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Geomorphology and urban geology of Bukavu (R.D. Congo): interaction between slope instability and human settlement

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Abstract: The city of Bukavu, on the south coast of Lake Kivu in the Democratic Republic of Congo, suffers from frequent landsliding, which leads to continual damage and destruction of buildings, roads, waterworks and sewerage infrastructure. Thirty-one landslides identified on aerial photographs of 1954 and 1973 are located outside the Bukavu micro-rift and are related to actively incising rivers. Their origin is thought to be due to increases in hydrostatic pressure. Six landslides occur within the Bukavu micro-rift, four of which are much larger and wider than other slope failures in the study region. These large landslides are adjacent to, or crossed by, active faults. They fall far below the topographic threshold envelope, a relationship of slopes at the head of the slide and the surface area drained into it, indicating seismic or anthropomorphic triggering. The Bukavu landslides still reactivate occasionally. Deforestation, followed by a large increase in the population, have been indirect causes of the reactivated mass wasting processes. On the steep slopes in the south of the city the high density of newly built houses has led to reduced water infiltration and enhanced runoff, causing landslides and mudflows. Very high spatial resolution IKONOS satellite images have recently been used as base maps for geohazard assessments of Bukavu. A geographical information system (GIS) has been developed for Bukavu's planners: this shows the locations of buildings, roads and tracks, the river network, the water distribution system and the sewerage infrastructure, as well as areas of slope instability.

The city of Bukavu on the west bank of the Ruzizi outlet of Lake Kivu (Fig. 1) has always been affected by slow ground movements. Accelerated landsliding and sudden gully development also occur. In many districts, houses have to be rebuilt frequently and roads are generally in bad condition. The town is in a continual state of repair and rebuilding, with disruption to both the water supply infrastructure and the sewerage system. However, this has not discouraged people from settling in Bukavu (many seeking refuge from regional military conflicts), with the population increasing from 147 647 in 1977 to some 450 000 in 2002 (UNESCO 2002).

Slope instability and soil erosion in and around Bukavu have long been of concern to the local government. As early as 1945, the Belgian authority installed the so-called 'Mission anti-érosive' in Kivu. However, the subsequent deployment of soil conservative measures was not very successful in halting soil movements in Bukavu. First, the main action taken was the installation of intersection trenches for water and eroded soil, positioned at distances of tens of metres parallel to slope contours. By 1959 most hills in Bukavu were trenched in this way. Such trenches can stop soil wash, but have been proven in neighbouring Rwanda to actively contribute to mass wasting (Moeyersons 1989, 2003). By the 1980s it was realized that the main problem in Bukavu was mass wasting, rather than soil erosion (Lambert 1981). Furthermore, it took time to realize that mass wasting at Bukavu was driven not only hydrogeologically, but also tectonically–seismically. Ground investigations led to the realization that Bukavu is crossed by a north–south-trending micro-graben; moreover, that it lies at the intersection of tectonic lineaments trending SSE–NNW (Tanganyika trend) and SSW–NNE (Albertine trend) (Cahen 1954; Ilunga 1989; UNESCO 2002).

The debate concerning the origin of landsliding in Bukavu continues today (Ilunga 1978, 1991; Moeyerson *et al.* 2004). It was first thought that low-quality construction of house roofs and leakages in waterworks contributed to high soil water contents, leading to landsliding. To lower the impact of humans on the environment, the 1958 Mission d'Etalement de la Population redistributed the inhabitants from high population density areas

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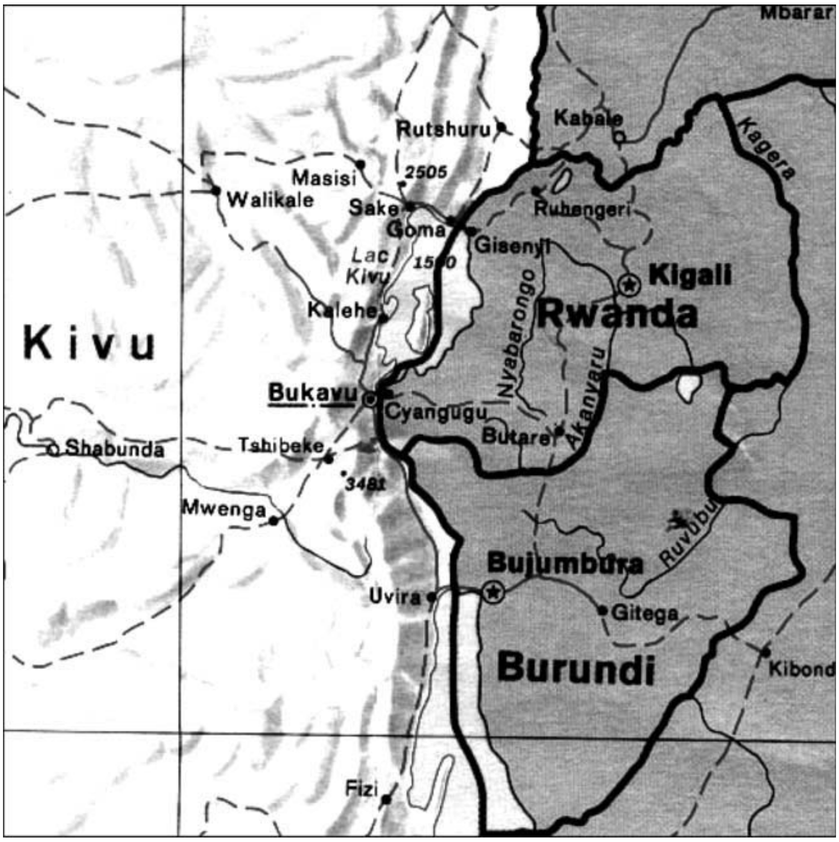

