognised UNESCO World Heritage Serengeti-Mara conservation areas which support the annual migration of 2 million herbivores. In addition, the Mara River and its floodplain wetlands provide essential resources to local human and wildlife populations. Despite its regional and global importance, the Mara River system is under pressure from anthropogenic and climate change impacts, which are threatening important water resources. Moreover, the Mara system is poorly understood in terms of its recent historical geomorphic development and provides a unique opportunity to investigate how this system has responded over the recent past to hydroclimatic and anthropogenic changes. An improved understanding of a dryland river system from a less well documented region is an important contribution to the global research on dryland fluvial geomorphology.

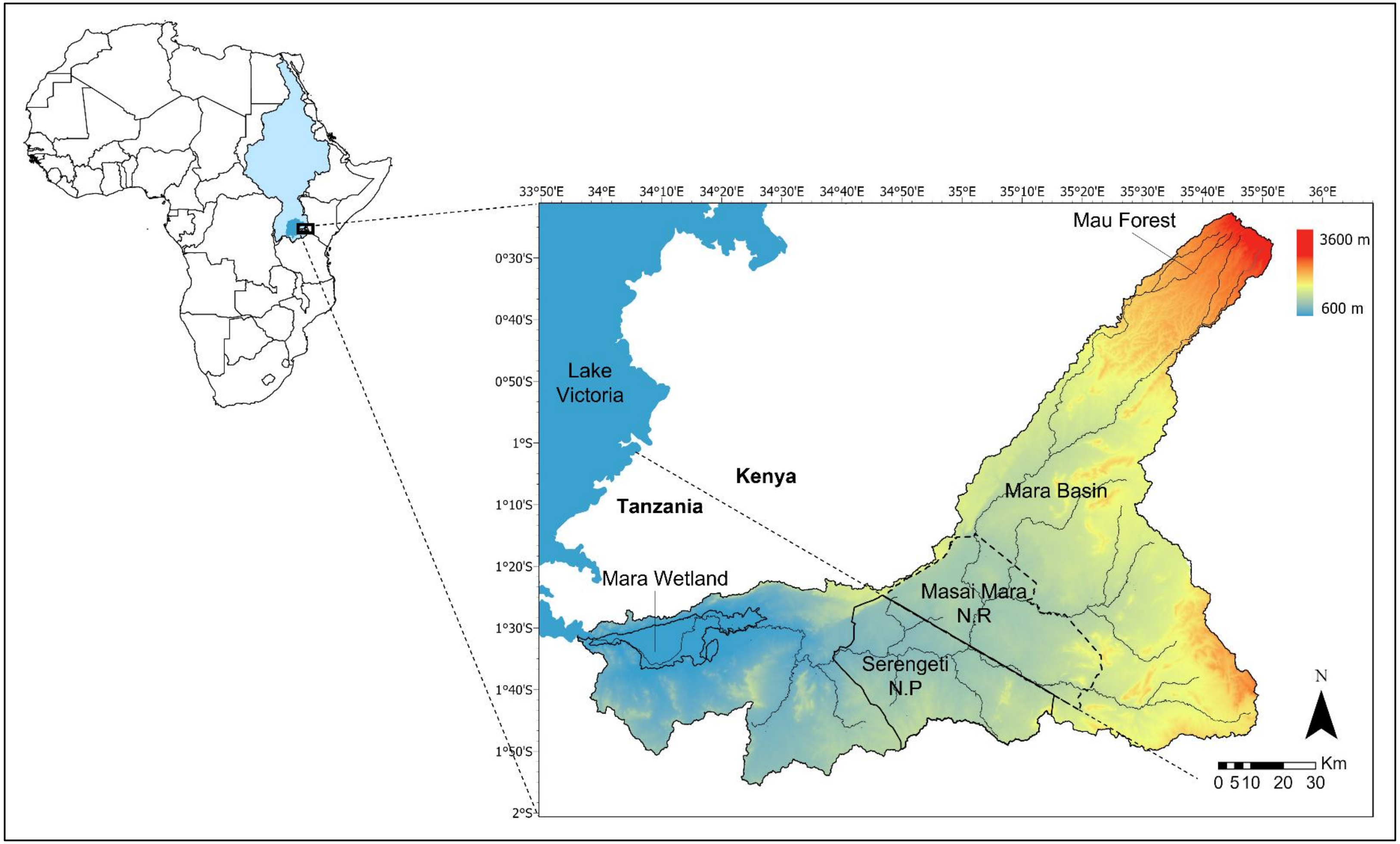


Figure 1.2. Location of the transboundary Mara River catchment shared between Kenya and Tanzania in East Africa. The Mara catchment is a subcatchment of the Nile River basin (light blue shading) and hosts the UNESCO World Heritage Serengeti-Mara ecosystem comprising the Masai Mara National Reserve and the Serengeti National Park. Elevation data derived from NASA Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) (https://earthexplorer.usgs.gov).

3.1 The Mara River catchment

East Africa is characterised by prominent plateaus and escarpments associated with the East African Rift System (EARS). The eastern branch of the EARS, known as the Gregory Rift Valley, is a narrow, linear, down-faulted feature that is bounded by escarpments, and it transects Kenya and northern Tanzania (Scoon, 2018). The rift valleys are characterised by numerous shallow lakes, whereas the rift platforms have been significantly uplifted forming high-elevation escarpments with temperate climates and extensive montane forests, despite the equatorial setting (Scoon, 2018). The Mau Escarpment forms part of the southern end of the Gregory Rift Valley and supports the Mau forest complex which remains one of the largest closed canopy forests in East Africa. The Mau forest on the escarpment forms the headwaters of the Mara River catchment which is a large, transboundary catchment shared between Kenya and Tanzania (Fig. 1.2). The 13 750 km^2 catchment extends from the Mau forest escarpment in south western Kenya (3000 m a.s.l) to its outlet at Lake Victoria (600 m a.s.l) in north western Tanzania and forms an important subcatchment of the upper Nile River Basin (Mati et al., 2008; Bregoli et al., 2019). The upper section of the catchment is subhumid, but the rest of the catchment is semiarid. The catchment is largely dominated by agricultural lands and rangelands and supports a population of ~1.2 million people (Zermoglio et al., 2019).

The Mara River is a perennial, but strongly seasonal, river (Fig. 1.3 A, B) that is free of any major natural or artificial reservoirs and flows 395 km from the steep escarpment in its upper reaches through the more gradual slopes of the semiarid Serengeti-Mara ecosystem in its middle reaches, down to the Mara wetland in its lower reaches. In the lower Mara River, the upper reach is characterised by vegetated channel banks but as the river transitions to the middle and lower reaches the channel banks become less vegetated and sand bars become more prominent (Fig. 1.3 C, D). The Mara River flows across a large, flat alluvial floodplain where it decreases in size and becomes unchanneled in the Mara Wetland (Fig. 1.3 E-G). At its downstream end, the floodplain wetland abuts a northeast-southwest trending ridge, known as the Utimbara Fault, which forces the Mara River into a narrower, reformed channel prior to its confluence with Lake Victoria (Fig. 1.3 H). The Mara Wetland covers an area ranging from 390 km^2 to 500 km^2 depending on seasonal flooding and relies on flows from the more humid headwaters, representing an allogenic hydrological system (Mati et al., 2008). The wetland provides critically important hydrological services, such as regulating the quality and flow of water entering Lake Victoria and serves as a groundwater recharge zone

(Omolo et al., 2018). In addition, it provides essential ecosystem services that sustain the livelihoods and wellbeing of the surrounding communities.

The Mara River catchment exhibits a bimodal rainfall regime with two distinct rainy seasons that occur in March–May (the long rains) and October–December (the short rains) (Alemayehu et al., 2017). Rainfall varies spatially over the catchment largely due to topographical variations, coastal influences, and presence of lakes, with higher mean annual precipitation (~1750 mm a^{-1}) occurring in the headwaters and declining toward the catchment outlet (~600 mm a^{-1}) (McClain et al., 2014). A general decreasing precipitation trend has been observed in the catchment, with the greatest decline occurring during the long rains season (Borhara et al., 2020). However, a weak increasing precipitation trend is evident for the short rains season around Lake Victoria which contradicts the current decreasing lake level. There is significant intra- and inter-annual variability of rainfall that is largely related to the interaction between the Indian Ocean Dipole (IOD) and El Niño-Southern Oscillation (ENSO) (Nicholson, 2017). Conditions that promote widespread flooding in the Mara system are associated with a positive IOD and ENSO resulting in El Niño events that lead to higher rainfall during the wet season (Endris et al., 2019). Enhanced dry season rainfall but lower wet season rainfall is associated with a negative IOD resulting in La Niña events. El Niño or La Niña events typically occur once every two to seven years (Zermoglio et al., 2019).

The Mara River catchment has undergone major land-use changes due to settlements and deforestation over the last 50 years (Olang and Kundu, 2011), which has altered the hydrology and water quality in the Mara River, resulting in increased peak flows, erosion rates, and suspended sediments and nutrients in the river (Mati et al., 2008; LVBC and WWF-ESARPO, 2010; Mango et al., 2011; McClain et al., 2014; Dutton et al., 2018). These changes have led to increased sediment and pollutant loads in the river, which have impacted the morphological characteristics and functioning of the floodplain wetland. In addition, increased sedimentation has led to a four-fold increase in the size of the Mara Wetland (Mati et al., 2008). Management authorities have found that increased levels of total suspended solids and nutrients in the Mara River may be associated with eutrophication in Lake Victoria and the overall decline in aquatic ecosystem health, with significant social implications for domestic water users (Hecky et al., 2010; LVBC and WWF-ESARPO, 2010).

Figure 1.3. Images of the Mara River in Tanzania. A, B) Aerial images of the sinuous Mara River close to the border between Kenya and Tanzania (looking downstream; credit: Sonja Metzger and Christopher Dutton). C) UAV oblique photo and D) photo of the Mara River near the Mara Mine gauging station (looking downstream). E) UAV oblique photo of the Mara wetland highlighting how the local communities utilise the wetland for farming. F, G) Photos of the Mara wetland before it enters the dense papyrus vegetation of the core wetland highlighting the importance of the wetland for livestock grazing and collecting resources (e.g. fish, papyrus for charcoal) (looking downstream). H) The confluence of the Mara River with

Lake Victoria at Kirumi Bridge (looking downstream; photos C – H, credit: Francesco Bregoli). All photos were used with permission.

The few previous geomorphological investigations of the Mara River and its floodplain wetlands have focussed on anthropogenic impacts on river morphology (e.g. Stoop, 2017; Bregoli et al., 2019) and sediment and palaeoenvironmental conditions (e.g. Dutton et al., 2018; 2019). Yet these studies do not consider valley- and catchment-scale controls on river processes or patterns of channel adjustment, or the factors that influence river sensitivity and hydrogeomorphic connectivity that are relevant to conservation and management. However, hydrological modelling and environmental flow planning has been undertaken to understand impacts of future climate and anthropogenic changes as well as future water resource development on hydrology within the catchment (LVBC and WWF-ESARPO, 2010; Hoffman et al., 2011; Dessu and Melesse, 2012; Dessu et al., 2014; Mwangi et al., 2016; Zermoglio et al., 2019). Currently, water resource development is relatively limited in the Mara catchment, but research suggests that illegal abstraction and water use by large-scale commercial farms has significantly reduced dry season low flows in the past decade (LVBC and WWF-ESARPO, 2010; Kihwele et al., 2021). These trends of increasing water extraction will likely be exacerbated if the proposed hydropower projects in the headwater catchment are approved (Zermoglio et al., 2019; Mngube et al., 2020). Therefore, an understanding of how future climate and/or human impacts will affect geomorphological and hydrological processes in the river is necessary to effectively manage this important fluvial system and sustain its ecosystem services.

4 Thesis aims, research questions, and structure

This research develops a case study of the Mara River to explore the key geomorphic controls driving dryland river morphology and floodplain wetland formation (Table 1.1). To address the main aim of the thesis, five research objectives were identified:

A) Characterise downstream geomorphological changes in the lower reaches of the modern Mara River and its adjacent palaeochannels;
B) Examine the extrinsic controls and intrinsic processes driving the character and behaviour of the modern river and its palaeochannels;
C) Quantify the spatiotemporal distribution of channel adjustments and landform sensitivity in the lower Mara River;

D) Quantify the spatiotemporal patterns of hydrological and sediment connectivity in the Mara catchment and assess its influence on fluvial geomorphology; and to
E) Use landform sensitivity and landscape connectivity theory to assess future trajectories of river response to climate and anthropogenic change.

This thesis comprises five chapters, and mapping of the related research questions, thesis objectives and chapter contents are shown in Table 1.1. **Chapter 1** – has introduced the main themes of the thesis and reviews the current understanding of dryland river functioning with a focus on the Mara River in East Africa. **Chapter 2** – explores the extrinsic and intrinsic controls driving the character and behaviour of the modern river and its palaeochannels (Objectives A and B). **Chapter 3** – examines the historic patterns and processes of geomorphic adjustment and how they relate to landform sensitivity (Objective C). **Chapter 4** – assesses the spatial and temporal variation in hydrological and sediment connectivity at the catchment and wetland scale and its influence on the geomorphology of the river (Objectives D and E). **Chapter 5** – provides a synthesis of the thesis and concludes the main findings of this research.

Chapters 2, 3, and 4 are based on research papers that are published in peer-reviewed journals and thus are written and formatted in a self-contained style with introduction, aims and objectives, description of study site and methods, results, interpretation, discussion, and conclusion. The contributions of various co-authors for these three research papers are shown in Table 1.2.

Table 1.1. Outline of thesis structure including the research questions, objectives, and chapters with key topics and areas of research covered

RESEARCH QUESTIONS	**RESEARCH OBJECTIVES**	**CHAPTER 1 - Introduction and background**	**CHAPTER 2 - Controls**	**CHAPTER 3 - Adjustment**	**CHAPTER 4 - Connectivity**	**CHAPTER 5 - Synthesis and conclusion**
1) What are the main geomorphic controls that influence river morphology and floodplain wetland formation in the Mara River system?	A) Characterise the downstream geomorphological changes in the lower reaches of the modern Mara River and its adjacent palaeochannels.	• Geomorphology of dryland rivers and wetlands	River and floodplain wetland development			Global dryland river and floodplain wetland evolution
		• Geomorphic river response of dryland rivers and wetlands	Palaeochannel geomorphology and hydrology			Palaeochannel geomorphology and hydrology
	B) Examine the extrinsic controls and intrinsic processes driving the character and behaviour of the modern river and its palaeochannels.	• Extrinsic and intrinsic controls driving geomorphic thresholds	Modern geomorphology and hydrology	Modern geomorphology and hydrology		Modern channel geomorphology and hydrology
		• Equilibrium and nonequilibrium responses	Extrinsic and intrinsic geomorphic thresholds (i.e. avulsion)	Extrinsic and intrinsic geomorphic thresholds (i.e. avulsion)		Interplay between extrinsic forces and intrinsic processes
2) Which hydrogeomorphic processes drive river adjustment and landform sensitivity (i.e. natural range of variability) and define the overall character and behaviour of the Mara River and its floodplain wetlands?	C) Quantify the spatiotemporal distribution of channel adjustments and landform sensitivity in the lower Mara River.	• Geomorphic adjustments and feedback to river sensitivity		Historical patterns of channel adjustment	Historical patterns of channel adjustment	Spatiotemporal distribution of channel adjustment and related river sensitivity
		• Sensitivity and resilience of dryland rivers and wetlands		River sensitivity	River sensitivity	
3) How do patterns of hydrological and sediment connectivity and landform sensitivity affect the geomorphology of the Mara River system?	D) Quantify the spatiotemporal patterns of hydrological and sediment connectivity in the Mara catchment and assess its influence on fluvial geomorphology.	• Hydrological and sediment connectivity of dryland rivers and wetlands • Connectivity and sensitivity as key controls on fluvial geomorphology			Catchment and wetland scale hydrological and sediment connectivity and its influence on fluvial geomorphology	Catchment and wetland scale hydrological and sediment connectivity and its influence on fluvial geomorphology
4) How will the Mara River respond to future changes in hydroclimatic or anthropogenic impacts?	E) Use landform sensitivity and landscape connectivity to assess future trajectories of river response to climate and anthropogenic change.	• Forecasting future biophysical change to dryland rivers and wetlands			Impacts of future climate change on the geomorphology of dryland rivers and wetlands	Impacts of future climate change on the geomorphology of dryland rivers and wetlands

Table 1.2. The author contributions to chapter conception, data collection and chapter/manuscript preparation

Chapter in thesis	Intellectual contribution and chapter conception	Data collection	Chapter/manuscript preparation			
			Data analysis	**Data interpretation/ discussion**	**Writing**	**Figures and tables**
Chapter 1 Introduction	MG (100%)	MG (100%)	MG (100%)	MG (100%)	MG (96%) drafted the chapter, TR (2%), and MH (2%) provided feedback	MG (100%)
Chapter 2 Controls	MG (50%), TR (30%), MH (20%)	MG (98%), ML (2%) assisted with data collection	MG (100%)	MG (60%), TR (30%), MH (10%)	MG (78%) drafted the chapter, TR (10%), MH (10%), and MB (2%) edited the manuscript and provided feedback	MG (100%)
Chapter 3 Adjustment	MG (50%), TR (30%), MH (20%)	MG (100%)	MG (100%)	MG (50%), TR (40%), MH (10%)	MG (80%) drafted the chapter, TR (10%), and MH (10%) edited the manuscript and provided feedback	MG (100%)
Chapter 4 Connectivity	MG (60%), TR (30%), MH (10%)	MG (85%), CH (15%) assisted with data processing	MG (100%)	MG (70%), TR (20%), MH (10%)	MG (78%) drafted the chapter, TR (10%), MH (10%), and CH (2%) edited the manuscript and provided feedback	MG (100%)
Chapter 5 Discussion	MG (100%)	MG (100%)	MG (100%)	N/A	MG (95%) drafted the chapter, TR (2%) and MH (2%) provided feedback	MG (100%)

Note: MG – Megan Gomes, TR – Tim Ralph, MH – Marc Humphries, MB – Marion Bamford, CH – Carl Helander, ML – Morgan Leigh

CHAPTER 2

Valley-scale controls and hydrogeomorphic processes driving channel breakdown in a dynamic floodplain wetland system: The Mara River, Tanzania

This chapter has been published in the journal Geomorphology.

See Table 1.2 in Chapter 1 for author contributions.

Gomes, M., Ralph, T. J., Bamford, M., and Humphries, M. S. (2023). Valley-scale controls and hydrogeomorphic processes driving channel breakdown in a dynamic floodplain wetland system: The Mara River, Tanzania. Geomorphology, 425,108584. https://doi.org/10.1016/j.geomorph.2023.108584

Abstract

The character and behaviour of dryland rivers are driven by complex interactions between extrinsic and intrinsic controls. A long-term perspective is necessary to assess the sensitivity of dryland rivers to extrinsic forcing, such as hydroclimatic changes, and to contextualise the threshold channel responses. The semi-arid Mara River in northern Tanzania is the only perennial river in the UNESCO World Heritage Serengeti-Mara ecosystem and provides water resources for human and wildlife populations. Satellite imagery and discharge modelling were used to assess the valley-scale controls and hydrogeomorphic processes driving the morphological adjustments of the lower Mara River and its floodplain wetland. Both the modern and palaeochannels undergo downstream morphological and hydrological changes as they traverse the broad, alluvial floodplain. In response to marked downstream declines in discharge (from ~300 $m^3.s^{-1}$ to ~45 $m^3.s^{-1}$) and stream power (from ~40 $W.m^{-2}$ to ~0.5 $W.m^{-2}$), the modern channel exhibits a nonequilibrium river response resulting in downstream declines in channel size (from ~60 m to ~10 m wide) and eventual channel breakdown in the floodplain wetland. Palaeochannels in the unconfined reaches are typically larger with higher palaeodischarges than the modern channel. While some palaeochannels exhibit similar downstream trends to the modern channel, others may have maintained a continuous channel farther into the wetland. Comparison of the Mara River to other dryland river systems highlights the importance of valley setting and hydroclimate as long-term controls which influence geomorphic river response over time. The lower Mara River represents a nonequilibrium river response to declining discharges related to transmission losses which leads to channel bed aggradation and avulsion, constituting an inherent condition in many dryland alluvial rivers. An improved understanding of the interplay between intrinsic and extrinsic controls is important for the assessment of river character, behaviour, and floodplain wetland development, particularly under future projections of more variable or extreme climate conditions.

Keywords: alluvial river, crevasse splays, avulsion, nonequilibrium river response, wetland in drylands

1 Introduction

Rivers provide a range of critical ecosystem services in water-stressed drylands (dry sub-humid, semi-arid, arid, and hyper-arid regions), which cover 40–50% of Earth's land surface and host ~28% of the world's population (Millennium Ecosystem Assessment (MEA), 2005). Drylands are characterised by net water deficits owing to low, variable rainfall and high evapotranspiration, but despite water scarcity, many drylands host important perennial, intermittent or ephemeral rivers (Tooth and McCarthy, 2007). Perennial dryland rivers (e.g. the Okavango Delta in Botswana) are typically maintained by allogenic flows from distal, more humid headwater catchments, with periodic additions from local rainfall-runoff events (McCarthy, 2013; Tooth, 2013). Dryland rivers often provide the only surface water resource to sustain local human and wildlife populations in otherwise dry environments (van Dam et al., 2014; Larkin et al., 2017a). However, these systems are under increasing pressure globally as a result of anthropogenic (e.g. water abstraction, river regulation, hydropower generation, and land use change) and climate change impacts (e.g. decreased rainfall, increased temperature and evapotranspiration, and greater climatic variability) (Knighton and Nanson, 1993; Pekel et al., 2016; Sabater, 2018; Larkin et al., 2020b).

Dryland rivers are dynamic, self-adjusting systems and their character and behaviour develop in response to the interplay between extrinsic controls and intrinsic processes (Ralph and Hesse, 2010; Larkin et al., 2017a). Extrinsic forces control the environmental parameters (or flux boundary conditions) (Fryirs et al., 2012) of a system and define the natural or 'expected' range of variability. Examples of extrinsic forces, include climate, hydrology, catchment lithology, tectonic activity, and anthropogenic activity that determines the flow regime, slope, and sediment load of the system. Intrinsic processes relate to the efficiency with which discharge, and sediment supply are transported downstream and drive river adjustment within a range of variability. Importantly, intrinsic processes of adjustment (i.e. threshold channel responses) can occur independently of changes to the external environment. Although many studies have focused on the influence that intrinsic processes and extrinsic controls exert on dryland river characteristics, many uncertainties remain (Tooth, 2013; Grenfell et al., 2014; Larkin et al., 2017a, 2017b). For instance, the complex interaction between lithology, climate, and other factors governing threshold responses, lags and feedbacks in rivers remain poorly understood. A long-term perspective on dryland river development can improve understanding of the relationships between intrinsic and extrinsic controls, particularly by defining how they interact to influence changes in river character and behaviour (Larkin et al., 2017a). Chronologically constrained geoproxies, such as palaeochannels preserved on the floodplain provide evidence of the timing of their development and therefore past morphological and hydrological conditions (e.g. Page et al., 2009; Kemp and Rhodes, 2010; Hesse et al., 2018a, 2018b; Larkin et al., 2020a). Palaeochannels may have different channel planforms compared to the modern channel and can provide insights into the role of stable or changing intrinsic and extrinsic controls that drive fluvial character and behaviour (Larkin et al., 2020b). An improved understanding of the interaction between these controls is particularly important considering future projections of increasing aridity and declining freshwater availability in many drylands globally (Milly et al., 2005; Pekel et al., 2016; Larkin et al., 2020b).

As a contribution to addressing these uncertainties, this study examines the key geomorphic controls driving dryland river behaviour and floodplain wetland development in a poorly documented region of the world. The Mara River in East Africa falls within a transboundary river catchment that provides an important water resource in a semi-arid region (Mati et al., 2008; Omolo et al., 2018; Bregoli et al., 2019; Kihwele et al., 2021). The Mara River flows from its headwaters in southern Kenya through the UNESCO World Heritage Serengeti-Mara conservation area and eventually into Lake Victoria in northern Tanzania (Fig. 1). The river catchment is of international conservation significance as it provides the only perennial water source for the semi-arid Serengeti-Mara ecosystem. This water supply is crucial for sustaining human, livestock, and wildlife populations (including international migratory birds and threatened species) that are directly dependent upon the river (Mati et al., 2008; Omolo et al., 2018). East Africa has recently observed an increase in drought frequency and decline in precipitation during the long rain season (March to May) (Lyon and Vigaud, 2017). Nevertheless, some future climate projections indicate that this region will experience increased temperatures, while other climate models project an increase in rainfall, more intense wet seasons, and less severe droughts (Giannini et al., 2008; Shongwe et al., 2009; Niang et al., 2014). Further, climate models project that with a rise in temperatures there will be an associated strengthening of the El Nino Southern Oscillation (ENSO) and more frequent occurrences of the positive phase of the Indian Ocean Dipole (IOD) (Dore, 2005), although evidence for this remains controversial (Collins et al., 2010). This disconnect between modelled and observed precipitation trends highlights the uncertainty of future climate projections for this region (Beverly et al., 2020). In this context it is important to understand how the semi-arid Mara River system has changed in the past, and how it may respond in the future, to hydroclimatic change. In this study, we investigated the valley-scale controls and hydrogeomorphic processes driving the geomorphological origin and dynamics of the Mara River and its floodplain wetland. The objectives of this study were to: (i) characterise the downstream hydrogeomorphic trends of the modern Mara River; (ii) determine the broad-scale controls on river behaviour and floodplain wetland characteristics; (iii) identify and characterise the palaeochannels in the system; (iv) assess the influence of intrinsic and extrinsic controls on the development of the palaeochannels and the subsequent transition to the modern river; and (v) compare the behaviour and characteristics of this floodplain wetland with other dryland river systems.

2 Regional setting

2.1 Study site

The transboundary Mara River catchment is one of the more pristine sub-catchments in the upper Nile River catchment and is shared between Kenya and Tanzania covering an area of 13 750 km^2 (Fig. 1A) (Mati et al., 2008). The Mara River is a perennial, allogenic system that originates from the Napuiyapui swamp on the Mau Escarpment (3000 m a.s.l.) in the highlands of Kenya. The river flows through small-scale settlements, agricultural and grazing land, and the Serengeti-Mara conservation area before entering the Mara wetland and finally debouching into Lake Victoria (600 m a.s.l) at Musoma Bay in Tanzania (Kassenga, 1997). In the Mara River basin, the upper catchment has undergone major land use and land cover changes caused by legal and illegal settlements and deforestation since the 1970s (Olang and Kundu, 2011). Several studies have highlighted the impacts of land use changes in the catchment, including increased runoff and erosion rates, and increased suspended sediments and nutrients, with substantial consequences for the hydrology and water quality in the Mara River and its floodplain wetland (McClain et al., 2014; Mwangi et al., 2016, 2017; Bregoli et al., 2019; Dutton et al., 2019). The principal study site is in the lower Mara catchment focusing on the Mara River floodplain (total length 130 km), which extends from the Mara Mine gauging station through the Mara wetland to the outlet at Lake Victoria (Fig. 1B).

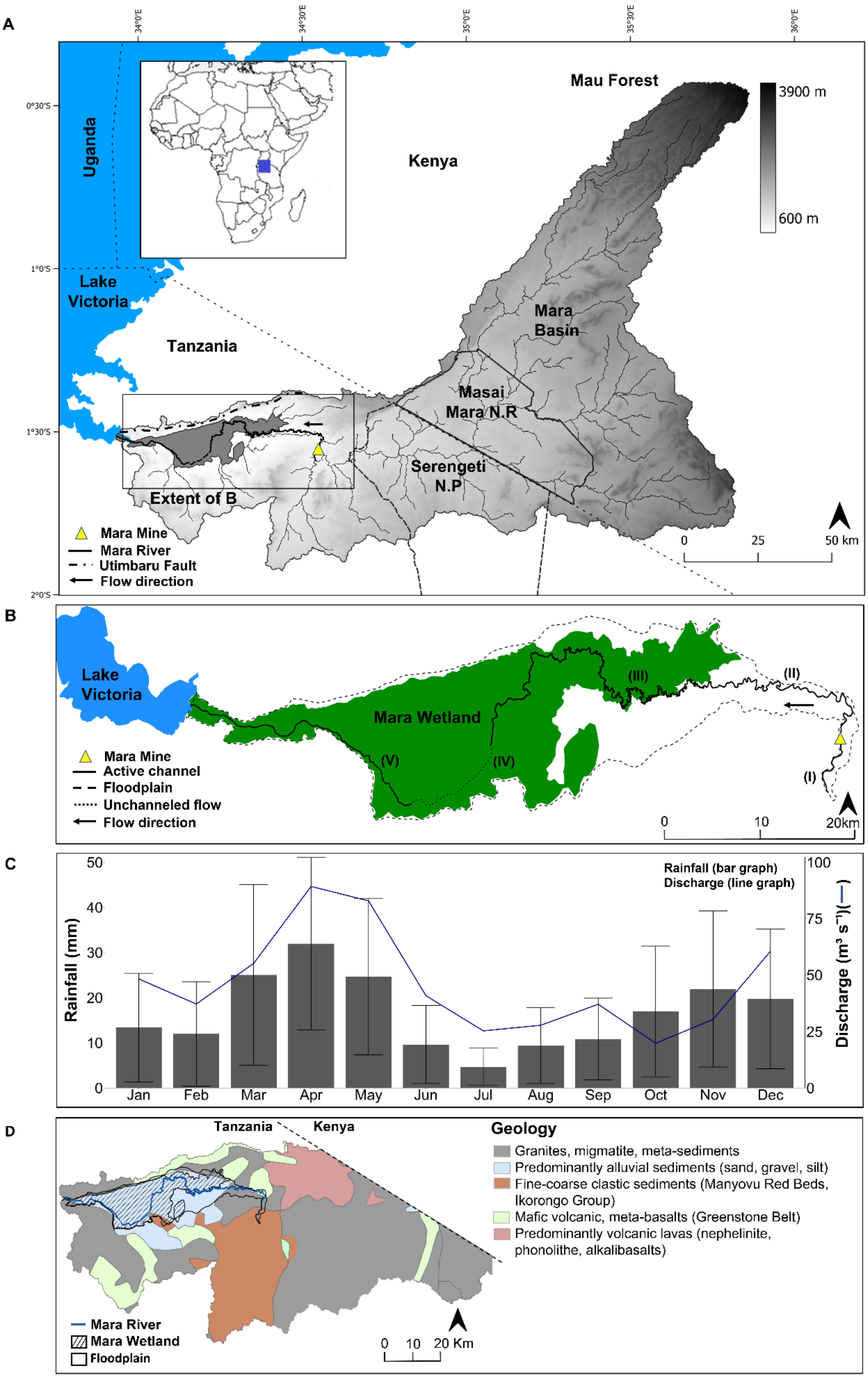


Figure 1. (A) The Mara River catchment in Kenya and Tanzania. The Mara River flows through the important conservation areas of the Masai Mara National Reserve and the Serengeti National Park before entering the Mara Wetland. (B) The principal study site is the

lower section of the Mara River (starting point at Mara Mines gauging station) and its floodplain wetland in northern Tanzania. The five river types shown include: upper, partly confined reach (R-I), middle, partly confined reach (R-II), lower, unconfined continuous, reach (R-III), lower unconfined discontinuous reach (R-IV), and lower, partly confined reach (R-V) (after Fryirs et al., 2016). (C) Hydrological time series representing the mean monthly precipitation and discharge in the lower Mara River. Bar graph reflects the mean monthly precipitation data from 1981 to 2020 with error bars indicating the standard error (data obtained from the Climate Hazards Infrared Precipitation with Stations (CHIRPS); Funk et al. 2015; https://data.chc.ucsb.edu/products/CHIRPS – 2.0/). Line graph reflects the mean monthly discharge data from 1969 to 2012 (data obtained from McClain et al., 2014). (D) Geological map of the lower Mara River obtained from the Geological survey of Tanzania (https- //www.gmis-tanzania.com/).

The Mara wetland is ~45 km long and up to ~14 km wide and has no formal protection status, except for being listed as an "Important Bird and Biodiversity Area" (Omolo et al., 2018). Previous research suggests that the wetland has expanded in size by over 300% since the 1970s, which has been associated with increasing sediment loads driven by land-use changes in the catchment and lake level fluctuations (Mati et al., 2008; Dutton et al., 2019). The floodplain wetland acts as a sediment store for alluvial sediment supplied from the catchment and thus provides accommodation space for the river to laterally migrate, avulse and expand (Fig. 1D). The wetland also acts as a filter, reducing the impacts of increased sediment and mercury contamination on Lake Victoria (Dutton et al., 2019). The northern boundary of the wetland is characterised by a steep escarpment that is bounded by a normal dip-slip fault, known as the Utimbaru Fault (Miocene age), that is buried under the wetland (Kabete et al., 2012), whereas the southern boundary is more gently sloping and punctuated by several granitic inselbergs (Fig. 1B). The subsidence of the wetland has likely provided vertical accommodation space for sediment deposits in the floodplain wetland, however, there is no evidence of neotectonic activity in this region. Sediment cores collected to a maximum depth of 189 cm and dated to 2691 ± 147 cal year BP (Dutton et al., 2019), provide a conservative estimate of the depth of alluvial deposits in the floodplain wetland.

The geology of East Africa is comprised of three terranes, including the basement complexes, regional plateaus, and the East African Rift System (EARS). The basement complexes are mainly dominated by hard, crystalline, metamorphic rocks that typically crop out as small hills or inselbergs from the Archaean and Neoproterozoic Eras (Scoon, 2018). The oldest of the basement complexes in this region is the Lake Victoria Terrane (age of 2.810–2.560 Ga), which forms part of the Central African craton. The Archaean-age Lake Victoria Terrane comprises of two main components including the Musoma–Mara Greenstone Belt (predominantly mafic volcanics with subordinate meta-basalts) (Manya et al., 2006) interspersed by alternating granitoid-gneisses (granites, migmatite, meta-sediments) of the North Mara Belt (Fig. 1D). The underlying geology of the lower Mara River is predominantly sedimentary rocks formed in the fault-bounded basins of the Lake Victoria Terrane. The upper reach (R-I) is underlain by fine-coarse detrital clastic sediments that transition into granites, migmatite, and meta-sediments. The middle reach (R-II) is underlain by mafic volcanic sediments that transition into granites. The lower reaches (R-III, IV) are underlain by predominantly alluvial sediments (i.e. sand, gravel, silt sediments) in the floodplain wetland that transitions into granites in the lower reach (R-V) near the confluence with Lake Victoria.

2.2 Modern hydroclimate

The climate of East Africa is complex owing to the large-scale controls such as topography, lakes, and coastal influences in addition to the seasonal dynamics of tropical circulation (Liu et al., 2017). East Africa is characterised by a bimodal rainfall pattern that is driven by the annual migration of the Intertropical Convergence Zone (ITCZ) and the Congo Air Boundary (CAB) (Nicholson, 2017; Beverly et al., 2020). The Mara River catchment exhibits seasonal rainfall that is characterised by two distinct rainy seasons (Fig. 1C), which occur during March–May (the long rains) and October–December (the short rains) (Alemayehu et al., 2017). These rains are characterised by high intra- and inter-annual variability because of the Indian Ocean Sea Surface Temperature (SST) anomalies that are related to the Indian Ocean Dipole (IOD) and El Nino-Southern Oscillation (ENSO; Liu et al., 2017). A positive IOD phase and ENSO can lead to an increase in East African rainfall during the wet season through the weakening of the westerly winds, which allows more moisture influx from the Indian Ocean (Saji et al., 1999), however this positive phase may also reduce the dry season rainfall from Lake Victoria (Pennycuick and Norton-Griffiths, 1976). Conversely, the occurrence of La Nina events and negative IOD phases may enhance westerly winds from Lake Victoria, which blocks moisture influx from the Indian Ocean, leading to higher dry season rainfall and lower wet season rainfall.

Rainfall in the Mara catchment also varies spatially as a function of elevation, with higher mean annual precipitation (1750 mm a^{-1}) on the Mau Escarpment and a declining trend (600 mm a^{-1}) toward Lake Victoria (McClain et al., 2014; Dutton et al., 2018). River discharge in the catchment reflects the dominantly bimodal rainfall regime with a mean annual discharge of 47.2 $m^3.s^{-1}$, a minimum of 1.5 $m^3.s^{-1}$ and a maximum of 921 $m^3.s^{-1}$ (as recorded at Mara Mine gauging station; McClain et al., 2014). Because of the seasonality of rainfall, the Mara River and its floodplain are characterised by bi-annual flood events, with larger floods occurring every 2-3 years interspersed with periods of low (∼1 $m^3.s^{-1}$) flow in both wet and dry years (McClain et al., 2014).

3 Methods

3.1 Morphological mapping and morphometrics

Field campaigns were not possible during this study and therefore remotely sensed data formed the primary method of data collection. The advantages of using satellite imagery are that it provides information over large areas that are often inaccessible, and it is relatively cost effective. Satellite imagery from Google Earth Pro was used to perform geomorphological mapping and characterise downstream channel trends of the modern Mara River and its palaeochannels. Here palaeochannels are defined as any abandoned channel on the floodplain, which no longer transports flow or sediment, and may include some recent avulsions. Visualization, manual digitization, and quantification of morphometric parameters (i.e. bankfull channel width, channel sinuosity, and floodplain width) were calculated at 1 km intervals for the lower Mara River (Fig. 1B). In addition, the extent of permanent wetlands as well as geomorphological features, such as oxbows, alluvial ridges, crevasse splays and palaeochannels were mapped. To verify the accuracy of morphometric measurements made using Google Earth imagery, high-resolution WorldView2 (WV2) imagery (50 cm resolution) was used. However, because of cost restrictions, WV2 imagery was only obtained for a section of the lower Mara River. We compared the median bankfull width measurements of the modern channel from the Google Earth image (5 m resolution) with those from the WV2 image (50 cm resolution) from the same period (June 2018). A significant positive correlation exists between the median bankfull widths derived from the

Google Earth imagery and WV2 imagery ($r = 0.95$, $p < 0.05$) (Supplementary information- Fig. 1S). This indicates that the lower resolution Google Earth imagery are reliable tools for remotely sensed morphometric measurements of both the modern channel and palaeochannels on the floodplain and as such, all morphometric data reported here are derived from Google Earth imagery.

The digital elevation model (DEM) of the study site was obtained from the global DEMs Shuttle Radar Topography Mission (SRTM) V3 released in 2015 (1 arc-second resolution (~30 m resolution at equator)) (https://earthexplorer.usgs.gov). Pre-processing of the DEM involved sink filling using standard methods (Kwast and Menke, 2019). The DEM was used to generate a hillshade raster and multiple flow direction and flow accumulation model using the SAGA toolbox in QGIS 3.20.2. A hillshade raster was used to enhance visualization to define the valley margin (i.e. confinement) of the lower Mara River by defining the boundary between the floodplain and valley hillslopes. The flow accumulation model was used to delineate the stream network for the Mara catchment. Based on the stream network, the upstream area contributing to discharge at the outflow point (i.e. Lake Victoria) was used to calculate the catchment area of the Mara River. The DEM and stream network were used to generate a longitudinal profile of the lower Mara River along which the different river types were identified (*Section 3.2*). In addition, a high-resolution digital surface model (DSM) (12 m resolution with a vertical accuracy of < 4 m) of the lower Mara River was obtained from the Airbus Defense and Space GEO satellites (TerraSAR-X and TanDEM-X stereo radar satellites) and used to quantify floodplain and channel gradients. Because of cost restrictions, the high-resolution DEM only covered a section of the trunk channel with the purpose of providing greater accuracy for slope measurements which were used in the discharge modelling (*Section 3.3*).

3.2 Characterisation of river types

The lower Mara River system was characterised into different river types using Stage 1 of the River Styles Framework (Brierley and Fryirs, 2005; Fryirs and Brierley, 2018). Five river types were identified based on the position of the channel within the valley (i.e. channel position relative to the confining geology which influences valley confinement), the presence of floodplain pockets or continuous floodplain, and the channel planform characteristics (i.e. channel slope, width, sinuosity, channel continuity) (Fryirs et al., 2016; O’Brien et al., 2019).

