Geomorphology and Landscapes of the Limpopo River System

16

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Abstract

The Limpopo River system is a major drainage pathway in southern Africa but very little is known about its catchment-scale geomorphology and dynamics. This study maps its geomorphology using the River Styles Framework as an interpretive tool. This analysis highlights that river geomorphology varies spatially, in particular between bedrock-controlled and overbank floodout reaches which are found throughout the river system. In addition, much of the present reach-scale geomorphology does not correspond to present climate forcing—even though flood events are important drivers of geomorphic change, flood effects are spatially variable. This is due in part to different substrate types and valley width, but also to flow constrictions that compartmentalize the integrity of the river sediment system into different morphodynamic zones. The ephemeral tributaries drawing water from Botswanan territory into the Limpopo are strongly affected by human activity, including river damming and groundwater abstraction. This significantly impacts on river discharge and thus sediment dynamics. The net outcome is that there is limited streamwise sediment connectivity through these tributaries and thus through the Limpopo River system as a whole.

Keywords

Climate change • Flood events • Limpopo • River geomorphology • River Styles • Semiarid

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16.1 Introduction

The Limpopo River is a major drainage system of southeast Africa (Fig. 16.1). It has a total drainage area of 412,938 km^2 and draws water from Botswana, Zimbabwe, South Africa and Mozambique. The Limpopo drains 14% of the land surface area of Botswana. This drainage system in this part of southern Africa has ancient origins: the Limpopo River system became isolated from adjacent systems at the end of the Cretaceous as a result of epeirogenic uplift (Moore and Larkin 2001; Moore et al. 2012). This uplift in headwater areas reduced catchment area and possibly flow and sediment contribution to the lower parts of the Limpopo system, rejuvenated bedrock incision and, in combination with climate changes, gave rise to variations in sediment provenance from the Limpopo and adjacent river systems (Setti et al. 2014; Schüürman et al. 2019). Thus, this river system has both evolved over long time periods and has experienced significant climatic and environmental changes over the Cenozoic (last 66 million years) (Knight and Grab 2016). From this, it can be inferred that river geomorphology may have also evolved in different ways over this time period, and that evidence for past river dynamics (terraces, flood boulder deposits, abandoned meanders, underfit channels, bedrock incision features, waterfalls) may exist along the river system. Previous studies from rivers elsewhere in the region have discussed the role of seasonal flooding in rapidly changing river sediment distribution and morphodynamics (e.g. Rowntree et al. 2000; Heritage et al. 2015), and this is also seen from the Limpopo River (Spaliviero et al. 2014; Mvandaba et al. 2018). However, the Limpopo River is understudied in comparison with other semiarid rivers in southern Africa, such as the Sabie (Heritage and Moon 2000; Heritage et al. 2001a), Olifants (Rountree et al. 2001) and Letaba (Heritage et al. 2001b; Moon and Heritage 2001). Thus, the interpretation of channel geomorphology and dynamics of the Limpopo River undertaken in this study is set into this wider regional

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context. A good overview of the properties and dynamics of the Limpopo River and its catchment is given by FAO (2004). Here, this overview is supplemented with more detailed mapping and analysis of different aspects of catchment properties and processes.

In detail this study (1) describes the major properties of the Limpopo River catchment as a whole; (2) presents new evidence for river geomorphology based on reach-scale analysis of river channel patterns and sediment distributions throughout the river system, using the River Styles Framework; and (3) discusses this evidence in the context of river morphodynamics and the critical role of floods in geomorphic change, with a geographical focus on that part of the Limpopo River system that lies within Botswana. A critical outcome of this study is that, for the first time, the Limpopo drainage has been mapped and classified, providing the context for future more detailed studies.

16.2 Physical Background

The Limpopo Basin as a whole includes a range of rock types of different ages and origins. Geology in the wider region is summarized by Schlüter (2006) and encompasses part of the northern margin of the Witwatersrand basin. Rocks present in this region include conglomerates, sandstones and shales interbedded with basaltic lavas, as part of the Soutpansberg and Waterberg groups, and the Transvaal Supergroup. This