Fig. 1. Location of Bukavu in South Kivu, Democratic Republic of Congo.

to low-density districts. In the proceedings of the 'Erosion at Bukavu' conference (Ischebeck *et al.* 1984), there was still a tendency to consider even the largest mass movements to be the result of human mismanagement. However, geomorphological surveys of Bukavu have revealed an apparently active double fault step. More recently, a seismic origin for the larger landslides at Bukavu has been suggested by Munyololo *et al.* (1999).

Detailed geological mapping and geotechnical investigations have only recently started and synoptic geomorphological descriptions, as well as movement rate measurements, are still lacking. To redress this situation, the 2002 UNESCO project 'Géologie urbaine de Bukavu: interaction entre la stabilité du sol et la pression démographique', was initiated, based on the following.

(1) A geomorphological map of Bukavu, based on a stereoscopic study of panchromatic aerial photographs from 1954 and 1973. This included the mapping of active tectonic structures and landslides; the determination of spatial relationships between tectonic structures, such as fault steps and landslides; and extensive use of the existing geomorphological data to unravel the origin of the landslides. The first practical outcome of this study has been the identification of landslide mechanisms and triggering factors for dangerous sectors of the town.

(2) An updating of Bukavu city maps in geographical information system (GIS) format, based on recent very high spatial resolution remote sensing data (IKONOS) and a digital elevation model, as well as field surveys focused on geology, weathering facies, geomorphology, hydrology, slope instability, mud flows, degradation of infrastructure and pollution.

Geology and tectonics

In the Bukavu area, the folded and faulted Precambrian substrate is covered by thick Tertiary and Quaternary basalt traps, resulting mainly from fissural outflow. The oldest series, not present at Bukavu itself, predates the local rifting and has

