FLOODPLAIN WETLAND FORMATION AND AVULSION IN THE SEMIARID TSHWANE-PIENAARS CATCHMENT, SOUTH AFRICA

Pienaars River floodplain wetlands – dry season vs. wet season

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Declaration

I hereby declare that this thesis has not been previously submitted to any other institution or university for a higher degree. Except where otherwise acknowledged, this thesis is comprised entirely of my own work.

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9th October 2015

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Abstract

Controls on floodplain wetland formation and river avulsion (channel relocation on the floodplain) are diverse and can include external (e.g. geology, climate) or internal (e.g. sediment deposition, erosion) drivers. Using a range of techniques including mapping historical channel change, morphological analysis of downstream channel characteristics, and optically stimulated luminescence dating of recently deposited floodplain sediment, this thesis investigates floodplain wetland formation and avulsion in the Tshwane-Pienaars catchment in northern South Africa.

The broadest scale control on river character and wetland development is catchment lithology, which affects floodplain width and accommodation space for unconfined alluvial reaches and floodplain wetlands. Downstream declines in discharge account for the overall morphology and behaviour of the Tshwane and Pienaars Rivers and their wetlands. Downstream channel diminution due to declines in discharge leads to aggradation of levees and alluvial ridges, and lateral adjustment occurs by channel migration and avulsion on the lower reaches of both rivers. Avulsion of the Tshwane River occurs autogenically during meander belt development in response to reductions in sediment transport capacity. The Tshwane River has a high avulsion frequency (~4.6 avulsions ka^{-1}) and a high vertical overbank sedimentation rate (~11 mm a^{-1}), which provides a well constrained dataset to demonstrate that sedimentation rate and avulsion frequency are correlated.

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CHAPTER 1 – INTRODUCTION

1.1 WETLANDS IN DRYLANDS

Wetlands are areas that are permanently, seasonally or intermittently inundated by fresh or saline water, typically supporting a remarkably diverse range of flora and fauna that are adapted to the wet conditions (Tooth and McCarthy 2007). In addition to high biodiversity, wetlands provide a number of ecosystem services (defined as benefits obtained by people from ecosystems) such as flood attenuation, water quality improvement, food and water provision and recreational opportunities (Mitsch and Gosselink 2000a; MEA 2005; Clarkson *et al*. 2013). While wetlands are most common in tropical and temperate zones with frequent, reliable rainfall, they also persist in drylands (i.e. hyper-arid, arid, semi-arid and dry subhumid regions), which cover ~50% of the Earth's land surface (UNEP 1992; Tooth and McCarthy 2007). The presence of wetlands in drylands makes these wetlands disproportionately important providers of ecosystem services. In otherwise dry environments, wetlands in drylands may provide the only reliable source of food and water resources, supporting human settlements, agriculture and migratory animals.

Much of the research on wetlands has focused on humid (tropical and temperate) regions (Mitsch and Gosselink 2000a; Morosoza and Smith 2000; Törnqvist and Bridge 2002; Assine 2005; Makaske *et al*. 2012). Contemporary wetland geomorphology is beginning to acknowledge the diversity of wetlands in drylands, which include pans, dambos and floodplain wetlands (Tooth and McCarthy 2007) (Table 1.1). This thesis will focus on floodplain wetlands, which, like all wetlands in drylands, have distinct and unique characteristics that are a function of the climatic conditions (low, variable rainfall and high evapotranspiration), variable discharge, and complex internal morphodynamic processes (Tooth and McCarthy 2007). A long-term perspective on wetland development over decades to millennia (or longer) is crucial to understand how they have formed and responded to changes in the past, and how they may change in the future (e.g. due to climate and land use change). Wetlands have been poorly managed in the past, with widespread degradation associated with agriculture, grazing, transport and urban land use, accounting for the destruction of an estimated ~50% of the world's wetlands (Mitsch and Gosselink 2000b). The geomorphological characteristics and processes that operate within wetlands are responsible for recycling sediment and nutrients, dictate the location and extent of flooding, and create a diverse array of habitats. Therefore, effective management of wetlands in drylands relies on a thorough geomorphological understanding of their structure and function (Tooth and McCarthy 2007; Tooth *et al*. 2009; McCarthy *et al*. 2010).

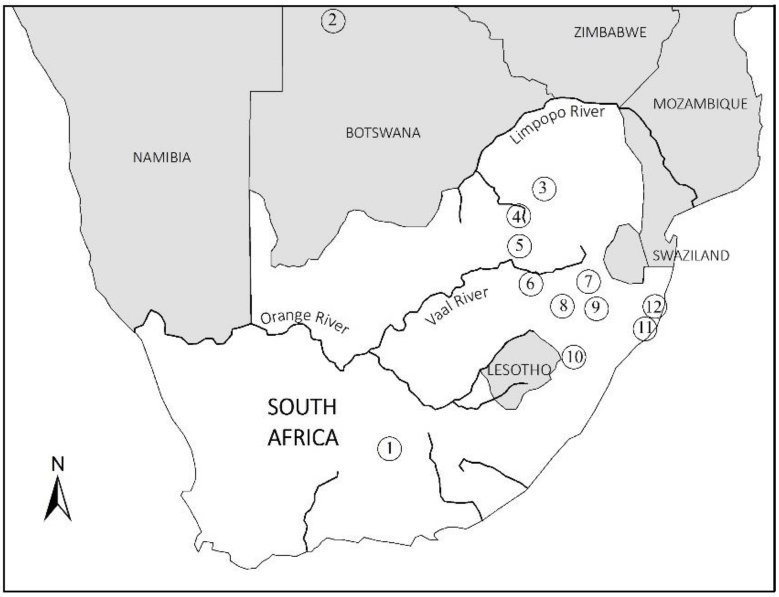
Table 1.1. The most common types of wetlands in drylands and a brief summary of their characteristics (using examples from McCarthy 1993; Tooth *et al*. 2002a; Tooth and McCarthy 2007; Ralph 2008; Grenfell *et al*. 2009; Humphries *et al*. 2010; Ralph and Hesse 2010).

WETLAND TYPE		BRIEF DESCRIPTION	EXAMPLES	
DELTAIC	Estuary, lagoon	Freshwater or saline swamps and lagoons formed at the mouth of a river as it reaches the ocean. The interaction between the river and the ocean creates unique characteristics, e.g. intermittently closed and open lagoons, tidal swamps.	-Mfolozi floodplain and estuary, eastern South Africa (image) -Greater Mkuze wetland system, eastern South Africa	
ALLUVIAL FAN	'Inland deltas'	Traditionally associated with piedmont zones, however in the drylands of Africa large, low-gradient alluvial fans have formed in response to tectonic subsidence. Distributary channel systems support extensive wetlands.	-Okavango Delta, northern Botswana (image) -The Sudd, Nile River, southern Sudan -Niger Inland Delta, Mali	
DEPRESSION	Pan, endorheic basin	Disconnected from river inputs, pans are fed by local rainfall or groundwater. Often formed by aeolian deflation and/or palaeo-fluvial activity. Due to their disconnection from fluvial systems, these wetlands are, by nature, ephemeral or intermittent.	-Western Zambian pans (image) -Etosha salt pan, northern Namibia	
	Playa, salt lake	Intermittent lakes that are hydrologically linked to a river system. Can be fresh or saline.	-Lake Eyre, central Australia (image) -Menindee Lakes, south eastern Australia	
VALLEY BOTTOM	Dambo, upland swamp	Channelled or unchannelled valley-fill wetlands without distinct floodplain features. Fed by local rainfall and/or groundwater. Often found in the low gradient headwaters of catchments.	-Zambezi River headwater dambos, western Zambia (image) -Klip River, (Johannesburg) eastern South Africa	
RIVERINE, FLOODPLAIN	Vlei, marsh, swamp	Valley bottom setting with a channel(s) and floodplain features (e.g. oxbows, levees, scroll and point bars). Can also include unchannelled floodouts or backswamps. Generally low gradient and low energy systems - erosion, sedimentation and periodic avulsion drive wetland change over time.	-Macquarie Marshes, eastern Australia (image) -Seekoeivlei, eastern South Africa	

1.2 SOUTHERN AFRICAN WETLANDS IN DRYLANDS

Wetlands in the semiarid to arid interior of southern Africa have been the focus of geomorphological research over the last couple of decades (McCarthy *et al*. 1991; Tooth *et al*. 2002a, 2004; McCarthy *et al*. 2007; Tooth and McCarthy 2007; Grenfell *et al*. 2008; Grenfell *et al*. 2009; Humphries *et al*. 2010; McCarthy *et al*. 2011; Joubert and Ellery 2013; Keen-Zebert *et al*. 2013; Grenfell *et al*. 2014; Tooth *et al*. 2014). However, a significant amount of research is still required to address key questions regarding the controls on wetland formation in dryland environments, the mechanisms by which these wetlands adjust, and the timescales associated with these processes.

In southern Africa, research has focused on the iconic Okavango Delta in northern Botswana, and on smaller systems throughout sub-humid to semiarid eastern South Africa (Fig. 1.1). Despite the relative scarcity of wetland systems studied in detail throughout southern Africa, there is a remarkable diversity in both the factors driving wetland formation, and characteristic morphology. Most wetlands in drylands are maintained by river inflows combined with other factors that act to dissipate flow and promote prolonged inundation. These factors can be structural (e.g. tectonic faulting, resistant lithology) or threshold responses to internal dynamics (e.g. downstream declines in discharge). The factors controlling river behaviour and floodplain wetland formation influence fluvial processes such as avulsion, meander cut-off, levee-building and lateral channel migration which determine the location and extent of wetlands on the floodplain.



1) Seekoei River, AI = 0.18
2) Okavango Delta, AI = 0.23
3) Nylsvlei, Nyl River, AI = 0.26
4) Tshwane-Pienaars, AI = 0.33
5) Johannesburg Klip River, AI = unknown
6) Schoonspruit, AI = unknown
7) Wakkerstrrom Vlei, AI = 0.40
8) Seekoeivlei, Klip River, AI = 0.42
9) Blood River, AI = 0.45
10) Hlatikhulu Vlei, Nsonge River, and Stillerust Vlei, Mooi River, AI = 0.59
11) Mfolozi River, AI = 0.64
12) Mkuze River, AI = 0.76

Fig. 1.1. Locations of previous geomorphological research in southern African floodplain wetlands. Numbered in approximate order of the level of aridity, from arid/semiarid to subhumid. Aridity index (AI) given by mean annual precipitation/mean annual evapotranspiration (UNEP 1992): (1) Grenfell *et al*. 2014; (2) McCarthy *et al*. 1991, 1992; McCarthy 2013; (3) McCarthy *et al*. 2011; (4) this study; (5) McCarthy *et al*. 2007; (6) Tooth *et al*. 2004; (7) Joubert and Ellery 2013; (8) Tooth et al. 2002, 2004, 2007; (9) Tooth *et al*. 2014; (10) Grenfell *et al*. 2008; Grenfell *et al*. 2013; Keen-Zebert *et al*. 2013; (11) Garden 2008; Grenfell *et al*. 2009; (12) Humphries *et al*. 2010; Ellery *et al*. 2012.

Research in southern African wetlands has also helped to improve understanding of fluvial processes such as avulsion and lateral channel migration in dryland regions (Rodnight *et al*. 2006; Tooth *et al*. 2007). Avulsion is the shift of a river course to a new position on the floodplain and is one of the most important processes by which rivers adjust, influencing flooding, ecological productivity, and human land use and settlement (Smith *et al*. 1989; Makaske 2001; Makaske *et al*. 2002; Slingerland and Smith 2004; Tooth and McCarthy 2007; Ralph *et al*. 2015). The factors controlling avulsion, however, are debated and more research is needed to collect field data, particularly in dryland rivers and wetlands which have received less scientific attention than temperate and tropical rivers and wetlands (Bryant *et al*. 1995; Mackey and Bridge 1995; Schumm *et al*. 1996; Slingerland and Smith 1998; Makaske *et al*. 2002; Tornqvist and Bridge 2002; Aslan *et al*. 2005; Jerolmack and Mohrig 2007; Stouthamer and Berendsen 2007). In their analysis of the frequency and mechanisms of avulsion in the Seekoeivlei wetlands on the Klip River, Tooth *et al*. (2007) found that avulsions of the Klip River support the oft-cited relationship between avulsion frequency and sedimentation rate. That is, avulsions are more frequent in rivers with higher long-term vertical sedimentation rates and less frequent in rivers with little or no vertical sedimentation (Tooth *et al*. 2007). However, there are relatively few studies of rivers worldwide with well constrained data of avulsion frequencies and sedimentation rates with which to test this assertion (see Fig. 1.2). This thesis aims to provide another dataset to supplement the sparse group of previous studies investigating the relationship between sedimentation rate and avulsion frequency.

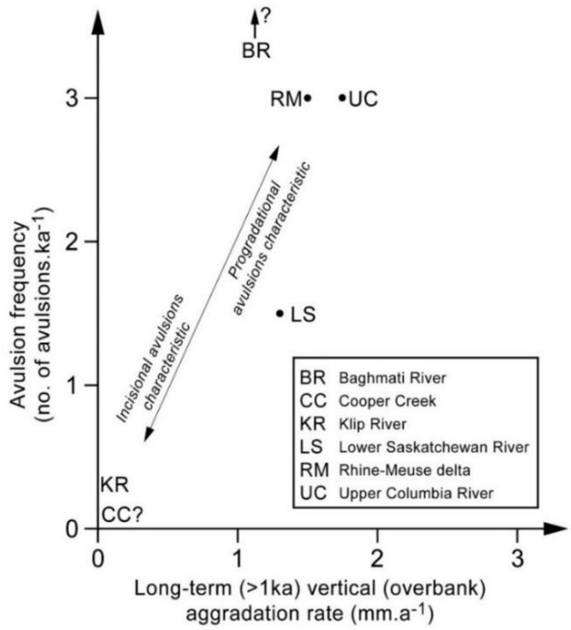


Fig. 1.2. The relatively sparse group of studies with well-constrained avulsion frequencies and sedimentation rates demonstrate a broad positive correlation between sedimentation rate and avulsion frequency. This figure includes rivers from drylands (Klip River and Cooper Creek) and from humid areas (Rhine-Meuse Delta, Saskatchewan and Columbia Rivers). Source: Tooth *et al*. (2007).

The extensive Tshwane-Pienaars floodplain wetlands in northern South Africa support adjacent informal settlements and subsistence grazing, and remain in excellent geomorphological condition. The wetlands are of significant regional importance as they provide habitat for numerous endemic and endangered bird species and likely improve the quality of water flowing out of greater Pretoria for downstream users (Marais and Peacock 2008). The wetlands have not been previously studied and new research in this system can provide insights into the factors controlling wetland formation in dryland environments. An interesting array of palaeochannels on the Tshwane River floodplain betrays several past avulsions and provides an opportunity to investigate important questions surrounding the mechanisms and frequency of avulsion in dryland alluvial rivers with floodplain wetlands. The findings from this study will have direct implications for river and wetland management by illustrating the natural processes which are responsible for the proper functioning of the wetlands and the timescales over which these processes operate.

1.3 Research questions and aims

The purpose of this thesis is to investigate the long-term and large-scale controls on avulsion and floodplain wetland formation and to develop a Late Holocene chronology of avulsion within the Tshwane-Pienaars wetlands. The overarching research question is: "What are the long-term controls on the formation and adjustment (avulsion) of the Tshwane-Pienaars floodplain wetlands?" This question will be addressed in two draft journal papers. The key aims that will be addressed in each paper are as follows:

Paper 1 – *Controls on river behaviour and floodplain wetland formation*

(i) Describe the geomorphology of the Tshwane and Pienaars rivers and their wetlands.

(ii) Determine broad-scale controls on river behaviour (especially avulsion) and the formation of floodplain wetlands in the Tshwane-Pienaars catchment.

(iii) Compare the Tshwane-Pienaars wetlands with other floodplain wetland systems throughout southern Africa.

Paper 2 – *Mechanisms and timescales of avulsion*

(iv) Develop a chronology of avulsion for the Tshwane River.

(v) Quantify floodplain sedimentation rates.

(vi) Determine whether avulsion frequency and sedimentation rates are correlated.

(vii) Determine if sedimentation rate influences avulsion style.

(viii) Discuss the role of allogenic (e.g. climate) and autogenic (e.g. meander dynamics) drivers of Tshwane River avulsion.

1.4 Structure of this thesis

This chapter introduced the background and key aims of this thesis. The next two chapters of the thesis consist of two draft papers to be submitted to separate journals. The first paper is titled '*Controls on river behaviour and floodplain wetland formation in the Tshwane-Pienaars catchment, South Africa*'. It is formatted as a stand-alone journal article with introduction, regional setting, methods, results, and discussion sections. This paper will concentrate on mapping (geomorphic and geological) and morphological analysis of the Tshwane and Pienaars Rivers to provide an understanding of the key factors controlling the formation of their floodplain wetlands. It will also explore the similarities and differences with other floodplain wetlands in southern Africa and provide insights into the underlying factors controlling the broad-scale diversity of wetland styles that have been observed in the drylands of South Africa.

The second paper is titled '*Mechanisms and timescales of avulsion in a rapidly adjusting South African dryland floodplain wetland*'. It is also formatted as a journal article with introduction, regional setting, methods, results and discussion sections. This paper uses historical analysis of channel change and single-grain optically stimulated luminescence to quantify the rates of channel adjustment (i.e. meander cut-offs and avulsion) on the Tshwane River and to address the often debated relationship between sedimentation rate and avulsion frequency.

Due to the nature of thesis-by-publication there may be some minor overlap and repetition between the papers, but the focus of each paper is distinct. A final conclusion chapter will bring the results of both papers together in context and frame questions for potential future research.

CHAPTER 2 – CONTROLS ON RIVER CHARACTER, BEHAVIOUR AND FLOODPLAIN WETLAND FORMATION

2.1 Purpose**:** This chapter presents original research that has been undertaken entirely within this MRes year. The chapter provides an introduction, methods, results and discussion related to the controls on river behaviour (including avulsion) and floodplain wetland formation in the Tshwane-Pienaars catchment, South Africa. There has been no previous geomorphological research undertaken in the Tshwane-Pienaars floodplain wetlands, therefore the catchment-scale morphological analysis undertaken in this chapter provides an important platform for further, more detailed, analyses of wetland forms and processes by illustrating the broad-scale processes controlling river behavior and formation of the Tshwane-Pienaars floodplain wetlands. This chapter will address aims i, ii, and iii highlighted in the introductory chapter.

2.2 Format**:** In accordance with the Macquarie University policy for higher degree research thesis by publication[1], this chapter has been written for submission to a peer-reviewed journal (*Earth Surface Processes and Landforms*). Repetition and any referencing and stylistic inconsistencies have been minimised to facilitate the thesis examination process. References from all chapters (including the papers) are combined in one reference list provided at the end of the thesis.

2.3 Author contributions**:** The author contributions for this research and the paper are as follows:

Zacc Larkin carried out fieldwork and sampling with T.R. and S.T., conducted laboratory work and mapping, analysed all data, designed and drafted all figures and tables, wrote and edited the paper.
Tim Ralph developed the study with S.T., carried out fieldwork and sampling with Z.L. and S.T., designed some figures with Z.L., provided comments on the paper, and supervised Z.L. in the research.
Stephen Tooth conceived of and designed the study, carried out fieldwork and sampling with Z.L. and T.R., provided comments on the paper, and co-supervised Z.L. in the research.

[1] The Macquarie University policy for thesis by publication states that a thesis may include a relevant paper or papers that have been published, accepted, submitted or prepared for publication for which at least half of the research has been undertaken during enrolment. The papers should form a coherent and integrated body of work. The papers are one part of the thesis, rather than a separate component (or appendix) and may be single author or co-authored. The candidate must specify their contribution and the contribution of others to the preparation of the thesis or to individual parts of the thesis in relevant footnotes/endnotes. Where a paper has multiple authors, the candidate would usually be the principal author and evidence of this should appear in the appropriate manner for the discipline. MQ Policy: http://www.mq.edu.au/policy/docs/hdr_thesis/policy.html

CONTROLS ON RIVER CHARACTER, BEHAVIOUR AND FLOODPLAIN WETLAND FORMATION IN THE SEMIARID TSHWANE-PIENAARS CATCHMENT, SOUTH AFRICA

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ABSTRACT

Controls on river styles and floodplain wetland formation in dry landscapes are diverse. External drivers include geological controls, tectonics and climate, while internal drivers include sediment deposition, erosion and other autogenic threshold responses. Understanding the long-term controls on rivers and wetlands in semiarid and arid landscapes is crucial for developing effective land and water management strategies. Using a combination of geomorphic and geological mapping, and morphological analysis of downstream channel characteristics, this paper investigates river adjustment and floodplain wetland formation in the Tshwane-Pienaars catchment in northern South Africa. The Tshwane-Pienaars wetlands are characterised by a prominently leveed, meandering trunk channel, oxbows, palaeochannels and backswamps in a relatively wide (1-2 km) floodplain. At the downstream end of the Pienaars River wetlands, floodplain width declines sharply and the channel becomes very straight within a confined bedrock valley. The wetlands are characterised by net sediment accumulation with fully alluvial channels reworking alluvium at least 5 m thick. The wetlands of the Tshwane and Pienaars Rivers have formed in response to a complex interaction between external geological controls and internal feedbacks related to downstream declines in discharge and stream power. Resistant lithology at the downstream end of the Pienaars wetlands acts as a local base level for the Pienaars River by resisting river incision, while, in the softer lithologies upstream, valleys widen gradually by lateral river migration. In conjunction with the geological influence on river character and behaviour, downstream declines in discharge and stream power related to transmission losses and declines in slope reduce sediment transport efficiency. This promotes channel and floodplain aggradation, avulsion and wetland formation. A conceptual model is developed that addresses variations in wetland morphology from through-going to floodout style wetlands along a sub-humid to semiarid climatic gradient in South Africa , which has implications for wetland management under future drier, more variable climates in southern Africa.

Keywords: alluvial river, local base level, trunk-tributary interaction, bedrock control, avulsion

1. INTRODUCTION

Semiarid, arid and hyper-arid (dryland) regions are characterised by a net deficit of water due to high evapotranspiration and low, often highly variable, precipitation (Tooth 2000). Despite these regions being water-stressed environments, many drylands contain perennial, seasonal or ephemeral rivers which are maintained by inflows from their headwater catchments. Many low-energy, dryland rivers are characterised by channel breakdown, avulsion and the development of floodplain wetlands (Ralph and Hesse 2010; Pietsch and Nanson 2011; Tooth *et al*. 2014). Wetlands that occur in drylands (wetlands in drylands) are very diverse and the factors dictating their formation and unique characteristics are equally varied (Tooth and McCarthy 2007).

At the broadest scale, most moderate to large wetlands in drylands form in response to either external factors (e.g. geology and climate) or internal factors (e.g. intrinsic threshold responses to downstream declines in discharge and sediment transport capacity) that influence river character and behaviour. External controls on wetland formation typically rely on the development of local base levels (e.g. tectonic faulting, outcrops of resistant bedrock, sedimentation on trunk or tributary channels), that promote low energy conditions and wetland formation upstream. Internal threshold changes, such as river channel diminution and sediment accumulation that occur in response to downstream declines in discharge and stream power, can drive channel avulsion and floodplain wetland formation without broader-scale changes in base level. However the style of river response to external and internal controls, or, to a combination of both, is varied. For example, rivers with meandering single channels can develop multiple, straight distributary channels and wetlands in response to a reduction in valley confinement and downstream tectonic barriers (e.g. Okavango River; McCarthy and Ellery 1998), or to changes in sea-level (e.g. Mfolozi wetlands; Grenfell *et al*. 2009; Table 1). Alternatively, downstream declines in discharge can lead to channel breakdown (termination) in wetlands (e.g. Macquarie River; Ralph and Hesse 2010; Table 1).

While the scientific understanding of external and internal controls on wetland formation and their interconnectedness is improving, it is clear that the diversity of wetland types and their composite features vary depending on specific geological, hydrological, climatic and other factors, such as water resource development and land use (Tooth and McCarthy 2007). In terms of wetland management, particularly with future climate change likely to impact significantly on these marginal environments, a substantial amount of research is needed to characterise and quantify the processes driving wetland formation in dryland areas. It is therefore crucial to provide a geomorphological basis for developing management policies and strategies to conserve and

Table 1. Different controls on wetland formation in dryland environments.

Dominant control on wetland formation	Example from southern Africa or Australia	Associated geomorphological features	Key references
Tectonic warping (e.g. subsiding graben, faulting)	Okavango Delta, Botswana	Meandering channel, palaeochannels, straight distributary channels, permanent wetlands, unchannelled swamp, salinized islands	McCarthy *et al*. 1991, 1992, McCarthy and Ellery 1998
	Barmah-Millewa wetlands, River Murray, southeastern Australia	Meandering channel, palaeochannels, permanent wetlands, unchannelled swamp, river red gum forest	Thoms 1995
Intrusive, erosion-resistant sills/dykes	Klip River, eastern South Africa	Meandering channel, palaeochannels, oxbows, lateral migration features (scroll and point bars), backswamps	Tooth *et al*. 2002, 2004, 2007
	Mooi River, eastern South Africa	Meandering channel, palaeochannels, oxbows, lateral migration features (scroll and point bars), backswamps	Grenfell *et al*. 2008, Keen-Zebert *et al*. 2013
	Nsonge River, eastern South Africa	Meandering channel, palaeochannels, oxbows, lateral migration features (scroll and point bars), backswamps	Grenfell *et al*. 2014
Tributary damming	Nyl/Mogalakwena River, northern South Africa	Trunk stream decreases in size downstream, floodouts, shallow lakes, unchannelled swamp	Grenfell *et al*. 2008, McCarthy *et al*. 2011
	Great Cumbung Swamp, Lachlan River, south-eastern Australia	Trunk stream decreases in size downstream, floodouts, shallow lakes, unchannelled swamp	O'Brien and Burne 1994
Sea level rise after the last glacial maximum	Mfolozi floodplain wetlands, eastern South Africa	Alluvial fan, lakes and pans, palaeochannels	Grenfell *et al*. 2009
Downstream declines in stream power and discharge related to transmission losses and lack of bedrock confinement	Macquarie Marshes, eastern Australia	Meandering channel that decreases in size downstream, straighter distributary channels, palaeochannels, backswamps and unchannelled floodouts, broad, unconfined alluvial plain	Yong and Hesse 2009, Ralph and Hesse 2010,
	Gwydir wetlands, eastern Australia	Meandering channel that decreases in size downstream, straighter distributary channels, palaeochannels, backswamps and unchannelled floodouts, broad, unconfined alluvial plain	Pietsch and Nanson 2011
	Blood River, eastern South Africa	Meandering channel that decreases in size downstream, palaeochannels, backswamps and unchannelled floodouts	Tooth *et al*. 2014
Preferential scouring forming permanent waterholes	Cooper Creek, east-central Australia	Preferentially deepened perennial waterholes, anastomosing channels, broad unconfined floodplain	Knighton and Nanson 1994, 2000

remediate these sensitive ecosystems (McCarthy *et al*. 2010). To address this knowledge gap, this paper aims to (i) describe the geomorphology of the Tshwane and Pienaars rivers and their wetlands, (ii) determine broad-scale controls on river behaviour (especially avulsion) and the formation of floodplain wetlands in the Tshwane-Pienaars catchment, and (iii) compare these with other floodplain wetland systems in southern Africa.

