The geomorphology of wetlands in drylands

Tooth, Stephen

Published in:
Geomorphology

DOI:
10.1016/j.geomorph.2017.10.017

Publication date:
2018

Citation for published version (APA):
Tooth, S. (2018). The geomorphology of wetlands in drylands: Resilience, non-resilience, or …? *Geomorphology*, *305*, 33-48. https://doi.org/10.1016/j.geomorph.2017.10.017

The geomorphology of wetlands in drylands: resilience, nonresilience, or …?

Stephen Tooth

Department of Geography and Earth Sciences, Aberystwyth University, Aberystwyth, Ceredigion, SY23 3DB, UK

Abstract

Over the last decade, much attention has focused on wetland resilience to disturbances such as extreme weather events, longer climate change, and human activities. In geomorphology and cognate disciplines, resilience is defined in various ways and has physical and socioeconomic dimensions but commonly is taken to mean the ability of a system to (A) withstand disturbance, (B) recover from disturbance, or (C) adapt and evolve in response to disturbance to a more desirable (e.g., stable) configuration. Most studies of wetland resilience have tended to focus on the more-or-less permanently saturated humid region wetlands, but whether the findings can be readily transferred to wetlands in drylands remains unclear. Given the natural climatic variability and overall strong moisture deficit characteristic of drylands, are such wetlands likely to be more resilient or less resilient? Focusing on wetlands in the South African drylands, this paper uses existing geomorphological, sedimentological, and geochronological data sets to provide the spatial (up to 50 km^2) and temporal (late Quaternary) framework for an assessment of geomorphological resilience. Some wetlands have been highly resilient to environmental (especially climate) change, but others have been nonresilient with marked transformations in channel–floodplain structure and process connectivity having been driven by natural factors (e.g., local base–level fall, drought) or human activities (e.g., channel excavation, floodplain drainage). Key issues related to the assessment of wetland resilience include channel–floodplain dynamics in relation to geomorphological thresholds, wetland geomorphological 'life cycles', and the relative roles of natural and human activities. These issues raise challenges for the involvement of geomorphologists in the practical application of the resilience concept in wetland management. A key consideration is how geomorphological resilience interfaces with other dimensions of resilience, especially ecological resilience and socioeconomic resilience, the latter commonly being defined in terms of ecosystem service delivery.

Keywords: dryland; environmental change; floodplain; resilience, resilient; wetland

1. Introduction

‘Wetland’ can be defined in various ways but is typically taken to be an area that is periodically or continually inundated by shallow water or has saturated soils and where plant growth and other biological activities are adapted to the wet conditions (Mitsch et al., 2009). The term thus covers a wide variety of coastal and inland areas that are transitional between fully terrestrial and fully aquatic, including many estuaries, deltas, tidal flats, peatlands, floodplains, swamps, marshes, and oases. Consequently, wetlands are key components of many landscapes worldwide and increasingly are regarded as providing a wide range of ecosystem services, including enhancement of biodiversity, water quality improvement, food supply, and recreational opportunities (Schuyt and Brander, 2004; Millennium Ecosystem Assessment, 2005a; Aber et al., 2012; Mitsch and Gosselink, 2015). At the same time, there is growing recognition that factors such as climate change, sea level rise, land use change, and population growth threaten the structure and functioning of many wetlands worldwide and that interdisciplinary scientific studies are urgently needed to support wetland management if ecosystem services are to be maintained or enhanced.

Against this backdrop, and in common with concern over geomorphological and ecological changes occurring in other landscapes, the concept of ‘resilience’ has become increasingly prominent in the diverse wetland literature. Although the literature does not always clearly or consistently define the concept, much attention has focused on the environmental and anthropogenic threats to wetlands and on the adaptation and mitigation strategies that may be required to ensure their resilience, especially vis-à-vis ecosystem service delivery. Given the particular concern over sea level rise and changing atmospheric CO_2 concentrations, coastal marshes and peatlands in humid regions have been the main focus of wetland resilience assessments (e.g., Morton and Barras, 2011; Swindles et al., 2016). As a consequence, the numerous permanent and temporary wetlands in the world’s extensive drylands (a collective term for subhumid, semiarid, arid, and hyperarid environments) have been relatively neglected. Given their presence in these climatically variable, moisture-stressed environments, however, the Millennium Ecosystem Assessment (2005b) recognised that wetlands in drylands may be disproportionately important in ecosystem service delivery. These services may include water and food supply for many marginalised communities, so here too wetland resilience assessments are needed. Tooth and McCarthy (2007) proposed that wetlands in drylands differ geomorphologically and sedimentologically from their humid region counterparts in several key respects (Table 1), so it is unclear whether findings regarding wetland resilience can be readily transferred from humid to dryland regions, with key questions remaining unanswered. For instance, given that wetlands in drylands exist in marginal environments where small differences in moisture supply (rainfall, river flow, groundwater) can lead to large differences in hydroperiods (depth, extent, and duration of inundation/saturation), are wetlands in drylands likely to be less resilient to environmental change than humid region wetlands (e.g., Williams, 1999)? Or given that wetlands in drylands have evolved under conditions of highly variable moisture supply, are they likely to be more resilient (e.g., Mohamed and Savenije, 2014)? Can we even generalise about wetland resilience in different hydroclimatic settings or might wetland resilience be determined more by other factors (e.g., lithology, geomorphology, edaphic and vegetative characteristics, human activities)? Other key scientific and applied questions regarding the resilience of wetlands in drylands include: how resilient have wetlands in drylands been to past environmental changes?; what is the relative importance of climatic changes and human activities in driving contemporary and future changes to the resilience of wetlands in drylands?; and can we identify changes in wetlands in drylands that might serve as early warning signs of altering resilience?

Table 1

Key geomorphological and sedimentological differences between the typical characteristics of wetlands in humid regions and wetlands in drylands, with emphasis placed on inland wetlands (after Tooth and McCarthy, 2007)

Characteristic	Wetlands in humid regions	Wetlands in drylands
Hydrological budgets	Some wetlands can be sustained by climatic inputs alone (e.g., ombrotrophic mires) and typically remain (near-)continuously saturated	Most moderate to large wetlands cannot be sustained by climatic inputs alone and are subject to more frequent and/or longer periods of desiccation
River channel processes and forms	Many floodplain wetlands have perennial, throughgoing channels that increase in size downstream	Some wetlands have perennial, throughgoing channels but commonly size decreases downstream, and some channels may locally disappear in floodouts before reforming farther downvalley
Geochemical budgets	Inland wetland sediments are not typically characterised by excessive chemical sedimentation (e.g., salt accumulation)	Inland wetland sediments are prone to chemical sedimentation (e.g., salt accumulation)
The role of fire and aeolian processes	Wetlands are typically (near-)continuously saturated, commonly leading to peat accumulation and limiting fires and aeolian deflation	Wetlands are commonly subject to desiccation, limiting peat accumulation and increasing susceptibility to fires and aeolian deflation
Timescales of development	Most wetlands have only developed since late Pleistocene deglaciation or with Holocene sea level rise	Many drylands escaped the direct effects of glaciation so most wetlands have longer histories that may extend far back into the Pleistocene or prior

To answer these types of questions, there is a critical need to have clear, consistent definitions and measures of resilience, but the application of the concept to wetlands — and more widely across geomorphology and the environmental sciences — is commonly shrouded by vagueness and imprecision. Creative ambiguity may be appropriate for some environmental terms and concepts (Levina and Tirpak, 2006), but tighter definitions and measures are commonly desirable because of the need for rigorous scientific assessments (e.g., the comparative resilience of different wetlands) or because of the attendant policy implications. For instance, maintaining or increasing resilience is often seen as a desirable target in environmental management (e.g., Klein et al., 2003; Côté and Darling, 2010), so seemingly small differences in definition and/or interpretation might create different expectations from different stakeholders (c.f. ‘adaptation’ - Levina and Tirpak, 2006). Hence, the aims of this paper are fourfold: (i) to provide an overview of the resilience concept, including its origins, multiple definitions, and use in geomorphology; (ii) to summarise previous studies of wetland geomorphology in the South African drylands and to interpret the findings in terms of some common definitions of resilience; (iii) to discuss the difficulties and potentials of assessing the resilience of wetlands in drylands more generally; and (iv) to outline the challenges for geomorphological inputs to practical applications of the resilience concept in wetland management. The emphasis is on wetlands in the South African drylands, but many of the points raised will apply to wetlands in other drylands across Africa and farther afield, as well as to wetlands more generally.

2. Origins and definitions of resilience

The concept of resilience arose largely in ecology (e.g., Holling, 1973; Westman, 1978; Hill, 1987), thereafter spreading more widely across the natural and physical sciences to studies of socioecological and social science systems (e.g., Adger, 2000, 2006; Folke, 2006, 2016; Folke et al., 2010). The concept is now widely embedded in natural hazards research (e.g., Klein et al., 2003; Zhou et al., 2010) and in discourses about climate and wider environmental change (e.g., Intergovernmental Panel on Climate Change, 2014; Tanner et al., 2015). Consequently, the concept has acquired multiple physical, social, and socioeconomic dimensions, as well as various links to other concepts such as vulnerability, sensitivity, susceptibility, persistence, equilibrium, thresholds/tipping points, recovery, and adaptive capacity.

A full review of resilience and related concepts is beyond the scope of this paper, but at least three definitions of system resilience can be identified in science and social science literature, namely an ability for a given system to: (A) withstand disturbance; (B) recover from disturbance; or (C) adapt, re-organise and evolve to a more desirable (e.g., stable) configuration.

Varying layers of vagueness are built into all these definitions (e.g., what system parameter(s) are being measured and over what spatial and temporal scales?), but each definition has fundamentally different expectations of the dynamics of a geomorphological, environmental, or social system that might occur in response to a disturbance such as an individual flood, sustained drought, longer-term climate changes, or human interventions. Definition A implies that the system undergoes no change or only limited change in response to disturbance and is sometimes defined as 'resistance' (e.g., Phillips, 2009; Côté and Darling, 2010; Frisbee et al., 2013). Definition B implies that the system changes away from an initial starting state in response to disturbance, but then a return (recovery) to that previous state occurs over some (commonly unspecified) time interval. Definition C implies that the system changes away from an initial starting state in response to a disturbance, but that the change is directional and occurs toward some specified (e.g., stable) end state. In this case, the disturbance could result from deliberate, direct human intervention; for example, as part of a proactive land management strategy.

In geomorphology, resilience has been discussed as part of broader treatments of sensitivity (e.g., Brunsden, 2001; Fryirs, 2017) but has also received more specific assessments across many subfields, including coastal, aeolian, and fluvial geomorphology (e.g., Long et al., 2006; Woodroffe, 2007; Nield and Baas, 2008; Biron et al., 2014; Wohl, 2014; Fryirs et al., 2015; Calle et al., 2017). Although clear, consistent definitions have not always been provided, geomorphologists most commonly employ definition B (cf. Phillips and van Dyke, 2016).

Application of the resilience concept to wetlands in drylands — and wetlands more generally — has particular challenges. First, unlike some relatively simple geomorphological systems (e.g., hillslopes), wetlands in drylands are not singular features; instead, many are composed of landform assemblages that may include various active and abandoned channels, levees, and floodplains. Second, many wetlands in drylands are archetypal ecogeomorphological systems where biota (plants and/or animals) are a key, even dominant, influence on geomorphological processes, forms, and dynamics (e.g., Tooth and McCarthy, 2004). Hence, one can attempt to define and measure wetland ecological resilience (e.g., using water quality guidelines, trophic structures, or measures of biodiversity), wetland geomorphological resilience (e.g., using landform structure or process connectivity), or some hybrid combination of the two. Many wetlands in drylands are also subject to various forms of management, commonly to enhance or maintain aspects of ecosystem service delivery (e.g., Wetlands International, 2014), and so increasing attempts are also being made to define and measure wetland socioeconomic resilience (e.g., Liersch et al., no date). A distinction can thus be drawn between natural (e.g., ecological, geomorphological) resilience and socioeconomic resilience, whereby society can use technologies to overcome local environmental constraints. In this paper, the focus is on wetland geomorphological resilience, but we need to bear in mind the sometimes intimate coupling with ecological and socioeconomic systems, not least because of growing recognition of the need to develop a shared language and common approaches if such systems are to be managed holistically and sustainably.