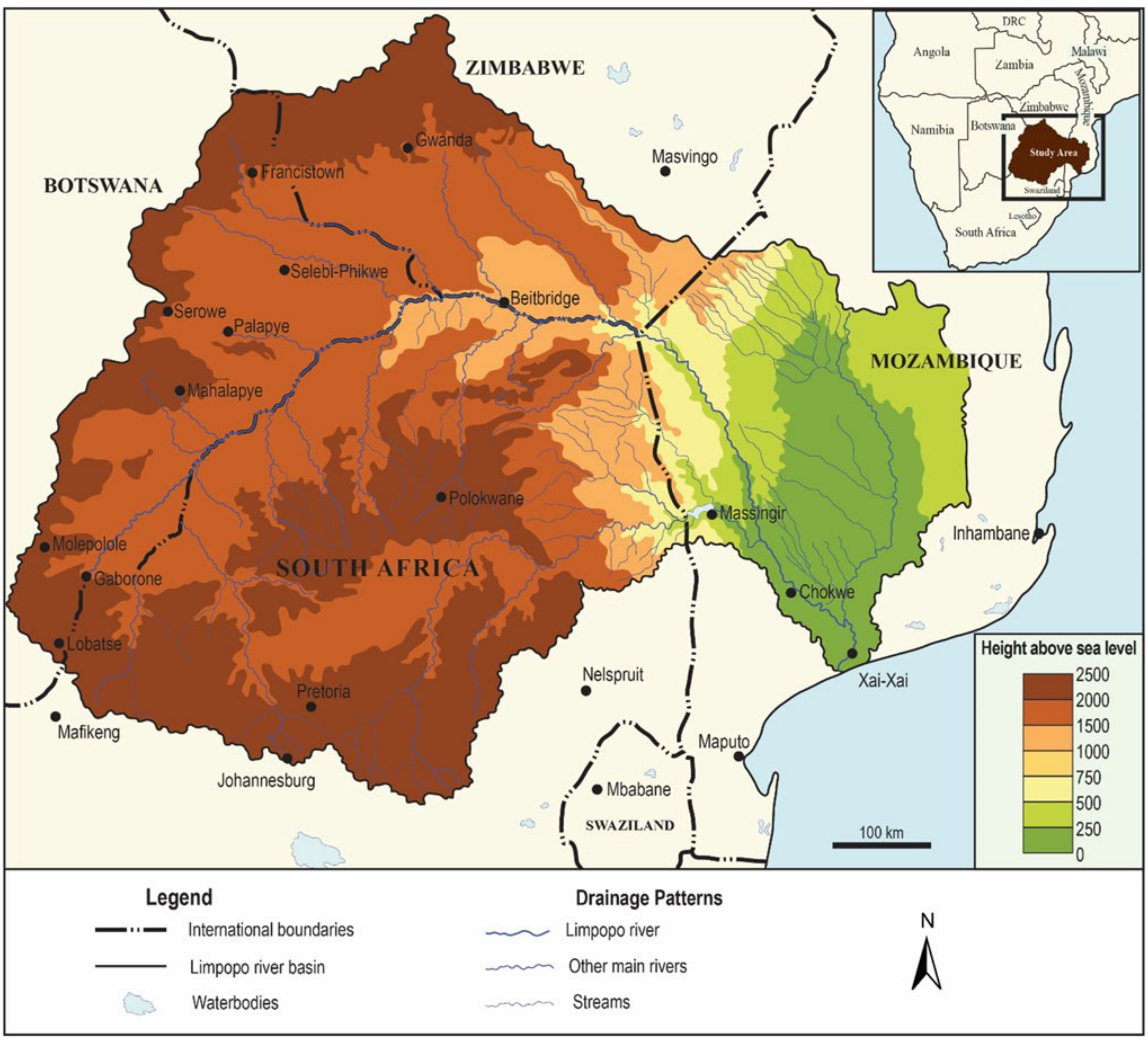

Fig. 16.1 Map of the Limpopo River catchment, showing catchment topography and major tributaries (named in Fig. 16.3)

also includes sandstones of the Tuli Basin, discussed below. Igneous and metamorphic rocks (mainly gneisses) are part of the Archaean Limpopo Belt and dominate in the Botswana part of the Limpopo catchment. The lowermost part of the catchment in Mozambique is dominated by mudstones and siltstones. These rock types have influenced regional soils and topography (FAO 2004). The topography of the region comprises higher relief headwater areas of the Drakensberg, Waterberg and Strydpoort mountains, with some areas above 2000 m asl. Large parts of the lower river course in Mozambique lie below 7 m asl. The river long profile (Fig. 16.2) broadly reflects this geological control, with steep, bedrock-dominated reaches corresponding to geological boundaries. It may also reflect episodic uplift of the southern Africa interior (Moore et al. 2012), consistent with rivers elsewhere in Botswana and in the Kalahari Desert (Nash and Eckardt 2016). FAO (2004) identifies different landscape physiographic types within the Limpopo catchment of which relatively flat plains are by far the most dominant throughout all areas of the catchment and along the main river channel. This reflects its long-term development by subaerial weathering and erosion (Knight and Grab 2016). Soil types are responsive to geology and landscape physiography. In the southeast Botswana sector of the catchment, soils around Francistown and Selebi Phikwe are clay-rich luvisols. Between Mahalapye and Molepolole sandy arenosols dominate, typical of savannas. Around Gaborone and in patches elsewhere are lixisols which are clay-dominated residual soils typical of weathered relict land surfaces. These soils are found in particular on higher elevation highveld plateau surfaces across this region (Runge 2016). Sandier soils are located dominantly at lower elevations on the lowveld and associated with floodplain elements.

