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ORIGINAL PAPER

River and landslide dynamics on the western Tanganyika rift border, Uvira, D.R. Congo: diachronic observations and a GIS inventory of traces of extreme geomorphologic activity

J. Moeyersons · Ph. Trefois · L. Nahimana · L. Ilunga · I. Vandecasteele · V. Byizigiro · S. Sadiki

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Abstract Uvira occupies a series of narrow alluvial fans squeezed between the NW corner of Lake Tanganyika (±710 m asl) and the W-shoulder of the Tanganyika rift, the Itombwe–Mitumba Plateau (±3,000 m asl). In 50 years, the fans progressed into the lake over distances up to some hundreds of metres. This happened during a few catastrophic flash floods issued from the torrents which cascade from the rift shoulder with a mean longitudinal gradient of 0.2 m m^{-1}. The last event in 2002 led to the destruction of parts of the town and to some 50 casualties. Landslides occurred in the hills. On the base of stereoscopic interpretation of aerial photographs from 1959, complemented with data from 2000 ETM and 2004 IKONOS imagery, a geographical inventory has been made of strongly incising ($10^{-1 \text{ to } 0}$ m in 43–45 years) river sections, of all types of landslides and of all tectonic structures, visible in the rugged hinterland of the fans. Traces of active N–S as well as E–W trending faults are present. Some of these faults and some surfaces, interpreted as degraded fault facets dip at angles of 40° or less and are probably remnants of formerly active lystric extension faults, originally at a depth of some 2 km, but now at the surface as a result of posterior uplift and erosion. Sixty landslides could be identified. Six slides fall far below the topographic threshold envelope, where the slope at the incision head is expressed as a function of drained surface. Therefore, they are considered to be seismic in origin. Most of the other landslides are located along strongly incising river sections. Temporary landslide barriers contribute to irregular river hydrographs. It is concluded that Uvira is threatened by landsliding, potentially massive (>18 × 10^6 m^3 debris), in the case of heavy seismicity. It is further discussed that the regularisation of the

J. Moeyersons (✉) · Ph. Trefois · I. Vandecasteele
Royal Museum for Central Africa, 3080 Tervuren, Belgium
e-mail: jan.moeyersons@africamuseum.be

L. Nahimana
University of Bujumbura, B. P. 2700, Bujumbura, Burundi

L. Ilunga · V. Byizigiro
Kigali Institute of Education, Kigali, Rwanda

S. Sadiki
Université Officielle de Bukavu, Bukavu, RD Congo

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river regime depends on soil and water conservation strategies, to be developed in the headwaters of the torrents Kavimvira, Mulongwe and Kalimabenge.

Keywords Mass movements · Natural hazards · Remote sensing · Rivers · Tectonics · Uvira

1 Introduction

The town of Uvira (29°7′E and 3°23′S) is a quickly growing agglomeration of 200,000 people located upon a 16 km^2 series of alluvial fans, actively progressing into the Tanganyika rift lake at a rate of some metres to hundreds of meters since the last 50 years. These fans form the only more or less flat area between the rugged and rough Mitumba–Itombwe Plateau rift shoulder and the lake and, therefore, form attractive poles for human settlement. But since a few decades, the torrential rivers, tumbling from the highlands, show an increasingly irregular regime. Unprecedented flash floods affected the Uvira fans in February 2002, destroyed hundreds of houses and killed at least 46 people. Gabions and concrete walls to stabilise the fan river sections were disrupted and transported and bridge foundations were badly affected. The increasingly hazardous character of the flash flood events asks for an explanation in order to maintain the site habitable.

The increasing river activity goes hand in hand with an intensification of the occurrence of landslides in the mountain fan catchments. Inhabitants of the Itombwe uplands report a growing landslide activity in the area. The landslide intensification is more than a local phenomenon (Munyololo et al. 1999). One of these landslides consists of an estimated 3.5×10^6 m^3 of debris, resting on a fault plane, looking over the town and the harbour. In 1986, this volume of earth and rocks suddenly slid downwards but stabilised before reaching the harbour (Fig. 1). We have no information about casualties, but the main road along the coast was destructed and had to be displaced.

In spite of the numerous complaints by the local population, surprisingly few hard data exist about the natural hazards occurring in the area before 2002. During visits in 2006 and

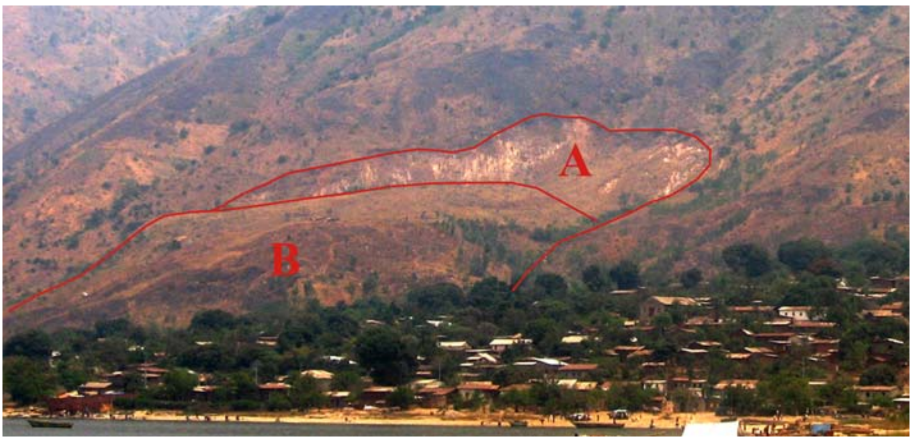

Fig. 1 A sudden remobilisation of the pre-1959 landslide lobe took place in 1986 but stopped before overriding the Kalundu harbour infrastructure. *A* and *B*: headscar and lobe of the 1986 remobilisation. The upper limit of A corresponds with the upper boundary of the lobe before 1959

2007, hundreds of pictures of traces of hazards of the last 20 years have been taken. Besides this database, partly on-line (http://www.metafro.be/geopic), few new detailed geological and physiographic information of Uvira and the Mitumba–Itombwe uplands exists since Weis (1959).

The aim of this article is to make a GIS inventory of traces of extreme geomorphological events having occurred in the past at Uvira and the Mitumba–Itombwe hinterland and to figure out about the possible reasons for the intensification of the natural hazards involved. The map of such an inventory can be considered as a first approximation of a natural risk assessment map, a document eagerly needed for regional sustainable development.

The only detailed documents available are the 1:50,000 aerial photo coverage of the area, delivered in 1959 by the Belgian authority. The cartographic inventory could be realised by remote sensing methods using the aerial photographs of 1959, combined with the ETM image of 2000, IKONOS image of 2004 and a SRTM DEM with 30 m resolution.

