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Flood risk analysis of the Limpopo River basin through past evolution reconstruction and geomorphological approach

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Abstract

This research reconstructs the past evolution of the Limpopo River, a transboundary system located in south-eastern Africa, and describes its geomorphological settings through literature review and field work activities, with aim to analyse the risk of floods in the basin. Major changes have occurred since the late Jurassic – early Cretaceous period due to successive tectonic events. The paper demonstrates that the apparently abandoned drainage conformation of the palaeo-Limpopo in the upper and middle stretches of the river constitutes today preferential flood-prone areas in case of major rainfall events. An important palaeo-delta is identified in the lower Limpopo, which imposes a particular drainage pattern to the floodplain in Mozambique and influences the floods dynamics at present. The adopted method is helpful in determining flood risk in a data-scarce area showing complex fluvial dynamics, and allows identifying unsuitable locations for human settlements.

1 Introduction

The Limpopo River belongs to a transboundary basin located in the south-eastern Africa with its outlet in the Indian Ocean (see Fig. 1). Spaliviero et al. (2011) noted that human settlements tend to concentrate closer to river streams due to the semi-arid or sub-humid conditions of the basin. These authors indicate that a demographic increase was registered in recent decades in the Botswana and South Africa sections of the basin, in the delta area and along the main river channel in Mozambique, as well as in the upper reaches of the basin in Zimbabwe, often in areas prone to flooding. The greater human density in these areas increases the level of vulnerability. Therefore, it becomes important to propose scientific methodologies that allow identifying unsuitable areas for developing human settlements with a fair level of accuracy, using the limited data available, and which can take into account the complex flood dynamics of the river.

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Spaliviero (2003), while studying the Tagliamento River in northern Italy, concluded that flood hazards tend to concentrate in the same locations where past fluvial changes occurred, allowing the identification of areas under major risk. Similarly, this paper aims to perform a flood risk analysis in the Limpopo River basin based on a good understanding of its past and geomorphological characteristics.

As stated by Goudie (2005), a detailed and systematic understanding of the complex African drainage system still requires further investigation. This statement particularly applies to the southern Africa region. Specifically, we will try to answer the following question: do clear relationships exist between past fluvial changes and flood risk in the Limpopo River basin?

From a methodological perspective, the description of the river's past evolution is combined with a geomorphological approach. In particular, the paper investigates the role played by tectonics (as underlined by Blum and Tornqvist, 2000) in determining major changes of the Limpopo River. First, it reconstructs the past river's development through an in-depth literature review regarding the geological evolution of southern Africa since the late Jurassic – early Cretaceous period. Then, it collates data resulting from participatory land use planning exercises undertaken in the upper-middle Limpopo and geomorphological observations made in the lower Limpopo during a field visit, to analyse how palaeo drainage patterns are re-activated by the floods at present. For the lower Limpopo, the fairness of this analysis is tested by referring to the actual geographical extent of the flood events that occurred in the years 2000 and 2013. Finally, the paper discusses the relevance of the approach proposed and derives some conclusions.

2 The geological evolution of southern Africa since the Jurassic period and its influence on the Limpopo River's development

For a better understanding of the current fluvial geomorphological settings of the Limpopo River basin, one needs to revert to the late Jurassic – early Cretaceous period

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corresponding broadly to the Gondwana disruption (separation of the supercontinent and formation of the existing continents due to plate tectonics). The sequence of events which have successively changed the territorial morphology of southern Africa from the Jurassic to present consisted in cycles of erosion (Maufe, 1935; King, 1963; Lister, 1987; Partridge and Maud, 1987). According to the pioneering interpretation of Du Toit (1933), which has then been substantiated by the findings of Moore (1999), Moore and Blenkinsop (2002), Cotterill (2003) and Moore et al. (2007, 2008, 2009a, 2009b), the referred erosion cycles were primarily triggered by crustal movements determining periodically new drainage patterns. These movements were derived from complex plate tectonic dynamics associated with rifting processes and deep-originating mantle plumes, resulting in crustal flexuring or warping.

Volcanic eruptions of the Karoo, which Moore and Blenkinsop (2002) estimated to have occurred from the Permo-Carboniferous to the lower Cretaceous period in association with the Gondwana fragmentation, have provoked a major reorganisation of the drainage system in southern Africa. By that time the Karoo plume (see location in Fig. 2), which is linked to the opening of the Indian Ocean, initially imposed a westwards flowing drainage pattern due to its doming effect. This pattern was reverted 40 to 50 million of years later (approximately during the Early Cretaceous) to a dominantly eastwards flowing system, due to the opening of the Atlantic Ocean related to the Paraná plume (see Fig. 2). While referring to White (1997), Moore and Blenkinsop (2002) explain that such change of flowing direction was also magnified by the subsidence of the Mozambique plain during the same period as a result of sediment loading. The East still represents the dominant flowing direction of the fluvial system in southern Africa today, with Mozambique, located downstream, receiving nine international rivers in its territory.

Figure 2 is derived from the drainage reconstructions of Moore (1999), who based some of his deductions from early intuitions of Du Toit (1933), later confirmed by De Wit (1999), Moore and Larkin (2001) and Goudie (2005). It shows clearly that the palaeo-Limpopo River during the early Cretaceous period was by far the largest river of south-

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ern Africa, as it was also including the southeast-flowing Cuando, Okavango and Upper Zambezi Rivers as main tributaries. The latter, which was most probably linked to the Limpopo through the Shashe River (Moore and Larkin, 2001), was receiving waters from the Kafue and Luangwa Rivers originally flowing to a southwest direction (Moore and Blenkinsop, 2002).

Moore and Blenkinsop (2002) and Moore et al. (2007) indicate that the palaeo-Limpopo River entered the coastal plain of Mozambique by exploiting the corridor traced by the Botswana dyke swarm oriented along a east-northwest direction (see Fig. 2). This important geological feature, related to the disruption of Gondwana and its associated volcanism, further confirms the rift control over important and long-lived drainage lines (Potter, 1978; Moore et al., 2007, 2009a). In addition, Moore et al. (2007) highlight the parallel southeast and southwest pattern of this major river system, which again confirms an important geological structural influence on the drainage pattern.

In his influential article, Moore (1999), based on preliminary suggestions from Du Toit (1933), has identified three main axis of crustal flexure (see Fig. 3) that arose due to plate tectonics in southern Africa. These axes of uplifting, which define the divides of important river watersheds today, have much influenced the drainage evolution in the region by determining successive river cuts and river captures (Moore and Lankin, 2001). According to Moore (1999) and Moore et al. (2009b), they appeared in the following chronological order:

- *Late Jurassic – Early Cretaceous:* uplifting of the *Escarpment Axis* running parallel to the coastline and linked to the rifting process that initiated the break-down of Gondwana (Partridge and Maud, 1987). The formation of this major geological feature started the erosion cycles which produced the "African Surface" (as it is often referred to in scientific literature) for the region, on top of which were progressively deposited the sediments leading to the Kalahari formation.

- *Late Cretaceous:* uplifting along the *Etosha-Griqualand-Transvaal (EGT) Axis* further closing the southern margin of the Kalahari formation (which today is

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a desert) and triggering the sedimentation process in the Kalahari. The latter started to sink slowly due to subsidence and became a large basin. This Axis defines the southern limits of the Limpopo River basin by separating it from the Orange River system.

