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The geomorphology of wetlands in drylands

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Published in:
Geomorphology

DOI:
[10.1016/j.geomorph.2017.10.017](https://doi.org/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>

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3 **1 The geomorphology of wetlands in drylands: resilience, nonresilience, or ...?**
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7 **Abstract**

8 Over the last decade, much attention has focused on wetland resilience to disturbances such as
9 extreme weather events, longer climate change, and human activities. In geomorphology and
10 cognate disciplines, resilience is defined in various ways and has physical and socioeconomic
11 dimensions but commonly is taken to mean the ability of a system to (A) withstand disturbance, (B)
12 recover from disturbance, or (C) adapt and evolve in response to disturbance to a more desirable
13 (e.g., stable) configuration. Most studies of wetland resilience have tended to focus on the more-or-
14 less permanently saturated humid region wetlands, but whether the findings can be readily
15 transferred to wetlands in drylands remains unclear. Given the natural climatic variability and
16 overall strong moisture deficit characteristic of drylands, are such wetlands likely to be more
17 resilient or less resilient? Focusing on wetlands in the South African drylands, this paper uses
18 existing geomorphological, sedimentological, and geochronological data sets to provide the spatial
19 (up to 50 km²) and temporal (late Quaternary) framework for an assessment of geomorphological
20 resilience. Some wetlands have been highly resilient to environmental (especially climate) change,
21 but others have been nonresilient with marked transformations in channel–floodplain structure and
22 process connectivity having been driven by natural factors (e.g., local base–level fall, drought) or
23 human activities (e.g., channel excavation, floodplain drainage). Key issues related to the
24 assessment of wetland resilience include channel–floodplain dynamics in relation to
25 geomorphological thresholds, wetland geomorphological ‘life cycles’, and the relative roles of
26 natural and human activities. These issues raise challenges for the involvement of
27 geomorphologists in the practical application of the resilience concept in wetland management. A
28 key consideration is how geomorphological resilience interfaces with other dimensions of
29 resilience, especially ecological resilience and socioeconomic resilience, the latter commonly being
30 defined in terms of ecosystem service delivery.

31 *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 CO₂ 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-

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183 59 stressed environments, however, the Millennium Ecosystem Assessment (2005b) recognised that
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185 60 wetlands in drylands may be disproportionately important in ecosystem service delivery. These
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187 61 services may include water and food supply for many marginalised communities, so here too
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189 62 wetland resilience assessments are needed. Tooth and McCarthy (2007) proposed that wetlands in
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191 63 drylands differ geomorphologically and sedimentologically from their humid region counterparts in
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193 64 several key respects (Table 1), so it is unclear whether findings regarding wetland resilience can be
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195 65 readily transferred from humid to dryland regions, with key questions remaining unanswered. For
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197 66 instance, given that wetlands in drylands exist in marginal environments where small differences in
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199 67 moisture supply (rainfall, river flow, groundwater) can lead to large differences in hydroperiods
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201 68 (depth, extent, and duration of inundation/saturation), are wetlands in drylands likely to be less
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203 69 resilient to environmental change than humid region wetlands (e.g., Williams, 1999)? Or given that
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205 70 wetlands in drylands have evolved under conditions of highly variable moisture supply, are they
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207 71 likely to be more resilient (e.g., Mohamed and Savenije, 2014)? Can we even generalise about
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209 72 wetland resilience in different hydroclimatic settings or might wetland resilience be determined
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211 73 more by other factors (e.g., lithology, geomorphology, edaphic and vegetative characteristics,
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213 74 human activities)? Other key scientific and applied questions regarding the resilience of wetlands
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215 75 in drylands include: how resilient have wetlands in drylands been to past environmental changes?;
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217 76 what is the relative importance of climatic changes and human activities in driving contemporary
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219 77 and future changes to the resilience of wetlands in drylands?; and can we identify changes in
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221 78 wetlands in drylands that might serve as early warning signs of altering resilience?
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243 **80 Table 1**

244 **81** Key geomorphological and sedimentological differences between the typical characteristics of wetlands in humid
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246 **82** regions and wetlands in drylands, with emphasis placed on inland wetlands (after Tooth and McCarthy, 2007)
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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

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272 **84** To answer these types of questions, there is a critical need to have clear, consistent definitions and
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274 **85** measures of resilience, but the application of the concept to wetlands — and more widely across
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276 **86** geomorphology and the environmental sciences — is commonly shrouded by vagueness and
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278 **87** imprecision. Creative ambiguity may be appropriate for some environmental terms and concepts
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280 **88** (Levina and Tirpak, 2006), but tighter definitions and measures are commonly desirable because of
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282 **89** the need for rigorous scientific assessments (e.g., the comparative resilience of different wetlands)
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284 **90** or because of the attendant policy implications. For instance, maintaining or increasing resilience is
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286 **91** often seen as a desirable target in environmental management (e.g., Klein et al., 2003; Côté and
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288 **92** Darling, 2010), so seemingly small differences in definition and/or interpretation might create
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290 **93** different expectations from different stakeholders (c.f. ‘adaptation’ - Levina and Tirpak, 2006).
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292 **94** Hence, the aims of this paper are fourfold: (i) to provide an overview of the resilience concept,
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294 **95** including its origins, multiple definitions, and use in geomorphology; (ii) to summarise previous
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296 **96** studies of wetland geomorphology in the South African drylands and to interpret the findings in
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 303 97 terms of some common definitions of resilience; (iii) to discuss the difficulties and potentials of
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 305 98 assessing the resilience of wetlands in drylands more generally; and (iv) to outline the challenges
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 307 99 for geomorphological inputs to practical applications of the resilience concept in wetland
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 309 100 management. The emphasis is on wetlands in the South African drylands, but many of the points
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 311 101 raised will apply to wetlands in other drylands across Africa and farther afield, as well as to
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 313 102 wetlands more generally.
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315 103 316 317 **2. Origins and definitions of resilience** 318

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 320 105 The concept of resilience arose largely in ecology (e.g., Holling, 1973; Westman, 1978; Hill, 1987),
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 322 106 thereafter spreading more widely across the natural and physical sciences to studies of
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 324 107 socioecological and social science systems (e.g., Adger, 2000, 2006; Folke, 2006, 2016; Folke et
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 326 108 al., 2010). The concept is now widely embedded in natural hazards research (e.g., Klein et al.,
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 328 109 2003; Zhou et al., 2010) and in discourses about climate and wider environmental change (e.g.,
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 330 110 Intergovernmental Panel on Climate Change, 2014; Tanner et al., 2015). Consequently, the concept
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 332 111 has acquired multiple physical, social, and socioeconomic dimensions, as well as various links to
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 334 112 other concepts such as vulnerability, sensitivity, susceptibility, persistence, equilibrium,
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 336 113 thresholds/tipping points, recovery, and adaptive capacity.
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 341 115 A full review of resilience and related concepts is beyond the scope of this paper, but at least three
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 343 116 definitions of system resilience can be identified in science and social science literature, namely an
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 345 117 ability for a given system to: (A) withstand disturbance; (B) recover from disturbance; or (C) adapt,
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 347 118 re-organise and evolve to a more desirable (e.g., stable) configuration.
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349 119
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 351 120 Varying layers of vagueness are built into all these definitions (e.g., what system parameter(s) are
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 353 121 being measured and over what spatial and temporal scales?), but each definition has fundamentally
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 355 122 different expectations of the dynamics of a geomorphological, environmental, or social system that
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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

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423 149 biodiversity), wetland geomorphological resilience (e.g., using landform structure or process
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425 150 connectivity), or some hybrid combination of the two. Many wetlands in drylands are also subject
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427 151 to various forms of management, commonly to enhance or maintain aspects of ecosystem service
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429 152 delivery (e.g., Wetlands International, 2014), and so increasing attempts are also being made to
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431 153 define and measure wetland socioeconomic resilience (e.g., Liersch et al., no date). A distinction
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433 154 can thus be drawn between natural (e.g., ecological, geomorphological) resilience and
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435 155 socioeconomic resilience, whereby society can use technologies to overcome local environmental
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437 156 constraints. In this paper, the focus is on wetland geomorphological resilience, but we need to bear
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440 157 in mind the sometimes intimate coupling with ecological and socioeconomic systems, not least
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442 158 because of growing recognition of the need to develop a shared language and common approaches
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444 159 if such systems are to be managed holistically and sustainably.
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446 160 447 448 161 **3. Wetland geomorphology in the South African drylands** 449

