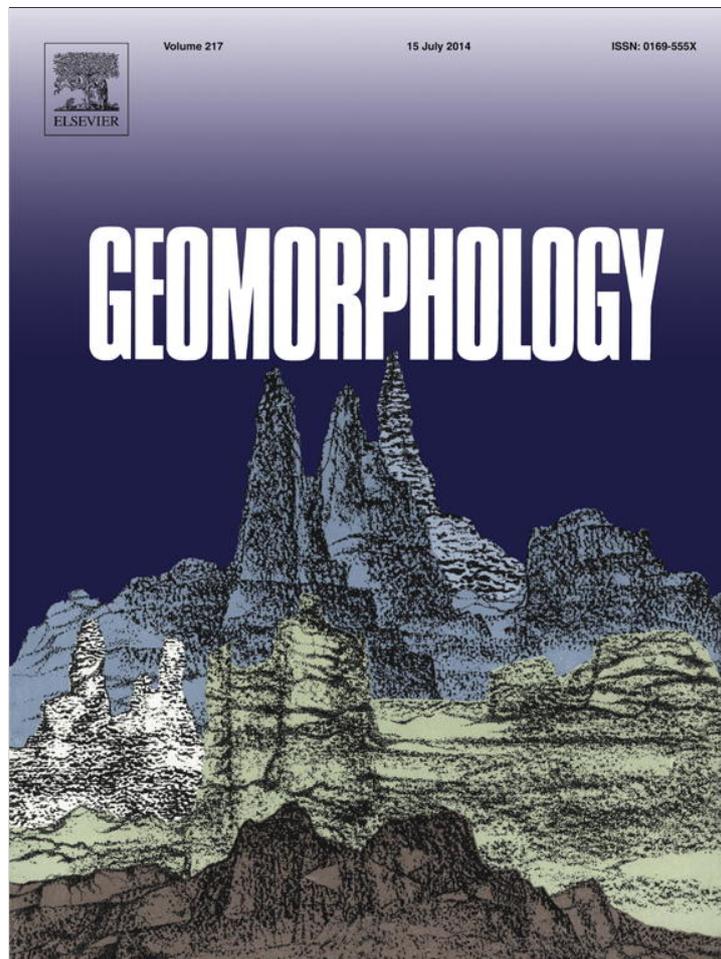


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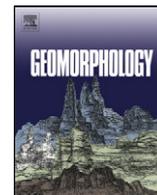
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Topographic and road control of mega-gullies in Kinshasa (DR Congo)

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ABSTRACT

Diachronic mapping (1957, 1967, 2007 and 2010) shows an exponentially growing mega-gully network since roads were constructed through in the forests and plantations which occupied the sandy soils of the high town of Kinshasa. We found that the spatial occurrence of the mega-gullies (width ≥ 5 m) in this newly urbanized environment is controlled by two factors. First, there is a topographic control, given by the relation $S = 0.00008A^{-1.459}$, with S being the slope gradient (m m^{-1}) of the soil surface at the gully head and A the drainage area (ha) above the head. There is also a 'road' control, expressed by $S = 22.991Lc^{-1.999}$, with Lc being the cumulated length of roads in the basin above the gully head. The co-existence of both controls reflects the fact that the local sands are highly permeable and hence roads are more important generators of continuous runoff. The S - A relation noted above should not be applied outside the town where the road network is less dense. In contrast, the S - Lc relation may be used in both the town and rural areas underlain by porous soils where roads are the only generators of continuous runoff. We further conclude that the high town of Kinshasa is one of the most vulnerable places for gullying, and gullying can potentially transform the town into a badland. 'Artisanal' gully treatment is more successful than generally believed and the S - Lc relation can be a tool for mega-gully prevention.

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1. Introduction

Many cities in Central Africa have experienced a fast urban expansion over the last decades. Urban growth very often leads to severe gully erosion. The high town of Kinshasa (DR Congo), a hilly region which dominates the lower town along the Malebo Pool (Fig. 1), is particularly prone to this erosion process (Trefois et al., 2010; Wouters and Wolff, 2010; Vandecasteele et al., 2011; Makanzu et al., 2013a) and the cost of damages by gullying to the urban infrastructures amounts to several millions of Euros each year (Makanzu et al., 2012).