3. Wetland geomorphology in the South African drylands

As Long et al. (2006) have noted in the context of coastal systems, resilience means little without a clearly defined spatial and temporal framework. If adopting definition B of resilience, for instance, there is a clear need to consider the spatial and temporal scales of disturbance and recovery. Consequently, attention hereafter is directed to four study sites (three extant wetlands and one former wetland) in the South African drylands where previous detailed investigations have been undertaken using a combination of remotely sensed images, geomorphological and sedimentological field data, and optically stimulated luminescence (OSL) dating. The OSL data sets in particular are among the most extensive for any wetlands in drylands and have enabled reconstructions of wetland geomorphological changes over spatial scales ranging up to ~50 km^2 and over timescales ranging from the late Pleistocene to the present. These reconstructions provide the basis for interpretation of the natural environmental and anthropogenic factors influencing wetland resilience.

All four study sites are located in the tectonically stable interior of northeastern and northern South Africa (Fig. 1) where many riverine wetlands are sustained by rainfall and flooding in the austral summer wet season (November through March) and undergo dessication during the drier winter season. Table 2 summarises the key climatic, catchment, river channel, and floodplain characteristics, while Figs. 2-5 illustrate some of the key geomorphological features and select OSL ages for fluvial landforms. The four sites have been influenced by various human activities that range from low-intensity cattle grazing to more direct flow manipulation (Table 2), but with some notable exceptions (detailed below), many reaches remain in a near-natural, little modified condition. Collectively, these wetlands represent a selection of the 'valley bottom' and 'floodplain wetlands' types highlighted in South African wetland classifications (Kotze et al., 2009a; Ollis et al., 2015), but for brevity, the term 'floodplain wetland' is applied hereafter as a generic descriptor.

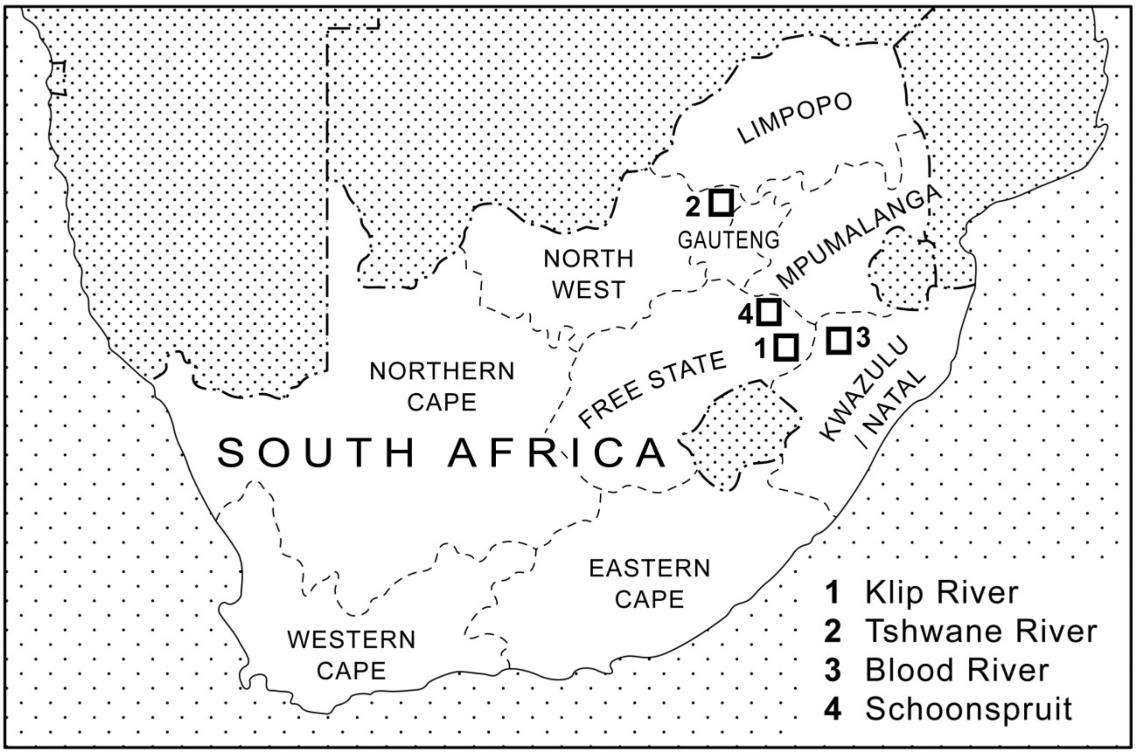

Fig. 1. Location of the four study sites in South Africa.

Table 2

Summary of key climatic, catchment, river channel, and floodplain characteristics for the four wetlands in the South African drylands

Wetland	**Ppt, PEt (mm)**[a]	**Catchment area (km^2)**[b]	**Slope (m m^{-1})**[c]	**Floodplain width (m)**	**Channel cross-sectional area (m^2)**	**Bankfull discharge (m^3 s^{-1})**	**Unit stream power (W m^{-2})**	**Sediment load**	**Key fluvial features**	**Human impacts**
Klip R.	~800, ~1400-2000	1140	~0.00018 to 0.00075	Up to ~1500	<73 (highest values in human-impacted middle reaches)	<10-90 (highest values in human-impacted middle reaches)	<10-15 (highest values in human-impacted middle reaches)	Mud, sand, minor gravel	Mixed bedrock-alluvial but meandering channel, scroll bars, oxbows, palaeochannels, minor levees and alluvial ridges, backswamps	Cattle grazing, controlled burns (e.g., reedbeds), channel excavation by early colonial settlers, installation of modern flow control structures (e.g., weirs)
Tshwane R.	~585, ~1750	1420	~0.00083	Up to ~1500	<20	<15 (declining downstream)	<10	Mud, sand, minor gravel	Fully alluvial meandering channel, oxbows, palaeochannels, prominent levees and alluvial ridges, backswamps	Light cattle grazing
Blood R.	~750-900, ~1700-1800	690	Upper part: <0.0015, with two local steepenings up to ~0.014 Lower part: <0.0004	Up to ~2500	<20 (upper reaches only, lower reaches largely moribund)	<15 (upper reaches only, lower reaches largely moribund)	<10 (upper reaches only, lower reaches largely moribund)	Mud, sand, minor gravel	Upper part: fully alluvial low sinuosity channel, active and abandoned channel-levee complexes, floodouts, reforming channels (waterhole),	Cattle grazing, controlled burns (e.g., reedbeds), earthen dams (now deliberately breached)

								palaeochannels, headcuts, hillslope dongas (gullies and badlands) and impinging tributary fans Lower part: mixed-bedrock alluvial but moribund and infilling meandering channel, oxbows, palaeochannels, local dongas (gullies)	
Schoonspruit	~600, ~1400-2000	325	<0.001	Up to ~1000 (inset floodplain <20)	70-250 (highest values in deeply incised reaches and likely overestimate flood discharges)	>15	Mud, sand, minor gravel	Incised mixed bedrock-alluvial channel with inset floodplain, abandoned floodplain wetland with oxbows and local palaeochannels, valley-margin dongas (gullies and badlands)	Light cattle grazing

[a] Ppt (precipitation) and PEt (potential evapotranspiration) vales are based largely on Midgley et al. (1994) and Schulze (1997).

[b] Catchment area to end of study reach.

[c] Channel slope where channel is present, otherwise floodplain slope.

3.1. Klip River floodplain wetland, Free State

The Klip River floodplain wetland (Fig. 2) has been the site of extensive geomorphological, sedimentological, and OSL dating work (Tooth et al., 2002, 2004, 2007, 2009; Rodnight et al., 2005, 2006; Marren et al., 2006; Keen-Zebert et al., 2013). Along the ~28-km-long study reach, the perennial, throughgoing, sinuous (*P* up to ~1.75) river is flanked by a floodplain wetland up to ~1.5 km wide (Fig. 2A). This floodplain wetland hosts numerous palaeochannels and oxbows with dimensions (e.g., widths, sinuosities, meander wavelengths) that are similar to the modern channel (Fig. 2B). Discharge, stream power, and channel cross-sectional area all increase slightly downstream (Table 2). Long-term net aggradation is essentially zero, for the channel bed remains grounded on relatively erodible mudstone/sandstone bedrock, but floodplain sediments 2-4 m thick are deposited by a combination of lateral point-bar, oblique, and abandoned-channel accretion (Marren et al., 2006). Locally, the channel sits atop an alluvial ridge elevated up to ~1 m above the surrounding floodplain but possesses only minor levees (<0.5 m high). At the lower end of the study reach, the river enters a valley carved into a resistant dolerite sill. Here, the channel markedly straightens and floodplains are restricted to <40 m wide (Figs. 2A and 2C). Cosmogenic isotope analyses indicate that channel-bed dolerite outcrop is denuding at ~38-73 mm ka^{-1} (Keen-Zebert et al., 2016), and so local base level remains essentially stable for extended periods of time (>10 ka). A conceptual model of floodplain wetland development (Tooth et al., 2002, 2004) highlights how this stable dolerite base level is a key factor promoting meander formation and valley widening in the upstream floodplain wetland (Fig. 6A).

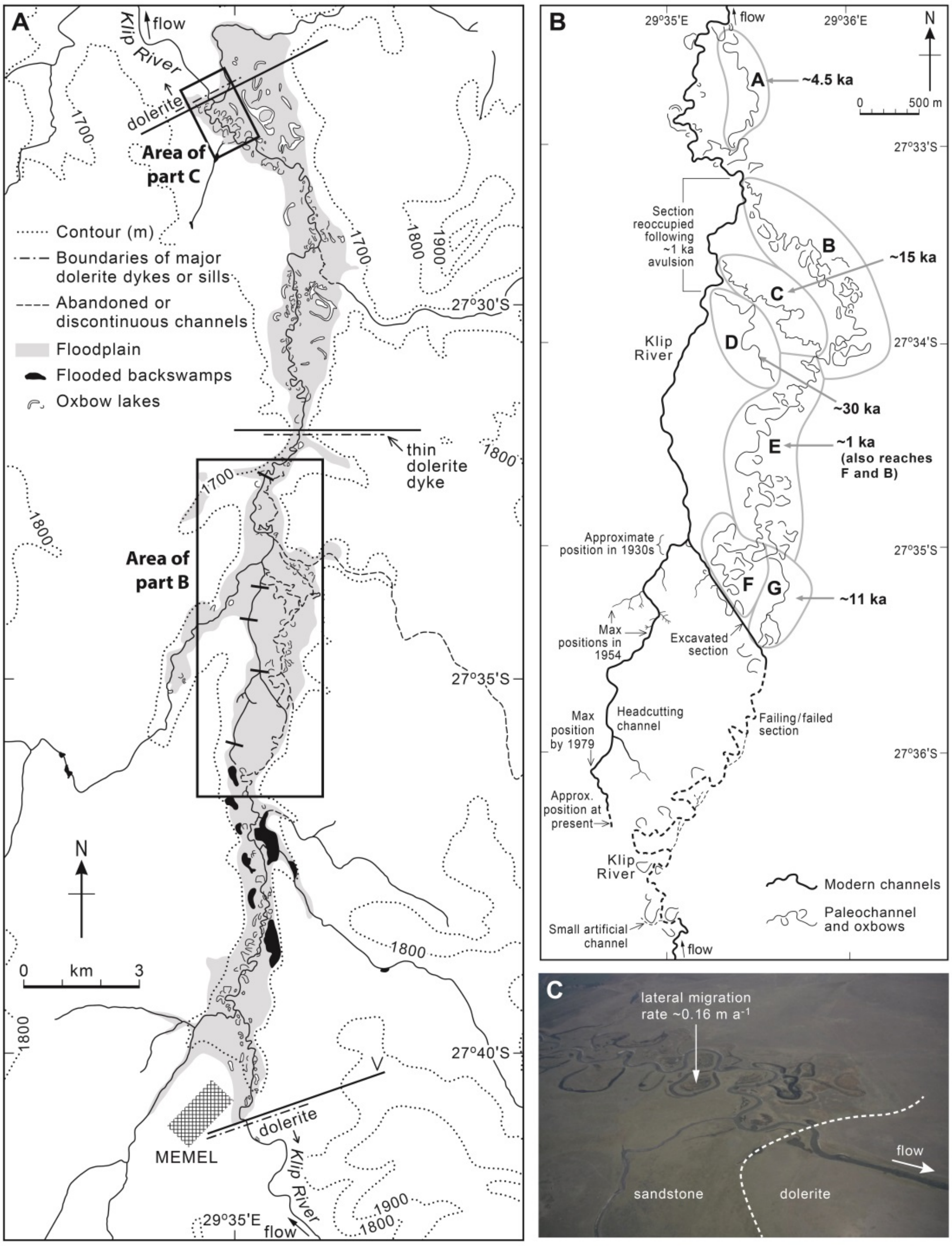

Fig. 2. Illustrations of some of the key geomorphological features and select OSL ages for landforms in the Klip River floodplain wetland (source: modified after Tooth et al., 2004, 2009).