450 162 As Long et al. (2006) have noted in the context of coastal systems, resilience means little without a
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452 163 clearly defined spatial and temporal framework. If adopting definition B of resilience, for instance,
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454 164 there is a clear need to consider the spatial and temporal scales of disturbance and recovery.
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457 165 Consequently, attention hereafter is directed to four study sites (three extant wetlands and one
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459 166 former wetland) in the South African drylands where previous detailed investigations have been
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461 167 undertaken using a combination of remotely sensed images, geomorphological and
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463 168 sedimentological field data, and optically stimulated luminescence (OSL) dating. The OSL data
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465 169 sets in particular are among the most extensive for any wetlands in drylands and have enabled
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467 170 reconstructions of wetland geomorphological changes over spatial scales ranging up to ~50 km² and
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469 171 over timescales ranging from the late Pleistocene to the present. These reconstructions provide the
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472 172 basis for interpretation of the natural environmental and anthropogenic factors influencing wetland
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474 173 resilience.
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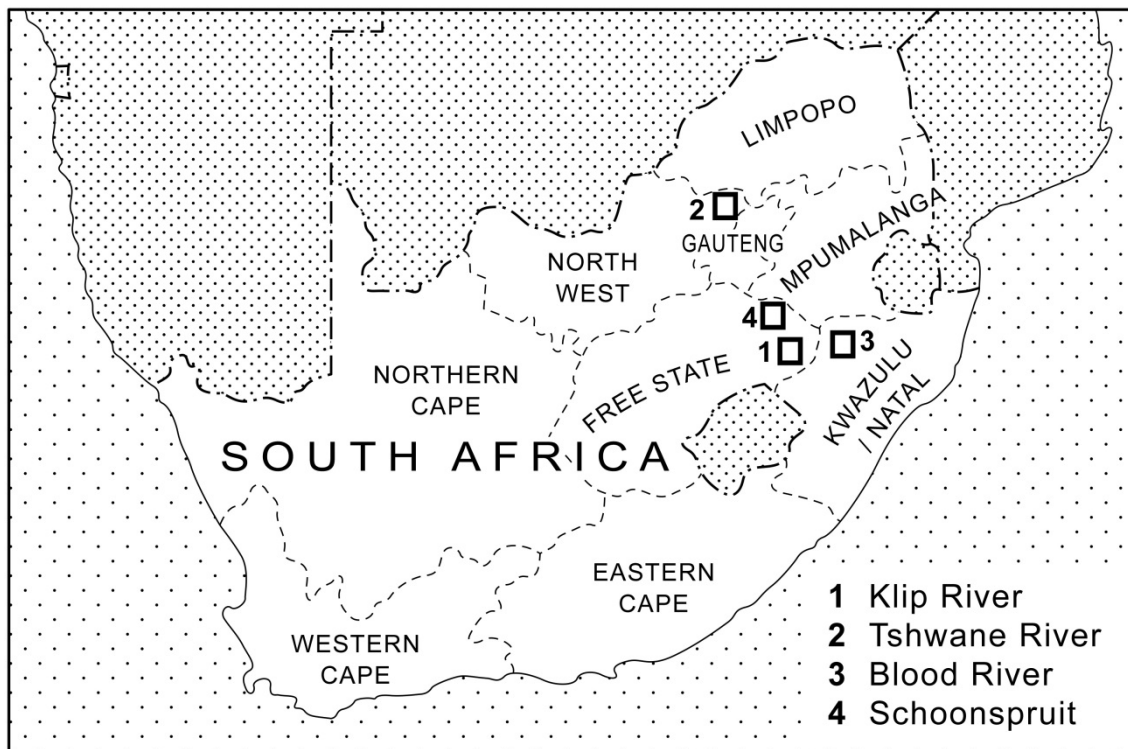
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 483 175 All four study sites are located in the tectonically stable interior of northeastern and northern South
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 485 176 Africa (Fig. 1) where many riverine wetlands are sustained by rainfall and flooding in the austral
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 487 177 summer wet season (November through March) and undergo desiccation during the drier winter
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 489 178 season. Table 2 summarises the key climatic, catchment, river channel, and floodplain
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 491 179 characteristics, while Figs. 2-5 illustrate some of the key geomorphological features and select OSL
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 493 180 ages for fluvial landforms. The four sites have been influenced by various human activities that
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 495 181 range from low-intensity cattle grazing to more direct flow manipulation (Table 2), but with some
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 497 182 notable exceptions (detailed below), many reaches remain in a near-natural, little modified
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 500 183 condition. Collectively, these wetlands represent a selection of the ‘valley bottom’ and ‘floodplain
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 502 184 wetlands’ types highlighted in South African wetland classifications (Kotze et al., 2009a; Ollis et
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 504 185 al., 2015), but for brevity, the term ‘floodplain wetland’ is applied hereafter as a generic descriptor.



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 529 187 **Fig. 1.** Location of the four study sites in South Africa.

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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)

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									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).

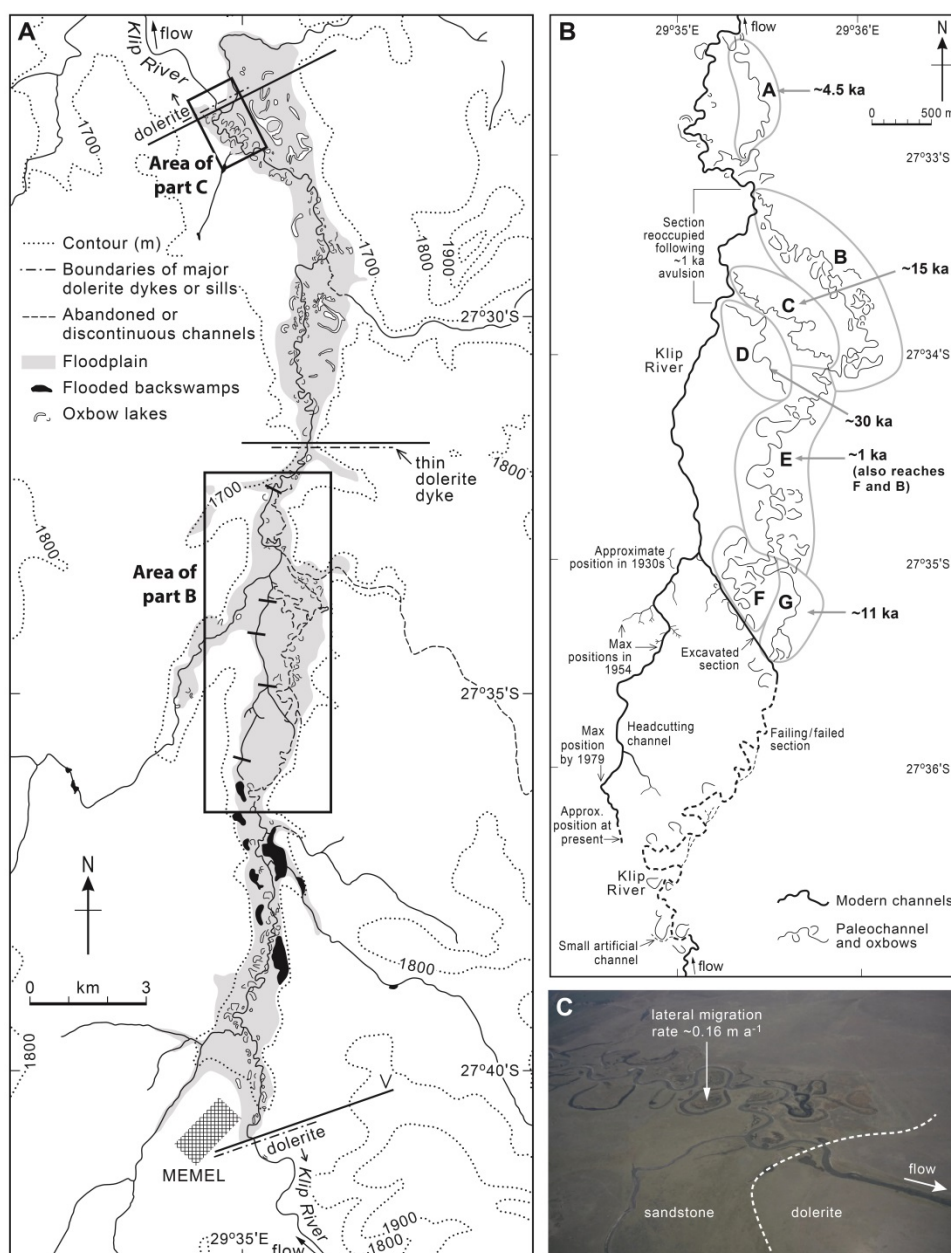


Fig. 2. Illustrations of some of the key geomorphological features and select OSL ages for landforms in the Klip River floodplain wetland (source: modified after Tooth et al., 2004, 2009).