2 Materials and methods

2.1 The study area

2.1.1 Physiographic setting of the study area

Lake Tanganyika is bordered to the West by three morphological entities, extending along the N–S border of the Lake Tanganyika—Rusizi Plain axis (Fig. 2). The rift shoulder itself, the Mitumba Range, locally called the Itombwe Plateau, is an undulating plateau at an altitude reaching 3,000 m asl. The plateau is drained to West. Below the eastern plateau escarpment extends a rugged area, about 10 km wide, steeply dipping to the East, and plunging into Tanganyika Lake at 774 m asl. The major torrents which drain this rugged area have built up an alluvial fan where they end into the Lake. The city of Uvira extends on the fans of the Kalimabenge (catchment: 91 km^2), Mulongwe (catchment: 115 km^2) and Kavimvira (catchment: 42 km^2) torrents. Apart from the basins of these torrents, the study area (Fig. 2) also includes the major part of the drainage basins of the Kawezi (143 km^2) and Kiliba (277 km^2) torrents, which end into the Rusizi Plain to the North of the lake. These rivers bridge in a distance of about 10 km a difference in elevation of about 2,000–2,300 m between the lake level (±770 m asl) and the top of the Mitumba–Itombwe plateau (>3,000 m asl).

2.1.2 Geology

The study area comprises two geological domains. The first contains Cenozoic to recent deposits of the alluvial fans along the Tanganyika Lake coast and the fans and underlying detritic fluvial–lacustrine deposits in the Rusizi Plain (Ilunga 1990; Tiercelin et al. 1992). The second forms the rift shoulder and includes the Proterozoic metamorphic and intrusive rocks of the Mitumba rift shoulder, displaying the SSE-NNW 'Ubende' lineament (Klerkx et al. 1998) direction. This folded and faulted massive is composed of alternating bands of quartzite, schist and intermediate lithology, with some granite intrusions and gneisses (Weis 1959), amphibolites, dolerites and quartz veins.

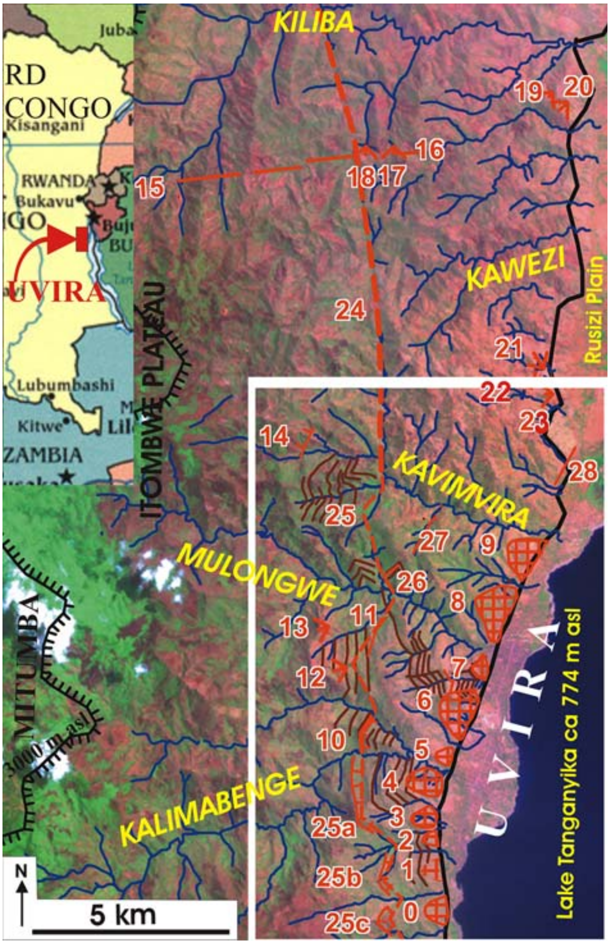

Fig. 2 The study area. The ETM basic layer is a false colour combination of bands 7, 4 and 2. Band 4 is represented in *green* so that vegetation is *green* on the image. Active tectonic structures (Sect. 3.1; Table 1) in *red*. *Blue lines* active river incisions (Sect. 3.2). River names in *yellow italics*. Geologic layers in *brown*. The *heavy black line* separates the flat alluvial fans and the Rusizi Plain from the rugged mountains. *White frame* IKONOS coverage

2.1.3 Tectonics

It is generally accepted that the Mitumba Range is composed of rift related dissected fault steps (Cahen 1954), which are still active today (Coussement et al. 1994; Reynes et al. 1993; Ebinger 1989; and others). According to Weis (1959), the study area is crossed by at least two S–N trending active faults. The first delimits the Tanganyika coastline and the Rusizi plain to the North. Another fault occurs about 5 km inland to the West. Vertical dislocations along these faults should have introduced two or three cycles of regressive erosion, having provoked a stepped morphology of the edge of the Mitumba–Itombwe plateau.

2.1.4 Climate and vegetation

The annual precipitation at Uvira remains below 1,000 mm, the period June–September showing restricted rainfall. But it increases with height to attain values of the order of 1,450 mm at above 2,000 m (Weis 1959). Growing seasonal irregularities in precipitation are reported (Muhigwa 1999). They concern the establishment of a humid period in the month of August, in the middle of the dry season. Local people consent that precipitations today are more irregular in time and more variable in importance compared to 50 years ago.

According to Weis (1959) the rugged area between lake and plateau has been greatly deforested in the 1940s and 1950s. Only some small forest remains. According to Weis (1959), sclerophyllic forest was present above the Lake till 1,600 m asl. Further upward the mesophyllic forest extended to 2,200 m asl and mesophyllic mountain forest covered the Itombwe Plateau and the upper plateau edge. Some remnants still garnish the upper, steepest slopes of the eastern Itombwe Plateau escarpment and are visible in Fig. 2 in green.

2.2 Types of natural hazards affecting the area

The steep main torrential river gradient of some 0.2 m m^{-1}, the seismic activity in the area (De Bremaecker 1959; Coussement et al. 1994), the intense agricultural soil use and the growing seasonal irregularities in precipitation (Muhigwa 1999) contribute to high erosion risks in the torrent catchments.

Local reports say that the torrential rivers Kalimabenge, Mulongwe and Kavimvira produce flash floods and inundate their respective alluvial fans with increasing frequency and magnitude. This leads to important fluvial events, destructing, burying or undercutting houses and to inundations provoked by the main road which acts as a barrier for all runoff as it perpendicularly crosses the stream direction on the fans. Especially in 2002, unprecedented inundations have destructed hundreds of houses and caused the death of 46 people at one occasion. Although not verified by measurements, people often express their opinion that the inundations are oversized in respect to the rain storms.

Only scarce oral information exists about mass wasting events in the mountainous hinterland. Water erosion and mass wasting are known to affect the catchments of the Uvira alluvial fans since a long time. Weis (1959) mentions three types of erosion. First, there is important vertical erosion by the torrential rivers descending the Mitumba. The second type of erosion is a combination of gullying and mass wasting by land slips and debris slides along spoon shaped slide surfaces affecting the torrential valley sides. Finally, he mentions the occurrence of many mass wasting phenomena, unrelated to the fluvial network. Weis (1959) also mentions the effect of an important seismic shock on the 4th of July 1954. The shock-damaged houses and big buildings in Uvira. In many places in the mountains deep fissuring of the soil occurred and two landslides, and several mud flows originated immediately after the earthquake in the middle of the dry season. Rivers, which normally are dry during that period started to flow. One of the mud flows produced muddy water during a whole month in the process of resettlement and drying after shock induced liquefaction.