2. Regional Setting and Study Sites

The Tshwane and Pienaars Rivers are tributaries of the upper Crocodile-Limpopo River system on the semi-arid bushveld in northern South Africa (Fig. 1). The combined catchment is ~6 940 km^2 upstream of Klipvoor Dam (Tshwane River catchment area is 1 420 km^2). The headwaters of both the Tshwane and the Pienaars Rivers begin in the Magaliesberg at an elevation of around ~1 470 m.a.s.l., then both rivers flow north for approximately 90 km towards the towns of Kgomo Kgomo and Pienaarsrivier, respectively. At Pienaarsrivier, the Pienaars River is deflected west by an intruded dolerite dyke (Fig. 2), and downstream of Klipvoor Dam the river flows to the Crocodile River. The Tshwane River joins the Pienaars River from the south near Kgomo Kgomo. Downstream of the Tshwane-Pienaars confluence the river is sometimes referred to as the Moretele River, but in this paper the river that the Tshwane joins upstream of Klipvoor Dam will be referred to only as the Pienaars River to avoid confusion.

The geology of the Tshwane-Pienaars catchments consists of Pretoria Group shales and quartzites in the headwaters, with sandstones, mudstones and shales of the Karoo Sequence (Ecca and Irrigasie Formation) in the lower reaches. Dolerite intrusions and exposed granites of the Bushveld Complex (Lebowa Suite) also crop out locally (Fig. 2).

The Tshwane and Pienaars catchments are dominated by savannah grassland and mixed-bushveld, open woodland. In the wetlands, the dominant vegetation is grasses (*Setaria incrassate, Ischaemum afrum*) and occasional willows (*Salix* spp.) on the channel banks, with reeds (*Phragmites* spp.) and bulrushes (*Typha* spp.) in the backswamps that hold near-permanent water. Reeds and bulrushes also line the regularly flooded palaeochannels and oxbows on the floodplain. Water lilies (*Nymphaea* spp.) occupy open standing water in abandoned meander bends (oxbows) and palaeochannels. There is very little shrubby or woody riparian vegetation aside from occasional willows which remain local features despite having increased in abundance since 1950. The drier hillslopes flanking the floodplain wetlands support larger shrubs and trees (e.g. *Senegalia mellifera, Acacia tortilis, Colophospermum mopane*) that can access deep groundwater.

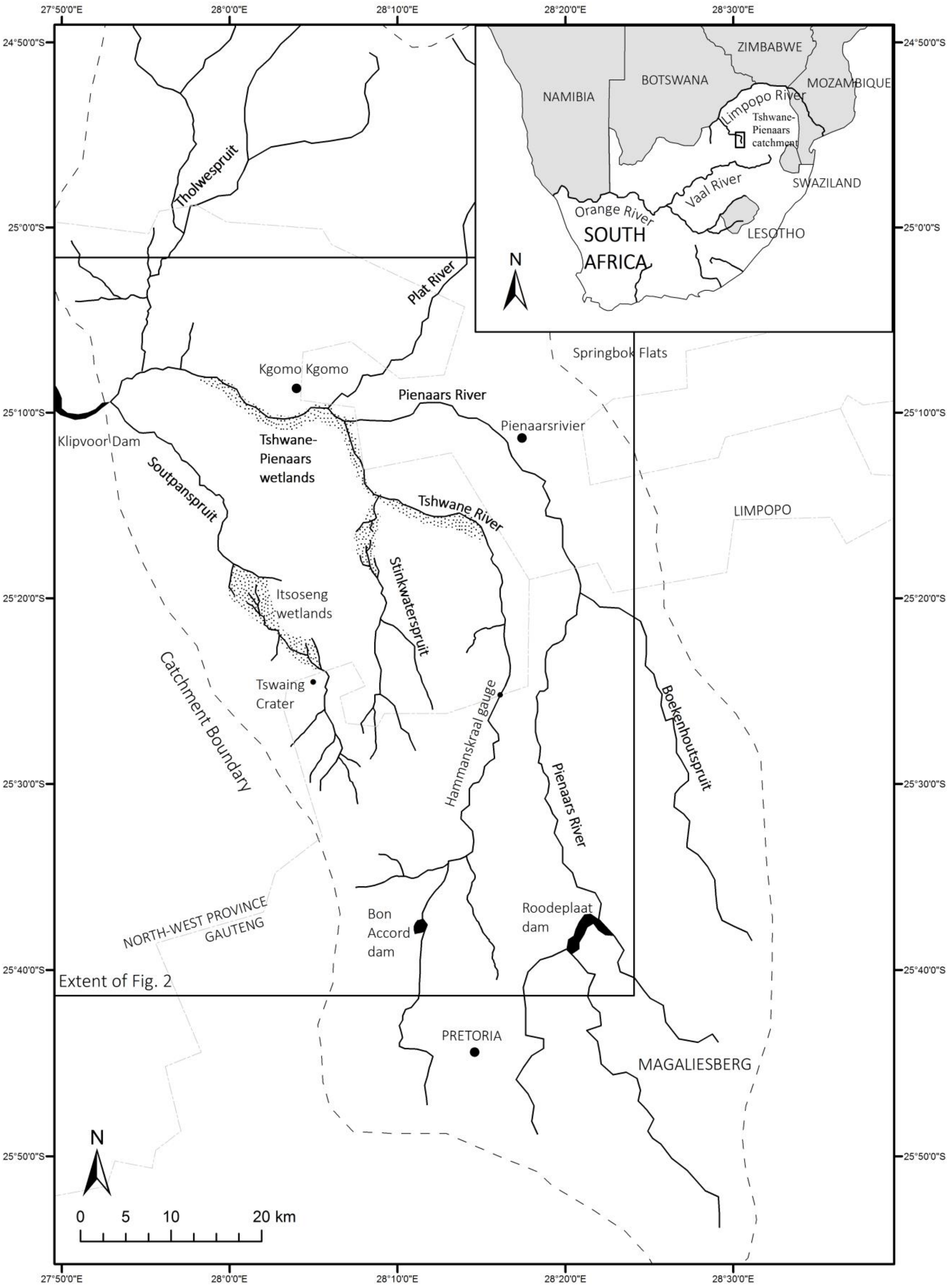

Fig. 1. The location and catchments of the Tshwane and Pienaars rivers in northern South Africa. Floodplain wetlands occur along the lower reaches of both rivers. Two other geomorphologically distinct wetlands characterised by channel breakdown and floodouts occur on the Soutpanspruit and Stinkwaterspruit tributaries.

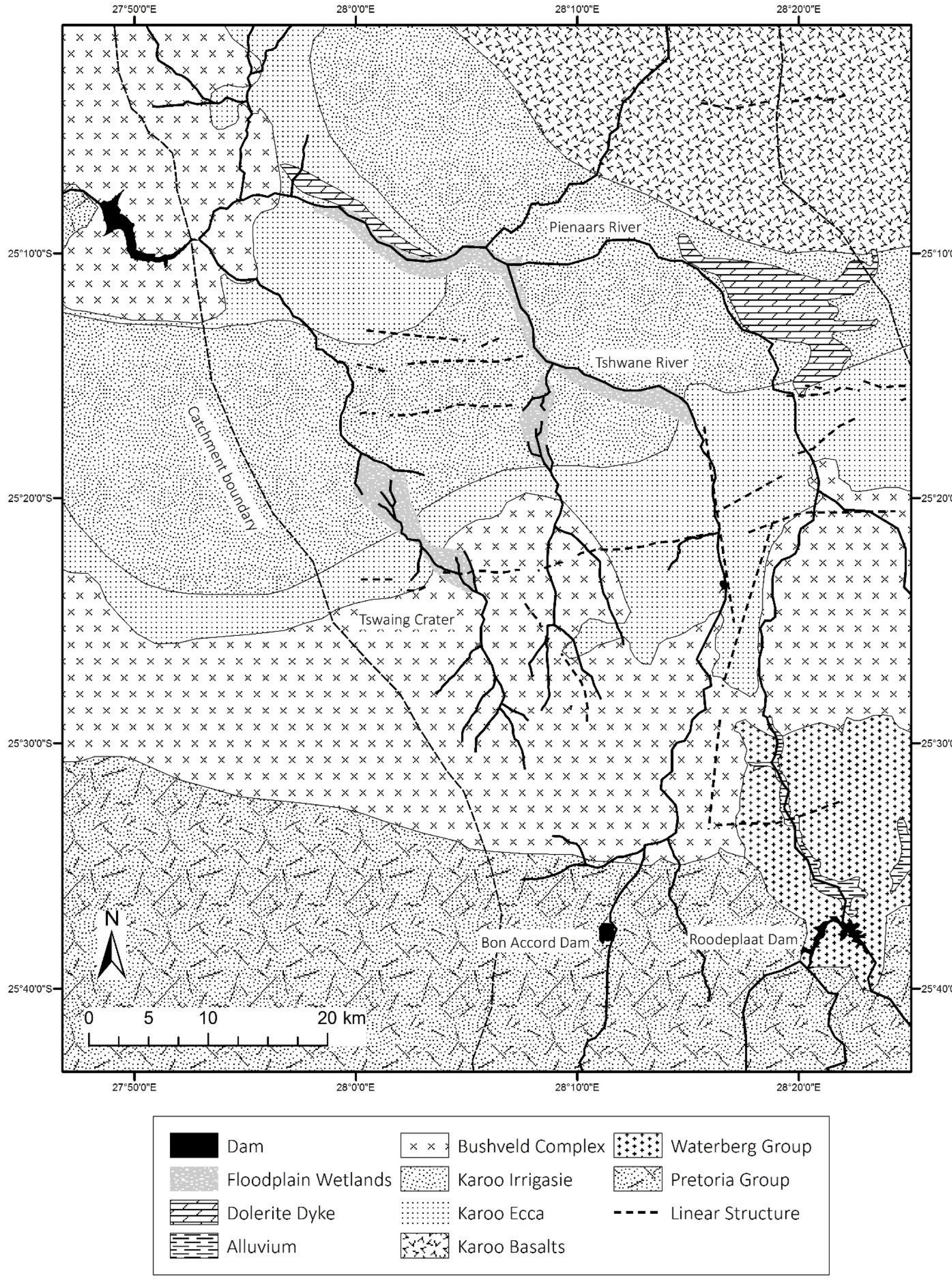

Fig. 2. Regional geology of the Tshwane and Pienaars catchments. Floodplain wetlands in their lower reaches are underlain by Karoo sedimentary rocks. Dolerite and granite may influence river alignment and baselevel, for example, where the Pienaars River crosses from Karoo sandstone and mudstone to Bushveld Complex granite, just upstream of Klipvoor Dam (redrawn from 1:250 000 geological maps, 2526 Rustenberg, and 2528 Pretoria).

The upper catchments of both the Tshwane and Pienaars Rivers in greater Pretoria are heavily urbanised, and in some areas the channel is canalised. Bon Accord Dam on the upper Tshwane River is a small earthen dam designed to provide water for local irrigation. Roodeplaat Dam on the upper Pienaars River is a much larger concrete arch dam providing water for irrigation and the suburbs of northern Pretoria (Fig. 1). The catchment becomes progressively less urbanised further north. There is substantial irrigated agriculture along the middle reaches of the Pienaars River that uses river water. The extensive basalt Springbok Flats to the north of the Pienaars River also support large agricultural properties, but these generally rely on groundwater from bores rather than water from the river (DWA 1999). In addition to large agricultural practices, there are numerous small, informal settlements along the lower reaches that use water from the rivers and bores to support small-scale subsistence agriculture.

The South African bushveld is characterised by strongly seasonal rainfall with distinct wet (November through March) and dry (April through October) seasons. Mean annual precipitation in the Tshwane-Pienaars catchment is ~585 mm, falling mostly in the wet season during convective thunderstorms whilst mean annual potential evapotranspiration is ~1 750 mm (aridity index = 0.33; aridity index given by mean annual precipitation / mean annual potential evapotranspiration; UNEP 1992) (Working for Wetlands 2008; GDARD 2011). Discharge in the Tshwane and Pienaars Rivers is perennial, but strongly seasonal, with high wet season flows (>60 $m^3 s^{-1}$) and low dry season flows (<4 $m^3 s^{-1}$) (Fig. 3). The floodplains of both rivers are inundated by overbank flows and local rainfall during the wet season, while low flows are confined to the main channel during the dry season and the backswamps and oxbows slowly desiccate.

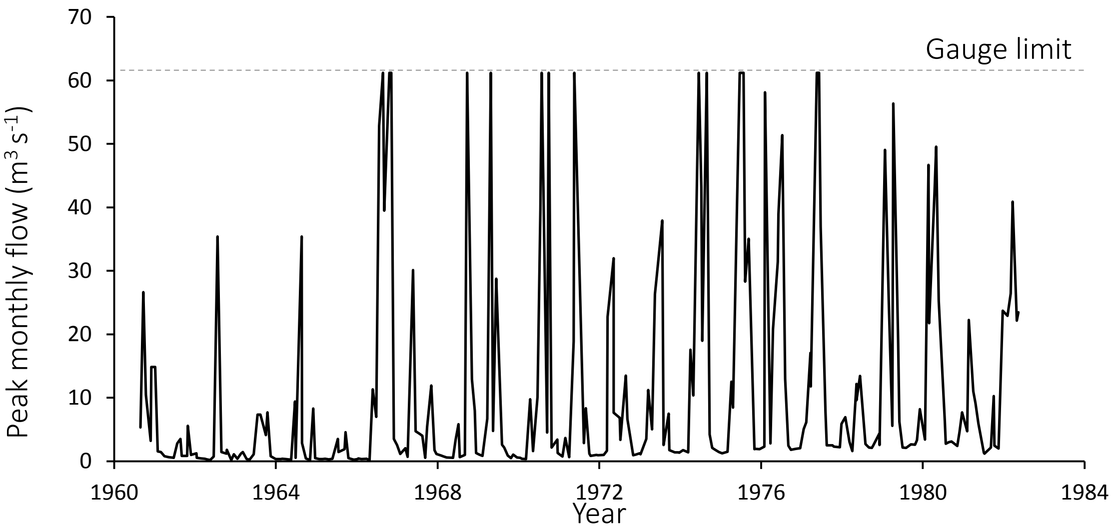

Fig. 3. Peak monthly flow at the Hammanskraal gauge on the Tshwane River for the period of gauge activity, 1961-1982 (see Fig. 1 for location). The seasonality of peak flows is clear, with flows regularly topping the gauge limit of 60 $m^3 s^{-1}$ during the wet season. Data sourced from DWA Hydrological Services (2015).

Depth to groundwater throughout much of the Pienaars River catchment is ~18 m, and little to no base flow in the river can be attributed to groundwater (DWAF 1999). The Tshwane and Pienaars Rivers are effluent in nature (i.e. they rely on surface runoff for all flow and may discharge some water to groundwater; DWAF 1999). Sewage discharge and irrigation returns have increased the base flow in both the Tshwane and Pienaars Rivers, which is potentially responsible for the apparent increase in dry season base flow between 1961 and 1982 (Fig. 3). It is almost certain that the water flowing into the wetlands is significantly contaminated by urban stormwater run-off and sewage discharge associated with greater Pretoria.

The study sites for this paper are in the lower alluvial reaches of the Tshwane River and extend downstream along the Pienaars River until ~10 km upstream of Klipvoor Dam (Fig. 1). These reaches are characterised by avulsion and the development of floodplain wetlands, and the main channels of both rivers are actively meandering within a relatively wide floodplain. Wetlands on the floodplain include oxbows, palaeochannels and backswamps that cover ~55 km^2 (Fig. 4 and 5). The wetlands are an important waterbird habitat and have been minimally altered by weirs or other flow control structures (Marais and Peacock 2008). Despite likely poor water quality and cattle grazing, the wetlands are in good geomorphological condition with no evidence of large dongas or deeply entrenched channels (Fig. 4).

Fig. 4. (A) Recent levee sedimentation on the modern Tshwane River (foreground), with adjacent backswamp in the depression to the right. Note the reedbed situated in the depression between the levee and the hillslope in the background (looking upstream), (B) Relatively straight section of the Tshwane River, which is beginning to form meanders by deposition on the inside bend and erosion on the outside bank (looking upstream), (C) Largely infilled palaeochannel on the Pienaars River floodplain (looking downstream), (D) Overbank flooding on the lower Tshwane River (looking downstream).

There are two other significant wetlands in the Tshwane catchment; the Itsoseng wetlands that occur in the floodout zone of the Soutpanspruit tributary, and wetlands in the floodout zone of the Stinkwaterspruit tributary (Fig. 1). These wetlands are geomorphologically different from the wetlands that are the focus of this paper along the trunk streams of the Tshwane and Pienaars Rivers. The Itsoseng wetlands occur where Soutpanspruit breaks down into a series of straight distributary channels, forming a densely vegetated floodout. Soutpanspruit has extensive unchannelled swamps with shallow channels acting as conduits for flow. Similarly, Stinkwaterspruit forms a floodout before reaching the Tshwane River with very little sediment being transported to the trunk stream, and water likely reaching the Tshwane only during large floods.

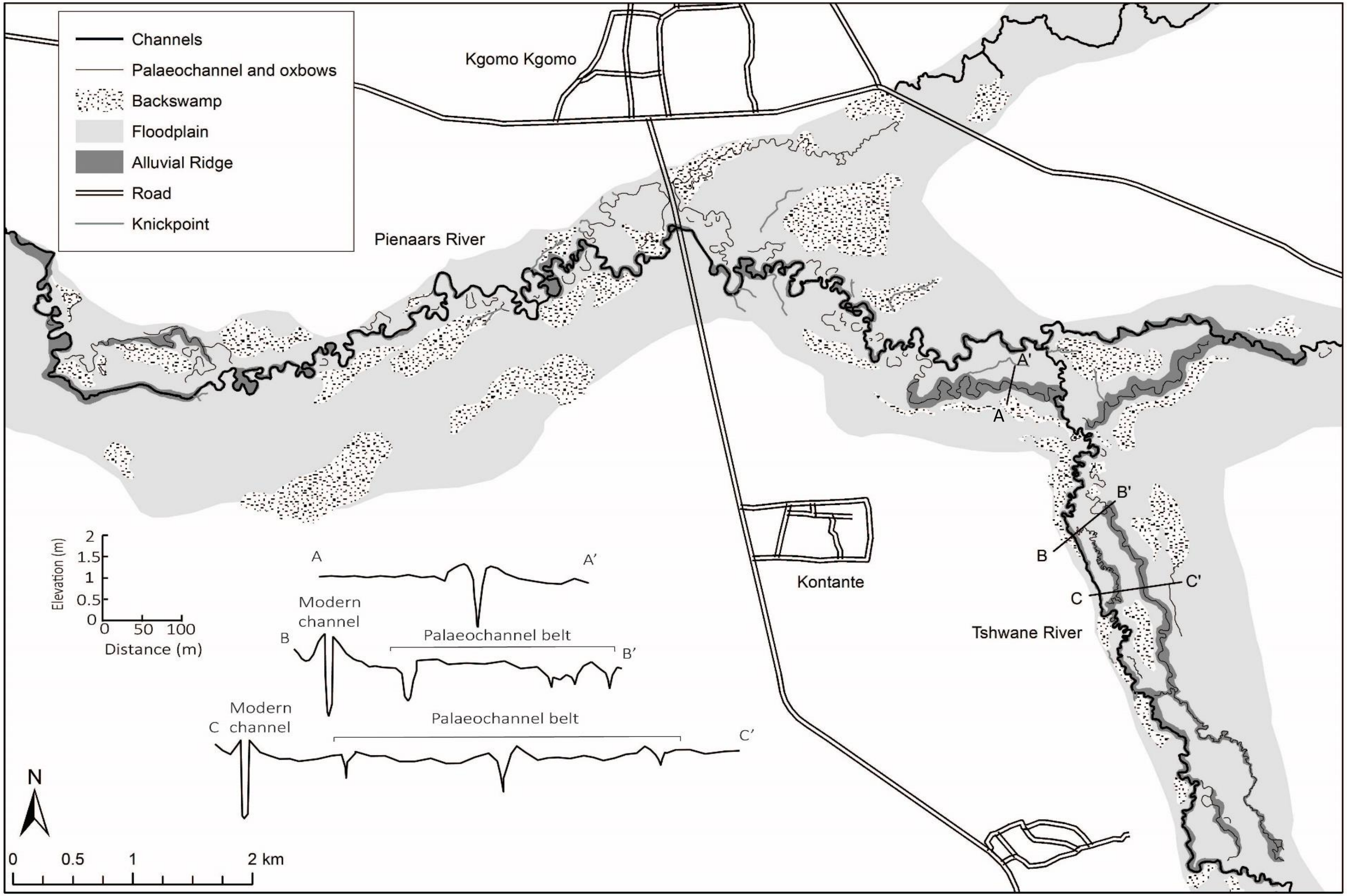

Fig. 5. Geomorphic map of the Tshwane-Pienaars floodplain wetlands and cross-sectional surveys of the Pienaars ridge (A-A'), and the lower Tshwane River (B-B', C-C').

3. METHODS

The morphology of the Tshwane and Pienaars rivers and their floodplain wetlands was investigated using a combination of aerial photograph, satellite imagery, geological maps and field surveys. Recent (2012) aerial photos of the Tshwane and Pienaars Rivers allows detailed mapping of distinctive river and wetland features, such as palaeochannels, oxbows, alluvial ridges, knickpoints and backswamps (Table 2). The framework for mapping of the Tshwane-Pienaars system is based on a hierarchical system developed for floodplain wetlands in Australia by Hesse and Ralph (2011) (Table 2). Terrain is the broadest scale unit and landforms within each terrain are grouped by their dominant processes of formation and modification (e.g. fluvial, aeolian, lacustrine, anthropogenic). Landforms are made up of landform types which can be quite diverse. Morphological analysis of river features is important for characterising rivers and wetlands and for defining their downstream trends. The characteristics quantified using standard methods for both the Tshwane and Pienaars Rivers include floodplain width, channel sinuosity, bankfull channel width, number of channels, and floodplain and channel gradients.

Table 2. Tshwane-Pienaars geomorphic mapping framework based on Hesse and Ralph (2011).

Terrain	***Landform***	***Landform type***
Fluvial	Channel	Meandering trunk stream
		Palaeochannel
		Oxbow
		Ephemeral channel
		Knickpoint
	Floodplain	Backswamp
		Alluvial ridge
		Floodplain
Anthropogenic	Channel	Canal
	Embankment	Road
		Dam
		Weir

Longitudinal profiles for the Tshwane and Pienaars Rivers were derived by using 5 m contour intervals from orthophoto maps and georeferenced topographic data in ArcMap. Several other studies of rivers and floodplain wetlands in South Africa have highlighted the influence of local geology on the morphology and characteristics of South African wetlands (e.g. Tooth *et al*. 2002; 2007; McCarthy *et al*. 2011, Keen-Zebert *et al*. 2013; Grenfell *et al*. 2014). In particular, longitudinal profiles can indicate areas of local steepening that result from changes in underlying bedrock (Tooth *et al*. 2004; Marren *et al*. 2006). Analysis of the underlying catchment bedrock was undertaken using 1:250 000 geological maps (series 2526 Rustenburg, and 2528 Pretoria).

Topographic field surveys were conducted using an automatic level and observations of the channel and floodplain morphology were recorded at regular intervals. The pattern of water flow and associated sedimentation during a wet season flood was noted while in the field. Water samples were collected from the Tshwane River at bankfull stage and suspended sediment concentration was determined by measuring the mass of suspended sediment in a known volume of water. Downstream changes in discharge and stream power were estimated by following the method of Bjerklie (2007). Measurements of meander wavelength, bankfull channel width, floodplain slope, and channel slope were made using satellite imagery, and an estimation of channel depth was made (held constant at 1.95 m, which is the average depth of the channel on the lower Tshwane River given by topographic cross sections). A velocity calculation based on these parameters allows discharge and stream power to be calculated (see Bjerklie 2007), and this process was completed at 1 km intervals downstream along the alluvial reaches of the Tshwane and Pienaars rivers. As meander wavelength is a key variable for this method of estimating velocity, discharge and stream power, estimations could not be made in the confined headwater and lower confined reaches where the channel is relatively straight.

4. RESULTS

4.1 Geological controls on the Tshwane and Pienaars Rivers

The underlying geology exerts strong controls on river and floodplain character in the Tshwane and Pienaars catchments. Confined straight channels with limited or absent floodplains (<0.2 km) are associated with more erosion-resistant lithologies (e.g. Pretoria Group quartzites and Bushveld Complex granites) and wide floodplains (~1-2 km) and meandering channels are associated with the weakly-cemented sandstones and shales of the Karoo Sequence (Fig. 6 and 7). The upper ~17 km of the Tshwane River is relatively steep (~0.01 m m^{-1}) and tightly confined without any floodplain pockets (Fig. 6). Continuous floodplain adjacent the Tshwane River begins at ~30 km downstream. Floodplain width increases from <0.4 km to >1 km once the Tshwane River crosses from Bushveld Complex granites to the low gradient (<0.001 m m^{-1}) Karoo Sequence sandstones and shales. The upper ~50 km of the Pienaars River is steep (~0.01 m m^{-1}) and tightly confined with infrequent pockets of floodplain. Downstream of Roodeplaat Dam floodplain width widens slightly up to ~0.4 km, before increasing sharply to >1.5 km once the Pienaars River crosses from the Bushveld Complex granites to the Karoo Sequence sandstones and shales. Floodplain gradient is very low atop the Karoo bedrock (~0.0008 m m^{-1}) before steepening significantly (~0.002 m m^{-1}) as the Pienaars River crosses from the Karoo sandstones to Bushveld granites at ~145 km downstream, with a concomitant sharp decline in floodplain width to <0.3 km (Fig. 7). The Pienaars River wetlands occur upstream of Bushveld Complex granite, which act as a base level control in this river, while there does not appear to be a direct geological control on base level for the Tshwane River upstream of its confluence with the Pienaars River.