According to Fryirs et al. (2016), valley confinement is defined as the percentage of the length of either channel margin (i.e. channel bank) that borders a valley bottom margin. A confined valley is usually bedrock-controlled and occurs if > 85% of either channel margin borders a valley bottom margin (Brierley and Fryirs, 2005). Floodplain pockets are usually rare in confined valley settings. A valley is considered partly confined, bedrock margin-controlled when 50 – 85% of either channel margin borders a valley bottom margin with the presence of discontinuous floodplain pockets, and where the bedrock valley mostly controls river meandering. Partly confined, planform-controlled valleys occur when 10 – 50% of either channel margin borders a valley bottom margin, and the river may migrate laterally with limited influence from the bedrock valley margins. Laterally unconfined valleys occur when <10% of either channel margin borders the valley bottom margin and where the floodplain is continuous along both channel margins. In this valley setting, lateral bedrock influence is absent, and channels can migrate freely within the valley margins in either continuous or discontinuous forms. Channel planform characteristics are also important for differentiating between river types. For instance, based on the presence of meandering reaches, sinuosity may be an important differentiating factor, where channels with sinuosities between 1.00 and 1.30 are characterised as low sinuosity/ straight reaches, whereas channels with sinuosities of > 1.30 and without the presence of cut-offs on the floodplain are characterised as sinuous reaches. In contrast, channels with sinuosities of > 1.30 and the presence of cut-offs are characterised as meandering reaches.

3.3 Discharge estimates for modern river and palaeochannels

As in many rivers in Africa, the lower Mara River is poorly gauged and available hydrological data are often discontinuous. Therefore, we modelled bankfull discharge and stream power using Bjerklie's equation (Supplementary information- Tables 1S and 2S), which utilises a combination of river channel hydraulic data derived from satellite imagery and statistical relationships that have been calibrated and validated on a large database of discharge measurements (Bjerklie et al., 2005; Bjerklie, 2007). Previous research comparing modelled discharge and stream power estimates using the Manning and Bjerklie's equation has shown positive correlations and the strength of the relationship highlights the similarity in the trends obtained by both methods (Larkin et al., 2017a). Remotely sensed channel hydraulic data (i.e. bankfull channel width and depth, sinuosity and meander wavelength, floodplain slope, and channel slope) were measured for the lower Mara River and used to calculate velocity, bankfull discharge and bankfull unit stream power (Supplementary information - Tables 1S and 2S). Mean bankfull channel widths were averaged over three measurements taken along each 1 km interval, focusing on meander inflection points to minimise overestimations and ensure consistency. Mean channel bankfull depth for this part of the system is 1.45 m (F. Bregoli, personal communication). Sinuosity was estimated for each kilometre by dividing the channel distance (along the channel thalweg) by the straight-line channel distance (along the valley). Mean floodplain widths were averaged over three measurements taken along each 1 km interval. The boundary of the floodplain was estimated using the hillshade raster by differentiating between distinct vegetation zonation patterns on the hillslope and floodplain. Floodplain slope was used to estimate channel slope by dividing floodplain slope by channel sinuosity for each kilometre segment (Supplementary information- Tables 1S and 2S; Bjerklie, 2007). The process of estimating palaeochannel discharge and stream power mirrored those of the modern channel.

4 Results

Downstream changes in channel and floodplain variables along the lower Mara River are qualitatively and quantitatively assessed in the following sections to provide insight into the processes and dynamics influencing the character and behaviour of the river and its floodplain wetlands.

4.1 Valley setting and river types

Along the single thread modern channel five reaches with different river types were identified based on downstream changes in valley confinement and channel planform characteristics related to the confining lithology (Fig. 2; Table 1). These river types differ in length, channel width and stream power reflecting the inherent longitudinal variations along the lower Mara River system. The five river types include: (I) the partly confined, bedrock margin-controlled upper reach with local floodplain pockets (0 – 12 km), underlain by fine-coarse detrital clastic sediments of the Bukoban Supergroup transitioning into the migmatite granitic complex of the Kavirondian-Nyanzian Supergroup; (II) the partly confined, planform-controlled meandering middle reach (12 – 34 km) with discontinuous floodplain pockets, which overlies mafic volcanic sedimentary complexes of greenstone belts and the transition to a migmatite granitic complex; (III) the laterally unconfined, continuous lower reach with continuous floodplain and numerous palaeochannels and cut-offs (34 – 90 km), dominated by alluvial sediments (i.e. sand, gravel, silt sediments) on the broad floodplain; (IV) the laterally unconfined, discontinuous lower reach in the wetland (90 – 120 km), which is characterised by channel breakdown and discontinuous floodouts that lie atop thick alluvial sediments; and (V) the partly confined planform-controlled lower reach with local floodplain pockets (120 – 135 km), which forms on a granitic complex near the margin of Lake Victoria. In the upper, partly confined reach (R-I), the valley and floodplain width are relatively narrow (<1 km wide), but increases to ~3 km in the middle, partly confined reach (R-II) where the lithology changes to sedimentary complexes of greenstone belts (Fig. 2). The floodplain width continues to widen (~8 km) as the river enters the lower unconfined continuous reach (R-III) dominated by alluvium and the floodplain wetland begins. Floodplain width reaches a maximum of ~15 km in the lower, unconfined discontinuous reach (R-IV), where the channel terminates into unchanneled flow in the wetland, before narrowing dramatically as the river enters the lower, partly confined reach (R-V) where the lithology changes back to the granitic complex and the channel reforms (Fig. 2).

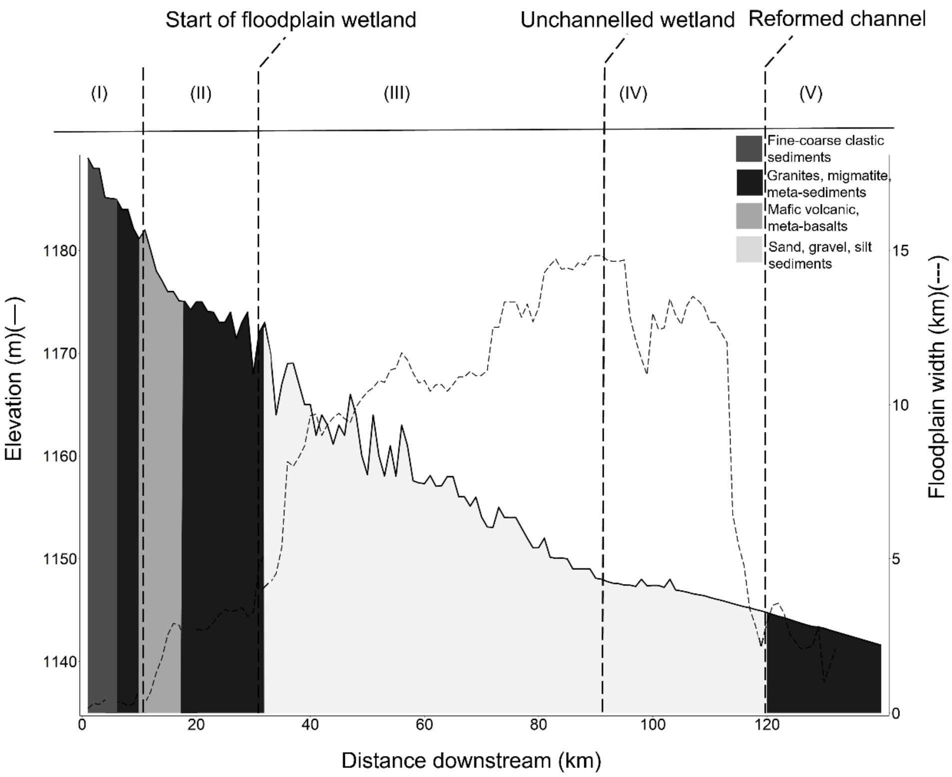


Figure 2. Longitudinal profile, confining lithology, and floodplain width (dashed line) of the lower Mara River (lithology obtained from the Geological survey of Tanzania https-//www.gmis-tanzania.com/).

Table 1. Downstream trends in the morphological characteristics of the modern channel in the lower Mara River and its floodplain wetland. Standard Error given in parentheses.

Reach	Reach descriptor	Distance downstream from Mara Mines (km)	Mean floodplain gradient ($m.m^{-1}$)	Mean floodplain width (km)	Mean Sinuosity	Mean channel width (m)	Dominant lithology/bed material
I	UPC: Upper partly confined	0 - 12 km	0.00074 (0.3)	0.4 (0.3)	1.2 (0.3)	61.5 (15.9)	Fine-coarse detrital clastic sediments (Manyovu Red Beds, Ikorongo Group, Kigonero flags, Igamba sandstone) transitioning into granites, migmatite, mafic and ultramafic, meta-sediments
II	MPC: Middle partly confined	12 - 34 km	0.00076 (0.4)	3.3 (0.9)	1.5 (0.5)	53.1 (11.4)	Mafic volcanics, meta-basalts, phyllite, volcano-sedimentary complex (greenstone belt) transitioning into granites, migmatite, mafic and ultramafic, meta-sediments
III	UNC: Lower unconfined continuous (floodplain wetland)	34 - 90 km	0.00039 (0.4)	10.9 (1.47)	1.9 (0.5)	21 (6.2)	Sandy, gravelly, silty sediments and predominantly alluvial sediments
IV	UND: Lower unconfined discontinuous (floodplain wetland)	90 - 120 km	0.00014 (0.08)	11.7 (4.67)	1.5 (0.4)	10.4 (3.3)	Sandy, gravelly, silty sediments and predominantly alluvial sediments
V	LPC: Lower partly confined	120 - 130 km	0.00015 (0.02)	2.4 (0.73)	1.0 (0.1)	128.5 (23.2)	Granites, migmatite, mafic and ultramafic, meta-sediments

4.2 Modern river downstream morphological changes

The modern channel experiences marked downstream changes in morphology. The upper, partly confined reach (R-I) is characterised by a wide (62 m), low sinuosity channel (1.2) that flows across a relatively steep gradient (0.00074 $m.m^{-1}$) and is flanked by a narrow floodplain (0.4 km) (Table 1; Figs. 3A-D; 4A-E). The river then enters the middle, partly confined reach (R-II) where the floodplain widens (3.3 km), channel sinuosity increases (1.5), and channel width decreases (53 m). Local steepening occurs at 30 km downstream owing to rock outcrops (inselbergs) in this region and sinuosity increases slightly in association with the increase in slope (Fig. 4B and E). The lower, unconfined continuous reach (R-III) is characterised by a low gradient (0.00039 $m.m^{-1}$), decline in channel width (21 m), and increase in sinuosity (1.9) as the channel becomes laterally unconfined and the floodplain broadens (11 km). The middle partly confined reach (R-II) and lower unconfined continuous reaches (R-III) are characterised by numerous local cut-offs, palaeochannels, and large crevasse splay complexes on the floodplain (Fig. 5A-D). The lower unconfined discontinuous reach (R-IV) in the wetland is characterised by an increase in floodplain width (12 km), decrease in slope (0.00014 $m.m^{-1}$) and decrease in channel sinuosity (1.5). Channel width continues to decline (<10 m) in this reach before it eventually terminates into unchanneled flow in the wetland. Downstream of the unchanneled wetland, a wide (128 m), low sinuosity (1), laterally confined channel reforms as the valley becomes partly confined once again before entering Lake Victoria (Table 1; Fig. 4A-E). Overall, a relationship exists between the width of the floodplain and channel width as well as sinuosity, where channel width declines as floodplain width increases (i.e. a negative correlation exists between floodplain width and channel width; Fig. 6A), while channel sinuosity tends to increase as floodplain width increases (i.e. a positive correlation exists between floodplain width and channel sinuosity; Fig. 6B).

Figure 3. Images of the lower Mara River study site: (A) Relatively straight section of the upper reach with vegetated channel banks and sand bars (looking downstream), (B, C, D) channel banks are slightly vegetated and comprised of sand and there is evidence of prominent sand bars along the channel as the river transitions from the upper to the middle reach (B, C looking upstream, D looking across the channel with flow direction from left to right).

4.3 Modern river discharge and stream power trends

Linked to the downstream morphological trends, the modern channel is characterised by a dramatic downstream decline in bankfull discharge and unit stream power (Fig. 4F-G). Bankfull discharge peaks (~300 $m^3.s^{-1}$) in the upper and middle partly confined reaches (R-I, II), before declining substantially (~45 $m^3.s^{-1}$) in the unconfined continuous lower reach (R-III) around 36 km downstream, as the river traverses the broad floodplain and floodplain gradient declines (Fig. 4F). Unit stream power initially peaks at ~40 $W.m^{-2}$ in the upper and middle partly confined reaches (R-I, II) before diminishing to a low of ~6 $W.m^{-2}$ around 20 km downstream (Fig. 4G). Stream power peaks again (~32 $W.m^{-2}$) at ~30 km coinciding with an increase in floodplain gradient before declining to ~1 $W.m^{-2}$ around 41 km downstream where it remains low as it enters the floodplain wetland. Based on the data from the Mara

Mine gauging station, mean discharge is 47.2 $m^3.s^{-1}$ with a recorded maximum of 921 $m^3.s^{-1}$ (McClain et al., 2014), thus we would expect that during large flood events the modelled bankfull discharge estimates will be exceeded and flow will be diverted onto the floodplain wetland.

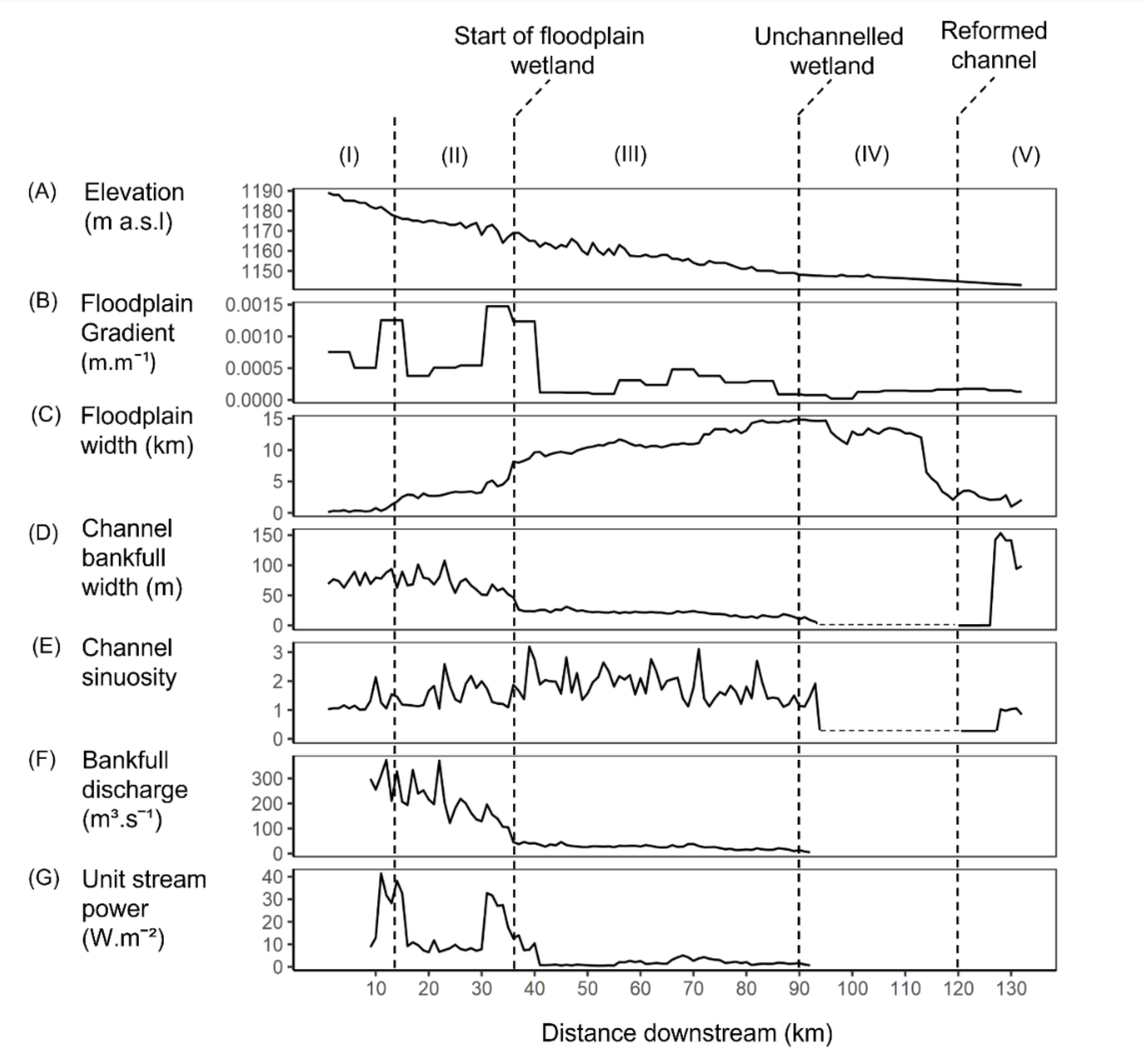


Figure 4. Downstream trends in the modern channel and floodplain characteristics; (A) longitudinal profile, (B) floodplain gradient, (C) floodplain width, (D) channel bankfull width, (E) channel sinuosity, (F) bankfull discharge, and (G) unit stream power.

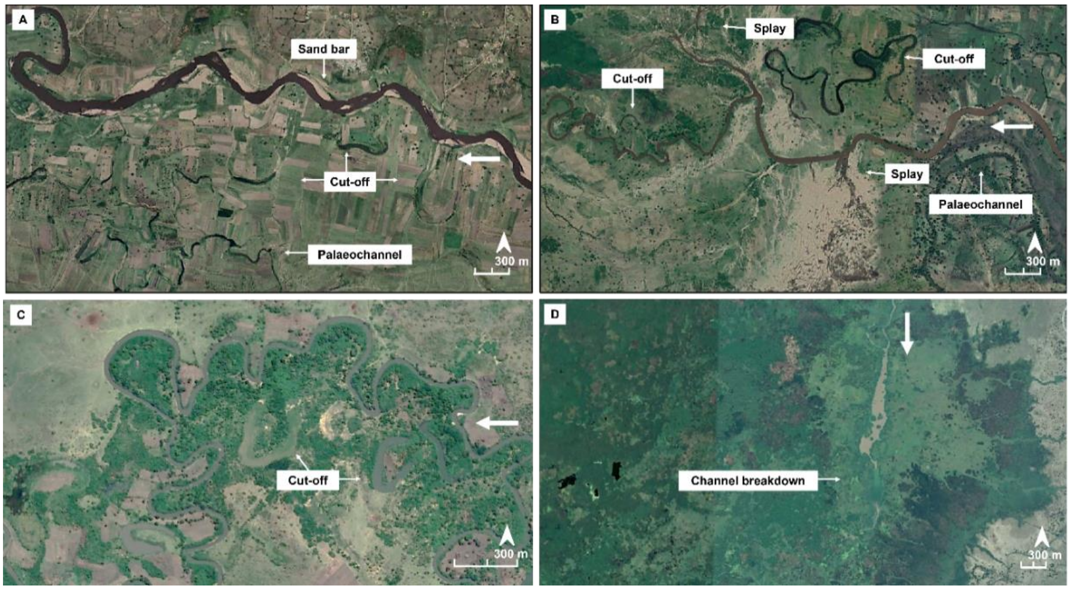


Figure 5. Geomorphological fluvial features in the different reaches of the lower Mara River. A) A meandering channel with numerous sand bars, cut-offs and palaeochannels on the floodplain in the middle, partly confined reach; B) two large crevasse splays, cut-offs and abandoned palaeochannels on the floodplain as the river transitions from the middle, partly confined to the lower, unconfined reach; C) channel capacity declines downstream of the splays, sinuosity increases and numerous cut-offs flank the channel; D) channel size declines further as it enters the floodplain wetland and ultimately breaks down into unchanneled flow. Large arrows indicate flow direction (Google Earth Image, Image © 2021 CNES/Airbus).

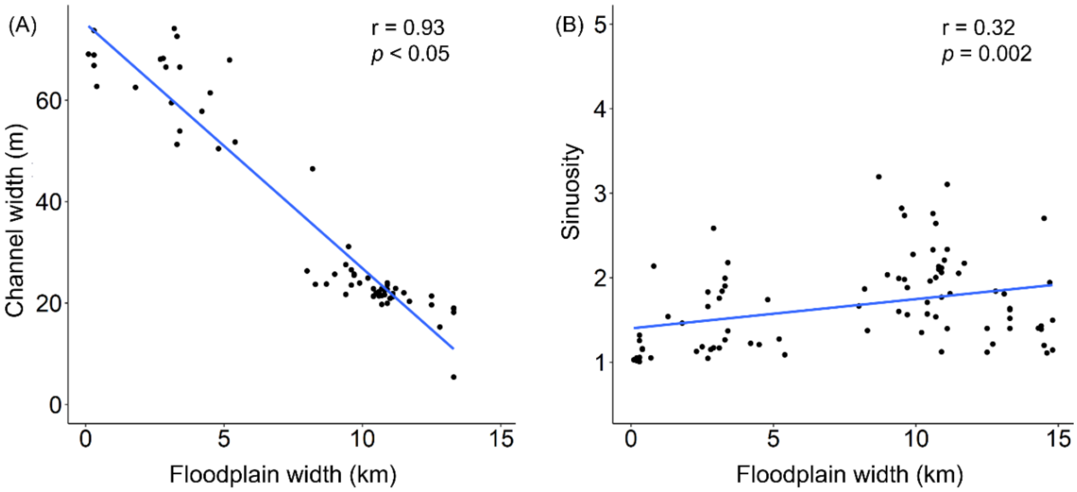


Figure 6. Correlations reflecting (A) a negative relationship between floodplain width and bankfull channel width; and (B) a positive relationship between floodplain width and sinuosity for the modern channel. The Pearson's r correlation coefficient indicates the strength of the relationship between both variables. The p-value (p) indicates the statistical significance of the relationship between the variables at 95% confidence level.

4.4 Palaeochannel morphometrics and discharge

Eleven palaeochannels were identified on the floodplain in the study area, highlighting the dynamic nature and evolution of the Mara River (Fig. 7). All palaeochannels (PC1 to PC11) exhibit a single thread, sinuous morphology with local meander cut-offs (i.e. oxbows). These palaeochannels terminate abruptly on the floodplain and only discontinuous segments are preserved. The presence of palaeochannels on the floodplain begins at 16 km downstream in the partly confined middle reach (R-II). The palaeochannels within this reach (PC1 – 4), have, on average, smaller channel widths and lower bankfull discharges compared to the modern channel at the equivalent position downstream (Table 2, Fig. 8A-B). Individual palaeochannels within the partly confined middle reach are estimated to have transported ~20 – 90% of the modern channel bankfull discharge (Table 2). Apart from PC2, the unit stream power of the palaeochannels in this reach is similar to, and in some cases exceeds, the modern channel (Table 2, Fig. 8A and C). In the unconfined continuous and discontinuous reaches (R-III and IV), PC9 – 11 have, on average, larger channel widths and higher bankfull discharges compared to the modern channel at the equivalent position downstream (Table 2; Fig. 8A-B). In contrast, PC4 – 8 experience similar downstream declines in discharge to the modern channel as they traverse the unconfined continuous alluvial floodplain (Fig. 8A-C), while PC9 – 11 were larger, higher energy systems each transporting ~4 to 6 times the total bankfull discharge of the modern channel at the equivalent position downstream (Fig. 8A-C). It is possible that individual palaeochannels were once connected forming a continuous channel, but that some segments are now buried in the wetland by either fluvial or aeolian sediments. For example, PC6 and PC8 may have been connected at some point, and PC11 likely functioned as a through-going channel that once flowed along the northern section of the wetland into Lake Victoria (Fig. 7).

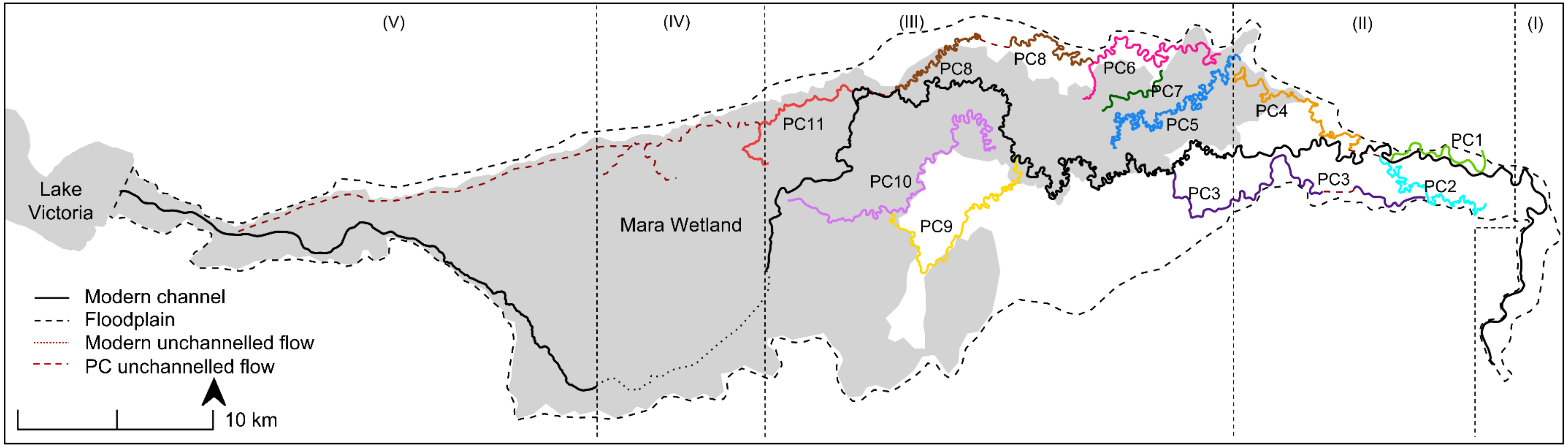


Figure 7. Location of the lower modern Mara River channel and palaeochannels (labelled PC1 – 11) on the floodplain. Channels that were possibly linked at some points are indicated (brown dashed line). Channel breakdown into unchanneled flow in the wetland is indicated (brown dotted line). The Mara wetland is represented by the grey-shaded area.

Table 2: Summary of morphological and hydraulic characteristics of the modern channel (MC) and palaeochannels (PC1 – 11) of the lower Mara River and floodplain wetlands. Standard Error given in parentheses.

Reach	Channel	Distance downstream from Mara Mines (km)	Mean channel width (m)	Mean sinuosity	Mean floodplain slope ($m.m^{-1}$)	Mean channel slope ($m.m^{-1}$)	Mean channel discharge ($m^3.s^{-1}$)	Proportion of modern channel discharge	Mean stream power ($W.m^{-2}$)	Proportion of modern channel stream power
I – V	MC	9-92	36.6	1.73	0.00048	0.00032	87.6 (10.9)	-	7.1 (1.1)	-
II	PC1	16-23	55.8	1.31	0.00052	0.00045	165 (21.8)	0.7	13.3 (4.7)	1.5
II	PC2	16-30	27.2	2.15	0.00047	0.00026	39.8 (3.2)	0.2	3.5 (0.3)	0.4
II – III	PC3	20-34	44.9	0.98	0.00072	0.0008	94 (7.8)	0.5	15.6 (2.7)	1.1
II – III	PC4	27-41	48.9	1.69	0.0011	0.00072	99.5 (16.8)	0.9	13.6 (1.7)	0.9
III	PC5	35-64	35.7	2.30	0.0004	0.00022	54 (3.4)	1.6	3.5 (0.9)	1.1
III	PC6	37-58	36.4	1.75	0.00034	0.0002	70.5 (11.6)	2.1	4.6 (1.5)	1.8
III	PC7	45-53	52.5	1.55	0.00011	0.00007	106 (9.9)	3.5	1.5 (0.1)	2.2
III	PC8	55-88	36.7	1.97	0.00024	0.00013	58.5 (3.7)	2.9	1.9 (0.19)	1.15
III	PC9	70-87	43.4	1.75	0.00029	0.00017	80.8 (4.6)	3.9	3.1 (0.2)	1.3
III	PC10	75-101	49.9	1.88	0.00021	0.00012	94 (6.7)	6.1	2.1 (0.1)	1.3
IV	PC11	89-102	30.5	1.22	0.00016	0.00013	44 (1.7)	5.0	1.9 (0.1)	2.4

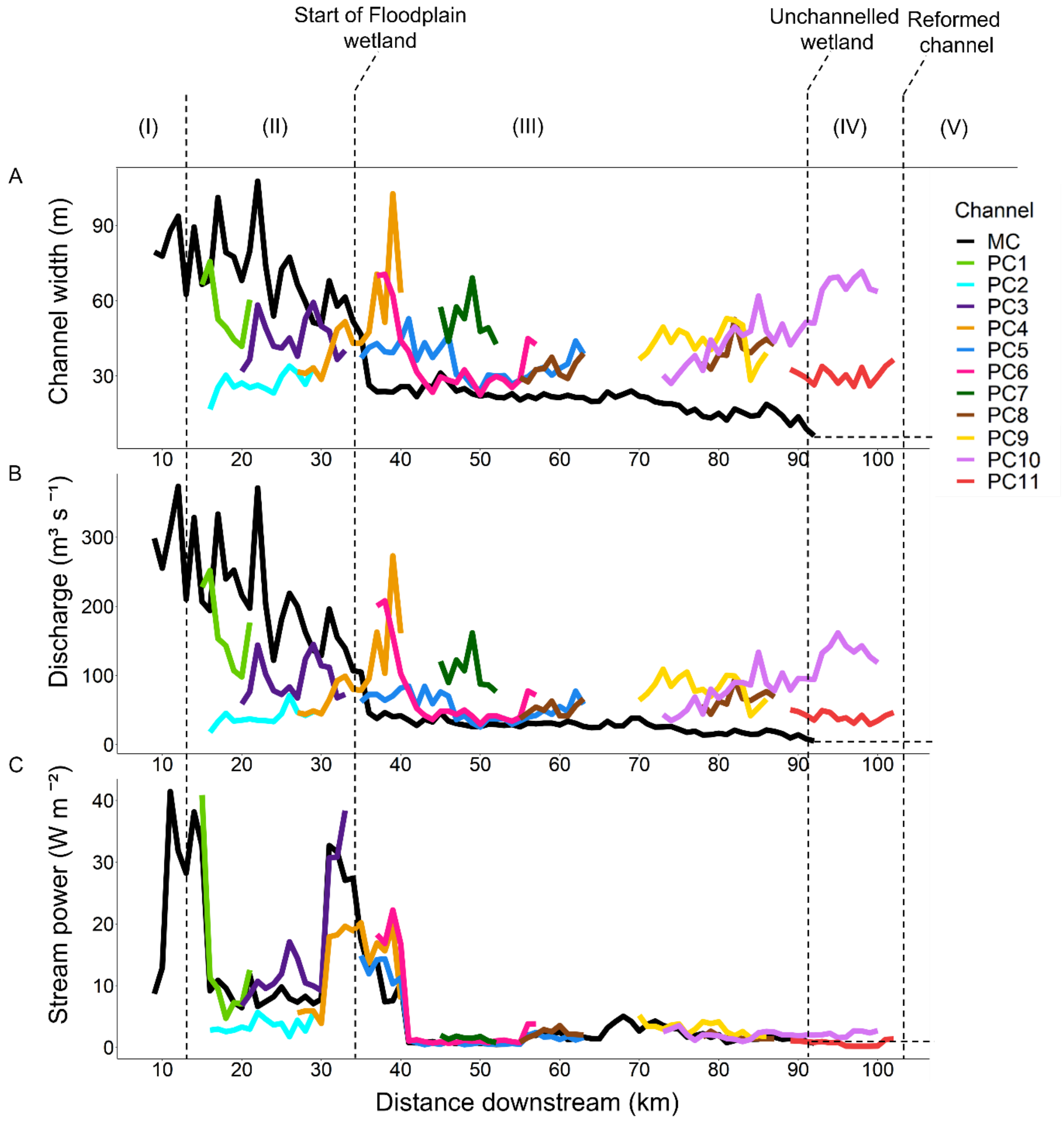


Figure 8. Comparison of downstream trends in (A) channel width, (B) bankfull discharge, and (C) unit stream power for the modern Mara River channel and the identified palaeochannels (PC1 – 11).

5 Discussion

5.1 Geomorphic controls on river response

The Mara River is a dynamic dryland alluvial system that has formed in response to intrinsic geomorphic threshold responses and feedbacks, and lithological and climatic controls. At a broad scale, catchment lithology (or imposed boundary conditions; Brierley and Fryirs, 2005) influences river character and floodplain wetland dynamics primarily through effects on valley confinement, sediment supply, floodplain width and accommodation space. Valley confinement essentially constrains the energy usage of a landscape through concentration (or dissipation) of flow energy (Brierley and Fryirs, 2005). In the lower Mara River, variations in these imposed boundary conditions influence the location of channel adjustments and floodplain wetland formation. For instance, the narrow, partly confined valley in the upper and lower reaches (R-I, V) restricts channel adjustments to within local floodplain pockets and thus lateral migration features are less common and palaeochannels are absent. Whereas in the partly confined middle (R-II) and unconfined lower reaches (R-III, IV), the channel can actively migrate as it crosses the broad alluvial floodplain. It is possible that the Utimbaru Fault extending across the northern boundary of the wetland has led to subsidence, providing vertical accommodation space for alluvial sediments. However, there is no evidence of neotectonic activity in this region and we consider loss of valley confinement to be the primary control on morphological adjustments in the lower reaches of the Mara River. Similar broad-scale lithological controls are evident in other dryland river systems (Yonge and Hesse, 2009; Ralph and Hesse, 2010; Tooth et al., 2014; Li and Bristow, 2015; Larkin et al., 2017a), where reductions in valley confinement affect floodplain width (i.e. (dis)continuous floodplains) and therefore accommodation space for unconfined alluvial reaches and floodplain wetlands.

In some dryland river systems lithology can exert a dominant control on floodplain wetland characteristics (e.g. Smith et al., 1997; Tooth et al., 2002, 2007; Grenfell et al., 2008). For example, erosion resistant dolerite outcrops form local base levels that exert a strong influence on river behaviour and floodplain wetland formation in the more erodible upstream reaches of three rivers on the South African Highveld (e.g. upper Klip River, Schoonspruit and Venterspruit; Tooth et al., 2004). Comparatively, in the Mara system, Lake Victoria forms a local base level that influences geomorphic processes of adjustment and river behaviour in the upstream reaches. The effects of lake level fluctuations on river response remain to be investigated but it is possible that during lake-level high stands, back flooding promotes low energy conditions upstream, leading to increased transmission losses, sediment deposition, avulsion, and wetland expansion. Previous studies have suggested that increased sediment deposition associated with sediment trapping by wetland vegetation and lake level fluctuations have led to avulsions and wetland expansion over time (Mati et al., 2008; Bregoli et al., 2019). Bregoli et al. (2019) reported that in the last 70 years four avulsions have resulted in the expansion of the wetland (by a factor of 3.6 combined). However, they found that while avulsions distribute water to different areas of the floodplain expanding the wetted area, other factors, such as non-quantified subsurface flows and groundwater stores likely maintain wet conditions that support the extended wetland ecosystem, especially during recent decades where river water volumes and lake levels have been relatively low (Bregoli et al., 2019). Therefore, further studies on the effects of backwater flooding and water balance (i.e. water storage capacity, groundwater contribution and lateral subsurface flows) on the wetland and river response upstream will be important to fully understand the hydrological dynamics between the river, wetland, and lake.

Other extrinsic forces, such as hydroclimate, have played an important role in driving long-term channel changes in the lower Mara River and its floodplain wetlands. Prior to the establishment of the modern channel, there is evidence that larger, higher energy, continuous palaeochannels existed on the floodplain that maintained higher flows farther into the wetland. These palaeochannels contrast to the smaller, lower energy modern channel that exhibits downstream declines in discharge and eventually breaks down in the floodplain wetland. Palaeochannels are absent in the partly confined upper reach (R-I) owing to valley confinement but are present in the partly confined middle reach (R-II) where the valley widens (Fig. 7). In the partly confined middle reach (R-II), palaeochannels are smaller, with lower discharges compared to the modern channel, suggesting a reduced capacity to transport sediments and maintain continuous, through-going channels, eventually leading to channel breakdown (Fig. 8A-C). These smaller palaeochannels may have been anabranches (i.e. recent avulsions) that subsequently terminated as they were unable to maintain fluvial efficiency owing to downstream declines in discharge and stream power. In contrast, palaeochannels in the unconfined lower reaches (R-III, IV) are larger, more sinuous, and laterally active, and have higher energy compared to the modern system at the equivalent position downstream (Fig. 8A-C), suggesting they had enhanced sediment transport capacity. The presence of numerous cut-offs (e.g. oxbows) flanking the palaeochannels indicate they were actively migrating and redistributing sediment and water leading to meander-belt floodplain aggradation. Similar processes are evident in other meandering river floodplains (e.g. Nsonge and Mfolozi rivers (M. C. Grenfell et al., 2009; S. E. Grenfell et al., 2009) and the Klip River (Tooth et al., 2002)), where meandering channels rework sediment stored on the floodplain. Nevertheless, most palaeochannels in the unconfined lower reaches (R-III, IV) exhibit similar, persistent downstream declines in discharge and stream power as the modern channel, resulting in sediment deposition, bed aggradation and avulsions. The development of levees may have primed some older, more elevated palaeochannel reaches for avulsion and abandonment, with flows being diverted into new channels on topographically lower parts of the floodplain. Palaeochannel 11 maintains a through-going channel along the northern boundary of the wetland to Lake Victoria and it is possible that during lake high-stands back flooding contributed to sediment deposition and wetland expansion, resulting in the subsequent avulsion of palaeochannel 11 to its southward position.

The behaviour of the palaeochannels suggests that loss of valley confinement in the floodplain has been an important long-term control of channel and floodplain wetland characteristics. However, in the absence of neotectonics, catchment geology in this system is invariant over geological timescales, suggesting that changes in hydroclimate likely drove the formation of larger, higher energy palaeochannels and subsequent transition to the modern channel. Dutton et al. (2019) found that ecological conditions in the Mara River catchment have remained stable over the last 2000–1000 cal. yr. BP. It is therefore likely that the transition of palaeochannels to the modern channel was related to hydroclimatic conditions prior to this period (late Holocene). However, without chronological control of the palaeochannels, it is not possible to pinpoint the timing of their development, climatic controls driving them, nor make direct comparisons with other dryland river systems. Nevertheless, it is evident that floodplain wetland development has been driven by different hydroclimatic conditions (i.e. timing, magnitude, and intensity) and the eventual breakdown of previously active channels was likely related to intrinsic threshold responses and avulsive behaviour. Developing a robust geochronology of these palaeochannels is a key knowledge gap and direction for future research.

5.2 Intrinsic geomorphic threshold responses

While catchment lithology and hydroclimate are important long-term controls on river character and floodplain wetland development in the lower Mara River, intrinsic controls related to processes such as sedimentation, erosion, and avulsion are responsible for the contemporary channel changes in the system. Intrinsic processes and associated geomorphic threshold responses drive ongoing channel adjustments that act to maximise flow efficiency (i.e. the ratio of sediment transported to the stream power expended) and determine whether equilibrium or nonequilibrium river responses (i.e. channel breakdown) prevail (Huang and Nanson, 2000; Nanson and Huang, 2008). In some sub-humid systems, rivers are characterised by wetter conditions, higher discharges and sediment throughput which helps maintain an equilibrium (i.e. continuous channel) river response (Tooth et al., 2007). Conversely, in more arid systems, rivers are associated with drier conditions, lower discharges, and reduced sediment throughput, leading to a nonequilibrium (i.e. discontinuous channel) river response (Ralph and Hesse, 2010; Grenfell et al., 2014; Tooth et al., 2014; Larkin et al., 2020a).