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

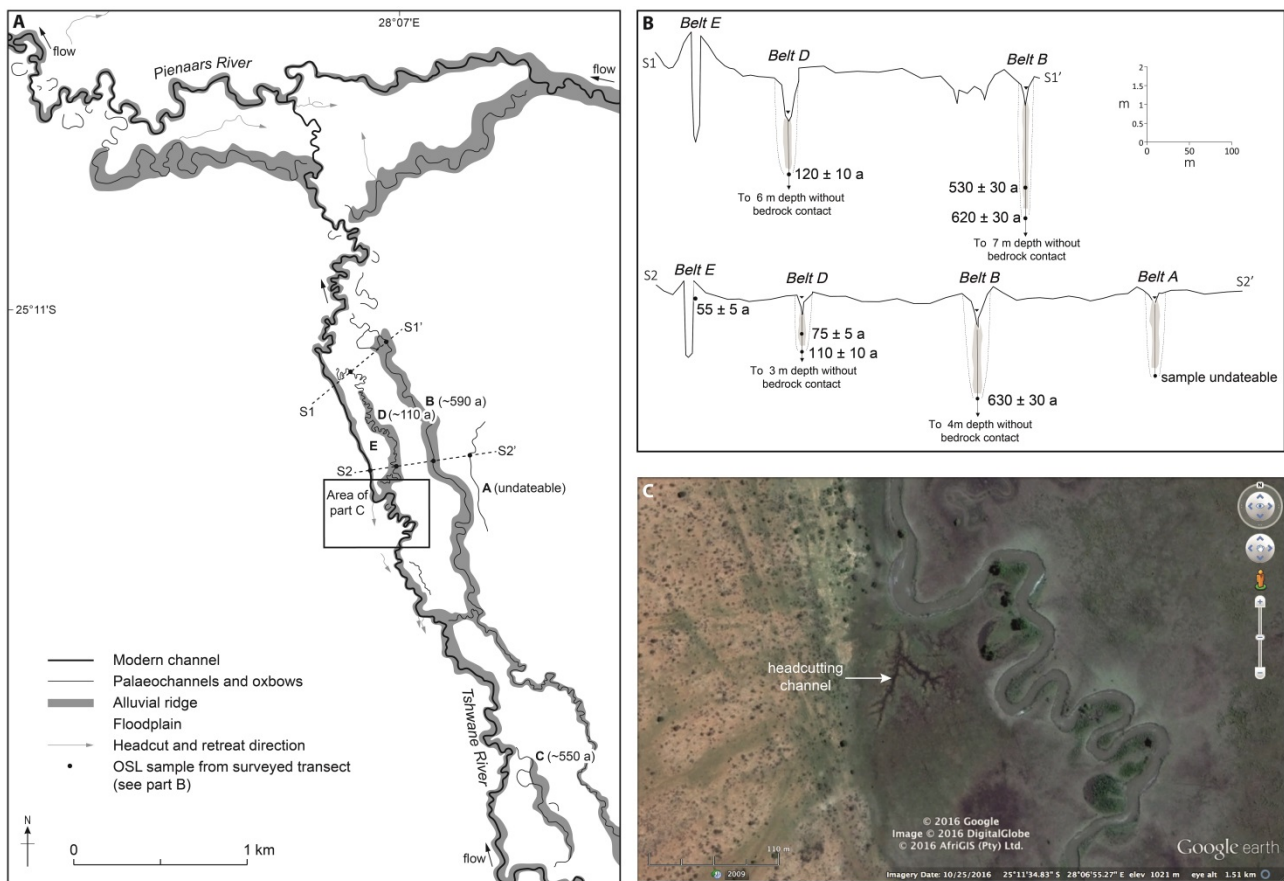
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 745 226 ages for scroll bar sequences (e.g., Fig. 2C) demonstrate that late Holocene meander migration rates
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 747 227 were $<0.2 \text{ m a}^{-1}$ (Rodnight et al., 2005; Tooth et al., 2009). In global terms, these rates are
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 749 228 relatively slow and are supported by aerial photograph analyses, which reveal that despite the high
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 751 229 density of oxbow lakes (up to 10/km of channel; Figs. 2A and 2C), only three cutoffs have occurred
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 753 230 in the study reach over the last 60-70 years (Tooth et al., 2009). Along with field observations,
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 755 231 these findings provide the basis for interpreting the processes and controls of avulsion. In this
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 757 232 setting, avulsions occur through an incisional process, whereby overbank floodwaters drain back to
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 759 233 the channel through a breach in the channel bankline, initiating a small headcutting channel. This
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 761 234 headcutting channel enlarges and extends by knickpoint retreat during periods of overbank flow,
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 763 235 ultimately diverting discharge and sediment from the older, typically elevated channel, which is
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 765 236 then abandoned. Along the Klip River, the lack of a clear, consistent link between regional
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 767 237 palaeoclimatic changes and individual avulsion events (Tooth et al., 2007) suggests that past
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 769 238 avulsions have not been extrinsically forced but rather have occurred intrinsically as a natural
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 771 239 outcome of meander-belt development.
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 775 241 An ongoing avulsion that is associated with the formation of a new 3.0-3.5 km long channel on the
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 777 242 western floodplain margin (Fig. 2B) provides an exception. Gully initiation and eventual channel
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 779 243 formation appear to have been initiated by the excavation of a trench across the wetlands (Fig. 2B)
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 781 244 following colonial settlement in the valley (late 1800s onward). This trench was probably
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 783 245 excavated in an attempt to drain the wetlands and improve access for grazing.
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 785 246

786 787 247 3.2. Tshwane River floodplain wetland, North West Province

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 789 248 The Tshwane River floodplain wetland (Fig. 3) has been the subject of recent geomorphological
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 791 249 investigations (Larkin et al., 2017a, b). Through the ~4-km-long study reach, the perennial,
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 793 250 throughgoing river has many morphological similarities to the Klip River. In many places, the river
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 795 251 is highly sinuous (P up to ~ 2.7) and is flanked by a floodplain wetland up to ~ 1.5 km wide that
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 805 252 hosts numerous palaeochannels and oxbows with dimensions similar to the modern channel (Fig.
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 807 253 3A). By contrast with the Klip River, however, discharge, stream power and channel cross-
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 809 254 sectional area all decrease downstream along the Tshwane River (Table 2), and the channel bed is
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 811 255 decoupled from bedrock, with floodplain sediments >7 m thick (Fig. 3B) being laid down by a
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 813 256 combination of lateral point-bar, oblique, abandoned-channel, and vertical accretion. Consequently,
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 815 257 many reaches of the modern channel sit atop an alluvial ridge elevated up to 1.5 m, and levees are
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 817 258 more prominent than on the Klip (Fig. 3B). The lower end of the study reach is formed by the
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 819 diffuse confluence with the aggrading Pienaars River (Fig. 3A), which provides the local base level
 820 259 for the Tshwane reaches upstream (Larkin et al., 2017a).
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 822 260