Gullies in the high town of Kinshasa are the result of hillslope incision by concentrated wash. They typically show a triangular cross-section, with width being about three times as large as depth (Makanzu et al., 2013a). Where they reach the water logged flat valley floors between the hills, they widen and give rise to water and sediment problems till far in the lower town.

Van Caillie (1983) proposed runoff reducing measures upslope of the gully heads. His idea was to stop further gully growth and prevent gullies from reaching their 'natural' equilibrium state by decreasing the size of the runon area above the valley or gully head due to headward retreat (Graf, 1977). This equilibrium state gives rise to the

concept of 'topographical control' describing threshold relations between topographical parameters of the gully. The relation between the slope gradient of the soil surface at the gully head (S) and the runon area flowing towards its head (A), also called contributing area or drainage area, has been studied in a range of different environments throughout the world: in the US (Patton and Schumm, 1975; Montgomery and Dietrich, 1988), France (I.G.N., 1983), Belgium (Govers, 1991; Vandaele et al., 1995; Poesen et al., 1996; Vanwallegem et al., 2003), the UK (Boardman, 1992), Portugal (Vandaele et al., 1995; Vandekerckhove et al., 1998), Spain (Vandekerckhove et al., 1998), Ethiopia (Nyssen et al., 2002) and Rwanda (Moeyersons, 2003). Montgomery and Dietrich (1994) show that when S and A are plotted in a log-log graph, the landscape can be divided into process regimes and a negative correlation between S and A appears. Fig. 2 is a fictive example of an S - A graph of a number of gullies in a 'homogeneous' region (Montgomery and Dietrich, 1994). This example shows that a gully free zone exists for lower values of S and A . This hydrologically stable zone is limited by an envelope at the lower edge of the cluster of points more or less parallel to a trend line through the data cloud. Below this envelope, no incision occurs. This threshold line or critical relation for gully development by hydraulic erosion can be represented by a power-type equation (Vandaele et al., 1996; Poesen et al., 2010):

$$S = aA^{-b} \quad (1)$$

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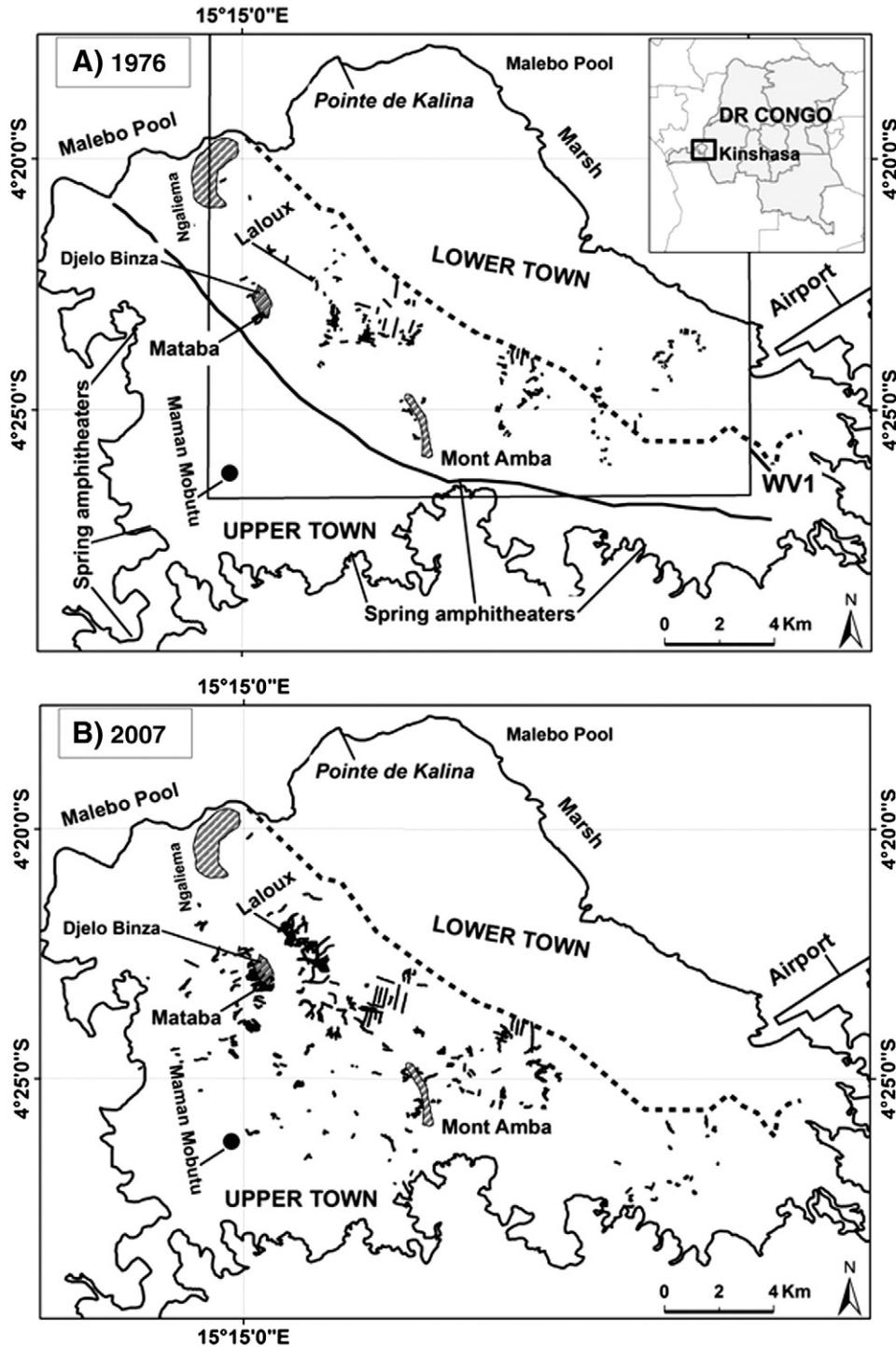