The region of the Limpopo basin as a whole lies mainly within Köppen climate zone BSh (semiarid, dry, hot). Annual rainfall is in the region of 450 mm, but varies according to seasonal ingress of Indian Ocean cyclones during the summer, which commonly results in seasonal flood regimes on rivers in this region (Jury and Lucio 2004; Malherbe et al. 2012; Jury 2016), including on the Limpopo River itself (Spaliviero et al. 2014; Sitoe et al. 2015). Climate and soils also impact upon ecosystem types and land cover. Most of the catchment as a whole (53%) comprises cultivated agricultural land/grassland followed by savanna grassland (bushveld) (25%) and open/xeric savanna grassland (20%) (FAO 2004). Grassland is found throughout the Botswana part of the catchment, with a small region of xeric shrubland found between Gaborone and Lobatse. Montane grasslands are found in higher elevation areas of the catchment, outside of Botswana, with tropical/subtropical forests near the Limpopo River mouth in Mozambique.

Discharge patterns of the Limpopo River are discussed in several studies (Trambauer et al. 2014; Jury 2016; Mosase and Ahiablame 2018), but there is a general lack of information on river hydrodynamics. Rainfall patterns (1979–2013) vary across the basin from 160 mm/yr in the west (including Botswana) to 1152 mm/yr in the east and southeast at the coast (Mosase and Ahiablame 2018). Seasonality of rainfall increases to the east but variance increases to the west, indicating higher rainfall variability in the Botswana part of the catchment. In turn, this can result in more variable river responses. To counter the general absence of detailed river discharge evidence, the Pitman rainfall–runoff relationship has been used to model runoff for the Mokolo, Mzingwani (Mvandaba et al. 2018), Luvuvhu (Oosthuizen et al. 2018a), Mogalakwena and Shashe rivers, which are tributaries of the Limpopo (Oosthuizen et al. 2018b). The results show that there is high uncertainty in this rainfall–runoff relationship, due mainly to the role of dams and irrigation in diverting water from river systems.

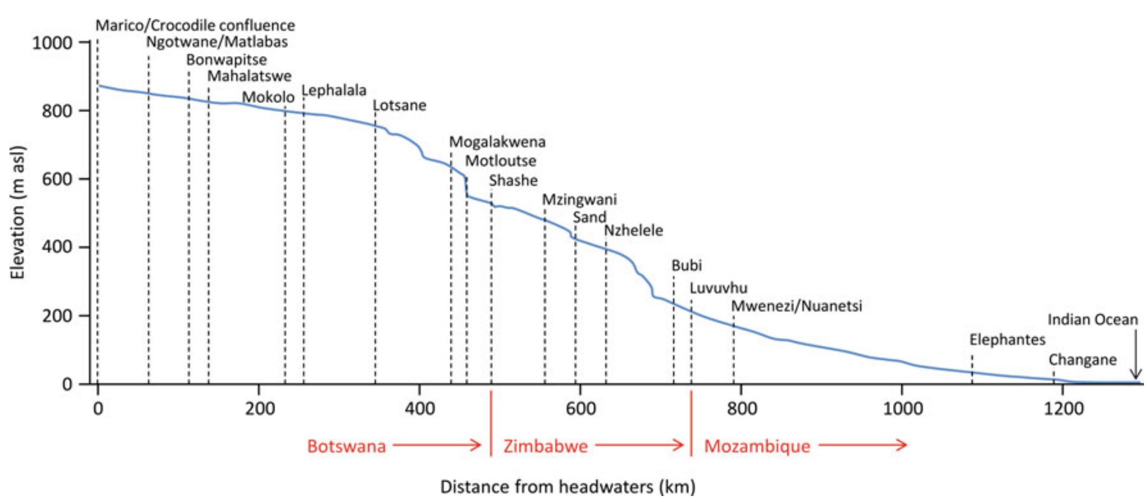

Fig. 16.2 Long profile of the Limpopo River system (redrawn after FAO 2004), indicating the confluence of major tributaries