850 262 **Fig. 3.** Illustrations of some of the key geomorphological features and select OSL ages for landforms in the Tshwane
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 852 263 River floodplain wetland (source: modified after Larkin et al., 2017b).
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854 264
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 856 265 The OSL ages for palaeochannels and associated oxbow fills (Figs. 3A and 3B) have established a
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 858 266 late Holocene avulsion history. Older, undated palaeochannels are present in the reach (e.g.,
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 865 267 palaeochannel A; Figs. 3A and 3B), but over the last ~650 years, avulsions occurred at ~590, ~550,
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 867 268 and 110 years ago (Larkin et al., 2017b). Aerial imagery and field evidence reveal that some other
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 869 269 sinuous reaches are being primed for avulsion, with headcutting channels having rapidly developed
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 871 270 in adjacent backswamps (Fig. 3C). Over this timeframe, the frequency of ~4.6 avulsions ka^{-1} is
 872
 873 271 significantly higher than on the Klip River (Larkin et al., 2017b). In the absence of well-defined
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 875 272 scroll bars along the Tshwane, meander migration rates have not been established, but aerial
 876
 877 273 photographs and field observations also reveal significantly higher rates of lateral activity along the
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 879 274 Tshwane than along the Klip River, with 14 cutoffs having occurred in the much shorter study reach
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 881 275 over the last 60-70 years (Larkin et al., 2017b). As on the Klip River, however, incisional avulsion
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 883 276 is the dominant process (Fig. 3C), and the lack of a clear, consistent link between regional
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 885 277 palaeoclimatic changes and individual avulsion events on the Tshwane River also suggests that
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 887 278 avulsions have been driven by intrinsic processes during meander-belt development.
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892 280 3.3. Blood River floodplain wetland, KwaZulu-Natal

893 281 The Blood River floodplain wetland (Fig. 4) has been the subject of previous geomorphological
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 895 282 investigations (Lyons et al., 2013; Tooth et al., 2014). The ~35-km-long study reach can be divided
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 897 283 into an upper part that contains sections of perennial but discontinuous, relatively straight ($P \sim 1.15$)
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 899 284 channels and a lower part that is traversed by a perennial to intermittent, sinuous ($P > 2.30$) channel
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 901 285 (Fig. 4A). In the upper part, the modern channel is flanked by several abandoned channel–levee
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 903 286 complexes (Fig. 4B). Discharge, stream power, and channel cross-sectional area rapidly decrease
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 905 287 downstream (Table 2), and the channel disappears within 0.5 km of entering the main area of
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 907 288 wetlands to form a ‘floodout’ (cf. Tooth, 1999, 2004), characterised here by an unchannelled
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 909 289 reedbed (principally *Phragmites australis*) up to ~1 km wide. This reedbed extends for ~1 km
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 911 290 downvalley (Fig. 4B), but traces of overgrown sinuous palaeochannels are present toward the
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 913 291 western floodplain margin. At the southeastern margin of the floodout, several small headcutting
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 915 292 channels start abruptly on a locally steepened (~0.014) gradient (Fig. 4B) and convey water that
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925 293 filters through the reedbed. As the gradient declines again downvalley, these headcutting channels
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927 294 coalesce into a single, low sinuosity, ~1.25-km-long 'reforming channel' (Tooth, 1999, 2004) that
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929 295 retains permanent water in a part of the wetlands that are otherwise seasonally dry (Fig. 4B). This
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931 296 reforming channel abruptly narrows and shallows toward its downstream end and disappears at
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933 297 another floodout up to ~2 km wide (Fig. 4A). This lower floodout extends for ~3 km downvalley
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935 298 and is also characterized by an unchannelled reedbed, although here too clear evidence exists of
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937 299 overgrown but throughgoing, sinuous palaeochannels. Similar to the situation upvalley, the
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939 300 southern limit of this lower floodout is also marked by several headcutting channels that start on a
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941 301 locally steepened (~0.001) gradient (Fig. 4C). These headcutting channels mark the transition to
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943 302 the lower part of the study reach where a continuous, sinuous channel is flanked by numerous
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945 303 oxbows, short palaeochannel sections, and small gullies known locally as dongas (Figs. 4A and
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947 304 4C). At the downstream end of the study reach, dolerite outcrop results in channel straightening
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949 305 and the floodplain decreases to <100 m wide (Fig. 4A).
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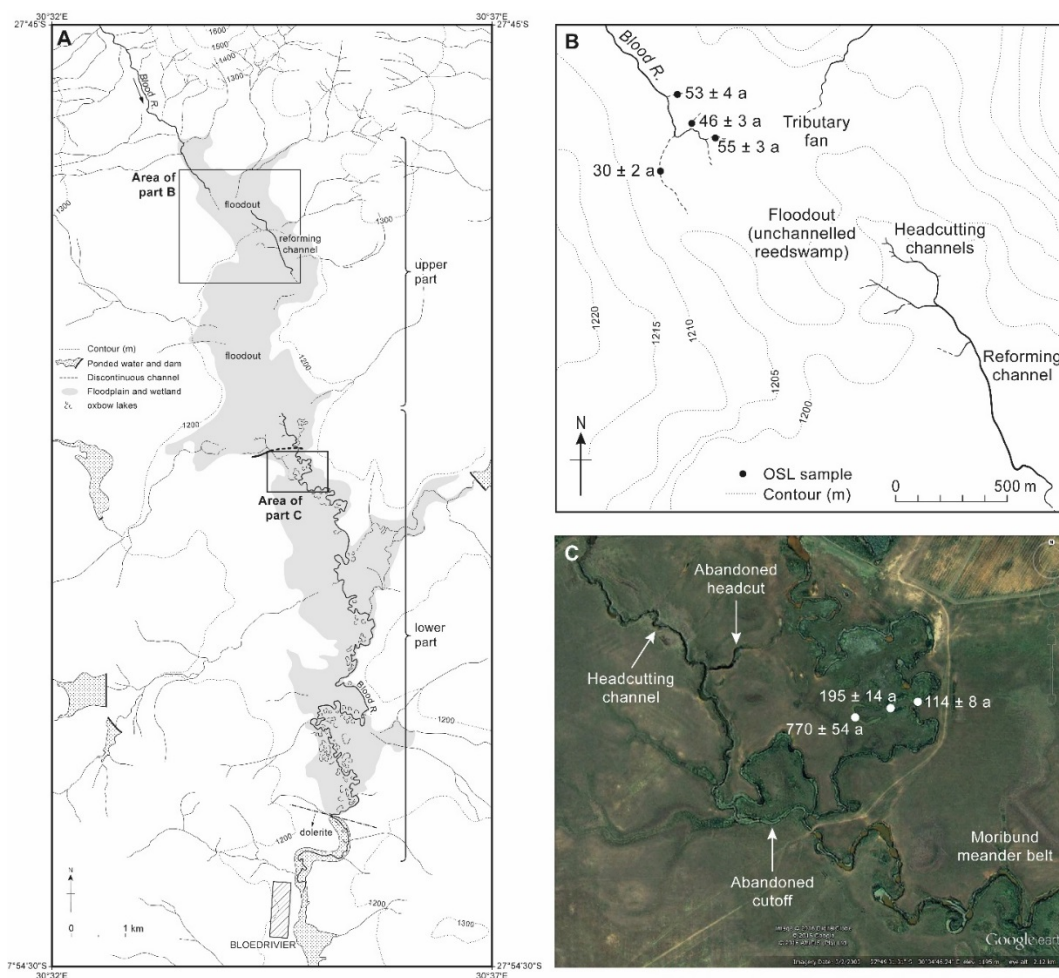


Fig. 4. Illustrations of some of the key geomorphological features and select OSL ages for landforms in the Blood River floodplain wetland (source: modified after Tooth et al., 2014).

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

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 1044
 1045 320 encroachment and within-channel establishment of sedges and grasses (e.g., *Phragmites australis*)
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 1047 321 in slow-flowing or stagnant sections of channel (Tooth et al., 2014). Following the establishment of
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 1049 322 the upper floodout, channel–levee complexes have formed and been abandoned on several
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 1051 323 occasions during the last ~60 years (Fig. 4B), leading to local redistribution of water and sediment
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 1053 324 (Tooth et al., 2014). Organo-clastic sediments >3 m thick have accumulated in the floodouts as
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 1055 325 broad lobes, in places burying the former meander-belt sediments and leading to local gradient
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 1057 326 increases. In combination with the limited flows that filter through the floodouts, these increased
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 1059 327 gradients have promoted the formation of the headcutting channels (Figs. 4B and 4C). During the
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 1061 328 70–80 year period covered by aerial photographs, some of the headcutting channels have widened
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 1063 329 slightly and extended some tens of metres upvalley into the floodout (Kotze, 1994; Tooth et al.,
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 1065 330 2014).