Fig. 1. Main urban zones and mega-gully evolution in Kinshasa. The hilly region is delimited to the North by the black dashed line. The southern limit of the hills is represented by the winding line which follows the string of spring amphitheatres ('erosion cirques'). The black frame indicates the coverage of the WorldView 1 image. (A) Situation in 1976. The solid black line indicates the southern limit of the urban zone in 1976; black patches indicate the mega-gullies in 1976 (Van Caillie, 1983). (B) Situation in 2007. The black line which coincides with the southern extension of the urban area in 2007 shows that the city is sprawling southwards and now reaches the belt of spring amphitheatres. Black patches represent the mega-gullies in 2007.

where a and b are constants that depend on environmental characteristics.

The envelope for gullying as illustrated in Fig. 2 is important for land management purposes, because it allows defining the area that can be drained and concentrated to a point with a given gradient without danger for hillslope incision. In this way the envelope is a device which can be used for gully prevention.

While all studies cited above concern rural areas, the current study addresses the problem of gullying in an urbanized area. Therefore, the first objective of this research is to verify the existence of a topographical control of the type of Eq. (1) in the urbanized area of the high town of Kinshasa. At stake is the possibility to foresee the locations in town potentially prone to gullying and further to develop a conceptual management device for a sustainable

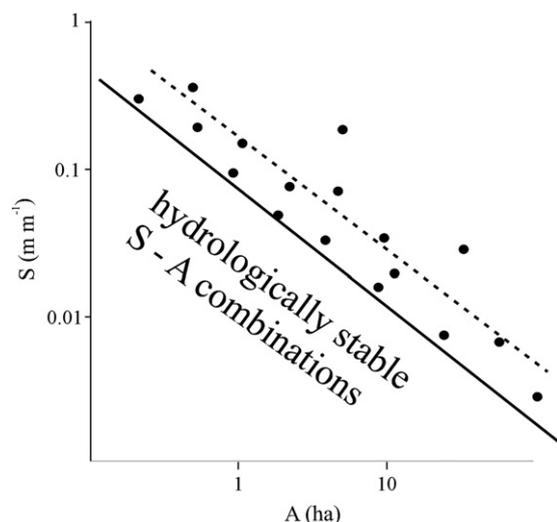


Fig. 2. Representation of gullies in a slope (S) versus runoff area (A) graph, in logarithmic scale. The solid line is the gully erosion envelope. The dashed line represents a power trend line through the data cloud.

urban planning. This is the first time that such a device for Kinshasa is developed.