16.3 Methods

This study undertakes a first-pass baseline survey of river geomorphology along the Limpopo River and its major perennial tributaries based on a simple geomorphic classification using Google Earth imagery (various dates in May 2019, austral winter, during low flow conditions when river geomorphology along perennial reaches is exposed). This methodology is based on the River Styles Framework (RSF) developed for semiarid Australian rivers by Brierley and Fryirs (2005). Implementation of the RSF has four successive stages: (1) baseline survey of river character and behaviour; (2) assessment of river evolution and geomorphic condition; (3) interpretation of the potential of river geomorphology to recover from flood events; and (4) application of this knowledge to river management. In this study, only stages 1 and 2 are undertaken for mapping reach-scale geomorphology through the Limpopo River system.

A river reach is defined as a certain length of river channel in which channel geomorphology (fluvial style, sediment distribution, landforms) is relatively uniform (Rowntree et al. 2000). Given the size of the Limpopo system, a standard reach length of 5 km is used in this study, providing a large-scale overview of the system. Six river styles are identified (Table 16.1). These have been shown to be useful in categorizing reach-scale geomorphology along the semiarid Sabie River, South Africa (Eze and Knight 2018). In this present study, 19 perennial tributaries of the Limpopo River were chosen (Table 16.2) because these are where year-round water flow is able to shape river geomorphology. Ephemeral rivers were excluded from this analysis. It is notable, however, that much of the drainage within the Botswana part of the catchment is by ephemeral rivers, including the Mahalatswe and Bonwapitse, and upper parts of the Lotsane and Ngotwane. The large Changane tributary in Mozambique was also excluded from this study because drainage is largely captured into a natural endorheic basin, which has some episodic and limited overflow into the Limpopo River. Various spellings of some of the main tributaries exist. The most commonly used spellings are the ones used here.

16.4 Limpopo River Analysis

16.4.1 Distribution of Channel Types

In total 931 5 km-length reaches were mapped (4655 km in total). The six river styles are identified in different locations through the Limpopo River system and in its major tributaries (Fig. 16.3). For illustrative purposes, different channel types are grouped together: channel types 1 and 2 (bedrock dominated reaches), types 3 and 4 (sand beds), and types 5 and 6 (palaeochannels, swamps and floodouts). Across the river system as a whole, planform-controlled sand beds are the most common river style (37% of total) with styles 3 and 4 (floodplain meanders), making up 63% of all reaches. However, styles 3 and 4 also include channels of different sinuosities, including straighter reaches found in a floodplain setting and where lateral bars rather than point bars and terraces are common. The river system is therefore sand-dominated and controlled by variations in water discharge that lead to periods of overbank deposition during floods and possibly meander migration. This conforms to other river systems in the region (e.g. Larkin et al. 2017). It is notable that the different tributaries have different geomorphic properties. Gorges are common in the Lephalala and Luvuvhu tributaries (Table 16.2). These rivers draw from mountain catchments. Bedrock dominated reaches (gorges, bedrock-forced meanders) are located in mid-river reaches within tributaries, reaching 21% in the Lephalala and 14% in the Ngotwane rivers. At the other end of the scale, floodouts are found in the upper part of the Limpopo catchment in the Marico and Matlabas tributaries, and in lower parts of the catchment in lowland regions of Mozambique, and have low long profile gradients. Floodouts are associated with highly sinuous and abandoned meanders, ox-bow lakes and overbank wetlands (swamps). The spatial distribution of reach styles highlights that different tributaries have different properties. For example, bedrock-dominated reaches are associated with more flashy and thus amplified flood responses downstream. Sand-dominated reaches, especially with wide floodplains, have higher potential for geomorphic change during floods where erosion and deposition buffer river discharge.

16.4.2 Examples from the Botswana Sector of the Limpopo River

There are few specific studies on Botswana rivers outside of the Okavango Delta region. Byakatonda et al. (2018b) evaluated rainfall–runoff regimes for some Limpopo River tributaries in Botswana, showing that there is a time lag between peak rainfall and peak river discharge (Fig. 16.4). This is attributed in part to water storage into, and flow regulation by, dams, and also to long-term changes in rainfall and temperatures (in particular during the summer), resulting in changes in water balance. For example, climate records at Francistown (since 1960) and Mahalapye (since 1971) show a linear temperature increase of ~ 0.15 °C/decade and 0.27 °C/decade, respectively; and rainfall at Mahalapye (since 1960) shows a linear decrease by 6%/decade (Byakatonda et al. 2018a). River channels are

Table 16.1 River Styles identified in this study (Brierley and Fryirs 2005) along the Limpopo River system