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1068 332 *3.4 Schoonspruit former floodplain wetland, Free State*

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1070 333 The Schoonspruit (Fig. 5) traverses an abandoned floodplain wetland and has been the subject of
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 1072 334 previous geomorphological investigations (Tooth et al., 2004; Keen-Zebert et al., 2013, 2016).
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 1074 335 Within the ~20-km-long study reach, the intermittent but throughgoing, sinuous (P ~1.99) channel
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 1076 336 has incised 3-5 m into the underlying mudstone. Consequently, the ~1-km-wide floodplain (Fig.
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 1078 337 5A) is now only rarely inundated by overbank flows, although rainfall can still lead to flooding in
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 1080 338 oxbows and abandoned channels. Along the incised channel, an inset floodplain up to ~20 m wide
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 1082 339 has formed by lateral and vertical accretion (Tooth et al., 2004), while gullies (dongas) have eroded
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 1084 340 into older, early to middle Pleistocene alluvial and/or colluvial sediments (Fig. 5B). At the lower
 1085
 1086 341 end of the study reach, the river transitions to a valley carved into a resistant dolerite sill and
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 1088 342 becomes less sinuous, with floodplains being restricted to <50 m wide (Fig. 5A). Cosmogenic
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 1090 343 isotope analyses indicate that channel-bed dolerite outcrop is denuding at ~100-255 mm ka⁻¹ (Keen-
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 1092 344 Zebert et al., 2016), with field evidence for flood-transported dolerite boulders and isolated
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 1094 345 pedestals of jointed dolerite outcrop within the channel bed (Fig. 5C) suggesting a recent phase of
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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).

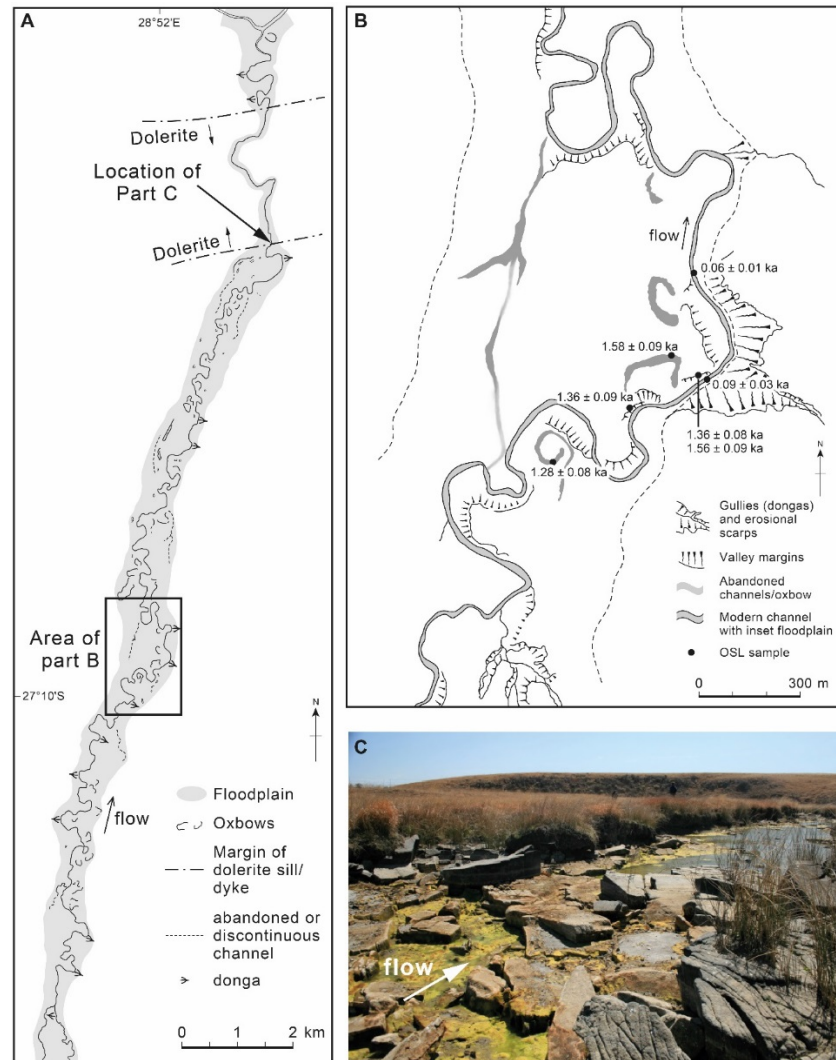


Fig. 5. Illustrations of some of the key geomorphological features and select OSL ages for landforms in the former floodplain wetland of the Schoonspruit (source: modified after Keen-Zebert et al., 2013).

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 $<10\text{-}15\text{ W m}^{-2}$ 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.

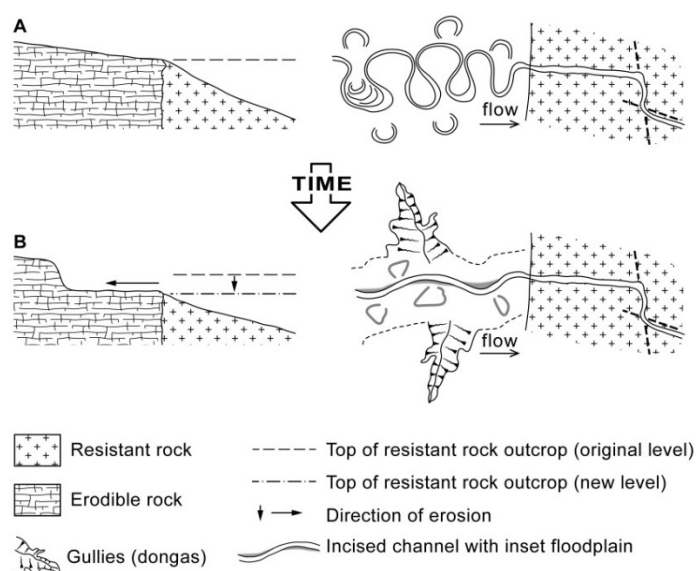


Fig. 6. Schematic illustration of the cycle of wetland development in the South African drylands: (A) meandering channels and floodplain wetlands initially form atop more erodible rocks (e.g., mudstone, sandstone) upstream of resistant outcrop (e.g., dolerite). Migrating meanders locally impinge on the 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).

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 1287 407 By strong contrast with the resilience to natural environmental change exhibited over most of the
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 1289 408 late Quaternary, however, the Klip River floodplain wetland has not been resilient to recent human
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 1291 409 impacts. Under natural conditions, avulsions have occurred just once every 3-6 ka since 15 kyr.
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 1293 410 Following colonial settlement (late 1800s onwards), however, an ongoing, potentially major
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 1295 411 avulsion has been initiated only ~1 ka after the last natural avulsion event and in a part of the
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 1297 412 floodplain wetland where avulsions have not occurred previously (Fig. 2B). The avulsion has led to
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 1299 413 major changes elsewhere in the reach, including failure of a 2-3 km long section of the original
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 1301 414 channel upstream (Fig. 2B), and dramatic channel widening and decreased overbank flooding
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 1303 415 downstream (Tooth et al., 2007, 2009; McCarthy et al., 2010).
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1308 417 *4.2. Resilience of the Tshwane River floodplain wetland*