The semi-arid Mara River exhibits marked downstream declines in discharge and stream power, and channel breakdown, representing a nonequilibrium river response. Similar downstream fluvial trends are noted in other dryland river systems throughout southern Africa and Australia (e.g. Macquarie River (Ralph and Hesse, 2010); Nyl River (McCarthy et al., 2011); Gwydir River (Pietsch and Nanson, 2011); Blood River (Tooth et al., 2014)). The downstream declines in discharge and stream power evident in the lower Mara River are related to several factors, including (i) upstream water abstraction (i.e. agriculture, mining), (ii) transmission losses through bed infiltration (driven by the back flooding related to rising lake levels and/or increases in sinuosity and related reductions in water surface slope), and (iii) overbank flow losses as the river crosses the wide, low-gradient alluvial floodplain. Bregoli et al. (2019) reported that during high flows nearly 70% of the discharge measured at the Mara Mine gauging station flows onto the floodplain with < 30% remaining in the channel. Furthermore, low-gradient floodplains act as buffers (Fryirs et al., 2007), reducing lateral connectivity and water inflow from hillslopes and tributaries to the trunk channel. In the Mara system declines in flow increase the sediment supply to discharge (Qs:Q) ratio, such that there is insufficient energy to transport the supplied sediment, leading to in-channel sedimentation.

Recent anthropogenic impacts (i.e. land-use changes since the 1960s) in the Mara catchment have further accelerated upstream sediment supply increasing the Qs:Q ratio in the floodplain wetland (Mati et al., 2008; Dutton et al., 2019). Jerolmack and Mohrig, (2007) show that increases in Qs:Q result in channels filling more rapidly than sediment can be incorporated into lateral accretion deposits, thus increasing the propensity for avulsion, the relocation of a channel to a new position on the floodplain. This is the case in the Mara, where rapid in-channel sedimentation decreases the reach-scale gradient while increasing its elevation above the surrounding floodplain, resulting in overbank flooding, levee breaching, and sometimes crevasse splay development. The location and frequency of these levee breaches may be influenced by downstream channel morphology and/or anthropogenic activities. For instance, the highly sinuous channel in the lower unconfined reach (R-III) may reduce the water surface slope and thus act as a constriction point for sediment upstream, promoting bed aggradation, overbank flow and breaching in reaches directly upstream.

Moreover, human activities (i.e. agricultural fields, livestock paths) resulting in local bank erosion and destabilisation further promotes levee breaching and risk of avulsion (Mati et al., 2008; Bregoli et al., 2019).

These crevasse splays represent the start of progradational avulsions where a single channel eventually develops through the splay deposits and extends downstream forming a new distributary channel. Progradational avulsions have an important local effect, contributing a substantial volume of sediment and water to the floodplain, and are an important mechanism driving sediment reworking through erosion and deposition processes in the lower Mara River. Interestingly, progradational avulsions tend to be associated with moderately to rapidly aggrading systems, particularly in humid regions such as the Rhine-Meuse Delta and the Upper Columbia River (Stouthamer and Berendsen, 2001; Makaske et al., 2002), and are less common in semi-arid systems. In some dryland river systems, crevasse splays are evident, but their development differs slightly to that of the Mara River (e.g. Tooth, 2005; Li and Bristow, 2015), while in other systems (e.g. Klip river (Tooth et al., 2007, 2009); Tshwane River (Larkin et al. 2017a)) crevasse splays are absent, and processes of incisional avulsions are dominant. Downstream of these avulsive channels, channel capacity and size are reduced, and sinuosity remains high. The channel is flanked by numerous oxbow lakes, indicating that lateral migration and meander cutoff are active processes of channel change in this part of the floodplain. The channel straightens to maintain a continuous channel as it enters the densely vegetated wetland but declines in size as flow leaks through the papyrus (*Cyperus papyrus*) lined banks before ultimately breaking down into unchanneled flow.

It is evident that intrinsic processes in combination with extrinsic controls are driving changes in river character, behaviour, and floodplain wetland development in the lower Mara River system. Lithological and hydroclimatic forces form the long-term controls in the system driving the transition of palaeochannels to the modern system, whereas intrinsic threshold responses (i.e. progradational avulsions) are key process by which meandering channels rework floodplain alluvium and contribute to floodplain aggradation. The results highlight a positive feedback relationship between declines in discharge, stream power, sediment transport capacity, and channel size, and ultimately breakdown, which relates to avulsive behaviour and nonequilibrium fluvial conditions in the floodplain wetland.

5.3 Future trajectories of channel response

The Mara River catchment has recently experienced a period of rapid change in the basin related to anthropogenic activities (i.e. deforestation, conversion of land to agriculture) that have substantially altered the hydrological connectivity, erosion, and sediment inputs into the fluvial network (Mati et al., 2008; Ogutu et al., 2009; Mwangi et al., 2017; Bregoli et al., 2019; Dutton et al., 2019). Upstream changes have led to rapid aggradation in the floodplain wetland over a relatively short period, leading to channel hotspots of overbank flooding with a greater propensity for avulsions. These impacts are expected to intensify as human populations and development continue to increase in East Africa (Zermoglio et al., 2019; Mngube et al., 2020). For instance, there are several hydropower projects planned for the Mara catchment that would considerably alter the hydrological and ecological processes of the river and floodplain wetlands further downstream. In addition, climate projections indicate that East Africa will experience future increases in temperature and greater inter-annual variability in precipitation (Niang et al., 2014; Pekel et al., 2016). Therefore, under future predictions of more intense land use and increasing climatic variability in East Africa (Shongwe et al., 2009; Niang et al., 2014; Bartzke et al., 2018), the Mara River is expected to undergo significant geomorphic changes. While river responses to climatic changes are difficult to predict because of complex internal threshold responses, it is possible that under increasingly drier climates and/or more variable rainfall, and more intense land-use changes, the Qs:Q ratio will likely increase, leading to a greater propensity for avulsion in the lower Mara River and wetland. This will have significant implications for changes to water distribution, sediment storage, ecological response, and ecosystem services in this region, with possible social implications. Indeed, avulsions may lead to rapid ecological succession in wetlands with less aquatic biodiversity and ecological resilience (i.e. maintenance of ecosystem character, processes, and services over time) (Ralph et al., 2011). Therefore, a more in-depth understanding of channel and floodplain responses (i.e. avulsive behaviour) to future climatic and anthropogenic changes in East Africa is important, particularly for developing adaptive management strategies for this dynamic system.

6 Conclusions

The Mara River is a dynamic dryland river and its modern channel and palaeochannels are characterised by substantial downstream hydrological and morphological changes. An analysis of the downstream trends provides insight into the geomorphic controls driving river behaviour and floodplain wetland development. The findings demonstrate that intrinsic processes and related geomorphic threshold responses drive ongoing channel adjustment, however the suite of processes and the rate at which they occur, are controlled by broad-scale extrinsic forces acting on the catchment, that is, valley setting and hydroclimate. In the lower Mara River, lithological and hydrological forces are important long-term controls driving the transition from the palaeochannels to the modern channel. However, contemporary channel changes, such as channel breakdown and floodplain wetland formation are driven by intrinsic threshold responses to downstream declines in discharge, stream power, and sediment transport capacity, which is related to avulsive behaviour and nonequilibrium fluvial responses in the floodplain wetland. Given the documented changes in river character and behaviour from the palaeochannels to the modern system, it is likely that the propensity for avulsion will increase and become the key mechanism for water and sediment distribution on the floodplain wetland under projected intensified land-use changes and more variable or extreme climate conditions.

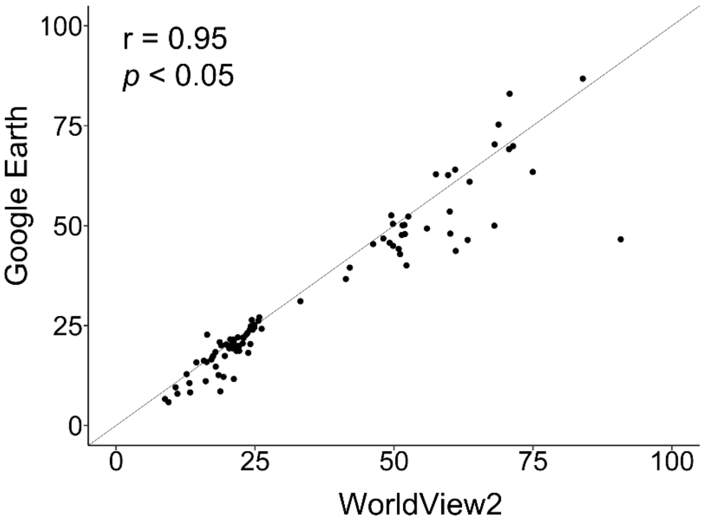
Supplementary Material

Supplementary Table 1S: Channel parameters and descriptors used in Bjerklie's equation for discharge modelling (Bjerklie, 2007)

Channel parameter	Descriptor
Average meander wavelength	*WL*
Sinuosity	*P*
Meander bend length	$L = WL*P$
Bankfull channel width	W_{bf}
Floodplain slope	S_f
Channel slope	$S_c = S_f/P$
Bankfull channel depth	D_{bf} (Eq. 1)
Length fraction	*m* (Eq. 2)
Velocity	V_{bf} (Eq. 3)
Bankfull discharge	Q_{bf} (Eq. 4)
Unit stream power	ω (Eq. 5)

Supplementary Table 2S: Formulas used in the Bjerklie's equation (Bjerklie, 2007) to estimate discharge and stream power. The channel parameters in Table 1S are used in the following equations

Equation	Formula
Equation 1	$D_{bf} = 0.08 \frac{W_{bf}^{0.39}}{S_c^{0.24}}$
Equation 2	$m = 9.67(S_c L)^{0.36}$
Equation 3	$V_{bf} = \sqrt{\frac{2 * 9.81 S_c L}{m}}$
Equation 4	$Q_{bf} = V D_{bf} W_{bf}$
Equation 5	$\omega = \frac{1}{W_{bf}} * 9800 * Q_{bf} S_c$



Supplementary Figure 1S: Significant positive correlation between the median bankfull channel at sites 1 km apart along the Mara River width taken from the Google Earth and WorldView2 imagery for the same period (June 2018). Line represents 1:1 ratio.

CHAPTER 3

Contemporary channel adjustment and geomorphic sensitivity of the lower Mara River and its floodplain wetlands, Tanzania

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See Table 1.2 in Chapter 1 for author contributions.

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Abstract

An understanding of river adjustment processes, previous landform changes, and sensitivity to flow regimes are prerequisites for predicting how rivers may respond to future climate change and anthropogenic disturbance. Geomorphic river sensitivity is an important concept that can be used to assess the capacity of adjustment for a river type and forecast river responses to hydroclimatic change over time. In this study, we use satellite imagery to characterise and quantify recent geomorphic river adjustment in a dryland river in East Africa, over the past 32 years (1988 – 2020). The natural or expected river behaviour (i.e. behavioural regime) and capacity for adjustment (i.e. valley confinement) are quantified to provide a measure of the reach-scale geomorphic sensitivity of the lower Mara River, Tanzania. Two behavioural river sensitivity classes are identified. The upper reach is classified as Passive sensitive, exhibiting a limited range of bend adjustments and low migration rates (0.89 m a^{-1}) owing to valley confinement and capacity to recover from disturbance events. The middle reach is classified as Fragile and shows the greatest capacity to adjust in response to intrinsic fluxes. This reach is characterised by numerous lateral migration features and cut-offs (0.2/km) on the floodplain and exhibits the highest migration rates (1.39 m a^{-1}). The lower reach is also categorised as Passive sensitive and undergoes bend and boundary adjustments within its behavioural regime and exhibits the lowest migration rates (0.63 m a^{-1}). However, this reach appears to be operating close to a threshold state and if subjected to a threshold-breaching disturbance event it may ‘switch’ to a Fragile system where avulsions are dominant. The Mara River shows that geomorphic sensitivity is an important consideration in assessing system response to short-term variability and forecasting future river behaviour and will be key in guiding the management and rehabilitation efforts of other dryland wetlands under different land use and climate change scenarios.

Keywords: semiarid Mara River, geomorphic processes, river behaviour, capacity for adjustment, behavioural sensitivity

1 Introduction

Dryland rivers in the world's dry subhumid to hyperarid regions provide critical resources to both human and wildlife populations and therefore have a high management priority (Millennium Ecosystem Assessment, 2005). These geomorphologically diverse river systems exist in marginal, water-stressed environments and are vulnerable to declining water availability driven by increasing climate variability, river regulation and land use change (Pekel et al., 2016; Best, 2019). These natural and human-induced impacts can considerably influence contemporary river forms and processes, with severe repercussions for ecosystem functioning (Wohl et al., 2019). There is a growing need to understand geomorphic processes and the capacity for river change in dryland systems, especially in East Africa where population growth, urbanisation, and land use changes are key pressures on water resources (i.e. rivers) (Zermoglio et al., 2019). Knowledge of the 'expected or natural' range of variability of these systems is important to understand as they respond in the absence of anthropogenic impacts and can be used to characterise past river behaviour which is necessary for forecasting future behaviour and informing management policies (Wohl, 2011; Reid and Brierley, 2015). These insights are imperative given the future projections of increasing aridity and declining freshwater availability in many drylands globally (Milly et al., 2005; Pekel et al., 2016; Rodell et al., 2018; Larkin et al., 2020).

Defining the natural range of variability of geomorphic processes in dryland river systems can be challenging as different river types adjust in different ways and rates, and in response to variability in flow and sediment regimes, and different forms of disturbance. One key concept that can be used to assess this variability is river sensitivity (Brunsden and Thornes, 1979; Allison and Thomas, 1993), which describes the ease with which fluvial landforms respond (i.e. adjust) to environmental disturbances (e.g. climate change, agriculture, mining, and modification to water/sediment regimes), where more sensitive landforms respond readily and are subject to high rates of adjustment, and less sensitive or resilient landforms have an inability to respond and instead minimise the extent of adjustment by absorbing excess energy (Lisenby and Fryirs, 2016; Fryirs, 2017; Tooth, 2018; Fuller et al., 2019). The spatiotemporal variability of river sensitivity exerts an important control on the ability of a river to respond, serving as a useful tool to assess past, present, and future river behaviour (Brunsden, 2001; Fitzpatrick and Knox, 2000, Reid and Brierley, 2015; Lisenby et al., 2017). To assess geomorphic sensitivity of rivers to adjust within its natural range of variability, a clear distinction needs to be made between river behaviour which refers to the form and rate of adjustment that is ‘expected’ for a given type of river (its behavioural regime) and river change which refers to a shift to new river type with a different behavioural regime (Brierley and Fryirs, 2005). Importantly, adjustment to channel form resulting from a rebalancing of intrinsic processes (i.e. discharge and sediment regimes) does not always induce river change, but rather a shift in the capacity for adjustment within the behavioural regime of the river (Brierley and Fryirs, 2005). Moreover, several factors can influence river sensitivity, including the proximity to a threshold state under which change occurs (Schumm, 1979), antecedent controls on contemporary forms and processes (Phillips, 2006), and ability to recover post-disturbance (Chappell, 1983). Although the importance of river sensitivity is well recognised and explored in various studies (Downs and Gregory, 1995; Brunsden and Thornes, 1979; Schumm, 1979; Fitzpatrick and Knox, 2000; Fryirs, 2017; Thoms et al., 2018; Tooth, 2018), a systematic and consistent approach to assess and measure geomorphic river sensitivity has not yet been adopted. Several studies (e.g. Lisenby and Fryirs, 2016; Joyce et al., 2020; Khan and Fryirs, 2020) have conducted historical quantitative analysis of channel adjustments and river sensitivity, however, these studies have focused exclusively on temperate and subtropical catchments impacted by anthropogenic activities. However, there have been no such studies conducted on dryland fluvial systems with relatively low anthropogenic impacts. As a contribution to existing studies of river sensitivity and to assess the applicability of these methods in different climatic settings, we apply a combination of methodological approaches to explore geomorphic adjustment and river sensitivity in a semiarid region. Addressing this need is expected to improve quantitative understanding of river response to natural and/or anthropogenic disturbances in dryland fluvial systems as well as guide management efforts by identifying river reaches that are sensitive to change.

In this paper, we quantify contemporary channel adjustments to assess the spatiotemporal distribution of river sensitivity and highlight potential geomorphic drivers of change over a 32-year period for the lower Mara River in semiarid northern Tanzania (Fig. 1A). The lower Mara River is highly dynamic, as evidenced by the numerous palaeochannels and abandoned channel segments on its lowland alluvial plain (Gomes et al., 2023a), and historic maps and analysis reported by Bregoli et al. (2019). Previous studies have shown that the modern channel and palaeochannels of the lower Mara River represent a nonequilibrium river response to downstream declines in discharge and stream power and related avulsive behaviour before breaking down and contributing to the formation of floodplain wetlands (Gomes et al., 2023a), which is similar to several other alluvial dryland rivers (Tooth and McCarthy, 2004; Ralph and Hesse, 2010; Tooth et al., 2014). We identify mechanisms driving variability in channel responses over time, which is important for predicting where, and under what conditions, adjustments are likely to occur in the future. Overall, we assess the key geomorphic variables that influence contemporary geomorphic adjustments and differentiate river types based on their sensitivity to adjust. Specifically, we: (i) characterise the fluvial system and identify different river types; (ii) quantify patterns of two-dimensional (2D) lateral planform adjustments and geomorphic variables over the past 32 years; and (iii) extract key geomorphic variables influencing channel planform adjustments.

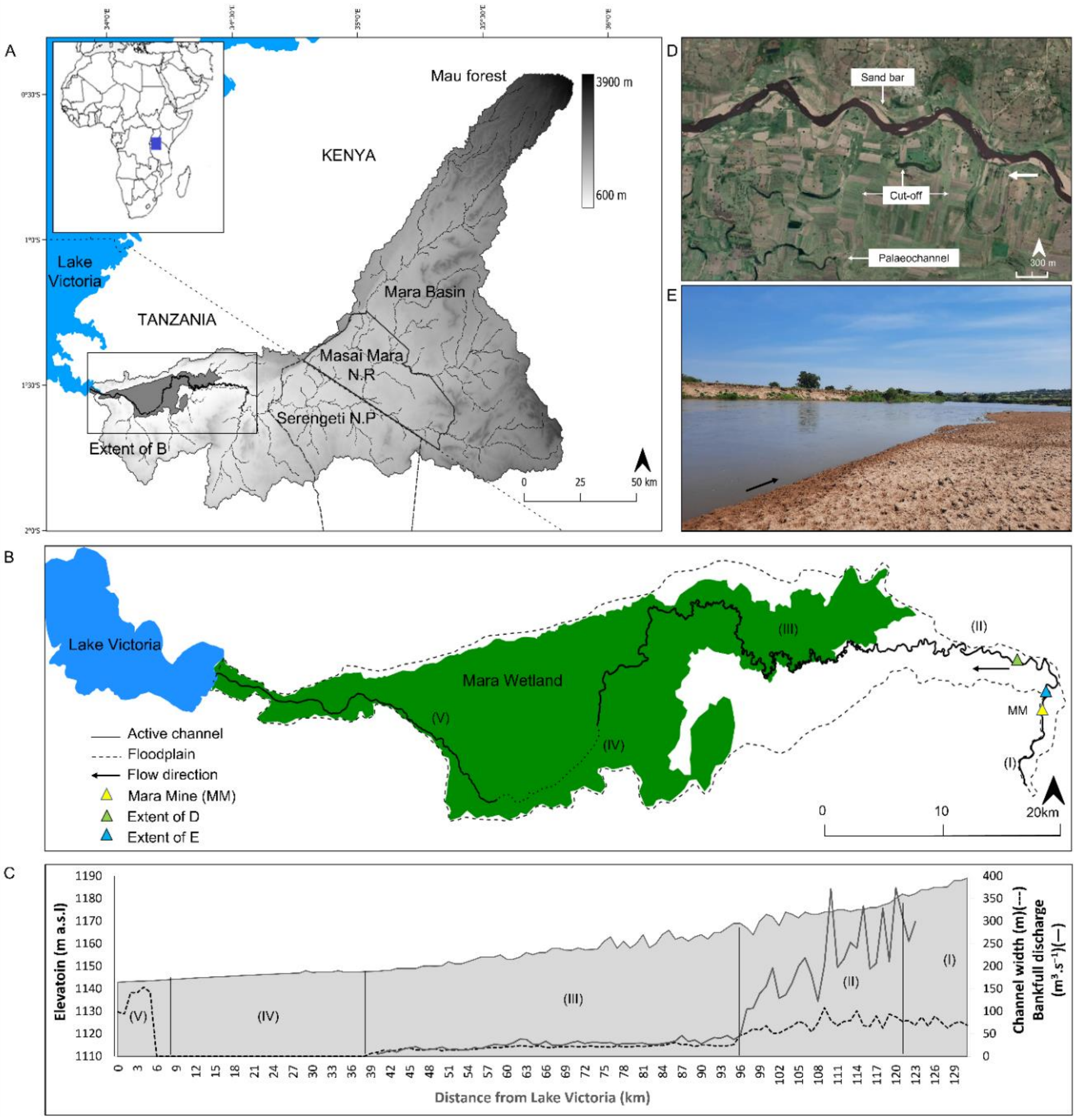


Figure 1. (A) The transboundary Mara River catchment flows through the Mara-Serengeti ecosystem before entering the Mara Wetland (shaded green) and debouching into Lake Victoria (shaded blue). (B) The principal study site is the lower section of the Mara River (MR) (starting point at Mara Mines gauging station (MM)) and its floodplain wetland in northern Tanzania. The five river reaches shown include: (I) upper, partly confined reach, (II) middle, partly confined reach, (III) lower, unconfined continuous reach, (IV) lower unconfined discontinuous reach (dotted line), and (V) lower, partly confined reach. The location of images shown in panes D and E are indicated. (C) The downstream trends in channel width and modelled bankfull discharge, and the longitudinal profile (shaded grey) of the lower Mara River. (D) Satellite images showing the dynamic nature of the middle reach indicating lateral migration and avulsion features and depositional features (Google Earth Image, Image © 2021 CNES/Airbus). (E) Photograph showing the slightly vegetated channel banks and prominent sand bars along the channel as the river transitions from the upper to the middle reach (arrow indicates flow direction).

2 Regional Setting

2.1. Study site

The Mara River is a large transboundary river catchment shared between Kenya and Tanzania covering an area of 13 750 km2 (Fig. 1A) (Mati et al., 2008; Bregoli et al., 2019). The Mara catchment is largely dominated by agricultural lands and rangelands and supports a population of ~1.2 million people (Zermoglio et al., 2019). In addition, the Mara River provides the only perennial water source for two conservation areas of international significance, including the Maasai Mara National Reserve in Kenya and the Serengeti National Park in Tanzania, which supports the annual migration of 2 million herbivores (Mati et al., 2008). The Mara River is perennial, but strongly seasonal, flowing 395 km from its headwaters in the highlands of Kenya (3000 m a.s.l.) through the Serengeti-Mara ecosystem where it is joined by the Tobora B, Somoche and Tigithe tributaries before entering the Mara Wetland in its lower reaches and finally debouching into Lake Victoria (1120 m a.s.l.) (Kassenga, 1997; Mati et al., 2008). Water resource development in the catchment (i.e. hydropower dams) is relatively limited, however, research suggests that illegal abstraction and water use by large-scale commercial farms has significantly reduced dry season low flows in the past decade (LVBC and WWF-ESARPO, 2010; Kihwele et al., 2021). The upper catchment has undergone major land use and land cover changes (i.e. agriculture, deforestation) in the recent past (Olang and Kundu, 2011), resulting in increased runoff and erosion, and increased suspended sediments and nutrients (McClain et al., 2014; Mwangi et al., 2016, 2017; Bregoli et al., 2019; Dutton et al., 2019).

The Mara wetland is ~45 km long and up to ~14 km wide and comprises permanently and seasonally inundated swamp areas. The wetland area ranges from 390 km2 to 500 km2 depending on the seasonal flood (Mati et al., 2008). The permanent swamp is dominated by dense papyrus (Cyperus papyrus) vegetation, whereas marshes and herbaceous vegetation dominate the seasonal swamp (Bregoli et al., 2019). The wetland provides an important hydrological function, regulating the quality and flow of water entering Lake Victoria and serves as a groundwater recharge zone (Omolo et al., 2018). In addition, it provides essential ecosystem services, such as water and food resources that sustain the livelihoods of the surrounding communities. The underlying geology of the lower Mara River and its floodplain wetland is dominated by the granitoid and greenstone belts of the Archean-age Lake Victoria Terrane (Kabete et al., 2012). The wetland comprises of predominantly alluvial sediments (i.e. sand, gravel, silt) and has formed in an asymmetric half-graben basin related to the Utimbaru Fault which extends along the northern boundary of the wetland as a steep escarpment. The southern boundary of the wetland is gently sloping and punctuated by granite inselbergs.

The principal study site is located in the lower section of the Mara River extending from the Mara Mine gauging station through the Mara Wetland to the outlet at Lake Victoria (total length 130 km) (Fig. 1B). In these lower reaches the Mara River is initially partly confined and characterised by a wide, relatively straight channel (R-I). However, as the valley becomes less confined and a broad floodplain develops, the channel actively adjusts and levees, cut-offs and palaeochannels become prominent features (R-II). Farther downstream (R-III) the channel undergoes marked downstream declines in discharge and stream power due to transmission losses through bed materials and overbank flooding, resulting in downstream in-channel sedimentation which primes the reach for avulsion. The channel declines in size and straightens to maintain flow but eventually break downs in the floodplain wetland (R-IV). At the downstream end of the floodplain wetland (R-V), the river channel reforms as flow converges where the valley becomes partly confined once again at the confluence of Lake Victoria.

2.2. Modern hydroclimate

The climate of East Africa is influenced by large-scale controls such as topography, lakes, and coastal regions. In addition, the seasonal dynamics of tropical circulation (Liu et al., 2017), such as the annual migration of the Intertropical Convergence Zone and the Congo Air Boundary results in a bimodal rainfall pattern across East Africa (Nicholson, 2017; Beverly et al., 2020). The Mara River catchment exhibits two distinct rainfall seasons that are characterised by the long rains (March–May) and short rains (October–December) (Alemayehu et al., 2017). Rainfall varies spatially over the catchment due to topographic effects and the regional influence of Lake Victoria (Camberlin et al., 2009), with the headwaters receiving the highest mean annual precipitation (1000 - 1750 mm a^{-1}) and the outlet at Lake Victoria receiving the lowest (300 - 600 mm a^{-1}) (McClain et al., 2014; Dutton et al., 2018). There is high intra- and inter-annual variability in these rains due to the Indian Ocean Sea Surface Temperature anomalies which are related to the Indian Ocean Dipole (IOD) and El Niño-Southern Oscillation (ENSO; Liu et al., 2017). Higher rainfall during the wet season is associated with a positive IOD phase and ENSO which weaken the westerly winds and allows more moisture influx from the Indian Ocean (Pennycuick and Norton-Griffiths, 1976; Saji et al., 1999). Whereas higher rainfall during the dry season is associated with the occurrence of La Niña events and negative IOD phases which enhance westerly winds from Lake Victoria and blocks moisture influx from the Indian Ocean.

The lower Mara River is poorly gauged and available hydrological data is limited and discontinuous over time. River discharge in the Mara river catchment reflects the dominantly bimodal rainfall regime (McClain et al., 2014; Dutton et al., 2018). The mean annual discharge in the lower Mara River near the Mara Mine is approximately 47.2 m3.s^{-1} while peak discharge has reached 921 m3.s^{-1} in historical records (McClain et al., 2014; Dutton et al., 2018). Modelled estimates of bankfull discharge and stream power for the lower reaches of the Mara range from (85 m3.s^{-1} to 321 m3.s^{-1}) and (0.5 W m^{-1} to 38 W m^{-1}), respectively, and decline downstream where the river channel breaks down in the floodplain wetland (Fig. 1C) (Gomes et al., 2023a). Flow passing through the wetland enters Lake Victoria, which forms part of the greater Nile River catchment that covers much of northern Africa.

3 Methods

To assess the contemporary geomorphic adjustments and behavioural sensitivity of the lower Mara River for the first time, the combined methodology of Khan and Fryirs, (2020) and Joyce et al. (2020) was employed (Fig. 2).

3.1 River characterisation, morphometrics and geomorphic adjustments

To assess 2D channel planform adjustments and geomorphic variables of the lower Mara River three key steps were followed. The first step involved identifying and characterising different river types along the longitudinal profile using Stage 1 of the River Styles Framework (Brierley and Fryirs, 2005) to map planform adjustments and extract geomorphic variables. For this step the hillshade raster and satellite imagery were used to differentiate river types based on valley confinement (position of the channel within the valley setting), the presence of floodplain pockets (continuous or discontinuous), and channel planform characteristics (channel slope, width, sinuosity, continuity) (Gomes et al., 2023a). Valley confinement is defined as the percentage of the length of either channel margin (i.e. channel bank) that borders a valley bottom margin and was categorised into different classes, (i) confined (>85%), (ii) partly confined bedrock margin-controlled (50–85%), (iii) partly confined planform-controlled (10–50%), and (iv) laterally unconfined (<10%) (sensu Fryirs et al., 2016; O'Brien et al., 2019).

The second step involved extracting catchment geomorphic variables and mapping contemporary river planform adjustments and was achieved in two parts. The first part involved extracting geomorphic variables at 1 km intervals along the lower Mara River from satellite images (Gomes et al., 2023a). Geomorphic variables included channel morphology (single thread or compound, number of channels), morphometric indices (channel width, depth, sinuosity, meander wavelength, floodplain gradient, floodplain width), and hydraulic data (bankfull discharge, unit stream power). For the morphometric variables, three measurements were taken along the 1 km stretch and then averaged. A fixed spacing interval approach (1 km) was employed as it has been shown to adequately detail the downstream changes in channel morphology (Fryirs et al., 2009; Lisenby and Fryirs, 2016). Mean bankfull channel widths were taken on meander inflection points to minimise overestimations and ensure consistency. Mean channel bankfull depth for this part of the system is 1.45 m (F. Bregoli, personal communication). Sinuosity was estimated by dividing the channel distance (along the channel thalweg) by the straight-line channel distance (along the valley). Mean floodplain widths were estimated by differentiating between hillslope and floodplain vegetation. Floodplain gradients were measured using a high-resolution digital surface model (DSM (12 m resolution with a vertical accuracy of <4 m) obtained from the Airbus Defense and Space GEO satellites (TerraSAR-X and TanDEM-X stereo radar satellites)). Due to cost restrictions, the high-resolution DEM only covered the trunk channel with the purpose of providing greater accuracy for slope measurements which were used in the discharge modelling. Floodplain slope was used to estimate channel slope by dividing floodplain slope by channel sinuosity. These morphometric indices were then used in Bjerklie's model, which utilises a combination of river channel hydraulic data and statistical relationships that have been calibrated and validated on a large database of discharge measurements (Bjerklie et al., 2005; Bjerklie, 2007), to estimate bankfull discharge and stream power (Supplementary information - Tables 1S and 2S).

The second part involved mapping lateral 2D planform adjustments for each river type over the 32-year period and included any morphological modification of the trunk channel excluding river change (i.e. shift in the behavioural regime of a reach that produces a different river type). Vertical adjustments were not quantified and thus it is possible that reaches categorised as stable may be undergoing vertical changes. Planform adjustments were only quantified for reaches (I, II, III) where a continuous channel is present. The channel breaks down into unchanneled flow in the wetland (R-IV) and subsequently forms a series of lakes in the lower partly confined reach (R-V) before entering Lake Victoria. Therefore, quantification of planform adjustments in these reaches was not possible. The form, frequency, extent, and location of different forms of channel adjustment were quantified for each river type (Fig. 2; Supplementary information- Table 3S) over decadal (1988 – 1999, 1999 – 2010, 2010 – 2020), intermediate (2010 – 2014, 2014 – 2018), and full (1988 – 2020) periods. The remotely sensed data used for identifying channel change are limited by the temporal availability and therefore 2D channel activity was mapped over 'periods' (e.g. 1988 – 1999). Channel planform adjustments rarely represent a linear or continuous change between any two periods and can exhibit complexity, for instance, adjustments can be instantaneous, lagged, cumulative and progressive over different temporal scales (Chappell, 1983). Moreover, we found that measuring channel planform adjustments at a higher temporal resolution (~2 years) resulted in very little difference when compared to measuring changes over longer periods. Therefore, we assess channel changes over decadal and intermediate periods to understand the long-term trends of periods of persistent adjustment and relative stability. Forms of channel adjustments were recorded based on the descriptions presented in (Supplementary information- Table 4S) and were organised into two broad categories, namely erosional and depositional adjustments (according to Fryirs et al., 2009; Lisenby and Fryirs, 2016). Depositional forms of adjustment were only recorded for the two intermediate time periods where satellite image resolution permitted visualisation, for instance it was not possible to identify very small sand bars during earlier time periods. Whereas erosional forms of adjustments were recorded over all the time periods. Erosional adjustments were further divided into the two sub-categories, including boundary and bend adjustments, where boundary adjustments refer a complete change in channel planform whereas bend adjustments refer to more localised change.

The third step combined parts 1 and 2 (from step 2) to develop an understanding of the key geomorphic variables influencing the types of planform adjustment and stability (according to Joyce et al., 2020). To link geomorphic variables to adjustment and stable reaches, the geomorphic variables that occurred over the reach length affected by adjustments were averaged. For example, if an adjustment occurred over a 1 km reach, it was assigned the mean geomorphic variables for the length of that reach and the same was done for reaches that remained stable. A one-way ANOVA and Tukey (HSD) post-hoc test were performed to determine whether differences in key geomorphic variables significantly influenced the location, extent, and form of channel adjustment. Comparisons of the mean values and variance were used to identify statistical significant differences at a 95% confidence interval and all the analysis were performed in the open-source statistical software programme R.

3.2 Remote sensing data acquisition and pre-processing

Field campaigns were not possible during this study and therefore remotely sensed data formed the primary method of data collection. Publicly available spatial datasets are useful as they provide information over large areas that are often inaccessible and are relatively cost effective. The spatial datasets included satellite imagery for the period 1988 to 2010 (obtained from the United States Geological Survey (https://earthexplorer.usgs.gov)), Google Earth Pro imagery for the period 2010 to 2020, and a digital elevation model (DEM; 1 arc-second resolution (~30 m resolution at equator) obtained from the global DEMs Shuttle

Radar Topography Mission (SRTM) V3 released in 2015 (https://earthexplorer.usgs.gov)) (Fig. 2). The satellite image collection included product type level-1 multispectral images of Landsat 4–5, 7 and 8 (30 m resolution). Pre-processing of the multispectral images involved pan-sharpening, which is a technique that involves merging the greyscale band 8 (15 m resolution) with the colour bands (30 m resolution) to improve the spatial resolution of images. This process can only be applied to Landsat 7 and 8 images (which have band 8) and improves their visualisation by increasing the spatial resolution to 15 m resolution while preserving specific spectral attributes of the images. Google Earth Pro imagery was used from 2010 onwards as it provides high-resolution data and required no pre-processing. These spatial datasets were used for detailed mapping of site-specific planform adjustments and geomorphic variables of the river. Visualisation, manual digitization, and morphometric analyses were performed with QGIS 3.20.2 (Section 3.2).

To verify the accuracy of morphometric measurements made using Landsat satellite imagery and Google Earth imagery, high-resolution WorldView2 (WV2) imagery (50 cm resolution) was used. We compared the median bankfull width measurements from Landsat 8 imagery (30 m resolution) with those from the Google Earth imagery (5 m resolution) and high-resolution WorldView2 (WV2) imagery (50 cm resolution) from the same period (June 2018). There was a significant positive correlation between the median bankfull widths derived from the Landsat 8 and WV2 imagery ($r = 0.89$, $p < 0.05$), Google Earth image and WV2 imagery ($r = 0.95$, $p < 0.05$) as well as the Google Earth and Landsat 8 imagery ($r = 0.88$, $p < 0.05$) (Supplementary information - Fig. 1S). These results indicate that the lower resolution Landsat imagery used for the period 1988 – 2010 and the Google Earth imagery used for the period 2010 – 2020 are reliable tools for remotely sensed morphometric measurements. Therefore, morphometric data reported here are all derived from either Landsat or Google Earth imagery. The DEM was used to produce two vector layers, including a hillshade raster and multiple flow direction and flow accumulation model (using the SAGA toolbox in QGIS 3.20.2; Kwast and Menke, 2019). Pre-processing of the DEM involved sink filling using standard methods (Kwast and Menke, 2019). The hillshade raster was used to map valley-scale conditions (i.e. valley confinement) and the flow accumulation model was used to delineate the stream network shapefile and longitudinal profile of the Mara River catchment along which the different river types were identified (Section 3.2).

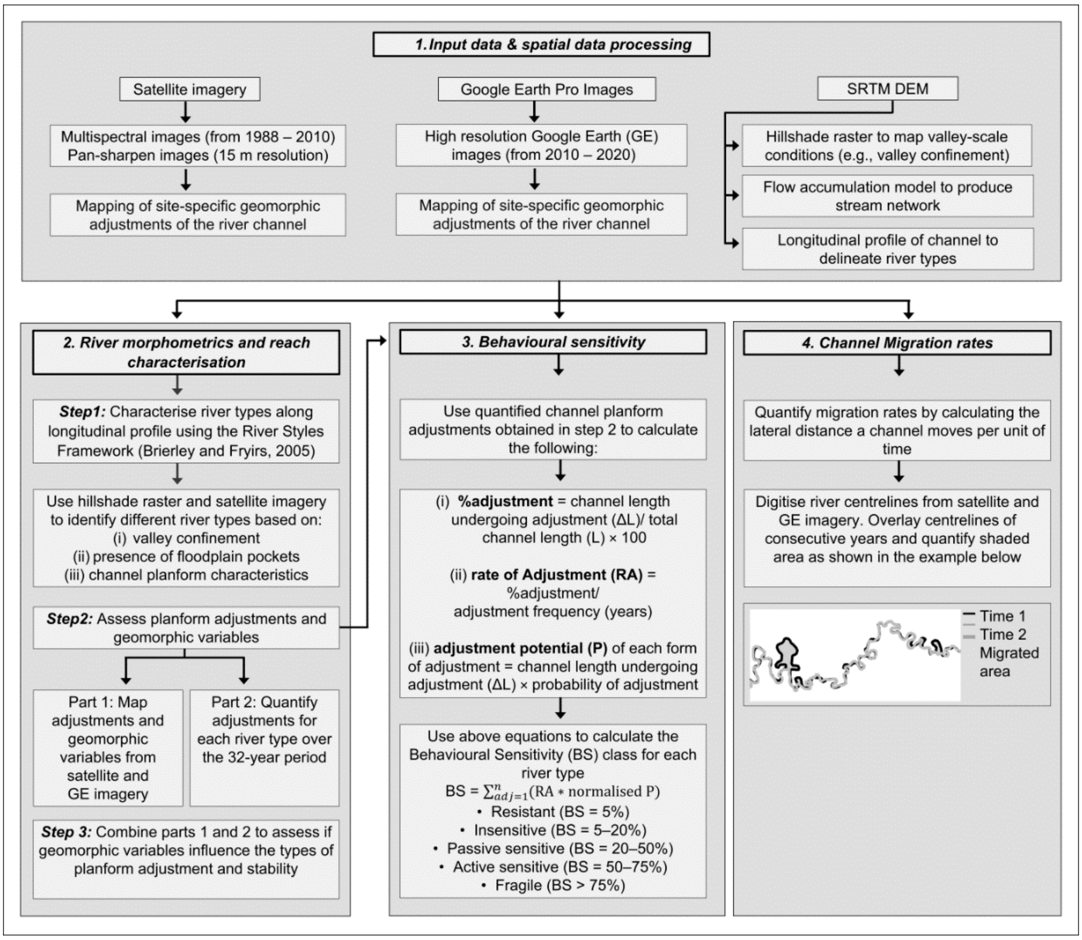


Figure 2. Datasets and workflow used for identifying and quantifying 2D planform adjustments and geomorphic variables. Section 1 involves data acquisition and pre-processing of satellite imagery and DEM data using QGIS. Section 2 involves three steps: (I) identify the different river types according to the River Styles Framework (Brierley and Fryirs, 2005); (II) quantify planform adjustments and extract geomorphic variables; (III) assess whether geomorphic variables influence the location of adjustments. Section 3 involves using outputs from section 2 (part 2) to quantify the behavioural sensitivity classes for each river type. Section 4 involves quantifying migration rates. Section 2, 3 and 4 are repeated for the different time periods.