The OSL dating has focused on sand-rich deposits in the middle and lower parts of the study reach. In the middle part, where gradient steepens slightly and floodplain sediments transition from dominantly mud to dominantly sand, OSL ages for palaeochannels and associated oxbow fills (Fig. 2B) reveal that avulsions occurred at ~30, ~15, ~11, ~4.5, and ~1 ka (Rodnight et al., 2006; Tooth et al., 2007, 2009). Over the last 15 ka, therefore, avulsions have occurred once every 3-6 ka, corresponding to a frequency of <0.3 avulsions ka^{-1} (Tooth et al., 2007). In the lower part, OSL ages for scroll bar sequences (e.g., Fig. 2C) demonstrate that late Holocene meander migration rates were <0.2 m a^{-1} (Rodnight et al., 2005; Tooth et al., 2009). In global terms, these rates are relatively slow and are supported by aerial photograph analyses, which reveal that despite the high density of oxbow lakes (up to 10/km of channel; Figs. 2A and 2C), only three cutoffs have occurred in the study reach over the last 60-70 years (Tooth et al., 2009). Along with field observations, these findings provide the basis for interpreting the processes and controls of avulsion. In this setting, avulsions occur through an incisional process, whereby overbank floodwaters drain back to the channel through a breach in the channel bankline, initiating a small headcutting channel. This headcutting channel enlarges and extends by knickpoint retreat during periods of overbank flow, ultimately diverting discharge and sediment from the older, typically elevated channel, which is then abandoned. Along the Klip River, the lack of a clear, consistent link between regional palaeoclimatic changes and individual avulsion events (Tooth et al., 2007) suggests that past avulsions have not been extrinsically forced but rather have occurred intrinsically as a natural outcome of meander-belt development.

An ongoing avulsion that is associated with the formation of a new 3.0-3.5 km long channel on the western floodplain margin (Fig. 2B) provides an exception. Gully initiation and eventual channel formation appear to have been initiated by the excavation of a trench across the wetlands (Fig. 2B) following colonial settlement in the valley (late 1800s onward). This trench was probably excavated in an attempt to drain the wetlands and improve access for grazing.

3.2. Tshwane River floodplain wetland, North West Province

The Tshwane River floodplain wetland (Fig. 3) has been the subject of recent geomorphological investigations (Larkin et al., 2017a, b). Through the ~4-km-long study reach, the perennial, throughgoing river has many morphological similarities to the Klip River. In many places, the river is highly sinuous (P up to ~2.7) and is flanked by a floodplain wetland up to ~1.5 km wide that hosts numerous palaeochannels and oxbows with dimensions similar to the modern channel (Fig. 3A). By contrast with the Klip River, however, discharge, stream power and channel cross-sectional area all decrease downstream along the Tshwane River (Table 2), and the channel bed is decoupled from bedrock, with floodplain sediments >7 m thick (Fig. 3B) being laid down by a combination of lateral point-bar, oblique, abandoned-channel, and vertical accretion. Consequently, many reaches of the modern channel sit atop an alluvial ridge elevated up to 1.5 m, and levees are more prominent than on the Klip (Fig. 3B). The lower end of the study reach is formed by the diffuse confluence with the aggrading Pienaars River (Fig. 3A), which provides the local base level for the Tshwane reaches upstream (Larkin et al., 2017a).

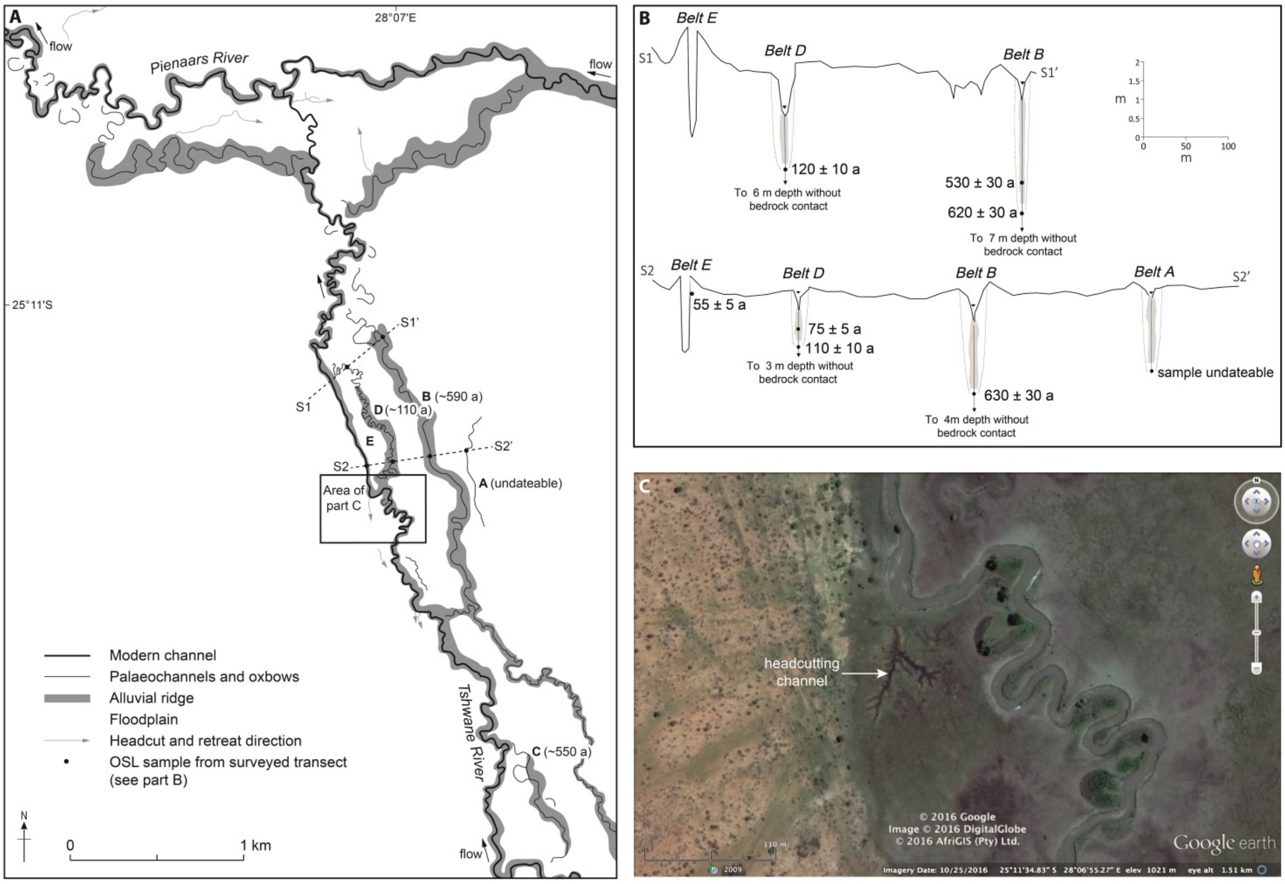

Fig. 3. Illustrations of some of the key geomorphological features and select OSL ages for landforms in the Tshwane River floodplain wetland (source: modified after Larkin et al., 2017b).

The OSL ages for palaeochannels and associated oxbow fills (Figs. 3A and 3B) have established a late Holocene avulsion history. Older, undated palaeochannels are present in the reach (e.g., palaeochannel A; Figs. 3A and 3B), but over the last ~650 years, avulsions occurred at ~590, ~550, and 110 years ago (Larkin et al., 2017b). Aerial imagery and field evidence reveal that some other sinuous reaches are being primed for avulsion, with headcutting channels having rapidly developed in adjacent backswamps (Fig. 3C). Over this timeframe, the frequency of ~4.6 avulsions ka^{-1} is significantly higher than on the Klip River (Larkin et al., 2017b). In the absence of well-defined scroll bars along the Tshwane, meander migration rates have not been established, but aerial photographs and field observations also reveal significantly higher rates of lateral activity along the Tshwane than along the Klip River, with 14 cutoffs having occurred in the much shorter study reach over the last 60-70 years (Larkin et al., 2017b). As on the Klip River, however, incisional avulsion is the dominant process (Fig. 3C), and the lack of a clear, consistent link between regional palaeoclimatic changes and individual avulsion events on the Tshwane River also suggests that avulsions have been driven by intrinsic processes during meander-belt development.

3.3. Blood River floodplain wetland, KwaZulu-Natal

The Blood River floodplain wetland (Fig. 4) has been the subject of previous geomorphological investigations (Lyons et al., 2013; Tooth et al., 2014). The ~35-km-long study reach can be divided into an upper part that contains sections of perennial but discontinuous, relatively straight (P ~1.15) channels and a lower part that is traversed by a perennial to intermittent, sinuous (P >2.30) channel (Fig. 4A). In the upper part, the modern channel is flanked by several abandoned channel–levee complexes (Fig. 4B). Discharge, stream power, and channel cross-sectional area rapidly decrease downstream (Table 2), and the channel disappears within 0.5 km of entering the main area of wetlands to form a ‘floodout’ (cf. Tooth, 1999, 2004), characterised here by an unchannelled reedbed (principally *Phragmites australis*) up to ~1 km wide. This reedbed extends for ~1 km downvalley (Fig. 4B), but traces of overgrown sinuous palaeochannels are present toward the western floodplain margin. At the southeastern margin of the floodout, several small headcutting channels start abruptly on a locally steepened (~0.014) gradient (Fig. 4B) and convey water that filters through the reedbed. As the gradient declines again downvalley, these headcutting channels coalesce into a single, low sinuosity, ~1.25-km-long ‘reforming channel’ (Tooth, 1999, 2004) that retains permanent water in a part of the wetlands that are otherwise seasonally dry (Fig. 4B). This reforming channel abruptly narrows and shallows toward its downstream end and disappears at another floodout up to ~2 km wide (Fig. 4A). This lower floodout extends for ~3 km downvalley and is also characterized by an unchannelled reedbed, although here too clear evidence exists of overgrown but throughgoing, sinuous palaeochannels. Similar to the situation upvalley, the southern limit of this lower floodout is also marked by several headcutting channels that start on a locally steepened (~0.001) gradient (Fig. 4C). These headcutting channels mark the transition to the lower part of the study reach where a continuous, sinuous channel is flanked by numerous oxbows, short palaeochannel sections, and small gullies known locally as dongas (Figs. 4A and 4C). At the downstream end of the study reach, dolerite outcrop results in channel straightening and the floodplain decreases to <100 m wide (Fig. 4A).