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 1310 418 Over the late Holocene, the Tshwane River floodplain wetland has been highly resilient to
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 1312 419 environmental change, with resilience also best defined in terms of definition A (i.e., resistance).
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 1314 420 During at least the last ~650 years, the Tshwane River has remained a throughgoing, meandering
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 1316 421 channel with roughly constant dimensions. Palaeoclimatic fluctuations appear to have had little
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 1318 422 impact on channel–floodplain morphology or dynamics, with relatively frequent avulsions
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 1321 423 occurring intrinsically as a natural outcome of meander-belt development. Avulsions have involved
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 1323 424 stepwise migrations of reaches up to ~5 km long (Fig. 3A) and have resulted in changing patterns of
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 1325 425 flooding and sedimentation, but channel–floodplain structure and connectivity has essentially been
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 1327 426 maintained throughout the incisional avulsion events. Meander belts have then reestablished along
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 1329 427 newly formed channels over successive decades to centuries (Larkin et al., 2017b). Local base
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 1331 428 level is determined by aggradation on the Pienaars River downvalley (Fig. 3A), but as along the
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 1333 429 Klip River, the low energy conditions (bankfull unit stream powers are $<10 \text{ W m}^{-2}$ throughout
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 1335 430 much of the study reach; Table 2) also minimise the potential for rapid and/or widespread erosion.
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 1337 431 Consequently, the Tshwane River also has been relatively unresponsive to late Quaternary
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1345 432 palaeoclimatic changes, with channel changes instead being driven by intrinsic processes. The
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1347 433 Tshwane River remains in a near-natural condition with human influence restricted to some
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1349 434 subsistence grazing, and the natural resilience of this floodplain wetland has been preserved.
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1351 435 1352 1353 436 *4.3. Resilience of the Blood River floodplain wetland* 1354

1355 437 The Blood River floodplain wetland is more difficult to assess in terms of resilience. Although the
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1357 438 timing and consequences of the development of the discontinuity can be established, the initial
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1359 439 cause(s) remain uncertain. Assuming that human activities have not led to development of the
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1361 440 discontinuity, however, then the most likely explanation is a combination of drought-induced
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1363 441 downstream decreases in discharge and sediment transport along with associated reedbed
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1365 442 establishment. Given the dramatic change to channel–floodplain structure that has occurred
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1367 443 subsequently, then one interpretation could be that the wetland has been nonresilient to
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1369 444 environmental change. On the steepened, downvalley sides of the sediment lobes that mark the two
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1371 445 floodouts, however, the presence of headcutting channels (Figs. 4B and 4C) suggests an alternative
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1373 446 explanation. The combination of headcutting channels and floodouts indicates partial analogy with
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1375 447 the system-scale, intrinsic morphological and sedimentary dynamics of those dryland fluvial
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1377 448 systems that are also characterised by a dynamic mosaic of channelled and unchannelled landforms
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1379 449 (e.g., discontinuous ephemeral streams and erosion cells; Schumm and Hadley, 1957; Pickup, 1985;
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1381 450 Bull, 1997). If headcutting through the lobes continues, then a throughgoing channel may
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1383 451 reestablish in the upper part of the wetland, possibly eventually linking with the sinuous but now
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1385 452 moribund channel in the lower part (Tooth et al., 2014). Given the aerial photograph evidence for
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1387 453 headcut retreat over the last 70-80 years (see above), it is plausible that reestablishment of a
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1389 454 throughgoing channel and associated longitudinal flow and sediment transport connectivity could
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1391 455 occur on a timescale of centuries to a few millennia. If this scenario were to unfold, then recovery
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1393 456 to a predisturbance (i.e., predrought) condition could occur. Over this timescale, therefore, the
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1405 457 Blood River floodplain wetland might then be regarded as resilient in terms of definition B (i.e.,
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1407 458 ability to recover from disturbance).
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1409 1410 1411 460 *4.4. Resilience of the Schoonspruit former floodplain wetland* 1412

1413 461 Over the last millennia, the Schoonspruit floodplain wetland has been nonresilient to environmental
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1415 462 change. By strong contrast with the Klip River where a slowly eroding dolerite sill provides an
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1417 463 essentially stable local base level (Fig. 6A), recent incision has occurred into the dolerite sill at the
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1419 464 downstream end of the Schoonspruit study reach (Figs. 5C and 6B). Incision has resulted in local
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1421 465 base-level fall and associated knickpoint retreat, leading to deep channel incision in reaches
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1423 466 upstream. Incision has dramatically transformed channel-floodplain structure and connectivity,
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1425 467 with the higher elevation, former floodplain wetland now rarely inundated by overbank flows, while
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1427 468 inset floodplains have formed at a lower elevation. If base level stabilises again (e.g., in a lower
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1429 469 section of the dolerite sill), however, then meandering, valley widening, and formation of extensive
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1431 470 floodplains might occur again in future (Tooth et al., 2004). The timescale for such a development
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1433 471 is little known, but based on the OSL dating results from this and other wetlands, the process likely
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1435 472 takes many hundreds of millennia. If this scenario were to unfold along the Schoonspruit, channel-
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1437 473 floodplain structure and connectivity would eventually exhibit some degree of recovery, albeit at a
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1439 474 lower topographic level, and this system might then also be regarded as exhibiting some degree of
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1441 475 resilience in terms of definition B.
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1444 1445 1446 1447 477 **5. Discussion** 1448

1449 478 The foregoing case studies demonstrate how wetlands in the South African drylands have exhibited
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1451 479 varying geomorphological resilience. Even in catchments with similar hydroclimates,
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1453 480 physiographies, lithologies, vegetation assemblages, and human impacts (Table 2), some wetlands
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1455 481 have been highly resilient to environmental change, but others have been nonresilient. Integration
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1457 482 of the findings from these case studies with results from the geomorphological investigations of
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1463 other wetlands in drylands, within the South African interior and farther afield, raises some key
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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

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1525 509 intrinsic thresholds does not threaten resilience as defined above because the changes occur as part
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1527 510 of natural autogenic dynamics that are unrelated to extrinsic disturbances. Nonetheless, as
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1529 511 considered further below, the movement toward or across intrinsic thresholds could leave systems
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1531 512 more prone to the crossing of extrinsic thresholds that could then threaten resilience.
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1535 514 In their consideration of the sensitivity and vulnerability of southern African wetlands to
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1537 515 environmental change — concepts that are closely related to resilience — Ellery et al. (2016)
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1539 516 outlined how low-order, valley bottom wetlands in inland South Africa can be classified into stable
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1541 517 (unincised) and incised (gullied/channelled) types and then discriminated on a bivariate plot of
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1543 518 wetland area versus wetland gradient (Fig. 7, inset). This plot provides the empirical underpinning
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1545 519 for a conceptual diagram (Fig. 7) that illustrates how individual wetlands may be driven across a
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1547 520 fuzzy threshold (defined as the ‘zone of vulnerability’) from a stable to an incised condition by (i)
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1549 521 an increase in wetland area (i.e., extent of inundation/saturation) for a given wetland gradient as,
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1551 522 say, discharge increases or sediment accumulation locally blocks or restricts water outflow (Fig. 7,
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1553 523 pathway A to B) or (ii) an increase in wetland gradient for a given wetland area as, say, aggradation
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1555 524 leads to localised valley floor steepening (Fig. 7, pathway A to C). Increases in wetland area or
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1557 525 gradient are necessary preconditions for incision, but the trigger itself may be related to extrinsic
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1559 526 factors such as climate change, local base-level fall, or land use change (Ellery et al., 2016).
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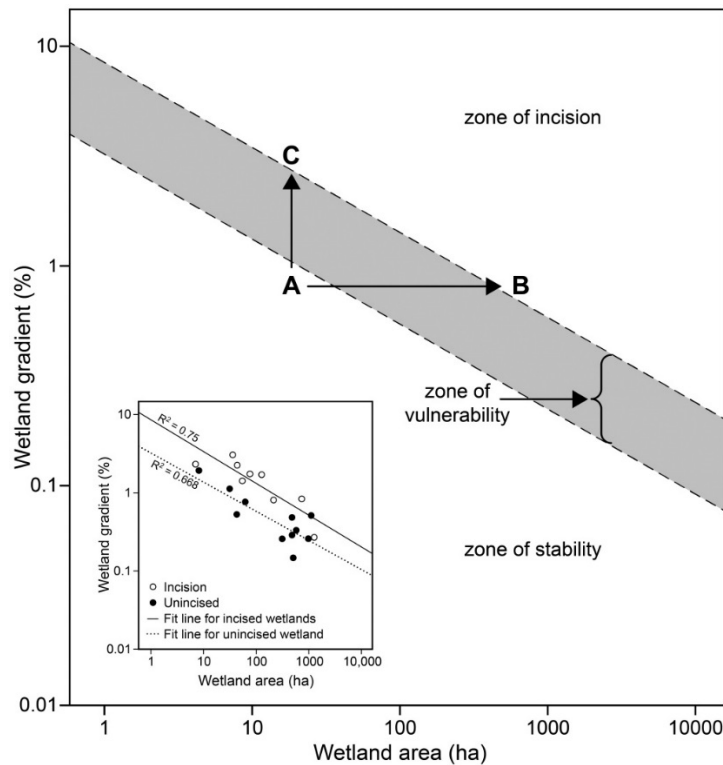


Fig. 7. Zones of stability, vulnerability, and incision for valley-bottom wetlands in southern Africa. Valley-bottom wetlands typically occur on low-order streams where the valley is narrow or impounded and tend to lack well-defined channels and characteristic floodplain features. The inset shows the 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).