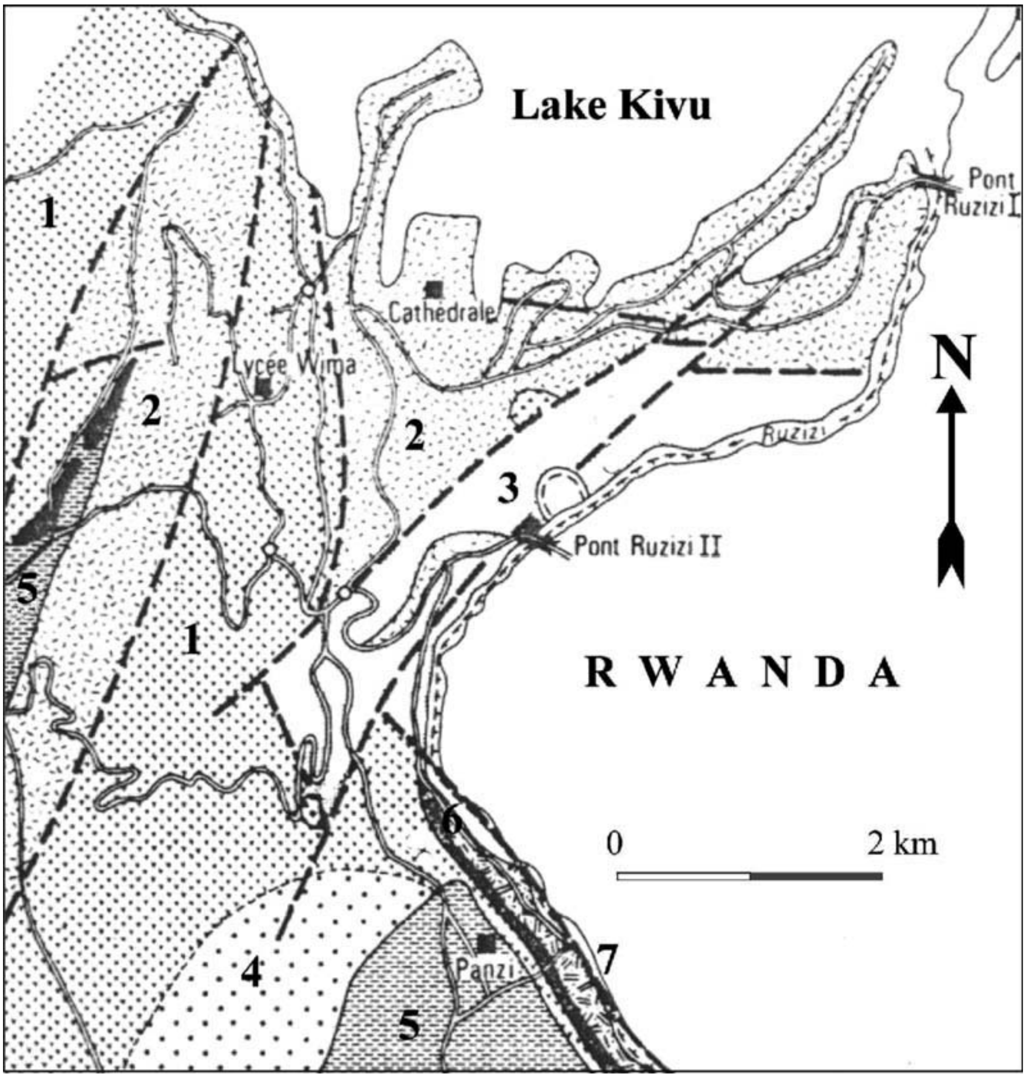

Fig. 2. Geological map of Bukavu, from Kampunzu *et al.* (1983). 1, Basalts of the upper series; 2–7, Mio-Pliocene alkaline lavas (2, basanite; 3, hawaiites and mugearites; 4, ankaratrite; 5, benmoreites; 6, Panzi pyroclastic series; 7, phonolites and trachytes). The dashed lines are normal faults.

been dated between 7 and 10 Ma (Pasteels *et al.* 1989). The middle and upper series are found at Bukavu. The middle series, of Mio-Pliocene age (Kampunzu *et al.* 1983; Pasteels *et al.* 1989), is intimately related to the rift faulting. The upper series dates from Pleistocene time and to the last century. The distribution of these deposits at Bukavu is shown in Figure 2.

Each lava series is believed to consist of numerous individual flows (UNESCO 2002). The complex geometry of the present lava layers is the result of successive rifting and eruptive episodes. Weathering and erosion, as well as normal faulting, occur between successive lava flow series, explaining the repeated occurrence of palaeorelief, contact metamorphism, smectite shrink–swell clay layers, probable shrink–swell vertisol palaeo-soils, and alluvial–colluvial clastic deposits.

In the absence of solid geological data, geomorphological evidence has often been used to locate active faults, believed to be the origin of the numerous escarpments crossing Bukavu (Fig. 3). However, there are doubts about geomorphological interpretations with regard to the exact locations of