- *Late Palaeogene:* uplifting along the *Ovambo-Kalahari-Zimbabwe (OKZ) Axis* that has rejuvenated the main drainages and initiated the erosion of the coastal side of the flexure. This geological feature forms the local boundary to the Kalahari formation. Importantly, according to Moore (1999), the uplifting of OKZ Axis cuts across the line of the Okavango and was therefore responsible for breaking the link with the Limpopo River by the end of the Cretaceous period (see squared area in Fig. 3), as originally predicted by Du Toit (1933). As a consequence, the Okavango, Upper Zambezi (which included the Kafue and the Lwangua Rivers) and Cuando Rivers, all attached to the palaeo-Limpopo River, became a huge endoreic drainage system. The latter supplied sediment to the Okavango and Makgadigadi depressions, originally identified by Du Toit (1933) as part of the Kalahari basin. Both the Upper Zambezi and the Cuando Rivers would then be captured by the Lower Zambezi during the Upper Pleistocene (Moore and Larkin, 2001; Moore et al., 2007).

The inferred ages of the above-described axes of flexure correspond to three major peaks in volcanic activity in the region (Moore, 1999). In addition, parts of these axes have increased their height during the Plio-Pleistocene period along a northeast-southwest direction (King, 1963; Partridge, 1998). This means that the more recent crustal flexures are probably associated with the continuation of the Great Rift Valley, which may determine an additional break-up of the African continent in the future. Therefore, it is suggested that these phenomena (volcanism and recent crustal flexuring) are linked to a common underlying tectonic/geological process (Moore, 1999).

Importantly, the three identified axes of flexure, namely the Escarpment Axis, the EGT Axis and the OKZ Axis, show a sequential uplifting according to a concentric

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pattern developing further inland (Moore, 1999). This triggered successive river rejuvenation on the coastal side of each axes of flexure, and hence activated the previously mentioned cycles of erosion (Moore et al., 2009b).

3 Linkages between the geomorphological evolution of the upper-middle Limpopo River and the risk of floods

The following scientific observations provide evidence of the disruption of the palaeo-Limpopo River due to the uplifting of the above-mentioned OKZ Axis of crustal flexure during Late Cretaceous – early Tertiary period:

- While the isopachs of the sub-Kalahari valley show a northwest flowing direction of the now abandoned Okavango River, the distribution of the ilmenites derived from the Orapa kimberlite field located to the north implies that this river originally flowed towards the southeast direction (Moore, 1999).
- The uplifting of the OKZ Axis determined several abandoned tributaries to the Limpopo, especially in Bostwana up to the border with Zimbabwe. There are braided river channels showing a width and gravels' size which cannot be explained by an ephemeral flow, thus constituting evidence that they were part of a major drainage system (Moore and Larkin, 2001).
- Moore et al. (2007) provide scientific references showing the occurrence of common fish and plant species between the Okavango and the Limpopo Rivers, which confirm that they belonged to the same drainage system in the past.

Figure 4 shows the probable paths followed by the Okavango, Cuando and Upper Zambezi Rivers when they were still major tributaries of the palaeo-Limpopo River during the Cretaceous period.

Participatory land use plans were prepared in various locations of the Limpopo River basin during a sub-regional project implemented between 2004 and 2007 by the United

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Nations Human Settlements Programme (UN-Habitat) in collaboration with the United Nations Environment Programme (UNEP). More details about this initiative can be found in Spaliviero et al. (2011). Each riparian country was requested to select particularly flood-prone settlements to implement this activity. The Government of Botswana indicated Shoshong village (see location in Fig. 4), which is crossed by a homonymous river system that reaches the Bonwapitse River, a tributary of the Limpopo River.

According to the information collected by Mpho (2007), Shoshong is regularly affected by flash-floods during the rainy season. Major events occur every five years in average since the 1990's, provoking severe loss of crops, livestock, physical property and sometimes even human life. In fact, this settlement of approximately 10 000 inhabitants is located in the middle of a former wide and important fluvial braiding system belonging to the Okavango River before the raise of the OKZ Axis of crustal flexure. The map in Fig. 5 shows clearly the high level of risk of Shoshong, with most of its built-up area lying in the flood plain (see also Fig. 6). The Shoshong River, despite being dried over long periods of time, can suddenly reactivate after persistent rainfall. This occurs essentially because its current geomorphological settings are the result of a much more important fluvial regime in the past, when the Okavango was a major tributary of the palaeo-Limpopo River. Therefore we can conclude that most of Shoshong settlement is located in an area prone to endemic floods.

Moore and Larkin (2001) infer that the important width of the floodplain of the Shashe River at its confluence with the Limpopo (more than 2 km – see Fig. 7) can be explained by the former course of the Cuando River. It maintained a southeast course and was part of the palaeo-Limpopo River (see Fig. 2) before being captured by the Zambezi drainage system as consequence of the uplifting of the OKZ Axis of flexure.

Similarly to what has been observed in Shoshong in Botswana, the confluence of the Shashe River is considered to be one of the most vulnerable locations to flooding in Zimbabwe along the Limpopo River today. This is confirmed by the participatory land use plan regarding the Shashe study area prepared by Murwira et al. (2006) within the framework of the mentioned UN-Habitat/UNEP Limpopo project. The local communities

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reported the loss of property, crops and destruction of infrastructure due to recurrent flooding. Figure 8 shows clearly that approximately 65 % of Shashe's population lives in areas of high flood hazard risk.

4 Linkages between the geomorphological evolution of the lower Limpopo River and the risk of floods

According to Du Toit (1933) a great part of the plain lying in southern Mozambique (hereafter referred as the "southern Mozambique Plain") is built of Cretaceous, Tertiary and Pleistocene sediments which have been raised above the sea level. These sediments result from river deposits that occurred during different geological periods, particularly as consequence of the successive erosion cycles induced by the crustal uplifting events. A chronological description of the past events leading to the formation of the southern Mozambique Plain, where the lower Limpopo River has been flowing since the Jurassic period, follows:

- As mentioned earlier, the Limpopo River has entered the southern Mozambique Plain by exploiting the crustal opening made by the Botswana dyke swarm in association with the Gondwana break-up (Moore and Blenkinsop, 2002; Moore et al., 2007), as shown in Fig. 2. Therefore, this fluvial system has been building up the southern Mozambique Plain through successive erosion periods by flowing mainly through that same corridor (where the Pafuri settlement can be found today) during at least the past 130 to 150 million of years. This had important implications for the geomorphological settings of the lower Limpopo River, as it facilitated the formation of a mega fluvial delta.

- Moore and Larkin (2001) refer to the presence of a prominent seaward bulge in the coastal plain of Mozambique lying between Beira and Maputo. They indicate that a sequence of sediments of 1.3 to 2 km thickness dating from the disruption of Gondwanaland (Jurassic to lower Cretaceous) can be found in the middle of

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the plain, parallel to the coastline. Much earlier, Dixey (1955) explained that the great thickness of Cretaceous terrestrial sediments observed in this area show that the coastline at that time was located much further east compared to its current location. This is consistent with the fact that the palaeo-Limpopo River was by far the most important fluvial system of southern Africa at that time, bringing huge loads of sediments to the eastern coast and progressively building up the southern Mozambique Plain. Accordingly, Burke (1996) indicate that this ancient river formed an important delta during the Jurassic-Cretaceous period (see Fig. 9). We note with interest that this palaeo-delta is proportional to the size the river basin had during that period. It is our opinion that there can be no other explanation for the formation of such a huge deltaic system. When referring to the thermal history data of organic material collected in deep wells in the southern Mozambique Plain, Burke and Gunnel (2008) confirm that, stratigraphically, the upper part of the delta complex started to form during the early Jurassic. These authors, by citing Wilkinson (2004), also mention the existence of a megafan in correspondence to the lower Limpopo River, together with other fourteen megafans scattered all over the African continent, which have not yet been sufficiently investigated.

– As mentioned earlier, the coastal plain of Mozambique started to progressively sink by the early Cretaceous due to the enormous amount of sediments deposited (White, 1997). This is again consistent with the great size of the palaeo-Limpopo at that time, and confirmed by the data presented by Burke and Gunnel (2008).