Channel type	River Style	Typical geomorphic features present
1	Gorge	Cascades, rapids, boulders, bedrock
2	Bedrock-forced meander	Bedrock, gravel, pools, runs
3	Low/moderate sinuosity, planform-controlled sand bed	Incised banks, pools, riffles
4	Meandering sand bed	Sand sheets, lateral bars, flood channels, palaeochannels
5	Low sinuosity, fine grained	Sand sheets, palaeochannels, point bars, point benches
6	Floodouts	Ponds, floodouts, swamps, crevasse splays

dominantly ephemeral; some specific examples from the Botswana sector of the Limpopo River system are shown in Fig. 16.5. Bedrock-controlled meanders of the perennial Ngotwane River (Fig. 16.5a) are uniformly incised into a relatively flat residual surface and framing the lateral extent over which the present underfit channel can meander (River Styles 1, 2). The presence of abandoned and cut-off meanders across this surface attests to past humid climate phases. These abandoned meanders are partly filled, similar to lowland Limpopo reaches (Sitoe et al. 2015) and other mixed sand–bedrock rivers (McCarthy 2004). Based on cosmogenic ^{3}He dating, Keen-Zebert et al. (2016) calculated bedrock erosion rates of 14–255 m/Ma and lateral erosion rates of 11–50 m/Ma on the mixed sand–bedrock Klip, Mooi and Schoonspruit rivers, South Africa. This is likely similar to the situation on the Ngotwane. The ephemeral Bonwapitse River is sand-dominated, and it is notable on Fig. 16.5b that water present within the channel drains through floodplain sediment before it reaches the Limpopo River confluence. Short ephemeral tributaries are also seen along the Bonwapitse. The confluence region is typical of a flood-dominated distributary plain, with meandering or braided channels during high flow and an exposed deflation plain during low flow conditions (River Styles 5, 6). This confluence area, of around 4 km^2, can be considered as a palaeo-delta similar to much larger versions identified on the Mozambique lowlands of the Limpopo catchment, formed by avulsion from the main channel and its meanders during past floods (Spaliviero et al. 2014). This behaviour is also well-marked at the Shashe–Limpopo confluence where there is a strong seasonal contrast in discharge and therefore river morphodynamics between the main channel (Limpopo) and incoming tributary (Shashe) (Fig. 16.6). The wide alluvial valley present near the ephemeral Mahalatswe River confluence with the Limpopo (Fig. 16.5c) shows a single low-sinuosity channel occupying different valley positions, outside of which are vegetated bars and floodplain surfaces (equivalent to River Styles 3, 4). This is the most common channel morphology within the Limpopo catchment (Table 16.2), in which a wide floodplain or alluvial-filled valley developed under more humid climates, and is now being reoccupied or reworked at different times in response to variations in discharge. This describes the most typical behaviour of such semiarid rivers in the region (e.g. Tooth et al. 2004, 2013; Larkin et al. 2017).

16.5 The Tuli Basin

Another important geomorphic element of the Limpopo River system within Botswana is in the area of the Tuli Basin, a Kalahari–Karoo Basin correlative of Triassic–Jurassic age found in southeast Botswana, broadly between Francistown and Gaborone. The Tuli Basin contains mainly sandstones with minor presence of siltstones and mudstones that accumulated in a fault-bounded basin. This region is of interest because its topography is significantly lower than elsewhere in Botswana (at $\sim$ 500 m compared to $\sim$ 1000 m asl), and this subdued surface may in turn have influenced river patterns within the Limpopo watershed. A well-known feature of the region today is Solomon's Wall, a prominent (30 m high) cliff-face and popular tourist site, developed along the lower Motloutse River by incision into a basalt dike (Fig. 16.7). It was likely that the more resistant dike once impounded water behind it, forming a lake and waterfall. This now-dry ancient system may correspond to a late Pleistocene pluvial phase. Although the sandstone geomorphology in the Tuli Basin region has not been fully described, this area is significant for its Late Stone Age archaeology (Forssman 2013) and rock art and engravings (van der Ryst et al. 2004). This evidence indicates a long cultural association of human activity with the Limpopo catchment landscape, extending farther east into the orbit of the Great Zimbabwe and Mapungubwe cultures (Forssman 2013).