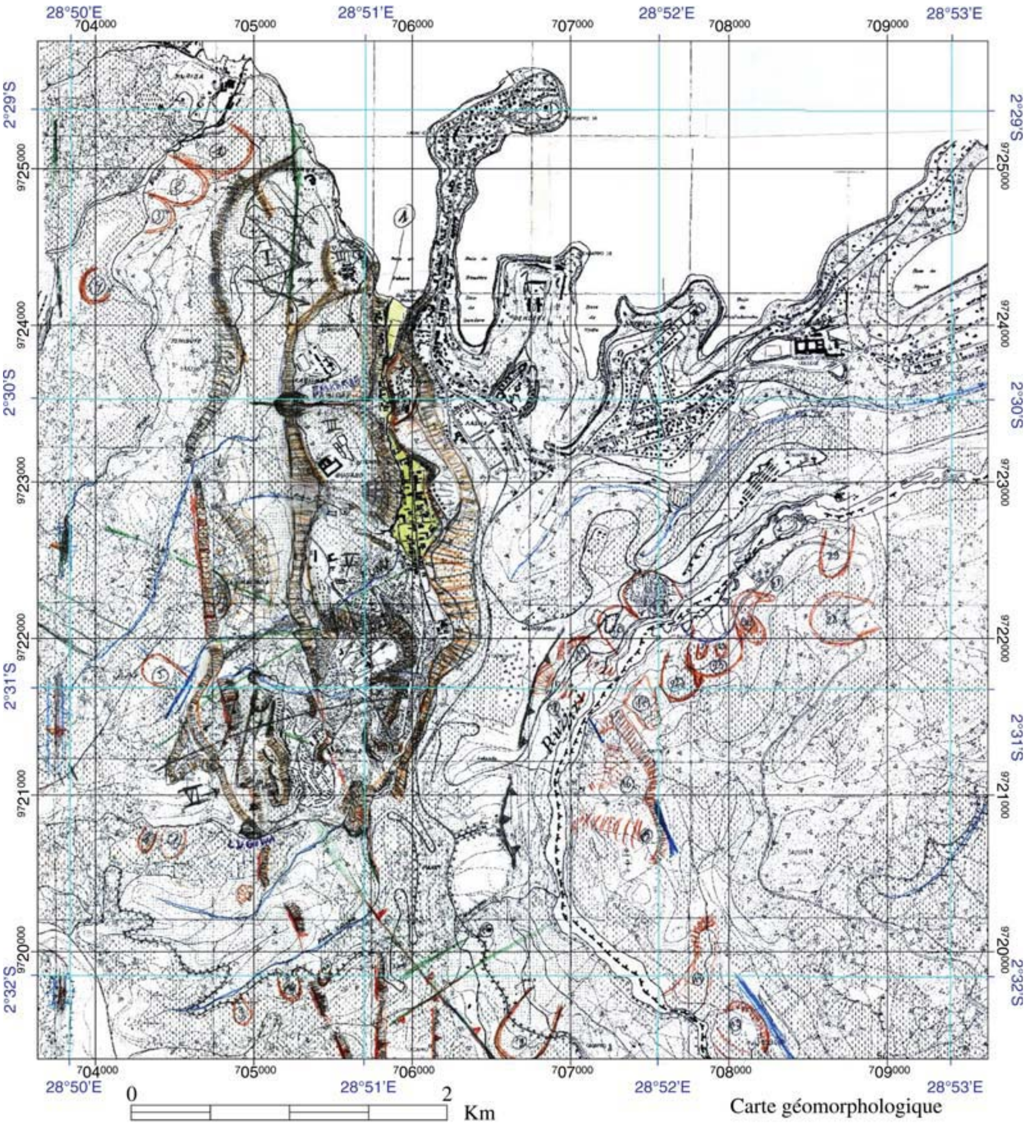

Fig. 3. Geomorphological map of Bukavu. BUK, Bukavu; BUG, Bugabo; ZA, Camp Zaïre; NY, Nyagongo; SA, Camp Saio; (1), (2), etc. are escarpments; 1, 2, etc. are landslides outside the micro-graben; I–VI are landslides inside the micro-graben.

the faults. Different geological maps indicate many different fault trajectories (Lambert 1981; Kampunzu *et al.* 1983; Mweze, cited by Munyololo *et al.* 1999).

Geomorphology

Bukavu lies on the west bank of the Ruzizi gorge, in a rolling landscape of convex and elongated hills, developed on the weathered lavas of Panzi–Muhungu–Dendere (1550–1650 m above sea level (a.s.l.)). This landscape is interrupted in the west by an asymmetrical north–south-trending corridor, the so-called 'Bukavu micro-graben' (UNESCO 2002). This starts at the Bay of Bukavu, gradually disappears south of Boholo, and is 1–1.5 km wide and about 4.5 km long. The Kawa River flows through the eastern side of the valley, bordered on the west by three successive north–south-trending escarpments that give rise to

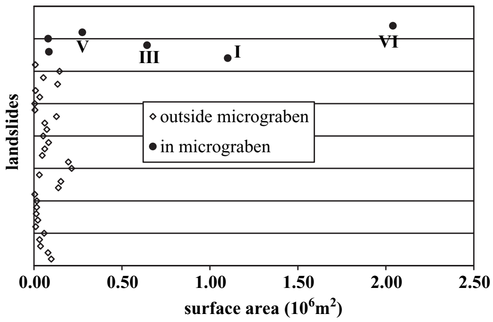

Fig. 4. Numbers of landslides by surface area in Bukavu district. Landslides (I), (III), (V) and (VI), located within the micro-graben or at its boundaries, are clearly larger than the others.

crest-lines at $\pm$1550 m (Kabumba–Bugabo–Boholo), 1700–1750 m (Tshimbunda) and 1800–2000 m a.s.l (Karhale). For convenience, the term 'micro-graben' is used in this paper to indicate the asymmetric valley of the Kawa River (Fig. 3).

Recent investigations have aimed to determine the origin and activity of mass movements that have detrimentally affected, and are expected to continue to affect the rapidly urbanizing area in and around Bukavu. These investigations were accomplished by aerial photograph interpretations, ground reconnaissance, comparison with similar phenomena and investigations carried out in adjacent Rwanda, and the application of theoretical landslide models developed in the USA. This information may prove useful for urban planning and for the general understanding of mass movements in the Bukavu area, and perhaps elsewhere in tectonically active humid tropical countries.

The interpretation of stereoscopic aerial photographs led to the recognition of large landslides spatially linked to the Bakuvu micro-graben (II, III, IV and VI in Fig. 4). About 15% of the surface area of the Bakuvu district is covered by visible landslides, many of them clearly active, especially those in the micro-graben. First, there is an enormous scar, affecting the SE flank of Tshibuye Hill (I in Fig. 4), which is affected by a second Bukavu slide and partially affected by the Kabumba–Bugabu incision (II and III, respectively, in Fig. 4). Another landslide belt is in the valley of the lower Funu River (V in Fig. 4). This depression is bounded at its upper end by a huge crown-like fissure, a sharply expressed escarpment on the aerial photograph, which it is interpreted as an active landslide.

Stereoscopic interpretation of aerial photographs also shows the presence of numerous landslide scars outside the Bakuvu micro-graben. In many cases the lobe still partially fills the scar (Dikau *et al.* 1996). These have been numbered from 1 to 31. These stereoscopic study also reveals that none of these 31 landslides is located on or in the vicinity of visible active faults. Only landslides 13 and 15 have their headscarp in contact with a fault. Landslides 1–31 are clearly different from groups I–VI with respect to their width/length proportions and their size. The average surface of a landslide outside the micro-graben is $\pm$6.5 ha, whereas the mean size of the landslides in the micro-graben is nearly 85 ha (Fig. 4). The landslides in the Bukavu micro-graben also appear to be relatively wide and short, suggesting some structural influence (Fig. 5).