3.3 Behavioural sensitivity

The data acquired in step 2 was used to quantify the behavioural sensitivity of the different river types (Fig. 2; Supplementary Information- Table S3). First, the percentage of reach length that experienced adjustment for each river reach was quantified. Next, the rate of adjustment and the adjustment potential of each type of adjustment was quantified. The adjustment potential quantifies the relative extent to which various forms of adjustment altered a reach and was calculated by multiplying the length of reach affected by an adjustment with the probability of the adjustment occurring (the inverse of the number of times that particular adjustment was recorded). The adjustment potential values were then normalised between 0 and 1 to calculate the normalised adjustment potential (P) for each river type. These metrics were then used to calculate the behavioural sensitivity (BS) score for each river type as follows: Resistant (BS = 5%), Insensitive (BS = 5–20%), Passive sensitive (BS = 20–50%), Active sensitive (BS = 50–75%), and Fragile (BS > 75%).

3.4 Channel migration rates

Channel migration rates were calculated to assess the lateral activity of different channel reaches and involved measuring the lateral distance a channel moved per unit of time (Hooke, 2013) (Fig. 2). To assess the change between successive time periods, river centrelines were manually digitised from satellite images using polyline features to mark the centre of the channel in QGIS. Centrelines of consecutive years were overlain to create a series of 'migration' polygons where polylines for Time 2 overlapped Time 1. The channel migration rate was then computed by dividing the sum of polygon areas for each reach by the length of the earlier of the two centrelines (Time 1) and by the time interval between the sequential channel centerlines (Time 2 – Time 1) (Shields et al., 2000; Donovan and Belmont, 2019).

4 Results

Contemporary river adjustments along the lower Mara River provide insight into the natural range of variability of the system and are used to assess the behavioural sensitivity of the different reaches. Detailed quantitative analysis of geomorphic adjustment and river sensitivity are outlined below and used to assess river response to future disturbance events.

4.1 Distinct reaches of the lower Mara River

The lower Mara River was characterised into five reaches based on the degree of valley confinement and channel planform characteristics (Fig. 3). Reach (I) is the partly confined, bedrock margin-controlled upper reach (0 – 12 km); reach (II) is the partly confined, planform-controlled meandering middle reach (12 – 34 km); reach (III) is the laterally unconfined, continuous channel in the lower reach (34 km– 90 km); reach (IV) is the laterally unconfined, discontinuous lower reach in the wetland (90 – 120 km); and reach (V) is the partly confined planform-controlled lower reach (120 – 130 km). Between these reaches downstream changes are evident in the channel-floodplain morphology. Longitudinal mean floodplain slope decreases from 0.00074 m.m−1 in the partly confined upper reach (R-I) to 0.00014 m.m−1 in the lowermost partly confined reach (R-V) and is most variable in middle reach (R-II) (Fig. 4A). Floodplain width increases by a factor of 30 downstream, from 0.4 km wide in the partly confined upper reach (R-I) to 12 km wide in the unconfined lower reach in the floodplain wetland (R-IV) (Fig. 4B). Channel width decreases substantially downstream in the wetland, from 53 – 62 m in the partly confined upper and middle reaches (R-I, II) to 10 – 20 m in the unconfined lower reaches (R-III, IV) (Fig. 4C). However, at the downstream end of the wetland (R-V) a partly confined channel reforms and the mean channel width increases by a factor of 12 from <10 m to 128 m where the valley becomes partly confined once again. Channel sinuosity increases downstream with the unconfined continuous lower reach (R-III) having the highest and most variable sinuosity (1.9), before sinuosity dramatically declines to 1 (straight) as the channel enters, and ultimately terminates in, the floodplain wetland (R-IV) (Fig. 4D). Stream power peaks at ~40 W.m−2 in the upper and middle partly confined reaches (R-I, II) before declining to ~1 W.m−2 around 41 km downstream where it remains low as it enters the floodplain wetland (Fig. 4E).

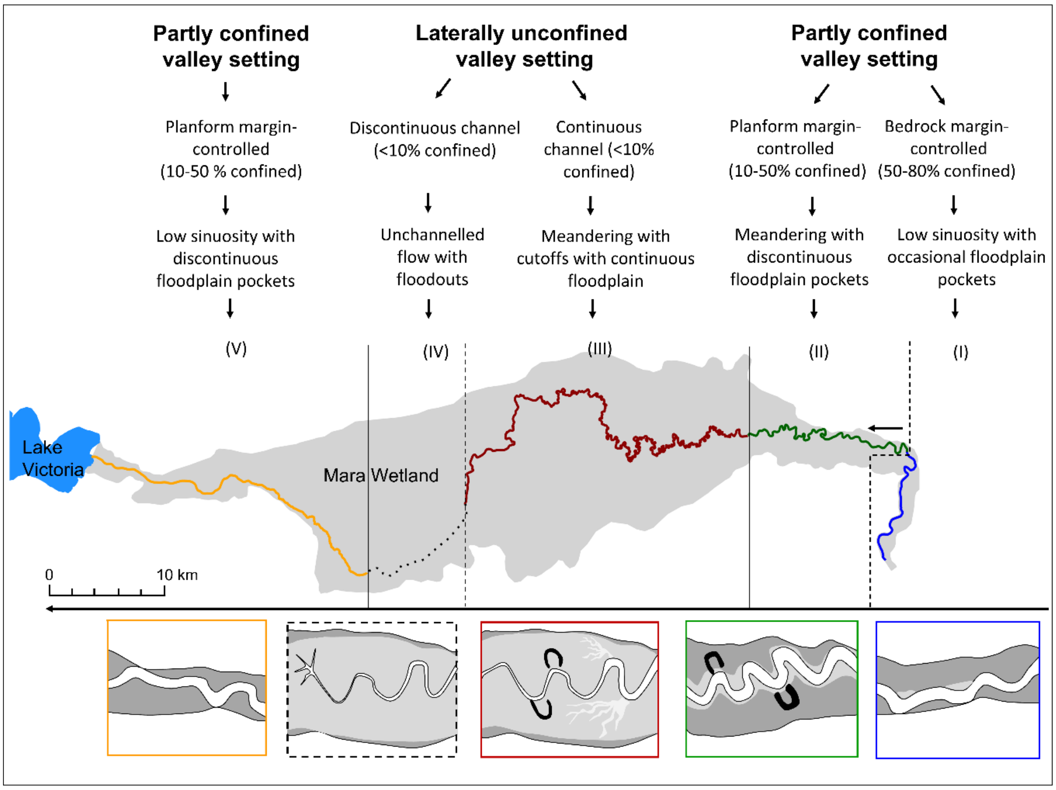


Figure 3. A schematic representing the five river reaches (I – V) identified for the lower Mara River and its floodplain wetland using the River Styles Framework (sensu Brierley and

Fryirs, 2005). Dark grey represents the confining valley and light grey represents the floodplain. Arrow indicates flow direction.

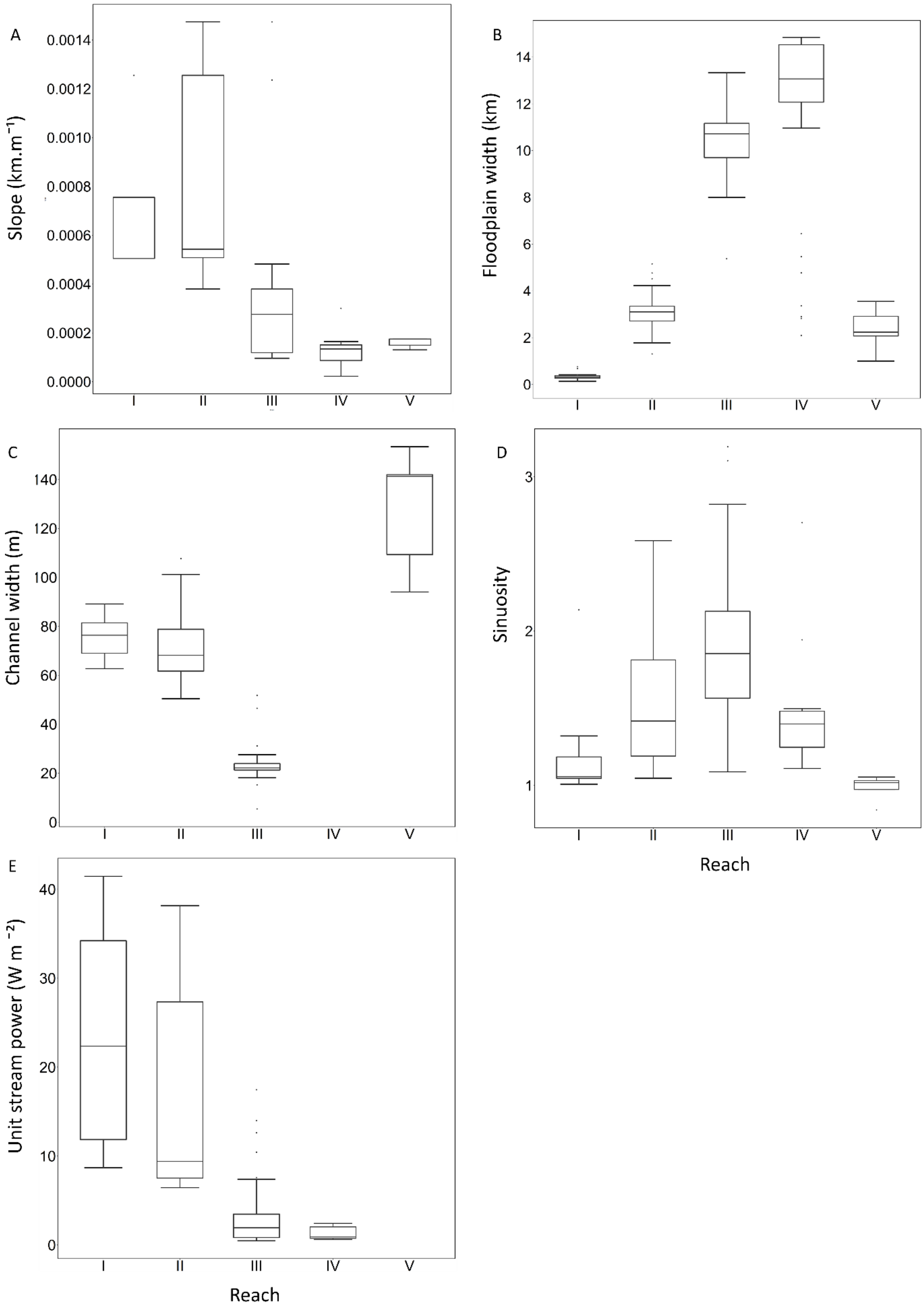


Figure 4. Box plots showing reach-scale summary trends of geomorphic characteristics (RI – V in order downstream) for the lower Mara River (data derived using satellite imagery from 2018), including (A) floodplain slope, (B) floodplain width, (C) channel width, (D) channel sinuosity, and (E) stream power. Channel width (plot C) in R-IV is discontinuous and breaks

down and is thus zero. Unit stream power (plot E) is not measured in R-V as the channel length was too short to obtain the required hydraulic parameters. The extent of the box indicates the 25th and 75th percentiles, respectively, the horizontal line within the box marks the median, and the whiskers indicate the 10th and 90th percentiles. Points above and below whiskers indicates outliers falling outside the 10th and 90th percentiles.

4.2 Contemporary geomorphic channel adjustments

Analysis of satellite imagery from the last 32 years for the lower Mara River indicates that the system has not undergone wholesale river change but has been adjusting significantly within its natural range of variability. This is evident by the lack of change in river types over the period of analyses. However, within each river reach various forms of planform channel adjustments have occurred due to erosional and depositional processes (Table 2). Erosional forms of adjustment, such as bend translation, rotation and extension are more common and occur over greater reach lengths and therefore have a high adjustment potential. Whereas channel straightening, chute cut-offs and complex bend change are less common and occur along localised sections of meanders and affect shorter lengths of the channel in each reach and thus have a low adjustment potential (Fig. 5). Depositional forms of adjustments were only recorded for the intermediate periods (2010 – 2014 and 2014 – 2018) but show that bars have moderate adjustment potential whereas sand sheets have high adjustment potential and can occur along greater lengths of the channel and across the floodplain (Fig. 5).

Table 2. Examples of different forms of planform adjustment occurring in the lower Mara River for the period (2010 – 2018). White arrows indicate direction of planform adjustment (Google Earth Images, Image © 2021 CNES/Airbus)

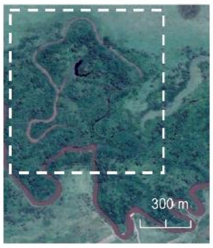
	Boundary adjustments	2010	2014	2018
Erosional forms of adjustment	Straightening/channel realignment			
	Chute cutoff			
	Bend Adjustments	2010	2014	2018
	Bend translation			
	Bend extension			
Depositional forms of adjustment	Depositional Adjustments	2010	2014	2018
	Sand sheet			
	Bar Adjustments			

Figure 5. A radial plot representing the normalised adjustment potential (P) calculated for various forms of geomorphic adjustments over the period of analysis. The adjustment potential quantifies the relative extent to which different adjustments affect a reach and the values were normalised between 0 and 1.

4.3 Multi-decadal adjustments

Over the full period of analysis (1988 – 2020), a total of 54 planform adjustments were identified with 77% of the total river length classified as adjusting and 23% (n = 23) of the river remaining stable (Fig. 6; Fig. 7). The frequency of planform adjustments and percentage of reach length affected increased downstream into the wetlands with the partly confined middle (R-II) and unconfined lower(R-III) reaches experiencing more adjustments along greater reach lengths (~81%, n = 50) compared to the partly confined upper reach (54%, n = 4) (Fig. 7; Fig. 8A). Bend adjustments affected a larger proportion (59%, n = 41) of the river length compared to boundary adjustments (19%, n = 13) (Fig. 8A). Moreover, the percentage of river length affected by bend adjustments increased downstream with the unconfined lower reach (R-III) being affected to the greatest extent (71%). Specifically, bend extensions were more common in the unconfined lower reach while complex bend change and bend rotation were more common in the partly confined middle reach (R-II) (Fig. 8B). In contrast, the percentage of river length affected by boundary adjustments decreased downstream with greater reach lengths (32%) affected in the partly confined upper reach (R-I) compared to the unconfined lower reach (R-III) (11%) (Fig. 8A). Specifically, channel straightening was more common in the partly confined upper reach (R-I) while chute cut-offs occurred in the partly confined middle (R-II) and unconfined lower (R-III) reaches (Fig. 8B).

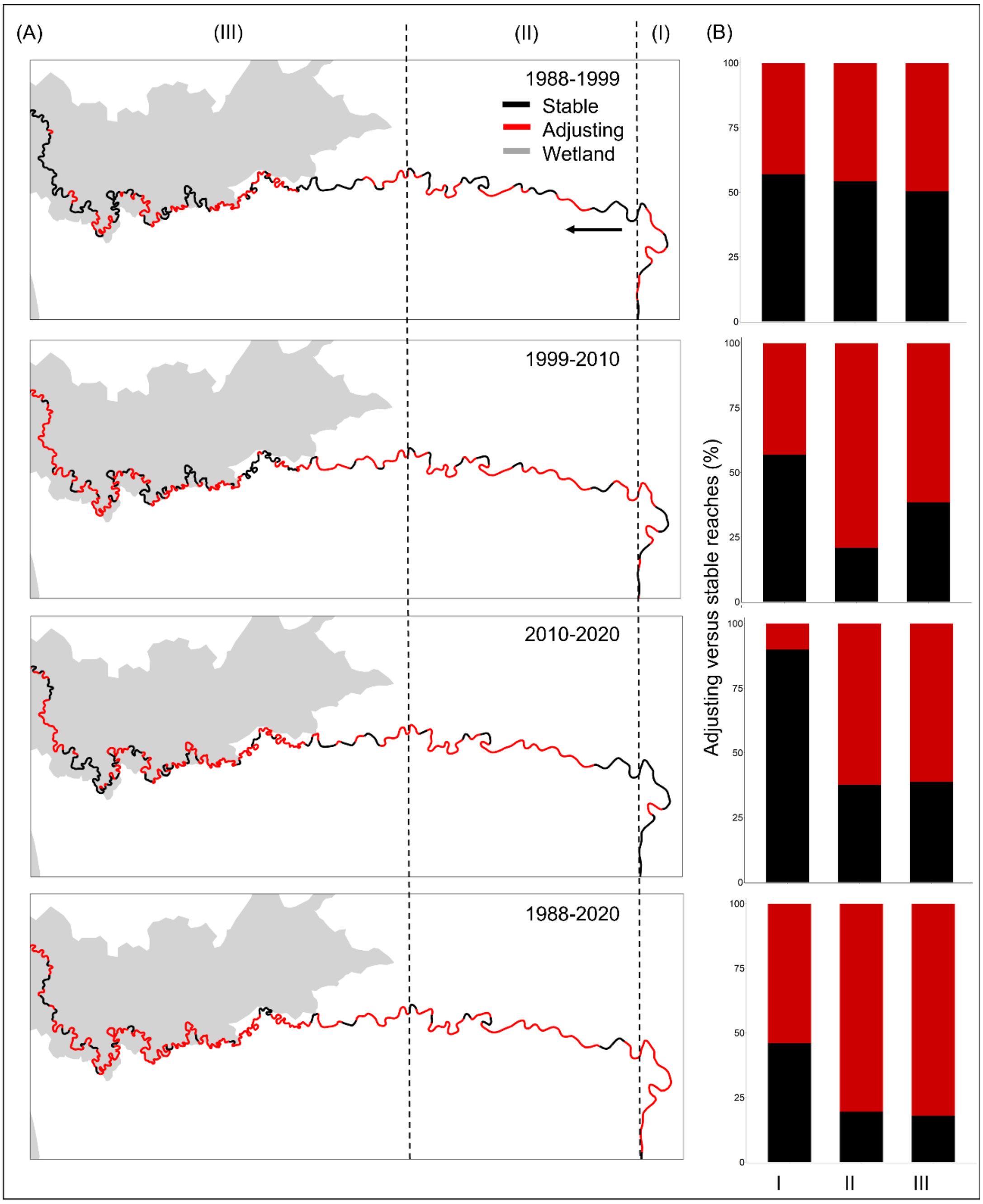


Figure 6. (A) The length of the river that is adjusting (indicated in red) and stable (indicated in black) over time for the lower Mara River. Arrow indicates flow direction (0 km – 90 km downstream). (B) Percentage of adjusting verses stable reaches over the decadal and full periods.

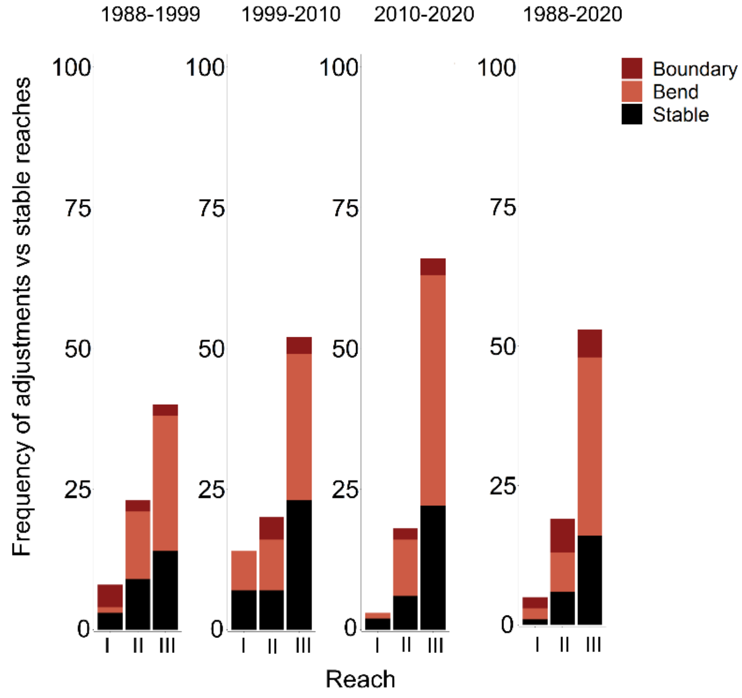


Figure 7. Frequency of planform adjustments by reach over the period of analysis. Decadal periods and full time periods are shown.

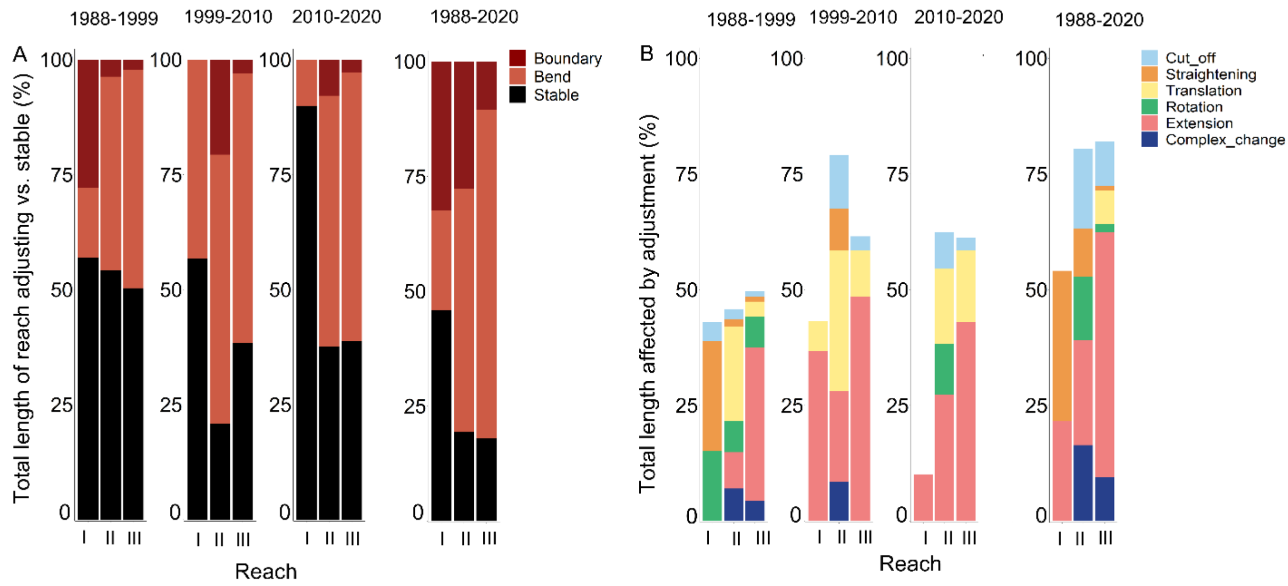


Figure 8. Geomorphic adjustments over the decadal and full period of analysis. The percentage of (A) the total channel length affected by geomorphic adjustment versus stable reaches, and (B) various forms of adjustment for each river reach (I – III).

4.4 Inter-decadal adjustments

Over the three decadal time intervals (i.e. 1988 – 1999, 1999 – 2010, 2010 – 2020), the percentage of planform adjustments versus stable reaches showed an overall increase in the percentage of river length affected by adjustments was observed over time (Fig. 7, Fig. 8). Planform adjustments affected a higher percentage of river length in 1999 – 2010 (63%, n = 49) and 2010 – 2020 (53%, n = 57) compared to 1988 – 1999 (47%, n = 45). Stable reaches affected a higher percentage of reach length in the partly confined upper reach (R-I) (57% in 1988 – 1999; 57% in 1999 – 2010; 90% in 2010 – 2020) compared to the partly confined middle (R-II) and unconfined lower (R-III) reaches, and this percentage increased over time (Fig. 8A). Bend adjustments affected a lower percentage of river length in the partly confined upper reach (R-I) over time and consisted of bend rotation and extension (Fig. 8B). In contrast, the partly confined middle, and unconfined lower reaches (R-II, III) had the highest percentage of river length affected by bend adjustments, specifically bend translation and extension, compared to boundary adjustments over time. Boundary adjustments, particularly channel straightening, affected a higher percentage of river length in the partly confined upper reach (R-I) during 1988 – 1999 (28%), while chute cut-offs affected greater reach lengths in the partly confined middle (R-II) and unconfined lower (R-III) reaches over time (Fig. 8B). The percentage of river length affected by boundary adjustments decreased downstream and, after 1988 – 1999, boundary adjustments were absent from the partly confined upper reach (R-I).

The intermediate time periods (2010 – 2014; 2014 – 2018) had a large percentage of river length that was stable in the partly confined upper (R-I) and unconfined lower (R-II) reaches (Fig. 9). During the 2010 – 2014 period, erosional (i.e. bend translation and extension) and depositional (i.e. sand sheet and bars) forms of adjustment affected 66% percentage of river length in the partly confined middle reach (R-II) (Fig. 9B). Bend adjustments were absent from the partly confined upper reach (R-I) whereas boundary adjustments were absent from the partly confined upper (R-I) and middle (R-II) reaches. Depositional adjustments were present in the partly confined upper and middle reaches (R-I, II), affecting 40% of these reaches, and absent in the unconfined lower reaches (R-III). During 2014 – 2018 depositional features, particularly bars, affected a 47% of river length in the partly confined middle reach (R-II) and were present in all three reaches. Bend adjustments were present in all three reaches, but bend extension affected a larger percentage (27%) of river length in the unconfined reach (R-III). Boundary adjustments and more specifically channel straightening only occurred in the partly confined middle reach (R-II).

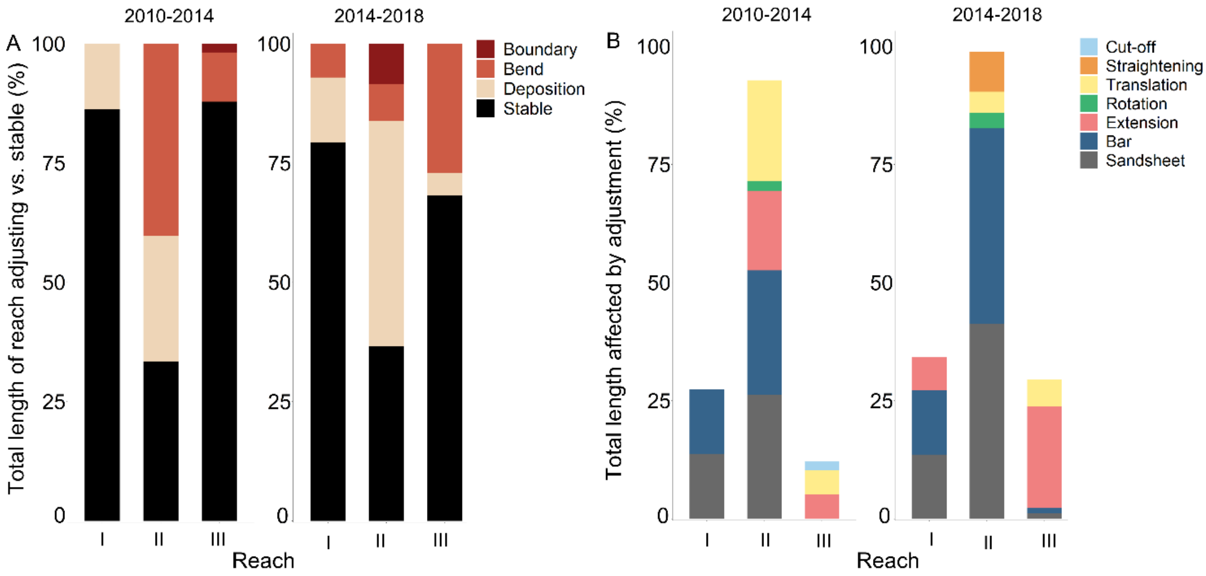


Figure 9. Geomorphic adjustments over the intermediate periods. The percentage of (A) the total channel length affected by geomorphic adjustment versus stable reaches, and (B) various forms of geomorphic adjustment for each river reach (I – III).

4.5 Migration rates and behavioural sensitivity

The lateral migration activity and behavioural sensitivity of the different reaches in the lower Mara River reflects the range of river responses and rates of adjustment over time (Supplementary information- Table 4S). The rate of channel migration in the partly confined upper reach (R-I) was the highest from 1988 – 1999 (~2.85 m a^{-1}), declining substantially during subsequent years (~0.59 m a^{-1}). This reach has a low behavioural sensitivity (37%) and is classified as Passive sensitive. Channel migration rates in the partly confined middle reach (R-II) remained consistently high (~2 m a^{-1}) over the whole period of analysis. This reach has a high behavioural sensitivity (84%) and is classified as Fragile. Channel migration rates in the unconfined continuous lower reach (R-III) were higher during 1988 – 1999 and 2010 – 2020 (~1 m a^{-1}) compared to 1999 – 2010 (~0.6 m a^{-1}). This reach has a low behavioural sensitivity (41%) and is also classified as Passive sensitive. Channel migration rates for all three reaches were lower over the full period (1988 – 2020) compared to the decadal periods.

4.6 Geomorphic conditions influencing channel planform adjustments

Geomorphic variables including floodplain width, channel width, floodplain slope and stream power are similar for stable reaches and reaches that exhibit bend adjustments; where mean floodplain width is relatively high (~7.9 km), channel width is high (~40 m), floodplain slope is low (~0.0005 m m^{-1}), and stream power is low (~7 W m^{-2}) (Fig. 10). However, stable reaches mainly occur in the partly confined upper reach (R-I), whereas bend adjustments mainly occur in the partly confined middle (R-II) and unconfined lower reaches (R-III). In contrast, boundary adjustments are restricted to the partly confined upper and middle reaches (R-I, II) where mean floodplain width is relatively narrow (~4.9 km), channel width is high (~58 m), floodplain slope is high (~0.0007 m $m^{-1),}$ and stream power is high (~12 W m^{-2}).

Significant differences between adjustment types and the geomorphic variables are evident in the partly confined upper (R-I) and unconfined lower reaches (III) (Supplementary information- Fig. 2S). Significant differences occur between boundary and stable as well as boundary and bend adjustments, and these adjustments are associated with variation in floodplain width and stream power. In the partly confined upper reach (R-I) there is a significant difference between stable reaches and boundary adjustments associated with stream power ($F = 6.53$; $p < 0.05$). In this reach, boundary adjustments occur where stream power is higher, whereas stable reaches occur where stream power is lower. In the unconfined lower reach (R-III) there is a significant difference between bend and boundary adjustments associated with floodplain width ($F = – 1.83$; $p < 0.05$). Bend adjustments occur where the floodplain is slightly wider compared to boundary adjustments which occur in slightly narrower floodplain widths.

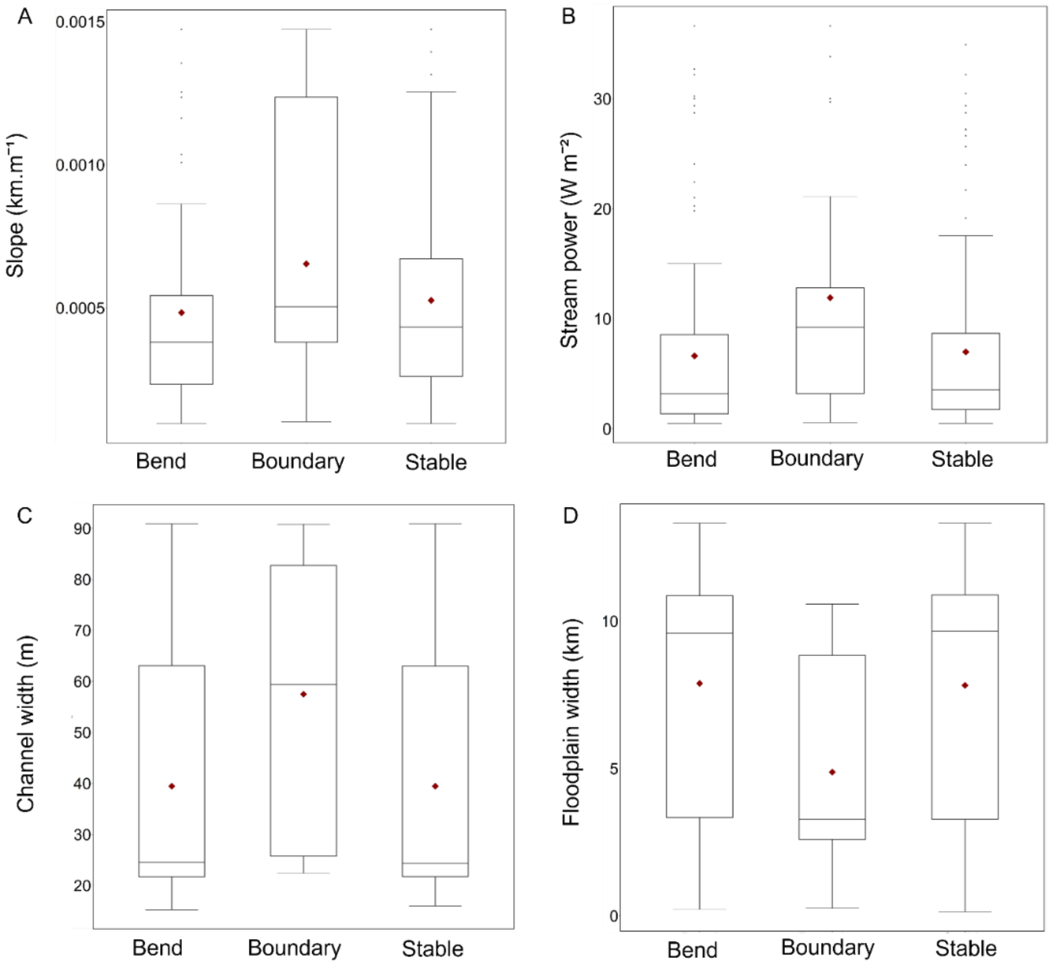


Figure 10. Geomorphic variables influencing stable, bend, and boundary adjustments along the lower Mara River for all time periods (data aggregated from decadal and full periods). (A) Slope, (B) stream power, (C) channel width, and (D) floodplain width. Mean geomorphic variables for stable and adjusting reaches are indicated by the red point. The lower and upper box boundaries represent the 25th and 75th percentiles, respectively. The line within the box marks the median, the lower and upper whiskers indicate the 10th and 90th percentiles, respectively. Points above and below whiskers indicates outliers falling outside the 10th and 90th percentiles.

4.7 Planform adjustments and hydroclimatic timeseries

Annual rainfall data (obtained from Climate Hazards Infrared Precipitation with Stations (CHIRPS)) and discharge data (obtained from Bregoli et al., 2019) were used to assess whether variations in the proportion of decadal adjustments can be explained by the hydrology of the system. During the first decade of analysis (1988 – 1999), the variation in annual rainfall is relatively high (CV = 15%) with the cumulative deviation showing an initial above-average trend at the beginning of the decade, indicating wetter conditions, followed by a progressive downward slope toward the end of the decade, indicating a drying trend (Fig. 11 C-D). Annual discharge volumes are relatively low (Fig. 11 B) but, overall, the river exhibits persistent stability with bend and boundary adjustments present but affecting a lower proportion of the river during this period (Fig. 11 A). During the second decade of analysis (1999 – 2010), the variation in annual rainfall is higher (CV = 18%) with the cumulative deviation fluctuating around the mean with periods of sporadic wetness. Annual discharge volumes are relatively high, and the river has a higher proportion of planform adjustments indicating lower stability overall. In the third decade of analysis (2010 – 2020), the variation in annual rainfall is highest (CV = 21%) with the cumulative deviation peaking above the mean at the beginning and end of the decade, indicating relatively wetter conditions interspersed with dryer conditions in the middle of the decade. Annual discharge volumes are relatively low, and the river has both patterns of stability and planform adjustments. In addition, the annual Southern Oscillation Index (SOI) and Indian Ocean Dipole (IOD) data are compared to annual rainfall over the period of interest to assess whether climate variability influences discharge and river adjustments (Fig. 11). In East Africa, positive phases of SOI and IOD are associated with higher rainfall periods; however, there was no clear link between these indices and rainfall in the Mara catchment over the period of analysis ($F = 0.1566$; $p > 0.05$) (Fig. 11 C-F).

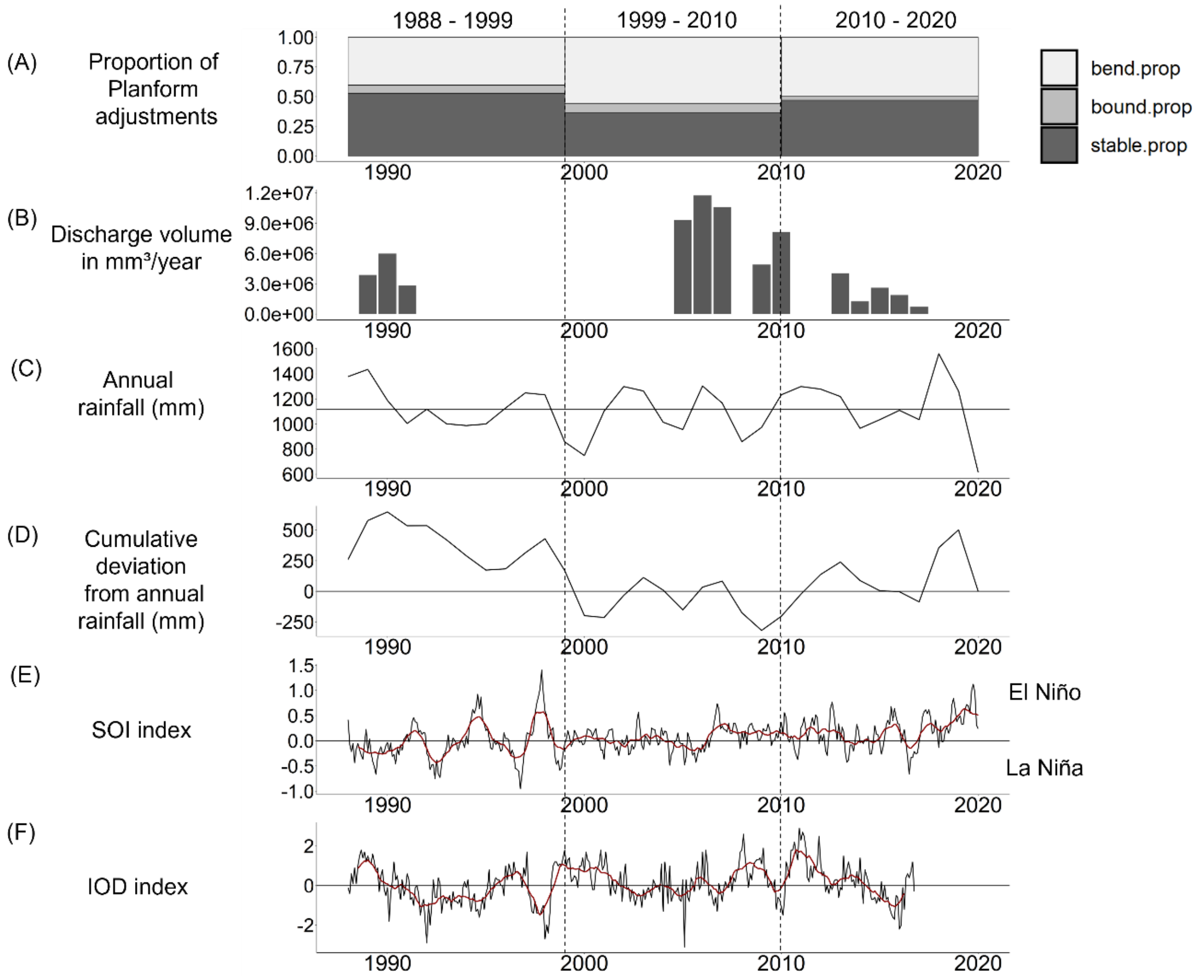


Figure 11. Contemporary geomorphic adjustments and hydroclimate timeseries for the lower Mara River. (A) The proportion of decadal geomorphic adjustments (bend, boundary and stable); (B) total annual discharge volume (adapted from Bregoli et al., 2019); (C,D) annual rainfall and cumulative deviation from the mean annual rainfall (Climate Hazards Infrared Precipitation with Stations (CHIRPS); Funk et al. 2015; https://data.chc.ucsb.edu/products/CHIRPS – 2.0/); (E) monthly Southern Oscillation Index (SOI; El Niño, +ve; La Niña, −ve); and (F) monthly Indian Ocean Dipole (IOD). Red curves for SOI and IOD represent annual running averages. Climate timeseries data obtained from (National Oceanic and Atmospheric Administration (NOAA)), (https://www.esrl.noaa.gov/psd/data/climateindices/list/).