Table 16.2 Proportion of different River Styles identified in different Limpopo River sectors. N = number of 5 km-long reaches examined. ***Italics bold*** indicate the most dominant class

	River style (%)						
	Gorge	Bedrock-forced meander	Low/moderate sinuosity, planform-controlled sand bed	Meandering sand bed	Low sinuosity, fine grained	Floodouts	N
Limpopo River (main channel, to Marico–Crocodile confluence)	0	12	25	***31***	19	13	244
Tributaries							
Marico	0	13	22	9	19	***37***	32
Crocodile	0	12	***66***	19	3	0	41
Ngotwane	14	***53***	25	0	3	5	36
Matlabas	0	18	***46***	0	18	18	17
Mokolo	9	34	***44***	9	4	0	32
Lephalala	21	25	***50***	4	0	0	28
Lotsane	0	18	38	0	***41***	3	34
Mogalakwena	0	15	***72***	13	0	0	47
Motloutse	0	6	24	32	***38***	0	47
Shashe	0	3	***57***	39	1	0	57
Mzingwani	0	8	***42***	27	19	4	52
Sand	8	16	27	***49***	0	0	37
Nzhelele	0	***84***	16	0	0	0	6
Bubi	0	12	***49***	35	4	0	51
Luvuvhu	31	19	***38***	8	4	0	26
Mwenezi	2	20	***40***	32	6	0	64
Elephantes (to Letaba–Olifants confluence)	10	0	16	***69***	5	0	19
Letaba	6	26	***45***	23	0	0	31
Olifants	0	17	26	***47***	10	0	30
Average across the entire catchment	***3***	*17*	***37***	***26***	***12***	***5***	

16.6 Discussion

16.6.1 Landscape Development in the Limpopo Catchment

The present geomorphology and dynamics of the Limpopo River and its major tributaries are driven by climate variability but strongly affected by geologic controls. Thus, this river system has evolved over long time scales in response to tectonic uplift, land surface denudation, and river and slope movement of weathered products through the river system and into the Indian Ocean (Setti et al. 2014; Schüürman et al. 2019). Variations in river long profile (Fig. 16.2) and the position of knickpoints and waterfalls may reflect the combination of geologic and tectonic forcing (Nash and Eckardt 2016). The varied distributions of different River Styles (Fig. 16.3) show that there is not a consistent relationship between reach position in the catchment context and its River Styles classification. Bedrock-controlled reaches are found along both the main and tributary channels but in topographically higher positions such as in the Waterberg Mountains around Polokwane (Fig. 16.1). A notable result is that lowland River Styles (low sinuosity channels and

Fig. 16.3 Distribution of different River Styles through the Limpopo's perennial rivers (named in italics). River Styles are numbered according to Table 18.1. Gaps in the river network are where dams (**D**) are present

floodouts) are found even within some headwater tributaries (Fig. 16.3). Most present active channels are underfit relative to the size of their hosting valleys, and that episodic floods cause abandoned channels to be reoccupied along certain river reaches, with overbank and crevasse splay deposition. The large floodplain/valley width means that there is a lot of low-energy standing water after flood events, and generally quite restricted or compartmentalized patterns of downstream sediment transport. This is what is seen in the flood dynamics of similar semiarid rivers elsewhere in the region (Knight and Evans 2017, 2018). A key inference from this observation is that the Limpopo River is not a straightforward water and sediment transport system, but that both these elements vary significantly spatially and temporally with constrictions in transport taking place where extensive sandy floodplain sediments facilitate water infiltration and buffer flood response. The RSF approach taken in this study provides a useful context for, first, categorizing the macro-scale geomorphology of the river system and, second, applying this knowledge to better understand its morphodynamics and evolution.

Some previous studies have examined geomorphic evidence for past flooding along the Limpopo. Dating of organic infills within abandoned ox-bow lakes in the lower part of the catchment shows episodes of flooding around mid-1200s AD, late 1300s, mid-1500s, and within the last century (Sitoe et al. 2015). Although the analysis in this study cannot inform on the timing of river floods or their specific impacts, the fact that partly-infilled meanders are present in the landscape 500–800 years after abandonment attests to the relict nature of at least some river landforms, and likely in headwater and middle reaches (Fig. 16.5) as well as in lowland areas.