In Figure 6, most Bukavu landslides fit within the topographic threshold envelope for North America (Chorley *et al.* 1984; Montgomery &

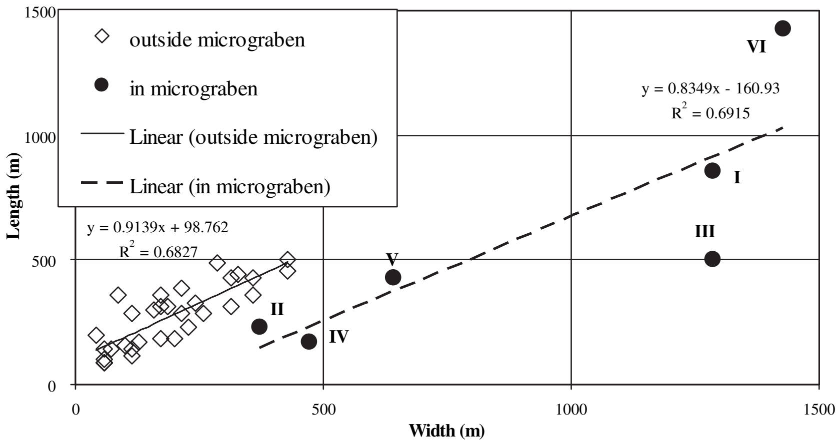

Fig. 5. Shape of the Bukavu landslides. The linear regression lines (length/width) show that the landslides in the micro-graben are significantly wider than the others.

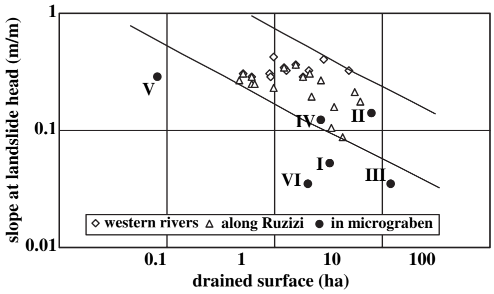

Fig. 6. Topographic thresholds of Montgomery & Dietrich (1994).

Dietrich 1994) and Rwanda (Moeyersons 2003), as delimited by the two lines. Landslides to the west of Bukavu are located in the valleys of the Wesha, Funu and Lugowa, as well as along Kahuma Gully. Landslides (I), (III), (V) and (VI) fall clearly below the Montgomery–Dietrich topographic threshold envelope. Their movement is probably not induced by hydrostatic pressures alone, but by such pressures in combination with tectonic and/or seismic activity. The validity of the topographic threshold criterion is supported by the fact that landslides (I), (III), (V) and (VI) are the only ones crossed or bounded by active faults.

Remote sensing

Data selection

This study used topographic maps from 1954, together with aerial photographs from 1959 and 1973. The main use of recent remote sensing data was for mapping the current city with regard to housing density, infrastructure, vegetation cover and slope instability features. This led to the following criteria for the selection of remote sensing data: (1) acquisition as recent as possible; (2) high spatial resolution (pixel size between 1 and 3 m); (3) multispectral data, allowing the rapid recognition of key features (soils, vegetation, buildings, roads, rivers) with simple image processing. In 2001, the

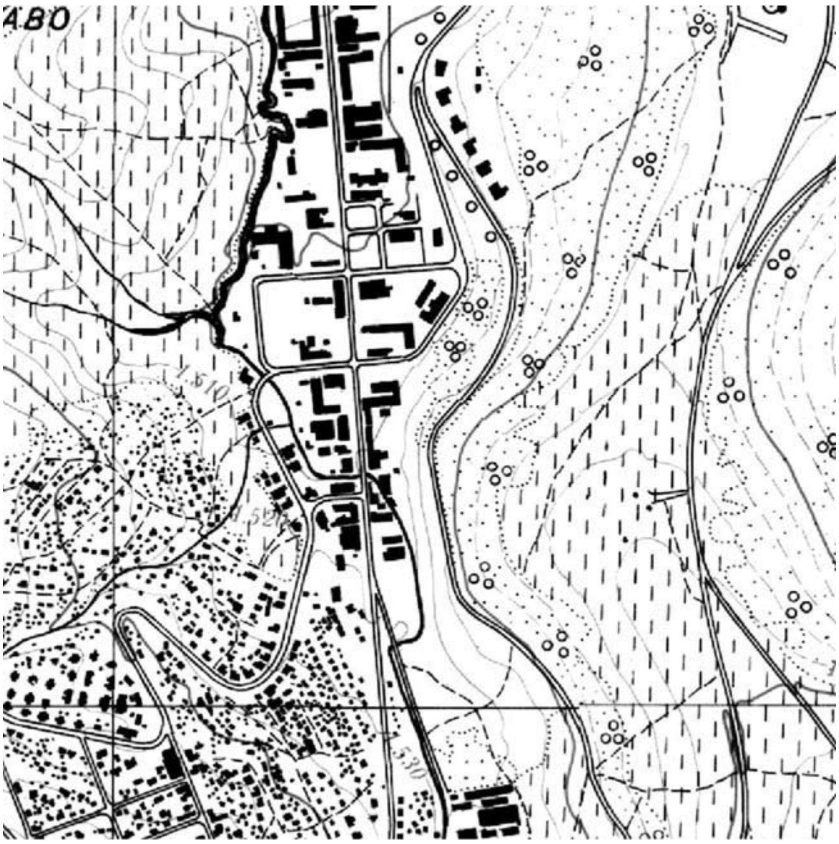

Fig. 7. The industrial area in 1954, surrounded by grass, bush and trees. The area shown is *c.* 1 km^2 (IGCB 1957).