2.3 Mapping of past natural hazards in Uvira and the mountain hinterland

It was thought useful to make an spatial inventory of recognisable landscape traces of high intensity geomorphic events having affected the study area over a certain period of time in the hope to find some correlations between the location of these events and geomorphologic, tectonic, geologic and land-use characteristics. Such correlations should enable to identify zones of higher than mean risks for high intensity geomorphic events under consideration. The traces of following events have been considered: gullying, vertical torrential river incision, inundations, mass movements like mud and debris flows, landslides and creep lobes. At the same time geological and lithological structures like stratification, folds and fractures have been mapped and special attention has been given to all possible morphological and other evidence for recent or active crustal movements and neotectonics in relation to the current process of rifting in the area. All these phenomena have been mapped in a MAPINFO 8.6 GIS on separate shape files overlying the IKONOS or ETM Image.

2.4 Remote sensing techniques used for mapping

Mapping of erosion phenomena was mainly done by stereoscopic interpretation of the 1:50000 aerial photo cover of the study area (red frame in Fig. 2). It appears, indeed, that the three-dimensional view, even only at a scale of 1:50000, allows a much better discrimination of landslide topographies than the much more detailed view with a 4 m precision on the monoscopic IKONOS image. On the other hand, IKONOS (coverage of the white frame, Fig. 2) and ETM (covering of the wider region) images in the near infrared are very superior to the aerial photographs for the reconnaissance of lithological and geological structures for two reasons. First, because of the possibility to use suitable combinations of spectral bands: for IKONOS, we used false colour images which combine band 4 (near-infra-red), 3 (red) and 2 (green) as RGB, and for the ETM image we used band 7 (short wave infrared), 4 (near infrared), 2 (green) as RGB. Secondly, because of the big area coverage by one image and the possibility to zoom out. This allows a much better synoptic view than on stereo pairs of aerial photographs. Furthermore, draped over the digital elevation model (DEM) of 30 m resolution, IKONOS—and ETM images could be transformed in three-dimensional terrain constructions by using ENVI-software.

The interactive use of satellite and aerial photographs appears to be a powerful and fast technique in thematic geomorphologic mapping of an area of about 180 km^2.

2.5 Method used to measure the topographic threshold values for landslides

On the slope map, derived from the 30 m resolution DEM (SRTM, NASA) local slopes have been measured in an ARCGIS 9.2 in order to establish slope—drained area graphs for the landslide heads and to compare them with the topographic thresholds found by Montgomery and Dietrich (1994). We estimate that slope measurements on a document based on the 30 m DEM can be aberrant to a high degree where rectilinear slope sections are shorter than 60 m. Also the way of calculation of the slope map can influence the results. But at a first approximation, it was considered that slope measurements should show a more or less Gaussian distribution around characteristic values in the field. Also the measurement of run-on areas shows important imprecision. The MAPINFO 8.5 GIS system does only allow the measurement of aerial extensions projected on a horizontal surface. For slopes up to 30°, which are very common in the study area, the underestimation is of the order of 15%.

3 Results of remote sensing documents analysis

3.1 Tectonic structures

3.1.1 The fracture of Galye-Munanira and other fractures

The ETM (channels 7, 4, 2, Fig. 2) shows a very pronounced N–S trending linear structure (24 in Fig. 2), well developed between the Kiliba and Kavimvira rivers. The latter follows this N–S trending rectilinear structure over a distance of about 7 km. To the South of the Kavimvira, the structure continues as a zigzag line (25 and 25 a, b, c and 10 and 11 in Fig. 2) ending in the South of the study area at less than 2 km to the West of Lake Tanganyika. The northern part of the zigzag line corresponds to the F2 Galye-Munanira fault, indicated by Weis (1959). Lines 24 and 25 are also indicated by Reynes et al. (1993), where they are interpreted as an active fault. Our own measurements on the slope map and our observations on the aerial photographs indicate that the zigzag line is not a normal fault. The zigzag trajectory results from a vertical and lateral dislocation along a fault plane, dipping towards the lake at about 40° only, crossing the East–West trending hill ranges at a nearly right angle. Table 1 shows the dip measurements on this plane at 25a, 25b and 25c (Fig. 2). At these particular locations, and also at location 10, the plane has been interpreted as a fault, which has been active in very recent geologic times because the four hill spurs at these localities have been dislocated. At 10, the visible dislocation is lateral and vertical. The lateral displacement of the spur East of the fault is about 200 m and affects also the river valleys North and South of the spur. The vertical downthrown of the hill spur to the East of the fault is of the order of 50–100 m. At 25a, 25b and 25c, there is only a clearly visible downthrown of the same order as at 10. The fault plane is visible in the sides of the hills and dip measurements are given in Table 1. Also to the North of the Kavimvira, the structure, although rectilinear, could be inclined in the same way but stereoscopic proof is lacking.

Longitudinal profiles on the base of the 30M SRTM of the major torrents do not show significant steps or other irregularities which might be attributed to active tectonic movements.

3.1.2 Fracture 15–16

In the northern part of the study area, the rectilinear structure 24 is crossed by the West–East trending linear structure 15–16. Local erosion in the Kiliba head waters has liberated the structure partially, showing that facets 17 and 18 correspond to a planar structure in the rocks, dipping to the North at 25° to 33° (Table 1).

3.1.3 Steep-sided facets along the Lake border

Seen from the lake, triangular hill spurs 0–3 (Fig. 2) steeply rise up to the West, showing slope angles between 34.71° and 39.19° as measured on the numerical slope map

Table 1 Morphological characteristics of 29 tectonic structures Uvira (Fig. 2)

Label number	Three steepest slopes in °			Morphological expression	State of reworking
	Slope 1	Slope 2	Slope 3		
0	35.07	34.71	36.56	Fault facet	Partially degraded
1	33.24	33.70	35.32	Fault facet	Affected by landslide 19 and gullies
2	38.61	39.19	38.27	Fault facet	Nearly intact
3	36.37	37.33	37.11	Fault facet	Intact
4	33.41	34.90	35.37	Fault facet	Affected by huge landslide 63
5	22.48	21.57	22.78	Fault facet	Affected by small landsliding and gullying
6	31.33	30.45	23.45	Fault facet	Affected by small landsliding and gullying
7	27.39	26.71	28.68	Fault facet	Affected
8	21.95	22.23	23.38	Fault facet	Affected by small landsliding and gullying
9	22.62	24.74	23.61	Fault facet	Affected by landslide 53
10				Part of line 25: dislocation of hill	Lateral dislocation of mountain reflected in curbs of Kalimabenge and confluent
11	37.61			Part of line 25	
12	40.07			Small fault facet, part of line 25	
13	41.2			Small fault facet	
14				Small escarpment	
15				Linear structure	
16				Linear structure	
17	25.14	33.11		Stripped rock disconformity	
18	21.07	18.35	25.83	Stripped rock disconformity	
19	35.17	32.54		Stripped rock disconformity	
20	30.25			Stripped rock disconformity	
21	33.95			Stripped rock disconformity	Gullied
22	42.35			Stripped rock disconformity	Not much reworked
23	39.56	38.89		Stripped rock disconformity	Not gullied but too small to give reliable measurement
24				Fracture	
25a	38.40	38.83		Angular fracture dislocation of hill	
25b	37.42	37.72		Angular fracture dislocation of hill	
25c	36.36	37.06		Angular fracture dislocation of hill	
26				Fracture	
27				Fracture	
28				Lineament: fracture	

(Table 1). However, spur 1 is strongly affected by the presence of an old landslide, visible on the 1959 aerial photographs and the slope angles refer to the extreme sides of the spur, which are more or less preserved. The landslide lobe in question has known a partial reactivation in 1986 threatening the harbour of Kalundu (Fig. 1). A close view shows that the three other spurs are affected by gullying and runoff. Weis (1959) considered spurs 2 and 3 as fault plane outcrops, so-called fault facets (Baulig 1966). Our observations confirm that facets 0–3 are fault planes because the facet surfaces cut the geological layers, indicated in brown (Fig. 2). The latter dip at about 60° in the sector considered, while the original dip of the facets (Table 1) is estimated at about 40° only. Further, they are also on a straight line, abstraction made of the lobe of the 'landslide of the harbour' on facet 1, which pulls out considerably.