– Moore and Larkin (2001) refer to a net reduction of sediment supply to the southern Mozambique Plain by the lower Tertiary. This probably corresponds to the beginning of the uplifting process of the OKZ Axis of crustal flexure during the late Palaeogene suggested by Moore (1999), cutting off the Okavango, Cuando and Upper Zambezi Rivers from the Limpopo River basin. This is also confirmed by Salman and Abdula (1995) who state that there was no active Limpopo delta during the early Cenozoic (approximately between 65 and 30 million of years ago). According to Moore et al. (2009a), the uplifting of the OKZ Axis then rejuvenated the drainage system and provoked a new cycle of erosion determining an increase of sediment supply during the Oligocene period. This triggered the displacement of the Limpopo River mouth southwards during the same period (Moore and Larkin, 2001). We suggest that any drainage modification of the lower Limpopo River, as consequence of crustal flexuring events which occurred after the existence of the palaeo-Limpopo River, could most probably not escape from the morphological conformation imposed by the huge delta or megafan of such an ancient river.

– The last major geological event which influenced the overall morphology of the southern Mozambique Plain was probably the general uplifting which occurred during the Plio-Pleistocene period (Maufe, 1935; Moore, 1999; Moore and Larkin, 2001). Partridge (1998) mentioned the uplifting of the Ciskei-Swaziland (C-S) Axis of crustal flexure during the same period, which is located between the Great Escarpment Axis and the current eastern coastline of southern Africa (see Fig. 2). This must have been an abnormally swift process raising the Tertiary sediments (Du Toit, 1933; Moore and Larkin, 2001), which were previously submerged and reworked by the sea, to form the present coastal plain. Such an uplift is also confirmed by Salman and Abdula (1995). Lister (1987) identified young Pliocene age sedimentary surfaces in the Mozambique Plain, most probably formed by an additional drainage rejuvenation triggered by the raising of the same C-S Axis. Interestingly, Du Toit (1933) explains the high speed of this general uplift by describing the topographical profile of the main southern African rivers crossing this Axis. This profile is slightly convex upwards, which proves that the erosional process has been slower than the uplifting. Furthermore, the series of parallel sea terraces indicated in Fig. 9 are probably features resulting from this rapid uplifting process.

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In October 2009, the authors of this paper conducted fieldwork in the lower Limpopo to examine the geomorphological settings of the area. Their findings, presented below according to four river stretches starting from the apex of the megafan to the Indian Ocean (see Fig. 9), confirm most of the aspects mentioned above.

4.1 Stretch 1: from the mega-delta apex to south of Mabalane

At the megafan apex we observed not fully consolidated conglomerates, probably dating from the Tertiary (see Fig. 10). The weathered, incised and terraced river gravels are possibly associated with the crustal uplifting that occurred during the Pliocene-Pleistocene period. This is much older than the terrace observed in the Macarretane area (see Fig. 9). Several river cuts are observed along the road Macarretane – Vila Eduardo Mondlane, especially to the North and South of the Mabalane area. These cuts were determined by the floods, showing a fluvial tendency to reactivate the palaeo-deltaic system.

4.2 Stretch 2: from the Olifants – Limpopo Rivers' confluence to Chókwè

In the lower Limpopo area, the confluence with the Olifants River represents a critically vulnerable location. In fact, fieldwork and interview with the local population confirmed that the settlements in that area, in particular Tchauque and Macaringue (see map in Fig. 9) were completely surrounded by water during the 2000 floods. The latter flood event will be described with more detailes in the next section.

A photo taken close to the confluence (see Fig. 11), where a data gauging station is located, shows the elevation reached by the high water mark. A closer interpretation of the relief of the confluence indicates that most probably the riverbed followed a different path in the past, slightly to the West of its current position, as interpreted in Fig. 9. This old path is reactivated in case of major floods, as it occurred in February 2000. The quantity, size and depth of round boulders found deposited in the quarries close to the confluence (see Fig. 12) and at Macarretane confirm that the Limpopo River at this stretch was a much larger fluvial system in the past.

4.3 Stretch 3: from Chókwè to Xai-Xai

In this stretch we find a complex system of elevated and old sandy levees (see Fig. 13). On top of these levees, which run parallel to the fluvial system, are located the first organised human settlements of the lower Limpopo in correspondence to the Bantu's migration to southern Africa, which occurred approximately 3000 yr ago. Interestingly, the levees also host the burial site of the heroic traditional leader Ngungunhane (1895). These geomorphological features represent elevated and secure locations away from the flood risk areas, thus a higher concentration of human settlements can be found there, including a railway system built by the Portuguese during the colonial times.

The settlement process was accompanied by a change in land use shifting from forest to agriculture. The deforestation provoked ravine erosion -contributing to sedimentation- which is very pronounced still today, especially in the Chibuto area, a compacted old dune system.

The area of confluence between the Changane and the Limpopo Rivers (see Fig. 9) is particularly complex from a topographic point of view, and highly susceptible to flooding (see Fig. 15). It is a large depressed area, probably due to the subsidence process caused by the load of sediment since it corresponds to a critical depositional area of palaeo-delta. In fact, during the 2000 floods, people observed that the water tends to flow from the Limpopo towards the Changane River and not the opposite. A multitude of large abandoned meanders can be found in this stretch, again confirming the presence of a much bigger fluvial system, part of the megafan.

4.4 Stretch 4: from Xai-Xai to the Limpopo River's outlet

The territorial morphology of the lowest part of the Limpopo River shows a strong marine influence. A complex and consolidated sand dune system distributed along the coastline seems to have deviated the river from its original southwards course towards the southeast direction to reach the Indian Ocean, as shown in the map in Fig. 14. In fact, during the dry period the sea tide influence reaches beyond Xai-Xai, the capital of Gaza Province located some 15 km away from the coast. Therefore, some important irrigation schemes can be observed in this area, which are provided with sluice systems to protect the agricultural crops from salty water invasion. Several of these irrigation schemes were completely destroyed during the 2000 floods.

The map shown in Fig. 14, which is derived from fieldwork and satellite image interpretation, describes both the dynamics and the extent reached by the waters during this flood event. The dykes were broken by the spinning force of the floodwaters which formed river wheels. As a result the community living on top of the sand dune of Chilaulene, located in the middle of the floodplain, was flooded from river waters coming from different directions and completely isolated for weeks. Mapping the flood dynamics allows better planning of flood mitigation measures.

5 Analysis of the 2000 and 2013 flood events in the lower Limpopo River and matching with the interpreted geomorphological conformation

A careful analysis of the geographical extent of the 2000 floods allows obtaining a better understanding of the flood risk of the southern Mozambique Plain. It also helps establishing linkages with the past geomorphological evolution of the plain described in the previous section. This dramatic event caused more than 700 deaths, displacing approximately 500 000 people and affecting a total population of two million people (Kundzewicz et al., 2002).

In the radar satellite image in Fig. 15, the flooded areas appear in dark while the maximum extent reached by the floods is indicated by the white arrows. To facilitate their identification, the maximum extent of the 2000 floods were digitised in blue in the Figure. It is noted that in addition to the typical invasion of the larger floodplain along the lower Limpopo River itself, the topographically lower eastern part of the identified

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palaeo-delta has been the most affected area by the 2000 floods, especially along the Changane River, a major tributary. The map presented in Fig. 16 confirms this pattern, which extends southwards to the right bank of the Limpopo River. This corresponds to the area south of Chókwè appearing whitish in Fig. 15 (see maximum extent of the floods).

To verify the accuracy of this interpretation, we now analyse the floods that occurred in January and February 2013 in the same area of the basin. This event determined approximately 50 deaths and displaced around 150 000 people (OCHA ROSA, 2013). Interestingly, these floods followed the same dynamics of the 2000 event. Once again floodwaters have concentrated along the lower area delimited by the mega palaeo-delta described above (see Fig. 17), which was built up millions of years ago when the Limpopo River basin was three to four times its current size.