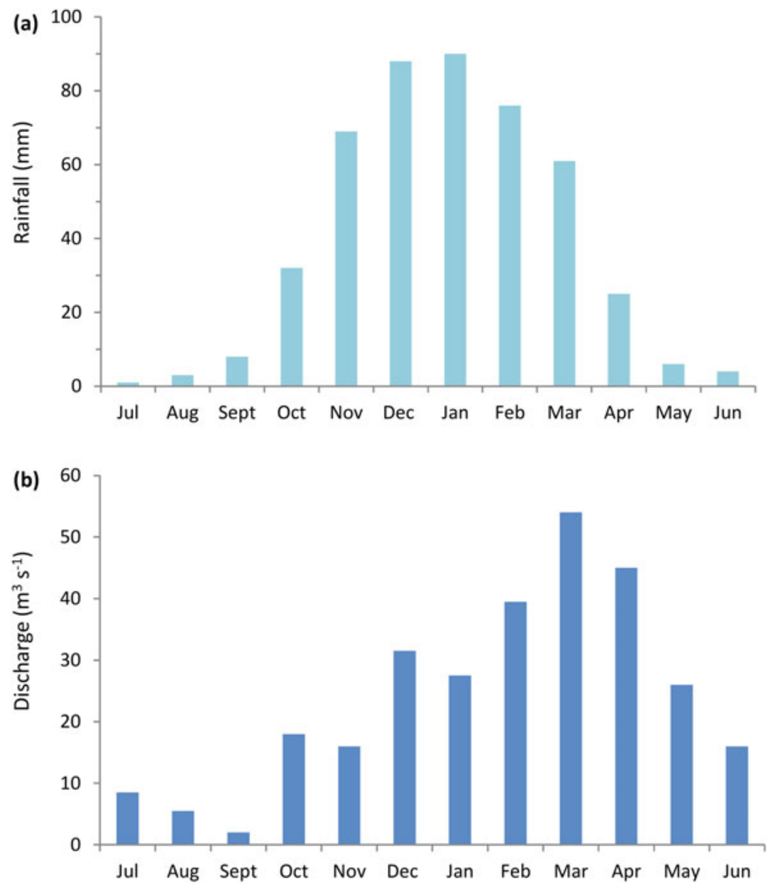

Fig. 16.4 Averaged monthly rainfall and river discharge data for the Limpopo River system, 1975–2014 (redrawn from Byakatonda et al. 2018b). **a** Rainfall (mm/month) averaged from three stations within the Botswana part of the Limpopo catchment (at SSKA, Mahalapye and Selebi Phikwe), and **b** river discharge at Buffel's Drift

16.6.2 Water and Flood Management in the Limpopo Catchment

Many studies have been concerned with water management along the Limpopo and its tributaries (Boroto 2001; Zhu and Ringler 2012; Meissner and Ramasar 2015; Oosthuizen et al. 2018b), and river basins themselves are viewed as the most suitable scale of analysis for river system and water management (Warner et al. 2008). Naturalized runoff (river discharge unimpeded by dams, irrigation or extraction) is significantly greater than the total recorded river discharge along Limpopo tributaries, because of the high water demand in the region. For example, the Ngotwane catchment, including urban centres such as Gaborone, loses 56% of its water by abstraction (FAO 2004). There is also high groundwater extraction from sandstone aquifers, resulting in reduced river baseflow. However, the amount of naturalized water varies considerably between catchments, with some increasing and others decreasing. For example, within the Limpopo system, the Lephalala experienced a decrease of 2% in the volume of naturalized water between 1920–1989 and 1920–2009 averaged values, whereas the Nzhelele catchment experienced an increase of 6% between these time periods (Bailey and Pitman 2016). The main reason is recent climate and human activity, not different datasets. Monitoring naturalized water flow is an important baseline against which to evaluate changes in water resource availability. This is also affected by cross-boundary transfer: for example, water export from South Africa to Botswana through the Limpopo River system is 102% of naturalized streamflow (FAO 2004).

Another important catchment factor is soil erosivity, mapped throughout the catchment by FAO (2004). In the Botswana sector, erosivity was mapped as moderate to high, likely reflecting the dry land surface, sparse vegetation, and high seasonal rainfall intensity. High soil erosivity values have implications for surface sediment yield into and through river channel systems, corresponding to the key role of flood events in driving river geomorphic change (Rountree et al. 2000; Jury and Lucio 2004).

16.7 Conclusions

The Limpopo River system is a significant drainage system in southern Africa but its geomorphology varies significantly between different tributaries and along its 1200 km-long main channel. Categorization of reach-scale geomorphology