The facets 4–9 are less well recognisable as such, because they are affected by small landslides and gullies. Especially, facet 4 from which landslide 63 (Sect. 3.3) starts is affected. In spite of this reworking, the mean dip of the facets still reaches values between 21.57° and 35.37° (Table 1). Furthermore, the direction of the geological layers makes an angle of about 40° with the direction of facets 4–9 (Fig. 2). This renders very improbable the hypothesis that the facets 4–9 originally corresponded to lithological boundaries. Remarkably, fault facets, recognisable as such, do not occur along the Rusizi Plain. Only facet 23 could be a fault facet, oriented to the plain. This observation suggests that the lake border might have known a last sudden vertical dislocation which did not affect the stretch of the Rusizi Plain North of the lake. Figure 3 shows a panoramic view on the Uvira coast, based on the available 30 m resolution DEM. Here the fault facets are indicated.

3.1.4 Other small scale structures

Many other small structures have been identified (Fig. 2). They concern either linear structures, best visible on the ETM image, and small steep-sided facets, only detectable on the aerial photographs. They are interpreted as the partially eroded underground extension of very local fractures. Recent small displacements along these fractures were probably the onset for their preferential rapid etching out by erosion. The alignment of structures 11, 26, 27, 21 and 22, nicely parallel to the alignment of facets 4–9 and structure 24, suggests tectonic control.

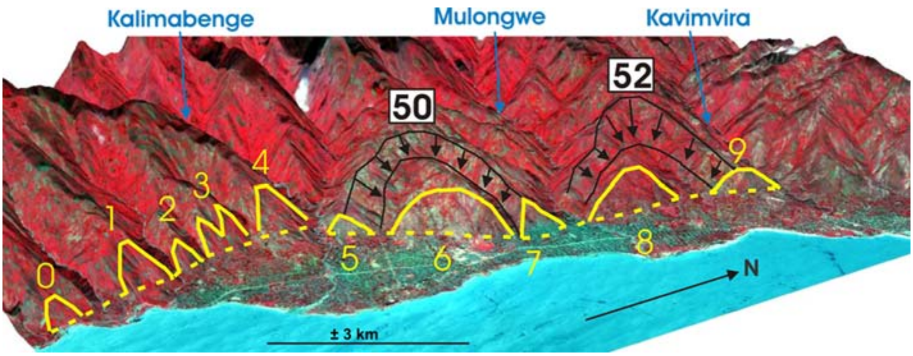

Fig. 3 3-D panoramic view of Uvira and part of the mountain hinterland. Fault facets 0–9 in *yellow*. The head scars of the ancient mega-landslides 50 and 52 in *black*. Both landslides have been undercut as a result of the downthrown along fault facets 5–9. IKONOS (bands 4, 3, 2 as RGB) draped on the 30 m SRTM, shown in ENVI, Vertical exaggeration: ×2

3.2 Fluvial activity

3.2.1 Fluvial activity and gullying on the alluvial fans

The Kavimvira, Mulongwe and Kalimabenge river fans have been subjected to important river and runoff activity since the last half century. Figure 4 compares the situation on the Kavimvira fan in 1959 with the one in 2004. The most spectacular change is the avulsion of the Kalimabenge. In February 2002, the river course was still closely following the 1959 trajectory. But as a result of two or three heavy rain storms, the river produced a huge flash flood and changed its course about 200 m downstream of the main road, visible on both images, and cut a new river bed across a densely populated area, South of the former river bed. The change in course, but also the dramatic enlargement of the Kalimabenge river bed on the fan are clearly visible in Fig. 4. The same thunderstorms produced comparable flash flooding on the Kavimvira and Mulongwe fans. In both cases, this did not lead to avulsion but to important lateral river bed enlargement with destruction of dozens of houses. But also small rivers like the Kandibula and his confluent, with a catchment of only 2.5 km^2 showed catastrophic behaviour. Figure 4 shows the development of the Kabindula gully in the middle of the town of Uvira. This gully became active in 1995 when part of an old landslide in the upper course of the river knew a very important remobilisation (Fig. 5). It should, however, been stressed that the major river inundations in the town result from flash floods coming out of the hills. On the 1959 image in Fig. 4, the stereoscopic view shows traces of important overbank flow on the fan, nearly uninhabited at that time. They are older than the construction of the main road after 1945, but they postdate the first phase of deforestation in the uplands (Weis 1959).

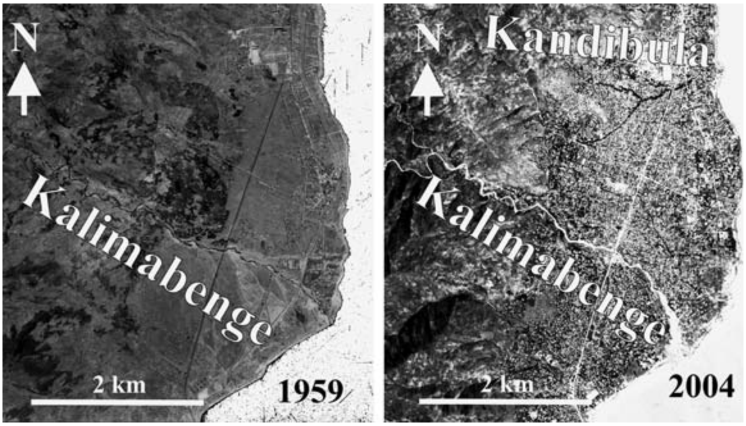

Fig. 4 The Kalimabenge alluvial cone and its mountain hinterland in 1959 and 2004. As a result of flash flooding in February 2002, the Kalimabenge changed its trajectory east of the main road and enlarged in the same time its bed. The Kandibula gully was not visibly present on the 1959 photos. The photo pair also illustrates the big change in soil use in the mountains, the eastern part of both images. In 1959, evidence of slash and burn exploitation with dark traces of bush fires, no parcelling. In 2004, the mountains are intensively cultivated, but no traces of soil and water conservation management are visible. The IKONOS image of 2004 has been printed in black and white in order to make comparison with the 1959 aerial photograph easier

Fig. 5 Kandibula slide remobilisation pictured in 2006

3.2.2 Fluvial activity in the torrential zone between the Itombwe Plateau and the alluvial fans

The comparison of the torrent bed morphology between the 1959 situation on the aerial photographs and the IKONOS 2004 image shows also a drastic historical change. On the 1959 images, the head torrent beds in the mountains are greatly hided below riparian vegetation. Even the river beds itself contain vegetation, peat and dark clays and water, all elements which contribute to the dark colour of river beds on the 1959 photographs. On the IKONOS and ETM images the river beds appear on many places as whitish well-visible ribbons (Fig. 4). This is interpreted as the result of evacuation of small vegetation, peat, and the presence of gravel and sand in a mostly dry river bed. The vertical incision in the most erosive torrential sections of the Kalimabenge, Kavimvira and Mulongwe rivers should be of the order of $10^{(-1 \text{ to } 0)}$ m in 45 years at least, because this is the presumed minimum thickness of peat and silt and clay layers with grassy and thick vegetation, evacuated. The erosive character of these whitish river sections is further corroborated by the fact that they mostly occupy the centre of a V-shaped valley, where river terraces are absent, and where slopes attain easily 30°.