Therefore, the territory defined by the northwest-southeast oriented triangular shape of the palaeo-delta can definitely be considered vulnerable to flooding. In fact, it is the opinion of the authors that the whole drainage system which is composed by the Rivers Chigombe, Panzene, Sangutane, Maqueze, Mabengane and Chichacuarre, all ending into the lower Changane River and showing a north-south orientation before reaching the lower Limpopo River, are simply defining the shape of this very ancient deltaic complex (see Fig. 9). It would not be surprising if most of this drainage system is alimented by the waters of the Limpopo River via sub-surface groundwater flow.

Importantly, Fig. 15 shows clearly that the identified flooded areas also correspond to the highest concentration of human settlements. This can be explained by the human dependency on agricultural activity (there are the most fertile soils) and the basic need to live close to fresh water.

6 Discussion and conclusion

The complexity of fluvial dynamics and of the morphological settings of any river basin, as well as the difficulty to reproduce the effects of anthropogenic intervention and of extreme flood events, are factors that limit the adoption of spatially distributed dynamic modelling for improving flood risk management at basin level. Baker and Twidale (1991) affirm that "theoretical models may fail to account for the field evidence and the larger spatio-temporal domain". This view is also supported by Baker (1994) and Pilkey and Pilkey-Jarvis (2007).

The development of flood dynamic models requires gathering a huge amount of data (Parker et al., 2008) during a consistent number of years, and the use of many variables (Hickin, 1983). Access to accurate data is often a problem (Fohrer, 2003), particularly in developing countries, as it involves high costs and adequate institutional capacity. Large basins channel response to a particular impact in a given time period is contingent upon all previous events (Wallick et al., 2007; Pahuja and Goswami, 2006). Threshold phenomena, which cause a rapid and often unpredictable change of state in systems, as it occurs for river channels (Newson, 2002), provide additional levels of complexity and simulation results become difficult to control (Kauffman, 2002; Parker et al., 2008).

Therefore, alternative flood risk assessment and management approaches need to be explored at river basin level. Steinberg (2004) acknowledges that, unfortunately, Man's perception of the river flow is limited and not consistent with a river's dynamic flooding and meandering history. In fact, to manage rivers and their related flood risk adequately, it is important to understand their evolution and nature, which can be done by investigating their past. Geomorphological flood analysis results from a long tradition of studying real processes operating in historical times, which are recorded in the sediments, landforms and erosional scars of past floods (Baker, 1994). As indicated by Gilvear (1999), fluvial geomorphology has the ability to recognise the significance of both ancient and active landforms as indicators of levels of landscape stability.

This paper shows that the Limpopo River is a drainage system located in south-eastern Africa exhibiting complex geomorphological settings, which result from a series of tectonic activities that have occurred since the late Jurassic period. Apparently abandoned valley floors of the ancient hydrography of the river, which was a much larger

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fluvial system during the Early Cretaceous, are today preferentially occupied by the floodwaters. Particularly vulnerable areas are the broken links between the Limpopo River and the Okavango, Upper Zambezi and Cuando Rivers such as Shoshong in Botswana and Shashe in Zimbabwe. Another very flood-prone territory is most of the area corresponding to the huge palaeo-delta identified in the Mozambican floodplain, which has imposed a peculiar drainage pattern shown by the Shangane River and its tributaries before joining the lower Limpopo. The influence of this important morphologic feature on the flood dynamics was clearly revealed by the geographical extent reached by the most devastating event of the last 50 yr which occurred in 2000, and was recently confirmed during the 2013 flood event. Similar flood risk analysis methods were described by Baker et al. (1988) and Kenny (1990) for data-scarce areas.

Therefore, in reply to the research question of this paper, the authors conclude that there are definitely clear relationships between the past fluvial changes and flood risk in the Limpopo River basin. The description of the past river's evolution combined with a geomorphological approach demonstrate, as per what Spaliviero (2003) suggested for the Tagliamento River in northern Italy, that flood hazards tend to concentrate in the same locations where major fluvial changes have occurred. Accurate and reliable flood risk information is essential to adequately apply flood mitigation measures in a given territory and to prepare a land use plan for developing human settlements with reduced vulnerability to this natural hazard.

The Limpopo River basin can be defined as relatively scarce in data, especially when referring to hydraulic and topographic data, which are commonly used to run dynamic flood simulations through spatial models in a Geographic Information System environment. The method proposed allows, when considering the natural complexity of the flood dynamics of a transboundary river such as the Limpopo, identifying unsuitable areas for developing human settlements, which are exposed to high flood risk connected to the past morphology of the river. The same method could be apply in other river basins of the developing world, showing complex flood dynamics.

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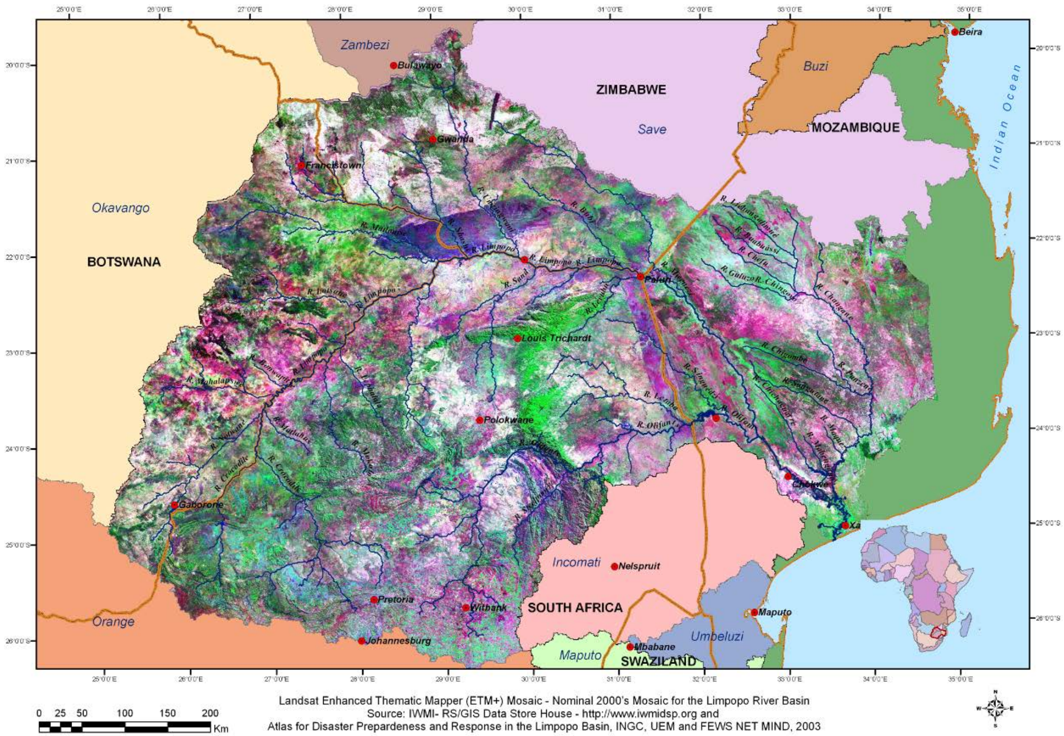

Fig. 1. Satellite image mosaic of the Limpopo River basin (Source: Maló, S., and Da Conceição, P.J.: Mapping and Spatial Analysis Results, UN-Habitat/UNEP Limpopo Project, unpublished, Nairobi, Kenya, 28 pp., 2007).