5 Discussion

5.1 Reach-scale patterns and controls of geomorphic adjustments

Contemporary development of the Mara system reflects variability in the nature, type, and rate of channel adjustment and thus sensitivity of the different river reaches along the lower

Mara River. The channel in the upper reach (R-I) is partly confined by the narrow valley bottom and reflects patterns of persistent 2D stability. This is consistent with other semiarid and sub-tropical rivers, where topographically confined channels in the upper and middle catchment are ‘resistant’ to adjustments and are mostly stable (Fryirs et al., 2009; Larkin et al., 2017; Fuller et al. 2019; Joyce et al., 2020; Khan and Fryirs, 2020). The Mara channel has a limited capacity to adjust (i.e. restricted to within floodplain pockets) and has sufficient discharge to transport the supplied sediment downstream. The presence of bend and depositional adjustments indicate that the channel is locally active and adjusting within its behavioural regime, and changes to the channel boundaries are less common. Although the channel in this reach is relatively laterally inactive, it is possible that non-quantified vertical changes are occurring. In contrast, the partly confined middle (R-II) and unconfined lower (R-III) reaches are less restricted by valley confinement and there is sufficient accommodation space to allow the channel to adjust and interact with the broad floodplain. As such, these reaches have the highest frequency of adjustments, and a greater length of the river is affected over time. Bend adjustments are dominant in these reaches, suggesting that the channel is continuously responding to variations in flow and sediment regimes, and flood events, with larger scale adjustments to the channel boundary occurring less frequently. However, downstream declines in discharge and stream power, related to transmission losses through bed material and limited tributary inputs, result in in-channel sedimentation. Moreover, the floodplain wetland serves as a sediment store, limiting lateral connections from hillslopes and tributaries into the trunk channel.

In-channel sedimentation leads to overbank flooding during high flows which can instigate larger-scale adjustments, such as avulsions and eventual channel breakdown (i.e. non-equilibrium response) (Gomes et al., 2023a). This is evidenced by large crevasse splays and avulsive distributary channels that rework floodplain sediment in the lower reaches. Similar findings are evident in other semiarid river systems (Ralph and Hesse, 2010; Larkin et al., 2017), where the highest prevalence of adjustments occur in the downstream reaches as the channel enters the unconfined, alluvial valley and starts to spread water and sediment over a wider floodplain, influencing channel capacity, avulsion behaviour, and channel breakdown. These results highlight the importance of extrinsic (i.e. valley conditions) and intrinsic (i.e. geomorphic threshold responses) controls in influencing the accommodation space and available energy for geomorphic adjustments.

The statistical analysis highlighted the importance of catchment geomorphic variables in influencing different types of planform adjustment (Supplementary information- Fig. 2S). Variation in unit stream power and floodplain width can be used to identify differences in stable reaches, bend, and boundary adjustments. For instance, boundary adjustments in the partly confined upper reach (R-I) only occur where unit stream power is high (Fig. 10), indicating that significant energy is required to induce changes to the channel boundary (i.e. chute cut-off or channel straightening). In this case, unit stream power in this section of the river is likely to be the dominant driver of larger scale adjustments with other geomorphic variables mostly consistent along the length of the reach. Whereas boundary adjustments in the unconfined lower reach (R-III) tend to occur in sections where floodplain width is slightly narrower (Fig. 10), indicating that the vegetated channel banks may limit lateral adjustment to some degree. Here, the channel experiences threshold-driven adjustments, where continued in-channel sedimentation primes the reach for larger scale adjustments such as avulsions. Overall, it is clear from the analysis that geomorphic variables in isolation are not responsible for a particular type of adjustment, but rather adjustments occur in response to the interplay of multiple geomorphic variables. Moreover, adjustments can occur in combination and thus it is difficult to attribute individual planform adjustments to specific geomorphic variables (Joyce et al., 2020). This highlights the complexity of channel adjustments and the importance of assessing multiple geomorphic variables over longer timescales to understand the dynamics of the system.

The hydroclimatic timeseries is used to assess whether climatic variables may influence the spatial and temporal distribution of geomorphic adjustments in the lower Mara River (Fig. 11). The lower Mara River was largely stable during the first decade (1988 – 1999) with bend and boundary adjustments affecting a lower proportion of river length, whereas during the second (1999 – 2010) and third (2010 – 2020) decades the river was less stable. These patterns may reflect the large-scale precipitation patterns in the basin (i.e. natural decadal oscillation) in conjunction with increasing rainfall extremes and sediment accumulation rates experienced in the Mara basin since the 1960s (Bartzke et al., 2018; Dutton et al., 2019). Wetter periods and extreme floods would have a greater capacity to transport more sediments compared to drier periods. Indeed, Dutton et al. (2019) showed that periods of higher annual rainfall resulted in increased sediment accumulation rates, whereas periods of extreme drought resulted in decreased sediment accumulation rates. This is evident in the second decade (1999 – 2010) where fluctuations in the cumulative deviation in annual rainfall, reflected periods of alternating wet and dry conditions. Wetter climatic conditions would likely have affected catchment connectivity, sediment runoff, and the ability of the river to maintain sediment throughput as high flow conditions prevailed, resulting in greater downstream sediment accumulation in the lower reaches. Therefore, during these wetter periods, higher sediment accumulation rates likely primed the channel for larger scale adjustments, such as avulsion, whereas drier periods resulted in periods of relative stability.

5.2 Analysis of geomorphic river sensitivity

Intrinsic geomorphic channel adjustments are an integral part of river character and behaviour, thus past analysis of adjustments can be used to determine the natural range of geomorphic variability and differentiate river reaches based on their sensitivity to adjust (Brierley and Fryirs, 2016). In the lower Mara River, the different river reaches exhibit variable forms of geomorphic adjustments resulting in the identification of two behavioural sensitivity classes, including Fragile and Passive sensitive reaches. These two classes are incorporated into a conceptual diagram to explain the variability in river sensitivity for the different river reaches of the lower Mara River over time (Fig. 12). In the lower Mara River, the partly confined upper (R-I) and unconfined lower (R-III) reaches have lower migration rates compared to the partly confined middle reach (R-II) and are characterised as Passive sensitive rivers (both reaches represented by the green line; Fig. 12). Whereas the partly confined middle reach (R-II) reflected higher migration rates compared to the partly confined upper (R-I) and unconfined lower (R-III) reaches over time and is classified as Fragile (represented by the red line; Fig. 12).

Passive sensitive rivers exhibit a limited range of geomorphic adjustments and often adjust progressively within their behavioural regime and can recover from disturbance (Downs and Gregory, 2014). Moreover, these rivers are usually confined to some degree and have limited space to adjust (Fryirs et al., 2009; Fryirs et al., 2015), and tend to undergo localised geomorphic adjustments during high magnitude disturbance events that would elsewhere produce a dramatic river response (Lisenby and Fryirs, 2016). The upper reach of the Mara (R-I) is characterised by a relatively straight reach with isolated floodplain pockets in a partly confined bedrock-controlled valley, whereas the lower reach (R-III) is characterised by a

meandering reach with passive cut-offs in a laterally unconfined valley. Despite the variation in geomorphic conditions of these two reaches, they exhibit a relatively narrow range of localised adjustments and undergo more subtle channel responses to disturbance events (i.e. floods) with rapid recovery (green line; Fig. 12). In addition, antecedent effects of previous events do not induce drastic changes in the ability of the system to respond to subsequent events and these reaches continue to adjust within their behavioural regime.
Interestingly, we would expect the unconfined lower reach (R-III) to be classified as Fragile instead of Passive sensitive owing to the numerous cut-offs and palaeochannels evident on the floodplain indicating avulsive behaviour. However, due to the low unit stream power and consolidated channel banks in this reach (i.e. fine sediments and vegetated banks; Bregoli et al., 2019), the channel has insufficient energy to induce change and exhibits limited adjustments, representing a Passive sensitive river. Nevertheless, the low energy conditions in this reach promote in-channel sedimentation, overbank flooding and avulsive behaviour during high flow events, indicating a threshold-driven state and the potential to switch to a Fragile river. This is consistent with other semiarid river systems that reflect downstream, threshold-driven reaches with declining discharge and consolidated channel banks that ultimately prime the reach for larger adjustments (e.g. McCarthy et al., 1998; Ralph and Hesse, 2010; Li and Bristow, 2015). Moreover, anthropogenic activities in the catchment (i.e. land-use changes) have led to substantial increases in erosion and sediment supply into the fluvial system (Mati et al. 2008; Mwangi et al., 2017; Bregoli et al., 2019; Dutton et al., 2019), resulting in rapid in-channel sedimentation and an increase in the propensity for avulsion in the lower floodplain wetland. Therefore, the intrinsically driven threshold responses in this reach suggest that the channel is sensitive to disturbance events and under increasing anthropogenic impacts it may switch to a Fragile state in the future.

In contrast, the partly confined middle reach (R-II) is characterised by a sinuous channel with numerous cut-offs and is classified as Fragile (represented by the red line; Fig. 12). Fragile rivers have significant capacity for geomorphic adjustments (i.e. channel straightening, widening, or avulsion) and can be referred to as hypersensitive (Brierley and Fryirs, 2005; Khan and Fryirs, 2020). The middle reach of the Mara (R-II) exhibits a high proportion of erosional and depositional forms of adjustment in response to minor disturbances, which is indicative of the high quantum of geomorphic work being performed in this reach. This is possible due to the non-cohesive, coarse-grained channel bed and bank materials (Bregoli et al., 2019), such that the eroded sediment is deposited in the form of bars and floodplain sand sheets (i.e. large crevasse splays). In addition, antecedent effects of previous events reduce the ability of this reach to respond to subsequent events resulting in a shift in the behavioural regime (i.e. 'expanded' capacity for adjustments) (Fig. 12). Importantly, Fragile rivers have the capacity to undergo wholesale change (i.e. from one river type to another) (Thomas, 2001; Lisenby and Fryirs, 2016; Fryirs, 2017), for example, in response to anthropogenic disturbances in the Richmond catchment in Australia, several rivers have undergone wholesale river change and now operate as a different river type with a 'new' behavioural regime (Khan and Fryirs, 2020). Comparatively, in the lower Mara, the Fragile middle reach (R-II) has not undergone wholesale river change over the past 32 years and continues to operate within its behavioural regime. However, this reach has the highest propensity for change and if exposed to major disturbances, such as increased sediment supply related to anthropogenic activities in the catchment or large flood events, it may change to a different river type with a 'new' behavioural regime (Fig.12).

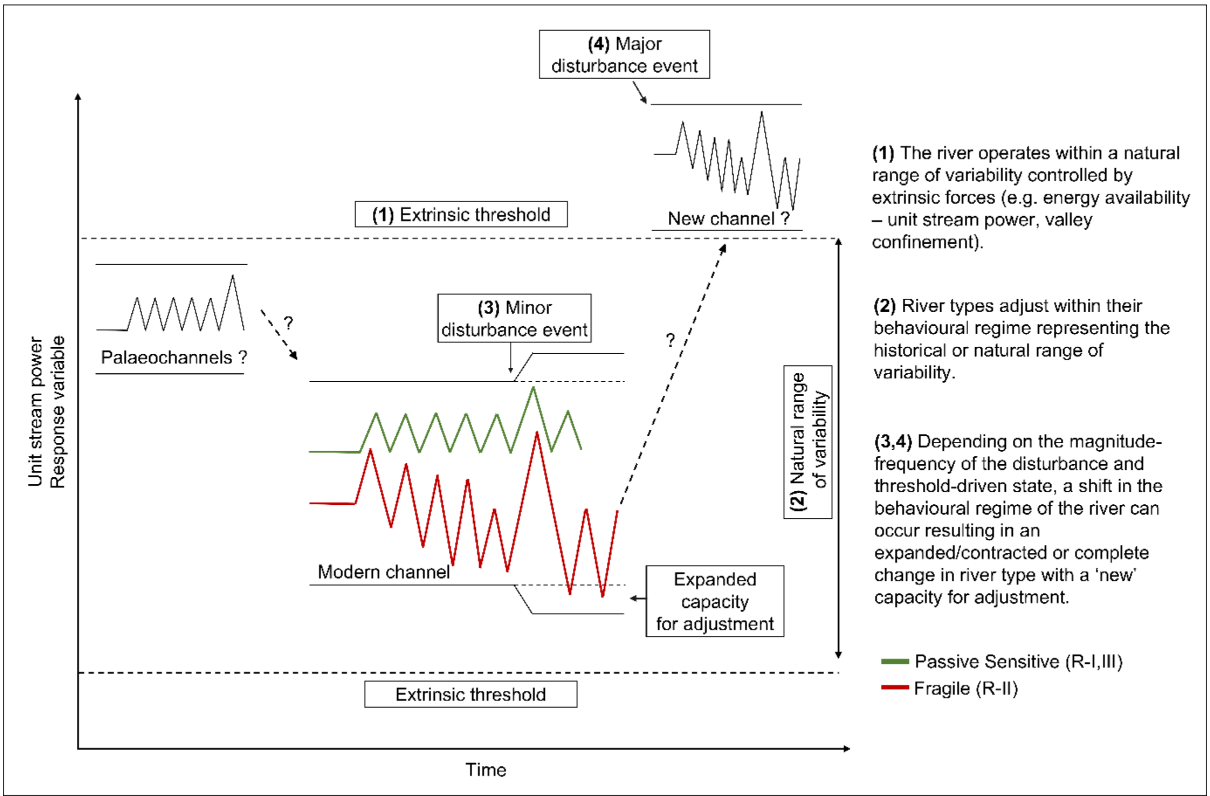


Figure 12. Conceptual diagram showing the river response of the different river reaches with their behavioural sensitivity (i.e. Fragile and Passive sensitive) for the lower Mara River. The partly confined upper reach (R-I) and unconfined lower reach (R-III) are characterised as Passive sensitive rivers, whereas the partly confined middle reach (R-II) is characterised as

Fragile. Larger, higher energy palaeochannels may have persisted as different river types before transitioning to the modern system. Depending on the behavioural sensitivity of the reach, minor disturbances may result in an expanded capacity for adjustment, whereas major disturbances may induce a shift to a different river type with a 'new' behavioural regime. The conceptual diagram has been adapted from the river evolution diagram of Brierley and Fryirs (2005, 2016) and Fryirs (2016).

Overall, it is evident that the lower Mara River has not undergone wholesale river change over recent decades (32-years) and has adjusted within its natural range of variability. However, evidence of numerous palaeochannels on the floodplain suggest that the trunk channel has likely avulsed multiple times, indicating that the river is prone to wholesale change over longer timescales. These palaeochannels were larger, higher energy systems that likely persisted under different hydroclimatic conditions (prior to 2000-1000 cal. yr. BP) (Gomes et al., 2023a) and may have operated as different river types before transitioning to the modern channel. This highlights the importance of assessing channel change over longer timescales to provide a comprehensive understanding of the natural range of variability of a system, especially for guiding climate adaption management strategies. Altogether, this study provides a contemporary assessment of geomorphic adjustments and sensitivity of the lower Mara River in response to variation in discharge and increasing upstream sediment supply related to rapid changes (i.e. deforestation, agriculture, urbanisation) in the Mara River catchment (since the 1970's) (Mati et al. 2008; Mwangi et al., 2017; Bregoli et al., 2019; Dutton et al., 2019), which is important for understanding how natural and/or anthropogenic disturbances have impacted past channel change and river sensitivity, and for predicting future changes.

5.3 Future forecasting of behavioural sensitivity

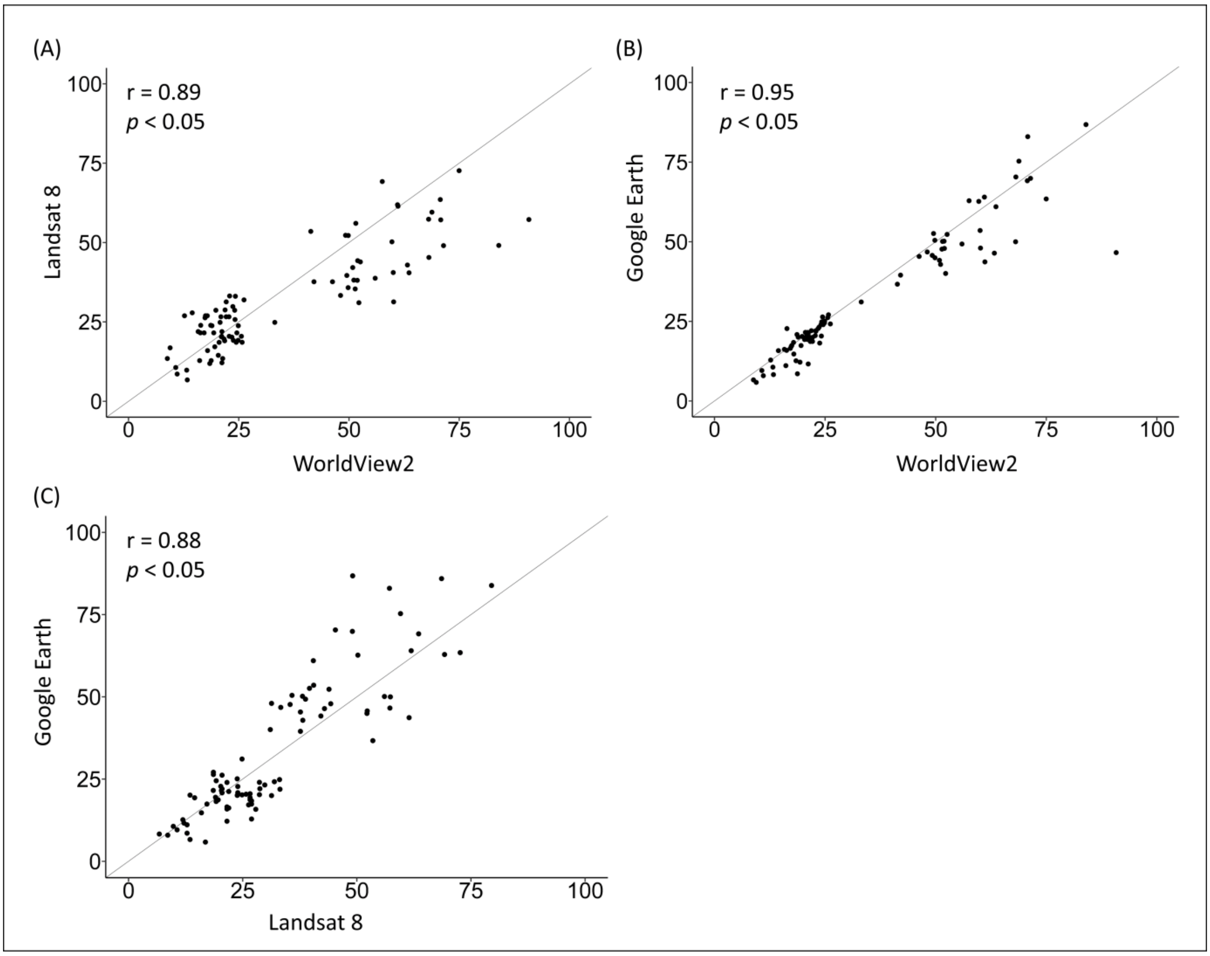
Tracking the range of river behaviour and sensitivity over time, highlights the notion that the behavioural sensitivity of a river can evolve over time, such that some rivers can become more sensitive to future disturbances, while others may become more resilient (Lisenby and Fryirs, 2016; Fryirs, 2017; Khan and Fryirs, 2020). In the lower Mara River, the different river reaches have remained in their sensitivity classes over the period of analysis and continue to operate within their behavioural regime. However, the Fragile reach (R-II) has the greatest capacity to adjust and a high propensity to undergo wholesale change when subjected to recurrent natural and/or anthropogenic disturbance events. This is because large disturbance events can reduce the ability of a system to respond to future events by preconditiong the system to undergo a dramatic change or ‘switch’ in river sensitivity (Schumm, 1979). Therefore, we expect this reach to become more sensitive or undergo wholesale river change to future disturbances over time which could have significant social implications. For instance, in the event of large disturbance events (i.e. floods transporting large sediment loads), Fragile rivers can flood and/or rework large areas of floodplain which may impact communities and anthropogenic development in the surrounding channel-floodplain boundary (Reid and Brierley, 2015).

The Passive sensitive reaches are considered more ‘resilient’ to disturbance events and less prone to wholesale river change. Since the partly confined upper reach (R-I) is restricted by imposed confinement, we expect it to continue operating within its current behavioural regime, undergoing localised adjustments while remaining relatively ‘resilient’ over time. However, the unconfined lower reach (R-III) is more vulnerable to change as the channel is threshold driven and we expect this reach to become more sensitive and possibly undergo wholesale river change in the future, especially when subjected to more extreme cycles of dry and wet conditions as seen during the period 1999 – 2010 (Fig. 11) or more intense anthropogenic disturbances. Overall, tracking river adjustment and sensitivity has provided a useful record to understand how contemporary channel planform has evolved over the recent past and to identify parts of the system that may be susceptible to future adjustments. The geomorphic concept of river sensitivity serves as a valuable tool to identify and understand past river behaviour and to forecast future channel responses, which is important for guiding management and restoration strategies. The methodology employed in this paper has shown to be a robust approach for quantifying geomorphic adjustments and behavioural sensitivity in a semiarid river. This approach provides a reach-scale analysis of channel adjustments and successfully distinguishes between behavioural and change sensitivity of different river reaches within a catchment. The quantification of 2D planform adjustments (Joyce et al., 2020) and behavioural sensitivity (Khan et al., 2020) used in this paper provides an approach with which future scenarios of channel change can be assessed in dryland fluvial systems.

6 Conclusion

River responses to environmental disturbances are driven by a complex array of geomorphic processes that vary in space and time. To better understand this geomorphic complexity and predict how rivers may respond to future disturbances, concepts such as river sensitivity can be used. The spatiotemporal patterns of river adjustments for the different river reaches in the lower Mara River over the past 32 years provide significant insight into how the system has responded to natural and/or anthropogenic disturbances (i.e. downstream declines in discharge and increased sediment supply). Our analysis shows that the Mara River is a dynamic system that has been adjusting within its behavioural regime over the period of analysis. The results highlight that the middle partly confined and lower unconfined reaches are more susceptible to becoming more sensitive if subject to recurrent future disturbance events. This assessment of river sensitivity of the Mara River is important as it allows us to forecast trajectories of geomorphic adjustments and 'hotspots' of sensitivity, which is imperative for understanding the likely impacts of future land use change, anthropogenic modification, and climate change in this ecologically important dryland system. The interpretations of river sensitivity outlined in this paper can be used to establish expectations of geomorphic adjustment, develop reach-scale management strategies, and forecast future channel behaviour in other dryland rivers.

Supplementary Information



Supplementary Figure 1S: Significant positive correlation between the median bankfull channel at sites 1 km apart along the Mara River width taken from the A) Landsat 8 and WorldView2 imagery and B) Google Earth and WorldView2 imagery for the same period (June 2018), and C) Google Earth and Landsat 8 imagery for the same period (June 2018). Line represents 1:1 ratio.

Supplementary Table 1S: Channel parameters and descriptors used in Bjerklie's equation for discharge modelling (Bjerklie, 2007)

Channel parameter	Descriptor
Average meander wavelength	WL
Sinuosity	P
Meander bend length	L = WL*P
Bankfull channel width	Wbf
Floodplain slope	Sf
Channel slope	Sc = Sf/P

Channel parameter	Descriptor
Bankfull channel depth	Dbf (Eq. 1)
Length fraction	m (Eq. 2)
Velocity	Vbf (Eq. 3)
Bankfull discharge	Qbf (Eq. 4)
Unit stream power	ω (Eq. 5)

Supplementary Table 2S: Formulas used in the Bjerklie's equation (Bjerklie, 2007) to estimate discharge and stream power. The channel parameters in Table 1S are used in the following equations

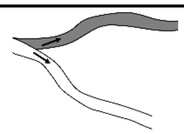
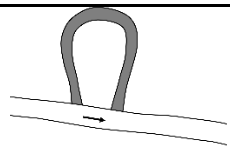
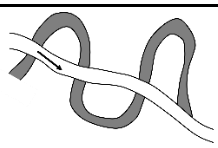
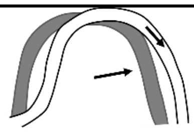
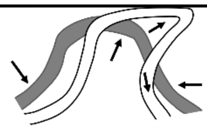
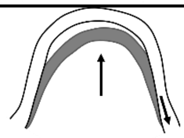
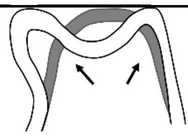
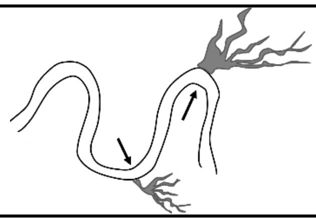
Equation	Formula
Equation 1	$D_{bf} = 0.08\frac{W_{bf}^{0.39}}{S_c^{0.24}}$
Equation 2	$m = 9.67(S_c L)^{0.36}$
Equation 3	$V = \sqrt{\frac{2 * 9.81 S_c L}{m}}$
Equation 4	$Q_{bf} = V D_{bf} W_{bf}$
Equation 5	$\omega = \frac{1}{W_{bf}} * 9800 * Q_{bf} S_c$

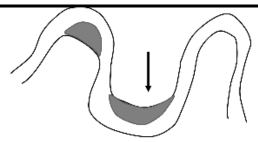
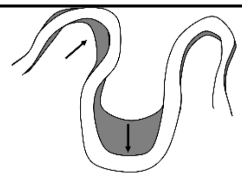
Supplementary Table 3S: Description of the methodology used to quantify adjustments and behavioural sensitivity, including the variables and equations (adapted from Khan and Fryirs, 2020).

Variables	Description	Equation
Percentage of reach length affected by adjustments	• The percentage of reach length affected by adjustments for each reach was calculated for each time slice. • The type and extent of each form planform adjustment was recorded for the intermediate, decadal, and full time periods.	%adjustment = channel length undergoing adjustment (ΔL)/ total channel length (L) × 100
Rate of Adjustment	• The rate of adjustment was calculated by dividing the percentage of reach length affected (%adjustment) by the	Rate of Adjustment (RA) = %adjustment/ adjustment frequency (years)

Variables	Description	Equation
	number of times (frequency) the adjustment was recorded.	
Adjustment potential	• The adjustment potential provides a measure of the relative extent to which various forms of adjustments can alter a reach and was calculated for each form of adjustment. • The reach length affected by that adjustment (ΔL) was multiplied with the probability of adjustment for all the time slices. • The probability of adjustment was calculated by inversing the number of times the adjustment was recorded (frequency) and multiplying it by the length affected by adjustment (ΔL). The values of adjustment potential were normalised between 0 and 1.	adjustment potential (P) of each form of adjustment = channel length undergoing adjustment (ΔL) × probability of adjustment
Behavioural sensitivity	• The behavioural sensitivity for each river type was calculated by multiplying the rate of adjustment by the normalised adjustment potential for each form of adjustment across all time periods. • The behavioural sensitivity for each river type is a function of the reach length affected by adjustment and the potential for that form of adjustment to instigate geomorphic change and alter a reach.	Behavioural Sensitivity (BS) = $\sum_{adj=1}^{n}$(RA $*$ normalised P)
Behavioural sensitivity class	• The behavioural sensitivity class (river response) of each reach was defined based on the behavioural sensitivity. • Two behavioural sensitivity classes were identified for the Lower Mara River system	Passive sensitive Rivers (BS = 20 – 50%) can withstand adjustment within its behavioural regime. Fragile Rivers (BS > 75%) have a wide capacity for adjustments.

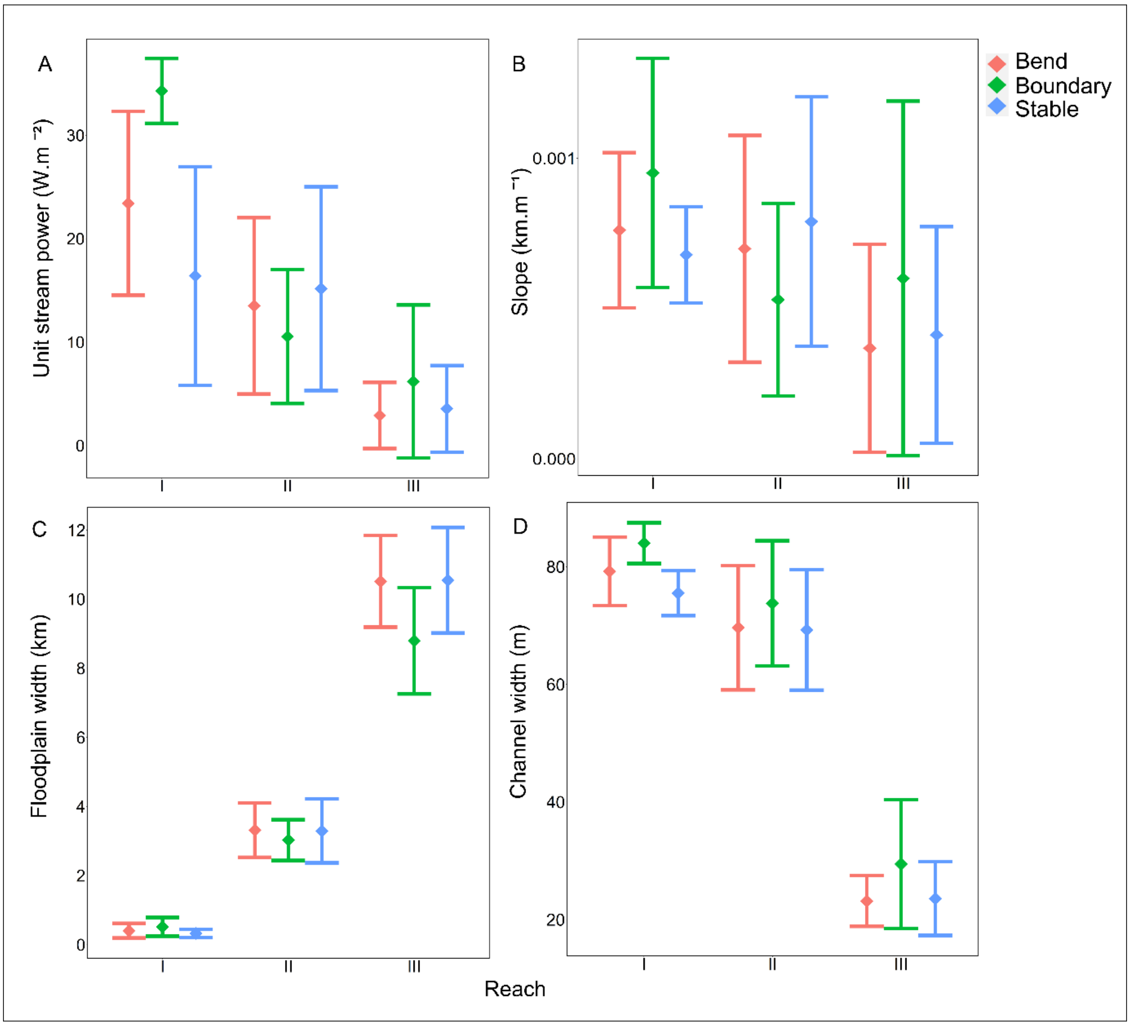
Table 4S. Channel planform adjustment types (erosional and depositional) and definitions adapted from Brierley and Fryirs (2005) and Fryirs et al. (2009). Grey segments represent the 'old' channel before adjustment and white segments represent the 'new' channel after adjustment

Type of adjustment	Description	Diagram
Erosional adjustments		
Boundary		
Avulsion	Shift in channel position across the floodplain, generating a new or reoccupying older channels.	
Cut-off	Bend cut-off occurs through chute cut-off or meander neck migration. During high flows where channel bank surfaces are breached a new straighter, channel path is cut leaving an abandoned meander loop on the floodplain.	
Straightening/ realignment	Multiple channel bends are realigned or cut-off forming a new channel with low sinuosity (straight). This process is often associated with avulsion(s).	
Bend		
Translation	Shift in the position of the bend (upstream or downstream), without altering the basic shape of the bend.	
Rotation	Adjustment of the bend axis to a new position.	
Extension	Bend position shifts laterally causing an increase in amplitude and channel length.	
Complex bend change	Various forms of adjustment operating together.	
Depositional adjustments		
Sand sheet	During high flows, floodwater breaks the channel banks (usually on bends) and is dispersed over the floodplain. Sediment may form crevasse splay complexes.	

Type of adjustment	Description	Diagram
Bars	Sediment deposition in and around the channel during low to medium flow stages.	
Channel migration		
Lateral migration	Movement of the channel laterally across its floodplain, usually involving erosion of the outer banks and deposition on the inner banks which results in the development of meander bends and chute cut-offs.	

Supplementary Table 5S: Decadal migration rates for each river reach of the lower Mara River system

Reach descriptor	Distance down valley from (km)	Mean migration rate (m/year)				Behavioural sensitivity class
		1988 – 1999	1999 – 2010	2010 – 2020	1988 – 2020	
I: Partly confined upper	0 – 12 km	2.86	0.98	0.59	0.89	Passive sensitive (37%)
II: Partly confined middle	12 – 34 km	2.10	2.23	2.14	1.39	Fragile (84%)
III: Laterally unconfined lower	34 – 90 km	1.46	0.68	1.07	0.63	Passive sensitive (41%)



Supplementary Figure 2S: Mean geomorphic variables influencing the location and extent of stable, bend and boundary adjustments by reach (I – III) for all time periods (decadal and full periods). (A) Stream power, (B) slope, (C) floodplain width, and (D) channel width. The mean and standard error are shown.

CHAPTER 4

Landscape connectivity dynamics of the transboundary Mara River catchment, East Africa, and implications for river and wetland response in a globally important conservation region

This chapter is in review in the journal Catena*.*

See Table 1.2 in Chapter 1 for author contributions.

Abstract

Wetlands in semiarid regions are important systems that provide numerous ecosystem services in otherwise dry environments. Their functioning depends on the connected transfer of materials from source to sink which is determined by the degree of landscape connectivity. A combination of catchment characteristics, climatic variables and human activities are important factors driving landscape connectivity; however, wetland management rarely considers all these factors when conserving these systems. In this paper, we evaluate the landscape connectivity of the Mara River catchment in East Africa to understand the hydrogeomorphic processes driving material transfer to the floodplain wetlands. This semiarid catchment hosts the UNESCO World Heritage Serengeti-Mara ecosystem providing a unique opportunity to assess the influence of protected areas on wetland-catchment connectivity patterns. We use the index of connectivity and Emerging Hot Spot analysis to assess the hillslope-channel connectivity and identify specific subcatchments which have contributed positively to the wetland's connectivity over time. The catchment-scale analysis highlights significant spatiotemporal variability in connectivity patterns and associated sediment dynamics. The results reflect that the Upper catchment is highly connected owing to the steep slopes and high rainfall and is likely responsible for the greatest sediment inputs into the fluvial network. Under greater future climatic and anthropogenic pressures, this region is expected to contribute increased sediment inputs into the river which will likely affect the geomorphic response of the downstream floodplain wetlands and may need to be prioritised for management. The protected areas are generally poorly connected due to intact vegetation and their local sediment contribution to the fluvial network is comparatively lower. Consideration of their placement in the catchment is important for managing these ecologically significant areas. Understanding the patterns and variability of hillslope-channel connectivity and the broader-scale landscape connections can help to identify and prioritise existing and emerging hotspots of change in large, semiarid catchments.

Keywords: hydrological and sediment connectivity, hydrogeomorphic drivers, geomorphic adjustments, floodplain wetlands

1 Introduction

Wetlands are important ecosystems that are considered to be hotspots of ecosystem service delivery (Tooth et al., 2015), including flow regulation and flood attenuation, groundwater recharge, nutrient cycling, sediment buffering and carbon sequestration (Millennium Ecosystem Assessment, 2005; Zedler and Kercher, 2005; Mitchell, 2013; Mitsch et al., 2013). Despite the high ecological value of these systems, increasing pressure from indirect (e.g. changing native land cover, climate change) and more direct anthropogenic impacts (e.g. flow regulation, channelisation, floodplain drainage, riparian grazing) are progressively leading to wetland degradation and permanent loss globally (Zedler and Kercher, 2005; Gardner et al., 2015; Tooth, 2018; Grenfell et al., 2022). This trend is particularly alarming for wetlands in arid and semiarid regions (drylands) that tend to be less resilient due to the inherent scarcity of vital resources, such as water (Tooth, 2018).

The ecological structure and functioning of wetlands are primarily controlled by hydrology but vary based on their hydrogeomorphic setting (e.g. geology, tectonics, climate) and catchment-scale processes (e.g. sedimentation, erosion) (Ellery et al., 2016; Grenfell et al., 2019). As such, wetlands are intricately connected to their surrounding landscape and depend on the spatial redistribution of water and sediment fluxes across the landscape (Thorslund et al., 2017; Branton and Robinson, 2020). Transport of such fluxes is determined by the linkages of transfer pathways and is essential for maintaining the biophysical processes and feedbacks in wetlands (Okin et al., 2015; Fryirs et al., *in press*). This is particularly true for allogenic wetlands in lowland floodplains that are directly dependent on connected flow from more humid, upstream catchments (Ralph and Hesse, 2010; Okin et al., 2015; Lara-Pulido et al., 2018). Current wetland management, however, often focuses on individual wetlands and their hydrological processes, such as restoring hydrological connectivity (Singh et al., 2017; Singh and Sinha, 2019), and maintaining hydroperiods (Paudel et al., 2020) and less often considers the broad-scale landscape connectivity and hydrogeomorphic processes that govern wetland functioning and dynamics (McCarthy et al., 2010; Singh and Sinha, 2020; Grenfell et al., 2022). Therefore, an integrated approach that assesses the hydrogeomorphic connectivity of floodplain wetlands within the broader catchment is crucial for understanding wetland formation, maintenance, and modification over time.

One such approach that is used to understand system complexity is landscape connectivity (e.g. Brierley and Fryirs, 1998; Hooke, 2003; Pringle, 2003; Lexartza-Artza and Wainwright, 2009; Fryirs, 2013; Bracken et al., 2015; Pöppl et al., 2017; Singh et al., 2017; van der Waal and Rowntree, 2018; Singh and Sinha, 2019). Landscape connectivity encapsulates sediment and hydrological connectivity and refers to the connected transfer of matter (e.g. water, sediment, nutrients) through a system of interconnected compartments (e.g. drainage basins, hillslopes, floodplains, wetlands) from a source to a sink (Okin et al., 2015; Wohl et al., 2019). Both natural (e.g. catchment morphology, slope, elevation, valley confinement, land-use changes, land abandonment) and anthropogenic features (e.g. roads, agricultural lands, weirs, and dams) can alter landscape structures and/or processes that either increase or decrease connectivity and thus affect water and sediment movement across a landscape (Fryirs et al., 2007a; Saco et al., 2018). For instance, land degradation resulting in changes in vegetation cover will affect runoff and erosion processes on hillslopes and hence connectivity patterns (Wainwright et al., 2011; Saco et al., 2018). Furthermore, due to the complex hydrogeomorphic processes and feedbacks driving material transfer across the landscape, connectivity can be used to understand river and wetland ecosystem functioning farther downstream, as well as geomorphic processes and adjustments and thus sensitivity to human and natural perturbations (Brunsden and Thornes, 1979; Brunsden, 2001; Pöppl et al., 2017). For instance, land use changes that lead to increased connectivity (i.e. increased runoff and erosion) and subsequent sediment deposition in the valley bottom, may lead to hotspots of geomorphic adjustments and an increase in the propensity for avulsions, the relocation of a channel to a new position on the floodplain, resulting in wetland formation. However, an increased rate of avulsions may make the system more sensitive to disturbance events, with potential impacts for ecological succession and ecosystem services (Ralph et al., 2011; Lisenby and Fryirs, 2017). Conversely, a decrease in connectivity may lead to increased channel bank erosion and enlargement, and channel incision, resulting in the loss of wetland functioning. It is, therefore, necessary to understand how landscape connectivity patterns and associated sediment dynamics, affect river and wetland processes to develop effective management of a catchment (Lexartza-Artza and Wainwright, 2009).