The 'whitish' river beds, which are considered as actively eroding sections, have been indicated in Fig. 2. In the reach of the IKONOS image (white frame in Fig. 2), it was rather easy to map these strongly eroding river bed sections. But outside this frame, we had only the 2000 ETM image at our disposal. The accuracy of mapping 'whitish' river sections is much lower here due to the lower spatial resolution. Figure 2 shows these river sections which clearly incised. Two remarks should be made. First of all, the tectonic block between faults 24 and 15 undergoes (Fig. 2) less pronounced fluvial erosion than most other parts of the study area. Furthermore, first-order valleys are steep sided and do not contain perennial courses. This indicates the absence or scarceness of powerful springs in the area. The important river springs are to be located high on the rift escarpment where rivers apparently are less erosive and where, according to the 2000 ETM image, the land is still forested to a high degree. The really erosive behaviour of the rivers should not only be related to the high gradients but also to the low spring activity in the deforested belt, which indicates high runoff coefficients on the stream divides and, hence, flash floods in the river channels.

3.2.3 On the Itombwe Plateau

Valley morphology and river dynamics are completely different on the Itombwe Plateau. An evolution as on the rift escarpment is not visible on the ETM image. The valleys are flat bottomed, with only sporadic vertical incision. This is confirmed by the presence of vegetation along the river courses, often even gallery forest, hiding the river bed. Rivers are generally heading from the centre of amphitheatre-like spring incisions, strongly suggesting that rivers are much more spring sensitive than runoff sensitive.

3.3 Landslides

All landslides, visible on the 1959 aerial photographs have been inventoried (Fig. 6; Table 2) and the following parameters have been measured:

1. The drained area upslope of the head scar of landslides.
2. The local slope angle just upslope or aside of the location of the landslide head scar. When drained areas are very small, the pixel size of 30 m $\times$ 30 m of the DEM from which the slope map was derived, did not allow precise measurements. In these cases, measurements have been done as indicated in Table 2.
3. The size (km^2) of scar and lobe (erosion and deposition belt).
4. Length (L) and width (W), measured in km, of the lobe.

Table 2 gives remarks about size, form or location of the landslides, mapped and indicates all topographic properties of the landslides as measured. The inventory numbers 2, 16 and 62 are lacking. 60 landslides have been labelled.

3.3.1 Landslide activity between 1959 and today: reactivations

The study of the aerial photographs allowed us to recognise 60 landslides in the study area (Fig. 6). Qualitative observations in 2006 and 2007 showed that several landslides, identified in 1959, did partly reactivate during the last 49 years. Some of these reactivations are well reported, like the one above the harbour (landslide 19) and the one along the Kabindula river (landslide 4). Many old and recent traces of extensive soil slips are visible, but they do not seem to be restricted in location to the 1959 landslides. Most landslide activities further in the mountains did never reach the media.

3.3.2 Triggering factors of landslides in the study area

In a tectonically active belt like the Tanganyika graben, it cannot be ruled out that shocks and earthquakes trigger landslides. In Bukavu, Munyololo et al. (1999) stressed the seismic origin of landslides. In Uvira, the role of seismics in landslide initiation was tried to be evaluated in two ways. First of all, the landslide location in relation to the tectonic structures described in Sect. 3.1 has been verified. It appears that the majority of the landslides are less than 1 km away from a tectonic structure. Some landslides are even resting on the fault facets described (Fig. 2). Only landslides 14, 17, 56, 57 and 58 (Fig. 6) are at a distance between 2 and 4 km away from structures interpreted as tectonic in origin. This short distance makes that all landslides in the area are potentially seismically triggered. In the case of Uvira, distance to tectonic structures does not seem to be a potential discriminator of landslide type. Also, Weis (1959) considered the seismic activity as a factor of mass movement initiation for the whole area.

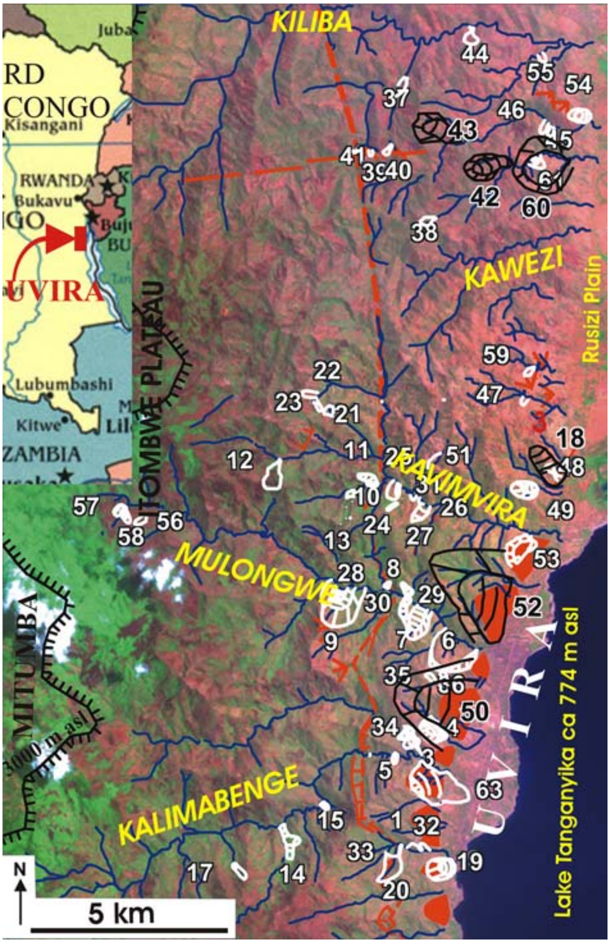

Fig. 6 Landslides distinguished on the aerial photographs (1959) located on the 2000 ETM image. Table 2 gives typology. *Dark coloured* landslides 18, 42, 43, 50, 52, 60 are classified below and to the *left* of the M–D envelope (see Sect. 3.3) and are interpreted as seismic landslides. The other landslides are indicated in *white* and are interpreted as triggered by hydrostatic pressures. Most *whitish* landslides are distributed along actively incising sections of the hydrographical network