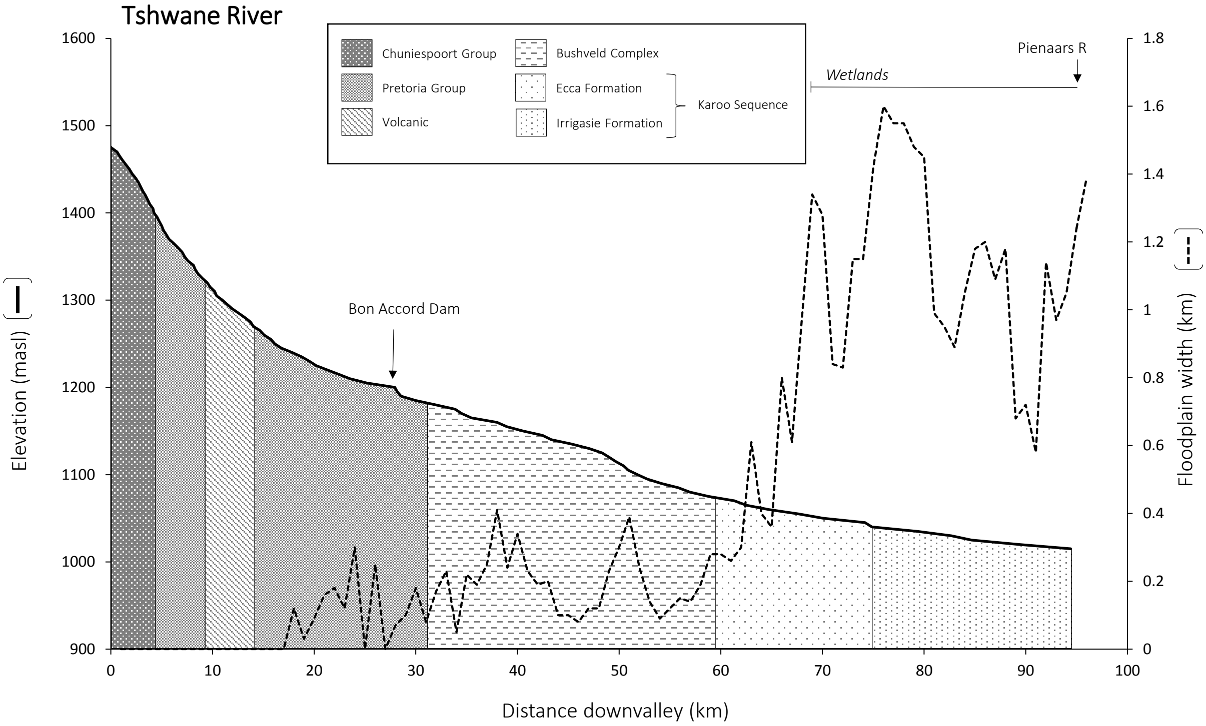

Fig. 6. Longitudinal profile of the Tshwane River superimposed onto underlying geology and showing the relationship with floodplain width (geology generalised from 1:250 000 geological map, series 2528 Pretoria).

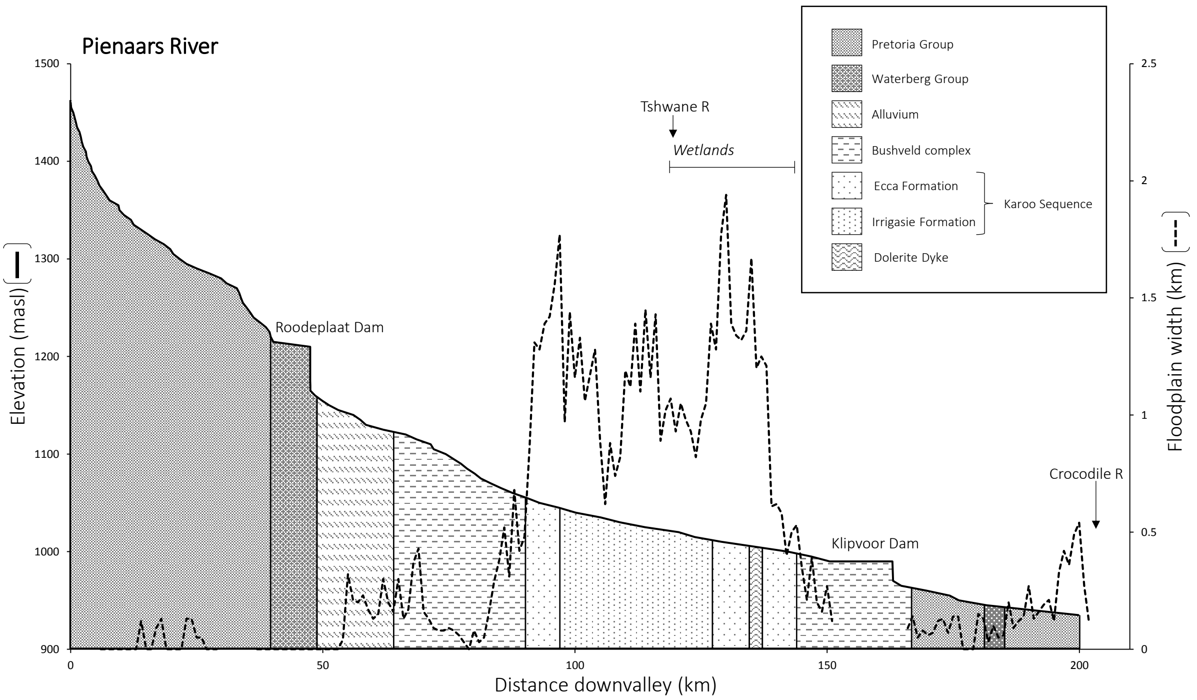

Fig. 7. Longitudinal profile of the Pienaars River superimposed onto underlying geology and showing the relationship with floodplain width (geology generalised from 1:250 000 geological maps, 2528 Pretoria and 2526 Rustenburg).

An indirect influence of the catchment geology on the Tshwane and Pienaars Rivers is the calibre and quantity of sediment being supplied to the system, with quartzites of the Pretoria group and granites of the Bushveld complex breaking down to supply predominantly fine-grained material (e.g. sand, silt, and clay) to the lower reaches of both rivers.

4.2 Downstream changes in channel and floodplain morphology

There are three distinct river-floodplain styles in both the Tshwane and Pienaars Rivers: the confined headwater reaches; the partly confined middle reaches; and the laterally unconfined alluvial reaches with floodplain wetlands further downstream (Table 3). The laterally confined reaches are relatively steep, are often grounded on bedrock and have wider channels (Table 3). The partly confined middle reaches are relatively straight (sinuosity <1.3) and are partly alluvial with floodplain pockets adjacent the channel, although still bedrock controlled. The unconfined alluvial channels with floodplain wetlands in the lower reaches are smaller than in the upstream reaches, and are fully alluvial, planform controlled meandering channels (sinuosity >2) (Table 3). In both rivers, avulsion becomes the dominant form of channel adjustment in the middle and lower alluvial reaches where floodplain width is sufficient to allow whole channel-belts to shift laterally on the floodplain, in addition to more subtle lateral shifts by meander migration within the channel belt. Downstream of the floodplain wetlands on the Pienaars River, the channel becomes laterally confined again and is similar in morphology to the headwater reaches.

Sinuosity of the Tshwane River in the confined headwater reaches is ~1.2 (locally up to 1.4), before it increases sharply after crossing over Karoo Sequence bedrock to a maximum of ~2.7 in the wetlands (Fig. 8). Channel sinuosity increases as floodplain width increases and there is a strong positive correlation between the two factors (R^2 = 0.69; Fig. 9), the latter initially increasing sharply upon traversing Karoo Sequence bedrock (Fig. 8). Contrasting with the marked sinuosity increase is the fact that once the Tshwane River starts to meander in a widened, unconfined floodplain, channel width steadily declines towards the Pienaars junction from ~20 m to ~9 m (Fig. 8). Only one channel is active along the length of the Tshwane River, but the number of abandoned channels on the floodplain increases in the lower alluvial reaches with floodplain wetlands (up to three adjacent to the modern channel; Fig. 8). Floodplain gradient decreases downstream, with the lowest gradients (~0.0015 m m^{-1}; and even <0.001 m m^{-1} in the furthest downstream reaches) associated with the wetlands (Table 3; Fig. 8). The Tshwane River floodplain wetlands occur where floodplain width and sinuosity are greatest

Table 3. Downstream morphological characteristics of the Tshwane River and the Pienaars River.

TSHWANE RIVER	Average Gradient (m m^{-1}) [a] Floodplain (± SD)	Channel (± SD)	Average sinuosity [b]	Average floodplain width (± SD; km) [c]	Average channel width (± SD; m) [d]	Dominant underlying lithology [e]	Bed material [f]
Confined headwaters	0.015 ± 0.009	0.015 ± 0.009	1.00 - 1.20	0.05 ± 0.09	20.7 ± 6.5	Quartzite, Shale, Granite	Bedrock, sands and gravels
Partly confined middle reaches	0.0048 ± 0.004	0.0051 ± 0.007	1.20 – 1.70	0.31 ± 0.29	19.3 ± 4.0	Sandstone, Mudstone, Shale	Mud, sand and minor gravels - partly alluvial
Floodplain wetlands	0.0015 ± 0.0007	0.00083 ± 0.0003	1.50 – 2.70	1.13 ± 0.28	10.9 ± 1.5	Sandstone, Mudstone, Shale	Mud, sand and minor gravels - fully alluvial
PIENAARS RIVER							
Confined headwaters	0.012 ± 0.01	0.011 ± 0.01	1.00 - 1.19	0.02 ± 0.04	19.7 ± 3.7	Quartzite, Shale	Bedrock, sands and gravels
Partly confined middle reaches	0.003 ± 0.002	0.002 ± 0.001	1.49 - 2.07	0.59 ± 0.52	14.1 ± 3.7	Sandstone, Mudstone, Shale	Mud, sand and minor gravels - partly alluvial
Floodplain wetlands	0.0008 ± 0.0001	0.0004 ± 0.00005	1.71 – 3.60	1.23 ± 0.28	9.2 ± 1.7	Sandstone, Mudstone, Shale	Mud, sand and minor gravels – fully alluvial
Lower confined reach	0.001 ± 0.0009	0.001 ± 0.0009	1.00 - 1.50	0.19 ± 0.18	20.5 ± 4.0	Granite	Bedrock, sands and gravels

[a] Floodplain and channel gradient measured using 5 m contour topographic data and measuring tool in ArcMap (elevation change / valley *or* channel distance).
[b] Sinuosity measured along 1 km reaches of the channel (channel distance / straight line distance).
[c] Floodplain width measured every kilometre downstream. Boundary between floodplain and valley hillslope estimated using topographic data derived from a 30 m DEM of the region and distinct vegetation zonation patterns (hillslope vegetation vs. floodplain vegetation).
[d] Bankfull channel width measured every 1 km downstream, generally focusing on straighter sections to avoid results being skewed by local increases in channel width at meander bends.
[e] Lithologies given by 1:250 000 geological map series (2526 Rustenburg and 2528 Pretoria).
[f] Channel bed material estimations follow field observations and identification of bedrock outcrop in channels in aerial photographs.

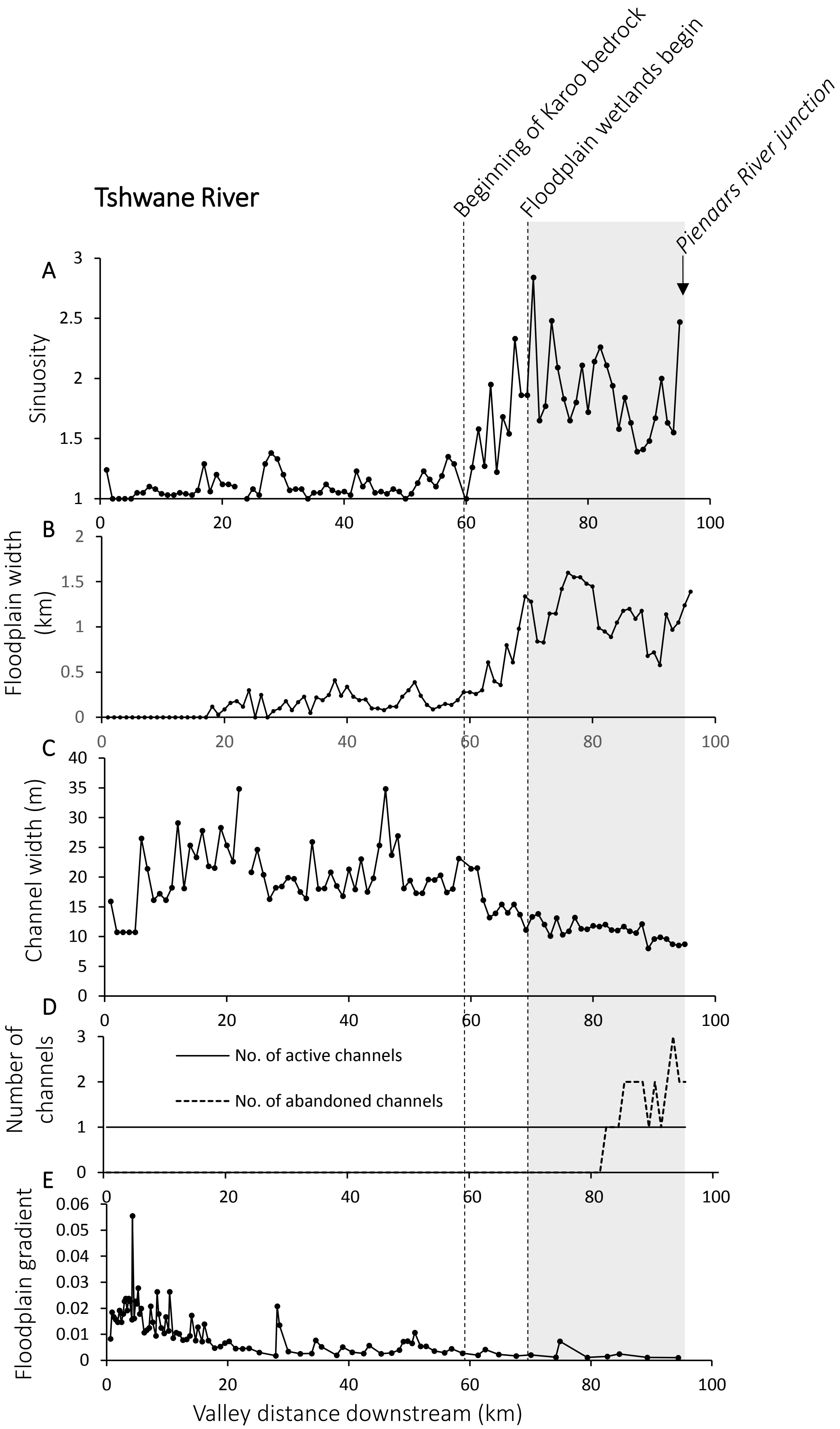

Fig. 8. Downstream morphological characteristics of the Tshwane River at 1 km intervals, (A) sinuosity; (B) floodplain width; (C) trunk channel bankfull width; (D) number of active channels and number of abandoned palaeochannels on the floodplain; (E) floodplain gradient. Apparent gap in the data is the location of Bon Accord Dam.

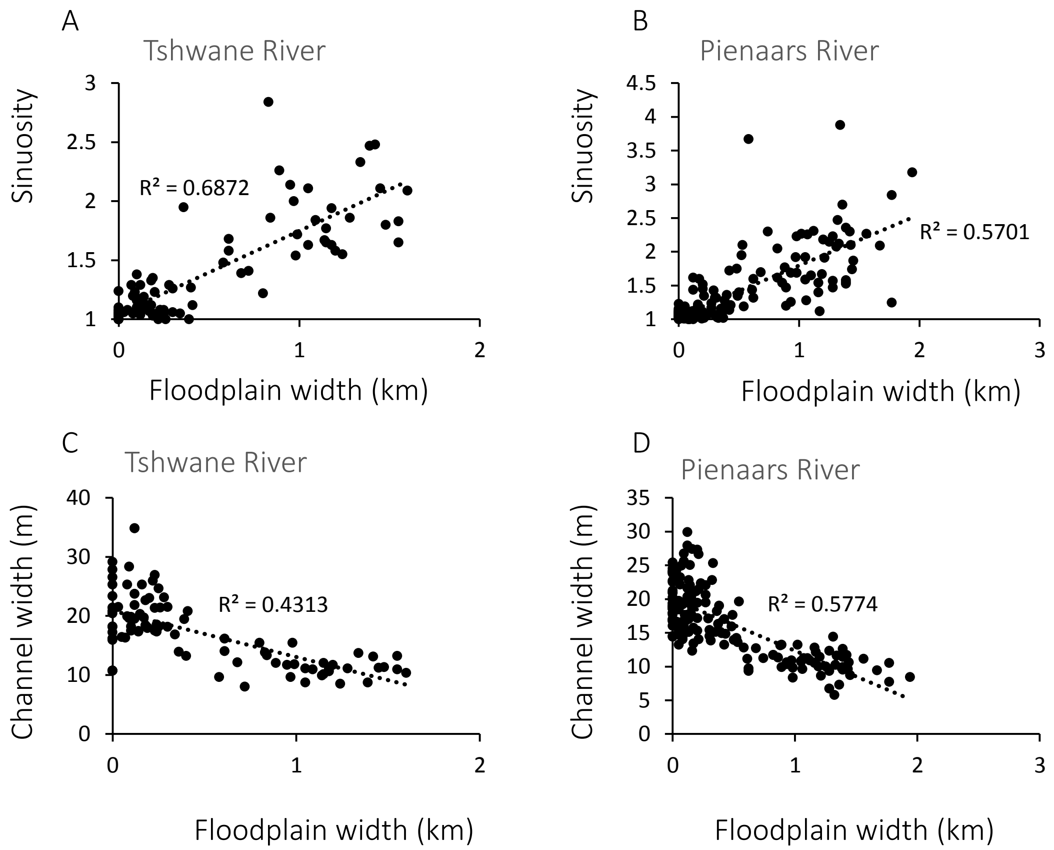

Fig. 9. Correlation between floodplain width and sinuosity for the (A) Tshwane River, and (B) Pienaars River. Correlation between floodplain width and channel width for the (C) Tshwane River, and (D) Pienaars River.

Sinuosity of the Pienaars River in the confined headwater reaches is ~1.1 (locally up to 1.5), before increasing significantly after emerging onto the wide floodplain associated with the Karoo bedrock ~90 km downstream. Sinuosity in the unconfined alluvial reaches is initially quite variable (~1.5-2.5), and reaches a peak of >3.5 in the floodplain wetlands, immediately below the junction with the Tshwane River (Fig. 10). Channel sinuosity increases with floodplain width and there is a positive correlation between the two factors ($R^2 = 0.54$; Fig. 9), and both decline (floodplain width to <0.3 km and sinuosity to <1.3) after crossing from the Karoo Sequence bedrock to the harder granites of the Bushveld Complex. Channel width is variable in the confined headwater reaches (mean ~20 m) and narrows when the river crosses begins to meander on the wide, unconfined floodplain atop the Karoo bedrock (Fig. 10). Channel width in the Pienaars River wetlands is more variable than in the lower Tshwane River wetlands, however, and locally reaches a minimum of ~5 m. One channel is active throughout while the number of abandoned channels on the floodplain is significantly higher in the wetlands (up to three adjacent to the modern channel). Floodplain gradient is very low in the Pienaars River wetlands (~0.0008 m m^{-1}). The Pienaars River floodplain wetlands occur where floodplain width and sinuosity are greatest.

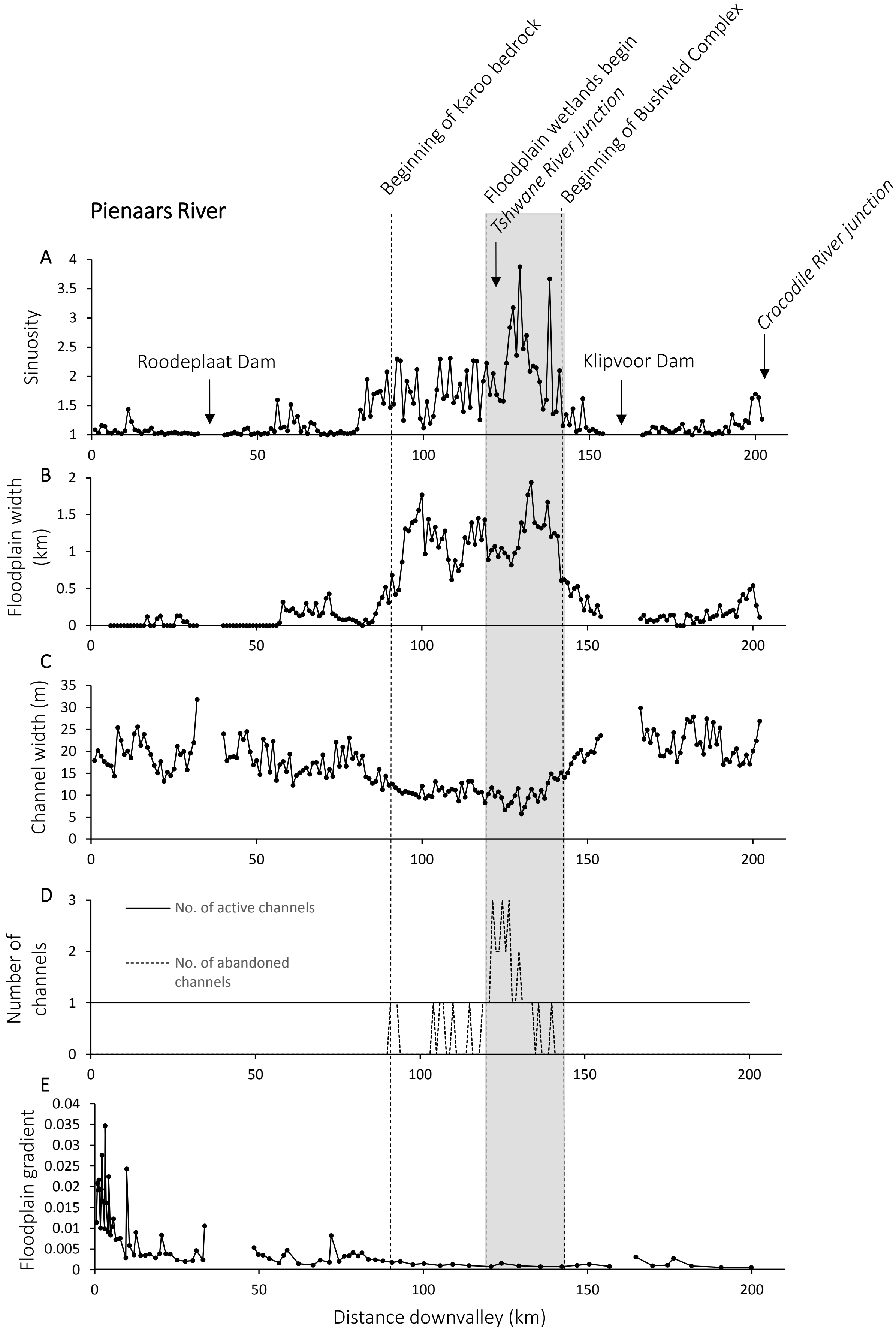

Fig. 10. Downstream morphological characteristics of the Pienaars River at 1 km intervals, (A) sinuosity; (B) floodplain width; (C) trunk channel bankfull width; (D) number of active and abandoned channels; (E) floodplain gradient. Apparent gaps in the data are the locations of Roodeplaat Dam and Klipvoor Dam.

4.3 Downstream changes in discharge and stream power

A comparison between the estimated bankfull discharge (Q) and unit stream power after Bjerklie (2007) and estimates using Manning's *n* equation with channel dimensions from cross-sectional surveys along the lower Tshwane River gave a $R^2 = 0.8$ for discharge and $R^2 = 0.7$ for stream power (Fig. 11). Despite slight over and underestimation of the modelled discharge and stream power, the strength of the relationship indicates that similar trends will be identified with both methods. The method used to estimate discharge and stream power from measurements of channel dimensions using satellite imagery includes significant errors (~24 %) due to the assumptions that must be made without field measurements of cross-sectional area or roughness (Bjerklie 2007).

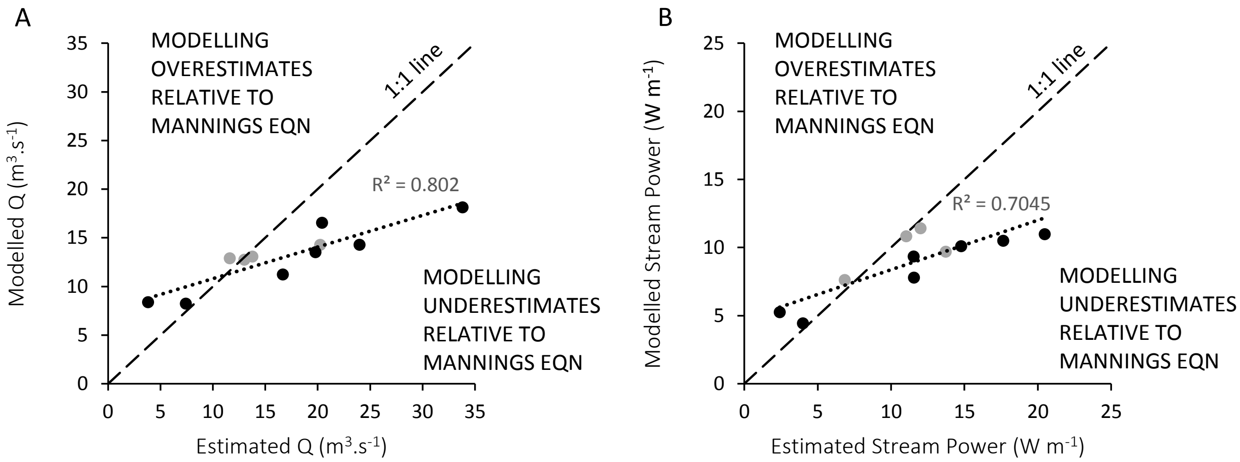

Fig. 11. (A) Modelled bankfull discharge (following Bjerklie, 2007) plotted against estimated bankfull discharge using Manning's equation for the lower Tshwane River, (B) Modelled unit stream power using Bjerklie's (2007) discharge estimate plotted against estimate of unit stream power using Manning's estimate of discharge (Q) for the lower Tshwane River. Grey data points are estimates for the modern channel, and black data points are estimates for palaeochannels whose depth is known after augering to bedload sand.