Fig. 8. The same area as in Figure 6, seen on the 2001 IKONOS image. The area shown is *c*. 1 km^2.

only data corresponding to these characteristics came from the IKONOS sensor. A scene of 11 km $\times$ 11 km was acquired, with a resolution of 4 m in the visible and near-infrared (VNIR) range and 1 m in the panchromatic channel.

Geometric corrections

The relief and the differences in altitude in the area are very important, with slopes dropping more than 500 m in a few kilometres, resulting in high values of parallax displacements in the image. Moreover, the angle of incidence of the IKONOS image acquisition was $28^\circ 18'$, makes the geometric corrections more difficult. In these conditions, it becomes impossible to register the image to a cartographic projection system using simple warping with a polynomial transformation on *x*, *y* co-ordinates. The image was therefore orthorectified using geodetic control points from the Belgian Royal Africa Museum archive and a digital elevation model (DEM) derived from contour lines of the 1:10 000 scale 1954 topographic map.

Image processing and interpretation

The first step in the image processing was sharpening the 4 m pixel multispectral image by fusion with the 1 m pixel panchromatic channel, producing multispectral imagery with 1 m pixels. A true colour image at 1 m resolution was used as the 'base map' for the following GIS analyses and synthesis. Simple indices were computed to extract useful information for the project: the Normalized Difference Vegetation Index (NDVI) for vegetation cover and a brightness index for quantifying the growth of urban areas. A visual comparison between the 1954 map and the IKONOS image directly reveals the huge change in urbanization (Figs 7–10). Over much of Bukavu, the grass and bush areas of 1954 have been replaced by very high-density housing.

Field survey

Rapid geomorphological surveys were carried out to provide the GIS with updated information.