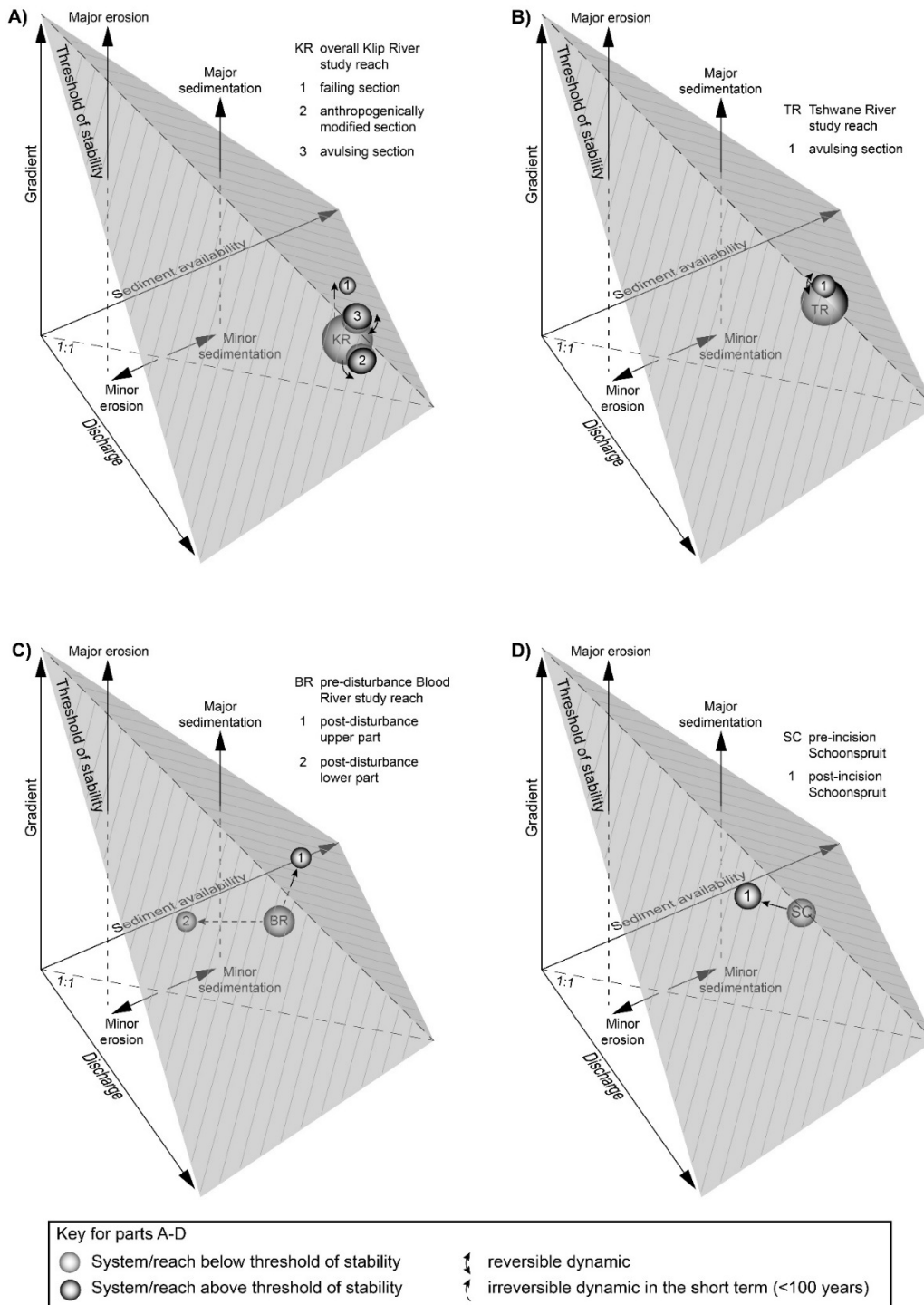


Fig. 8. Conceptual diagrams illustrating the diverse channel–floodplain dynamics that underpin the resilience or nonresilience of wetlands in the drylands of South Africa: (A) Klip River floodplain wetland; (B) Tshwane River floodplain wetland; (C) Blood River floodplain wetland; and (D) former floodplain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

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 1707 552 Figure 8 attempts to address one of the problems common to many conceptual treatments of
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 1709 553 geomorphological or environmental system dynamics in that any given system is typically treated
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 1711 554 as just one point in a phase space, with attention usually being focused on temporal macroscale
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 1713 555 dynamics (e.g., points A, B, and C in Fig. 7; for an ecological example, see Côté and Darling,
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 1715 556 2010). In reality, most wetlands — especially large floodplain wetlands — are not singular
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 1717 557 landforms but are typically composed of a complex assemblage of channel and floodplain features
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 1719 558 with controls (e.g., gradient, discharge, sediment availability) that vary spatially, downstream and
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 1721 559 across the valley. Hence, many microscale and mesoscale spatial and temporal dynamics may
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 1723 560 occur alongside the temporal macroscale dynamics and are represented here as bounded departures
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 1725 561 (smaller spheres with numbers) from the typical range of temporal macroscale system behaviour
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 1727 562 (larger spheres with upper case letters). For instance, avulsions within large floodplain wetland
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 1729 563 systems represent local, threshold-crossing system instabilities (Figs. 8A and 8B), but so long as the
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 1731 564 overall wetland system remains stable (or recovers stability), then these instabilities do not affect
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 1733 565 the resilience of the system as a whole.

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 1737 567 The dynamics of the Klip River floodplain wetland provide a case in point. Throughout much of
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 1739 568 the late Quaternary, the essentially nonaggrading Klip system has operated — and in many reaches
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 1741 569 continues to operate — far below a threshold (Fig. 8A). Channel gradient is more-or-less stable,
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 1743 570 while discharge and sediment availability are in approximate long-term balance. Local and regional
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 1745 571 environmental (especially palaeoclimatic) changes have not been of sufficient magnitude or
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 1747 572 duration to alter this balance and push the system across a threshold. Movement across a threshold
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 1749 573 has occurred infrequently only in the avulsion-prone middle part of the study reach (Fig. 8A –
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 1751 574 ‘avulsing section’) where valley gradient steepens slightly and sediment becomes sandier.