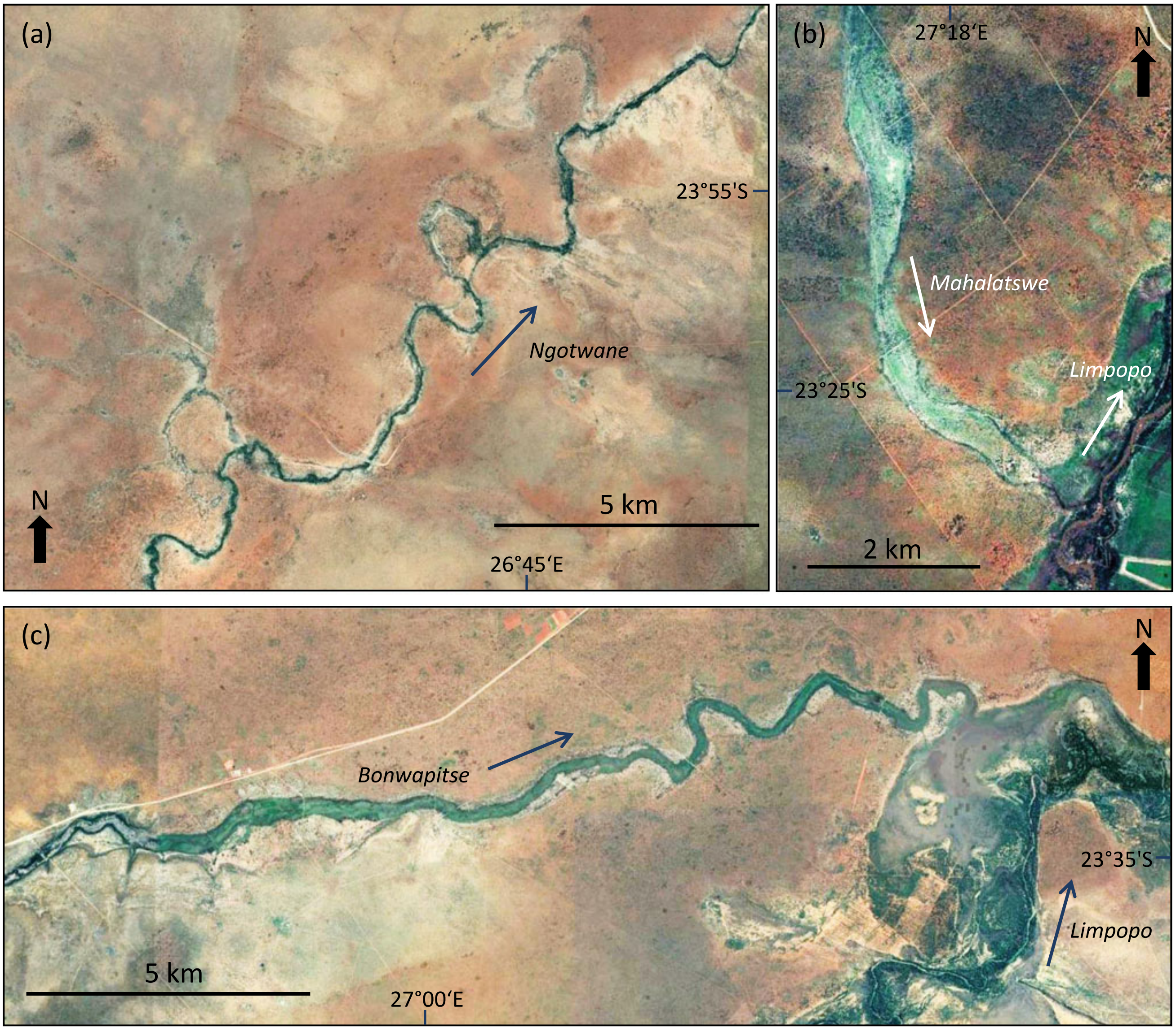

Fig. 16.5 Examples of river geomorphology within the Botswana sector of the Limpopo River catchment. Arrow indicates water flow direction. **a** Abandoned meanders along the Ngotwane River; **b** Mahalatswe River confluence with the Limpopo River; **c** Bonwapitse River confluence with the Limpopo River. *Image source* Google Earth, image date: 31 December 2016

using the River Styles Framework provides a baseline for evaluating both its morphodynamics and evolutionary history, and also for considering the potential impacts of flood events which may have significant negative impacts on both the river system and human activity. The approach adopted in this study can be used at a more detailed, local level with shorter reach lengths, and enables different rivers or reaches to be compared with one another. Limpopo River geomorphology in the Botswana sector of the catchment is also quite different to the Zambezi and Okavango drainages elsewhere within Botswana. This may have implications for how such diverse hydrological systems are compared, monitored and managed.

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Fig. 16.6 Panoramic view looking to the northeast at the Shashe–Limpopo confluence during **a** the dry summer season (date: 22 July 2014) and **b** the wet winter season (date: 13 February 2017). River flow is from left to right. Note the largely ephemeral Shashe (S) and perennial Limpopo (L). *Photos* Stefania Merlo

Fig. 16.7 View of Solomon's Wall in the lower part of the Motloutse River, Botswana. *Photo* Frank D. Eckardt

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