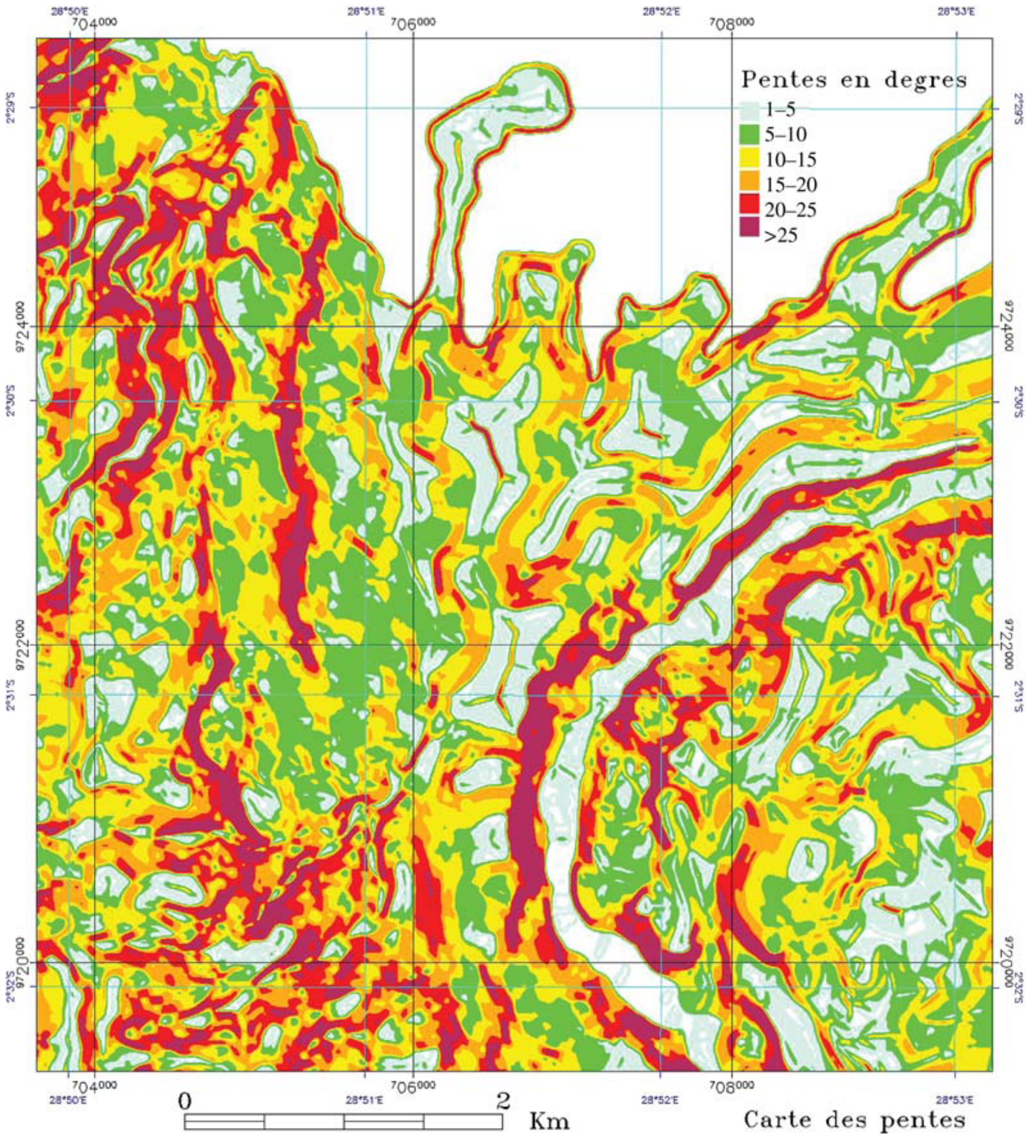

Fig. 9. Bukavu slope steepness map.

Archive information on Bukavu buildings and infrastructure was also digitized to complete the information set. The main topics covered were: outcrop locations and descriptions; locations of springs; the river network; biological pollution of drinkable water; street maps; the water distribution network and state of degradation; the sewerage network and state of degradation; slope instability (landslides, debris flows, mud flows); damage to buildings and infrastructure. Black and white image maps, based on the panchromatic IKONOS image, were edited at 1/5000 scale in a easy-to-use booklet format and used to locate the field observations. All of the field results were digitized and added to the Bakavu GIS database.

GIS synthesis

The GIS layers built during the Bukavu project allow the fast production of on-demand maps, at any required scale, according to user needs. The

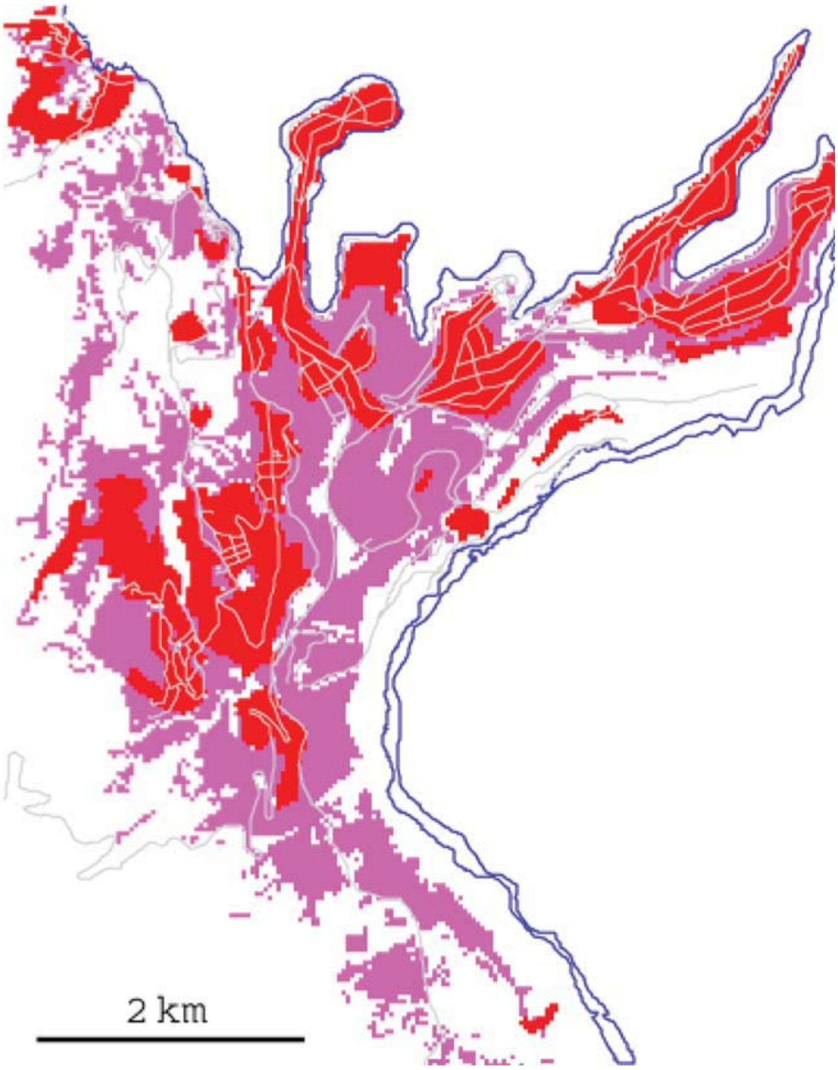

Fig. 10. Bukavu urban areas. Red: 1954, from the topographic map. Red + pink: 2001, from IKONOS.

GIS-generated maps are easily understood, even for non-specialists, because of the IKONOS image background. Furthermore, the GIS-based maps can be rapidly updated when new information is available. Figure 11 shows an example of the many possible data layer combinations.