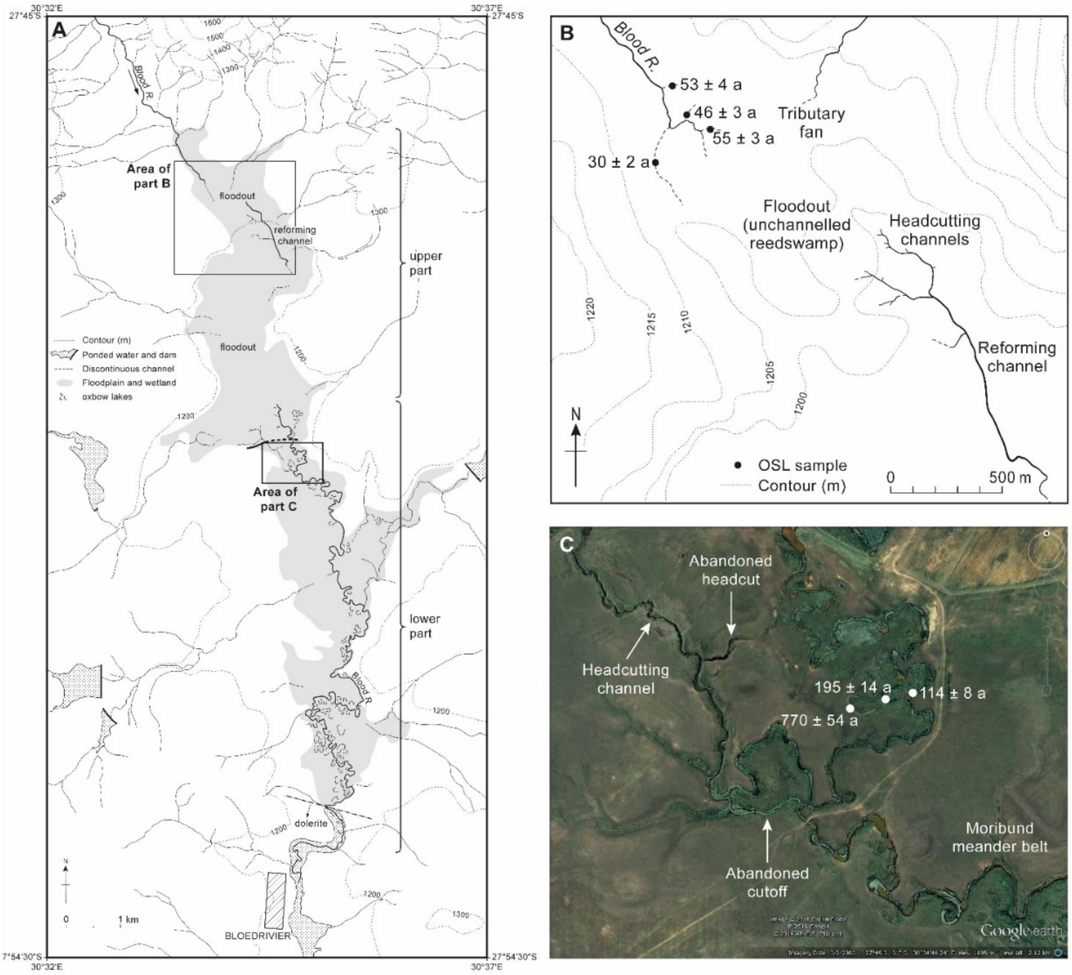

Fig. 4. Illustrations of some of the key geomorphological features and select OSL ages for landforms in the Blood River floodplain wetland (source: modified after Tooth et al., 2014).

The OSL dating has established that the discontinuity represented by the two floodouts developed during the very late Holocene. The OSL ages for oxbows within the lower part of the study reach (Fig. 4C) reveal that between ~800 and 100 years ago, the wetlands were characterised by a throughgoing, meandering channel (Tooth et al., 2014). A sinuous channel remains in this lower part but is now largely moribund, and during the last ~100 years, major morphological and sedimentary changes have occurred upvalley. Here, a former throughgoing, meandering channel has been replaced by straighter sections of channel that decrease in size downstream and terminate in floodouts (Fig. 4B). The initial cause(s) of this change are uncertain. Human activities cannot be discounted, but the change may have resulted from downstream decreases in discharge and sediment transport induced by the severe 1930s drought, possibly in combination with rapid encroachment and within-channel establishment of sedges and grasses (e.g., *Phragmites australis*) in slow-flowing or stagnant sections of channel (Tooth et al., 2014). Following the establishment of the upper floodout, channel–levee complexes have formed and been abandoned on several occasions during the last ~60 years (Fig. 4B), leading to local redistribution of water and sediment (Tooth et al., 2014). Organo-clastic sediments >3 m thick have accumulated in the floodouts as broad lobes, in places burying the former meander-belt sediments and leading to local gradient increases. In combination with the limited flows that filter through the floodouts, these increased gradients have promoted the formation of the headcutting channels (Figs. 4B and 4C). During the 70–80 year period covered by aerial photographs, some of the headcutting channels have widened slightly and extended some tens of metres upvalley into the floodout (Kotze, 1994; Tooth et al., 2014).

3.4 Schoonspruit former floodplain wetland, Free State

The Schoonspruit (Fig. 5) traverses an abandoned floodplain wetland and has been the subject of previous geomorphological investigations (Tooth et al., 2004; Keen-Zebert et al., 2013, 2016). Within the ~20-km-long study reach, the intermittent but throughgoing, sinuous (P ~1.99) channel has incised 3-5 m into the underlying mudstone. Consequently, the ~1-km-wide floodplain (Fig. 5A) is now only rarely inundated by overbank flows, although rainfall can still lead to flooding in oxbows and abandoned channels. Along the incised channel, an inset floodplain up to ~20 m wide has formed by lateral and vertical accretion (Tooth et al., 2004), while gullies (dongas) have eroded into older, early to middle Pleistocene alluvial and/or colluvial sediments (Fig. 5B). At the lower end of the study reach, the river transitions to a valley carved into a resistant dolerite sill and becomes less sinuous, with floodplains being restricted to <50 m wide (Fig. 5A). Cosmogenic isotope analyses indicate that channel-bed dolerite outcrop is denuding at ~100-255 mm ka^{-1} (Keen-Zebert et al., 2016), with field evidence for flood-transported dolerite boulders and isolated pedestals of jointed dolerite outcrop within the channel bed (Fig. 5C) suggesting a recent phase of incision. This phase of dolerite incision has been interpreted as initiating a fall in local base level, thereby generating a headward-retreating knickpoint that resulted in the channel incision evident in the reaches upstream (Tooth et al., 2004; Keen-Zebert et al., 2013, 2016).

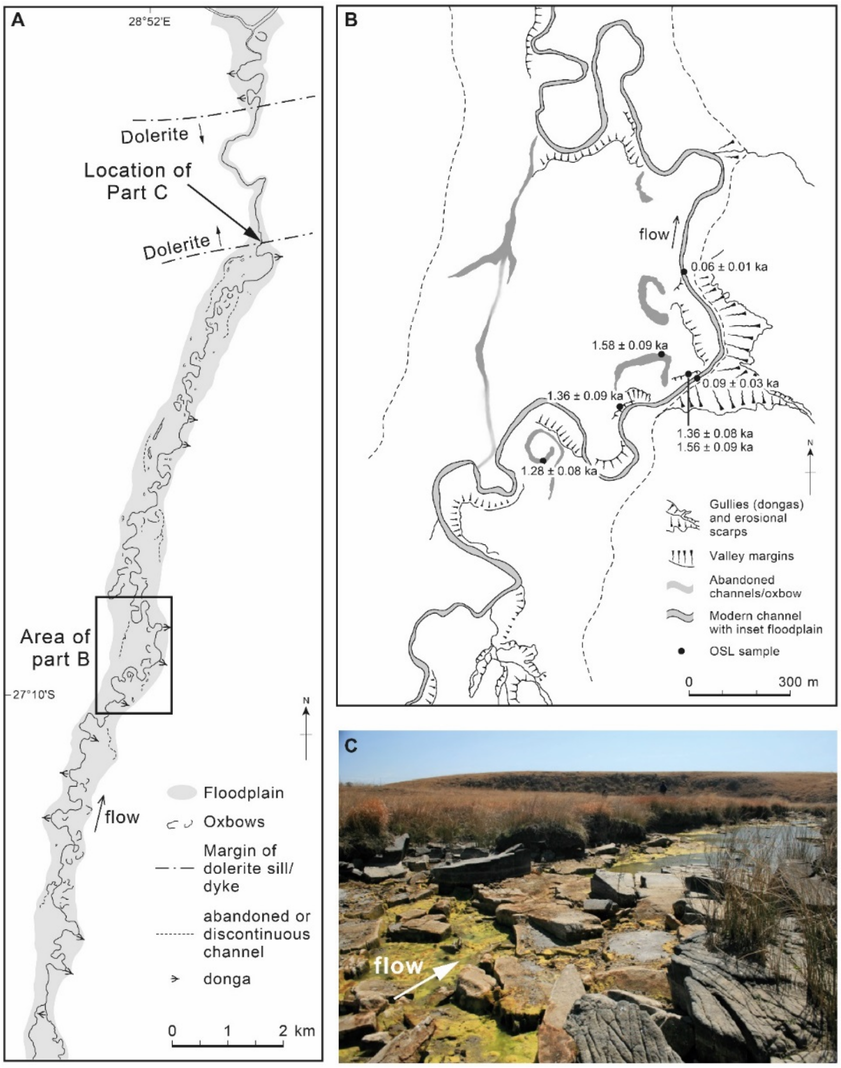

Fig. 5. Illustrations of some of the key geomorphological features and select OSL ages for landforms in the former floodplain wetland of the Schoonspruit (source: modified after Keen-Zebert et al., 2013).

The OSL dating has established the timing of floodplain deposition and channel incision. The OSL ages for sediments from the abandoned floodplain demonstrate that oxbow formation and overbank sedimentation occurred between ~1.56 and 1.28 ka (Fig. 5B) and are indicative of the last phase of channel–floodplain connectivity before incision occurred (Keen-Zebert et al., 2013). Incision began after ~1.28 ka and probably continued for ~1000 years, with renewed sedimentation at ~0.09 to 0.06 ka then leading to formation of the inset floodplains (Fig. 5B).

4. Interpretation

The findings from the four South African study sites provide the basis for an assessment of the comparative resilience of each of the wetlands to natural environmental and anthropogenic drivers.

4.1. Resilience of the Klip River floodplain wetland

Prior to the last 100-150 years, the Klip River floodplain wetland appears to have been highly resilient to environmental change, with resilience best defined in terms of definition A (i.e., resistance). Over at least the last ~30 ka, the Klip River has remained a throughgoing, meandering channel with roughly constant dimensions. Regional and local palaeoclimatic fluctuations appear to have had little impact on channel–floodplain morphology or dynamics, with infrequent avulsions (<0.3 ka^{-1}) occurring intrinsically as a natural outcome of meander-belt development. Avulsions have involved stepwise migrations of reaches up to ~4 km long (Fig. 2B), resulting in changes to patterns of flooding and sedimentation, but the incisional avulsion process means that channel–floodplain structure and connectivity have essentially been maintained throughout avulsion events. Meander belts have then slowly reestablished along newly formed channels over successive centuries to millennia (Tooth et al., 2007).

Given the evidence for the dramatic late Quaternary transformations (e.g., braided to meandering, or aggrading to incising) that have occurred along many other rivers worldwide in response to discharge and sediment supply changes (e.g., Anderson et al., 2004; Hudson et al., 2008; Macklin et al., 2010), this long-term overall stability of channel dimensions and channel–floodplain structure and connectivity along the Klip River study reach is remarkable. Tooth et al. (2009) attributed this stability to a combination of three factors. First, a low sediment supply relative to the capacity for onward transport means that the channel bed remains grounded on bedrock and that levee formation and alluvial ridge building is limited, so the aggradational factors that tend to promote avulsion

(Slingerland and Smith, 2004) are reduced in importance. Second, at the downstream end of the floodplain wetland, a resistant dolerite barrier (Fig. 2C) acts as a stable local base level (Fig. 6A) and thus has limited the potential for channel incision during the late Quaternary, as is indicated by the absence of alluvial terraces in the study reach. Third, the low energy conditions (bankfull unit stream powers are <10-15 W m^{-2} throughout much of the study reach; Table 2) minimise the potential for rapid and/or widespread erosion, even during floods. Together, these factors have meant that the Klip River has been relatively unresponsive to late Quaternary palaeoclimatic changes, with most channel–floodplain changes instead being driven by slow-acting and/or infrequent intrinsic processes.