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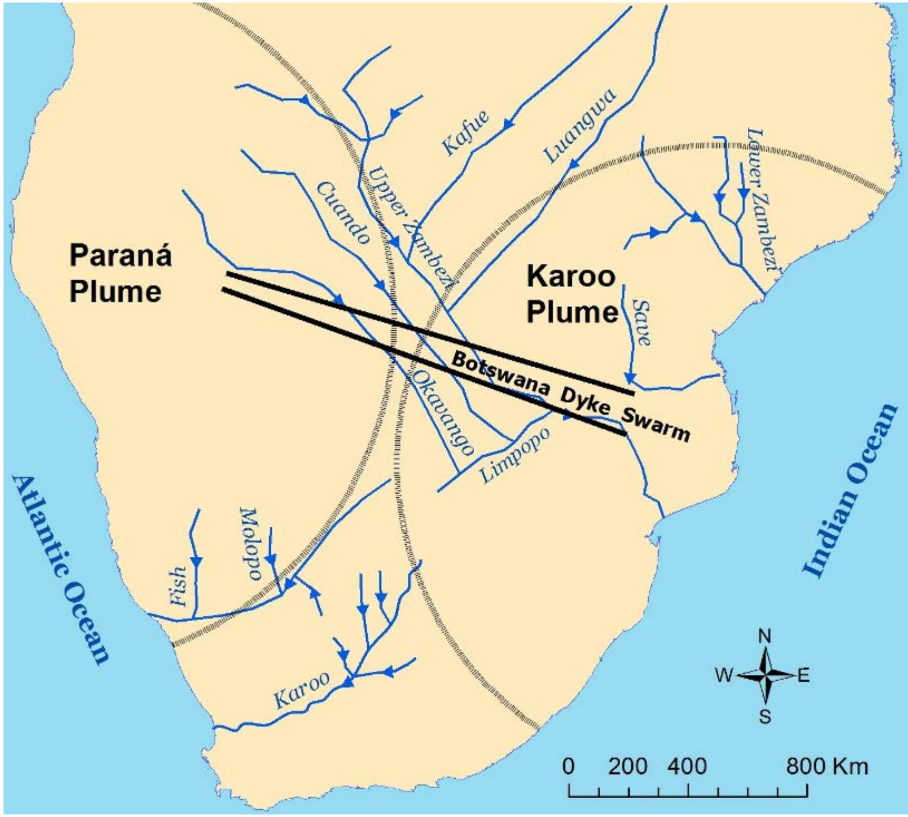

Fig. 2. Main drainage system of southern Africa during the Early Cretaceous period (Adapted from: Moore, 1999).

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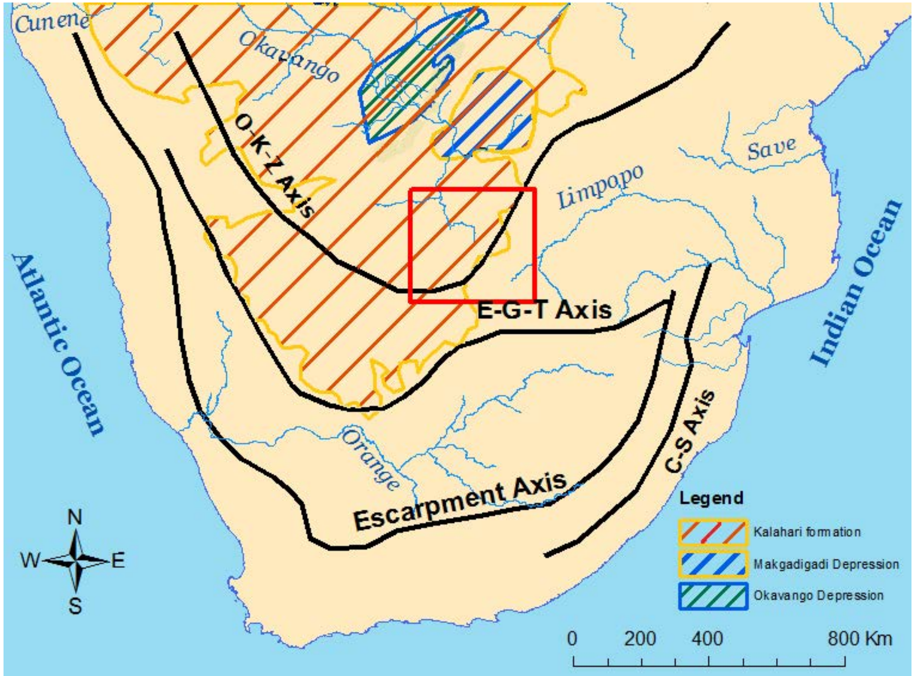

Fig. 3. Axes of crustal flexure of southern Africa defining the major water divides (Adapted from: Moore, 1999).

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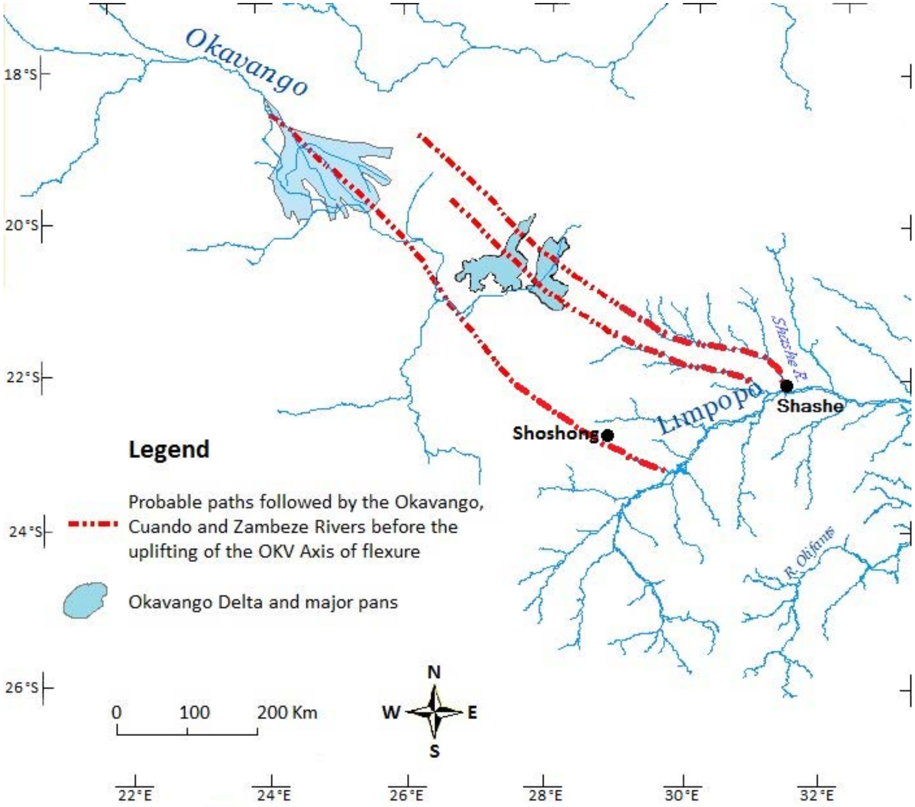

Fig. 4. Probable paths followed by the Okavango, Cuando and Zambezi Rivers when they were still major tributaries of the palaeo-Limpopo River (Adapted from: Moore and Larkin, 2001).