While several studies have highlighted the importance of landscape connectivity for evaluating floodplain wetland dynamics and as a potential management tool (Singh et al., 2017; Singh and Sinha, 2019; Yeo et al., 2019), they have primarily focussed on the hydrodynamics (i.e. hydrological processes) governing wetland functioning in small catchments. Here we focus on the hydrogeomorphic processes driving wetland-catchment connectivity dynamics in a large, transboundary river catchment in East Africa, namely the Mara River. Catchment-scale hydrological and sediment connectivity analysis and its broader implications for managing wetland systems is lacking in this part of the world. The Mara River catchment provides a unique setting to assess landscape connectivity changes, as it not only supports one million inhabitants and their various economic activities, but also hosts important conservation areas including the UNESCO World Heritage Serengeti-Mara ecosystem. Several studies on the Mara River have focused on the effect of land use change (e.g. deforestation) on sediment yield and runoff, and subsequent changes in the hydrology and health of the aquatic ecosystem (LVBC, WWF-ESARPO, 2010; McCartney, 2010; Mango et al., 2011; Defersha and Melesse, 2012), with fewer studies quantifying the contribution of different regions of the catchment to suspended sediment in the Mara River (Dutton et al., 2013; 2018; 2019). As such, we examine the Mara River catchment and its floodplain wetlands to understand how the spatiotemporal variability of landscape connectivity influences the geomorphic response of this system.

The geomorphological development of the semiarid Mara River highlights the dynamic nature of the system over the recent past. Evidence of numerous palaeochannels, channel adjustments and avulsions (Gomes et al., 2023a), highlight the sensitivity of this system to natural and anthropogenic impacts over annual and inter-annual timescales (Gomes et al, 2023b). Understanding how natural or anthropogenic induced changes in hydrological and sediment connectivity in the catchment can further influence the biophysical processes and geomorphology of the wetland is critical for managing these important systems. Moreover, the role of protected areas on wetland-catchment connectivity dynamics is poorly understood and can be used to identify regions that require intervention and/or need to be prioritised for management. In this paper we examine the hydrogeomorphic processes driving the spatial and temporal variation in connectivity patterns and identify regions within the catchment that exhibit hotspots of distinctively high and low connectivity patterns. We also assess the influence of catchment-scale connectivity on the geomorphic threshold responses of the river and its floodplain wetlands and the implication for conservation and management of these ecologically important fluvial systems.

2 Study area

2.1 Mara River catchment

The transboundary Mara River catchment, shared between Kenya and Tanzania, covers an area of 13 750 km^2 (Fig. 1) (Mati et al., 2008; Bregoli et al., 2019). The river originates in the Mau Escarpment in Kenya and flows south through the Serengeti-Mara ecosystem before entering the Mara Wetland and finally debouching into Lake Victoria in Tanzania (Kassenga, 1997; Mati et al., 2008). The elevation of the catchment varies between 3000 m a.s.l. (metres above sea level) at the Mau Escarpment, 1480 m at the Serengeti-Mara conservation reserves and 600 m at Lake Victoria (McClain et al., 2014). The river basin is both regionally and globally important as it supports a local population of ~1.2 million people, with 62% directly reliant upon the river for their domestic water needs, as well as the annual migration of 2 million herbivores which is a major source of ecotourism for these countries. The river basin has undergone major land use changes due to settlements and deforestation over the last 50 years (Olang and Kundu, 2011). Mati et al. (2008) found that between 1973 and 2000, rangelands and forest cover decreased substantially, while agricultural cover increased by 203%. These land use changes, combined with increasing water abstraction, have altered the hydrology and water quality in the Mara River, resulting in increased peak flows, erosion rates, and suspended sediments and nutrients in the river (Mati et al., 2008; LVBC and WWF-ESARPO, 2010; Mango et al., 2011; McClain et al., 2014; Dutton et al., 2018). These changes have also led to increased sediment and pollutant loads in the river as well as a four-fold increase in the size of the Mara Wetland (Mati et al., 2008). Moreover, management authorities have found that increased levels of total suspended solids and nutrients in the Mara River may be associated with eutrophication in Lake Victoria and the overall decline in aquatic ecosystem health, with significant social implications for domestic water users (Hecky et al., 2010; LVBC and WWF-ESARPO, 2010). The Mara Wetland has been recognised for its importance in buffering the effects of land use changes in the catchment on Lake Victoria (O'Sullivan et al., 2016). For example, the Mara Wetland is estimated to annually remove ~ 75 tons of nitrogen (Mayo et al., 2013), and acts as a sink for mercury contamination (Dutton et al., 2019).

The Mara River catchment exhibits seasonal rainfall characterised by two distinct rainy seasons linked to annual oscillations of the inter-tropical convergence zone, which occur during March–May (the long rains) and October–December (the short rains) (Alemayehu et al., 2017). Rainfall varies spatially over the catchment owing to topographic effects and the regional influence of Lake Victoria (Camberlin et al., 2009). The upper catchment receives the highest mean annual precipitation (1000 - 1750 mm a^{-1}) whereas the lower catchment receives the lowest (600 - 1100 mm a^{-1}) (Mati et al., 2008; McClain et al., 2014; Dutton et al., 2018). The Mara River catchment can be delineated into five major subcatchments based on the drainage network pattern, and includes the Upper, Middle, Talek River, Sand River and Lower catchments (Fig. 1). The Upper catchment (2348 km^2, 17% of the catchment) hosts the two main perennial tributaries that form the Mara River, the Nyangores and Amala Rivers, and comprises small-scale settlements, small-scale agriculture, and forested regions within the Forest Reserves. The Middle catchment (1483 km^2, 11% of the catchment) includes the main Mara River channel up to the border between Kenya and Tanzania and comprises the Masai Mara National Reserve and Community Conservancies (LVBC and WWF-ESARPO, 2010). In the Middle catchment, the Mara River is joined by two ephemeral tributaries, the Talek River and the Sand River which originate in the Loita Hills and drain the Sannia and Loita Plains. The Talek River and Sand River catchments make up 2650 km^2 (20%) and 4060 km^2 (30%) of the catchment area and these areas provide important dry-season resources for both domestic livestock and wildlife populations (Olang and Kundu, 2011). The Lower catchment covers 2949 km^2 (22%) of the catchment area and includes the Mara wetland which provides critical resources (e.g. fish, papyrus, charcoal) for the economic sustenance and wellbeing of the surrounding local communities (Mati et al., 2008). The Mara wetland has no formal protection but is recognised as important bird and biodiversity region.

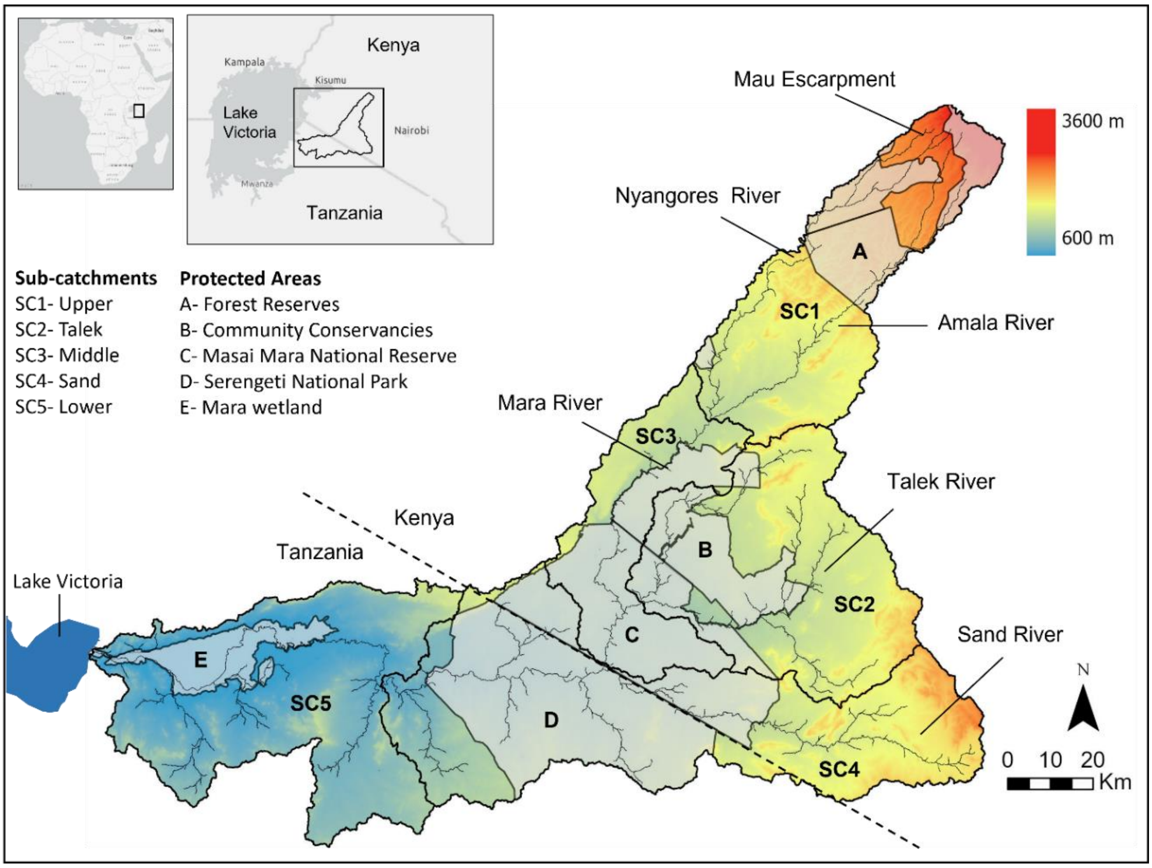


Figure 1. The transboundary Mara River catchment shared between Kenya and Tanzania with its five major subcatchments and protected areas. Protected areas are shaded in grey. Subcatchments are represented with solid black outlines.

2.2 Protected areas

The Mara River catchment hosts several conservation areas that have different protection statuses and management goals (Fig. 1). The Forest Reserves (FRs) in the Upper catchment form part of the greater Mau Forest complex, which is the largest remaining near-continuous block of indigenous montane forest in East Africa (Olang and Kundu, 2011). It encompasses seven forest blocks, of which three (i.e. Trans-mara, Southwest Mau and Olpusimoru blocks) occur within the Mara River catchment. These forests form the headwater catchments of the western part of the country and are managed by the Kenya Forest Service. The Community Conservancies (CCs) in the Middle catchment comprise of 16 conservation areas that border the Masai Mara National Reserve (MMNR) and form part of the greater Serengeti-Mara ecosystem (MMWCA, 2019). The CC programme is a wildlife conservation model that incentivises landowners and communities to protect and manage wildlife and their habitat outside state-protected areas. These conservancies provide connected landscapes that facilitate the dispersal of wildlife while benefiting the local community and are managed under the Maasai Mara Wildlife Conservancies Association and the Kenya Wildlife Conservancies Association. The Serengeti National Park (SNP) and the MMNR are government controlled protected areas with high levels of protection and they provide major economic benefits through ecotourism (MMWCA, 2019).

3 Methods

We used remotely sensed data to quantify the index of connectivity (IC) (Crema and Cavalli, 2018) and Emerging Hot Spots (EHS) to evaluate the spatiotemporal dynamics of hydrological and sediment connectivity across the Mara River catchment (Fig. 2). This analysis was used to understand the hydrogeomorphic processes driving connectivity and identify regions in the catchment that showed complimentary and/or contrasting connectivity patterns. The IC quantifies the potential for transfer of material to a 'target', such as a standing water body or channel, from a given location. Calculation of the IC was performed on a per-pixel basis and based on three input datasets: a sink-filled DEM, a ‘target’ shapefile layer, and a weighting layer. In this case, the target layer was the stream network, and the weighting layer was an NDVI layer used as a proxy to model flux impedance by vegetation, which was assumed to be the primary factor driving inter-annual and seasonal variability in connectivity. Subsequent EHS analysis assessed the temporal connectivity trends for each cell within a DEM. The IC and EHS workflows are described in greater detail below and in Figure 2.

3.1 Remote sensing data acquisition and pre-processing

Pre-processing of the DEM and NDVI weighting layers for calculation of the IC was performed in a multi-step process. Acquisition of satellite imagery (for calculation of NDVI) and a DEM, as well as pre-processing was completed using the open-access Digital Earth Africa Sandbox platform (https://www.digitalearthafrica.org/), which provides access to analysis-ready remote-sensing data for Africa. We obtained USGS Level 2 surface reflectance imagery products from Landsat 5, 7 and 8 (30 m resolution) for the years (2000 – 2020), and a SRTM DEM (90 m spatial resolution, acquired in February 2000). Pre-processing of Landsat imagery involved resampling to 90 m resolution for compatibility with the SRTM DEM (using nearest neighbour method), masking to eliminate cells beyond the spatial extent of the Mara catchment, generating cloud-free geometric median (geomedian) composite images, and subsequently calculating normalised difference vegetation index (NDVI) (for use as a weighting layer in the IC calculation). The coarser resolution imagery was used as it was less computationally intense and suitable for identifying hotspots of connectivity at the catchment-scale. Geomedian composites were produced for wet (March through May) and dry (June through August) seasons for each year between 2000 and 2020, yielding 40 individual NDVI layers. NDVI provides a measure of the amount of vegetation at the surface (i.e. primary production) and serves as a proxy for water and sediment impedance, where high NDVI values represent healthy vegetation (high impedance) and low NDVI values represent unhealthy and sparse vegetation (low impedance) (Karaburun, 2010). The maximum and minimum values for all available NDVI layers were used to obtain their corresponding C-factor values (weighting factor used in the IC calculation) (Supplementary information- Fig. 1S). This was achieved by converting high NDVI values to low values and vice versa and rescaling the values between [0 – 1] to allow for relative comparison. Therefore, C-factor values, zero and one, represented maximum and minimum impedance, respectively.

Using the Spatial Analyst toolbox and the ArcHydro extension in ArcGIS Pro (Version 2.8.0), the DEM was pre-processed to fill the sinks (Kwast and Menke, 2019), and a flow direction and flow accumulation raster was developed from which the stream network layer was calculated with an area threshold of 134 km^2 for stream initiation (for use as a target layer in the IC calculation). This threshold was chosen as it accurately represents the catchment and provides adequate detail in the connectivity model. To ensure the generated stream network aligned correctly with the natural stream, drainages were confirmed using high-resolution ESRI World imagery (ESRI, 2017). Based on the derived drainage patterns, the Mara River basin was divided into five tributary subcatchments (Upper, Middle, Talek, Sand, and Lower), which was used for later assessment of the degree of effective catchment contribution to the Mara wetland’s connectivity. A 10 m buffer was applied to the resulting stream network to produce a polygon geometry as required by SedInConnect. Landsat imagery (30 m resolution) and Google Earth Pro imagery (~5 m resolution) was used to identify and map the presence of sedimentary buffers (e.g. floodplain, alluvial fan, levee, trapped tributary fills) across the catchment (Fryirs et al., 2007b).

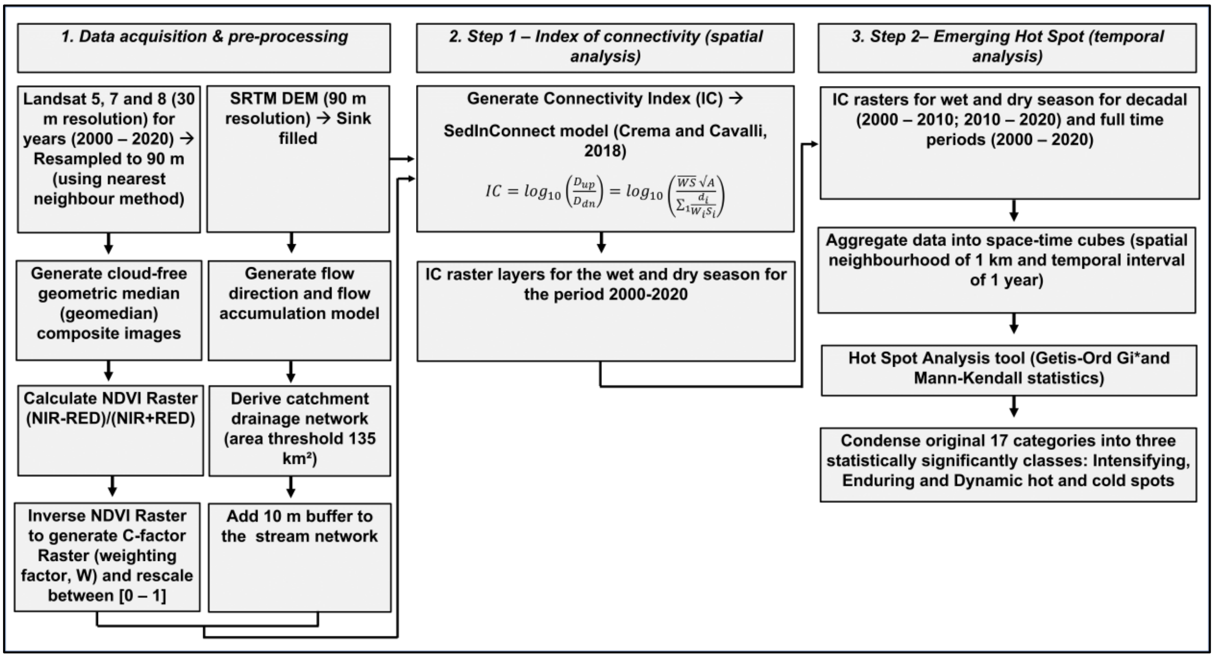


Figure 2. Workflow illustrating the datasets and methodology used in the present study. Section 1 involves data acquisition and pre-processing of satellite imagery and DEM data using ArcGIS Pro. The processed data was then used to generate the C-factor raster and stream network. Section 2 involved using the DEM, stream network and C-factor in the SedInConnect model to calculate the connectivity index (IC) rasters (spatial analysis). Section 3 involved using outputs from section 2 to run the Emerging Hot Spot analysis (temporal analysis).

3.2 Spatiotemporal dynamics of connectivity

Step 1 – Index of connectivity (spatial analysis)

We used the standalone SedInConnect connectivity model by Crema and Cavalli, (2018) to assess the seasonal hydrological and sediment connectivity for the Mara River catchment over a 20-year period (2000 – 2020). The topography-based IC was initially developed by Borselli et al. (2008) and later refined by Cavalli et al. (2013). Cavalli et al. (2013) introduced surface roughness as a weighting factor to model impedance to sediment delivery, which substituted the original soil and land-use criteria used by Borselli et al. (2008) and changed the D8 algorithm to D-infinity to calculate flow direction in areas with dispersive flow. Previous studies have applied the modified IC to smaller river catchments with very high resolution DEMs (e.g. Borselli et al., 2008; Cavalli et al., 2013; Singh et al., 2017), with fewer studies applying it to larger river catchments with coarser-resolution DEMs (e.g. Mishra et al., 2019). In this paper, we have applied the IC to a large river catchment (13 750

km^2) with a coarser DEM (90 m resolution) to understand the interaction between hillslopes and channels, and the broader-scale connections between source, transfer, and deposition zones in the catchment.

The input parameters of the IC model included a sink-filled DEM (90 m spatial resolution, for slope measurements), weighting factor (NDVI layer for vegetation impedance), and stream network of the catchment (against which the connectivity potential was calculated) (Fig. 2). The IC algorithm was calculated for each raster cell of the DEM and divided into two parts, the upstream (D_{up}) and downstream components (D_{dn}). The D_{up} was used to estimate the potential for water and sediment movement downslope by considering several variables (e.g. slope, upslope contributing area, and a weighting factor). The D_{dn} component was used to calculate the flow path length to the target (stream network) as a function of the slope and weighting factor chosen. To account for potential flow divergence on hillslopes, the upstream contributing area was calculated using the multiple flow D-infinity algorithm, while the steepest flow path was calculated using the D8 algorithm to assign the downslope component of the IC index. Equation (1) describes the calculation of the index of connectivity.

$$IC = log_{10}\left(\frac{D_{up}}{D_{dn}}\right) = log_{10}\left(\frac{\overline{WS}\sqrt{A}}{\sum_1 \frac{d_i}{W_i S_i}}\right) \qquad (1)$$

In the upstream component, A is the upslope contributing area (m^2), $\overline{W}$ is the average weighting factor or surface roughness (dimensionless), and $\overline{S}$ is the average slope of the upslope contributing area ($m.m^{-1}$). In the downstream component, d_i is the length (m) of the flow path of the i^{th} raster cell along the steepest downslope pathway, and W_i, and S_i are the weighting factor and slope gradient of the i^{th} raster cell, respectively. The revised IC values are defined in the range of $[-\infty, +\infty]$, with potential connectivity increasing for more positive IC values. The weighting factor or surface roughness ($\overline{W}$) represents the impedance to runoff and sediment fluxes due to vegetation and/or soil properties and is calculated by the NDVI weighting layer. The output of the model included IC raster layers for each season over the period of analysis and each pixel represented a connectivity value.

Step 2 – Emerging Hot Spots (temporal analysis)

The IC raster outputs from the previous step were grouped into wet and dry seasons, and decadal (2000 – 2010; 2010 – 2020) and full time periods (2000 – 2020), resulting in six datasets. The datasets were aggregated into space time cubes which consisted of individual bins that incorporated spatial and temporal data into the analysis (Rew and Davis, 1990; ESRI, 2018 a, b). Each bin was characterised by a spatial neighbourhood of 1 km and temporal time-step interval of 1 year, with the value of each bin representing the potential connectivity for a given location in a specific year. Space time cubes were used to run the Emerging Hot Spot (EHS) analysis tool in ArcGIS Pro to assess the spatiotemporal patterns of connectivity across the Mara River catchment. The EHS tool was used to identify regions or 'hotspots' that exhibited a statistically significant clustering of high and low connectivity over time. Hotspots represented regions where underlying spatial processes were occurring and not solely the result of random processes (Getis and Ord, 2010).

The degree of clustering and temporal trends of these hotspots were calculated using the Getis-Ord Gi* and Mann-Kendall statistics, respectively (Mann, 1945; Ord and Getis, 1995; Harris et al., 2017). The Gi* statistic was used to compare the averages of the local IC values (specific region) to the global IC values (whole Mara catchment) and assigned statistically significant z-scores and p-values to regions that had distinct local averages (Ord and Getis, 1995; ESRI, 2018c). The statistically significant regions were clustered into hotspots if the local IC values were greater than the global IC values and coldspots if the local IC values were lower than the global IC values. For example, if the difference between the local and global averages was too large to be a result of random chance, the point was given a statistically significant z-score ($-1.96 < z > 1.96$) and p-value ($p < 0.05$) representing the presence of a hotspot or coldspot. The larger the z-score ($z > 1.96$) the more intense the hotspot and the smaller z-score ($z < -1.96$) the more intense the coldspot (Esri 2018c).

The Mann-Kendall trend test, which is a non-parametric application of Kendall's rank order correlation test, was used to analyse the temporal connectivity patterns in the Mara catchment over the 20-year period. Each bin was ranked by comparing the current time step bin with the previous year's bin and assigned a ranking value of [+1, -1, or 0] if the bin in the current time step is greater, less than, or equal to the previous bin, respectively. These ranks were summed and used to determine if there was a significant difference or not. A region with a positive z-score indicates an increasing connectivity trend over time (Esri 2018c). The statistically insignificant clusters were discarded from the analysis. A False Discovery Rate correction was applied to reduce errors associated with false positives for a given confidence level and adjusts the critical p-value. To reduce the noise of the EHS outputs, we condensed the original 17 categories into three statistically significantly classes by combining categories that represented similar spatiotemporal dynamics. The three new classes included intensifying, enduring and dynamic hot and cold spots (Table 1). The enduring and intensifying classes represent regions that have consistently reflected higher or lower connectivity over time. Whereas the dynamic connectivity class represents regions that are not stable but rather continuously fluctuate between high and low connectivity over time.

Table 1. Classes and descriptions representing the Emerging Hot Spots (Esri 2018a). The original classes were modified into new classes by combining categories that represented similar spatial and temporal dynamics. Hot spots refer to regions of high connectivity and cold spots refer to regions of low connectivity

New Class	**Original class**	**New class descriptions**
Intensifying Hot Spot	Intensifying Hot Spot	Location where statistically significant *hotspots* occur for more than 90% of the time (years), including the last time step. Specific regions exhibit statistically significant increases in high values compared to the entire catchment.
Enduring Hot/Cold Spots	Persistent	Location where statistically significant *hot or cold spots* occur for more than 90% of the time (years).
	Historical	
	Diminishing	
Dynamic Hot/Cold Spots	Sporadic	Location where statistically significant *hot or cold spots* occur for less than 90% of the time (years).
	Oscillating	
	New	
	Consecutive	
Intensifying Cold Spot	Intensifying Cold Spot	Location where statistically significant *coldspots* occur for more than 90% of the time (years), including the last time step. Specific regions exhibit statistically significant increases in low values compared to the entire catchment.
No Pattern Detected	No Pattern Detected	Location does not represent a clear and obvious pattern.

4 Results

4.1 Connectivity patterns through the catchment

Different sections of the river (i.e. source, transfer, sink zones) have different connectivity signatures, and this is highlighted in Figure 3. The source zone in the Upper catchment, at elevations between 1700 m and 2700 m, has the steepest gradient (>0.01 m.m^{-}1) and high mean annual precipitation (1570 mm). This region reflects the highest connectivity patterns in catchment with higher IC values in the wet season (-4.66) compared to the dry season (-4.98). The transfer zone in the Middle catchment begins 115 km downstream from the headwaters, at 1700 m, and continues for 175 km downstream to 1200 m in elevation. This region is characterised by gradual slopes (0.003 m.m^{-}1) and low mean annual precipitation (1095 mm) and reflects moderate connectivity patterns for both seasons (-5.05). The sink zone in the Lower catchment, at elevations between 1200 m and 600 m at the Mara River confluence with Lake Victoria, comprises the lower 104 km of the trunk (main) stream. This region is characterised by very gradual slopes (0.0007 m.m^{-}1) and low mean annual precipitation (1170 mm) and reflects the lowest connectivity patterns in the catchment, with higher values in the dry season (-5.06) compared to the wet season (-5.17). In the dry season the longitudinal downstream trends in connectivity are less pronounced compared to the wet season.

4.2 Connectivity patterns over time

4.2.1 Decadal periods

During the first decadal period (2000 – 2010), the Upper and Sand River catchments reflect the highest proportion of total enduring hotspots representing an area of 220 km^2 and 185 km^2 during the wet season (Fig. 4; Fig. 5). This pattern is similar in the dry season, but the proportion of total enduring hotspots covers a smaller area (78 km^2 and 134 km^2). The Sand River catchment has the highest proportion of total wet season intensifying hotspots (51%) representing an area of 222 km^2. The highest proportion of total enduring and intensifying coldspots also occur in the Sand River catchment representing an area of 508 km^2 and 8 km^2, respectively. A similar pattern is observed in the dry season, but enduring hot spots cover a smaller area of 219 km^2 while intensifying hotspots cover a larger area of 106 km^2. Similar trends during the second decade (2010 – 2020) are evident. For instance, the Upper and Sand River catchments are also the main contributing subcatchments during this period and reflect the highest proportion of total enduring hotspots representing an area of 893 km^2 and 1198 km^2, respectively, during the wet season (Fig. 4, Fig. 5). This pattern is similar in the dry season, but the Sand River catchment contributes towards maximum net connectivity of the catchment as it comprises a higher proportion of the total enduring hotspots and covers a greater area (1681 km^2). In both the wet and dry season, the Sand River catchment comprises the highest proportion of total intensifying hotspots representing an area of ~20 km^2. The Lower catchment exhibits the highest proportion of total enduring coldspots, representing an area of 663 km^2 and 219 km^2 in the wet and dry season. The highest proportion of intensifying coldspots occurred in Talek River catchment in both seasons, indicating that this catchment has regions of low connectivity potentials that contribute minimally towards catchment's connectivity during this period.

4.2.2 Full period (2000 – 2020)

On average 63% of the total catchment is covered by dynamic coldspot clusters in both seasons (Fig. 4, Fig. 5). These clusters represent regions that are regularly changing between hot and coldspots (Table 1), indicating that no continuous positive nor negative contribution is being made toward the catchment's connectivity over time. At the subcatchment scale, the Upper and Sand River catchments have higher connectivity potential and hence, contribute towards higher net connectivity to the catchment in both seasons over time. The Sand River catchment comprises 30% of the total catchment area and accounts for 40% of the total enduring hotspots, representing an area of 650 km^2 in the wet season (Table 2; Fig. 4, Fig. 5). A similar trend is observed in the dry season, but enduring hotspots cover a smaller area (506 km^2). The Upper catchment comprises 32% of the total enduring hotspots covering an area of 530 km^2 and this trend is lower (26%; 302 km^2) in the dry season.

Although the Upper catchment only comprises 17% of the total catchment area, it accounts for 91% of the total intensifying hotspots representing an area of 70 km^2 (Table 2). In contrast, the Talek River catchment contributes minimally towards the catchment's connectivity for both seasons over time. The highest proportion (44%) of total enduring coldspots representing an area of 611 km^2 occurs in the Talek River catchment and this is followed by the Lower catchment (24%, 331 km^2) in the wet season. However, in the dry season the Talek River and Sand River catchments comprise a lower proportion of total enduring coldspots and cover a smaller area (~8 km^2). The Sand River catchment comprises

64% of total intensifying coldspots representing an area of 253 km^2 in the wet season. A similar pattern is evident in the dry season but total intensifying coldspots are dominant in both the Talek River and Sand River catchments covering a larger area (~280 km^2).

Table 2. Proportion of the subcatchments area in relation to the total catchment

Subcatchment	**Subcatchment area (km^2)**	**Proportion of catchment**
All subcatchments	13489	1
Upper	2348	0.17
Talek River	2650	0.2
Middle	1483	0.11
Sand River	4060	0.30
Lower	2949	0.22

4.3 Connectivity patterns in the protected areas

The FRs in the Upper catchment cover a smaller area (800 km^2) of the total catchment area compared to the larger SNP (3256 km^2), MMNR (1517 km^2), and CC (900 km^2) in the mid-catchment (Fig. 6). The protected areas in the Upper catchment exhibit isolated pockets of enduring and intensifying hotspots in the first decade, however in the second decade, enduring hotspots increase by a factor of seven and represent the dominant connectivity pattern in this area. Similar increases in enduring hotspots between the two decades are evident in the dry season. Interestingly, areas of dynamic and enduring coldspots in the FR intensify between the two decades exhibiting strengthening coldspots. In the Middle catchment, the SNP, MMNR and CC areas reflect predominantly dynamic connectivity patterns over time (Fig. 6). Between the two decadal periods enduring hotspots increase by a factor of 18 in the SNP and 15 in the MMNR and CC areas in the wet season. Similar patterns are evident in the dry season, but the increase in enduring hotspots is more pronounced between the two decades compared to the wet season. The floodplain wetland in the Lower catchment exhibits enduring coldspots that intensify in the second decade, indicating persistently low connectivity over time.

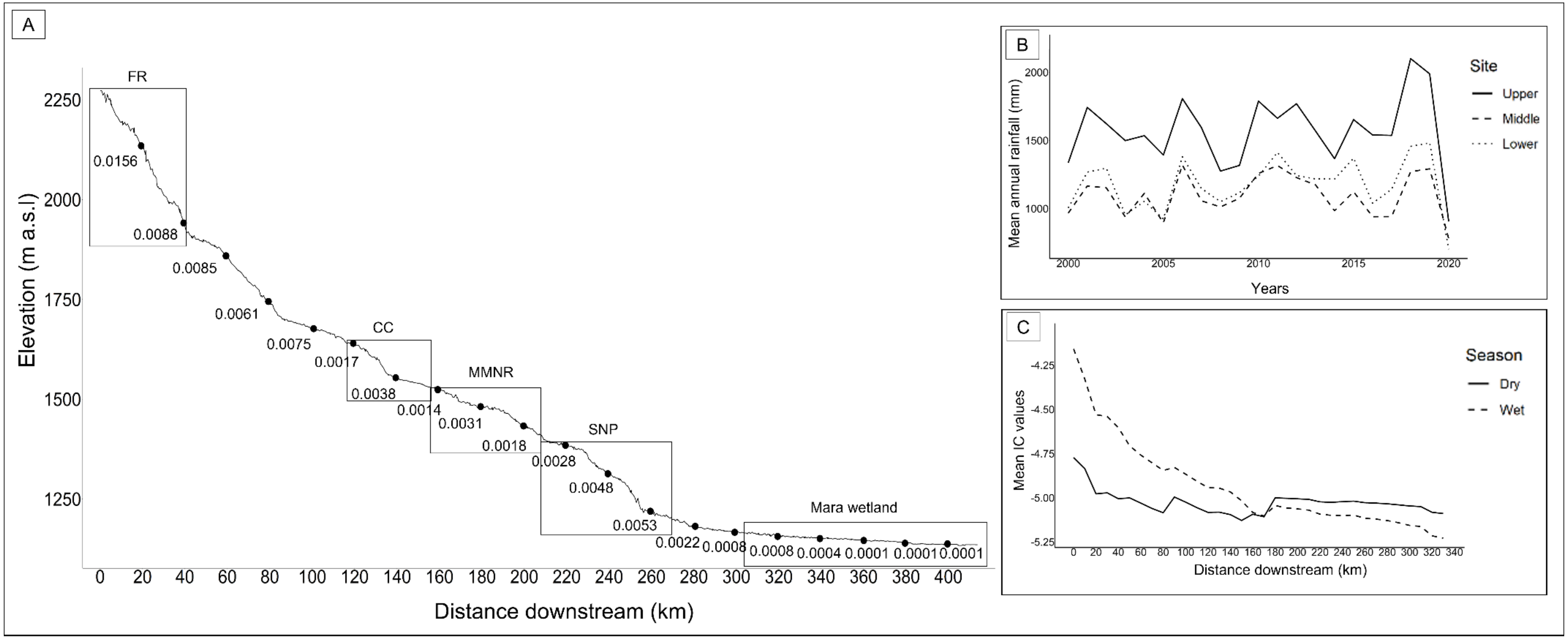


Figure 3. The connectivity index is plotted along the longitudinal profile of the Mara River, highlighting the different connectivity signatures of different sections of the river (e.g. upstream source zone, middle transfer zones, downstream deposition zones). A) Elevation profile highlighting the protected areas and change in slope downstream. The protected areas include FR – Forest reserves, CC – Community conservancies, MMNR – Masai Mara National Reserve and SNP – Serengeti National Park. B) The mean annual precipitation of the upper, middle, and lower reaches of the catchment over the full timeslice (2000 – 2020) (Climate Hazards Infrared Precipitation with Stations (CHIRPS); Funk et al. 2015; https://data.chc.ucsb.edu/products/CHIRPS – 2.0/). C) The mean IC values along the longitudinal profile for the wet and dry seasons over time.

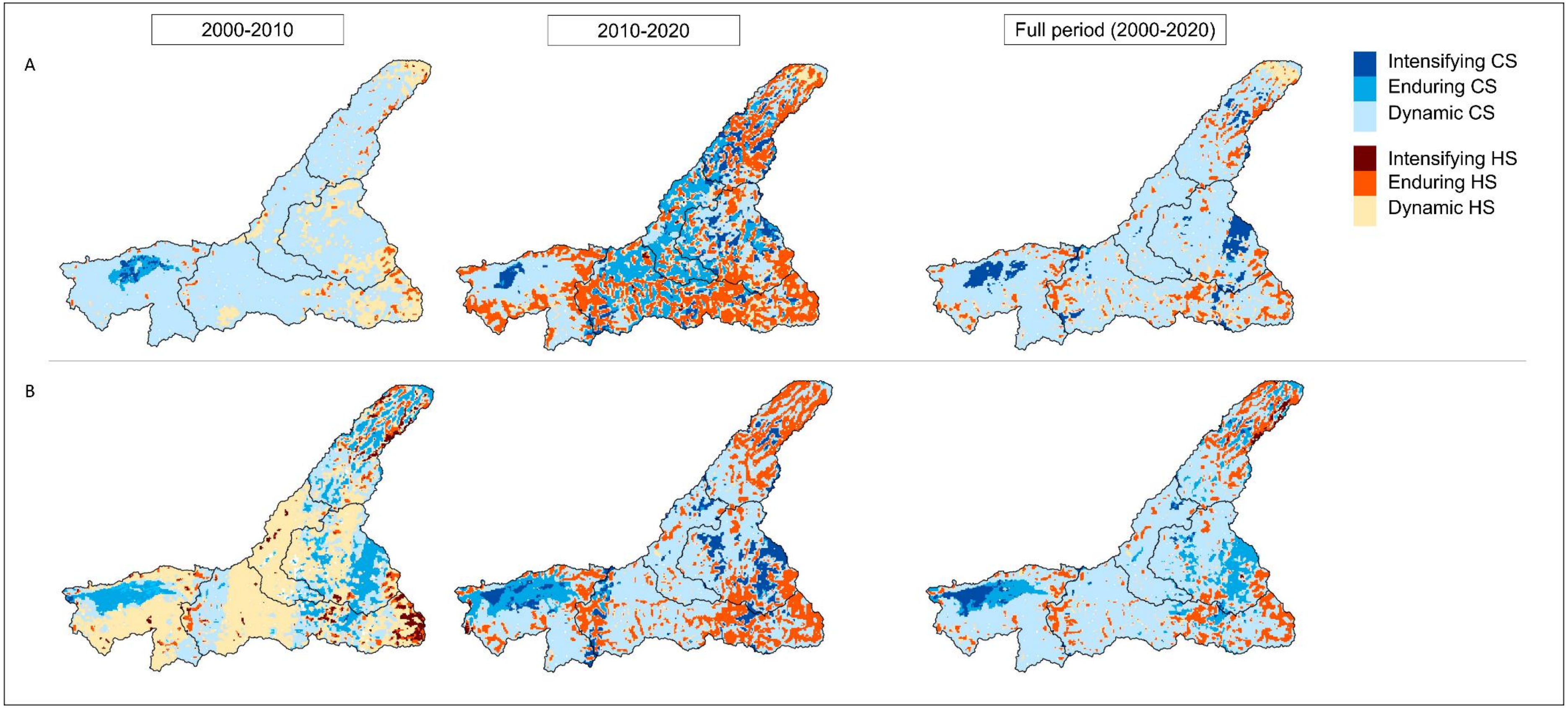


Figure 4. Subcatchment-scale connectivity patterns for the A) dry season and B) wet season over the decadal timeslices (2000-2010; 2010-2020) and the full timeslice (2000-2020). Coldspots (CS) and hotspots (HS) represent low and high connectivity, respectively.