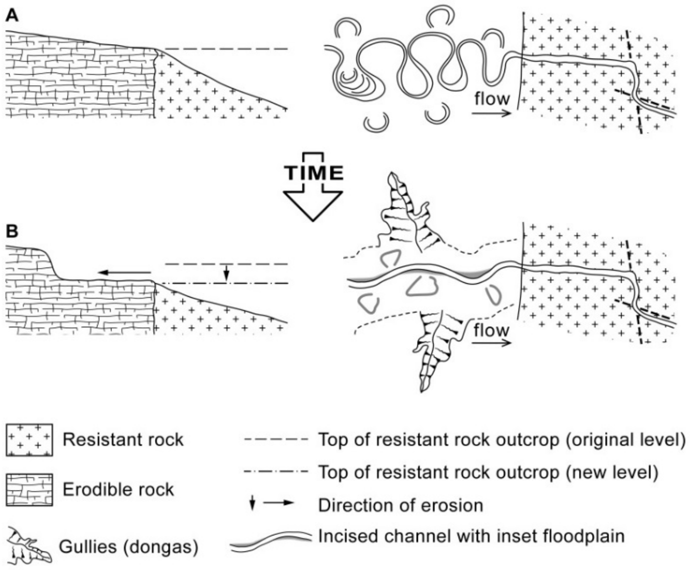

Fig. 6. Schematic illustration of the cycle of wetland development in the South African drylands: (A) meandering channels and floodplain wetlands initially form atop more erodible rocks (e.g., mudstone, sandstone) upstream of resistant outcrop (e.g., dolerite). Migrating meanders locally impinge on the valley sides and over time lead to valley widening; and (B) with incision through the resistant outcrop, knickpoint migration leads to straightening and deepening of the channel. This leads to wetland abandonment and desiccation and commonly initiates the formation of large gullies that erode the former floodplain wetland sediments. If base level stabilises (e.g., in a lower part of the resistant rock mass), then meandering channels and floodplain wetlands can form anew in the reaches upstream, albeit at a lower topographic level. The timescales over which these processes occur is poorly constrained but within the floodplain wetlands aerial photograph analyses and OSL dating demonstrate that channel changes (meander bend migration, bend cutoff, avulsion) occur on timescales of years to many tens of thousands of years (source: modified after Tooth et al., 2004, and Keen-Zebert et al., 2013).

By strong contrast with the resilience to natural environmental change exhibited over most of the late Quaternary, however, the Klip River floodplain wetland has not been resilient to recent human impacts. Under natural conditions, avulsions have occurred just once every 3-6 ka since 15 kyr. Following colonial settlement (late 1800s onwards), however, an ongoing, potentially major avulsion has been initiated only ~1 ka after the last natural avulsion event and in a part of the floodplain wetland where avulsions have not occurred previously (Fig. 2B). The avulsion has led to major changes elsewhere in the reach, including failure of a 2-3 km long section of the original channel upstream (Fig. 2B), and dramatic channel widening and decreased overbank flooding downstream (Tooth et al., 2007, 2009; McCarthy et al., 2010).

4.2. Resilience of the Tshwane River floodplain wetland

Over the late Holocene, the Tshwane River floodplain wetland has been highly resilient to environmental change, with resilience also best defined in terms of definition A (i.e., resistance). During at least the last ~650 years, the Tshwane River has remained a throughgoing, meandering channel with roughly constant dimensions. Palaeoclimatic fluctuations appear to have had little impact on channel–floodplain morphology or dynamics, with relatively frequent avulsions occurring intrinsically as a natural outcome of meander-belt development. Avulsions have involved stepwise migrations of reaches up to ~5 km long (Fig. 3A) and have resulted in changing patterns of flooding and sedimentation, but channel–floodplain structure and connectivity has essentially been maintained throughout the incisional avulsion events. Meander belts have then reestablished along newly formed channels over successive decades to centuries (Larkin et al., 2017b). Local base level is determined by aggradation on the Pienaars River downvalley (Fig. 3A), but as along the Klip River, the low energy conditions (bankfull unit stream powers are <10 W m^{-2} throughout much of the study reach; Table 2) also minimise the potential for rapid and/or widespread erosion. Consequently, the Tshwane River also has been relatively unresponsive to late Quaternary palaeoclimatic changes, with channel changes instead being driven by intrinsic processes. The Tshwane River remains in a near-natural condition with human influence restricted to some subsistence grazing, and the natural resilience of this floodplain wetland has been preserved.

4.3. Resilience of the Blood River floodplain wetland

The Blood River floodplain wetland is more difficult to assess in terms of resilience. Although the timing and consequences of the development of the discontinuity can be established, the initial cause(s) remain uncertain. Assuming that human activities have not led to development of the discontinuity, however, then the most likely explanation is a combination of drought-induced downstream decreases in discharge and sediment transport along with associated reedbed establishment. Given the dramatic change to channel–floodplain structure that has occurred subsequently, then one interpretation could be that the wetland has been nonresilient to environmental change. On the steepened, downvalley sides of the sediment lobes that mark the two floodouts, however, the presence of headcutting channels (Figs. 4B and 4C) suggests an alternative explanation. The combination of headcutting channels and floodouts indicates partial analogy with the system-scale, intrinsic morphological and sedimentary dynamics of those dryland fluvial systems that are also characterised by a dynamic mosaic of channelled and unchannelled landforms (e.g., discontinuous ephemeral streams and erosion cells; Schumm and Hadley, 1957; Pickup, 1985; Bull, 1997). If headcutting through the lobes continues, then a throughgoing channel may reestablish in the upper part of the wetland, possibly eventually linking with the sinuous but now moribund channel in the lower part (Tooth et al., 2014). Given the aerial photograph evidence for headcut retreat over the last 70-80 years (see above), it is plausible that reestablishment of a throughgoing channel and associated longitudinal flow and sediment transport connectivity could occur on a timescale of centuries to a few millennia. If this scenario were to unfold, then recovery to a predisturbance (i.e., predrought) condition could occur. Over this timescale, therefore, the

Blood River floodplain wetland might then be regarded as resilient in terms of definition B (i.e., ability to recover from disturbance).

4.4. Resilience of the Schoonspruit former floodplain wetland

Over the last millennia, the Schoonspruit floodplain wetland has been nonresilient to environmental change. By strong contrast with the Klip River where a slowly eroding dolerite sill provides an essentially stable local base level (Fig. 6A), recent incision has occurred into the dolerite sill at the downstream end of the Schoonspruit study reach (Figs. 5C and 6B). Incision has resulted in local base–level fall and associated knickpoint retreat, leading to deep channel incision in reaches upstream. Incision has dramatically transformed channel–floodplain structure and connectivity, with the higher elevation, former floodplain wetland now rarely inundated by overbank flows, while inset floodplains have formed at a lower elevation. If base level stabilises again (e.g., in a lower section of the dolerite sill), however, then meandering, valley widening, and formation of extensive floodplains might occur again in future (Tooth et al., 2004). The timescale for such a development is little known, but based on the OSL dating results from this and other wetlands, the process likely takes many hundreds of millennia. If this scenario were to unfold along the Schoonspruit, channel–floodplain structure and connectivity would eventually exhibit some degree of recovery, albeit at a lower topographic level, and this system might then also be regarded as exhibiting some degree of resilience in terms of definition B.

5. Discussion

The foregoing case studies demonstrate how wetlands in the South African drylands have exhibited varying geomorphological resilience. Even in catchments with similar hydroclimates, physiographies, lithologies, vegetation assemblages, and human impacts (Table 2), some wetlands have been highly resilient to environmental change, but others have been nonresilient. Integration of the findings from these case studies with results from the geomorphological investigations of other wetlands in drylands, within the South African interior and farther afield, raises some key issues related to the assessment of wetland resilience. These include a consideration of wetland dynamics and geomorphological thresholds, wetland geomorphological 'life cycles', and the relative roles of natural environmental and human impacts. In turn, these issues raise challenges for geomorphological inputs to practical applications of the resilience concept in wetland management.

5.1. Wetland dynamics and geomorphological thresholds

A key factor determining the resilience of any given geomorphological system is its dynamics in proximity to extrinsic thresholds (Schumm, 1973, 1979; Bull, 1979). For a system operating far from a threshold, significant changes to extrinsic controls (e.g., a disturbance event such as a flood, sustained drought, or fire) may be required to push the system across that threshold and cause a dramatic change in system structure and functioning. For a system operating close to a threshold, however, even relatively minor changes to extrinsic controls may lead to crossing of that threshold and to significant changes in structure and functioning. In either case, threshold crossing would mean that the system would not be deemed as resilient under definition A (i.e., resistance). If subsequent changes to extrinsic controls enable movement back across the threshold, however, then a return to a previous condition may occur over time. Under this scenario, the system may be deemed resilient under definition B (i.e., recovery). Hence, for any given geomorphological system, identifying where thresholds lie and what controls the nature and rate of movement across these thresholds is critical.

In many wetlands in drylands, major channel–floodplain changes can be driven by the crossing of intrinsic thresholds (e.g., internal process-form adjustments driven by downstream discharge decreases) and/or by the crossing of extrinsic thresholds (e.g., event-based or more sustained changes in flow and/or sediment supply induced by tectonic activity, climate change, or human impacts; Ralph and Hesse, 2010; Grenfell et al., 2014; Larkin et al., 2017a). The crossing of intrinsic thresholds does not threaten resilience as defined above because the changes occur as part of natural autogenic dynamics that are unrelated to extrinsic disturbances. Nonetheless, as considered further below, the movement toward or across intrinsic thresholds could leave systems more prone to the crossing of extrinsic thresholds that could then threaten resilience.

In their consideration of the sensitivity and vulnerability of southern African wetlands to environmental change — concepts that are closely related to resilience — Ellery et al. (2016) outlined how low-order, valley bottom wetlands in inland South Africa can be classified into stable (unincised) and incised (gullied/channelled) types and then discriminated on a bivariate plot of wetland area versus wetland gradient (Fig. 7, inset). This plot provides the empirical underpinning for a conceptual diagram (Fig. 7) that illustrates how individual wetlands may be driven across a fuzzy threshold (defined as the 'zone of vulnerability') from a stable to an incised condition by (i) an increase in wetland area (i.e., extent of inundation/saturation) for a given wetland gradient as, say, discharge increases or sediment accumulation locally blocks or restricts water outflow (Fig. 7, pathway A to B) or (ii) an increase in wetland gradient for a given wetland area as, say, aggradation leads to localised valley floor steepening (Fig. 7, pathway A to C). Increases in wetland area or gradient are necessary preconditions for incision, but the trigger itself may be related to extrinsic factors such as climate change, local base–level fall, or land use change (Ellery et al., 2016).

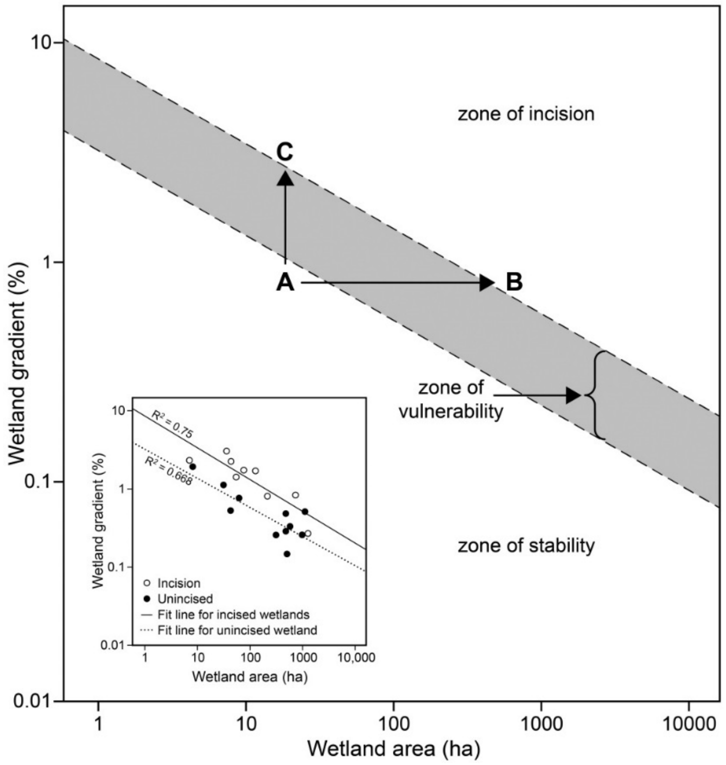

Fig. 7. Zones of stability, vulnerability, and incision for valley-bottom wetlands in southern Africa. Valley-bottom wetlands typically occur on low-order streams where the valley is narrow or impounded and tend to lack well-defined channels and characteristic floodplain features. The inset shows the underpinning empirical data set (figures modified after Ellery et al., 2016). This conceptual diagram is similar to the threshold-based models for gully incision (e.g., Patton and Schumm, 1975), but wetland area rather than drainage area (a surrogate for catchment runoff) is used on the *x* axis, in part because the former is easier to measure (Ellery et al., 2016).