Both the Tshwane and the Pienaars Rivers experience a downstream decline in discharge and stream power once they enter their partly-confined and unconfined alluvial reaches (Fig. 12). Initially, bankfull discharge along the middle Tshwane River is ~40 $m^3 s^{-1}$, before declining to ~9 $m^3 s^{-1}$ at the junction with the Pienaars River. Unit stream power follows a similar pattern, declining from ~30-60 W m^{-1} at the upper floodplain to <5 W m^{-1} at the Pienaars River junction. The Pienaars River experiences a downstream decline in discharge from ~20-30 $m^3 s^{-1}$ to ~5-15 $m^3 s^{-1}$ in the unconfined alluvial reaches (Fig. 12). Stream power along the Pienaars River also declines from ~20-25 to ~5 W m^{-1} in this part of the system (Fig. 12).

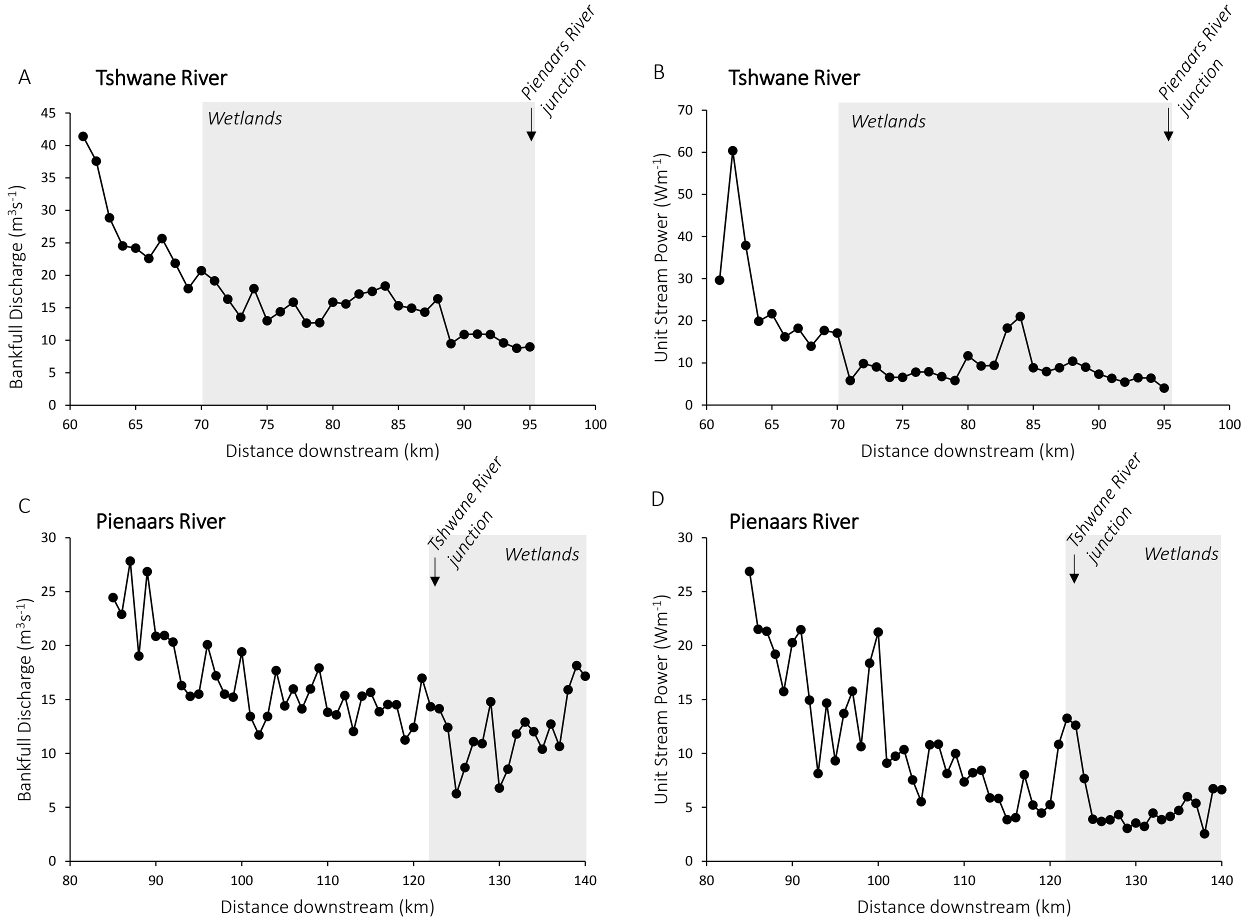

Fig. 12. Downstream change in bankfull discharge and unit stream power along the Tshwane River and Pienaars River where they traverse wide floodplains. (A) bankfull discharge along the Tshwane; (B) unit stream power along the Tshwane; (C) bankfull discharge along the Pienaars; (D) unit stream power along the Pienaars. Discharge and stream power calculations follow Bjerklie (2007), using measurements from satellite imagery to estimate velocity and thus discharge and stream power.

4.4 Channel and floodplain morphology within the Tshwane-Pienaars wetlands

The Tshwane River has a single-thread, prominently leveed meandering channel with local avulsions that lead to the abandonment of ~1-5 km long reaches in the floodplain wetlands (Fig. 5). The main Tshwane channel is sinuous (~1.8) with regular meanders, generally decreasing in width from ~14 to ~9 m. Local cut-offs that have formed oxbow depressions and straight sections of the modern channel are separated by more sinuous reaches, with all channel reaches displaying prominent levees up to 0.6 m above the adjacent floodplain. Following bankfull floods (March 2015), oblique accretion of clay, silt, and fine sand on point bars and counterpoint bars was observed, as was vertical accretion on levees (Fig. 4). Additionally, bank collapse (toppling and slumping) was observed along the Tshwane River along straighter reaches and on concave banks (Fig. 13). The lack of significant trees and shrubs in the riparian vegetation to stabilise the banks likely means that as floodwaters recede the steep, saturated banks collapse under their own weight. Numerous small knickpoints extend from channels into backswamps. Bedload is transported along the base of the active channel and is sequestered in abandoned channels after avulsions or meander cut-offs, but there is no evidence of bedload deposition on the floodplain in the form of crevasse splays.

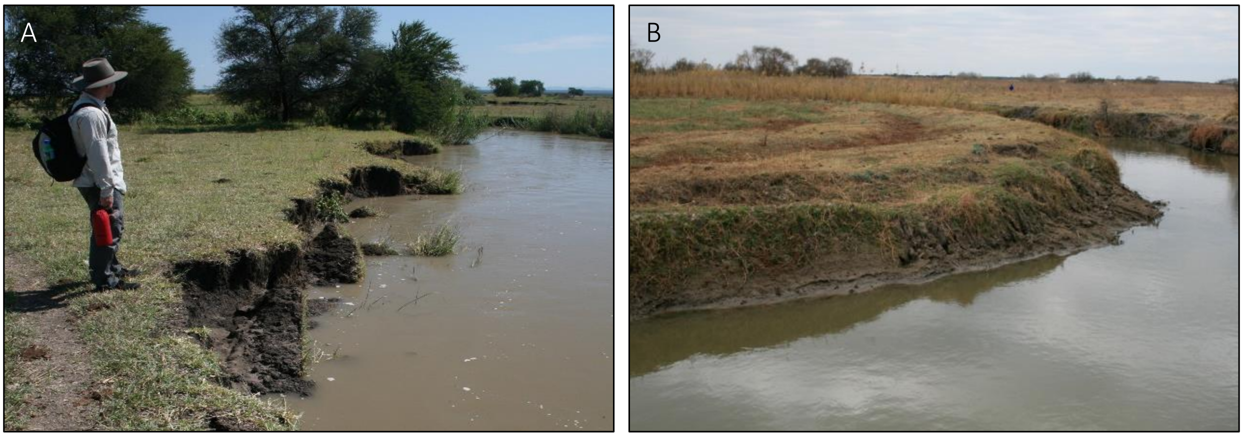

Fig.13. (A) Bank collapse on the outside cut bank of a bend on the lower Tshwane River (looking downstream), (B) Scroll bars on a meander bend of the Pienaars River (looking upstream).

Numerous palaeochannels, backswamps and oxbows occur on the Tshwane River floodplain and the fine-grained nature of floodplain sediment (dominantly clay, silt, and minor sand with bedload sand and minor gravel in the channels) means that overbank floodwater or rainfall does not infiltrate readily and often ponds on the surface. Palaeochannels on the floodplain surface are discrete in terms of their length (from ~1 km to ~5 km) and sinuosity (1.2 to 2.7). The full length and sinuosity of some palaeochannels is subdued due to their age, having been partly or wholly buried by floodplain sedimentation following their abandonment, particularly at their upstream and downstream ends. Occasional knickpoints extend from the channel into adjacent backswamps. Backswamps occur in low points on the Tshwane floodplain, and are common on the western edge of the valley where they are situated in the low depression between the levee of the channel and the adjacent hillslope (Fig. 5). Backswamps also persist towards the confluence with the Pienaars River, where floodwater ponds against prominent levees (~0.5 m high) along a palaeochannel of the Pienaars River (Fig. 14). The alluvial ridge of the Pienaars River promotes overbank flows and backflooding along the lower Tshwane River (Fig. 14).

Fig. 14. High-resolution satellite imagery of the Tshwane-Pienaars River junction taken after a period of flooding (date unknown). Note the pronounced alluvial ridge visible along the abandoned Pienaars River palaeochannel. See Fig. 5 for topographic survey (A-A').

The Pienaars River has a highly sinuous (>2.5), prominently leveed meandering channel with numerous meander cut-offs within the floodplain wetlands (Fig. 5). Many of the larger meanders have distinct scroll bar (ridge and swale) topography associated with lateral migration (Fig. 13). The Pienaars River meanders are regular with numerous oxbow lakes formed by meander cut-offs throughout the wetlands. The trunk channel in the wetlands does not have significant trees and shrubs in the riparian zone (occasional willows) and has steep cut banks that are relatively easily eroded without riparian stabilisation. Upstream of the wetlands, trees are well established in the riparian zone (Fig. 14), likely imposing more stability on the Pienaars River in these reaches.

Despite its larger size, the Pienaars River floodplain has fewer palaeochannels, although numerous oxbows are present (Fig. 5). Backswamps form in depressions associated with the alluvial ridge along the main channel. Backswamps are also found on distal low points of the floodplain, where fine-grained floodplain sediments encourages ponding of floodwater and local rainfall in slight depressions. Numerous knickpoints extend from channels into backswamps, and locally appear to reoccupy meander cut-offs.

Overall, the Tshwane and Pienaars floodplain wetlands are similar in terms of their morphology and mechanisms of channel adjustment. Both are prominently leveed, highly sinuous, meandering rivers displaying evidence of lateral channel adjustment (meander migration, meander cut-off, avulsion) with downstream declines in discharge, stream power, channel size and channel stability.

5. *Discussion*

5.1 Controls on river character, behaviour and wetland formation

The wetlands of the Tshwane and Pienaars Rivers have formed in response to a complex interaction between external geological controls and internal feedbacks related to downstream declines in discharge and stream power. The broadest scale control on river character and wetland development is catchment lithology, which affects floodplain width and therefore accommodation space for unconfined alluvial reaches and floodplain wetlands. For both the Tshwane and the Pienaars Rivers, lithology controls the transition from tightly confined, straight headwater reaches to partly confined, bedrock controlled middle reaches, to the laterally unconfined, fully alluvial reaches with floodplain wetlands. The Pienaars River reverts to a laterally confined, straight channel at the downstream end of the wetlands where Bushveld Complex granites restrict lateral valley widening. This granite acts as a local base level for the Pienaars River upstream (see Fig. 15). The Tshwane River does not have a geological base level control in its lower reaches, however the aggrading Pienaars River acts as the local base level for the Tshwane River with prominent levees that hold back floodwaters coming down the Tshwane River and prolonging inundation of the lower Tshwane River wetlands (Fig. 15).

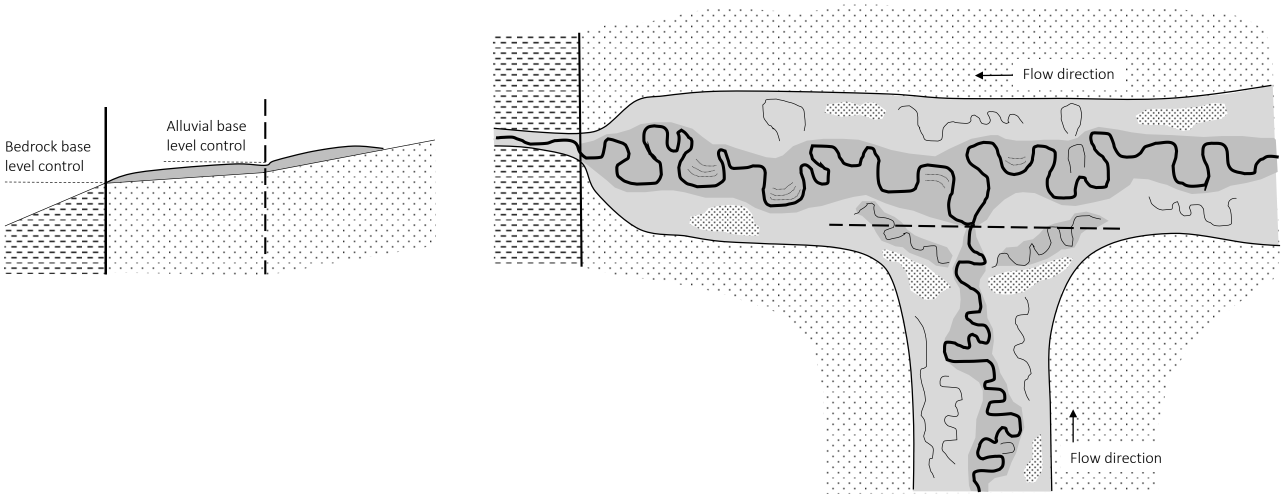

Fig. 15. Schematic illustration of the different base level control on the Tshwane and Pienaars Rivers. The base level for the Pienaars River is the hard granites of the Bushveld Complex, while the base level for the Tshwane River is the aggrading Pienaars River.

Downstream declines in discharge account for the overall morphology and behaviour of both the rivers and their wetlands. In the laterally confined headwater reaches of the rivers, high relative discharge transports a coarse sediment bedload and the channels are characterised by net incision. Once the channel begins to traverse the wide floodplain of the lower alluvial reaches, discharge declines related to transmission losses (seepage through bed and banks, and evapotranspiration as water spreads out over the wide floodplain during floods increasing surface area for evaporation), and a lack of tributary inputs. Downstream channel diminution due to declines in discharge results in net aggradation along alluvial ridges and lateral adjustment is dominated by channel migration and avulsion on these lower reaches.

Topographic surveys show the prominent levees and alluvial ridges of the modern channels and palaeochannels in the Tshwane-Pienaars wetlands, and augering has indicated that all channels are fully alluvial and not grounded on bedrock. This is significant as it indicates net aggradation and sediment storage on the Tshwane and Pienaars floodplains. The development of prominent levees on the Pienaars River has implications for the pattern of flooding along the Tshwane River during large flows. Overbank floodwater coming down the Tshwane River backs up against the Pienaars ridge and increases the extent and duration of overbank flooding on the lower reaches of the Tshwane River. This backflooding effect of the aggrading Pienaars River likely has a significant influence on avulsion and meander dynamics of the lower Tshwane River.

As noted in a number of other South African floodplain wetlands (Tooth *et al*. 2004; Grenfell *et al*. 2008; Keen-Zebert *et al*. 2013; Grenfell *et al*. 2014), lithology exerts a strong control on the formation of local base levels and floodplain wetland formation in upstream reaches. The Bushveld Complex granites downstream of the Tshwane-Pienaars floodplain wetlands are more resistant to erosion than the horizontally-bedded Karoo sandstones, mudstones and shales, thus acting as a local base level for the Pienaars River. This slows down-cutting of the river and promotes valley widening in the reaches upstream. This model of floodplain wetland development was described by Tooth *et al*. (2002). This valley widening has provided the accommodation space for the extensive Tshwane-Pienaars floodplain wetlands, whilst lateral widening of the valley is largely inhibited in the harder bedrock of the Bushveld Complex granites. The Tshwane River, however, does not encounter dolerite or granite and the base level is controlled by the aggradation of the Pienaars River.

Although broad-scale lithology is an important factor controlling river behaviour and wetland formation in the Tshwane-Pienaars catchment, internal feedbacks including downstream declines in discharge and stream power and increasing sediment storage in the alluvial reaches are critically important in determining floodplain wetland characteristics. Downstream declines in discharge and stream power, such as that seen along the Tshwane and the Pienaars Rivers, are common in laterally unconfined, semi-arid rivers throughout southern Africa and also Australia (e.g. Lachlan River, O'Brien and Burne 1994; Macquarie River, Ralph and Hesse 2010; Nyl/Mogalakwena River, McCarthy *et al*. 2011; Gwydir River, Pietsch and Nanson 2011; Blood River, Tooth *et al*. 2014). This downstream trend results in the reduction of sediment transport capacity in the channel, which increases the amount of sediment that is deposited on and stored in the floodplain. Low energy flows and greater sedimentation lead to downstream declining channel size and increased lateral instability, with avulsion becoming more common on the lower reaches. This is particularly the case for the Tshwane River, which displays at least four palaeochannels abandoned by avulsion on the floodplain surface on its lower reaches.

The timing of the transition of the Tshwane and Pienaars Rivers from incisional systems that lowered the gradient and widened the valleys upstream of the Bushveld Complex granite in the Late Quaternary to the present aggradational regime in the Holocene is unknown. An increase in aridity over time may have led to a threshold response where channels contract and the systems became characterised by net aggradation, however without chronological control on the timing of this shift, it is not possible to invoke any particular climatic change.

Altogether, the complex interaction between external and internal controls in the Tshwane-Pienaars system determines the broad-scale changes in river character, behaviour and the development and morphology of wetlands. At a smaller scale, fluvial dynamics such as avulsion control the distribution and extent of channels and wetland environments within the fully alluvial reaches. However, the fluvial mechanisms and rates of fluvial processes (i.e. sediment deposition rates and knickpoint erosion rates) that drive channel change (i.e. development of sinuous channels, meander cut-offs and avulsion) and influence the distribution and extent of these various wetland environments are unknown. This will be the focus of future research (see Larkin *et al*. *in prep* [Chapter 3 in this thesis]).

5.2 Contrasting through-going and floodout style rivers and their wetlands

The floodplain wetlands on the Tshwane and Pienaars Rivers have been the focus of this paper, but other wetlands in the catchment, namely the Itsoseng wetlands on the Soutpanspruit and the Stinkwaterspruit, are characterised by channel breakdown and floodout formation and are therefore morphologically very different. Stinkwaterspruit is a discontinuous, ephemeral tributary of the Tshwane River with a small catchment (~165 km^2 upstream of the floodout zone; Fig. 1 and 16A). Numerous small dams, banks and diversion channels have been constructed along the channel to increase the amount of limited water coming down the channel for use by people living in informal settlements adjacent to the river. Approximately 8 km upstream from its junction with the Tshwane River, the Stinkwaterspruit channel breaks down completely, forming a floodout with numerous straight ephemeral distributary channels (Fig. 16A). Local waterholes occur toward its distal end, but are likely related to a raised bank built for a road. It is likely that water is only transported to the Tshwane River in large floods.

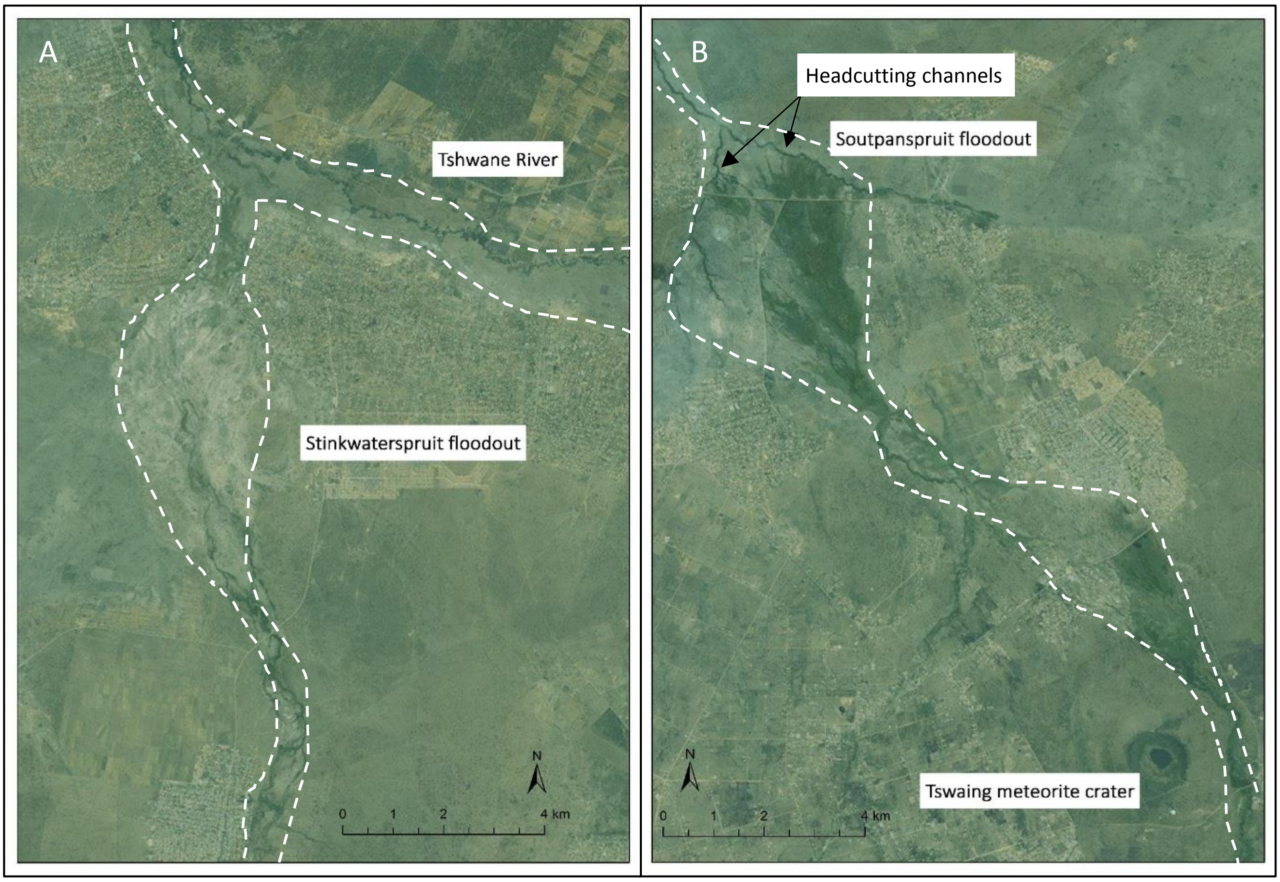

Fig. 16. Images showing floodouts on the (A) lower reach of the ephemeral Stinkwaterspruit, and (B) Soutpanspruit.

Similarly, Soutpanspruit has a small catchment (~120 km^2 upstream of the floodout zone) and the main channel breaks down into a floodout with a series of straight distributary channels, ephemeral marsh channels and unchannelled swamps, collectively known as the Itsoseng wetlands (Fig. 1 and 16B). Sediment deposition in the floodout zone has formed a pronounced fan-shaped lobe that has gradually filled the valley at its widest point (Fig. 16B and 17). The floodout-fan has a slightly steepened downstream end and upstream eroding (headcutting) channels occur at the toe of the floodout. Soutpanspruit breaks down initially on the Bushveld Complex granite bedrock and the Itsoseng wetlands are found atop the Karoo Sequence bedrock. Further sedimentological analysis of the Itsoseng wetlands is required to determine whether floodout formation is related to a break in slope (and associated reduction in stream power and sediment transport capacity) that appears to coincide with the downstream transition from granites to Karoo Sequence sandstones and mudstones (Fig. 17). The floodouts in the Tshwane-Pienaars catchment have similarities with discontinuous ephemeral rivers in semiarid western North America (Schumann 1989; Bull 1997; Merritt and Wohl 2003) and floodouts in eastern Australia (Gore *et al*. 2000).

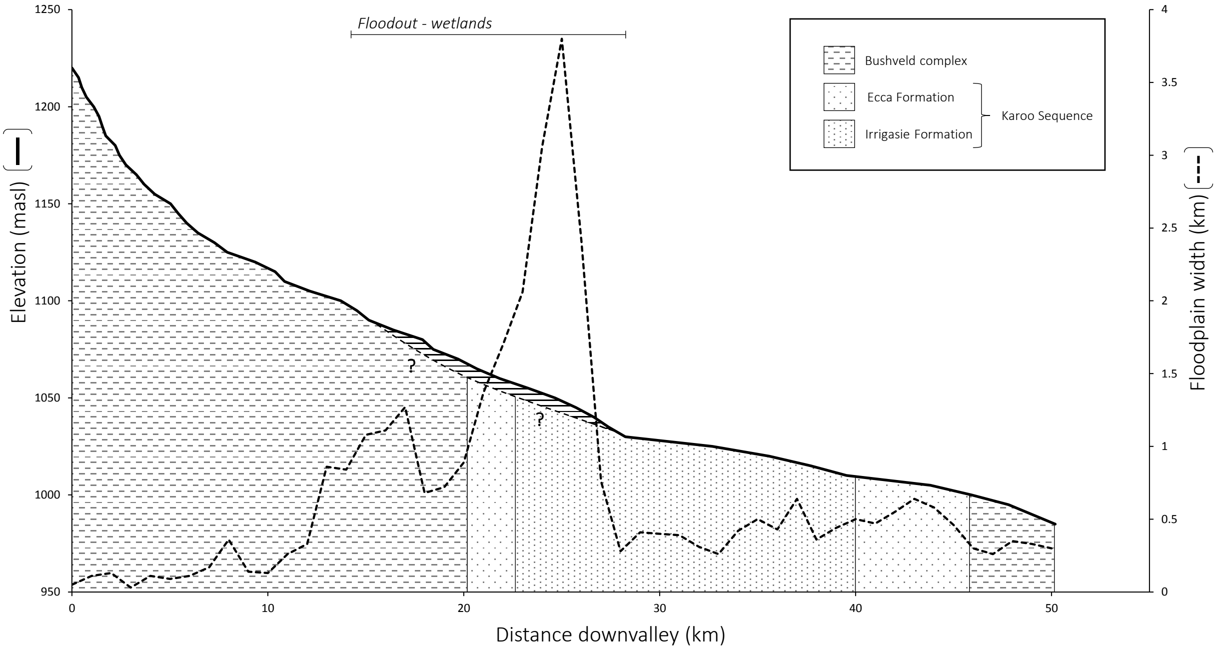

Fig. 17. Longitudinal profile of the Soutpanspruit superimposed onto underlying geology and the relationship with floodplain width (geology generalised from 1:250 000 geological map, series 2528 Pretoria). The location of the floodout is marked by the pale green band. An estimation of the extent of the floodout sediment lobe is given by the horizontal stripes.