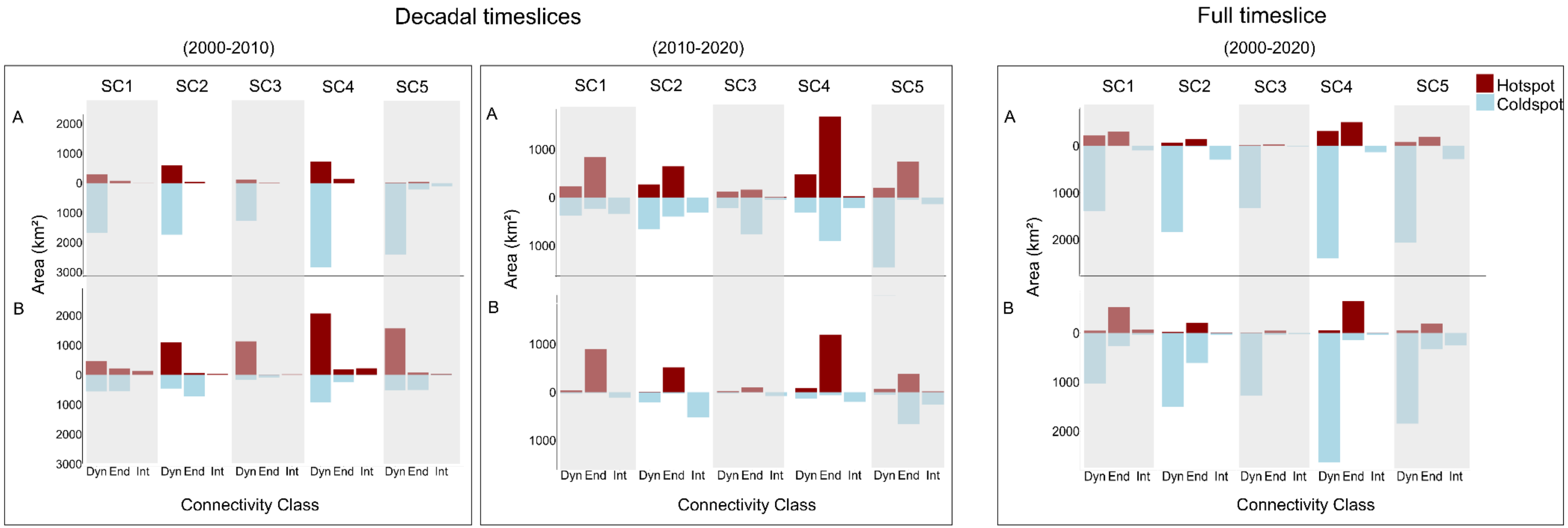


Figure 5. Total area of each subcatchment (SC) contributing towards the wetland's connectivity for the A) dry season and B) wet season over the decadal timeslices (2000-2010; 2010-2020) and the full timeslice (2000-2020). The connectivity patterns include Dynamic (Dyn), Enduring (End) and Intensifying (Int).

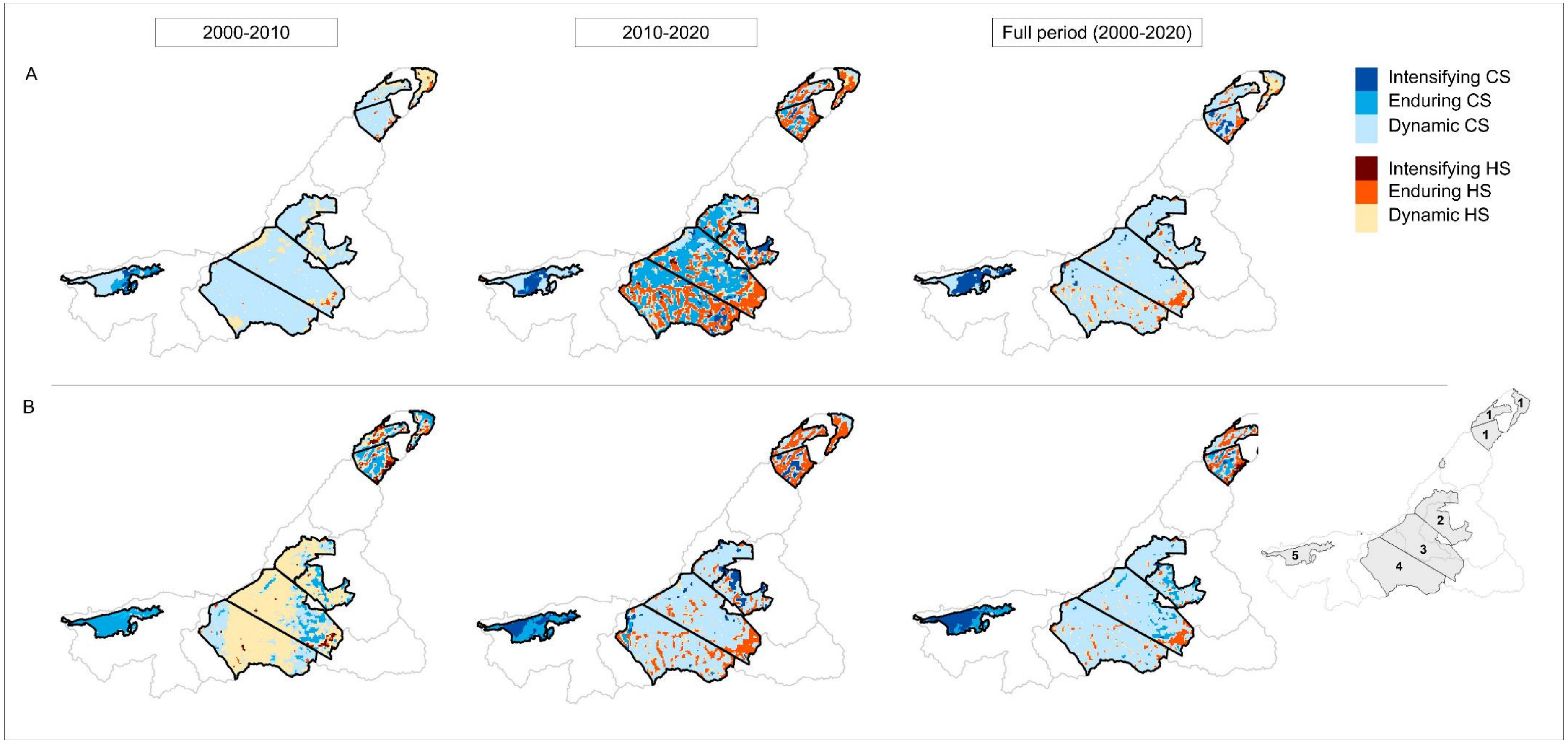


Figure 6. Connectivity patterns of the formally protected areas for the A) dry season and B) wet season over decadal timeslices (2000-2010; 2010-2020) and the full timeslice (2000-2020). The protected areas are highlighted on the map (bottom right) and include the 1) Forest Reserves (FR), 2) Community conservancies (CC), 3) Masai Mara Nature Reserve (MMNR), 4) Serengeti National Park (SNP), and 5) Mara wetland (UNEP-WCMC, 2018). Coldspots (CS) and hotspots (HS) represent low and high connectivity patterns, respectively.

4.4 Seasonal variation in connectivity

Seasonal variation in connectivity patterns is evident at the catchment and subcatchment scales and is reflected by their contrasting mean IC values (Fig. 7). The spatial hydrological connectivity index (IC) varies from (−) 5.94 to (−) 4.73, where high values represent the potential connection between hillslopes and channel and low values represent the potential disconnection resulting from the effects surface impedance, flow length and slope characteristics. The mean IC values for all the subcatchments are significantly higher in the dry season compared to the wet season over time ($t = 5.929$, $df = 5$, $p < 0.05$). An exception to this is evident in the Upper catchment which reflects higher connectivity patterns in the wet season (Fig. 7). The mean IC values for the wet season are highly variable compared to the dry season over the years. The Upper catchment exhibits the highest mean connectivity (-5.37 ± 1.02) for the wet season over the years, while the Middle catchment exhibits the lowest mean connectivity (-5.43 ± 1.02). In contrast, the Talek River catchment exhibits the highest mean connectivity (-5.13 ± 1.00) for the dry season over the years, whereas the Lower catchment exhibits the lowest mean connectivity (-5.20 ± 1.04).

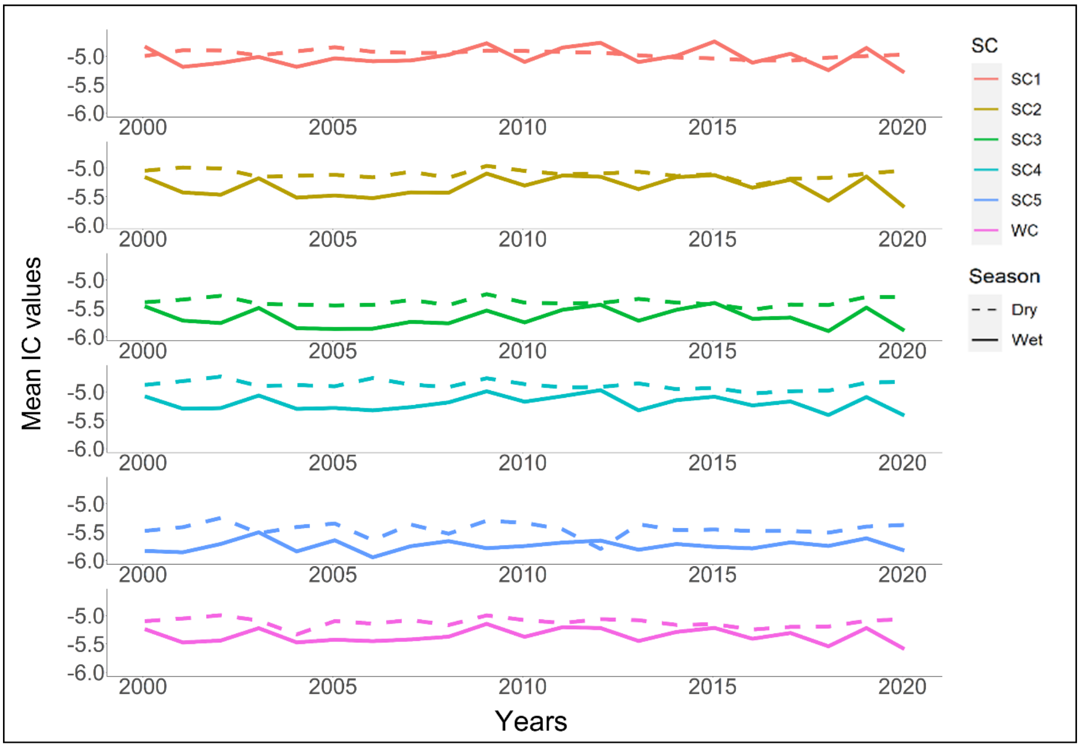


Figure 7. Mean IC values representing the spatiotemporal patterns of connectivity for the wet and dry seasons. The mean IC values are shown for the whole catchment (WC) and subcatchments (SC).

5 Discussion

5.1 Controls on catchment connectivity

The IC is a topography-based sediment index where slope and surface roughness are the main factors influencing hydrological connectivity and associated sediment dynamics (Cavalli et al., 2019). The steep-gradient topography in the Upper catchment (i.e. source zone) is highly connected and facilitates unimpeded sediment supply and transport along the fluvial corridor. The confined valleys in the upper reaches limit accommodation space and sediment storage capacity, allowing direct coupling between tributary valleys and the trunk river channel. As such, the channel is unable to adjust, resulting in a higher potential for sediment reworking and transfer downstream. The steep slopes coupled with high rainfall in this region result in greater energy to mobilise the supplied sediment and thus lateral (hillslope to channel) connectivity is high (Fig. 3). Slope is the dominant control on catchment connectivity in this region and surface roughness and/or buffers have a minimal effect. Slope and valley confinement decrease in the Middle catchment (i.e. transfer zone) resulting in sediment deposition and the formation of buffers. The presence of alluvial floodplain pockets in this region indicates that sediment storage occurs along the channel margin, which provides space for channel adjustments. Sedimentary buffers (e.g. alluvial levees and tributary fills) restrict sediment delivery from hillslopes to channels and act as disconnectors in the landscape (Fryirs et al., 2007). Moreover, owing to the gradual slopes in this region, vegetation impedance becomes an important factor influencing sediment transport over the land surface to the channel, resulting in moderate lateral connectivity. This contrasts with the Lower catchment (i.e. sink zone) where slope and valley confinement decline substantially in the valley bottom, resulting in sediment deposition and the formation of hydrogeomorphic buffers, such as floodplains and wetlands, which allows the channels to laterally migrate and adjust (Gomes et al., 2023b). Floodplains act as sedimentary buffers at the base of hillslopes where sediments mobilised on slopes are re-stored (e.g. Grenfell et al., 2009; Tooth et al., 2014). Floodplains also block tributary confluences and restrict sediment transport to the trunk channel (Brierley and Fryirs, 1999), resulting in very low lateral connectivity.

The flat topography of the floodplain in the sink zone reduces the rate of in-channel energy transfer and sediment transport capacity, resulting in sediment deposition and channel bed aggradation over time (Gomes et al., 2023a). This leads to overbank flooding and the formation of splays and avulsions, during large flood events, which results in greater lateral channel-floodplain interactions via sediment and nutrient deposition on the floodplain. Therefore, channel-floodplain connectivity is high in the wetland but the contributary lateral connections from the surrounding hillslopes to channel is low as it is buffered by the floodplain. Similar downstream morphological and hydrological changes, resulting in sedimentation and avulsions, form the primary mechanisms of channel and floodplain wetland adjustment in other dryland rivers, which are important processes driving anastomosis, and distributary formation (i.e. channel-floodplain connections), and hence wetland formation and abandonment (Ralph and Hesse, 2010). Lateral connections between the trunk channel and floodplain are critical for maintaining biophysical processes, ecosystem functioning and integrity, and feedbacks in the wetland (Ralph et al. 2011; Wohl, 2014; Fryirs et al., in press). There are a few limitations of the IC index, one of which is that it does not account for distributary outflows, highlighted by the locally suppressed connectivity in the Mara Wetlands, which is an important process that facilitates channel-floodplain connectivity. Another limitation is that it does not account for transmission losses in hyporheic zones, which is a critical component of the hydrological dynamics in alluvial rivers (Wohl et al., 2019). In this study, the IC index was useful for highlighting the hillslope-channel connectivity and the contrasts in connectivity between source, transfer and sink zones in the catchment. Overall, the catchment characteristics and hydrogeomorphic processes (e.g. confinement, slope, sedimentary buffers) are important factors that influence the (dis)connectivity of the landscape and associated sediment transport across the catchment (Fryirs et al., 2007a; Lexartza-Artza and Wainwright, 2009; Cavalli et al., 2013).

5.2 Spatiotemporal dynamics of connectivity

The catchment-scale analysis shows substantial spatial and temporal variation in connectivity patterns in the Mara River catchment reflecting the variable sediment routing efficiency of different subcatchments (Fig. 4; Fig. 5). These differences are related to a combination of controlling factors, including topographical parameters (e.g. dynamic vegetation characteristics, slope angle, contributing catchment area, and downstream distance to the stream network), climatic variables (e.g. rainfall intensity and duration) and anthropogenic activities (e.g. LULC changes), that act as boosts or barriers/buffers to the connectivity (Fryirs et al., 2007b; Lexartza-Artza and Wainwright, 2009). Throughout the catchment, connectivity patterns regularly fluctuate between high and low connectivity (e.g.

dynamic class) over time. The IC uses vegetation (in this case NDVI) as a proxy for surface roughness or impedance (Cavalli et al., 2013), and thus fluctuations in connectivity can be linked to the inter-annual and seasonal variability in vegetation cover. The natural land cover in the Mara catchment consists mainly of grasslands, savannah woodlands, and shrublands (Bartzke et al., 2018), which are sensitive to seasonal changes. For instance, grasslands respond rapidly to seasonal changes in rainfall (Anderson et al., 2007), such that higher rainfall in the wet season enhances water availability in surface soils resulting in greater grass cover (Saco et al., 2018; D'Onofrio et al., 2019). Greater vegetation cover during the wet season can increase infiltration and reduce runoff, resulting in low connectivity, whereas the opposite is true in the dry season. As such, a positive feedback cycle occurs, where greater infiltration facilitates more vegetation growth and less runoff (Saco et al., 2018). Broader climatic conditions such as drought events can also significantly affect vegetation condition (Ogutu et al., 2008; Mngube et al., 2020) and affect connectivity over time. Moreover, high magnitude events (e.g. floods) that occur during drier periods, when vegetation density is low, will likely generate higher runoff, discharge, erosion, and sediment transport into the fluvial network (e.g. Souza and Hooke 2021). This is evident in the Mara catchment where the dry season connectivity potentials are consistently higher compared to the wet season (Fig. 7). Interestingly, the Upper catchment reflected slightly higher connectivity potentials during the wet season, which can be attributed the dominant influence of the steep-gradients on connectivity patterns in this region. Overall, seasonal effects on vegetation cover, particularly in dryland regions, influence the broad-scale connectivity patterns and the long-term sediment dynamics in the catchment.

Specific regions in catchment have reflected significant variability in connectivity over time and these regions are referred to as 'hotspots' (Singh and Sinha, 2019). Over the decadal periods, hotspots of high connectivity are most prominent in the Upper and Sand River catchments (Fig. 4). Considering that these subcatchments drain steep escarpments, hydrological connectivity and associated sediment transfer is expected to be high in these high energy regions. However, the significant increases in connectivity over time, suggests that other variables, such as anthropogenic induced impacts have contributed to increased sediment mobilisation and may be responsible for driving these changes. Several studies have noted considerable changes in in land use and land cover (LULC) in these subcatchments over the past 30 years related to climatic factors, such as varying temperature and precipitation as well as anthropogenic activities, such as deforestation and conversion to agriculture lands, rangelands, and barren lands (Mati et al., 2008; Ogutu et al., 2009; Mwangi et al., 2017; Mngube et al., 2020). These changes have consequently resulted in general disturbance, reduction in vegetation cover, and enhanced runoff and erosion in the catchment. For example, Mwangi et al. (2017) reported that deforestation and the conversion to agricultural land accounted for a 25% forest loss in the Upper catchment over the past decades. They found that changes in LULC had altered the lateral connectivity patterns (hillslope-channel linkages) and contributed to higher sediment inputs into the fluvial network, consequently affecting important hydrological (i.e. increased peak flows and reduced base flows) and geomorphological processes (i.e. increased sediment deposition) farther downstream. Therefore, deforestation on steep slopes in the Upper Mara catchment has enhanced the hydrologic response during rainfall events resulting in greater runoff and soil erosion into the fluvial network (Olang and Kundu, 2011; Mwangi et al., 2016, 2017; Bregoli et al., 2019). In the Sand River catchment, the main LULC changes are attributed to mechanised agriculture (e.g. wheat cultivation) in the Loita Plains and the increase in domestic animal populations (e.g. livestock grazing) (Ogutu et al., 2011), which contributes to increased sheetwash erosion (Rapp, 1977). While the direct contributions of livestock paths and dirt roads to the Mara catchment's connectivity was not quantified in this study, it is likely that these landscape features enhance the connectivity potential and concentrate water and sediment flow into the fluvial network. In other large, steep catchments, such as the Vuvu catchment in South Africa, van der Waal and Rowntree (2017) found that gullies, roads, and livestock tracks resulted in an increase in both the down- and cross-slope funneling of water, which limited infiltration and concentrated flows, thus increasing hillslope-channel connectivity and greater sediment inputs into the fluvial network.

In the Mara catchment, the increases in sediment inputs into the fluvial network over time has resulted in downstream river change. Sediment deposition occurs farther downstream and accumulates in existing sediment buffers in the lowland floodplain wetland. Recent sediment dating research supports this and shows how increases in LULC changes in the Upper catchment over the past decade have led to substantial increases in sediment inputs in the Mara wetland (Dutton et al., 2018; 2019). In addition, some studies suggest that these increases in sediment loads have led to an increase in wetland area (> 300%) over time (Mati et al., 2008). Dutton et al. (2019) found that the highest proportion of suspended sediment entering the Mara wetland originated from the Upper catchment followed by Sand River and then Talek and Middle Mara. This provides support for our results and highlights the importance of the Upper catchment as the primary contributor of sediment inputs to the fluvial network. Interestingly, they also found that the proportion of total sediment entering the wetland from the Upper catchment had decreased over time, despite the quantity of sediment increasing (Dutton et al., 2019). This change in proportional sediment load was attributed to the increasing contribution of sediment from the Talek catchment over time. This is evident in Figure 4, which shows increasing hotspots of high connectivity in the Talek region during the second decade. The Talek River catchment has experienced landscape degradation since the 1970s, with the region now being dominated by rangelands and agriculture, which has resulted in increased erosion (Rapp, 1977). Therefore, with continued LULC changes, it is likely that this region may become an increasingly important sediment source to the fluvial network and wetland in the future (Dutton et al., 2019). The increased sedimentation in the lowland floodplain wetland (Dutton et al., 2019) have also been linked to changes in channel morphology and avulsive behaviour in the wetland (Gomes et al., 2023b). Therefore, it is important to understand how climatic and/or anthropogenic related impacts affect connectivity patterns in the catchment as this has important implications for sediment dynamics, geomorphic processes, and ecosystem infrastructure farther downstream in the floodplain wetland.

5.3 Connectivity patterns and management implications

An understanding of how different river reaches are connected and may respond to disturbances can help identify regions that need to be prioritised for management, and to decide whether parts of a system can and/or should be managed independently of other parts. The highly connected, confined river in the upper reaches can be classified as ‘resistant’ as it is unable to adjust and thus can effectively propagate disturbances downstream (Khan and Fryirs, 2020). Whereas the moderately connected, partly confined river in the middle reaches acts as a corridor of sediment transport and can be classified as ‘passive sensitive’ (Khan and Fryirs, 2020). This river reach can absorb and recover from disturbance events and thus disturbances are less effectively propagated downstream. In contrast, the poorly connected, unconfined river in the lower reaches can be classified as ‘sensitive’ as it can re-configure on the floodplain wetland in response to disturbances (Khan and Fryirs, 2020). Therefore, under future predictions of increasing pressure from anthropogenic and climate impacts in this region (Bartzke et al., 2018), the catchment is expected to become more connected which may lead to increased sediment loads into the fluvial network. For instance, if deforestation intensifies or population expansion results in increased LULC change, it is likely that the highly connected river in the upper catchment will remain ‘resistant’ and continue to contribute substantial sediment loads into the fluvial network. As such, this region may need to be prioritised for management to reduce increased sediment loads being transported downstream to the floodplain wetland and associated increases in pressure along the sensitive reaches. Catchment-scale restoration efforts should focus on increasing disconnectivity at the hillslope-scale, thereby buffering the landscape and increasing sediment storage. For instance, current conservation efforts to restore forest growth (e.g. afforestation) in the Upper catchment (Mngube et al., 2020), which would likely greatly reduce erosion on steep hillslopes, could be expanded to other regions. Moreover, management efforts could focus on designing sustainable sediment management strategies in highly connected parts of the catchment and along the trunk stream.

The moderately connected river in the middle catchment will likely remain stable as this region is well protected and is currently of least concern. In general, protected areas in the catchment are less well-connected due to intact/natural vegetation and limited anthropogenic impacts. As such, lateral connectivity is lower in these areas, and they contribute lower sediment inputs into the fluvial network compared to unprotected regions. However, intensification of natural and/or anthropogenic disturbances within and outside these protected areas may lead to the river becoming more ‘sensitive’. For instance, wildlife migratory routes that traverse the river may increase hillslope-channel connectivity as well as destabilise channel banks, thereby contributing greater quantities of sediment into the fluvial network. Similarly, increased anthropogenic pressure (e.g. domestic grazing stock) along park borders may increase sediment inputs into the river (Veldhuis et al., 2019; Kihwele et al., 2021). In both cases, wildlife and livestock tracks can reduce vegetation cover, resulting in enhanced runoff and hydrological connectivity that may lead to channel incision by gullies. These hydrological and geomorphological changes concentrate surface and sub-surface flow, thereby increasing sediment inputs into the fluvial network. In other studies livestock tracks have been shown to contribute to gully erosion by routing runoff downslope along entrenched pathways, as well as created cross-slope pathways that consequently increased the drainage density and thus connectivity in the catchment (van der Waal and Rowntree, 2018).

Therefore, management efforts in these regions will need to focus on targeting localised impacts if these trends continue. For instance, restoration of vegetation cover and buffers in and around gullies, livestock tracks and dirt roads (e.g. tourism vehicles) can reduce runoff by facilitating sediment deposition and water infiltration.

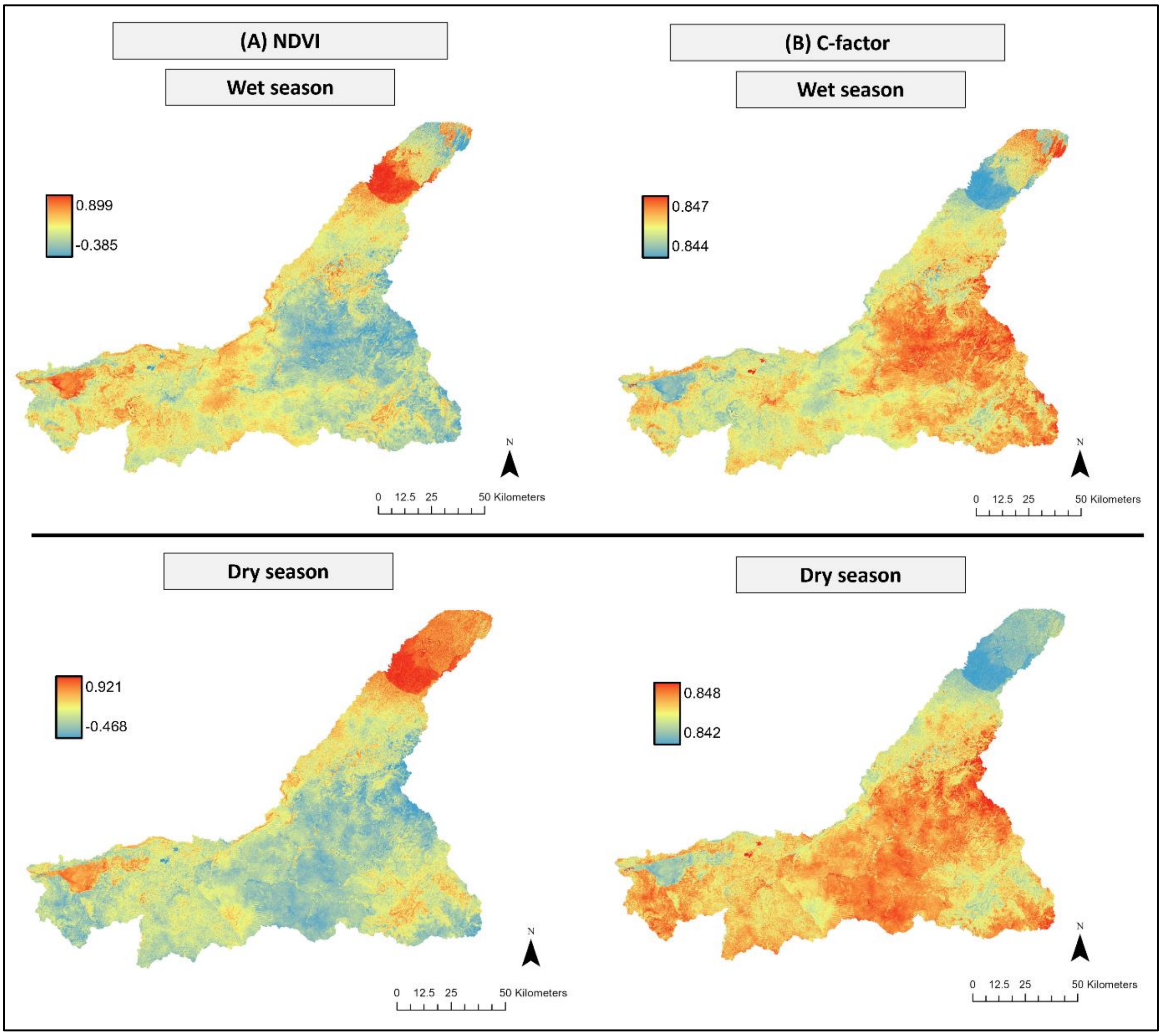
In contrast, the poorly connected river in the floodplain wetland may become more 'sensitive' and undergo more frequent avulsions due to an increase in upstream sediment supply, resulting in in-channel sedimentation, with the potential of becoming longitudinally disconnected. Avulsions increase channel-floodplain interactions which is critical for maintaining ecological functioning, biodiversity dynamics and feedbacks in the wetland, however the rate at which avulsions occur may increase, with potential negative impacts on ecological succession and wetland evolution (Ralph and Hesse, 2010, Ralph et al., 2011; Wohl, 2014). Moreover, this region is heavily inhabited by local communities who utilise the floodplain for agriculture, livestock grazing and harvesting resources (Bregoli et al., 2019) and thus may need to be managed in terms of sediment aggradation and associated risks (i.e. avulsions and floods), while preserving ecosystem functioning and associated services. Nevertheless, the allogenic nature of the wetland emphasises the need to focus management efforts on sediment dynamics in the upper reaches of the catchment. Along the trunk stream, a combination of land use, vegetation, and animal (wildlife and grazing stock) management will be needed to promote stable river channels (bed and banks) as well as an appropriate balance of water to sediment transport. For instance, an increase in catchment connectivity will likely lead to an increase in the propensity for avulsions, whereas a decrease in connectivity may lead to increased bank erosion, with potential negative impacts on the wetland (i.e. channel incision and loss of wetland functioning). Overall, the connectivity analysis has proven useful for identifying regions within the catchment that may be more sensitive to disturbances and that need to be prioritised for management. Managers can then concentrate on these regions and employ higher-resolution analysis to develop localised management strategies.

6 Conclusion

In this study we assess the hydrological and sediment connectivity of the Mara River catchment to understand the large-scale hydrogeomorphic processes driving sediment transfer across the catchment. The Mara River catchment is characterised by varying landscape properties and contrasting LULC patterns that affect sediment mobilisation from hillslopes to channel, as well as along the channel to the floodplain wetlands in the lower reaches. We use the IC model and EHS analysis to assess the seasonal and decadal patterns of connectivity and identify specific subcatchments that have contributed positively to the wetland's connectivity over time. We find that the highly connected Upper catchment is responsible for contributing the highest sediment inputs into the fluvial network, which affects the geomorphic processes and functioning of the river and floodplain wetland farther downstream. Under greater anthropogenic and climatic pressures, the Upper catchment may need to be prioritised for management to protect the river's natural hydrological and sediment regime and reduce further increases in sediment inputs into the fluvial network. In addition, increasing attention should be given to conservation of the Sand and Talek subcatchments. This is particularly important to maintain ecosystem functioning and biophysical processes in protected areas farther downstream. Crucially, it is essential that when managing and restoring wetland systems, managers need to address the original cause of changes to sediment and water supply patterns in the catchment. Although conservation areas, such as the Serengeti-Mara ecosystem and the Mara Wetland are managed in isolation, new approaches may need to be adopted to account for anthropogenic impacts emanating from the upstream catchment. Concerns surrounding water quality and quantity and the drivers of sedimentation rates in the Mara River have been an important issue in the last decade, both from a political and conservation standpoint. Water resource management efforts are needed in the Mara River to sustain the livelihoods of local communities, as well as the preservation of the protected areas, with potential consequences for the region's economy, wildlife, and human health.

The results also highlight that the connectivity analysis presented here can be beneficial to understand the broad-scale wetland-catchment connectivity dynamics in a large river basin, where extensive fieldwork campaigns for mapping hillslope-channel linkages are not possible or feasible. However, addressing hotspots of connectivity at a finer, system scale (with higher resolution imagery) may also be useful for identifying more localised patterns in a large heterogenous catchment. An important area of further investigation is to understand the role of climate and its influence on LULC in driving connectivity patterns. Ultimately, understanding the patterns and variability of hillslope to channel connectivity and the broader-scale connections between source, transfer, and deposition zones in the catchment can help to identify and prioritise existing and emerging hotspots of change in hydrological landscapes.

Supplementary Information



Supplementary Figure 1S. The weighting factor used in the connectivity model. (A) NDVI rasters for the wet and dry season scenarios for 2019, and (B) the corresponding C-factor rasters (inverse of NDVI). Regions of high connectivity are represented by high values (red) and regions of low connectivity are represented by low values (blue).

CHAPTER 5

Discussion and synthesis

1 General overview

This thesis has examined the recent geomorphological development of an ecologically significant dryland river system in East Africa. Evidence from the transboundary Mara River system provides novel insights into dryland river character and behaviour, as well as the hydrogeomorphic controls that have driven geomorphic adjustments in the recent past. In the lower Mara River, numerous large, sinuous meandering palaeochannels adjusted primarily by lateral channel migration and periodic avulsion on the floodplain, before transitioning to the smaller, sinuous modern system that exhibits splays, avulsions and a nonequilibrium response to hydrological decline through channel breakdown in the floodplain wetlands (**Chapter 2**). The threshold responses of the Mara River are related to the system's capacity to adjust, with more sensitive reaches in the unconfined floodplain experiencing greater adjustments and higher migration rates (**Chapter 3**). These geomorphic responses in the lowland floodplain wetlands are largely influenced by the broad-scale hydrological and sediment connectivity in the catchment (**Chapter 4**). Overall, the analysis of river morphology and channel discontinuity of the Mara system has highlighted the importance of valley setting and hydroclimate as long-term controls in defining fluvial geomorphology, and the significance of understanding likely river responses to future impacts from anthropogenic activities and climate change.

This discussion chapter is structured around the key questions that guided this research (Table 5.1). First, the intrinsic processes of, and extrinsic controls on river morphology and floodplain wetland formation in the Mara River system will be discussed in relation to other dryland rivers, thereby contributing to the existing fluvial geomorphology literature on the development of dryland fluvial systems (**Section 5.2**). Second, the key controls of landform sensitivity and landscape connectivity in driving geomorphic responses of dryland river systems will be discussed (**Section 5.3**). Third, the geomorphological impacts of future climate and anthropogenic change on dryland rivers and wetlands, as well as management implications are considered (**Section 5.4**). Finally, the limitations of this research are acknowledged, and directions of future research is highlighted (**Section 5.5**).

Table 5.1. Outline of the main research questions and associated objectives, the research approaches used, and the key findings of each chapter in this thesis

Research questions	Thesis objectives	Thesis chapters and research approaches used therein	Key findings
1) What are the main geomorphic controls that influence river morphology and floodplain wetland formation in the lower Mara River system?	A) Characterise the downstream geomorphological changes in the lower reaches of the modern Mara River and its adjacent palaeochannels. B) Examine the extrinsic controls and intrinsic processes driving the character and behaviour of the modern river and its palaeochannels.	**Chapter 1:** - Introduction to dryland rivers and wetlands. - Overview of key controls and processes. **Chapter 2:** - Morphometric analysis and mapping of palaeochannels and modern channel using satellite imagery. - Discharge and stream power modelling using morphometric variables to estimate the palaeo-discharge and contrast with modern river discharge.	**Chapter 2:** - The larger, higher energy paleochannels transported greater discharges compared to the smaller, lower energy modern river. - Both the modern channel and palaeochannels exhibit channel decline, avulsions, and channel breakdown in the floodplain wetlands representing a nonequilibrium response to rapidly declining fluvial energy.
2) Which hydrogeomorphic processes drive river adjustment and landform sensitivity (i.e. natural range of variability) and define the overall character and behaviour of the lower Mara River and its floodplain wetlands?	C) Quantify the spatiotemporal distribution of channel adjustments and landform sensitivity in the lower Mara River.	**Chapter 3:** - Use satellite imagery to quantify the spatiotemporal distributions of historic channel adjustments. - Use geomorphic adjustments to quantify river sensitivity. - Establish scenarios of future river responses and sensitivity states.	**Chapter 3:** - In the lower Mara River the upper and lower reaches are ‘Passive sensitive’ exhibiting limited adjustments and low migration rates. Whereas the middle reach is ‘Fragile’ exhibiting numerous adjustments and higher migration rates. - The lower reach appears to be threshold driven and may switch to a Fragile state where avulsions become dominant.

Research questions	Thesis objectives	Thesis chapters and research approaches used therein	Key findings
3) How do patterns of hydrological and sediment connectivity and landform sensitivity affect the geomorphology of the lower Mara River system?	D) Quantify the spatiotemporal patterns of hydrological and sediment connectivity in the Mara catchment and assess its influence on the geomorphology of the floodplain wetlands.	**Chapter 3:** - Consider the role of connectivity and landform sensitivity. **Chapter 4:** - Determine patterns of connectivity in relation to catchment setting and conservation reserves. - Discuss hydrogeomorphic controls driving hydrological and sediment connectivity and assess its influence on the geomorphology of the floodplain wetlands.	**Chapter 4:** - The upper catchment is highly connected and is responsible for the greatest sediment inputs into the fluvial network which results in downstream sedimentation. - Increased sedimentation results in changes to wetland geomorphology and hence ecosystem services with implications for management.
4) How will the lower Mara River respond to future changes in hydroclimatic or anthropogenic impacts?	E) Use landform sensitivity and landscape connectivity to assess future trajectories of river response to climate and anthropogenic change.	**Chapter 5:** - Conceptual model of geomorphological changes in the Mara system. - Highlight the utility of threshold river response, sensitivity, and connectivity in assessing past, present and future geomorphological changes in the Mara system.	- The findings from this thesis provide novel insights into dryland river character and behaviour, as well as the hydrogeomorphic processes that contribute to geomorphic adjustments in the Mara system. - A deeper understanding of the biophysical controls, forms, and processes of river adjustment as well as states of sensitivity and patterns of connectivity are imperative for guiding conservation and management efforts.

2 Geomorphic response of dryland fluvial systems

The detailed analysis of the geomorphological development of the lower Mara River and its floodplain wetlands presented in this thesis contributes fundamental insights into the controls and mechanisms that drive dryland river character and behaviour, as well as highlighting the type of river response and geomorphological sensitivity of this dryland river system. Despite a long history of channel change seen through palaeochannels in the lower Mara, over a relatively short period (the previous 32 years), the modern Mara River exhibits significant morphological and hydrological changes (e.g. channel adjustments, avulsions, declines in discharge), resulting in adjustments to its channel behaviour. While previous studies have attempted to disentangle the role of intrinsic and extrinsic controls in driving changes in river response globally, isolating the relative importance of each control remains challenging. In the following section, a compilation of published research on dryland rivers (Table 5.2) is used to explore variability in the mechanisms driving river response in these different systems and contextualise the major findings from the Mara River system presented in previous chapters of this thesis. Although the timescales of geomorphological development of these different dryland fluvial systems vary, the processes responsible for their formation can still be broadly compared. The significance of the Mara River system is also discussed, and key aspects of the changing character and behaviour of dryland rivers and their predominant controls are synthesised.