Conclusion

A geomorphological approach to assessing geo-hazards in Bukavu, based on airphoto-based mapping of landslide morphologies and investigations into the geomorphological thresholds of the landslides, allowed a good understanding of local slope instability mechanisms and triggering factors, in the context of regional geological structures and seismic activity.

An orthorectified IKONOS satellite image served as a GIS base map for further spatial data. Combined with a DEM, the IKONOS image was very useful for highlighting the huge increase in urbanization, particularly on the steep to very steep slopes. Field observations and archive compilations formed the basis of GIS thematic layers, providing a flexible database for the production of on-demand maps by specific users.

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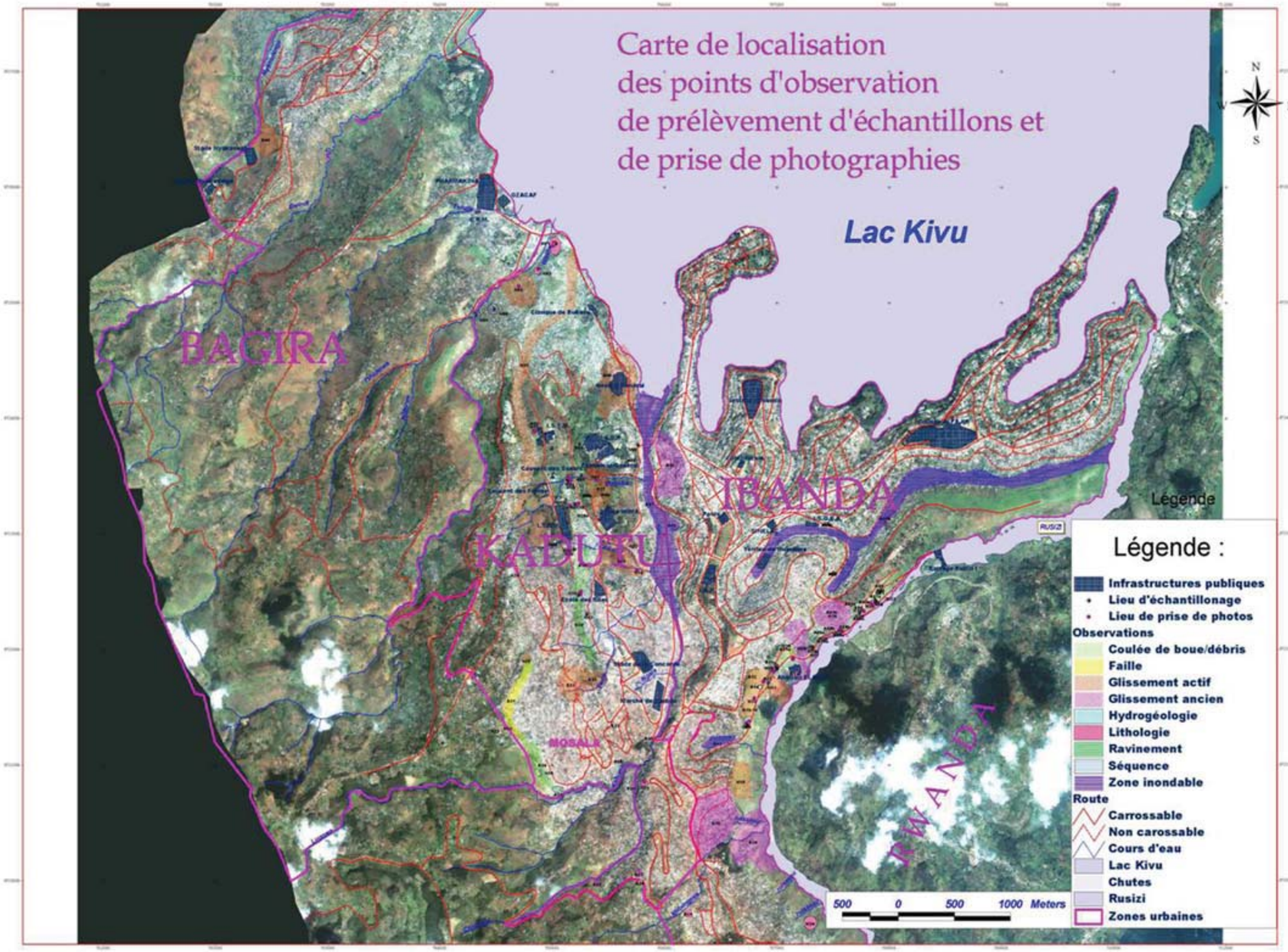

Fig. 11. GIS vector layers obtained from archives and from field surveys (river network, roads, mud flows, landslides, faults, location of field observations), with the 2001 IKONOS image as background.

démographique' project, contract SC/RP205.580.1, between the Royal Museum of Central Africa, Belgium, and UNESCO, as part of the Geological Networking (GEONET) Programme. The orthorectification of the IKONOS image and the map of settlements in 1954 and 2001 were computed at the 'SURFACES' laboratory of Liège University, Belgium.

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