This conceptual approach can be adapted and extended to cater for the dynamics associated with the larger floodplain wetlands that are the main focus of this paper. Figure 8 is an attempt to capture these dynamics for the four South African study sites considered above. Gradient (for the channel or unchannelled floodplain), discharge, and sediment availability form the three axes (Fig. 8), and together determine system dynamics. Gradient can be measured from topographic maps or surveys, and discharge can be measured or approximated, but few sediment supply or sediment transport data exist to enable quantification of sediment availability. Nonetheless, the points for each system can still be plotted in approximate relative positions and in relation to a common extrinsic threshold that separates stable dynamics (i.e., minor aggradation/incision or no change) from more sustained, system-transforming, sedimentation or erosion (Fig. 8).

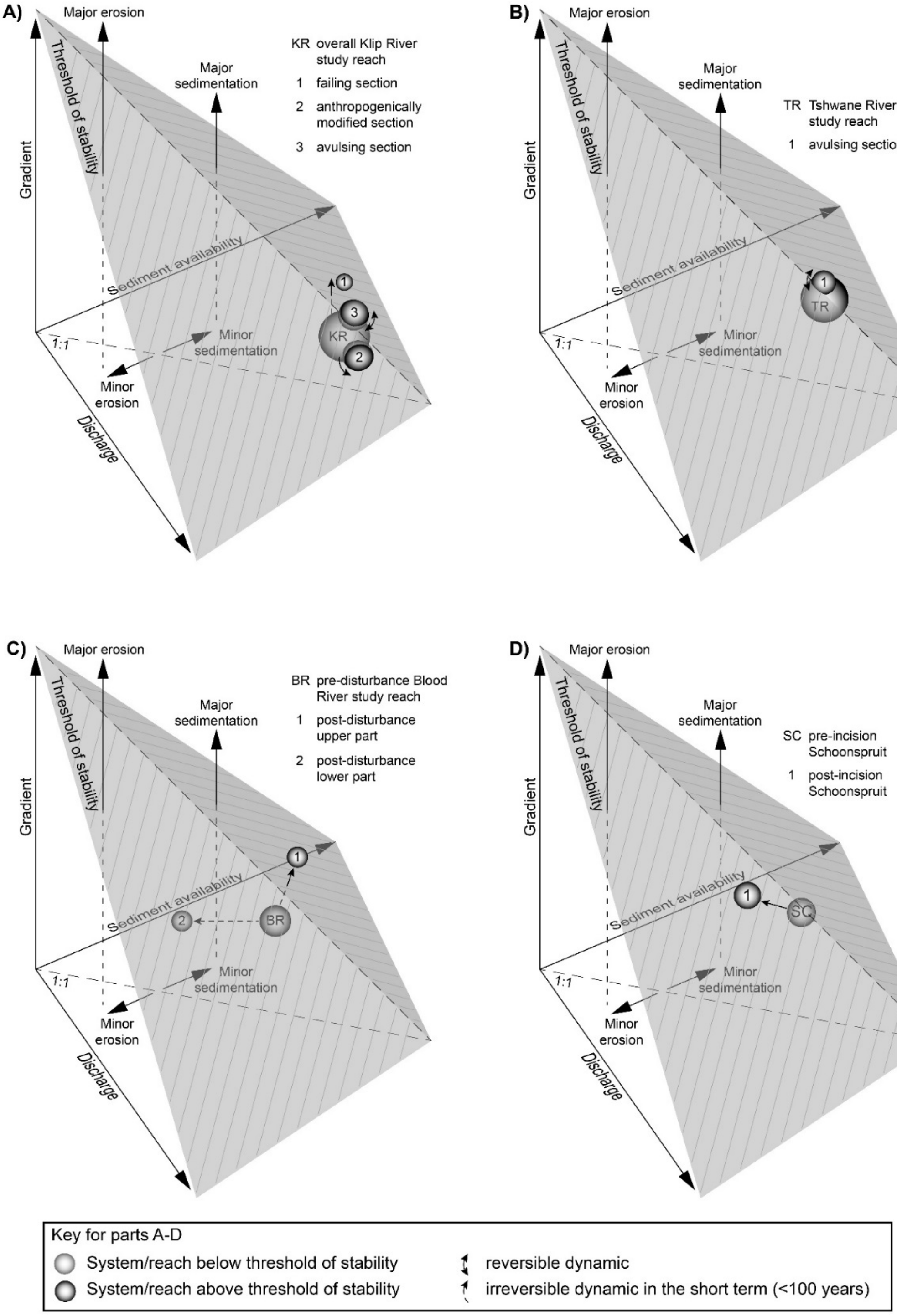

Fig. 8. Conceptual diagrams illustrating the diverse channel–floodplain dynamics that underpin the resilience or nonresilience of wetlands in the drylands of South Africa: (A) Klip River floodplain wetland; (B) Tshwane River floodplain wetland; (C) Blood River floodplain wetland; and (D) former floodplain wetland of the Schoonspruit.

Figure 8 attempts to address one of the problems common to many conceptual treatments of geomorphological or environmental system dynamics in that any given system is typically treated as just one point in a phase space, with attention usually being focused on temporal macroscale dynamics (e.g., points A, B, and C in Fig. 7; for an ecological example, see Côté and Darling, 2010). In reality, most wetlands — especially large floodplain wetlands — are not singular landforms but are typically composed of a complex assemblage of channel and floodplain features with controls (e.g., gradient, discharge, sediment availability) that vary spatially, downstream and across the valley. Hence, many microscale and mesoscale spatial and temporal dynamics may occur alongside the temporal macroscale dynamics and are represented here as bounded departures (smaller spheres with numbers) from the typical range of temporal macroscale system behaviour (larger spheres with upper case letters). For instance, avulsions within large floodplain wetland systems represent local, threshold-crossing system instabilities (Figs. 8A and 8B), but so long as the overall wetland system remains stable (or recovers stability), then these instabilities do not affect the resilience of the system as a whole.

The dynamics of the Klip River floodplain wetland provide a case in point. Throughout much of the late Quaternary, the essentially nonaggrading Klip system has operated — and in many reaches continues to operate — far below a threshold (Fig. 8A). Channel gradient is more-or-less stable, while discharge and sediment availability are in approximate long-term balance. Local and regional environmental (especially palaeoclimatic) changes have not been of sufficient magnitude or duration to alter this balance and push the system across a threshold. Movement across a threshold has occurred infrequently only in the avulsion-prone middle part of the study reach (Fig. 8A – 'avulsing section') where valley gradient steepens slightly and sediment becomes sandier. Avulsions have led to redistribution of water and sediment but channel–floodplain structure and functioning have been maintained throughout, meandering belts have reestablished slowly over time, and reach-scale and overall system resilience have been largely maintained (Fig. 8A).

By contrast, over at least the last ~650 years, the vertically aggrading Tshwane system has been operating closer to a threshold condition (Fig. 8B). Here, downstream decreases in discharge and sediment flux promote vertical aggradation, as reflected in more prominent levee and alluvial ridge growth (Fig. 3B), and the local decreases in channel gradient and increases in cross-floodplain gradient that occur along developing meander belts help to prime reaches for more frequent avulsions. Nonetheless, channel–floodplain structure and functioning have been maintained, meandering belts have reestablished rapidly over time, and here too reach-scale and overall system resilience have been maintained.

The situations are different on the Blood River and the Schoonspruit floodplain wetlands, where a substantial portion (Blood River) or the whole of the study reach (Schoonspruit) has moved across a threshold (Figs. 8C and 8D). As discussed above, both systems may in time move back across the threshold and exhibit some degree of recovery but only over timescales of centuries or far longer, and therefore at present can be characterised as nonresilient.

5.2. Wetland geomorphological 'life cycles'

A key point emerging from this analysis is that resilience may change through the geomorphological 'life cycle' of a wetland (cf. Ellery et al.'s (2016) discussion of changing wetland sensitivity in peat-accumulating systems). As an example, intrinsic changes (e.g., aggradation and slope steepening that occur in response to downstream discharge decreases) may bring the wetland close to an extrinsic threshold, leaving the system prone to event-based (e.g., flash flood) or more sustained (e.g., prolonged drought) extrinsic disturbances that facilitate more dramatic changes and threaten resilience. As shown by the example of the Blood River, such changes may occur in combination with strong biotic feedbacks such as reedbed establishment (Tooth et al., 2014).

Alternatively, wetlands may be driven across thresholds by extrinsic controls that operate essentially independently of intrinsic dynamics. The long-term macroscale dynamics of the Klip River and Schoonspruit floodplain wetlands, for instance, are controlled by the stability of their respective lithologically controlled local base levels (a function of the rate and nature of bedrock erosional processes), but the two systems currently are at different stages in the wetland development cycle. The Klip River remains unincised above an essentially stable local base level (Fig. 6A), while the Schoonspruit has undergone recent deep incision in response to local base–level fall (Fig. 6B).

5.3. Relative roles of natural environmental and human impacts

Over the late Quaternary, the four South African study sites have been relatively unresponsive to local and regional palaeoclimatic changes, probably owing to factors such as the characteristically low stream powers, relatively low rates of sediment supply, and (in some cases) stable local base levels. Nonetheless, in the absence of human activities, wetland changes have been driven by a variety of natural factors including intrinsic process-form dynamics (Klip, Tshwane), possibly short-term weather extremes (drought in the Blood River), and lithologically controlled base–level fall (Schoonspruit). As the examples of the Klip and Tshwane rivers show, however, such changes have not necessarily threatened wetland resilience.

By contrast, even some floodplain wetlands that have been resilient to natural factors have been greatly impacted by human activities over the last 100-150 years. With colonial settlement in the Klip valley, for instance, a situation of long-term resilience changed dramatically, with parts of the floodplain wetland now degraded. Within South Africa and farther afield, many other wetlands in drylands also have been severely impacted by land use changes, commonly leading to the loss of natural resilience (e.g., Richardson et al., 2005; Kotze et al., 2012; Cole and Cole, 2015).

5.4. Challenges for geomorphological inputs to practical applications of the resilience concept

Evidence for the deleterious impacts of human activities on many wetlands in drylands, either deliberate or inadvertent, highlights that debates about resilience are more than just academic exercises but have potential application in management contexts. Indeed, maintaining, enhancing, or restoring resilience is a common objective in many wetland management, conservation, and restoration strategies (e.g., Kotze et al., 2009b). Even well-intentioned management strategies, however, have been subject to varying degrees of success (e.g., Grenfell et al., 2009; Ralph et al., 2015), and as study of the Klip River has shown, in some instances management interventions may have even led to decreases in natural resilience (McCarthy et al., 2010). In a practical sense, therefore, can geomorphologists have greater input in developing guidelines for defining, measuring, and identifying resilience as part of an holistic approach to wise or sustainable use of wetlands in drylands? In attempting to do so, there are at least three interrelated considerations.

First, as previous studies (e.g., Côté and Darling, 2010) and this paper have stressed, there is a need to have clear definitions of resilience in environmental management. Is the management objective to aim for definition A (resistance) or definition B (recovery from disturbance) or definition C (a more desirable configuration)?

Second, in many management contexts, consideration needs to be given to the interface between geomorphological resilience and other resilience dimensions, namely ecological resilience and socioeconomic resilience, the latter perhaps being defined in terms of ecosystem service delivery (e.g., Liersch et al., no date; Gitay et al., 2011; Wetlands International, 2014). In natural systems, these dimensions are often closely interrelated because many wetlands develop as a consequence of water, sediment, and biotic activity acting in combination, and this leads to strong links between wetland structure, functioning and ecosystem services. In management contexts, however, restoration, maintenance, or enhancement of geomorphological resilience (e.g., natural channel–floodplain forms) may not be the primary objective, with greater emphasis perhaps being placed on managing for ecological resilience (e.g., biodiversity) or with priority being given to other aspects of ecosystem service delivery (e.g., flooding alleviation). Again, a study of the Klip River floodplain wetland provides an instructive example (McCarthy et al., 2010). In an ideal world, remediation of the degraded parts (Fig. 8A) would strive to return the wetland to its natural, precolonial, geomorphological condition. In reality, other management goals have priority, namely maintaining current habitat and biodiversity (this has the added advantage of promoting local tourism, especially bird watching) and using the wetlands for water quality enhancement. Attempts to return the wetlands to their precolonial geomorphological condition (e.g., by removing exotic willow trees and erosion control structures) would in fact reduce habitat and biodiversity, permanently in the case of some avian species that now use the willows for perching, roosting, and nesting, and for centuries in the case of some aquatic species owing to the very slow natural rates of channel and floodplain change (Fig. 2C). In assessing the various management options for remediating the degraded parts of these wetlands, McCarthy et al. (2010) concluded that while further active, ongoing management intervention could restore some of the ecological and hydrological functions, the wetland is likely to remain very far from its natural geomorphic condition essentially in perpetuity. Hence, the natural resilience of part of this wetland appears to have been lost permanently, but some degree of 'artificial' or 'managed' resilience could probably be achieved. In this and other cases, therefore, channel and ecological management may be increasingly used to 'engineer' wetlands toward configurations deemed more desirable, thereby meeting definition C of resilience. Regardless of whether or not geomorphological resilience is the primary concern, however, geomorphological insights are still needed for a comprehensive, holistic understanding of the other dimensions of resilience.