The Plat River, which joins the Pienaars River from the north near the town of Kgomo Kgomo (Fig. 1), is ephemeral and does not maintain a channel to its confluence with the Pienaars, but terminates in a series of backswamps. An old palaeochannel that probably represents a period when the Plat maintained a channel as far as its junction with the Pienaars is slowly being infilled (Fig. 5). Upstream of its breakdown, the Plat River is characterised by a discontinuous and sinuous channel with degraded meanders and highly variable width. It is likely that base level rise associated with the aggradation of the Pienaars River has driven the breakdown of the Plat River.

It is intriguing that such a variety of river and wetland types occur in the same catchment with the same external controls (i.e. climate and bedrock). Both the Tshwane and Pienaars Rivers have through-going channels and do not form floodouts, despite having unstable channels and extensive wetlands related to downstream declines in discharge and stream power. However a possible explanation is that the Tshwane and Pienaars Rivers have significantly larger catchment areas and greater discharge to maintain their meandering channels in the alluvial reaches. By contrast, the Stinkwaterspruit and Soutpanspruit do not have sufficient regular discharge to transport sediment and maintain through-going channels, thus leading to sediment deposition and floodout formation in this semiarid environment. Avulsion leads to the formation of new through-going channels in the Tshwane and Pienaars Rivers, while avulsion forms distributary channels in the smaller tributaries leading to channel breakdown. Nonetheless, the Tshwane and Pienaars systems may be close to a threshold between through-going floodplain wetlands and the floodout style wetlands that characterise the Stinkwaterspruit, Soutpanspruit and Plat River tributaries.

5.3 Comparison with other wetlands in drylands

Parallels can be drawn with other southern hemisphere wetlands in drylands. For instance, the Tshwane River wetlands, which have formed due to a combination of internal downstream declines in channel width, increasing channel instability, and backflooding from the Pienaars River, have similarities with the Great Cumbung Swamp on the lower Lachlan River in southeastern Australia and the Nyl/Mogalakwena River in northern South Africa. The Lachlan River breaks down into a terminal swamp because the alluvial ridge of the Murrumbidgee River is an insurmountable barrier that prevents the low-energy, through-going Lachlan River channel from being maintained (O'Brien and Burne 1994). The Nyl/Mogalakwena River breaks down due to the progradation of coarse-grained tributary sediments across the valley which the low-energy Nyl/Mogalakwena River cannot overcome, and hence backponding occurs in wetlands and shallow lakes (McCarthy *et al*. 2011). These examples of trunk-tributary influences on wetland formation cause complete channel breakdown and floodout formation, however the Tshwane River still maintains a channel to the confluence with the Pienaars. The ephemeral Plat River does not maintain a channel to the Pienaars River and disappears in a backswamp, probably because of its small and low-relief catchment on the southern edge of the Springbok Flats that results in very low discharge and stream power and so is easily defeated by the aggrading Pienaars River.

The Tshwane-Pienaars floodplain wetlands have similarities with other southern African wetlands that have meandering trunk streams with numerous oxbow lakes and palaeochannels on the floodplain (Tooth *et al*. 2002, 2007, 2014; Keen-Zebert *et al*. 2013; Grenfell *et al*. 2014). However, the Tshwane-Pienaars channels within the wetlands are not grounded on bedrock as is the case in the Klip, Mooi and Nsonge Rivers in eastern South Africa (Tooth *et al*. 2002, 2004; Keen-Zebert *et al*. 2013; Grenfell *et al*. 2014). The Klip, Mooi and Nsonge Rivers are all located in sub-humid regions with higher rainfall and lower evapotranspiration and are not characterised by downstream declines in discharge. This is a critical difference that explains variations in floodplain formation processes and characteristics between long-term incisional systems such as the Klip, Mooi and Nsonge Rivers, and aggradational systems such as the Tshwane-Pienaars and the Nyl Rivers, in northern South Africa.

Attempts to isolate the influence of climate on wetland forms and processes in drylands of South Africa have been made previously. Grenfell *et al*. (2014) investigated the influence of climate for two different wetlands that have formed on Karoo Sequence sandstones and mudstones upstream of an intrusive dolerite dyke; the Nsonge River in the Drakensberg foothills, eastern South Africa and the Seekoei River in central South Africa. The Nsonge River is located in a sub-humid climate (aridity index 0.59) and is characterised by a through-going, laterally migrating channel that is planing the underlying bedrock with very little vertical aggradation (Grenfell *et al*. 2014). The Seekoei River is located in a semi-arid setting (aridity index 0.18) and is characterised by a discontinuous channel separated by floodouts. Reforming channels occur on the steepened downstream end of the floodout lobe, and avulsion is driven by aggradation on the floodout. Grenfell *et al*. (2014) argue that while the more humid Nsonge River maintains a single through-going channel and slowly recycles floodplain sediment (over millennia) with lateral migration of the channel, higher aridity at the Seekoei River means that seasonal, sporadic flows are not sufficient to maintain a meandering channel and sediment is sequestered for long periods of time in floodouts.

Similarly, different styles of wetlands in the Tshwane-Pienaars catchment (aridity index 0.33) may reflect the fact that the rivers are operating close to a threshold between discontinuous and through-going wetland styles, as influenced by local climate and discharge. The Soutpanspruit and Stinkwaterspruit floodouts and the Tshwane-Pienaars wetlands highlight that threshold responses in marginal environments can cause significant variations in morphology within regions that otherwise have similar lithology, climate and anthropogenic influence. Perhaps the Tshwane River has sufficient energy to maintain a channel, but is closer to a threshold condition for floodout formation than the Pienaars River, while Soutpanspruit and Stinkwaterspruit have crossed the floodout threshold. A further detailed sedimentological and morphological analysis of the Soutpanspruit and Stinkwaterspruit floodouts is required to fully understand the importance of geology, gradient, floodplain width and catchment size on their formation.

5.4 South African climatic gradient and the influence on floodplain wetlands

Using these observations and interpretations, a conceptual model is proposed for the influence of climate on inland wetlands in southern Africa. A strong climatic gradient is found across the African subcontinent, with increasingly arid conditions found to the west and north. The Klip River in eastern South Africa (aridity index 0.42), the Tshwane-Pienaars Rivers (aridity index 0.33) and the Nyl River in northern South Africa (aridity index 0.26) are found along this gradient, with significantly different fluvial geomorphology and mechanisms of wetland formation (Table 4). The Klip River wetlands have formed upstream of a thick, erosion-resistant dolerite sill that encourages lateral migration and valley widening in the reaches upstream (Tooth *et al*. 2007). The Klip River adjusts very slowly (lateral migration rates are <0.2 cm a^{-1}), avulses infrequently (approximately once every 3-6 ka) and long-term net vertical sedimentation rates are effectively zero (Rodnight *et al*. 2005; Tooth *et al*. 2007, 2009). The Tshwane-Pienaars wetlands have a more arid climate than the Klip River, which leads to downstream declines in discharge and stream power driving channel diminution, avulsion and floodplain wetland formation. Tshwane-Pienaars river and wetland morphology indicates that some key differences in long-term processes (or rates of these processes) control the development of the wetlands, although the rates of channel adjustment and avulsion frequency are unknown (but see Larkin *et al*. *in prep* [Chapter 3 of this thesis]). For example, prominent alluvial ridges, alluvial channels that decrease in size downstream, and backflooding of the Tshwane River suggest long-term net aggradation within the system, quite different to the Klip River where the channel remains grounded on bedrock. The Nyl River is different again with the Nyl channel getting progressively smaller downstream before it breaks down in the floodout zone to form unchannelled wetlands. High levels of evapotranspiration in the Nyl system have also caused chemical sedimentation and the formation of salinized islands similar to those described by Dangerfield *et al*. (1998) and McCarthy *et al*. (1998) in the Okavango Delta in Botswana. The Nyl River wetlands are characterised by infrequent avulsion associated with channel breakdown and long-term sediment storage in thick floodplain deposits (maximum depth 35 m). The three wetlands compared in Table 4 support the hypothesis that increasing aridity, with its influence on the variability and total amount of precipitation, is associated with a reduction in the ability of rivers to maintain through-going channels and an increase in the propensity for floodout formation and long-term sediment storage in wetlands. Grenfell *et al*.'s (2014) study also highlights a similar relationship, with the discontinuous, semi-arid, transport-limited Seekoei River and the through-going, sub-humid Nsonge River displaying drastically different morphologies, with the only major variable being the level of aridity.

Future climate projections suggest that total rainfall in southern Africa will either decline or remain constant, but in either instance is likely to become more spatially and temporally variable (Pachauri *et al*. 2014). While the response of fluvial systems to climatic change is hard to predict due to the range of internal threshold responses and autogenic channel and floodplain changes involved, the climatic gradient model proposed and the application of ergodic reasoning may provide an indication of the future developmental pathways of some floodplain wetlands under increasingly arid climates and/or more variable rainfall. That is, currently through-going rivers and their wetlands may become discontinuous under more arid climates, capturing sediment, aggrading and forming floodouts, with significant implications for river and wetland management. Further research into

Table 4. Comparison of the Klip, Tshwane-Pienaars and Nyl River wetlands and the influence of variations in aridity on wetland type and geomorphology.

	Wetland	Local climatic setting (MAP, MAE [a] and aridity index [b])	Key factors influencing development of floodplain wetlands	Avulsion style/frequency	Geomorphological features and processes associated with the wetlands	Key references and other example wetlands
Through-going wetlands to floodout style wetlands along a climatic gradient in South Africa ↓	Klip River, Free State, South Africa	Sub-humid (~800 mm, ~1890 mm; aridity index – 0.42)	Wetlands formed upstream of erosion-resistant dolerite sill, which resists down-cutting and encourages lateral migration and floodplain wetland formation upstream.	Incisional Infrequent	Mixed bedrock-alluvial through-going channel, oxbows, backswamps, palaeochannels, meandering channels, scroll bars, muted levees and alluvial ridges	Tooth *et al*. 2002, 2004, 2007 Nsonge River, eastern SA – Grenfell *et al*. 2014
	Tshwane-Pienaars, North West Province, South Africa	Semi-arid (~585 mm, ~1750 mm; aridity index – 0.33)	Pienaars wetlands formed upstream of resistant granite bedrock. Downstream declines in discharge and stream power promote channel diminution and instability, sediment accumulation and wetland formation.	Incisional Frequent (see Larkin *et al. in prep* [chapter 3 of this thesis])	Fully alluvial through-going channel, oxbows, backswamps, palaeochannels, prominent levees and alluvial ridges, floodouts on some tributaries	This study
	Nylsvlei, Northern Province, South Africa	Semi-arid (~623 mm, ~2400 mm; aridity index – 0.26)	Tributary fan sediments prograding across the Nyl floodplain encourage ponding and floodout formation upstream of the blockage. Downstream declines in channel size and sediment transport efficiency predispose the Nyl to channel breakdown.	Infrequent avulsion associated with floodouts and channel breakdown	Downstream declines in channel size and eventual floodout formation, backswamps, islands formed by chemical sedimentation resulting from high evapotranspiration	Tooth *et al*. 2002; McCarthy *et al*. 2011 Seekoei River, central SA – Grenfell *et al*. 2014

[a] MAP – mean annual precipitation, MAE – mean annual potential evapotranspiration
[b] Aridity index given by MAP/MAE (UNEP 1992)

floodplain wetland morphology throughout southern Africa will improve our understanding of the influence of climate on river character, behaviour and wetland styles.

6. Conclusion

The findings from the Tshwane and Pienaars Rivers and their floodplain wetlands demonstrate the complex interactions between lithology, downstream declines in discharge and stream power, and backflooding as the key controls on their development. Broadly, base level for the Pienaars River is primarily controlled by erosion resistant bedrock, while base level for the Tshwane River is controlled by aggradation of the Pienaars River floodplain. Avulsion and lateral channel migration dominates river behaviour within the floodplain wetlands of both systems. It is clear that a range of factors influences the development of wetlands in drylands, but the findings from this study enhance our understanding of systems that are characterised by net aggradation and provide a contrast with several other previously studied systems in South Africa. The proposed model of climatic influence on through-going channels and floodplain wetland morphology has implications for wetland management under future drier, more variable climates in southern Africa. Recognition and understanding of the factors responsible for the development and characteristics of floodplain wetlands is crucial in developing effective management strategies for these dynamic features. Furthermore, the specific mechanisms and timescales of river avulsion within floodplain wetlands require future investigation.

7. Acknowledgements

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8. References

See combined reference list at the end of the thesis.

CHAPTER 3 – MECHANISMS AND TIMESCALES OF AVULSION

3.1 Purpose: This chapter presents original research that has been undertaken within this MRes year. The chapter provides an introduction, methods, results and discussion related to the mechanisms and timescales of channel avulsion in the Tshwane River, South Africa. The findings presented in this chapter are central to this thesis and build upon the findings from Chapter 2 by investigating the factors that drive avulsion and the relationship between the timing of avulsion, avulsion frequency and sedimentation rates, which are commonly stated to have a positive correlation, yet lack well-constrained data. This chapter will address aims iv, v, vi, vii, and viii highlighted in the introductory chapter, using a combination of historical channel change analysis and optically stimulated luminescence dating of palaeochannel deposits.

3.2 Format: In accordance with the Macquarie University policy for higher degree research thesis by publication[2], this chapter has been written for submission to a peer-reviewed journal (*The Holocene*). Repetition and any referencing and stylistic inconsistencies have minimised to facilitate the thesis examination process. Supplementary material referred to in the paper is provided in appendices at the end of the thesis, and is intended to become supplementary material provided online in the published version of this paper. References from all chapters (including the papers) are combined in one reference list provided at the end of the thesis.

3.3 Author contributions: The author contributions for this research and the paper are as follows:

Zacc Larkin carried out fieldwork and sampling with T.R. and S.T., conducted mapping, analysed and interpreted data, designed and drafted all figures and tables, and wrote and edited the paper.

Tim Ralph developed the study with S.T., carried out fieldwork and sampling with Z.L. and S.T., designed some figures with Z.L., provided comments on the paper, and supervised Z.L. in the research.

Stephen Tooth conceived of and designed the study, carried out fieldwork and sampling with Z.L. and T.R., provided comments on the paper, and co-supervised Z.L. in the research.

Geoff Duller undertook OSL analysis and assisted Z.L. with data interpretation, analysis and presentation of results for the paper.

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[2] The Macquarie University policy for thesis by publication states that a thesis may include a relevant paper or papers that have been published, accepted, submitted or prepared for publication for which at least half of the research has been undertaken during enrolment. The papers should form a coherent and integrated body of work. The papers are one part of the thesis, rather than a separate component (or appendix) and may be single author or co-authored. The candidate must specify their contribution and the contribution of others to the preparation of the thesis or to individual parts of the thesis in relevant footnotes/endnotes. Where a paper has multiple authors, the candidate would usually be the principal author and evidence of this should appear in the appropriate manner for the discipline. MQ Policy: http://www.mq.edu.au/policy/docs/hdr_thesis/policy.html

MECHANISMS AND TIMESCALES OF RIVER AVULSION IN A RAPIDLY ADJUSTING FLOODPLAIN WETLAND: TSHWANE RIVER, NORTH WEST PROVINCE, SOUTH AFRICA

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ABSTRACT

River avulsion is generally accepted to be a key characteristic of aggrading fluvial systems, and avulsion seems to occur more frequently in rivers with greater vertical sedimentation rates. However, there is a lack of well-constrained field data from rivers around the world to support this hypothesis. The Tshwane River in semiarid, northern South Africa is characterised by a single through-going channel that traverses floodplain wetlands, while numerous palaeochannels exist on the floodplain. Historical aerial photograph analysis and optically stimulated luminescence dating of the modern river and palaeochannel deposits reveal three reach-scale avulsions over the last 650 years, equivalent to 4.6 avulsions ka^{-1}. Local sedimentation rates up to ~11 mm a^{-1} occur adjacent to channels, which promotes the formation of low levees and alluvial ridges with pronounced cross-floodplain gradients. Avulsion of the Tshwane River occurs autogenically during meander belt development in response to a reduction in sediment transport capacity. At the catchment scale, downstream declines in discharge and stream power result in downstream diminution of the main channel and an increase in the propensity for avulsion. Locally, increases in channel sinuosity and greater in-channel and near-channel sedimentation cause reductions in channel slope and fluvial efficiency. Concomitant increases in floodplain slope away from the channel due to levee sedimentation encourages overbank flow away from the main channel, and the formation of a new channel starts as an incisional headcut which retreats until the failing reach is short-circuited and abandoned. The coupled sedimentation-erosion mechanism and rapid frequency of avulsion on the Tshwane River demonstrates the importance of fluvial processes and thresholds leading to avulsion at the more rapidly adjusting end of the fluvial spectrum in drylands.

Keywords: chronology of avulsion, sedimentation rate, sinuosity threshold, wetlands in drylands

1. *INTRODUCTION*

Avulsion is the shift of a river course to a new position on the floodplain, and is one of the most important processes by which rivers form new channels and adjust laterally across floodplains (Smith *et al*. 1989; Makaske 2001, Makaske *et al*. 2002; Slingerland and Smith 2004; Makaske *et al*. 2012). The original channel may be abandoned due to avulsion, or may continue to operate as a distributary or anastomosing branch of the river. Along with lateral migration, aggradation and incision, avulsion is one of the key processes in the development of floodplain wetlands and deltas (Tooth and McCarthy 2007). The style and frequency of avulsion has significant implications for the distribution of water and sediment on floodplains and influences ecological processes and human land use and settlement (Slingerland and Smith 2004; Ralph *et al*. 2015).

Despite the importance of avulsion in rivers, the key controls on, and mechanisms of, different styles of avulsion are debated. The underlying mechanisms and ultimate triggers for avulsion differ in different settings (Bryant *et al*. 1995; Mackey and Bridge 1995; Schumm *et al*. 1996; Slingerland and Smith 1998; Tornqvist and Bridge 2002; Aslan *et al*. 2005; Jerolmack and Mohrig 2007; Stouthamer and Berendsen 2007), while the frequency of avulsion also varies in different systems (Makaske 2002; Tooth *et al*. 2007). For example, in cold and wet landscapes, progradation of floodplain splays and prolonged floodplain inundation and associated sedimentation can cause avulsion (Morosova and Smith 2000; Slingerland and Smith 2004; Assine 2005). There are also a number of factors that have been shown to influence avulsion in semi-arid and arid landscapes (drylands), including sedimentation and a lack of floodplain confinement (McCarthy *et al*. 1992; Ralph and Hesse 2010; Makaske 2012), barriers to flow (Makaske *et al*. 2002), substrate composition (Aslan *et al*. 2005), vegetation and biota (e.g. hippopotamus trails, McCarthy *et al*. 1992; and beaver dams, Polvi and Wohl 2013).

In aggrading river systems, avulsion can be triggered by the build-up of natural levees or alluvial ridges near the channel, which increases the cross-floodplain gradient (i.e. increases slope of the potential new channel course) and promotes overbank flow away from the channel (Brizga and Finlayson 1990; Tooth and McCarthy 2007; Tooth *et al*. 2007; Ralph and Hesse 2010). When these overbank flows are associated with significant crevasse splay deposits on the floodplain, they are known as progradational avulsions (Slingerland and Smith 2004). A channel network forms in the crevasse splay deposits, but eventually a single channel develops through the splay deposits and extends downstream. The downstream extension of the new channel is made possible by the favourable cross-floodplain gradients and further deposition along the new course of the channel (Slingerland and Smith 2004). This style of avulsion has been noted in various rivers around the world, and is generally associated with moderately to rapidly aggrading systems, particularly in humid regions such as the Rhine-Meuse delta and the Upper Columbia River (Makaske *et al*. 2002).

Avulsion can also occur when overbank flows returning to a river erode into the channel banks forming a knickpoint. Known as an incisional avulsion, the knickpoint retreats upstream, cutting a new channel in the floodplain, which may cause a section of the main channel to be abandoned if and when it reconnects with another section of the main channel upstream (Makaske 2001; Tooth *et al*. 2007). This style of avulsion is most commonly identified in rivers with very low vertical sedimentation rates, such as the Klip River in eastern South Africa (Tooth *et al*. 2007) and Cooper Creek in east-central Australia (Knighton and Nanson 1993). A third style of avulsion, known as reoccupational avulsion (Slingerland and Smith 2004), occurs when a new channel reworks or reoccupies an abandoned channel on the floodplain. Reoccupational avulsions have been noted on the aggrading lower Mississippi River where sandy palaeochannel sediments promote preferential scour of old channels during floods (Aslan *et al*. 2005). Often, a large magnitude flood can trigger avulsion, but the river must be near an avulsion threshold (primed) for avulsion to occur.

The underlying cause of avulsion often relates to preferential floodplain gradients. Jones and Schumm (1999) identify three scenarios that lead to an increase in the potential avulsion course slope relative to the existing channel slope. The first occurs when the potential avulsion course slope increases while the slope of the existing channel does not change. The second occurs when the potential avulsion course slope does not change but the existing channel slope declines. The third occurs when there is both a reduction in the existing channel course slope and an increase in the potential avulsion course slope (Jones and Schumm 1999). Decreases in existing channel slope can occur as sinuosity increases, or due to tectonic uplift or faulting perpendicular to the direction of the valley, or due to in-channel sedimentation (McCarthy *et al*. 1992; Smith *et al*. 1997). Conversely, increases in the slope of the potential avulsion course can occur by levee and alluvial ridge development or faulting parallel to the direction of the valley, which both act to steepen the cross-floodplain gradient relative to the downstream gradient (Brizga and Finlayson 1990). Various other factors, such as log jams, ice jams, vegetation encroachment within the channel or another form of channel blockage can act as triggers for avulsion (McCarthy *et al*. 1992; Ralph *et al*. 2015), however, a gradient advantage down the potential avulsion course is usually required for avulsion in most systems (Jones and Schumm, 1999).

It is generally accepted that systems with higher vertical sedimentation rates will have higher avulsion frequencies, while systems with negligible vertical sedimentation rates have lower avulsion frequencies. This hypothesis hinges on the fact that sedimentation is generally concentrated within the channel, or near the channel, forming levees and/or alluvial ridges that increase the cross-floodplain gradient, thereby increasing the gradient advantage for a newly forming channel. However there is a lack of well-constrained field data to quantify the relationship between sediment aggradation rate and avulsion frequency (Tooth *et al*. 2007). More research is required to provide well constrained chronologies of channel change that can be used to test the hypothesis that sedimentation rate and avulsion frequency are positively correlated, especially in rivers and wetlands in drylands.

The Tshwane River in semi-arid, northern South Africa is characterised by downstream declines in discharge and stream power and avulsion is the dominant form of lateral adjustment in its lower reaches where significant floodplain wetlands occur (Larkin *et al*. *in prep* [Chapter 2]). This study aims to: (i) develop a robust chronology of avulsion for the Tshwane River, (ii) quantify floodplain sedimentation rates, (iii) determine whether avulsion frequency and sedimentation rates are correlated, (iv) determine whether sedimentation rates influence avulsion style, and (v) discuss the roles of allogenic (e.g. climate) and autogenic (e.g. internal sediment dynamics) drivers of avulsion. Understanding mechanisms and timescales of avulsion in the Tshwane River is important because effective river and wetland management requires a solid knowledge of the processes driving change and the timescales associated with these processes.

2. Regional Setting and Study Sites

The Tshwane River is located on the semi-arid bushveld of northern South Africa, in the upper Crocodile-Limpopo River system (Fig. 1). The confined headwaters of the Tshwane River begin in the Magaliesberg at an elevation of around ~1 470 m.a.s.l., before flowing north through the heavily urbanised city of Pretoria in Gauteng Province. Downstream of Hammanskraal, the valley becomes unconfined and the Tshwane joins the Pienaars River in rural North West Province. The lower Tshwane River has extensive floodplain wetlands in its unconfined alluvial reaches, while wetlands also occur nearby on the Pienaars River (total area of Tshwane and Pienaars floodplain wetlands is ~55 km^2) (Fig. 1). The geology of the Tshwane catchment consists of Pretoria Group shales and quartzites and Bushveld Complex granites in the headwaters, with sandstones, mudstones and shales of the Karoo Sequence (Ecca and Irrigasie Formation) in the lower reaches.

The South African bushveld is characterised by strongly seasonal rainfall with distinct wet (November through March) and dry (April through October) seasons. Mean annual precipitation in the Tshwane catchment is ~585 mm, falling mostly in the wet season during convective thunderstorms whilst mean annual potential evapotranspiration is ~1750 mm (Working for Wetlands 2008; GDARD 2011). Flow in the Tshwane River is perennial, but strongly seasonal, with high wet season flows (>60 $m^3 s^{-1}$) and low dry season flows (<4 $m^3 s^{-1}$) (DWA Hydrological Services 2015). The floodplain of the Tshwane River is inundated regularly during the wet season, while low flows are confined to the main channel during the dry season, when backswamps, oxbows and palaeochannels on the floodplain slowly desiccate. Palaeochannels exist as slight depressions with levees on the floodplain surface, infilled to varying degrees, while wetlands fill the accommodation space between the channels.

The Tshwane River catchment is dominated by savannah grassland and open woodland. The dominant vegetation in the wetlands is grass (e.g. *Setaria incrassate, Ischaemum afrum*) and occasional willow trees (*Salix* spp.) occur on the channel banks, with reeds (*Phragmites spp.*) and bulrushes (*Typha spp.*) growing densely in the backswamps. Water lilies occupy open standing water in oxbows and palaeochannels. Aside from occasional willows, which remain localised despite their increase in abundance since the 1950s, there are very few shrubs or trees in the riparian zone. In the reaches upstream and downstream of the wetlands, dense riparian vegetation (trees and shrubs) flanks the channel. The drier hillslopes support larger shrubs and trees (e.g. *Senegalia mellifera, Acacia tortilis, Colophospermum mopane*) that can tap into deep groundwater.