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 1753 575 Avulsions have led to redistribution of water and sediment but channel–floodplain structure and
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1765 576 functioning have been maintained throughout, meandering belts have reestablished slowly over
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1767 577 time, and reach-scale and overall system resilience have been largely maintained (Fig. 8A).
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1771 579 By contrast, over at least the last ~650 years, the vertically aggrading Tshwane system has been
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1773 580 operating closer to a threshold condition (Fig. 8B). Here, downstream decreases in discharge and
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1775 581 sediment flux promote vertical aggradation, as reflected in more prominent levee and alluvial ridge
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1777 582 growth (Fig. 3B), and the local decreases in channel gradient and increases in cross-floodplain
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1779 583 gradient that occur along developing meander belts help to prime reaches for more frequent
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1781 584 avulsions. Nonetheless, channel–floodplain structure and functioning have been maintained,
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1783 585 meandering belts have reestablished rapidly over time, and here too reach-scale and overall system
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1785 586 resilience have been maintained.
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1790 588 The situations are different on the Blood River and the Schoonspruit floodplain wetlands, where a
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1792 589 substantial portion (Blood River) or the whole of the study reach (Schoonspruit) has moved across a
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1794 590 threshold (Figs. 8C and 8D). As discussed above, both systems may in time move back across the
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1796 591 threshold and exhibit some degree of recovery but only over timescales of centuries or far longer,
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1798 592 and therefore at present can be characterised as nonresilient.
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1801 593 1802 1803 594 *5.2. Wetland geomorphological ‘life cycles’*

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1805 595 A key point emerging from this analysis is that resilience may change through the
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1807 596 geomorphological ‘life cycle’ of a wetland (cf. Ellery et al.’s (2016) discussion of changing wetland
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1809 597 sensitivity in peat-accumulating systems). As an example, intrinsic changes (e.g., aggradation and
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1811 598 slope steepening that occur in response to downstream discharge decreases) may bring the wetland
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1813 599 close to an extrinsic threshold, leaving the system prone to event-based (e.g., flash flood) or more
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1815 600 sustained (e.g., prolonged drought) extrinsic disturbances that facilitate more dramatic changes and
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1825 601 threaten resilience. As shown by the example of the Blood River, such changes may occur in
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1827 602 combination with strong biotic feedbacks such as reedbed establishment (Tooth et al., 2014).
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1831 604 Alternatively, wetlands may be driven across thresholds by extrinsic controls that operate
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1833 605 essentially independently of intrinsic dynamics. The long-term macroscale dynamics of the Klip
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1835 606 River and Schoonspruit floodplain wetlands, for instance, are controlled by the stability of their
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1837 607 respective lithologically controlled local base levels (a function of the rate and nature of bedrock
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1839 608 erosional processes), but the two systems currently are at different stages in the wetland
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1841 609 development cycle. The Klip River remains unincised above an essentially stable local base level
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1843 610 (Fig. 6A), while the Schoonspruit has undergone recent deep incision in response to local base-
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1845 611 level fall (Fig. 6B).
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1848 612 1849 1850 613 *5.3. Relative roles of natural environmental and human impacts* 1851

1852 614 Over the late Quaternary, the four South African study sites have been relatively unresponsive to
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1854 615 local and regional palaeoclimatic changes, probably owing to factors such as the characteristically
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1856 616 low stream powers, relatively low rates of sediment supply, and (in some cases) stable local base
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1858 617 levels. Nonetheless, in the absence of human activities, wetland changes have been driven by a
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1860 618 variety of natural factors including intrinsic process-form dynamics (Klip, Tshwane), possibly
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1862 619 short-term weather extremes (drought in the Blood River), and lithologically controlled base-level
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1864 620 fall (Schoonspruit). As the examples of the Klip and Tshwane rivers show, however, such changes
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1866 621 have not necessarily threatened wetland resilience.
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1870 623 By contrast, even some floodplain wetlands that have been resilient to natural factors have been
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1872 624 greatly impacted by human activities over the last 100-150 years. With colonial settlement in the
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1874 625 Klip valley, for instance, a situation of long-term resilience changed dramatically, with parts of the
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1876 626 floodplain wetland now degraded. Within South Africa and farther afield, many other wetlands in
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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

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1945 653 water, sediment, and biotic activity acting in combination, and this leads to strong links between
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1947 654 wetland structure, functioning and ecosystem services. In management contexts, however,
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1949 655 restoration, maintenance, or enhancement of geomorphological resilience (e.g., natural channel–
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1951 656 floodplain forms) may not be the primary objective, with greater emphasis perhaps being placed on
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1953 657 managing for ecological resilience (e.g., biodiversity) or with priority being given to other aspects
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1955 658 of ecosystem service delivery (e.g., flooding alleviation). Again, a study of the Klip River
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1957 659 floodplain wetland provides an instructive example (McCarthy et al., 2010). In an ideal world,
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1959 660 remediation of the degraded parts (Fig. 8A) would strive to return the wetland to its natural,
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1961 661 precolonial, geomorphological condition. In reality, other management goals have priority, namely
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1963 662 maintaining current habitat and biodiversity (this has the added advantage of promoting local
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1965 663 tourism, especially bird watching) and using the wetlands for water quality enhancement. Attempts
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1967 664 to return the wetlands to their precolonial geomorphological condition (e.g., by removing exotic
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1969 665 willow trees and erosion control structures) would in fact reduce habitat and biodiversity,
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1971 666 permanently in the case of some avian species that now use the willows for perching, roosting, and
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1973 667 nesting, and for centuries in the case of some aquatic species owing to the very slow natural rates of
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1975 668 channel and floodplain change (Fig. 2C). In assessing the various management options for
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1977 669 remediating the degraded parts of these wetlands, McCarthy et al. (2010) concluded that while
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1979 670 further active, ongoing management intervention could restore some of the ecological and
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1981 671 hydrological functions, the wetland is likely to remain very far from its natural geomorphic
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1983 672 condition essentially in perpetuity. Hence, the natural resilience of part of this wetland appears to
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1985 673 have been lost permanently, but some degree of ‘artificial’ or ‘managed’ resilience could probably
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1987 674 be achieved. In this and other cases, therefore, channel and ecological management may be
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1989 675 increasingly used to ‘engineer’ wetlands toward configurations deemed more desirable, thereby
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1991 676 meeting definition C of resilience. Regardless of whether or not geomorphological resilience is the
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1993 677 primary concern, however, geomorphological insights are still needed for a comprehensive, holistic
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1995 678 understanding of the other dimensions of resilience.
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2007 680 Third, in assessing wetland resilience for management purposes, identification and monitoring of
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2009 681 wetland dynamics in relation to geomorphological thresholds is needed. Whether wetlands are
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2011 682 operating far from or close to thresholds will determine the appropriate management strategies for a
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2013 683 given set of objectives. In small headwater wetlands in South Africa, Grenfell et al. (2005)
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2015 684 proposed the use of floristic and edaphic indicators as early warning indicators of slow, progressive
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2017 685 changes related to upslope water resource developments (e.g., forestry), but these approaches need
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2019 686 to be developed for larger floodplain wetlands. Wohl (2014) discussed methods for determining
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2021 687 resilience, thresholds, and metrics in the context of dryland channel networks; similar approaches
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2023 688 could be adapted for larger wetlands in drylands, many of which are associated with dryland
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2025 689 channels (Tooth and McCarthy, 2007). In many wetlands in drylands, recent severe droughts have
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2027 690 provided opportunities to identify early warning signs of wetland change. For instance, during
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2029 691 Australia's 'millennium drought' (c. CE 2001-2009), severe declines in water quality (e.g., acid
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2031 692 drainage) were reported from some 'billabongs' (water-filled depressions), although the ending of
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2033 693 the drought led to rapid recovery of water quality, demonstrating some degree of resilience to these
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2035 694 short-term hydrochemical changes (Murray Darling Wetlands Working Group Ltd., 2017). With
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2037 695 more sustained or more frequent droughts projected in future, however, such rapid recovery in
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2039 696 water quality may not be so forthcoming; more fundamental structural and functional adjustments
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2041 697 may be expected in many wetlands in drylands, particularly where this is linked with increasing
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2043 698 human pressure on wetlands for dwindling resources. Judging by the example of Blood River
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2045 699 (Tooth et al., 2014), even relatively simple indicators such as signs of reed encroachment in
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2047 700 stagnant or slow-flowing, drought-impacted channels might provide low cost, early warning signs
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2049 701 of potential threshold-crossing behaviour and might give rise to simple management mitigation
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2051 702 strategies (e.g., targeted reed harvesting from critical channel reaches).
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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

2183
2184
2185 756 University, The Royal Society, Natural Environment Research Council, National Research
2186
2187 757 Foundation, National Science Foundation, National Geographic, the Skye Foundation, and the
2188
2189 758 British Society for Geomorphology. I thank Zacc Larkin (Macquarie University) for helping to
2190
2191 759 modify the Tshwane River figures, and also Antony Smith (Aberystwyth University) for the re-
2192
2193 760 drafting of other figures. I also appreciate the constructive comments of the two anonymous
2194
2195 761 reviewers on the initial submission.
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