In a second time, the topographic thresholds of the slides at Uvira have been compared to the topographic thresholds for hydrostatically induced landslides in America, as defined by Montgomery and Dietrich (1994). Figure 7 shows the tangent of the topographic slope values (m m^{-1}) at the head scar against drained surface (ha) for the 60 landslides, distinguished at Uvira (Table 2). The landslides are distributed over two groups, nicely separated by the Montgomery–Dietrich (M–D) envelope as established in America. Of the 60 landslides, 54 are to the right of the M–D envelope, where Montgomery and Dietrich (1994) placed the American hillslope incisions triggered by pore water pressures. It has been shown that the M–D envelope is also valid for landslides and gullies in the neighbouring Rwanda (Moeyersons 2003), if it is translated slightly to the right, according to the equation:

Table 2 Uvira landslide topographic characteristics and brief description (Fig. 6)

Label (Fig. 6)	Length (km)	Width (km)	Length/width	Drained surface (ha)	Slope in ° at head scar	Remarks about size, form or location of landslide. Labels preceded by (#) refer to tectonic structures in Table 1 and Fig. 2
1	0.211	0.141	1.4965	0.65	33.64	Empty scar: structural planform
3	0.416	0.212	1.9623	3	26.61	Debris flow along Kalimabenge
4	0.558	0.621	0.8986	6.3	27.00	Mudflow along Kandibula, vertical incising river. The 1995 remobilisation affects this slide 4
5	0.281	0.112	2.5089	1.8	32.01	Soil slippage, structural planform
6	0.994	1.141	0.8712	3.7	31.00	Along incising river Mulongwe
7	0.885	0.800	1.1063	1.7	32.00	Along Mulongwe
8	0.366	0.151	2.4238	2.6	20.62	Soil slippage structural planform
9	1.149	0.968	1.187	1.8	35.00	Head scar upslope prolonged in fault facet #13
10	0.338	0.228	1.4825	3.7	22.40	Debris slide
11	0.474	0.224	2.1161	3.5	17.17	Soil slip structural planform
12	0.736	0.386	1.9067	4.8	40.79	Empty bottle neck
13	1.101	0.225	4.8933	3	28.89	Soil slippage and heavy runoff: structural planform
14	0.867	0.162	5.3519	20.9	30.81	Debris flow
15	0.222	0.113	1.9646	2.3	32.99	Rotational slide
17	0.444	0.131	3.3893	2.2	41.57	Block slide into river
18	1.054	0.551	1.9129	0.05	6.00	Hill sized lobe like type 43, 42 and 60
19	0.688	0.542	1.2694	7.1	35.00	Landslide of the harbour with remobilisation in 1986
20	1.046	0.400	2.615	0.98	32.00	Sits upon fault line #25 (Table 1; 2), evacuation of layer edge
21	0.205	0.243	0.8436	1.1	36.01	Empty bottle neck slide
22	0.383	0.141	2.7163	1.1	32.65	Empty scar
23	0.302	0.092	3.2826	0.5	36.77	Gravitational by undercut
24	0.308	0.069	4.4638	9.2	23.35	Spring erosion
25	0.221	0.086	2.5698	1.2	31.54	River undercut
26	0.143	0.323	0.4427	2.1	30.24	Rotational slide, bluff erosion
27	0.526	0.270	1.9481	1.3	31.58	Empty scar, elongated, along Kavimvira
28	0.355	0.297	1.1953	9.46	35.52	Soil slippage, structural planform
29	0.501	0.135	3.7111	0.5	31.41	Soil slippage structural planform
30	0.169	0.079	2.1392	3	40.72	Rotational slide, bluff erosion
31	0.096	0.128	0.75	8.5	32.30	Creep slide bluff erosion
32	0.190	0.270	0.7037	3	37.58	Debris flow on fresh fault plane
33	0.231	0.385	0.6	23.9	29.01	Debris flow structural planform
34	0.448	0.172	2.6047	4.2	21.63	Rotational slide along Kalimabenge
35	0.271	0.119	2.2773	1.8	22.11	Empty scar
36	0.208	0.117	1.7778	1.5	24.63	Empty scar
37	0.271	0.552	0.4909	21.6	32.42	Rotational slide along river bank
38	0.394	0.216	1.8241	1.2	32.64	Bottle neck with very long channel
39	0.127	0.087	1.4598	1.1	16.67	Soil slippage on facet #17 (Table 1; Fig. 2)
40	0.291	0.087	3.3448	2.3	18.92	Soil slippage on facet #17 (Table 1; Fig. 2)

Table 2 continued

Label (Fig. 6)	Length (km)	Width (km)	Length/width	Drained surface (ha)	Slope in ° at head scar	Remarks about size, form or location of landslide. Labels preceded by (#) refer to tectonic structures in Table 1 and Fig. 2
41	0.055	0.088	0.625	1.2	25.05	Soil slippage on facet #17 (Table 1; Fig. 2)
42	0.894	0.460	1.9435	0.07	7.00	Hill creep movement: bottleneck flow type: in prolongement of tectonic line #16 (Table 1; Fig. 2)
43	0.915	0.480	1.9063	0.056	11.00	Hill movement: bottleneck flow type: in prolongement of tectonic line #16 (on Table 1; Fig. 2)
44	0.421	0.343	1.2274	1.4	35.04	Empty bottle neck + gully
45	0.234	0.102	2.2941	1.5	19.65	River undercut soil slippage
46	0.296	0.124	2.3871	1.8	24.55	Slide, river undercut
47	0.174	0.151	1.1523	0.9	31.81	Wide soil slippage
48	0.448	0.213	2.1033	1.1	26.83	Interpreted as bottle neck with wide gully and cut of
49	0.630	0.402	1.5672	5.7	31.49	Bottleneck type
50	0.649	1.141	0.5688	0.8	4.00	Huge rock slide: lobe and scar sides cut off by fault facets #5, #6, #7 (Table 1; Fig. 2). Inside is drained by Kandibula. Secondary slides 4, 35 and 36. 1995 'remobilisation of the Kandibula slide' affects movement 4
51	0.316	0.559	0.5653	9.2	29.99	Planar slide to river bank
52	0.585	1.162	0.5034	0.07	5.00	Huge rock slide: lobe cut off by fault facet 8, northern scar rim by facet #9 (Table 1; Fig. 2)
53	0.500	0.917	0.5453	2.2	23.00	Rotational slide and creeping lobe. sits upon fault facet #9 (Table 1; Fig. 2)
54	0.508	0.31	1.6387	2.1	30.12	Rests on fault plane of facets #19 and #20 (Table 1; Fig. 2)
55	0.233	0.171	1.3626	0.29	32.84	Planar slide, soil slippage
56	0.346	0.139	2.4892	2	34.80	Bottle neck + gully
57	0.345	0.204	1.6912	5.1	20.51	Scar and debris flow
58	0.207	0.332	0.6235	2.7	21.43	Translational slide to river bank
59	0.289	0.147	1.966	0.5	23.75	Bottle neck slide
60	1.053	0.886	1.1885	0.475	4.10	Mountain creep movement: bottleneck flow type: in prolongement of tectonic line #16 (Table 1; Fig. 2)
61	0.393	0.286	1.3741	1.3	22.29	Widening: debris flow
63	1.22606	0.801	1.5307	5.1	33.00	Landslide on fault facet 4 reaching the alluvial fan

$$S_{cr} \approx 0.3A^{-0.6} \tag{1}$$

where S_{cr} is the tangent of the critical slope angle at the head of the hill incision and A is the drained area in ha.