The Tshwane River floodplain wetlands are characterised by a prominently leveed, single-thread, meandering channel with highly sinuous sections (up to ~3) separated by straighter reaches (sinuosity <1.2) (Fig. 1). The Tshwane River floodplain wetlands have formed due to the complex interaction between external lithological controls, internal downstream declines in discharge and stream power, and aggradation of the adjacent Pienaars River (Larkin *et al*. *in prep* [chapter 2]). Transmission losses to the floodplain and a lack of tributary input results in a downstream trend of declining discharge and stream power, particularly pronounced when the channel starts to traverse a relatively wide floodplain (~1-2 km). This leads to a reduction in sediment transport capacity which, coupled with the backflooding effect of the aggrading Pienaars River, causes a reduction in channel size as more sediment is sequestered in the channel and on the floodplain, which in turn leads to channel instability and avulsion. Despite a good understanding of the catchment-scale conditions and context for avulsion (Larkin *et al*. *in prep* [chapter 2]), the rates of channel aggradation and avulsion frequency are not known.

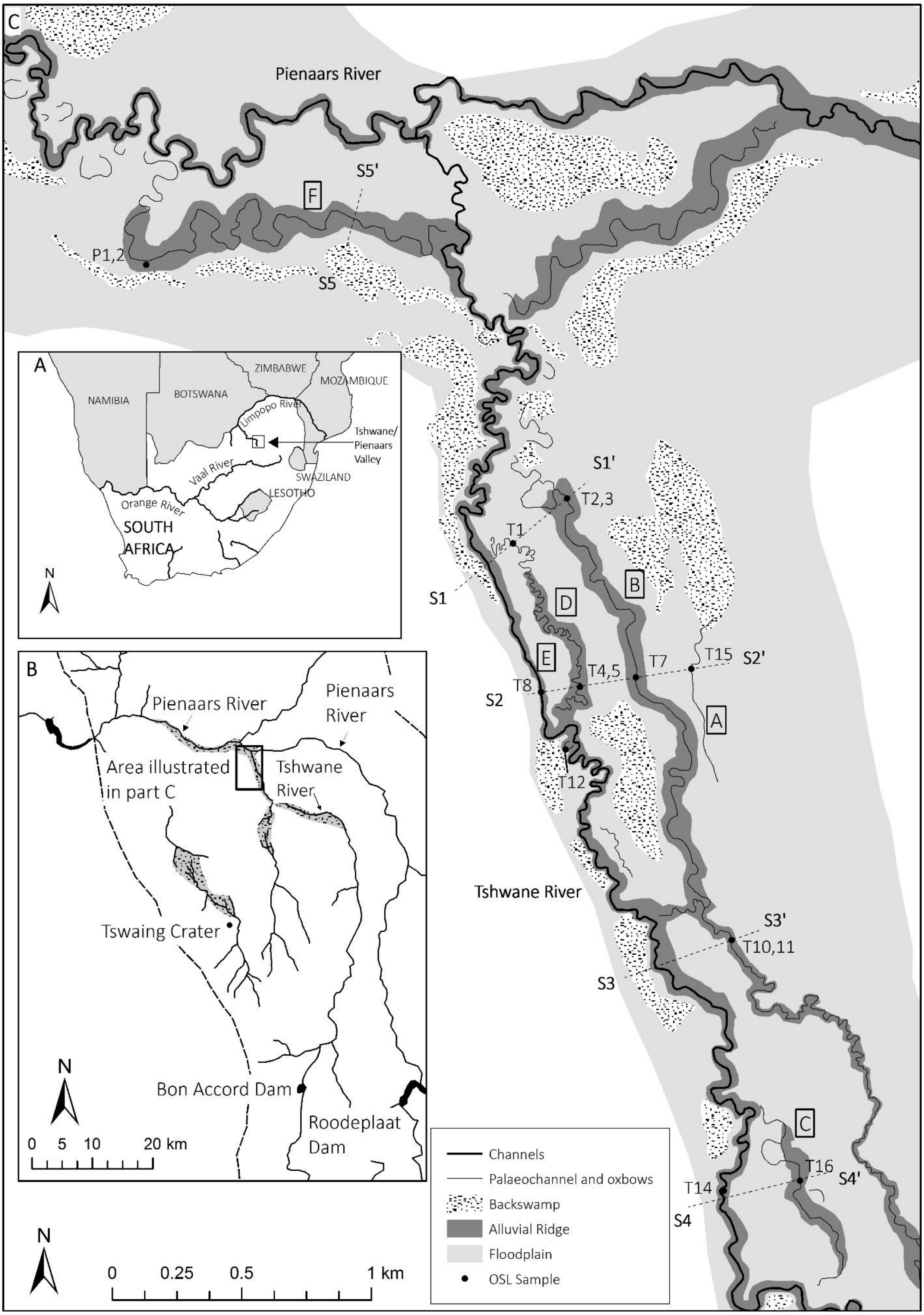

Fig. 1. (A) Location of the Tshwane and Pienaars Rivers, northern South Africa. (B) The Tshwane and Pienaars catchment with the study reach location. (C) Geomorphic map of the Tshwane River floodplain wetlands showing the 13 OSL sample locations along four surveyed transects (S1-S4), and a further two samples that were taken from an abandoned alluvial ridge on the Pienaars River floodplain (near S5).

The lower Tshwane River transports a mixed load with fine-grained suspended sediment (~0.8 g L^{-1}) and medium-coarse sandy bedload. The lower Tshwane River floodplain generally consists of structureless fine-grained medium to heavy clays. There are no crevasse splay deposits on the floodplain anywhere in the Tshwane River wetlands. The study sites on the lower Tshwane River are located along four transects across the floodplain, with one transect across the Pienaars River floodplain (Fig. 1).

3. METHODS

The morphology of the Tshwane River and its floodplain wetlands were investigated using aerial photography (from 1950, 1972, 2005 and 2012) to create detailed geomorphic maps and a historical time series of change for the last 65 years. Aerial photographs have been shown to be useful for developing an understanding of dynamic channel resulting from to avulsion in wetlands in drylands throughout the latter half of the 20th century (e.g. Ralph *et al*. 2015).

Four distinct palaeochannels were identified and mapped on the lower Tshwane floodplain surface (Fig. 1). Detailed topographic surveys of the modern channel, floodplain and palaeochannels were undertaken using an automatic level. Eleven palaeochannel samples, one oxbow and three levee samples were collected for optically stimulated luminescence (OSL) dating from the Tshwane and Pienaars systems (see Fig. 1 for OSL sample locations). Palaeochannel samples (T1-T5, T7, T10, T11, T15, T16) were collected by hand augering through clay-rich channel infill until the uppermost medium-coarse bedload sands were reached. A ~30 cm length metal tube ~7 cm in diameter was then fitted to the end of the auger extension rods. The metal tube was pushed into the bedload sands at the base of the auger hole, and sediment samples retrieved without exposure to sunlight, as described by Rodnight *et al*. (2006) and Munyikwa *et al*. (2011). The one oxbow sample was collected by digging through ~45 cm of infill sediment with a spade and an OSL sample tube was hammered horizontally into the bedload sand. These bedload sand samples are representative of the last time that the channels were actively transporting bedload and thus OSL dating of these samples can provide a maximum age of channel abandonment. Sample T8 was collected from levee deposits in a bank exposure on the modern channel by hammering a steel tube horizontally into the face. Samples P1 and P2 on the levee of the abandoned Pienaars River palaeochannel were collected with a percussion coring system which was capable of extracting intact 1 m sections of sediment to a depth of ~5 m. These cores and all other OSL samples were not exposed to sunlight, and wrapped in thick black plastic for transport, and subsequently sub-sampled in subdued red-light conditions.

OSL samples were processed in the Aberystwyth Luminescence Research Laboratory at Aberystwyth University. Standard methods were used to isolate the 125-212 µm quartz fraction of sediment, to dissolve carbonates and organics in acid (hydrochloric acid and hydrogen peroxide, respectively), to remove heavy minerals and feldspars by density mineral separations, and to etch grains with 40 % hydrofluoric acid to remove the alpha irradiated outer grain surface (see Aitken 1998).

Prior to single-grain OSL analysis, a dose response and preheat test was performed to determine the optimum thermal treatment for the samples. All samples were measured with a preheat temperature of 220 °C for 10 seconds and a cut-heat of 160 °C for 10 seconds. At least 800 grains were analysed and individual grains were accepted based on criteria outlined in Jacobs *et al*. (2006), which are: recycling ratio within 10 %, test dose error less than 10 %, and Tn signal greater than three times the standard deviation of the background. After application of these criteria, between 135 and 495 individual equivalent dose (D_e) values were determined using Risø Analyst software (Duller 2007). All samples display D_e distributions that indicate heterogeneous bleaching prior to burial (see Appendix 1 for radial plots). As such, the unlogged minimum age model was used to calculate D_e values for each sample (Galbraith *et al*. 1999).

The environmental dose rate was calculated by thick source alpha counting and Gieger-Muller beta counting of dried and milled material taken from the ends of sample tubes, which is representative of sediment surrounding the OSL sample. The cosmic ray contribution was estimated from the data given by Prescott and Hutton (1994), taking into account altitude, geomagnetic latitude and thickness of sediment overburden. Water content was kept constant for palaeochannel and oxbow samples at 25±5 %, and at 15±5 % for levee samples, which dry out more readily and regularly than samples in the base of infilling channels. Equivalent dose is divided by the dose rate to derive an OSL age estimate (Huntley *et al*. 1985; Aitken 1998).

4. Results

4.1 Historical channel change in the Tshwane floodplain wetlands

The array of palaeochannels and cut-offs on the Tshwane River floodplain surface indicate that there has been significant adjustment of the river in the past due to avulsion. The patterns of channel change over the past ~65 years from aerial photographs highlights this dynamic nature and gives an indication of the rate at which adjustment of the Tshwane River occurs (Fig. 2). The most dramatic and detectable form of lateral channel adjustment is avulsion. Meander bend cut-off is seen throughout the historical period, but rates of channel migration cannot be accurately calculated due to the low-resolution imagery. Between 1950 and 1972, a major incisional avulsion caused the abandonment of a highly sinuous (~2.7) ~1 km reach of the main channel and formed a new, much straighter (sinuosity ~1) channel course (Point [ii] in Fig. 2B). Prior to 1950, a backswamp existed to the west of the main channel (Point [ii] in Fig. 2A). The knickpoint responsible for abandoning the sinuous reach between 1950 and 1972 retreated a total distance of 760 m at a minimum rate of 34.5 m a^{-1} (if it took 22 years to complete the avulsion), or at a maximum rate of 760 m a^{-1} (if the avulsion was complete within a single year). As the knickpoint incised and widened, the backswamp desiccated. Once the knickpoint joined the main channel upstream, to the south, the original channel appears to have been abandoned very quickly, and began infilling with fine sediment from its upstream and downstream ends, as indicated by the loss of channel definition at both ends. This most recent avulsion has effected a net shortening of the Tshwane River's length by >1 km and resulted in a local steepening of the channel (Fig. 3). The gradient of the new channel is roughly the same as the local floodplain gradient (~0.0009 m m^{-1}) due to its straightness and its alignment parallel with the valley.

Between 1972 and 2005, several meander bends were also cut-off (for example, points [i] and [iii] in Fig. 2A and 2C, respectively). After detailed analysis of the historical photos, a total of 14 meander bends were cut-off during this period (equivalent of ~1 cut-off every 4.5 years on average), but only cut-offs at points [i] and [iii] (Fig. 2A and 2C) are easily visible at this scale. A contemporary knickpoint (Fig. 2D; Fig. 4C) is developing to the south of the 1950-1972 avulsion. The knickpoint threatens to retreat upstream through a reed bed located between the levee of the modern channel and the hillslope. Further high resolution monitoring will be required to establish the rate of headcut retreat and the timing of potential future avulsion.

As well as avulsion, the 14 separate meander cut-offs between 1950 and 2012 caused significant changes in sinuosity along the ~3.5 km lower reach of the Tshwane River. Despite a major reduction in sinuosity in the avulsive reach, the reaches upstream and downstream of the avulsive reach experienced a net increase in sinuosity during the historical period (from 1.16 to 1.35 and 1.25 to 1.61, respectively; Fig. 5). These sinuosity changes are a result of lateral channel migration (i.e. the extension and translation of meander bends) that more than compensated for cut-off development. Changes in sinuosity are a proxy for rates of lateral channel migration and indicate rapid rates of lateral channel migration. The recently avulsed reach, however, increased in sinuosity only very slightly from 1.03 to 1.06 between 1972 and 2012. Around 94 km downstream, sinuosity varied between 1950 and 2012 but there was no net change in its sinuosity which remained quite high at ~3 (Fig. 5).

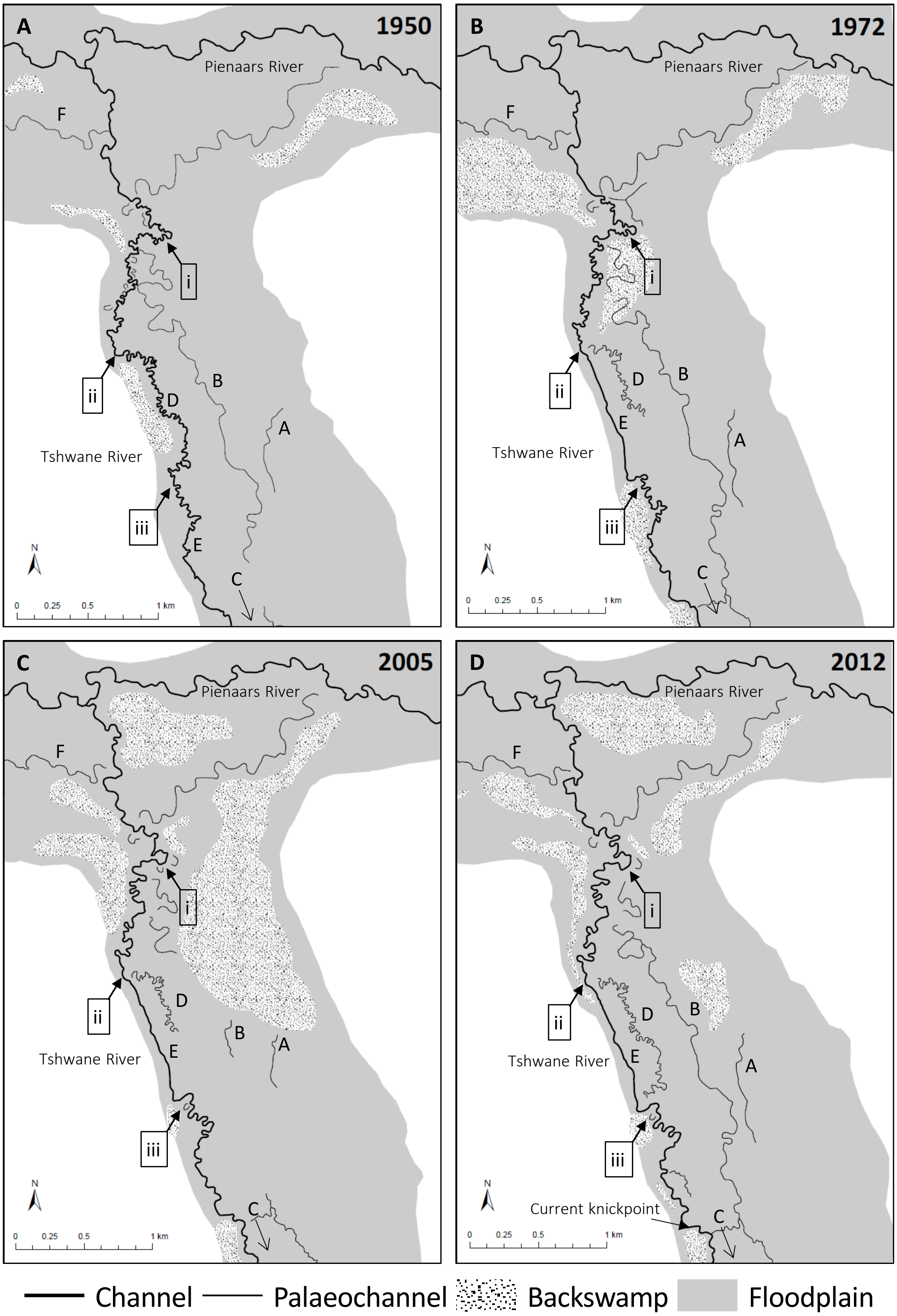

Fig. 2. Historical time series maps of the Tshwane River and floodplain wetlands derived from aerial photography from (A) 1950, (B) 1972, (C) 2005 and (D) 2012. Flow direction is from south to north. Channel belts are labelled from A-F. Palaeochannels on the floodplain are not clearly visible in all aerial photographs owing to tonal contrast, vegetation and water levels. The location and extent of backswamps varies vastly between each frame of the time series due to the distribution of water at the time the photo was taken, with photos taken during the wet season likely to show a much larger extent of swamps than photos taken during the dry season. Black arrows are shown in the same location of each frame to highlight some of the more obvious adjustments of the river between 1950 and 2012 (avulsion or meander cut-off).

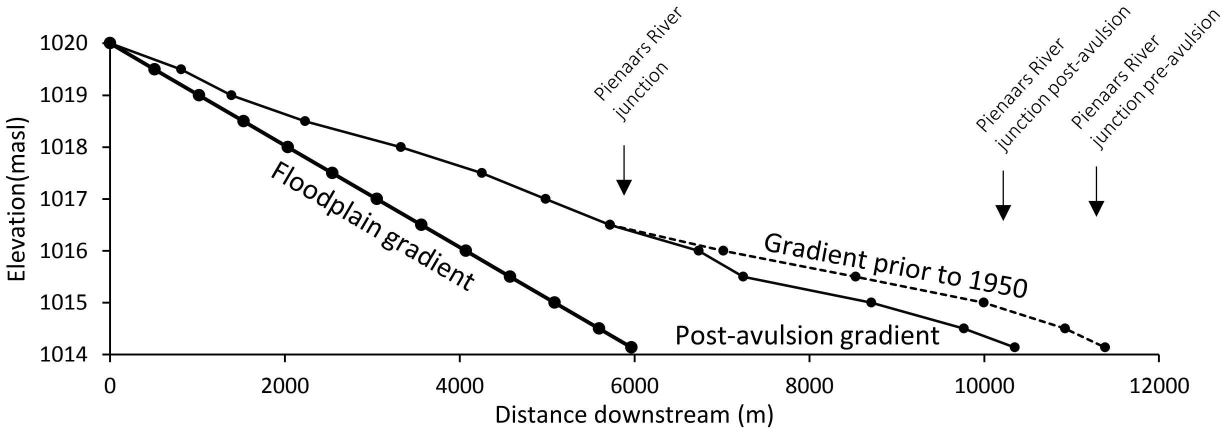

Fig. 3. Graph of downstream channel gradient, highlighting the local steepening caused by the 1950-1972 avulsion. Channel gradient is lower than floodplain gradient due to the sinuosity of the channel. Note that valley gradient has been assumed to be even between topographic contours 1020 m.a.s.l. and 1015 m.a.s.l. and extrapolated to 1014 m.a.s.l. – it is likely that there are local variations but it is not possible to account for these at this scale.

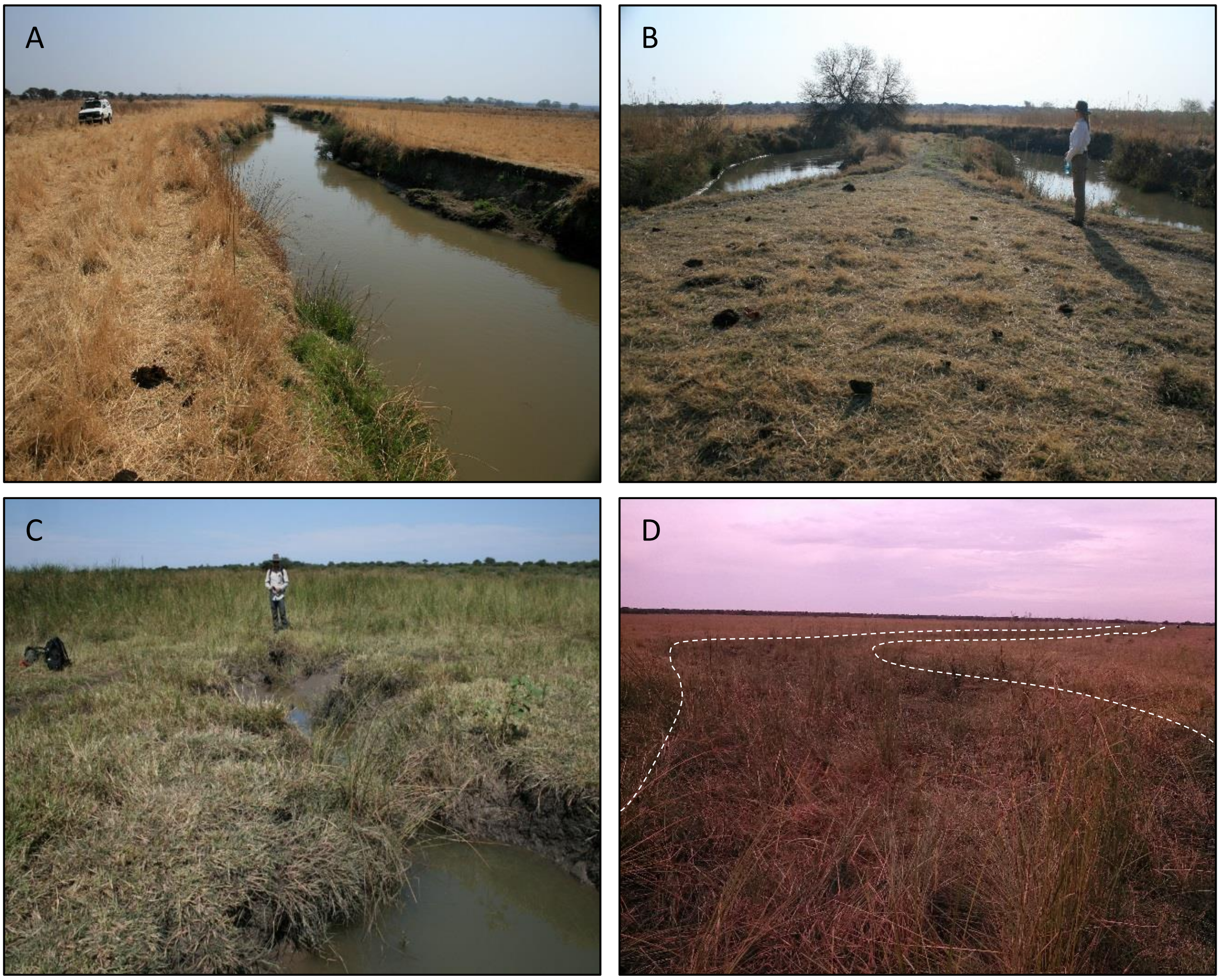

Fig. 4. (A) Straight reach of the Tshwane River, looking downstream. (B) Tight meander bend on a sinuous reach of the Tshwane River; flow from left to right. (C) Current knickpoint threatening adjacent backswamp and reed bed (See Fig. 2 for location), photo looking south-southwest, with flow towards the camera. (D) Infilling palaeochannel on the Tshwane River floodplain (channel belt C; looking upstream).

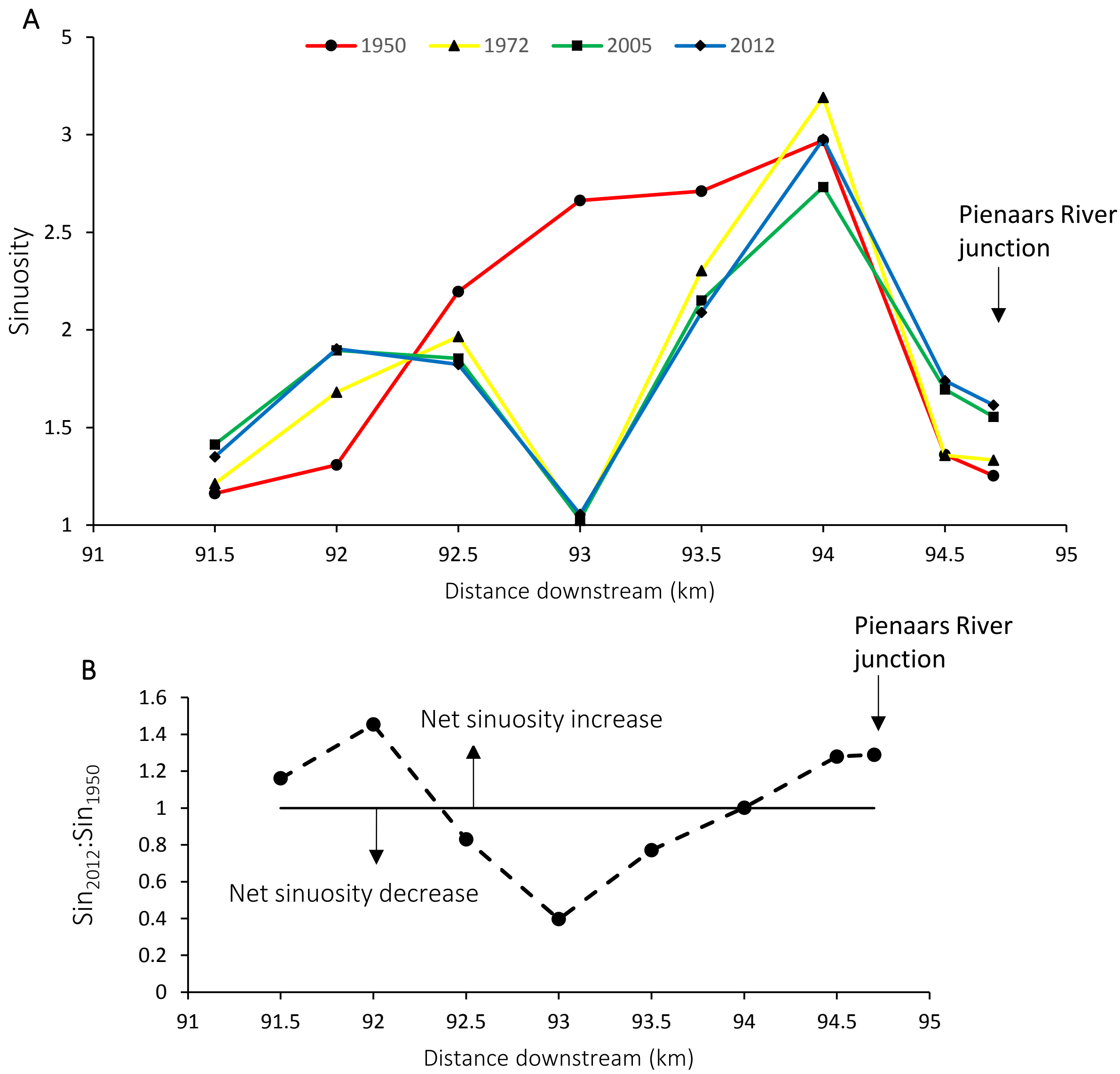

Fig. 5. (A) Sinuosity variations along 500 m reaches of the lower Tshwane River between 1950 and 2012. Note the profound influence of the 1950-72 avulsion on sinuosity for the following years. (B) $Sinuosity_{2012}$:$Sinuosity_{1950}$ ratio illustrates reaches with net increases or decreases in sinuosity between 1950 and 2012. A ratio of >1 relates to a net sinuosity increase, and a ratio <1 relates to a net decrease in sinuosity.