Third, in assessing wetland resilience for management purposes, identification and monitoring of wetland dynamics in relation to geomorphological thresholds is needed. Whether wetlands are operating far from or close to thresholds will determine the appropriate management strategies for a given set of objectives. In small headwater wetlands in South Africa, Grenfell et al. (2005) proposed the use of floristic and edaphic indicators as early warning indicators of slow, progressive changes related to upslope water resource developments (e.g., forestry), but these approaches need to be developed for larger floodplain wetlands. Wohl (2014) discussed methods for determining resilience, thresholds, and metrics in the context of dryland channel networks; similar approaches could be adapted for larger wetlands in drylands, many of which are associated with dryland channels (Tooth and McCarthy, 2007). In many wetlands in drylands, recent severe droughts have provided opportunities to identify early warning signs of wetland change. For instance, during Australia's 'millennium drought' (c. CE 2001-2009), severe declines in water quality (e.g., acid drainage) were reported from some 'billabongs' (water-filled depressions), although the ending of the drought led to rapid recovery of water quality, demonstrating some degree of resilience to these short-term hydrochemical changes (Murray Darling Wetlands Working Group Ltd., 2017). With more sustained or more frequent droughts projected in future, however, such rapid recovery in water quality may not be so forthcoming; more fundamental structural and functional adjustments may be expected in many wetlands in drylands, particularly where this is linked with increasing human pressure on wetlands for dwindling resources. Judging by the example of Blood River (Tooth et al., 2014), even relatively simple indicators such as signs of reed encroachment in stagnant or slow-flowing, drought-impacted channels might provide low cost, early warning signs of potential threshold-crossing behaviour and might give rise to simple management mitigation strategies (e.g., targeted reed harvesting from critical channel reaches).

6. Conclusion

Like many other key concepts in geomorphology, resilience is an important but rather slippery and amorphous concept. For wetlands in drylands, the ambiguities in clearly defining resilience are compounded by the wide variety of wetland characteristics resulting from diverse combinations of hydroclimatic, geological, geomorphological, edaphic, vegetative, and anthropogenic controls, as well as the practical difficulties in measuring resilience. Nevertheless, using case studies from the South African drylands, this paper has shown how aerial imagery, field data, and geochronology can provide clearly defined spatial and temporal frameworks that enable assessment of wetland resilience. A synthesis of available research shows that these South African wetlands have exhibited varying levels of geomorphological resilience and nonresilience, with a key determining factor being the operation of channel–floodplain dynamics in proximity to extrinsic thresholds. While local threshold-crossing instabilities (e.g., intrinsically driven avulsions) may be experienced, this may not necessarily affect overall wetland resilience but other factors (e.g., severe drought, base–level changes) may push wetlands across a threshold with an effective loss of resilience. For many South African floodplain wetlands, consideration of the changing stability of downstream local base levels illustrates how resilience may also change through the wetland 'life cycle'. Hence, on the basis of the findings from these South African wetlands and limited studies from farther afield, generalising about the resilience of wetlands in drylands is hard. As a group, wetlands in drylands cannot be characterised as more resilient or less resilient than wetlands in more humid regions.

One clear conclusion emerges, however: even some wetlands in drylands that have been highly resilient to natural factors (e.g., climate change) throughout much of the late Quaternary have been greatly impacted by recent human activities. In some cases, human activities have driven wetlands across thresholds, with the changes to channel–floodplain structures and connectivity being of sufficient magnitude to preclude a return to preimpact reference conditions, and resilience has effectively been lost. This trend is not unique to wetlands in drylands, and many wetlands in humid regions have been subject to similarly rapid, anthropogenically forced changes, particularly from the second half of the twentieth century onward (Maltby, 1986; Dugan, 1993; Millennium Ecosystem Assessment, 2005b; Mitsch and Gosselink, 2015).

Given that maintaining or enhancing resilience is often seen as a desirable target in wetland management, the issue for geomorphologists is to operationalise the resilience concept and to demonstrate how geomorphological resilience interfaces with other dimensions of resilience. A key priority is to try to identify early warning indicators of changes to wetland structure and functioning that will enable wetland managers to identify and measure those wetlands operating close to resilience-threatening thresholds. This information can then be used to develop adaptation and/or mitigation strategies that are consistent with management objectives. In a putative Anthropocene, increasing our understanding of coupled natural-human systems is being emphasised (e.g., Kotchen and Young, 2007; Folke and Rockström, 2009; Chin et al., 2014), and related discussions about socioecological and sociogeomorphological systems are being aired (e.g., Folke et al., 2010; Ashmore, 2015). Clearly, abundant scope exists for wetland geomorphologists — and geomorphologists more broadly — to improve communication of emerging insights regarding resilience and to engage in educational and training activities that will enable society to meet the mounting twenty-first century environmental management challenges.

Acknowledgements

My research on South African wetlands in drylands has been conducted over a number of years in collaboration with a number of colleagues worldwide; this has enabled numerous insights to emerge regarding the structure, functioning, dynamics, and management of wetlands in drylands. Research for the publications cited herein has been generously supported by funding from a number of organisations including Aberystwyth University, University of the Witwatersrand, Macquarie

University, The Royal Society, Natural Environment Research Council, National Research Foundation, National Science Foundation, National Geographic, the Skye Foundation, and the British Society for Geomorphology. I thank Zacc Larkin (Macquarie University) for helping to modify the Tshwane River figures, and also Antony Smith (Aberystwyth University) for the re-drafting of other figures. I also appreciate the constructive comments of the two anonymous reviewers on the initial submission.

References

Aber, J.S., Pavri, F., Aber, S., 2012. Wetland Environments: A Global Perspective. Wiley-Blackwell, Chichester, 437 pp.

Adger, W.N., 2000. Social and ecological resilience: are they related? Progress in Human Geography 24, 347–364.

Adger, W.N., 2006. Vulnerability. Global Environmental Change 16, 268-281.

Anderson, E., Harrison, S., Passmore, D.G, Mighall, T.M., Wathan, S., 2004. Late Quaternary river terrace development in the Macgillycuddy's Reeks, southwest Ireland. Quaternary Science Reviews 23, 1785–1801.

Ashmore, P.E., 2015. Towards a sociogeomorphology of rivers. Geomorphology 251, 149-156.

Biron, P.M., Buffin-Bélanger, T., Larocque, M., Choné, G., Cloutier, C.-A., Ouellet, M.-A., Demers, S., Olsen, T., Desjarlais, C., Eyquem, J., 2014. Freedom space for rivers: a sustainable management approach to enhance river resilience. Environmental Management 54, 1056–1073.

Brunsden, D., 2001. A critical assessment of the sensitivity concept in geomorphology. Catena 42, 99-123.

Bull, W.B., 1979. Threshold of critical power in streams. Geological Society of America Bulletin 90, 453–464.

Bull, W.B., 1997. Discontinuous ephemeral streams. Geomorphology 19, 227–276.

Calle, M., Alho, P., Benito, G., 2017. Channel dynamics and geomorphic resilience in an ephemeral Mediterranean river affected by gravel mining. Geomorphology 285, 333-346.

Chin, A., Galvin, K.A., Gerlak, A.K., Harden, C.P., Wohl, E., 2014. The future of human-landscape interactions: drawing on the past, anticipating the future. Environmental Management 53, 1-3.

Cole, A.T., Cole, C., 2015. An overview of aridland ciénagas with proposals for their classification, restoration, and preservation. The New Mexico Botanist Special Issue No. 4, 28-56.

Côté, I.M., Darling, E.S., 2010. Rethinking ecosystem resilience in the face of climate change. PLoS Biology 8, e1000438.

Dugan, P.J. (Ed.), 1993. Wetlands in Danger. Mitchell Beazley and IUCN (World Conservation Union), London.

Ellery, W.N., Grenfell, S.E., Grenfell, M.C., Powell, R., Kotze, D., Marren, P., Knight, J. 2016. Wetlands in southern Africa. In: Knight, J., Grab, S. (Eds.), Quaternary Environmental Change in Southern Africa: Physical and Human Dimensions. Cambridge University Press, Cambridge, UK, pp. 188-202.

Folke, C., 2006. Resilience: the emergence of a perspective for social–ecological systems analyses. Global Environmental Change 16, 253-267.

Folke, C., 2016. Resilience (republished). Ecology and Society 21, 44.

Folke, C., Rockström, J., 2009. Turbulent times. Global Environmental Change 19, 1-3.

Folke, C., Carpenter, S.R., Walker, B., Scheffer, M., T. Chapin, T., Rockström, J., 2010. Resilience thinking: integrating resilience, adaptability and transformability. Ecology and Society 15, 20 [Online article, available at: http:// www.ecologyandsociety.org/vol15/iss4/art20/].

Frisbee, M., Wilson, J.L., Sada, D.W., 2013. Climate change and the fate of desert springs. Eos 94, 144.

Fryirs, K., 2017. River sensitivity: a lost foundation concept in fluvial geomorphology. Earth Surface Processes and Landforms 42: 55-70.

Fryirs, K., Lisenby, P., Croke, J., 2015. Morphological and historical resilience to catastrophic flooding: the case of Lockyer Creek, SE Queensland, Australia. Geomorphology 241, 55-71.

Gitay, H., Finlayson, C.M., Davidson, N., 2011. A framework for assessing the vulnerability of wetlands to climate change. Ramsar Technical Report No. 5, CBD Technical Series No. 57, Ramsar Convetion Secretariat, Gland, Switzerland.

Grenfell, M.C., Ellery, W.N., Preston-Whyte, R.A., 2005. Wetlands as early warning (eco)systems for water resource management. Water SA 31, 465-471.

Grenfell, M.C., Ellery, W.N., Grenfell, S.E., 2009. Valley morphology and sediment cascades within a wetland system in the KwaZulu-Natal Drakensberg foothills, eastern South Africa. Catena 78, 20–35.

Grenfell, S.E., Grenfell, M.C., Rowntree, K., Ellery, W.N., 2014. Fluvial connectivity and climate: a comparison of channel pattern and process in two climatically contrasting fluvial sedimentary systems in South Africa. Geomorphology 205, 142-154.

Hill, A.R., 1987. Ecosystem stability: some recent perspectives. Progress in Physical Geography 11, 315-333.

Holling, C.S., 1973. Resilience and stability of ecological systems. Annual Review of Ecology and Systematics 4, 1–23.

Hudson, P.F., Butzer, K.W., Beach, T. (Eds.), 2008. Fluvial Deposits and Environmental History:

Geoarchaeology, Paleohydrology, and Adjustment to Environmental Change. The 39th Annual Binghamton Geomorphology Symposium. Geomorphology 101, 1-412.

Intergovernmental Panel on Climate Change, 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

Keen-Zebert, A., Tooth, S., Rodnight, H., Duller, G.A.T, Roberts, H.M., Grenfell, M., 2013. Late Quaternary floodplain reworking and the preservation of alluvial sedimentary archives in unconfined and confined river valleys in the eastern interior of South Africa. Geomorphology 185, 54-66.

Keen-Zebert, A., Tooth, S., Stuart, F.M., 2016. Cosmogenic ^{3}He measurements provide insight into lithologic controls on bedrock channel incision: examples from the South African interior. Journal of Geology, 124, 423-434.

Klein, R.J.T., Nicholls, R.J., Thomalla, F., 2003. Resilience to natural hazards: how useful is this concept? Environmental Hazards 5, 35-45.

Kotchen, M.J., Young, O.R., 2007. Meeting the challenges of the anthropocene: towards a science of coupled human-biophysical systems. Global Environmental Change 17, 149-151.