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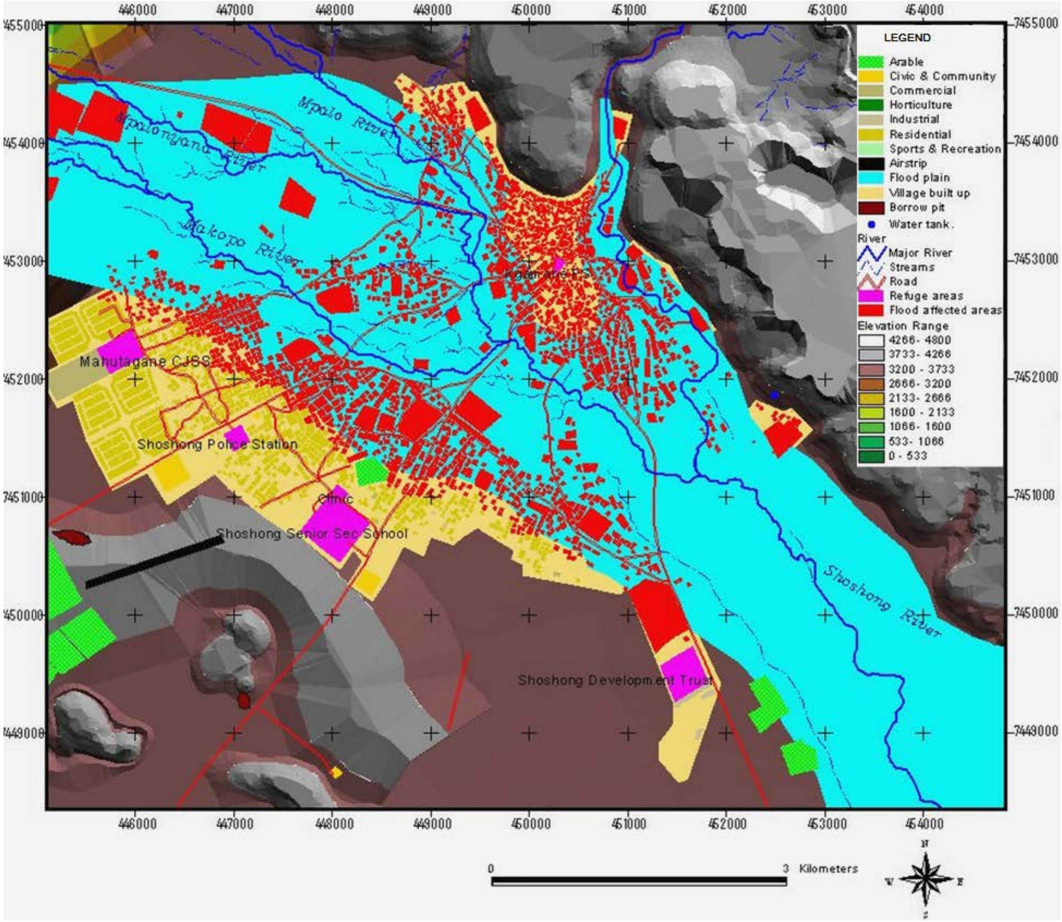

Fig. 5. Flood risk map of Shoshong settlement, Botswana (Source: Maló, S., and Da Conceição, P.J.: Mapping and Spatial Analysis Results, UN-Habitat/UNEP Limpopo Project, unpublished, Nairobi, Kenya, 28 pp., 2007).

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Fig. 6. Abandoned houses in the Shoshong floodplain (Photographer: Mpho, 2007).

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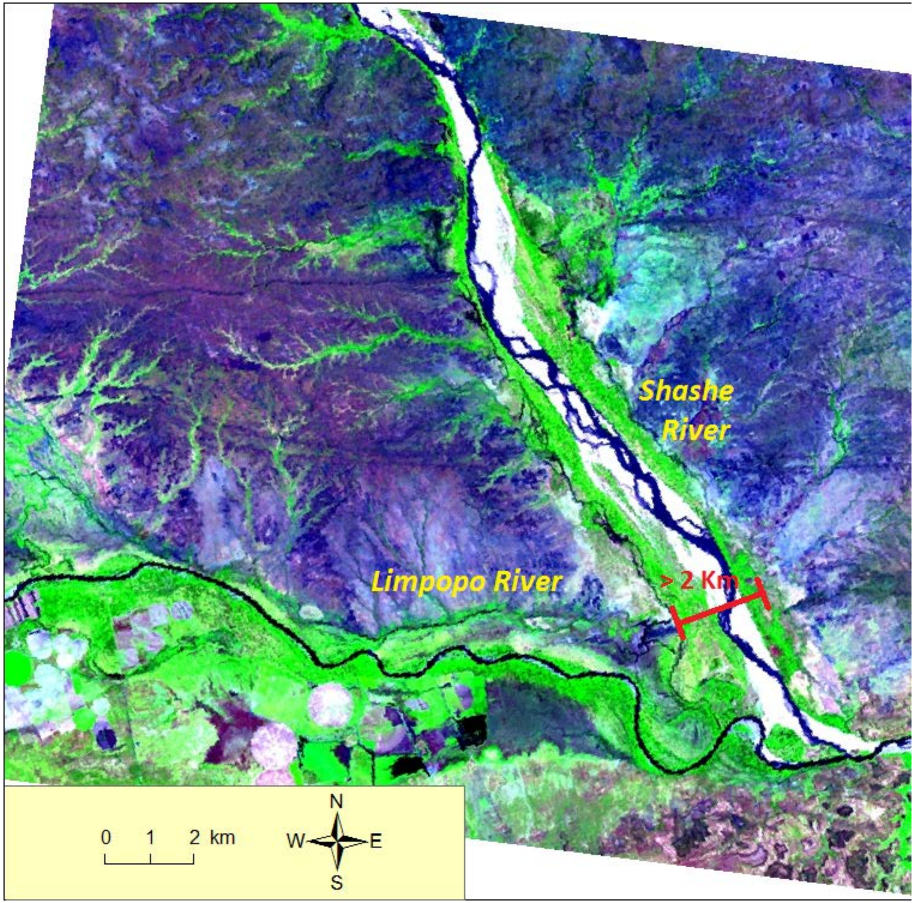

Fig. 7. False colour-composite Landsat 7 image of 2000 showing the confluence between the Shashe and the Limpopo Rivers.

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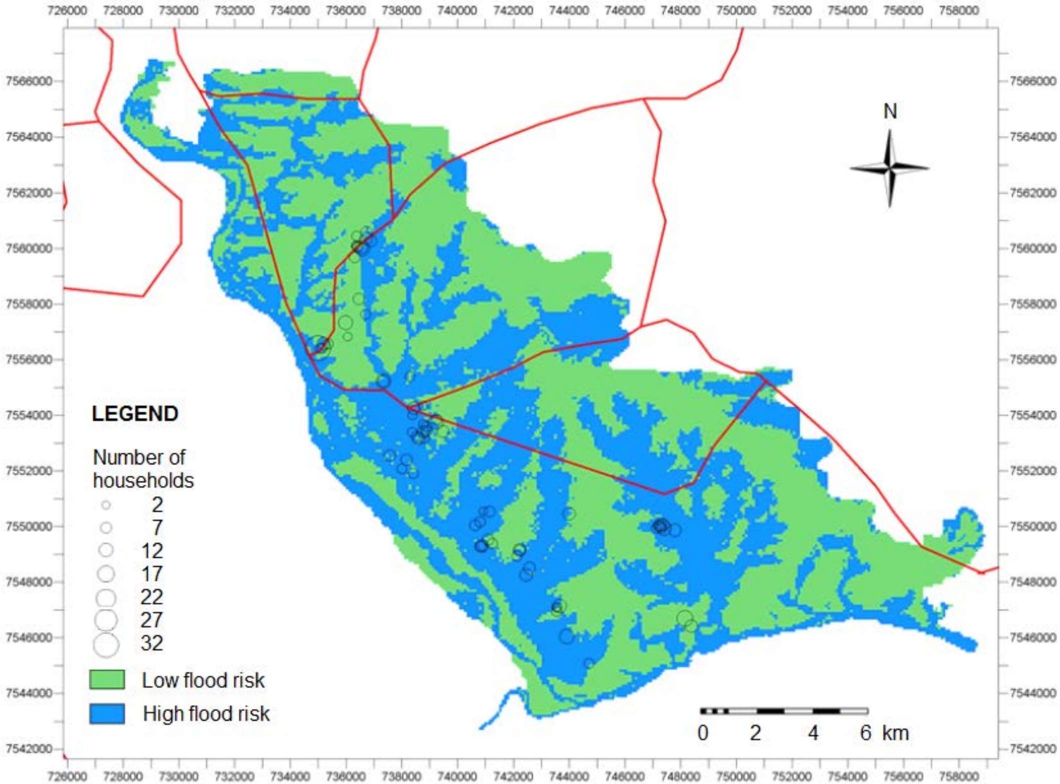

Fig. 8. Flood risk map of Shashe area (Source: Murwira et al., 2006).