4.2 Floodplain and palaeochannel sedimentology

The Tshwane River floodplain is comprised mostly of fine-grained mud with sand and minor amounts of small gravel in channel bedload deposits. Organic matter is found in the top ~20 cm of the sediment, but not at depth. Occasional pedogenic and carbonate nodules are found at depth (>2 m) in floodplain and palaeochannel sediments. Levee sediments (sandy clay) adjacent to the modern channel and palaeochannels are coarser than underlying floodplain deposits. The depth to bedrock and the morphology of the bedrock base below the lower Tshwane River is unknown, but augering has confirmed that the alluvium is at least 5 m thick and that the modern channels and palaeochannels are fully alluvial, with no bedrock contact. In the palaeochannels a relatively sharp boundary exists between coarse bedload sediment and the overlying fine infill sediment that settles out of suspension during a flood. A fining-upward trend occurs in the infill sediments, with fine sandy clays grading to medium-heavy clays near the surface (sediment described after Wentworth 1922).

4.3 Chronology of avulsion and sedimentation rates

Single-grain OSL dating shows that all of the palaeochannels on the Tshwane floodplain are Late Holocene in age (Table 1, Fig. 6). OSL ages from palaeochannel and oxbow bedload sediments are interpreted to represent the last timing of active bedload transport and therefore provide a maximum age for abandonment. Where two samples were taken from the same auger hole, ages are in correct stratigraphic order and samples from different locations of the same palaeochannel were very similar. Channel belt B was actively transporting sediment ~620 years ago, and channel belt C was last active ~550 years ago, whilst channel belt D was last active ~120 years ago. The D_e distribution for sample T15 (channel belt A) is highly unusual (see Appendix 2) and could not provide a D_e estimate using the minimum age model. As such, this OSL sample has not been included in further analysis despite the likelihood of channel belt A being the oldest on the floodplain.

Table 1. Optically stimulated luminescence (single-grain) sample details and analytical results. Ages are rounded to the nearest 10 years if between 100 and 1000 years old, and to the nearest 5 years if below 100 years old. Ages are given in years before AD 2015. See Fig. 1 for sample locations. See Appendix 1 and 2 for radial plots and dosimetry data. Prefix 'TSW' is the lab code, and samples are simplified to a prefix of 'T'.

Channel belt	Sample	Sample type	Depth (m)	Equivalent dose (MAM; Gys)	Dose Rate (Gy ka $^{-1}$)	Age (a)
A	TSW15 (T15)	Palaeochannel	1.81 ± 0.10	-	1.76 ± 0.08	-
B	TSW02 (T2)	Palaeochannel	1.60 ± 0.10	0.98 ± 0.09	1.86 ± 0.09	530 ± 30
	TSW03 (T3)	Palaeochannel	2.15 ± 0.10	1.08 ± 0.01	1.74 ± 0.08	620 ± 30
	TSW07 (T7)	Palaeochannel	1.68 ± 0.10	0.97 ± 0.01	1.54 ± 0.08	630 ± 30
	TSW10 (T10)	Palaeochannel	1.48 ± 0.08	1.18 ± 0.01	2.07 ± 0.10	570 ± 30
	TSW11 (T11)	Palaeochannel	1.95 ± 0.10	1.03 ± 0.01	1.76 ± 0.08	590 ± 30
C	TSW16 (T16)	Palaeochannel	2.10 ± 0.10	0.84 ± 0.01	1.54 ± 0.07	550 ± 30
D	TSW01 (T1)	Palaeochannel	1.05 ± 0.10	0.23 ± 0.01	1.96 ± 0.10	120 ± 10
	TSW04 (T4)	Palaeochannel	0.38 ± 0.08	0.14 ± 0.01	1.81 ± 0.08	75 ± 5
	TSW05 (T5)	Palaeochannel	0.85 ± 0.05	0.20 ± 0.01	1.91 ± 0.09	110 ± 10
E (modern)	TSW08 (T8)	Levee	0.55 ± 0.05	0.12 ± 0.01	2.27 ± 0.11	55 ± 5
	TSW12 (T12)	Oxbow	0.53 ± 0.08	0.06 ± 0.01	1.47 ± 0.06	40 ± 5
	TSW14 (T14)	Modern point bar	0.00 ± 0.05	0.03 ± 0.01	1.16 ± 0.05	25 ± 10
F	PC1-100 (P1)	Abandoned levee	1.13 ± 0.13	1.17 ± 0.27	2.10 ± 0.11	560 ± 140
	PC1-275 (P2)	Substrate	2.88 ± 0.13	30.4 ± 1.44	1.97 ± 0.09	15 500 ± 1100

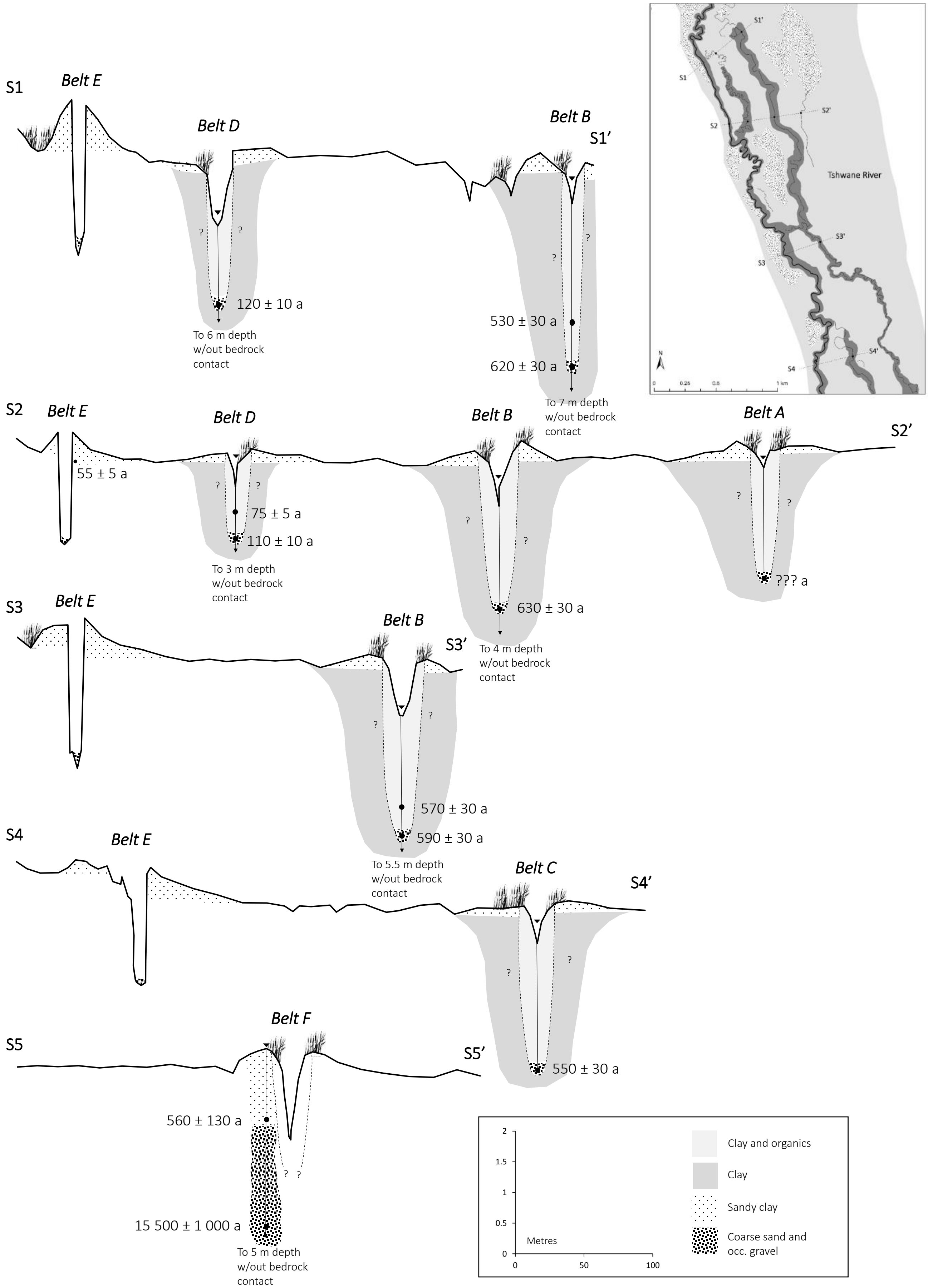

Fig. 6. Cross-sectional surveys 1-5 with sedimentology, and ages given by optically stimulated luminescence. Note that the core taken from the Pienaars ridge was not actually on the transect of survey 5, but it has been shown in an equivalent position on the survey for presentation purposes.

There have been three separate reach-scale avulsions on the Tshwane floodplain in the last ~650 years (ca. 620 a, ca. 550 a, and ca. 120 a). This yields an avulsion frequency of ~4.6 avulsions ka^{-1}. The most recent avulsion began ~120 years ago (c. 1895) when bedload sand in channel belt D was buried by in-channel sedimentation and was completed by ~60 years ago (c. 1955), when overbank sedimentation began forming a levee (T8) on the newly formed, modern channel. This suggests a period of ~60 a to complete the avulsion. Channel infill sedimentation rates are quite high (average ~4.7 mm a^{-1}), but vary between palaeochannels and appear to be highest immediately following channel abandonment (Table 2, Fig. 7). Where OSL samples were collected from the infill sediments above the bedload at three of the palaeochannel sites, linear regressions for the age-depth profiles suggest infill sedimentation rates between ~3 and 9 mm a^{-1} (Fig. 7). The rate of sedimentation on the modern levee is ~11 mm a^{-1} (Table 2).

Table 2. Sedimentation rates derived for each channel based on OSL dating (where depth 0 cm = time 0 years). Levee heights are means calculated for each channel belt. [a] Age given by optically stimulated luminescence in years prior to AD 2015. [b] Samples T1-8 and T10-12 were collected during fieldwork in 2008, hence the recorded depth is from 2008, whilst the measured age is years prior to 2015. Sedimentation rate calculations (depth/age) for these samples have been adjusted by subtracting seven years from the calculated age. [c] levee heights calculated from highest point on the levee to lowest point on the floodplain surface within 150 m of the channel. * denotes the mean sedimentation rate where two OSL samples were taken from the same profile (see Fig. 7).

Channel belt	OSL sample	Depth (mm)	Age (a) [a]	Sedimentation rate (mm a^{-1}) [b]		Levee height (m) [c]	Floodplain gradient		
				Infill	Levee		Down-stream (D/S)	Cross-floodplain (XFP)	D/S:XFP
A	T15	1810	-		-	0.22	0.001	0.0049	0.20
B	T2	1600	530	3.32*	-	0.29	0.001	0.0073	0.13
	T3	2150	620		-				
	T7	1680	630	2.70	-				
	T10	1480	570	3.00*	-				
	T11	1950	590		-				
C	T16	2100	550	3.82	-	0.16	0.001	0.0029	0.34
D	T1	1050	120	9.29	-	0.22	0.001	0.0034	0.29
	T4	380	75	7.44*	-				
	T5	850	110		-				
E (modern)	T8	550	55	-	11.46	0.41	0.001	0.011	0.09
	T12	530	40	16.06	-				
	T14	0	25	-	-				
F	P1	1130	560	-	2.02	0.41	0.0008	0.017	0.05
	P2	2880	15 500		-				

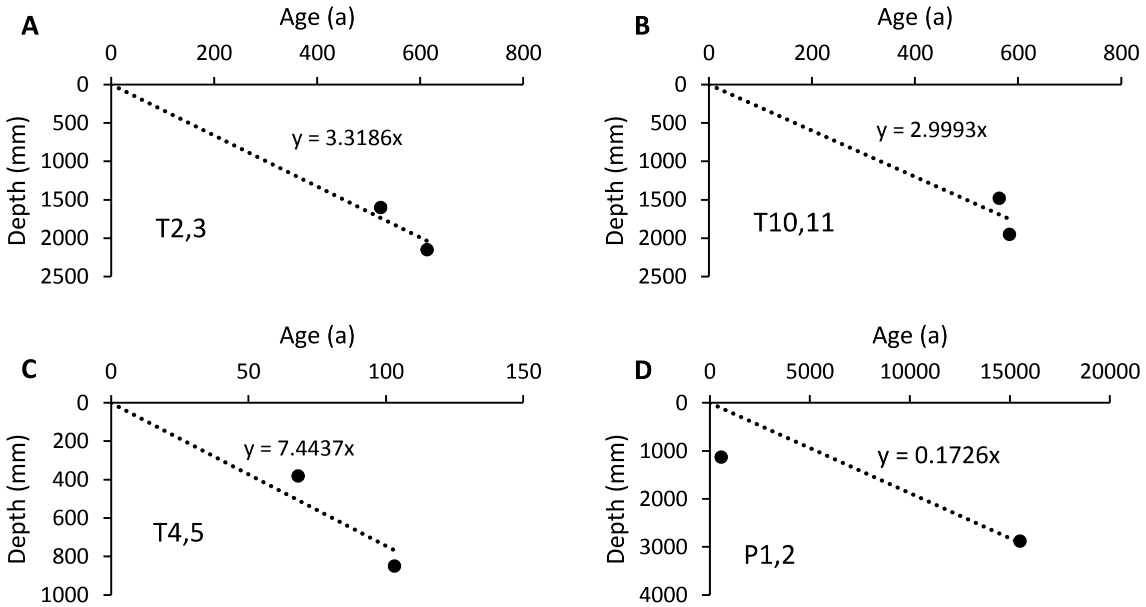

Fig. 7. Age-depth profiles of the four coring sites with OSL samples in succession. (A) and (B) channel belt B. (C) channel belt D. (D) channel belt F. The slope of the regression line fitted through time and depth zero, given by the equation, equals the mean sedimentation rate. Note: Ages for the 'T' samples have been adjusted to their age at collection in 2008.

5. *Discussion*

5.1 Timing and mechanisms of avulsion on the Tshwane River

The accuracy of single-grain OSL is confirmed by the corroboration between the OSL ages and the timing of historical channel change observed from aerial photographs. Sample T12 (location in Fig. 1) is from the bedload of a meander bend that was cut-off between 1972 and 2005 (Fig. 2), and OSL puts the timing of bedload deposition at c. 1975. Sample T8 is from the base of the levee along the newest channel that formed between 1950 and 1972, and OSL puts the sediment at the base of this levee at c. 1960. Assuming the T8 levee sample was only laid down once the new channel had formed, the knickpoint retreat rate is at least ~76 m a^{-1} between 1950 and 1960.

Altogether, the Late Holocene sequence of avulsion on the Tshwane River is well constrained by historical aerial photography and OSL results, and provides insight into the mechanisms of river adjustment. Prior to ~620 years ago, channel belt B was active before being abandoned ~570 years ago (i.e. bedload no longer being transported and the channel being infilled by fine sediment; Fig. 8). Due to the similarity in ages of active bedload transport between channel belts B and C, it is possible that they were part of the same channel belt, however they appear to be spatially distinct avulsions (channel belt C upstream and channel belt B downstream). Between ~620 and ~120 years ago, channel belt D gradually increased in sinuosity (up to ~2.7) while building prominent levees. Approximately 120 years ago (c. 1895), a sinuosity threshold was reached whereby the channel's sediment transport capacity was reduced to the point where fine sediment began to be deposited within the channel, burying the coarser bedload of channel belt D. Continued in-channel sedimentation further reduced channel capacity and the bed slope, contributing to the cross-floodplain gradient advantage for overbank flow distribution provided by the low levees (Fig. 8). A final threshold response to declining sediment transport capacity resulted in the formation of the new straight channel after 1950, but prior to ~1960. Following formation of the new channel, the former channel was abandoned and continued to infill from its upstream and downstream ends where it received overbank flow.

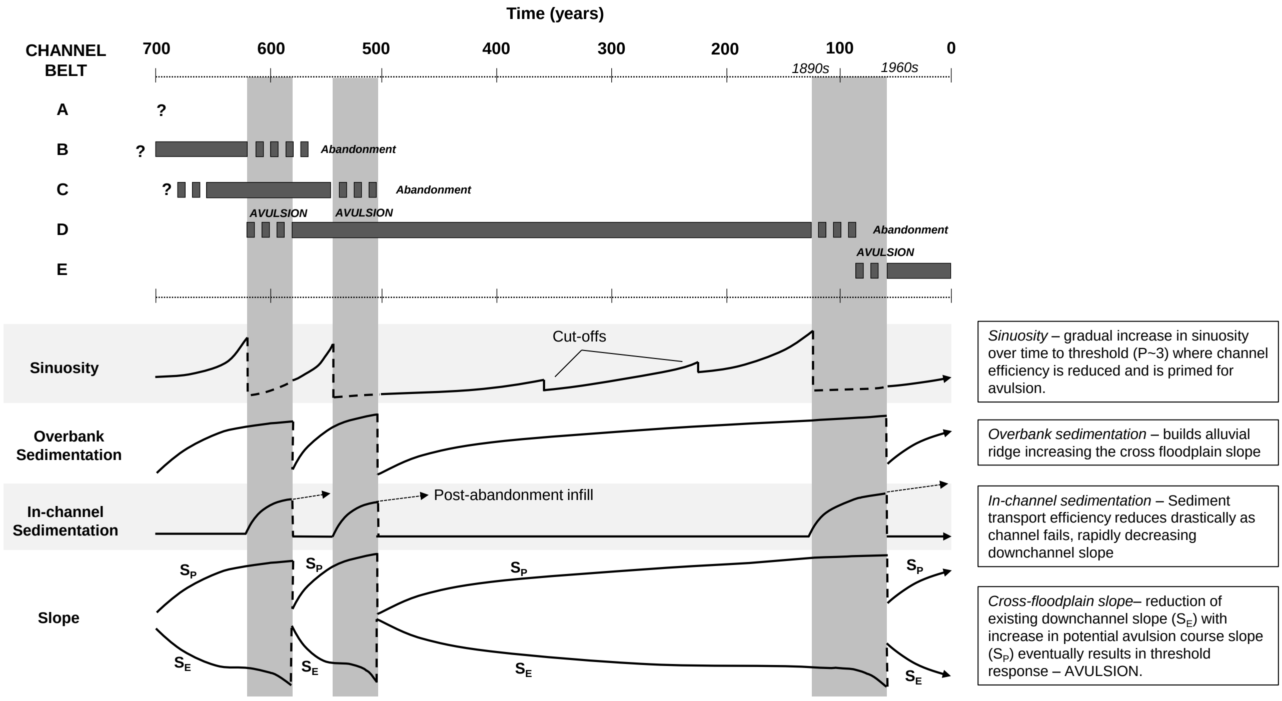

Fig. 8. Sequence of avulsions on the lower Tshwane River over the last ~700 years. Solid bars represent channel activity and the discontinuous ends represent the initial and terminal stages of channel activity. Lower half is a schematic illustration of threshold responses driving avulsion.

Insights from the most recent avulsion likely provide a mechanism for avulsion more generally in the lower Tshwane. Downstream declines in discharge and stream power along the Tshwane River result in a reduction in channel size and transport capacity at the system scale, with avulsion becoming the most important form of channel adjustment in the lower reaches (Larkin *et al*. *in prep* [Chapter 2]). Avulsion of the Tshwane River is an autogenically driven, threshold response to reductions in channel efficiency and sediment transport capacity. Over time, the Tshwane River builds a prominent alluvial ridge by overbank sedimentation which dramatically increases the cross-floodplain gradient away from the channel (Fig. 8). Wetlands form in the low points on the floodplain adjacent to these ridges. The river will simultaneously increase in sinuosity by lateral channel migration, which has been shown to be relatively rapid, at least over the historical period when aerial photographs were available (1950 onwards). The increase in sinuosity reduces the channel slope and, inevitably, the efficiency of the channel to transport sediment. Once the river reaches a threshold (~3), the trunk channel fails and bedload sediment is buried by in-channel sedimentation further reducing channel size, displacing more water onto the floodplain (Fig. 8). Meanwhile a knickpoint develops on the low point of the floodplain, as water returns to the channel in a low point on the bank. This often occurs at the downstream end of a backswamp after it has deposited sediment and is more erosive. The knickpoint generally has a gradient advantage as overbank floodwater from the main channel is directed away from the channel due to the prominent ridge and knickpoint retreat rates are rapid (~76 m a^{-1}). Once the knickpoint forms a new channel that reconnects to the trunk channel upstream, it receives all the channelised flow and the abandoned channel only receives occasional overbank flow, leading to the deposition of fining-upward palaeochannel infill sediments. The new channel is very straight and will immediately begin to form an alluvial ridge by overbank sedimentation and to increase in sinuosity. This mechanism explains the unusual pattern of alternating straight, moderately sinuous and highly sinuous reaches along the modern Tshwane River; the level of sinuosity relates to the amount of time since that channel formed by avulsion.

5.2 Avulsion frequency, style and sedimentation rate

There are limited field data that relate long-term sedimentation rates to avulsion histories for rivers around the world. Avulsions are most commonly associated with aggrading systems, and it is believed that systems with higher vertical sedimentation rates have higher avulsion frequencies, and that systems with negligible vertical sedimentation rates have much lower avulsion frequencies (Tornqvist and Bridge 2002; Slingerland and Smith 2004; Aslan *et al*. 2005; Tooth *et al*. 2007). The chronology of avulsion derived for the Tshwane River provides new evidence for the underlying intrinsic factors that drive avulsion in an unconfined alluvial river and provides data that supports the relationship between sedimentation rate and avulsion frequency.

The lower Tshwane River has a complex late Holocene avulsion history with avulsions occurring roughly once every 217 years (or ~4.6 avulsions ka^{-1}). In conjunction with a high avulsion frequency, sedimentation rates are also very high, with ~11 mm a^{-1} of vertical sedimentation on the levee adjacent to the modern channel. This study supports the hypothesis and adds another data point to Tooth *et al*.'s (2007) graph depicting the relationship between sedimentation rate and avulsion frequency (Fig. 9). In particular, this study shows that the Tshwane River and other wetlands in drylands can have very high rates of sedimentation and avulsion frequencies on timescales of centuries to millennia. It is important to note that avulsion frequency and sedimentation rates for the Macquarie Marshes and the Tshwane River have been extrapolated from relatively short periods of avulsion sequences with chronological constraint (100 years and 650 years, respectively). The Klip River however, has an avulsion record stretching back ~30 ka (Tooth *et al*. 2007). The difference between long-term avulsion records and short-term records needs to be addressed in future research, however the preservation of facies for several thousands of years in rapidly adjusting systems is generally very poor, and hence deriving long-term avulsion records and sedimentation rates from these systems is often very difficult.

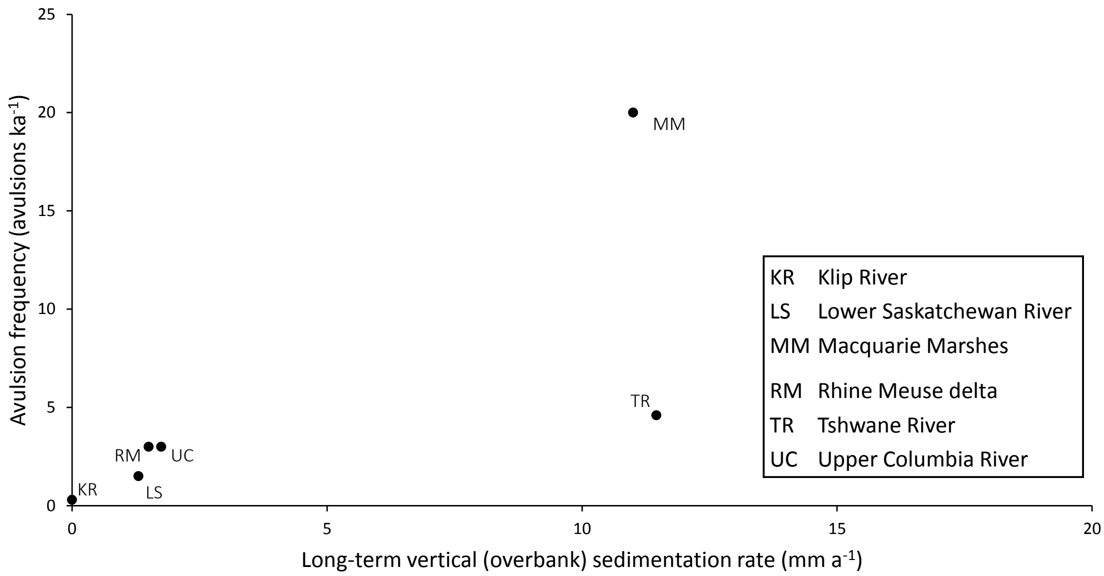

Fig. 9. Relationship between sedimentation rate and avulsion frequency. Graph updated from Tooth *et al*. (2007). Data for the Lower Saskatchewan River, Rhine-Meuse delta, and Upper Columbia River are taken from the compilation in Makaske *et al*. (2002; table 5). Data for the Macquarie Marshes are taken from Ralph *et al*. (2014, 2015).