Kotze, D.C., 1994. A management plan for Blood River Vlei. Report 501/8094. Water Research Commission, Pretoria.

Kotze, D.C., Marneweck, G., Batchelor, A., Lindley, D., Collins, N., 2009a. WET-EcoServices: a technique for rapidly assessing ecosystem services supplied by wetlands. Wetland Management Series, Water Research Commission Report No. TT 339/09. Water Research Commission, Pretoria.

Kotze, D.C., Ellery, W.N., Rountree, M., Grenfell, M., Marneweck, G., Nxele, I., Breen, C., Dini, J., Batchelor, A., Sieben, E., 2009b. WET-RehabPlan: Guidelines for Planning Wetland Rehabilitation in South Africa. Water Research Commission Research Report No. TT336/09. Water Research Commission, Pretoria, 62 pp.

Kotze, D.C., Ellery, W.N., Macfarlane, D.M., Jewitt, G.P.W., 2012. A rapid assessment method for coupling anthropogenic stressors and wetland ecological condition. Ecological Indicators 13, 284-293.

Larkin, Z.T., Ralph, T.J., Tooth, S., McCarthy, T.S., 2017a. The interplay between extrinsic and intrinsic controls in determining floodplain wetland characteristics in the South African drylands. Earth Surface Processes and Landforms, in press.

Larkin, Z.T., Tooth, S., Ralph, T.J., Duller, G.A.T., McCarthy, T.S., Keen-Zebert, A., Humphries, M., 2017b. Timescales, mechanisms and controls of incisional avulsions in floodplain wetlands: insights from the Tshwane River, semiarid South Africa. Geomorphology, in press.

Levina, E., Tirpak, D., 2006. Adaptation to Climate Change: Key Terms. Organisation for Economic Co-Operation and Development. International Energy Agency, Paris, 24 pp.

Liersch, S., Cools, J., Kone, B., Koch, H., Diallo, M., Aich, V., Fournet, S., Hatterman, F., no date. Assessing vulnerability of wetlands to change. WETwin Fact Sheet 7. Availability at: http://www.wetwin.eu/downloads/Wetwin_07.pdf [Last access date: 27/01/17].

Long, A.J., Waller, M.P., Plater, A.J., 2006. Coastal resilience and late Holocene tidal inlet history: the evolution of Dungeness Foreland and the Romney Marsh depositional complex (U.K.). Geomorphology 82, 309–330.

Lyons, R., Tooth, S., Duller, G.A.T., 2013. Chronology and controls of gully (donga) formation in the upper Blood River catchment, KwaZulu-Natal, South Africa: evidence for a climatic driver of erosion. The Holocene 23, 1875-1887.

Macklin, M.G., Tooth, S., Brewer, P.A., Noble, P.L., Duller, G.A.T., 2010. Holocene flooding and river development in a Mediterranean steepland catchment: the Anapodaris Gorge, south central Crete, Greece. Global and Planetary Change 70, 35–52.

Maltby, E., 1986. Waterlogged Wealth: Why Waste the World's Wet Places? Earthscan, London. 200 pp.

Marren, P.M., McCarthy, T.S., Tooth, S., Brandt, D., Stacey, G.G., Leong, A., Spottiswoode, B., 2006. A comparison of mud- and sand-dominated meanders in a downstream coarsening reach of the mixed bedrock-alluvial Klip River, eastern Free State, South Africa. Sedimentary Geology 190, 213–226.

McCarthy, T.S., Tooth, S., Kotze, D.C., Collins, N., Wandrag, G., Pike, T., 2010. The role of geomorphology in evaluating remediation options for floodplain wetlands: the case of Ramsar-listed Seekoeivlei, eastern South Africa. Wetlands Ecology and Management 18, 119–134.

Midgley, D.C., Pitman, W.V., Middleton, B.J., 1994. Surface Water Resources of South Africa 1990, vol. II. Water Research Commission, Pretoria, South Africa.

Millennium Ecosystem Assessment, 2005a. Ecosystems and Human Well-Being: Wetlands and Water. Synthesis. World Resources Institute, Washington, DC.

Millennium Ecosystem Assessment, 2005b. Ecosystems and Human Well-Being: Current State and Trends, Vol. 1. World Resources Institute, Washington, DC.

Mitsch, W.J., Gosselink, J.G., 2015. Wetlands (5th ed). John Wiley and Sons, New York. 744 pp.

Mitsch, W.J., Gosselink, J.G., Zhang, L., Anderson, C.J., 2009. Wetland Ecosystems. John Wiley and Sons, Chichester, 256 pp.

Mohamed, Y., Savenije, H.H.G., 2014. Impact of climate variability on the hydrology of the Sudd wetland: signals derived from long-term (1900-2000) water balance computations. Wetlands Ecology and Management 22, 191-198.

Morton, R.A., Barras, J.A., 2011. Hurricane impacts on coastal wetlands: a half-century of storm-generated features from southern Louisiana. Journal of Coastal Research 27, 27-43.

Murray Darling Wetlands Working Group Ltd., 2017. Wetland Resilience – Bottle Bend. Available at: http://www.murraydarlingwetlands.com.au/news-media/news/20133145594.asp [Last access date: 18th January 2017].

Nield, J.M., Baas, A.C.W., 2008. The influence of different environmental and climatic conditions on vegetated aeolian dune landscape development and response. Global and Planetary Change 64, 76-92.

Ollis, D.J., Ewart-Smith, J.L., Day, J.A., Job, N.M., Macfarlane, D.M., Snaddon, C.D., Sieben, E.J.J., Dini, J.A., Mbona, N., 2015. The development of a classification system for inland aquatic ecosystems in South Africa. Water SA 41, 727-742.

Patton, P.C., Schumm, S.A., 1975. Gully erosion, northwestern Colorado: a threshold phenomenon. Geology 3, 88-90.

Phillips, J.D., 2009. Changes, perturbations, and responses in geomorphic systems. Progress in Physical Geography 33, 17–30.

Phillips, J.D., van Dyke C. 2016. Principles of geomorphic disturbance and recovery in response to storms. Earth Surface Processes and Landforms 41, 971–979.

Pickup, G., 1985. The erosion cell — a geomorphic approach to landscape classification in range assessment. Australian Rangeland Journal 7, 114–121.

Ralph, T.J., Hesse, P.P., 2010. Downstream hydrogeomorphic changes along the Macquarie River, southeastern Australia, leading to channel breakdown and floodplain wetlands. Geomorphology 118, 48–64.

Ralph, T.J., Hesse, P.P., Kobayashi, T., 2015. Wandering wetlands: spatial patterns of historical channel and floodplain change in the Ramsar-listed Macquarie Marshes, Australia. Marine and Freshwater Research 67, 782-802.

Richardson, C.J., Reiss, P., Hussain, N.A., Alwash, A.J., Pool, D.J., 2005. The restoration potential of the Mesopotamian marshes of Iraq. Science 307, 1307-1311

Rodnight, H., Duller, G.A.T., Tooth, S., Wintle, A.G., 2005. Optical dating of a scroll-bar sequence on the Klip River, South Africa, to derive the lateral migration rate of a meander bend. The Holocene 15, 802–811.

Rodnight, H., Duller, G.A.T., Wintle, A.G., Tooth, S., 2006. Assessing the reproducibility and accuracy of optical dating of fluvial deposits. Quaternary Geochronology 1, 109–120.

Schulze, R.E., 1997. South African Atlas of Agrohydrology and Climatology. Report No. TT82/96. Water Research Commission, Pretoria, South Africa.

Schumm, S.A., 1973. Geomorphic thresholds and complex response of drainage systems. In: Morisawa, M. (Ed.), Fluvial Geomorphology. New York State University Publications in Geomorphology, Binghamton, NY, pp. 299–309.

Schumm, S.A., 1979. Geomorphic thresholds: the concept and its applications. Transactions Institute of British Geographers, New Series 4, 485–515.

Schumm, S.A., Hadley, R.F., 1957. Arroyos and the semiarid cycle of erosion. American Journal of Science 255, 161–174.

Schuyt, K., Brander, L., 2004. Living Waters: Conserving the Source of Life. The Economic Values of the World's Wetlands. World Wildlife Fund, Amsterdam.

Slingerland, R., Smith, N.D., 2004. River avulsions and their deposits. Annual Review of Earth and Planetary Sciences 32, 257–285.

Swindles, G.T., Morris, P.J., Wheeler, J., Smith, M.W., Bacon, K.L., Edward Turner, T., Headley, A., Galloway, J.M., 2016. Resilience of peatland ecosystem services over millennial timescales: evidence from a degraded British bog. Journal of Ecology 104, 621–636.

Tanner, T, Lewis, D., Wrathall, D, Bronen, R., Cradock-Henry, N., Huq, S., Lawless, C., Nawrotzki, R., Prasad, V., Ashiqur Rahman, Md., Alaniz, R., King, K., McNamara, K., Nadiruzzaman, Md., Henly-Shepard, S., Thomalla, F., 2015. Livelihood resilience in the face of climate change. Nature Climate Change 1, 23-26.

Tooth, S., 1999. Floodouts in central Australia. In: Miller, A.J., Gupta, A. (Eds.), Varieties of Fluvial Form. John Wiley and Sons, Chichester, pp. 219–247.

Tooth, S., 2004. Floodout. In: Goudie, A.S. (Ed.), Encyclopedia of Geomorphology, Vol. 1. Routledge, London, pp. 380–381.

Tooth, S., McCarthy, T.S., 2004. Controls on the transition from meandering to straight channels in the wetlands of the Okavango Delta, Botswana. Earth Surface Processes and Landforms 29, 1627–1649.

Tooth, S., McCarthy, T.S., 2007. Wetlands in drylands: key geomorphological and sedimentological characteristics, with emphasis on examples from southern Africa. Progress in Physical Geography 31, 3–41.

Tooth, S., McCarthy, T.S., Brandt, D., Hancox, P.J., Morris, R., 2002. Geological controls on the formation of alluvial meanders and floodplain wetlands: the example of the Klip River, eastern Free State, South Africa. Earth Surface Processes and Landforms 27, 797–815.

Tooth, S., Brandt, D., Hancox, P.J., McCarthy, T.S., 2004. Geological controls on alluvial river behaviour: a comparative study of three rivers on the South African Highveld. Journal of African Earth Sciences 38, 79–97.

Tooth, S., Rodnight, H., Duller, G.A.T., McCarthy, T.S., Marren, P.M., Brandt, D., 2007. Chronology and controls of avulsion along a mixed bedrock-alluvial river. Geological Society of America Bulletin 119, 452–461.

Tooth, S., Rodnight, H., McCarthy, T.S., Duller, G.A.T., Grundling, A., 2009. Late Quaternary dynamics of a South African floodplain wetland and the implications for assessing recent human impacts. Geomorphology 106, 278–291.

Tooth, S., McCarthy, T., Rodnight, H., Keen-Zebert, A., Rowberry, M., Brandt, D., 2014. Late Holocene development of a major fluvial discontinuity in the Blood River floodplain wetlands, eastern South Africa. Geomorphology 205, 128-141.

Westman, W.E., 1978. Measuring the inertia and resilience of ecosystems. BioScience 28, 705-710.

Wetlands International, 2014. The secret to Africa's drylands is the wetlands? What prospects for future food security?. Available at: https://www.wetlands.org/blog/the-secret-to-africas-drylands-is-the-wetlandsae-what-prospects-for-future-food-securityae/ [Last access date: 18th January 2017].

Williams, W.D., 1999. Conservation of wetlands in drylands: a key global issue. Aquatic Conservation:

Marine and Freshwater Ecosystems 9, 517–522.

Wohl, E.E., 2014. Dryland channel networks: resiliency, thresholds, and management metrics. In: Harmon, R.S., Baker, S.E., McDonald, E.V. (Eds.), Military Geosciences in the Twenty-First Century. Geological Society of America. Reviews in Engineering Geology 22, 147-158.

Woodroffe, C.D., 2007. The natural resilience of coastal systems: primary concepts. In: McFadden, L., Penning-Rowsell, E., Nicholls, R.J. (Eds.), Managing Coastal Vulnerability, Elsevier, Amsterdam, pp. 45-60.

Zhou, H., Wang, J., Wan, J., Jia, H., 2010. Resilience to natural hazards: a geographic perspective. Natural Hazards 53, 21-41.