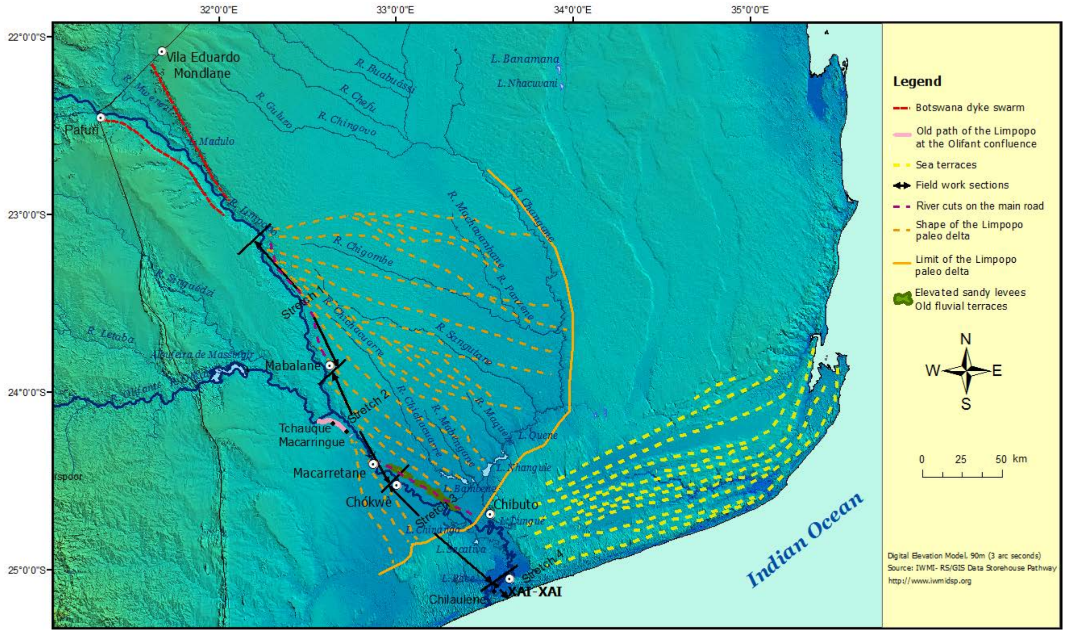

Fig. 9. Main geomorphological features of the lower Limpopo River.

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Fig. 10. Weathered, incised and terraced river gravels at the apex of the megafan (Photographer: De Dapper, 2009).

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Fig. 11. High water mark at the Olifants-Limpopo confluence (Photographer: De Dapper, 2009).

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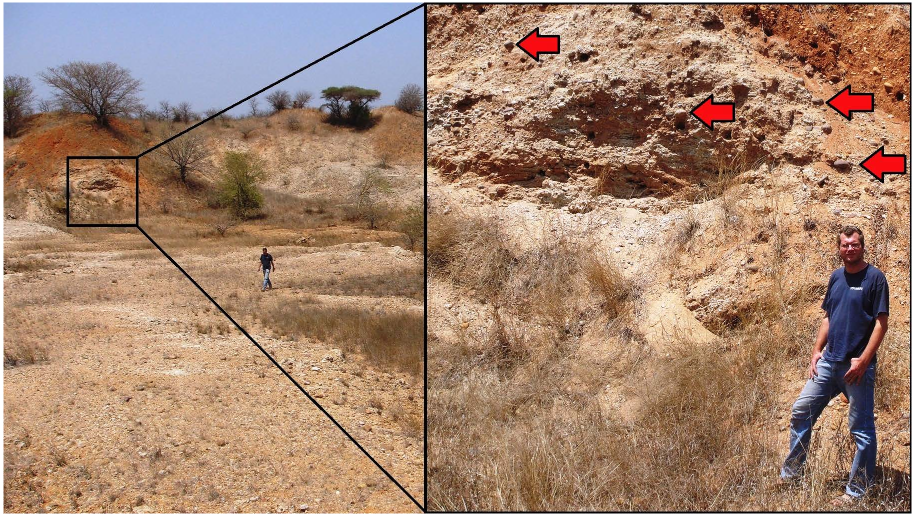

Fig. 12. Round boulders deposit at a quarry close to the Olifants River's confluence (Photographer: De Dapper, 2009).

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Fig. 13. The Limpopo River flowing next to Chibuto; elevated sandy levees can be observed at the horizon on the right side, as indicated by the red arrows (Photographer: De Dapper, 2009).

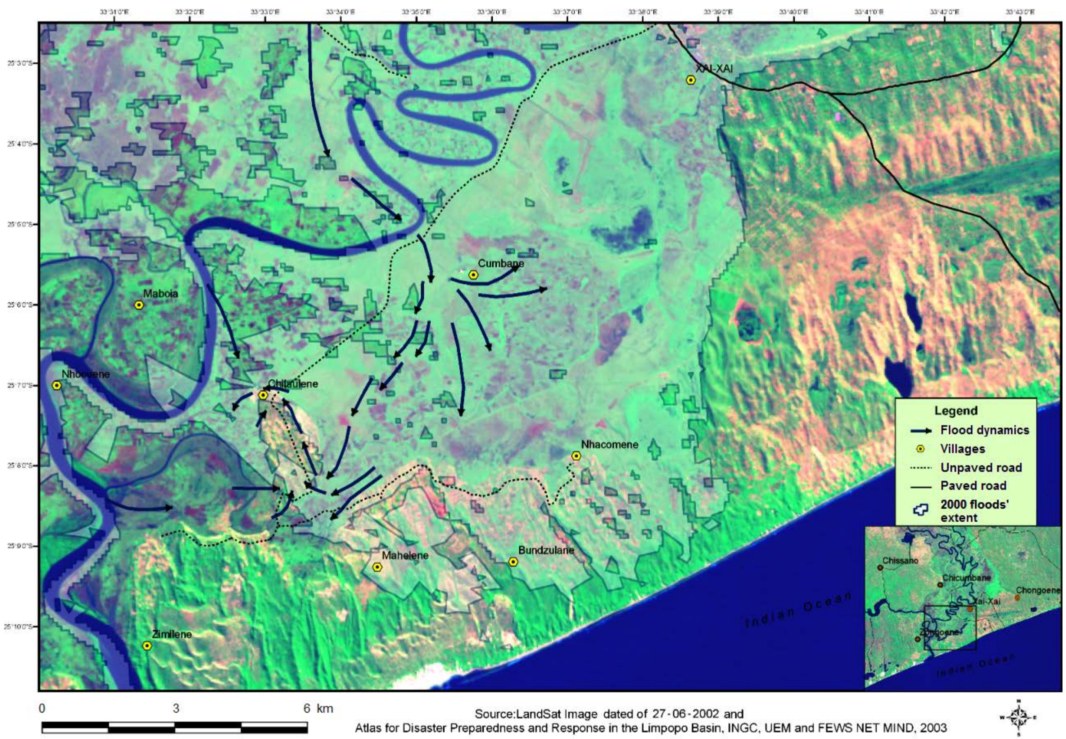

Fig. 14. Description of the 2000 floods' dynamics in the last stretch of lower Limpopo (Source: Maló, S., and Da Conceição, P.J.: Mapping and Spatial Analysis Results, UN-Habitat/UNEP Limpopo Project, unpublished, Nairobi, Kenya, 28 pp., 2007).