The presence of gullies is often linked to the occurrence of roads and other axial runoff conveyors (Moeyersons, 1991; Croke and Mockler, 2001; Jungerius et al., 2002; Nyssen et al., 2002; Valentin et al., 2005; Frankl et al., 2012). Makanzu (2010) observes that 91% of the mega-gully heads in Kinshasa are directly fed by a road, a lane, or a track. In many cases roads and their adjacent sewage trenches act as a gutter and receive and concentrate runoff from important surfaces. Moreover, roads in Kinshasa, tarred or not, are the most important runoff producers in the urbanized landscape (Makanzu et al., 2013b). Therefore, the second objective is to question if there exists, besides the topographical control, a cumulative road length control for mega-gullying in Kinshasa. A tool, based on road length instead of runoff area, should be easier to be applied for gully prevention.

2. Materials and methods

2.1. Study area

Kinshasa is located on the southern banks of the Malebo Pool (272 m a.s.l.), a lake-like widening in the lower reaches of the Congo River (Fig. 1). Kinshasa has a tropical wet and dry climate and the mean annual precipitation amounts to 1400 mm (Makanzu, 2010). The rainy season spans from September through May and the dry season runs between June and August (Bultot, 1971). The region used to be covered by dry dense forest, savannahs and semi-aquatic and aquatic formations in the valleys and around the Malebo Pool (Pain, 1984; Kikufi and Lukoki, 2008). Nowadays no vegetation but a few grasses are left (Tshibangu et al., 1997).

The city first developed in the plain along the shore of the Malebo Pool (Fig. 1). From 1957 to 2007 the population of Kinshasa increased by a factor 20 to reach 8 M (Hôtel de ville de Kinshasa, 2007) while the urbanized area grew from 94 to 443 km² (Makanzu et al., 2012). At the end of the 1960s, the whole plain along the river was occupied. The southern limit of the town (Fig. 1A) was bounded by the northern edge of an undulating and widely dissected plateau or hill belt culminating between 350 and 710 m a.s.l. (De Maximy, 1978; De Maximy and Van Caillie, 1978). Then the city started to sprawl over the plateau and today it is extending further southwards.

The plateau of the high town of Kinshasa covers 240 km² and is delimited to the South by a continuous sequence of spring amphitheaters giving an irregular and curved plan form of its border (Fig. 1A). The northern edge is believed to be an ancient bluff of the Malebo Pool (De Maximy, 1978). The whole area, including plateau and adjacent northern and southern plains is underlain by a subhorizontal series of Mesozoic reddish shale and soft sandstone (Egoroff, 1955). On the plateau, this series is overlain by a 50 to 100 m thick layer of Cretaceous and Tertiary sands (Cahen, 1954; De Ploey, 1963). The hills of the high town show a typical convex form and are etched out in these sands. The valleys between the hills correspond more or less to the top of the underlying shale–soft sandstone series, which acts as an aquitard compared to the overlying sands. Therefore, all hills of the plateau contain perched water with corresponding perennial springs at their foot (Van Caillie, 1983). This study concerns the urbanized plateau (Fig. 1B).

2.2. Diachronic gully inventory

The hilly plateau of the high town has been studied with 321 aerial photographs of 1957 and 1967. The scale of the photographs is about 1:20,000. A mirror stereoscope (Sokkisha, Tokyo 8426), with magnifying oculars enables objects larger than 2 m to be distinguished. With the stereoscope, the ground surface is visible between the palm oil trees, but not in the patches of primitive dry forest.

The geotechnical map of 1976/77 (1:20,000), which is part of the 'Carte Géomorphologique et Géotechnique de Kinshasa' (Van Caillie, 1988), has been introduced in the Geographic Information System (GIS) project. This map shows the gully distribution in 1976. Every gully is represented by a line indicating the gully length. Other data such as gully depth or gully volume are not available.

The 2007 distribution of the mega-gullies has been mapped on an anaglyph derived from two panchromatic SPOT 5 images (2006 and 2007) with a resolution of 5 m. All mega-gullies have been reported in ArcGIS 9.3 on the orthorectified 2007 SPOT image. A new digital elevation model (DEM), based on the two SPOT images, calibrated and georeferenced by 25 differential GPS (Pathfinder Pro Series, with ≤ 1 m of error) points and another 25 GPS (Garmin) points, enables us to place the mega-gullies in their topographical context (Makanzu et al., 2013a). The GIS project contains that DEM, a 10 m contour topographical map derived from the DEM, the orthorectified 2007 SPOT image and the 2007 gully polygons. The 5 m resolution of the SPOT image hampers the discrimination of the smallest gullies. However, thanks to the 3D effect of the anaglyph, gullies with a width ≥ 5 m could be distinguished as it was checked through field validation. For this reason, the gullies in this study are indicated as mega-gullies with a width ≥ 5 m.