In the case of Uvira, the M–D envelope for America is somewhat to the left of the right data cloud (Fig. 7). Like in the case of Rwanda, the American M–D envelope can be transferred to the right till it touches the data cloud. In that case, the local (Uvira) M–D

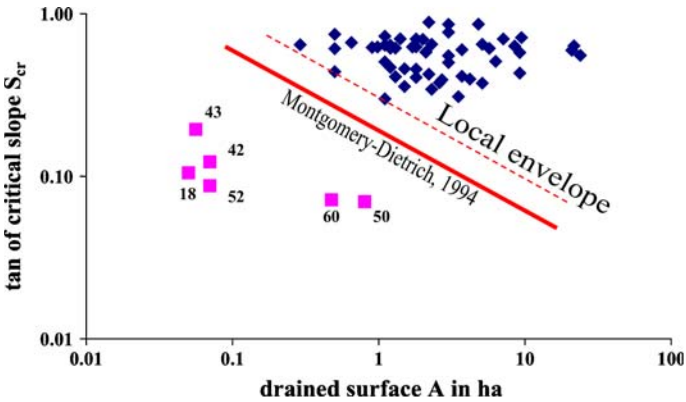

Fig. 7 The M–D topographic threshold for hillside incisions, as established for America, separates the two groups of landslides at Uvira. If the 'American' envelope is shifted to the edge of the right data cloud, it corresponds to the local envelope, established for Rwanda (Moeyersons 2003) where $S_{cr} \approx 0.3\ A^{-0.6}$

envelope fits the Eq. 1. The distribution of landslides in Fig. 7 indicates that the topographic characteristics of 54 landslides are such that no trigger other than gravity and/or seepage pressure has to be invoked. Of course, this cannot exclude the possibility that seismics might have interfered. On the other side of the M–D envelope, six landslides (18, 42, 43, 50, 52 and 60) do not obey to the topographic threshold conditions and, therefore, are considered as seismic in origin (Fig. 7). The two biggest slides, 50 and 52, are located 350–1,000 m to the East of the linearity of tectonic structures 27, 26, 11 (Fig. 6). Therefore, they should not be simple tectonic dislocations of hill spurs as is the case along 25a, b and c, discussed earlier. Remarkably, landslides 50 and 52 are cut off by fault facets 5–9 (Fig. 3). Landslide 18 is crossed by linear structure 28. Finally, landslides 42, 43 and 60 are in the eastern extension of the fault-like tectonic structure 15–16–17–18 and are also in the close vicinity of tectonic structures 19 and 20 (Fig. 6). While it is true that all the other landslides also are in the proximity of tectonic structures, they are in the mean time also located along strongly eroding streams (Fig. 6). Landslide 56 is one of the rare exceptions, affecting a hillside midway without reaching the river. It is assumed that this landslide lies within a belt deforested shortly before 1959. Landslide 48 is a partial reactivation of seismic landslide 18. As it falls to the right of the Uvira M–D envelope (Fig. 7), the seismic origin of second time slide 48 is not certain. Also, landslides 19, 53 and 63 do not reach a river. They affected the fault surfaces 1, 4 and 9. The fact that landslides 19, 53 and 63 fall in the non-seismic landslide group suggests that they originate during the course of weathering of the fault planes, showing a steeper dip than the mean equilibrium slope for weathered rocks in the area. Of course, seismic activity cannot be ruled out.

The other non-seismic landslides might be triggered by fluvial erosion which causes unloading at the base of the hill slopes. Uvira is not the only case where landslides are located along vertically incising rivers. In the Bukavu area, all non-seismic landslides are also located along incising rivers (Moeyersons et al. 2004; Trefois et al. 2007). The same is true in the eastern extension belt of Bujumbura. Therefore, it is thought that non-seismic landslides are mainly provoked by the renewed river activity in the rift area. The role of deforestation in landslide triggering seems to be mostly indirect: the increased floods and flash floods, attributed to it are held responsible for the vertical river incision. Statistically sound meteorological data are eagerly needed to test the hypothesis that there is a change in rainstorm regime which could partly explain the increase of storm flow in the rivers.

4 Conclusions

4.1 Tectonic activity

Section 3.1 describes several structures, interpreted as tectonic in origin and having been active in very recent geological times. They are mapped in Fig. 2. The fracture of Galye-Munanira (Weis 1959) continues South of the Kavimvira river as a zigzag line, being a discontinuity in the rocks, which dips towards the Tanganyika Lake at an angle of about 36°–40° (Table 1, structures 25, 10, 11,12). More or less parallel to this low dip fracture appear along the lake coast 10 inclined structural surfaces, interpreted as so-called fault facets, reworked by erosion processes but nevertheless showing dipping angles of 22°–30° and even up to 39° (Table 1). It is hypothesized that facets 0–9 and structures 10, 11, 12 and 25 (Fig. 3) correspond to low dipping fault planes. They could be the median parts of lystric faults, brought to the surface by the more than 2 km of erosion, which occurred close to Lake Tanganyika. Since Klerkx et al. (1998), it has been generally accepted that the rifting process along Tanganyika exploits the older Proterozoic weak structures. It should be checked whether the structures, described here do belong to lystric faults. At stake is the first structural indication of (former) extension along the Tanganyika rift.

4.2 River activity

Section 3.2 describes the river dynamics. The IKONOS image of 2004 (Fig. 4) of the alluvial fans shows divagating, braiding rivers with important lateral scour during peaks and massive dumping of sediments at the end of the stream floods and avulsion. The stereoscopic analysis of the 1959 aerial photograph shows that important overbank flow on the fan occurred already at that time. Chronic river flooding on the fans of Uvira started probably with the deforestation in the 1940s and the 1950s (Weis 1959) on the Mitumba escarpment.

In the mountain hinterland of Uvira, vertical erosion of the rivers is visible for the period 1959–2004 (IKONOS coverage) or 1959–2000 (ETM coverage). In river sections that appear as white ribbon on the IKONOS and ETM images this vertical erosion is estimated for both periods at a minimum of $10^{(-1 \text{ to } 0)}$ m (Fig. 2). The increasing vertical stream erosion in the Uvira uplands can only be explained as a result of stream floods, increasing in intensity and frequency. The deforestation phase since the 1940s and the intensification of agriculture since the 1960s is thought to be responsible for increasing runoff coefficients on the slopes, and hence for the changing river dynamics. There are, for the moment, insufficient statistical meteorological data to support the hypothesis that peak runoff is also increasing in magnitude as a result of heavier rainstorms.

4.3 Landslides

The M–D topographic threshold envelope suggests that only six landslides are seismic in origin. Landslides by seepage pressure and/or gravity obey to the topographic threshold equation (1).

Non-seismic landslides appear to result from renewed fluvial vertical incision, and from weathering of steep rock fault surfaces. The latter leads to a gradual reduction of the shear strength. In a general way, it is thought that deforestation and intensification of agriculture are only indirectly responsible for landsliding in as much as they trigger vertical incision by rivers.