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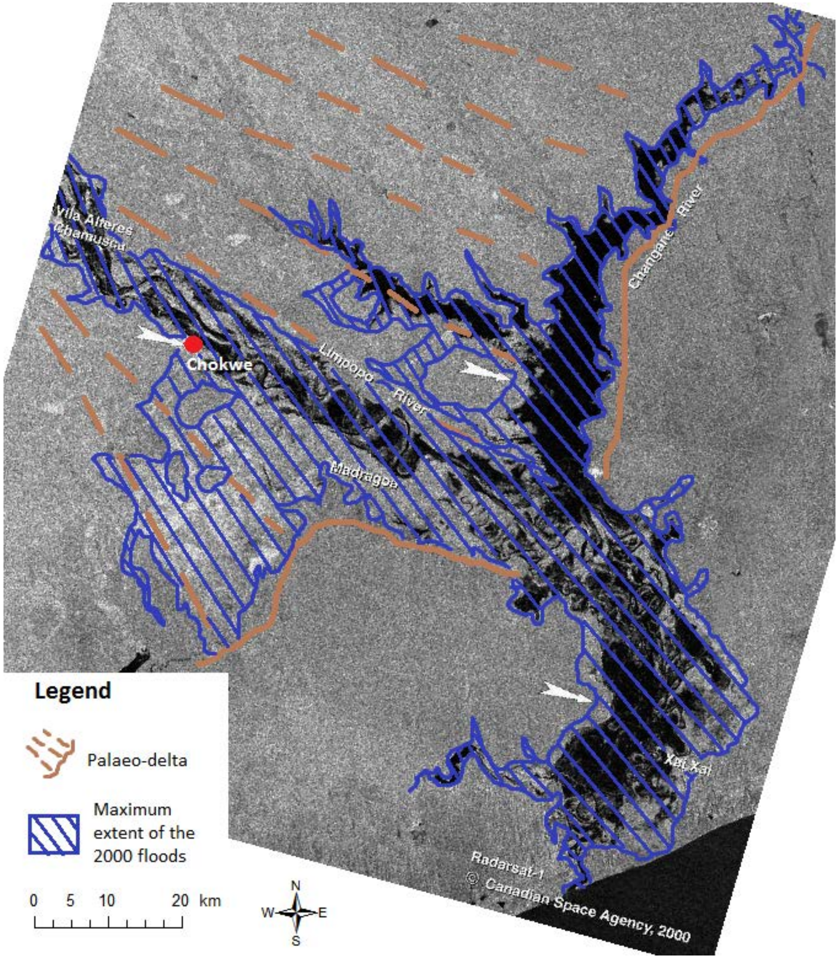

Fig. 15. Radarsat-1 image recorded on 28 February 2000 showing the maximum extent of the 2000 floods affecting the lower Limpopo.

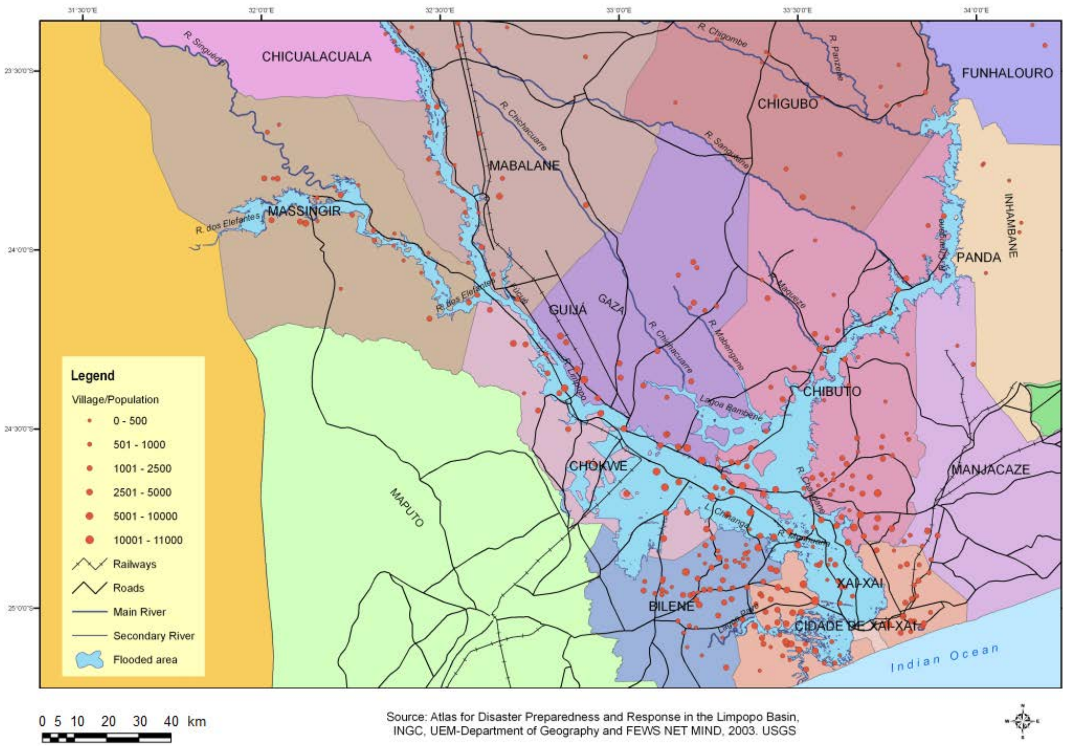

Fig. 16. Maximum extent of the 2000 floods in Mozambique (Source: INGC, UEM, FEWS NET MIND: Atlas for Disaster Preparedness and Response in the Limpopo Basin, Maputo, Mozambique, 156 pp., 2003).

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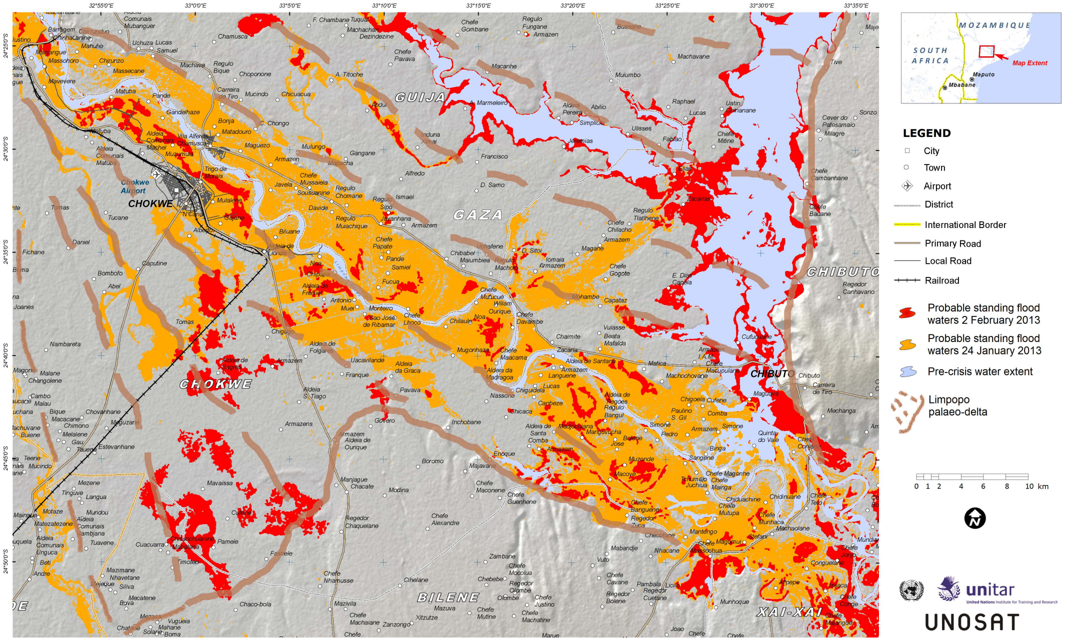

Fig. 17. Analysis of the 2013 flood extent in the lower Limpopo River through satellite image interpretation (Adapted from: http://www.unitar.org/unosat/maps/MOZ, accessed on 02 February 2013).

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