Table 5.2. Forms of geomorphic adjustments and states of connectivity and sensitivity in different dryland rivers and wetlands. Numbers in parentheses correlate to the map in Figure 1.1, Chapter 1 of this thesis

River system and climatic setting	Channel form and processes of adjustment	Geomorphological features associated with the wetlands	Connectivity and sensitivity	Timeframe of adjustments	References
(1) Lower Mara river, Tanzania (Semiarid – perennial but strongly seasonal)	• Discharge and stream power decrease downstream. Channel aggradation leads to overbank flooding and crevasse splays. • Avulsions develop through the splay deposits resulting in a distributary channel network that diverts flow from the main channel. • Persistent downstream declines in flow leads to channel breakdown in the floodplain wetland.	• Fully alluvial, meandering channel, oxbows, palaeochannels, levees and alluvial ridges. • Channel transitions between alternative states (continuous and discontinuous).	• Longitudinal sediment connectivity is high, but channel is sensitive as it actively migrates and is prone to avulsion and eventual breakdown.	• Late Holocene palaeochannels (last ~2000 years). Historical contemporary adjustments in the last 250 years.	(**This thesis**; Dutton et al., 2019; Bregoli et al., 2019)
(2) Tshwane River, South Africa (Semiarid)	• Discharge and stream power decrease downstream and reaches become transport limited. Lateral migration and channel aggradation leads to overbank flooding and incisional avulsions. • The river maintains a throughgoing channel.	• Fully alluvial meandering throughgoing channel, palaeochannels, oxbows, well-developed levees and alluvial ridges, backswamps, floodouts on some tributaries.	• Longitudinal sediment connectivity is maintained. • Channel is sensitive as it actively migrates and is prone to incisional avulsion.	• Late Holocene (last ~650 years)	(Larkin at al., 2017 a, b)
(3) Klip River, South Africa (Subhumid – perennial but strongly seasonal)	• Discharge and stream power increase downstream. Reaches are not transport limited and vertical aggradation and lateral migration occurs slowly and ultimately promote channel avulsions through an incisional mechanism. • The river maintains a throughgoing channel.	• Mixed bedrock-alluvial but meandering throughgoing channel, scroll bars, oxbows, palaeochannels, minor levees and alluvial ridges, backswamps.	• Longitudinal sediment connectivity is maintained. Despite slow lateral migration, the channel is sensitive as it is prone to incisional avulsion.	• Late Quaternary (last ~30 ka years). Historical contemporary adjustments in the last 100 years.	(Tooth et al., 2002, 2004, 2007; Marren et al., 2006)

River system and climatic setting	Channel form and processes of adjustment	Geomorphological features associated with the wetlands	Connectivity and sensitivity	Timeframe of adjustments	References
(4) Blood River, South Africa (Subhumid/semiarid – perennial but strongly seasonal)	• Main channel and tributaries decrease in size downstream and form floodouts. • Downstream decreases in discharge and sediment transport capacity means that the river is unable to maintain a continuous channel, leading to channel breakdown and floodouts. • Gully incision at the downstream end of the floodout has formed a headcutting channel.	• Upper region: fully alluvial low sinuosity channel, active and abandoned channels, floodouts, and reforming channels, palaeochannels, headcuts. • Lower region: mixed-bedrock alluvial, infilling meandering channel, oxbows, palaeochannels, gullies.	• Longitudinal sediment connectivity declines downstream leading to floodouts. • Channel is sensitive to gully incision downstream of the floodouts.	• Late Holocene palaeochannels (last ~800 years). Historical contemporary adjustments in the last ~100 years)	(Tooth et al., 2014)
(5) Okavango Delta, Botswana (Semiarid – Perennial but seasonal)	• Discharge and stream power decrease downstream due to water seeping laterally through the vegetated channel banks. Lateral migration is slow but leads to perched channel beds which promotes lateral flow dispersal through breaks in the vegetated banks into pre-existing pathways forming multiple distributary channels. • Incisional avulsion is a key mechanism leading to wetland formation.	• Fully alluvial, scroll bars, oxbows, and paleochannels. • Panhandle region: meandering channel, levees. Anastomosing channels in certain reaches. • Fan region: distributary channels that undergo avulsions.	• The panhandle channel is longitudinally connected and sensitive as it is laterally active and prone to avulsion.	• Late Holocene	(McCarthy et al., 1998) (Tooth and McCarthy, 2004) (McCarthy et al., 1998)
(6) Macquarie Marshes, Australia (Semi-arid)	• Discharge and stream power decrease downstream and reaches have an energy deficit. The downstream reaches become straighter, and the primary forms of adjustment include aggradation, channel breakdown, avulsion, and incision.	• Fully alluvial meandering channel, floodouts, shallow lakes, paleochannels. • Channel becomes discontinuous and terminates in the wetland.	• Longitudinal sediment connectivity is low, but the channel is still sensitive as it laterally migrates and is prone to avulsion.	• Historical contemporary adjustments (last ~166 years)	(Yonge and Hesse, 2009) (Ralph and Hesse, 2010) (Ralph et al., 2011) (Hesse et al., 2018)

River system and climatic setting	Channel form and processes of adjustment	Geomorphological features associated with the wetlands	Connectivity and sensitivity	Timeframe of adjustments	References
	• Local avulsions result in the formation of new anastomosing and distributary channels in the wetland. • The channel eventually breaks down in the floodplain wetland.				
(7) Warrego River, Australia, (Semiarid, intermittent to ephemeral)	• Discharge and stream power decrease downstream resulting in discontinuous channels that terminate at floodouts or in unchanneled floodplain wetlands.	• Fully alluvial, floodplain and floodout landforms.	• Decreased longitudinal sediment connectivity leading to floodouts.	• Mid-Holocene (last ~5 ka. years)	(Larkin et al., 2020)
(8) Ciénegas, North America (Semiarid to arid)	• Cycles of aggradation followed by gully incision (locally termed ‘arroyos’) results in alternative states between a continuous and discontinuous channel.	• Fully alluvial, floodplain and floodout landforms, gullies.	• Decreased longitudinal sediment connectivity leading to floodouts. • Channel is sensitive to gully incision.	• Late Holocene	(Heffernan, 2008; Hendrickson and Minckley, 1985; Minckley and Brunelle, 2007)
(9) Río Colorado, South America (Semiarid, ephemeral)	• Channel capacity (channel width, depth, and cross-sectional area) decreases downstream resulting in discontinuous channels that terminate in floodouts at the margins of Salar de Uyuni.	• Fully alluvial, floodplain and floodout landforms. • Crevasse channel and splays lead to avulsion and erosion cells.	• Decreased longitudinal sediment connectivity leading to floodouts.	• Historical contemporary adjustments (last 32 years)	(Donselaar et al., 2013) (Li et al., 2014)

2.1 Intrinsic processes and extrinsic forces driving the geomorphological development of the lower Mara River system

The lower Mara River is a highly dynamic system that exhibits ongoing adjustments to intrinsic processes and extrinsic controls. The geomorphological changes documented in the Mara system highlights its natural range of variability over the recent past. However, these changes represent a relatively short period in the evolution of this system and over longer timescales it may exhibit cyclical behaviour or alternative system states. The conceptual diagram (Fig. 5.1) highlights the cyclical behaviour of the Mara system over the recent past and the intrinsic geomorphic adjustments that drive the different river responses in the system. Both the modern river and its palaeochannels experience dramatic reductions in channel capacity, discharge, and stream power as well as changes in river behaviour (**Chapters 2 and 3**). As a result of declines in fluvial activity in the unconfined, low-gradient floodplain (sediment supply to discharge (Qs:Q) ratio increases) and the lower reaches of the river lose capacity and competence, and aggradation of sediment in the channel occurs (Fig. 5.1B). The reduced channel capacity led to overbank flooding and the formation of crevasse splays during low frequency, high-magnitude peak discharge events, which ultimately primed the reach for avulsion. The large number of preserved abandoned channels on the floodplain provides evidence for frequent avulsions and is also indicative of low rates of overbank aggradation. In the lower reaches of the floodplain, two active avulsions have diverted an increasing volume of flow and sediment onto the floodplain but have not resulted in the complete abandonment of the trunk channel. This is likely due to the low topographical gradient of the avulsed channels on the adjacent floodplain which does not provide a steep, favourable flow path that can divert the full flow volume from the trunk channel. Instead these avulsive channels operate alongside the trunk channel as single-thread, straight distributary channels. Indeed, these distributary channels may avulse completely in time but, as noted in other dryland systems (e.g. Sandover, Sandover-Bundey, Woodforde and Rio Colorado Rivers; Table 5.2), most crevasse splays do not lead to a complete avulsion of their trunk channel. Instead, crevasse splay activity eventually ceases due to aggradation-induced decreases in flow efficiency and backfilling of the splay channels. Nevertheless, these avulsions have an important local effect, contributing significantly to the overall distribution and volume of floodplain alluvium, and are an important mechanism driving sediment reworking on the floodplain through erosion and deposition processes in the lower Mara system. The river exhibits substantial energy deficits downstream of the avulsions and as a result the meandering, energy-consuming trunk channel cannot be maintained and instead an energy-enhancing straight channel forms as a final effort to surpass the wetlands, before breaking down into unchanneled flow and floodplain wetlands. The palaeochannels on the floodplain exhibit similar downstream nonequilibrium responses to the modern channel, indicating that similar avulsion processes have resulted in meander-belt floodplain aggradation over a much longer time frame.

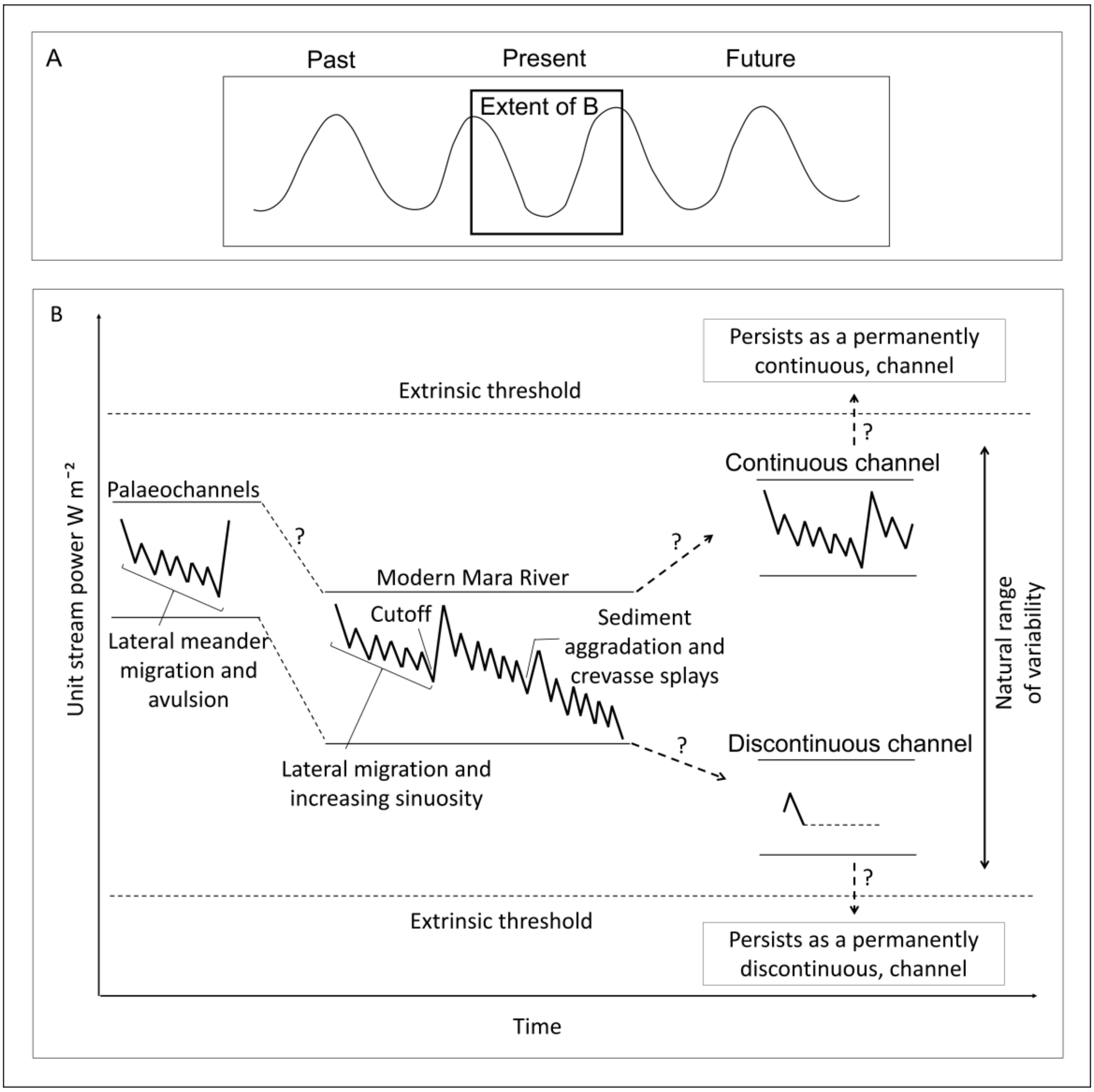


Figure 5.1. Conceptual diagram representing the river behaviour and evolution of the lower Mara River and its palaeochannels (adapted from Fryirs et al., 2012). A) The long-term (millennia) cyclical behaviour of the Mara system. This research examines the present (last 32 years) of geomorphological change in the system. B) The short-term (decades) evolution of the Mara system representing the dynamic nature of the river and highlighting the alternative system states (continuous and discontinuous channels).

The significant reductions in channel capacity and eventual breakdown of the lower Mara River and its palaeochannels in the wetlands are a response to intrinsically driven avulsions that result in a change in river behaviour (Fig. 5.1B). Intrinsic processes and associated threshold responses are responsible for ongoing channel adjustments that act to maximise flow efficiency (i.e. the ratio of sediment transported to the stream power expended) (Huang and Nanson, 2000). In some dryland rivers (e.g. Okavango, Tshwane, and Klip Rivers) (Table 5.2), reach-scale avulsions act to maximise flow efficiency to maintain a single, throughgoing channel, by abandoning inefficient reaches (Tooth et al., 2007; Larkin et al., 2017), while in others (e.g. Macquarie and Blood Rivers) (Table 5.2), similar mechanisms of channel avulsion do not always lead to channel maintenance and these rivers are characterised by channel breakdown and floodouts. For example, in the Macquarie River, persistent downstream declines in discharge and repeated avulsions result in channel termination in floodplain wetlands when channelised flow can no longer be maintained (Ralph and Hesse, 2010). Similarly, in the Mara system, avulsive behaviour leads to channel breakdown and the formation of floodplain wetlands. In this case, while the factors that prime the Mara River for avulsion are similar to the Macquarie, Okavango, Tshwane, and Klip Rivers (i.e. channel inefficiency, in- and near-channel aggradation, and advantageous lateral hydraulic gradients), ultimately avulsion is unable to improve flow and sediment transport efficiency, owing to the low-gradient floodplain topography, resulting in a discontinuous channel and a nonequilibrium response to fluvial decline.

Notably, the Mara River very recently transitioned from a discontinuous to a nearly continuous channel when what appears to be a shallow, sandy flow path cut through the Mara Wetland following significant local flooding (documented in January 2022) (Fig. 5.2). This change in morphology reflects the different system states that can occur within the natural range of variability, again highlighting the dynamic nature of the Mara system (Fig. 5.1B). Although the exact cause of this recent channel change is unknown, and it is also unknown whether the channel has bed and banks or is just a temporary flood scar in the vegetated wetlands, it is possible that wetter conditions within the catchment (i.e. greater hydrological connectivity) led to higher discharges and sediment throughput, resulting in channelised flow and a continuous state. Nevertheless, this change in river response may represent a transitional or alternative state (e.g. Heffernan, 2008; Grenfell et al., 2010, 2019, 2020), and under drier conditions, reduced flows may lead to backfilling of the new channel and vegetation re-growth, resulting in the river reverting to its previous, fairly long-lived, discontinuous state.

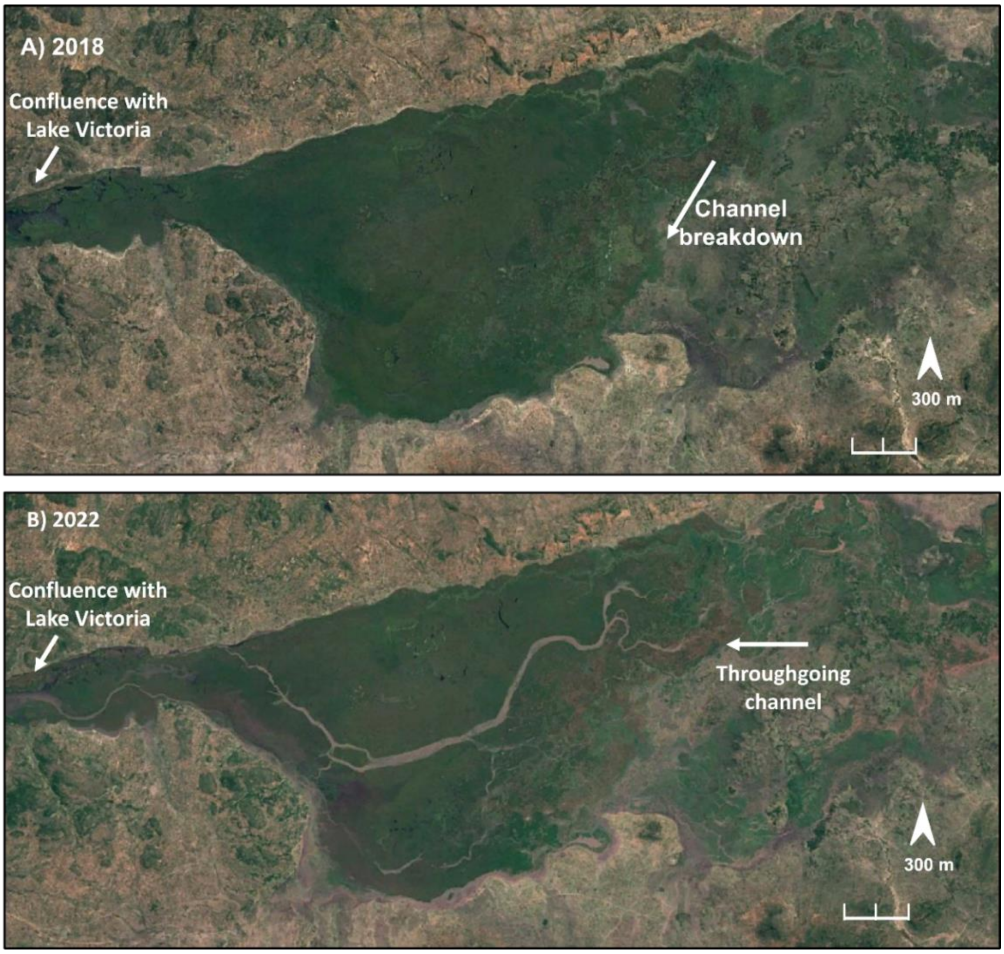


Figure 5.2. The Mara River wetland showing variable geomorphic states within a period of four years: A) in 2018, a system characterised by channel decline and breakdown, with a discontinuous channel and unchannelised wetlands representing a nonequilibrium response to persistent low flows over the preceding decades; and B) in 2022, a nearly continuous channelised system, possibly representing a short-term reversion due to recent flood scarring, or perhaps an equilibrium response to an emerging enhanced flow regime.

Although the persistence/longevity of the current (alternative) state cannot be assessed at present, Bregoli et al. (2019) found that a continuous palaeochannel persisted along the northern boundary of the wetland (ca. 1911-1957) before avulsing several times, highlighting that the river has been historically highly dynamic and switched between alternative states (continuous and discontinuous channels). Similar cyclical behaviour has been observed in other dryland regions of the globe (e.g. Graf, 1988; Heffernan, 2008; Grenfell et al., 2009, 2019; Tooth 2000, 2013; Jaeger et al. 2017). For example, Ciénegas located in the semiarid to arid American Southwest, exhibit cycles of sediment aggradation and subsequent incision (e.g. gullies), resulting in alternative states (Table 5.2) (Graf, 1988; Heffernan, 2008). In this case, different system states are influenced by wet/dry cycles, whereby dry conditions lower the water table resulting in reduced vegetation coverage, and successive wet periods increase runoff and erosion resulting in gully formation (Minckley and Brunelle, 2007). Persistent wet conditions in turn facilitate vegetation growth that stabilises bed and bank sediments and promotes channel and floodplain aggradation, resulting in the renewed development of the wetland (Heffernan, 2008). These alternative states have significant implications for ecosystem heterogeneity and resilience which influence the successional processes of floral and faunal ecology and hence ecosystem service delivery (Wohl, 2014; Grenfell et al., 2020; 2022). In the palmiet wetlands in South Africa, for example, Rebelo et al. (2022) demonstrated that disturbances (e.g. fire and/or incision) appeared to drive vegetation patchiness, and thus community diversity. They found that severe disturbances which cause switching between alternative states, influence future species assemblages, and thus disturbances play an important role in maintaining the long-term ecological structure and functioning of these wetlands. Overall, the above examples, including the Mara system, highlight the importance of intrinsic threshold responses in driving alternative system states within the natural range of variability or behavioural regime of these systems.

While intrinsic processes are important controls in the Mara system, the type of geomorphic adjustments and rate at which they occur are largely defined by extrinsic forces (e.g. valley-scale setting and hydroclimatic conditions) operating within the catchment over long time periods. Accordingly, if an extrinsic threshold is crossed (i.e. base-level fall or sustained shifts in the hydrological regime) because of climatic or anthropogenic impacts, it is possible that a permanent shift in the character and behaviour of the river may occur (Fig. 5.1B). Catchment lithology and its influence on the degree of valley confinement (i.e. floodplain width), has been an important long-term control of channel and floodplain wetland characteristics in the Mara system (**Chapters 2 and 3**). Similar broad-scale lithological controls are evident in other dryland river systems, where reductions in valley confinement resulting in floodplain width increases, influence lateral migration processes and floodplain wetland formation (e.g. Yonge and Hesse, 2009; Ralph and Hesse, 2010; Tooth et al., 2014; Li and Bristow, 2015; Larkin et al., 2017a). In some settings, however, the local lithology and geological structure exert a dominant control on fluvial processes and forms and hence floodplain wetland development (e.g. Smith et al., 1997; Tooth et al., 2002, 2007; Grenfell et al., 2008). A well-documented example is the Klip River in South Africa (Table 5.2), where downstream intrusions of resistant dolerite directly influence river behaviour in the immediate reach (e.g. by limiting lateral migration and restricting floodplain development) as well as form local base levels that influence river behaviour and floodplain wetland formation in the upstream, dominantly alluvial, valleys (e.g. by providing accommodation space for meandering). In addition, this system is in a long-term state of incision and thus over longer timescales (greater than tens of thousands of years) vertical erosion is inevitable in the upstream alluvial valleys as the downstream dolerites are lowered by erosion, resulting in channel incision, and eventual floodplain abandonment and wetland desiccation. Similarly, in the Mara system, Lake Victoria forms a local base level that influences upstream geomorphic processes of adjustment and river behaviour. As such, sustained changes in lake level will likely affect river response and the overall state of the system. For example, during lake high stands, back flooding may lead to sediment deposition and wetland expansion influencing upstream avulsion dynamics (e.g. an increase in avulsion frequency), channel breakdown and hence floodplain wetland evolution. Conversely, during lake low stands the river may form a continuous channel that incises through the wetland, potentially threatening the persistence of the floodplain wetlands due to reduced inundation (i.e. a change from floodout inundation to overbank flows and associated hydrodynamics).

Despite the broad-scale influence of the valley setting in the Mara system, catchment lithology has remained invariant over geological timescales, and thus other extrinsic forces, such as hydroclimate may also play an important long-term role in driving floodplain characteristics. Several studies have showed that river response and floodplain characteristics vary across a climatic gradient (e.g. subhumid to semiarid) (e.g. Grenfell et al., 2014; Larkin et al., 2017a). In these systems, increases in aridity and its associated influence on flow tends to reduce the river's capacity to maintain throughgoing channels and increases the propensity for channel breakdown and floodout formation (e.g. Ralph and Hesse, 2010; Grenfell et al., 2014; Larkin et al., 2017a, b). For example, Grenfell et al. (2014) compared two different wetlands in South Africa with similar geology but from different aridity settings: the Nsonge

River in subhumid KwaZulu-Natal and the Seekoei River in the semiarid Karoo. The Nsonge River maintained a throughgoing, laterally migrating channel with low rates of vertical aggradation, whereas the Seekoei River exhibited channel breakdown and floodouts. They argued that while the Nsonge River has higher fluvial energy to maintain a continuous channel that reworks floodplain sediment, the more seasonal flows (lower fluvial energy) along the Seekoei River are not sufficient, resulting in a discontinuous channel that sequesters sediments in floodouts for longer time periods. Comparatively, the Mara River, with its subhumid upper catchment that becomes increasingly arid downstream, coupled with upstream water abstraction (i.e. agriculture, mining), downstream transmission losses through bed infiltration, and overbank flow losses, is unable to maintain a throughgoing channel in response to downstream hydrological declines. However, as highlighted above, the river exhibits alternative states that are likely associated with variable hydrological conditions and associated sediment dynamics. As such, if an extrinsic and/or intrinsic threshold is crossed, the Mara River may either permanently persist in its historical discontinuous state or in its newly formed continuous state (Fig. 5.1B). Overall, this research provides a snapshot of the present cyclical behaviour of the Mara system and highlights the importance of assessing river responses over longer timescales to understand the natural range of variability, dynamic processes, and evolution of a system which has important management implications.

2.2 Sensitivity and connectivity dynamics – key controls on fluvial geomorphology

The range of geomorphic adjustments responsible for floodplain wetland formation discussed above highlights the ‘expected’ or historical range of adjustments (Lisenby and Fryirs, 2016) for the different wetland landscapes over time (Table 5.2). The influences on these adjustments, however, are not always localised and often extend beyond the boundary of the wetland and are related to the interaction between extrinsic and intrinsic controls that operate over a range of spatiotemporal scales (e.g. Larkin et al., 2017a). This highlights the notion that wetlands are intricately connected to the surrounding landscape and their processes and functions are influenced by hydrogeomorphic controls operating at the broader catchment-scale. However, wetland managers often only consider the hydrological conditions of these fluvial systems at the wetland-scale (i.e. surface water availability and flow regimes) and less often consider the geomorphological conditions at the catchment-scale, and thus develop an incomplete understanding of the biophysical processes, forms, and timescales of wetland dynamics (i.e. natural range of variability) (McCarthy et al., 2010; Grenfell et al., 2019). Therefore, a landscape perspective is necessary to fully understand wetland processes and dynamics over time. The geomorphological concepts of landform sensitivity and landscape connectivity encompass the interaction of these catchment-scale controls and are useful tools with which to understand the complex geomorphic responses of these fluvial systems (Lisenby et al., 2017). The spatiotemporal variability of landform sensitivity and landscape connectivity can modulate the geomorphic responses of catchments to disturbance events over time (e.g. Thomas, 2001; Poeppl et al., 2017; Lisenby, 2019), and act as key controls on both the ability of a system to respond to disturbance events and recover post-disturbance. Therefore, an understanding of how catchment-scale connectivity dynamics influence geomorphic responses and sensitivity of wetlands is necessary for developing effective strategies to manage these fundamentally important systems.

Although the concepts of landform sensitivity and landscape connectivity are considered separately in **Chapters 3 and 4**, they are discussed together, as they are interdependent – as forms of fluvial geomorphic adjustment (i.e. sensitivity) effectively represent exchanges of water and sediment (i.e. connectivity) (Fryirs, 2013). At a catchment-scale, the spatiotemporal patterns of hydrological connectivity and associated sediment transfer across a landscape are controlled by catchment conditions, climate and hydrology, and vegetation (e.g. land-use) (Fryirs et al., 2007a). In addition, anthropogenic activities including agriculture, mining, land clearance, urbanisation, and water resource development, resulting in changes to landscape structure, can alter the rate and extent of sediment transference (i.e. connectivity patterns) throughout catchments (Walling, 2006). This is the case in large agricultural catchments including the Mara River basin (**Chapter 4**), the Murray-Darling Basin in Australia, and the Kosi-Ganga basin in India (Wilkinson et al., 2013; Singh et al., 2017), where major land use changes linked to human settlement and economic development result in significant increases in mobilised sediment. The spatiotemporal variability of landscape connectivity in the catchment influences the geomorphic response and biophysical processes of the river in off-site, distal regions. This is evident in allogenic wetlands, such as the Mara and Okavango (Table 5.2), where changes in connectivity patterns in the headwater regions of the catchment can impact geomorphic processes farther downstream in the wetland. For instance, in the Mara River catchment, upstream anthropogenic activities have led to significant changes in land cover and resulted in increased sediment inputs into the fluvial network, consequently affecting important hydrological (i.e. increased peak flows and reduced base flows) and geomorphological processes (i.e. increased sediment deposition) (Mati et al., 2008; Ogutu et al., 2009; Mwangi et al., 2017; Bregoli et al., 2019). These upstream increases in sediment supply and connectivity have accelerated sediment aggradation rates in the floodplain wetland in the past decades (Dutton et al., 2019), and have likely influenced the complex geomorphic responses and adjustments observed in the lower Mara River. For example, increased connectivity and associated sediment inputs in the upper source zone over the past decade (2010-2020) (**Chapter 4**; Mwangi et al., 2017) coincided with the formation of the more frequent avulsions and a reduction in longitudinal connectivity in the wetland (**Chapters 2 and 3**). Avulsions increase channel-floodplain interactions which is critical for maintaining ecological functioning, biodiversity dynamics and feedbacks in the wetland, however more frequent avulsions may have potential negative impacts on ecological succession and wetland evolution (Ralph and Hesse, 2010, Ralph et al., 2011; Wohl, 2014). Moreover, the surrounding regions of the wetland are heavily inhabited by local communities who utilise the floodplain for agriculture, livestock grazing and harvesting resources and thus avulsions and floods may pose a risk to their livelihoods (Bregoli et al., 2019).

At the wetland-scale, forms of geomorphic adjustments can also influence lateral and longitudinal connectivity dynamics within the wetland. Various forms of erosional and depositional adjustments serve to distribute sediment and water across the Mara floodplain (**Chapters 2, 3 and 4**). For instance, depositional forms of adjustment (e.g. levees and floodplains) act as sedimentary buffers that reduce longitudinal connectivity (i.e. hillslope-channel linkages) but promote lateral channel-floodplain connectivity (e.g. avulsions) (e.g. the Mara, Okavango, Klip, Tshwane, Macquarie Rivers) (Table 5.2). Similarly, erosional forms of adjustment (e.g. bank incision and lateral channel migration) facilitate lateral channel-floodplain connectivity across the floodplain. In contrast, some forms of erosional adjustment, such as gully incision reduces sediment storage capacity and can increase longitudinal connectivity while reducing lateral channel-floodplain connectivity (e.g. Blood River, Ciénegas of Southwestern USA) (Table 5.2). The ease with which these different wetland systems can adjust, however, is dependent on the landform sensitivity. In the lower Mara River, the channel exhibits downstream declines in longitudinal hydrological and sediment connectivity where it enters the floodplain wetlands and is characterised as sensitive because it actively laterally migrates and becomes prone to avulsion and channel breakdown

(**Chapters 3 and 4**). Similarly, the Okavango Fan and Macquarie River channels have low longitudinal hydrological and sediment connectivity through the wetlands where they are sensitive to channel breakdown and avulsion (Table 5.2) (Tooth and McCarthy, 2004; Ralph and Hesse, 2010). Conversely, the Okavango Panhandle, Tshwane, and Klip River channels maintain longitudinal connectivity downstream but are nonetheless characterised as sensitive as they are laterally active and prone to channel abandonment and avulsion (Tooth et al., 2002; Larkin et al., 2017a, b; Tooth et al., 2022).

Although the degree of connectivity varies within these different floodplain wetlands, they all exhibit actively adjusting landforms and are characterised as sensitive (Table 5.2). Importantly, this landform sensitivity can either promote wetland development through lateral channel migration and avulsion or wetland abandonment through floodout and gully incision, with implications for the ecological functioning, biodiversity dynamics and persistence of these fluvial systems. For example, Ciénegas are characterised as sensitive systems as they are susceptible to gully incision which essentially increases longitudinal connectivity over time, thereby reducing the ecological functionality of these wetland systems (Minckley and Brunelle, 2007). The varying degrees of hydrological and sediment connectivity and landform sensitivity and associated geomorphic adjustment in these wetlands promotes dynamically stable, heterogenous, yet persistent wetland systems with implications for wetland biological succession and ecological communities (Ralph et al., 2011, 2016; Wohl, 2014).

2.3 Future trajectories and conservation implications for dryland rivers and wetlands

Global projections indicate that the world's drylands will experience increased aridity and/or climatic variability in the coming decades and centuries (Feng and Fu, 2013; Cook et al., 2014; Gosling and Arnell, 2016). Moreover, owing to the ever-increasing population growth and economic development, particularly in developing countries, demand for water will continue to increase into the future (Cai and Rosegrant, 2002), which will be particularly important in already water-stressed dryland regions. These climatic and anthropogenic impacts will affect the hydrological as well as the geomorphological characteristics of dryland rivers (Milly et al., 2005; Rodell et al., 2018), which will have significant impacts on the >2 billion people that live in drylands and depend on the ecosystem services they provide (Millennium Ecosystem Assessment, 2005).

Under future predictions of more intense land use and increasing climatic variability in East Africa (Shongwe et al., 2009; Niang et al., 2014; Bartzke et al., 2018), the Mara River is expected to undergo significant geomorphic changes. This region is expected to experience increases in temperature and higher inter-annual rainfall variability which will likely lead to drier conditions with more extreme climatic disturbances (i.e. more intense flood events). These climatic conditions coupled with increasing land cover changes will likely result in increased sediment inputs into the fluvial network with consequences for downstream longitudinal connectivity and river sensitivity. For instance, increased connectivity (i.e. increased runoff and erosion) and subsequent sediment deposition in the valley bottom may lead to hotspots of geomorphic adjustments and an increase in the propensity for avulsions (i.e. decreased longitudinal connectivity), making the system more sensitive to disturbance events (Gomes et al., 2023c), with consequences for ecological succession and wetland evolution (e.g. Ralph et al., 2011). Alternatively, persistent drier conditions may also lower lake levels (i.e. base level drop) which will lead to increased channel erosion and enlargement, and incision, resulting in a throughgoing channel (i.e. increased longitudinal connectivity) and the loss of wetland functioning, with implications for ecosystem services. The long-term effects of climatic-induced lake level fluctuations on river connectivity and sensitivity remain an important direction for future research. Although it is difficult to predict and manage for climatic induced impacts on wetland functioning, wetland managers can adopt a broad-scale catchment approach to understand the mechanisms and processes driving wetland change (e.g. natural or anthropogenic drivers) and the spatiotemporal scale of those changes (Phillips, 2018; Tooth, 2018; Lisenby et al., 2019). By taking a catchment-scale approach, managers can identify regions that are more vulnerable to change and decide whether intervention is required.

In the Mara River catchment, the upper catchment region is under increasing pressure from anthropogenic impacts and is already highly connected. Under increasing aridity and climatic variability these conditions will likely be exacerbated, resulting in increased connectivity (i.e. runoff and erosion). This will likely induce significant geomorphological changes in the lowland floodplain wetland with implications for ecosystem structure and functioning and hence ecosystem service delivery (**Chapter 4**). Despite the positive contributions of protected areas throughout the catchment, such as maintaining natural vegetation cover and reducing runoff, the impacts from the upper catchment may well outweigh these effects. As such, management efforts need to be prioritised in the upper regions of the Mara catchment and focus on designing sustainable sediment erosion management policies and expanding current restoration efforts (e.g. afforestation on hillslopes) to reduce erosion and sediment inputs into the fluvial network. This will contribute to wetland maintenance and resilience to future climatic and anthropogenic impacts, which is crucial for both human and wildlife populations that depend on the Mara River and its floodplain wetlands for resources.

It is imperative that wetland managers and scientists incorporate geomorphological perspectives into management planning to improve understanding of the natural range of variability in a system and to accurately assess the relative importance of natural and anthropogenic drivers of wetland adjustment and change (Lisenby et al., 2019; Grenfell et al., 2020). These insights are also useful for landscape evolution modellers to understand the historical range of variability of a system and to inform the possible trajectories, rates, and timescales of recovery in a system after disturbance events (Martin and Church, 2004; Tucker and Hancock, 2010). Knowledge of the past, present, and possible future states of landscape connectivity and landform sensitivity and their influence on the geomorphology of dryland rivers and wetlands is important for evaluating what type of recovery is possible and whether intervention is required (Brierley and Fryirs, 2016; Tooth, 2018). Overall an in-depth understanding of the catchment-scale hydrogeomorphic processes driving wetland dynamics is imperative for guiding management and conservation efforts for these valuable ecosystems.

2.4 Limitations and direction for future research

This research has provided novel insights into a dryland river's character and behaviour in a poorly documented region of the world. The findings from the Mara River and its floodplain wetlands in East Africa have highlighted the hydrogeomorphic controls driving major geomorphic adjustments, as well as states of sensitivity and patterns of connectivity in the catchment which are critical for enhanced conservation and management strategies. All of this was done using remote sensing techniques and associated mapping, and assessments of geomorphic controls, adjustments, river sensitivity, and catchment connectivity. However, it is recognised that there are some limitations to this research and future research could focus on addressing these knowledge gaps. For example, optical stimulating luminescence (OSL) dating could be used to constrain the ages of palaeochannel sediments which would enable the reconstruction of past sedimentation rates, depositional regimes, and associated environmental conditions and hydroclimates to provide a meaningful comparison of the Mara River dynamics with other dryland river systems over similar timescales. While it is acknowledged that extensive fieldwork and sediment coring to allow a palaeo-reconstruction of environmental conditions would be a valuable addition to this thesis, COVID-19 travel restrictions and university rules around research activities during the pandemic prohibited all fieldwork and laboratory work for the duration of the research. Nevertheless, the knowledge gap for river chronology provides an opportunity for future research to focus on coring and dating 'geoproxies' (e.g. palaeochannels, alluvial palaeosols, and river terraces) (Lyons et al., 2014) of dryland rivers, particularly in data deficient regions of the world. Geoproxies can provide information on past environments because their stratigraphy and spatial sediment distributions may reflect past environmental (e.g. hydroclimatic) changes (Thomas and Burrough, 2012). As such, environmental reconstructions are useful for understanding the long-term evolution of dryland fluvial systems which is necessary for predicting how they may change in response to future climatic or anthropogenic related impacts.

Other future research could assess the geomorphology of the upper and middle sections of the Mara River in Kenya and Tanzania to determine the dominant modes of fluvial adjustment and degree of river sensitivity there which may contrast with the Mara Wetlands, particularly where large reserves such as Serengeti National Park and Masai Mara National Reserve provide such vital areas for wildlife conservation. These geomorphic research efforts could be linked to existing assessments of hydrology and the effects of land-use change (e.g. McClain et al., 2014; Kihwele et al., 2021) to better understand and manage these internationally recognised ecoregions. Furthermore, environmental flow assessments in the upper Mara River catchment in Kenya would supplement the existing flow allocations in the lower catchment (LVBC & WWF-ESARPO, 2010) to provide a complete environmental flow assessment of the entire catchment. Quantification of flow reserves would inform water allocation plans for the Mara River catchment which has important management implications. Equitable distribution of available water resources is crucial in a semiarid catchment not only to fulfil the needs of ecosystems and people but also to allow for socioeconomic development and growth. Finally, ecosystem services are poorly documented in East Africa, and an assessment of these and the role of dryland rivers and wetlands such as the Mara would boost understanding and visibility of the importance of wetlands in drylands as hotspots of not just biodiversity, but a range of other critical processes for food and water provision, water quality, nutrient and contaminant capture, carbon sequestration, and many other factors (Wohl, 2014; Tooth et al., 2015; Grenfell et al., 2022).

3 Conclusion

Research on the dynamic fluvial processes and geomorphological sensitivity of dryland rivers to both natural and anthropogenic impacts is lacking, particularly in developing countries of the world, such as those in Africa. This thesis has addressed this short fall and made a novel contribution to the geomorphological theory of dryland rivers by assessing the geomorphic development and sensitivity of a dryland fluvial system in East Africa. **Chapters 2, 3 and 4**, provide an in-depth understanding of the hydrogeomorphic controls and threshold responses driving river character and behaviour in the ecologically significant Mara River system. The findings from this research provide important insights into the relative sensitivity of dryland rivers to climatic and anthropogenic impacts in Africa, which may be extended to other dryland rivers and wetlands globally with important management implications**.**

Dryland fluvial systems are rarely considered from a geomorphological perspective and the geomorphological impacts of future climate and anthropogenic change on dryland rivers is still unclear. Hydrological modelling has been at the forefront of understanding how rivers will adjust to the impacts of climate change and while this is important, it is also necessary to consider the geomorphological changes to these changing hydrological conditions. In the Mara River catchment, increasing demand for water resources coupled with intensive land use and climate change impacts, will likely result in considerable hydrological and geomorphological changes, such as increased landscape connectivity and landform sensitivity. These geomorphological changes will impact the structure and functioning of the lowland floodplain wetland with implications for ecosystem heterogeneity, resilience, and hence ecosystem service delivery with consequences to the human and wildlife populations that depend on these resources. Therefore, management approaches need to incorporate geomorphological perspectives over long time periods to understand the natural variability of dryland fluvial systems and the hydrogeomorphic processes driving dryland river response to climatic and anthropogenic impacts. As such, interdisciplinary, adaptive management approaches are required to allow ecosystems and communities to be more resilient to future changes in the character and behaviour of dryland rivers globally, especially in an era of rapid environmental changes.

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