5 Discussion

5.1 The town of Uvira, threatened by landslides

Figure 6 shows that fault facets 0–9 host the non-seismic landslides 19, 63 and 53. As discussed earlier, the landslides result in the first place from down wearing of the rock and consequent adjustment of the slope to the soil mechanical properties of the weathering material which allows less steep equilibrium slopes than the naked rock fault surface. As happened with landslide 19 in 1986, partial remobilisations are possible. Moreover, the seven other fault facets might also deliver landslide material to the town in the future. The seriousness of the situation is illustrated by the remobilisation of slide 19 of the harbour Kalundu (Fig. 1) in 1986 or by the extension of ancient landslide 63 which derived from fault facet 4 (Fig. 6). The lobe of this ancient slide reaches far into the present town and a lobe of this size, delivered by one of the 10 fault facets would destroy thousands of houses if it should come down at present. Every fault facet, looking over Uvira town, undergoes further weathering and can fail at any moment. Considering a total surface of more than 4 km^2 of fault facets which could loose a layer of 2 m thick, either by first or second time slides, the volume of rock and earth, threatening the town amounts to more than 8×10^6 m^3. As it concerns non-seismic landslides, this immense mass will probably not start to move all at once, but seismic shocks can advance the moment of failure and, therefore, could initiate a real disaster if it were to activate and/or reactivate this mass of soil and rocks at once.

Seismic landslides 50 and 52 (Fig. 3) constitute another risk. Because they are cut off along fault facets 5–9, their respective lobes are much shorter than normal. Table 2 shows that the length–width ratio of landslides 50 and 52 belongs to the lowest values of the whole set of mapped landslides. Both slides remain in place without the upslope oriented confining pressure of the lower part of the lobe, tectonically cutoff. Therefore, the remaining upper part of the lobes of landslides 50 and 52 should be in a stability situation lower than normal and seismic events could trigger their movement. The volume of both lobes is estimated as another 10^7 m^3.

5.2 The possible role of landslides more inland

Although landslides more inland should not be a direct threat to the town of Uvira, they would be able to influence the river regime in several ways as to increase peak discharge:

(1) Landslide head scar mobilisation can result in the release of soil water bodies perched above the scar and responsible for the building up of hydrostatic pressures in the soil mass evacuating the head scar. Experience in Rwanda (Moeyersons 1989) has shown that in some landslides water gushes out of pipes in the base of the head scar during several days or even weeks after the landslide movement. In other instances, the evacuation of the head scar does not suffice to release the spring and the water

continues to be injected into the landslide lobe. Due to the state of unsettlement of the lobe shortly after its movement, these waters find easily their way through the lobe and springs originate at the toe of the lobe, the water loaded by easily transportable liquefied mud from the lobe. Such a phenomenon has probably occurred in the headwaters of the Kalimabenge in 1954 (Weis 1959). We assume also that 'dewatering' of the partial remobilisation of non-seismic landslide 4 in the headwaters of the Kabindula has contributed to a flood which gave rise to the carving out of the Kabindula gully through the centre of the town.

(2) Mud flows or debris flows (Dikau et al. 1996) increase river discharge to higher levels than could be expected on the base of runoff calculations alone. This stems from the fact that mud flows contain some 60 vol% of mineral material (Embleton and Thornes 1979) which is added to the river water and contributes in the same time to extremely high sediment concentrations in the river water during the floods.

(3) Landslides 1, 3, 4, 5, 6, 7, 8, 9, 10, 11, 14, 15, 17, 22, 23, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 47, 49, 51, 57, 58, 61, mapped on the 1959 photos affect rivers and push them away and narrow the river bed. It is obvious that during landslide events, rivers become frequently barred. The formation and subsequent failure or overflow of the landslide lobes is an obvious reason for stream discharge irregularities, low tides as well as peak stages.

5.3 Remediation of the situation? Prevention?

Uvira faces three challenges. The first challenge is the threat of future devastating landslides, issued from the 10 hill spurs interpreted as fault facets and from the old tectonic landslides 50 and 62. In the worst scenario of heavy seismic shocks activating all potential landslide hearths at once, the town should be buried under nearly 18×10^6 m^3 of rocks, earth and mud. The mildest scenario foresees in not harmless reactivations, type reactivation landslide 19 (Fig. 1), spread over time and space and not necessary accompanying seismic activity. Prevention measures do not exist, especially in the case of seismic triggers. But the effect of possible hazards can be alleviated by avoiding heavy and high habitation constructions. In case of calamity, small buildings of light materials will provoke less casualties and reconstruction costs will be less. It is further strongly advised that a soil mechanical survey on the ten fault facets should be executed.

The second challenge is about flash floods, conveyed from the mountains through the river beds of Kalimabenge, Mulongwe and Kavimvira. They threaten the town directly by inundation and destruction of infrastructure and indirectly by provoking landslides in the mountain hinterland what, in turn, might lead to unforeseeable overbank stages in town. The origin of flash floods can generally be attributed to an increase of the runoff coefficient and/or to heavier rainstorms than before (Moeyersons and Trefois 2008) as a result of global change (Hulme et al. 2001; Dore 2005). Spring flow measurements in Rwanda between 1958 and 1979 have demonstrated that deforestation increases runoff coefficients and hence reduces annual spring flow (Rwilima and Faugère 1981). This is also one of the reasons why river hydrographs in Rwanda show increasing peaks and decreasing low stages. It is thought that deforestation of the mountain hinterland of Uvira has the same effect. But on the aerial photographs of 1959, the deforested area was already nearly as big as on the 2000 ETM image and the 2004 IKONOS images, while the devastating river floods and the increase of landslide activity started mainly in the 1960s and the 1970s and are still growing today. Weis (1959) indicates that important deforestation was going on in the 1940–1950s. The aerial photos show that since 1959 the intensity in soil use did increase dramatically in the deforested belt. In that year, the agglomeration of Uvira was nearly inexistent and in the mountains, big irregular dark patches of bush fires betray slash and burn practices. The ETM and IKONOS images show that at present most of the mountain hinterland is occupied by farmers, the land being organised in regular parcels, intensively cultivated and most natural vegetation being disappeared. Research in Ethiopia (Moeyersons et al. 2006; Nyssen et al. 2006) has shown that river activity, especially gullying, started to become significant not at the moment of first deforestation more than 3,000 years ago, but during the last 50 years, when agricultural exploitation was greatly intensified. Agricultural intensification, pushing up the runoff coefficient, is thought to be the main reason for the increasingly extreme river regime in the Uvira mountain hinterland. Of course, punctual channel bank stabilisation on the fans, like it is actually done along the Mulongwe, can remain effective until the next flash flood year, but the real sustainable solution for river regime normalisation has to be sought upstream, where land should be protected by soil and water conservation methods. Experience in Rwanda shows that correctly applied techniques remain efficient at present in spite of the till yet statistically unproven idea that rainstorms increase in intensity and frequency in the area.

The third challenge is a yearly increase of runon to the lower town, delivered by the extension zone of the agglomeration of Uvira upon the first hillsides West of the alluvial fans. Collection of rain water from the roofs, drainage ditches along the roads, grassy surfaces and green lungs with high water absorbing capacity are some of the measures which could be taken into consideration.

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