Previous research by Tooth *et al*. (2007) showed that vertical sedimentation rates on the Klip River in sub-humid eastern South Africa are very low and that avulsion frequencies are also very low (~0.3 avulsions ka^{-1}) (Fig. 9). Rates of lateral channel migration are also low (~0.16 m a^{-1}) on the Klip River (Rodnight *et al*. 2005), and the contrasting findings from the Tshwane River highlight the importance of detailed geochronological analysis in complex systems such as these. While the two systems have incisional avulsions and are similar in planform with comparable palaeochannels, oxbows, and backswamps, this study of the Tshwane River has distinguished fundamental differences in the rate of lateral channel migration, avulsion frequency and vertical sedimentation rate. The model suggesting the influence of aridity of wetland morphology proposed by Larkin *et al*. *in prep* [Chapter 2] may be applied here; the relatively wetter setting and associated seasonal discharge regime of the Klip River means that discharges are sufficient to maintain sediment throughput and is therefore not characterised by net aggradation within its valley. The Tshwane River, by contrast, is significantly drier with a flashier seasonal discharge regime and is characterised by downstream declines in discharge, which leads to greater sediment accumulation. Sediment accumulation primes the Tshwane for more frequent avulsions, suggesting that perhaps there is a climatic threshold between slowly adjusting systems and rapidly adjusting systems. This has implications for river and wetland management in the future, as southern Africa is projected to become drier (more spatially and temporally variable rainfall) (Pachauri *et al*. 2014) which may push systems over internal thresholds, but further research is required to fully understand the influence of variations in aridity on fluvial processes.

There have been links suggested between sedimentation rate and avulsion style, with higher sedimentation rates associated with progradational style avulsions and lower sedimentation rates associated with incisional style avulsions (Tooth *et al*. 2007). While there is a correlation between sedimentation rate and avulsion frequency at the Tshwane River, the incisional style avulsions of the Tshwane River differ from what would be expected in a rapidly aggrading system. Infrequent, incisional style avulsions are characteristic of the Klip River, and also Cooper Creek in central Australia, which has a very low aggradation rate (0.04-0.1 mm a^{-1}; Tooth *et al*. 2007). In contrast, frequent (≥3 avulsions ka^{-1}), progradational style avulsions occur on the moderately to rapidly aggrading systems such as Baghmati River, India (~0.7-1.5 mm a^{-1}; Jain and Sinha 2004; Sinha *et al*. 2005) and the Upper Columbia River, Canada (~1.75 mm a^{-1}; Makaske *et al*. 2002). Incisional avulsions have not been documented in many long-term aggradational systems, apart from the Macquarie Marshes in Australia (Ralph *et al.* 2011; 2015) and the Okavango Delta in northern Botswana (McCarthy *et al.* 1992), where avulsions are the result of a complicated interaction between in-channel sedimentation, channel-lining vegetation, and local preferential flow paths. This indicates that the proposed links between sedimentation rate and avulsion style require further appraisal.

5.3 Long-term controls on avulsion frequency

Avulsion can be controlled by allogenic processes such as external drivers such as tectonics or climate change, or autogenic processes such as internal dynamics such as lateral channel migration and sedimentation patterns (Stouthamer and Berendsen 2007). Local avulsion and anastomosis in the panhandle of the Okavango Delta, Botswana, has been shown to be controlled by neotectonic movement (Smith *et al*. 1997). Subsidence of a small graben within the panhandle has resulted in a reduction in slope, increased aggradation and localised avulsion and anastomosis (Smith *et al*. 1997). Tooth *et al*. (2007) found no correlation between regional climatic changes and avulsion frequency on the Klip River based on a range of Late Quaternary palaeoclimatic proxy records, instead arguing that avulsion of the Klip River is autogenically controlled. In distinguishing between autogenic and allogenic controls on avulsion, Stouthamer and Berendsen (2007) note that if the frequency of avulsions and the period of activity of a channel belt remains constant despite variations in climate or tectonic activity, then it follows that avulsion is most likely autogenically driven.

Palaeoclimatic fluctuations over southern Africa throughout the Quaternary have been illustrated by several studies (Partridge *et al*. 1997; Holmgren *et al*. 1999; Petit *et al*. 1999; Tyson 1999; Backwell *et al*. 2014). There are likely older palaeochannels on the Tshwane floodplain that have not been addressed in this study, however throughout the last ~650 years there have been no significant or persistent variations to the regional climate (Partridge *et al*. 1999; Tyson 1999). Therefore it is clear that avulsion of the Tshwane River is an autogenic process related to internal thresholds rather than to external change. While individual avulsions are not driven by climatic factors, the aridity of the region is a contributing factor responsible for declining downstream discharge and stream power which, through a series of autogenic threshold responses, results in channel avulsion. A fluvial system does not operate in isolation from the climate (or other external factors), so any studies distinguishing allogenic and autogenic drivers of channel change must recognise the climate, geology or tectonic setting as not just a background state, but an overarching control that influences internal autogenic responses. For example, avulsion of both the Tshwane and Klip River occurs autogenically as part of meander belt development, but the rivers are operating in distinct climatic regions which may be influencing the rate of these autogenic processes (i.e. avulsion, channel migration).

5.4 The role of avulsion in wetlands in drylands

The style and frequency of avulsion leads to a variety of channel and floodplain planforms. These can include single-thread rivers with an array of abandoned channels on the floodplain, distributary systems with multiple co-existing, divided channels (e.g. deltas and some large floodplain wetlands), or anastomosing systems with numerous co-existing, dividing and rejoining channels. Many anastomosing or anabranching rivers with several simultaneously active channels, are dominated by avulsive processes that instigate the formation of a new channel but do not result in the abandonment of the former channel, or by the fact that the abandonment proceeds so slowly that new and former channels are effectively simultaneously active (Makaske 1998). Avulsion is particularly critical in wetlands in drylands where river channels and the water they carry are essential in otherwise water-stressed environments.

Avulsion can either be a threshold response to declining sediment transport capacity or a process that maintains sediment transport efficiency forming multiple, stable channels. Anabranching and anastomosing channel systems are thought to be most efficient in terms of sediment transport in regions of very low slope, and are characterised by downstream increases in sediment transport efficiency (Nanson and Knighton 1996; Tooth and Nanson 2000). Cooper Creek is an example of a large anastomosing system on a broad floodplain in east central Australia that is characterised by such dynamics, and other examples can be found in southeast Australia on the Ovens and King Rivers (Knighton and Nanson 1994, 2000; Schumm *et al*. 1996; Judd *et al*. 2007). This is in contrast to many distributary systems with floodplain wetlands that, like Tshwane River, are characterised by downstream decreases in sediment transport efficiency. The efficiency of sediment transport directly relates to rates of sedimentation, with inefficient systems having higher sedimentation rates (e.g. Macquarie Marshes, Ralph *et al.* 2011; Tshwane River, this study) and efficient systems having lower sedimentation rates (e.g. Cooper Creek, Nanson and Knighton 1996; Klip River, Tooth *et al*. 2007). While avulsion of the Tshwane River is a response to sediment transport inefficiency, the system maintains a single active, through-going channel, suggesting a form of dynamic equilibrium in the Tshwane River. Other systems characterised by extreme sediment transport inefficiency cannot maintain sediment throughput and break down into areas of floodouts and wetlands. For example, channels in the Macquarie Marshes frequently avulse but more often than not avulsion is not completed (Ralph *et al*. 2015). In the last ~100 years, two avulsions have started and completed, while a further eight have started but have not completed (Ralph *et al.* 2015). Reach-scale avulsion in the Macquarie Marshes is a non-equilibrium response to sediment transport inefficiency (Ralph, 2008). It is important to understand whether avulsion in a river system helps to maintain a dynamic equilibrium or is a long-term non-equilibrium response.

5.5 Implications for management

The Tshwane and Pienaars floodplain wetlands are in good geomorphological condition and are naturally dynamic with rapid rates of channel adjustment, wetland formation and desiccation. From a wetland management perspective, an understanding of the historical and longer-term adjustment of the system is crucial. Below are some of the most important characteristics of the Tshwane River wetlands that are important to consider when managing a system such as this.

1) *Frequent avulsion and rapid channel adjustment* – Historically, the Tshwane River wetlands are quite dynamic with frequent channel adjustments such as meander bend cut-offs and avulsion. OSL dating of palaeochannels has shown that the system has been frequently avulsing over at least the last 650 years. The inherent channel instability in the Tshwane River wetlands is important for determining the location of sedimentation, flooding and ecological productivity. Individual avulsions may result in the abandonment of a particular backswamp, but this is a natural aspect of wetland evolution and does not indicate that intervention is necessary. Increased sedimentation along the newly formed channel will likely result in the development of new flanking backswamps with no net decrease in wetland area. Interventions designed to impose stability on the rapidly adjusting channels (e.g. weirs) are likely to be ineffective in the long-term and may cause problems by trapping additional sediment and forcing flows overbank, which are fundamental drivers of channel avulsion and wetland rejuvenation. After depositing sediment behind a weir, water is more erosive downstream, which will likely cause bed and bank erosion and entrenchment of the channel reducing the hydrological connection between the channel and the floodplain which is vital for wetland health. McCarthy *et al*. (2009) discuss impacts of intervention (embankments, weirs, introduction of willows, and excavation of channels) in the Seekoeivlei floodplain wetlands on the Klip River. Ongoing impacts from these interventions have been significant, including a human-induced avulsion that is occurring in part of the wetlands that had not experienced avulsion before. Erosion of the excavated channel reach has enlarged the channel significantly and reduced the hydrological connection between the channel and the adjacent floodplain. Weirs built to reduce erosion have been successful in the short-term, although they require ongoing maintenance due to seasonal floods bypassing the structures (McCarthy *et al*. 2009).
2) *Long-term aggradation and local erosion* – The Tshwane/Pienaars wetlands are characterised by sediment sequestration and net aggradation. However, localised erosion is associated with the incisional avulsions typical of this system, as well as with lateral meander bend migration. As noted above, avulsion is a natural feature of channel adjustment in this system and localised erosion is not a cause for concern. Relatively rapidly, the new channel will stabilise and become more sinuous and will aggrade until the channel avulses again.
3) *Predicting avulsion* – Whilst we can identify the most important factors driving avulsion in the Tshwane River wetlands (e.g. high sinuosity, pronounced levee/alluvial ridges, in-channel sedimentation, adjacent low-lying backswamps), predicting where or when certain avulsions will

occur is difficult without regular, high resolution monitoring of channel and knickpoint change. Nonetheless, it is possible to highlight reaches that are most likely to be abandoned by avulsion.

6. Conclusion

Avulsion is a complex process that is influenced by a range of regional and site-specific factors that create unique avulsion characteristics in different rivers around the world. The lower Tshwane River is characterised by frequent, incisional style avulsions and high sedimentation rates that build prominent alluvial ridges. Throughout the last ~650 years, the Tshwane River has avulsed at least three times due to autogenic threshold responses to declines in sediment transport efficiency. The Tshwane River is inherently unstable but avulsion allows it to maintain dynamic equilibrium with a through-going channel. The high rates of channel adjustment (channel migration, cut-off and avulsion) contrast markedly with other systems throughout southern Africa, however provide support for the proposed positive correlation between sedimentation rate and avulsion frequency. Incisional style avulsions have not been documented well in long-term aggradational settings, indicating that the proposed idea that sedimentation rate controls avulsion style requires further appraisal. Understanding the mechanisms and timescales of avulsion on the Tshwane River has implications for river and wetland management. By appreciating the natural rate of change within the system and acknowledging that channels are inherently unstable, and that any attempts to enforce stability upon them will likely be unsuccessful in the long-term, effective management strategies can be employed. This study has provided a well-constrained dataset that supports the hypothesis that high sedimentation rates are correlated with high avulsion frequencies, however more chronologies are required from rivers around the world to fully understand the relationship and to investigate the processes of avulsion in dryland areas and humid areas alike.

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8. References

See combined reference list at the end of the thesis.

CHAPTER 4 – CONCLUSION

4.1 INTEGRATION OF KEY FINDINGS FROM BOTH PAPERS

Recent geomorphological research into wetlands in drylands has focused on important questions regarding the key controls on wetland formation, the mechanisms by which these wetlands adjust, and the timescales associated with these processes. However continued research is required throughout the world's drylands and in other environments to develop an understanding of the full diversity of wetland types. This project investigated the factors controlling river behaviour, floodplain wetland formation and avulsion in the Tshwane and Pienaars Rivers in South Africa. Complex interactions between local lithological variations, downstream declines in discharge and stream power, and intrinsic threshold responses to sinuosity and sedimentation are responsible for the development of the aggrading, frequently adjusting (by lateral migration and avulsion) floodplain wetlands of the Tshwane-Pienaars catchment. Wetlands occur on wide floodplains where river sinuosity is greatest and are fed by overbank flow (Aim i). Catchment-scale channel diminution as the Tshwane and Pienaars Rivers meander across laterally unconfined floodplains results in sediment deposition within the channel and adjacent to the active channel forming prominent alluvial ridges (Aim ii). Increases in channel sinuosity prime the Tshwane River for avulsion by reducing the longitudinal gradient and sediment transport efficiency (Aim ii). Avulsion frequency is high (Aim iv) and in-channel and near-channel sedimentation is a fundamental driver of avulsion in the lower reaches of the Tshwane River (Aims v and vi). The catchment-scale morphological analysis and detailed geochronological investigation of avulsion on the Tshwane River provide a robust understanding of how broad controls influence the location and extent of the wetlands, while internal threshold responses to sedimentation drive frequent reach-scale avulsions where new channel formation is dominated by erosional processes (Aim vii).

A range of factors influence the development of wetlands in drylands, but the findings from this study enhance our understanding of systems that are characterised by net aggradation and rapid channel adjustment, providing a contrast with several other previously studied systems in South Africa (e.g. Klip River, Nsonge River, Mooi River). There have been no other South African inland wetlands in drylands documented that maintain a single through-going channel while being characterised by rapid aggradation and rapid lateral adjustment (Aims iii and viii). The Tshwane-Pienaars floodplain wetlands appear to be a system near to the threshold between through-going and floodout style wetlands. This thesis has proposed that the major factor influencing this transition is the level of aridity. The proposed model of climatic influence on river (dis)continuity and floodplain wetland morphology has implications for river and wetland management under future drier, more variable, climates in southern Africa. Particularly considering the influence aridity may have on channel diminution, sediment sequestration and subsequent high avulsion frequencies.

In addressing the relationship between sedimentation rate and avulsion frequency, this project has demonstrated that more frequent avulsions are associated with higher vertical sedimentation rates in the Tshwane River, and has provided a well-constrained Late Holocene chronology of avulsion in a South African wetland. Avulsion of the Tshwane River occurs autogenically due to threshold responses to downstream declines in discharge, sinuosity increases, and in-channel and near-channel sedimentation. Interestingly, high sedimentation rates do not lead to progradational style avulsions on the Tshwane River, as may be expected. Incisional style avulsions have not been documented in rapidly aggrading systems such as the Tshwane River previously, and therefore the proposed link between avulsion style and sedimentation rate requires further appraisal.

4.2 Directions for future research

Future avenues of research arising from the findings of this research include:

1. A detailed investigation of the Stinkwaterspruit and Soutpanspruit catchments and their floodout style wetlands in the Tshwane-Pienaars catchment to determine the factors responsible for channel breakdown, avulsion and floodout formation. This research will be an important part of understanding the apparent threshold between through-going incising, through-going aggrading, and floodout style wetlands related to the level of aridity.
2. A detailed morphological analysis of floodplain wetlands throughout South Africa from specific climatic zones (sub-humid to arid) to determine the strength of the relationship between river (dis)continuity and the level of aridity identified in this project.
3. Further research is required to develop well-constrained chronologies of avulsion and sedimentation rates in rivers around the globe to better define the relationship between sedimentation rates and avulsion frequency in different landscapes, particularly drylands.
4. The Tshwane-Pienaars wetlands are in good geomorphological condition and receive water from an urbanised headwater catchment that is very likely polluted. An investigation of the ecosystem services provided by the Tshwane-Pienaars wetlands (e.g. water quality improvement, flood attenuation, provision of grazing land) would be a good case-study to investigate how properly functioning floodplain wetlands can buffer the impacts of urban development and pollution for downstream users.

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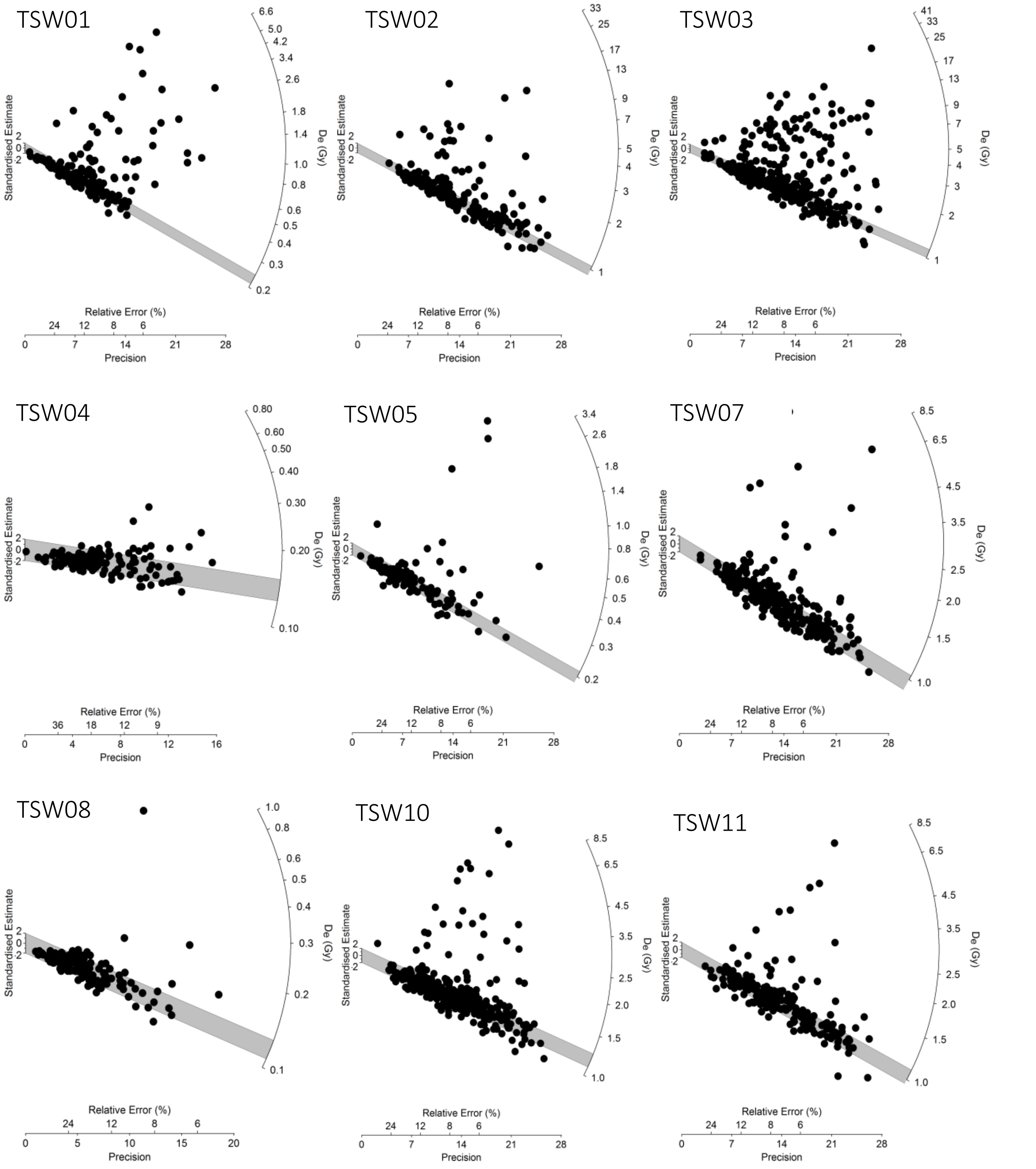
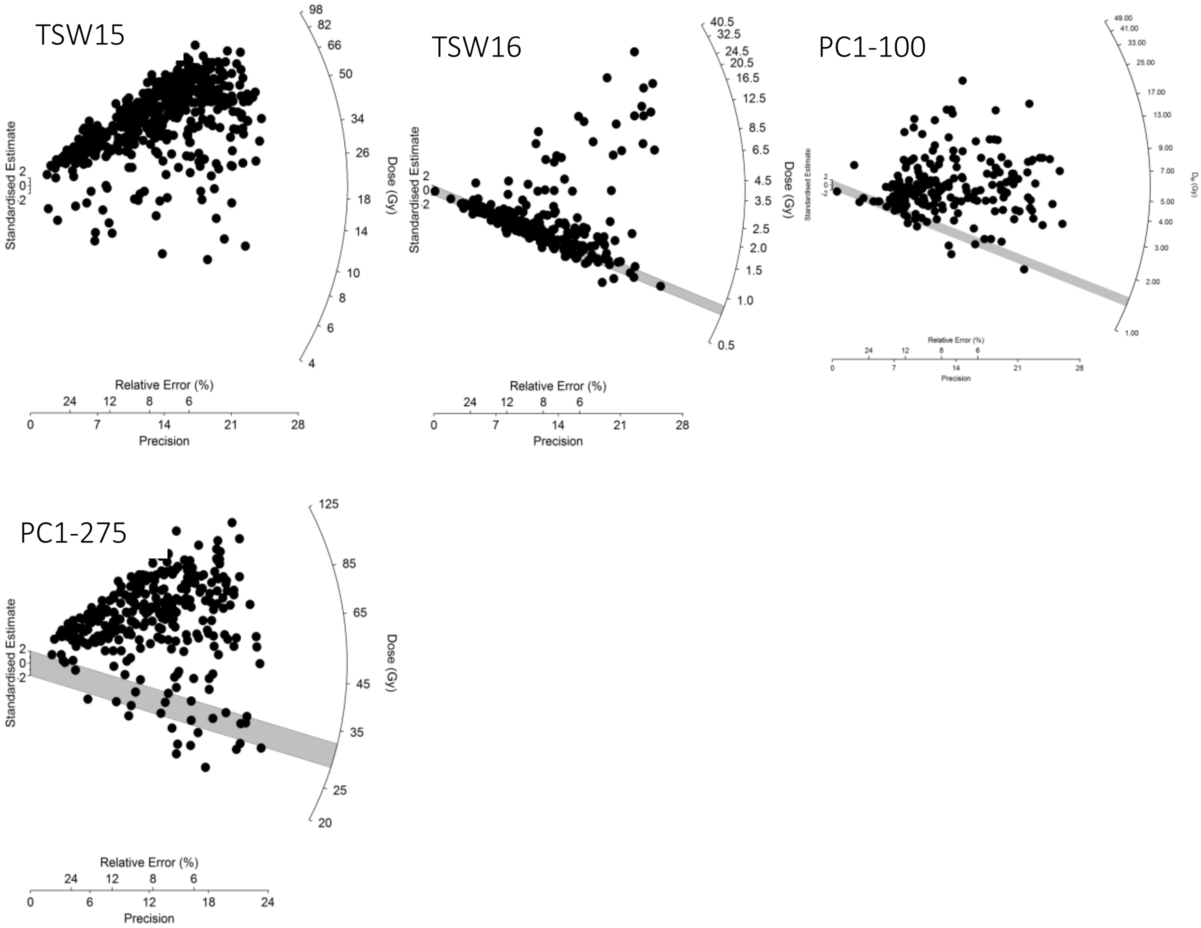
APPENDICES

OPTICALLY STIMULATED LUMINESCENCE DATA





Appendix 1. Equivalent dose radial plots for the Tshwane River OSL samples. The grey shaded bar represents the minimum D_e given by the minimum age model. Samples TSW12 and TSW14 were too young to display in a log scale radial plot due to some negative D_e values. Note the unusual D_e distribution of sample TSW15. The minimum age model could not provide a minimum D_e estimate with such a distribution, and as such an age estimate has not been given for TSW 15.

Appendix 2. Tshwane dosimetry data

Sample	Depth (m)	Water content (%)	Grain size (µm)	Beta Dose (Gy ka^{-1})	Gamma Dose (Gy ka^{-1})	Cosmic Dose (Gy ka^{-1})	Total Dose Rate (Gy ka^{-1})
TSW01	1.05 ± 0.10	25 ± 5	125-250	0.93 ± 0.06	0.84 ± 0.08	0.19 ± 0.01	1.96 ± 0.10
TSW02	1.60 ± 0.10	25 ± 5	180-212	0.92 ± 0.05	0.76 ± 0.07	0.18 ± 0.01	1.86 ± 0.09
TSW03	2.15 ± 0.10	25 ± 5	150-212	0.79 ± 0.05	0.78 ± 0.07	0.17 ± 0.01	1.74 ± 0.08
TSW04	0.38 ± 0.08	25 ± 5	180-212	0.86 ± 0.05	0.72 ± 0.06	0.23 ± 0.02	1.81 ± 0.08
TSW05	0.85 ± 0.05	25 ± 5	150-212	0.91 ± 0.05	0.81 ± 0.07	0.20 ± 0.01	1.91 ± 0.09
TSW07	1.68 ± 0.10	25 ± 5	180-212	0.68 ± 0.04	0.69 ± 0.06	0.18 ± 0.01	1.54 ± 0.08
TSW08	0.55 ± 0.05	15 ± 5	150-180	1.10 ± 0.07	0.96 ± 0.08	0.22 ± 0.01	2.27 ± 0.11
TSW10	1.48 ± 0.08	25 ± 5	180-212	1.00 ± 0.06	0.89 ± 0.08	0.18 ± 0.01	2.07 ± 0.10
TSW11	1.95 ± 0.10	25 ± 5	180-212	0.83 ± 0.05	0.76 ± 0.07	0.17 ± 0.01	1.76 ± 0.08
TSW12	0.53 ± 0.08	25 ± 5	180-212	0.68 ± 0.04	0.58 ± 0.05	0.22 ± 0.01	1.47 ± 0.06
TSW14	0.00 ± 0.05	25 ± 5	150-212	0.43 ± 0.03	0.42 ±0.04	0.31 ± 0.01	1.16 ± 0.05
TSW15	1.81 ± 0.10	25 ± 5	150-212	0.84 ± 0.05	0.74 ± 0.05	0.17 ± 0.01	1.76 ± 0.08
TSW16	2.10 ± 0.10	25 ± 5	180-212	0.71 ± 0.04	0.66 ± 0.05	0.17 ± 0.01	1.54 ± 0.07
PC1-100	1.13 ± 0.13	15 ± 5	180-212	0.95 ± 0.09	0.96 ± 0.09	0.19 ± 0.01	2.10 ± 0.11
PC1-275	2.88 ± 0.13	15 ± 5	180-212	0.87 ± 0.05	0.78 ± 0.06	0.15 ± 0.01	1.80 ± 0.08