WorldView 1 image of 2010, covering the biggest part of the town (Fig. 1) is also used to map the gullies. In spite of the higher precision of the image, only gullies wider than 5 m are mapped so that a more relevant comparison can be made with the 2007 situation.

2.3. Slope gradient at gully heads in 2007 and 2010

In Kinshasa, Makanzu et al. (2012) observe that runoff during rainstorms is not diffuse but mainly axial and concentrates on roads, streets, lanes, tracks, sewage ditches and trenches. The concentration of water along these axes is mainly due to the low infiltration capacity of tarmacs, paved surfaces and over-consolidated sand surfaces like earthen roads. To a lesser extent, waters from roofs and roof gutters flowing towards the axes also contribute to runoff concentration.

In the case of an axial gully or road-gully (Jungerius et al., 2002), the slope gradient (S) is the longitudinal gradient of the road. This is easily computed from a contour map derived from the SPOT DEM. The horizontal angle ω (degrees) between the road axis upslope of the gully head and the local slope line, perpendicular to the contours is considered. This angle is 90° when the road axis follows a contour and 0° when the road axis follows the slope line. The relation

between S (m m^{-1}) and the gradient of the natural slope at the gully head S_n (m m^{-1}) (Fig. 2) is given by:

$$S = S_n \cos \omega. \quad (2)$$

In many cases part of the axial runoff (road runoff) dissipates along lateral 'leakages'. The reason for this lateral loss can be intentional if caused by a trench or sewage diverter which directs runoff away from the road or trench into the field aside of the road, or unintentional if fissures in the trench or road degradation lead to the same effect. When the natural slope gradient aside the road or the runoff losing axis is higher than the gradient of the road or runoff axis, gully development is possible (Moeyersons, 2003). If such a 'dissipation' or 'leak' gully is consequent, S in Eq. (1) is the gradient of the natural slope at the side of the road and can be read directly on the slope map. But in the case of an oblique 'leak' gully, S is calculated as in Eq. (2).

2.4. Definition of A and the cumulated road length

The concentration axes thoroughly reorganize the natural runoff pattern so that the parameter A in Eq. (1) is governed by a combination of the natural topography (Fig. 3), and the location of the water conveying axes. Therefore, A was measured manually on a street map of Kinshasa combined with the 10 m numerical model. A road, a trench, a sewer or any other type of axial drain/ditch, crossing natural slope lines, acts as a gutter redirecting runoff from the slope in the direction of the axis. Fig. 3 shows the example of the historical Laloux megagully (location is shown in Fig. 1). It appears that the incision would have led to a very small value of A if only the natural topography, given by the numerical model, was considered. The precision and accuracy of the delineation of runon areas depend on the field knowledge of the investigator.

Given the predominant role of roads in runoff production and organization, we also verify whether there exists, besides the topographical control, a 'road' control for gully, using the cumulative road length L_c (m) in the runon area. Data for all gullies are plotted in a log–log S – L_c graph to derive an envelope for the road length control:

$$S = cL_c^{-d} \quad (3)$$

where c and d are constants that depend on environmental characteristics.

2.5. Envelope for gullying

A straight line which delimits the envelope of gully incision was drawn manually on the log–log graph. When the gully cluster is highly elongated and a clear relation between S and A appears (e.g., Fig. 2), a (rectilinear) envelope can be easily defined parallel to the trend line. This is verified in the Rocky Mountains (Montgomery and Dietrich, 1994) and in southern Rwanda (Moeyersons, 2003). In other cases, however, the gully cluster tends to be quasi-horizontal and wide (Vandekerckhove et al., 1998, 2000; Achten et al., 2008) and the statistical relation between S and A becomes weak and even insignificant (low R^2 values). In these cases an envelope has been drawn parallel to the insignificant trend line under the data cloud. However, in Uvira on the western shoulder of the Albertine rift (Moeyersons et al., 2011), for example, it has been demonstrated that the trend line and the envelope for mass movements are not parallel (Moeyersons et al., 2009). This can also occur in the case of gullying. Consequently, here we take the lower limit of the data cloud as the envelope of gully erosion without considering any trend line for both A and L_c thresholds.

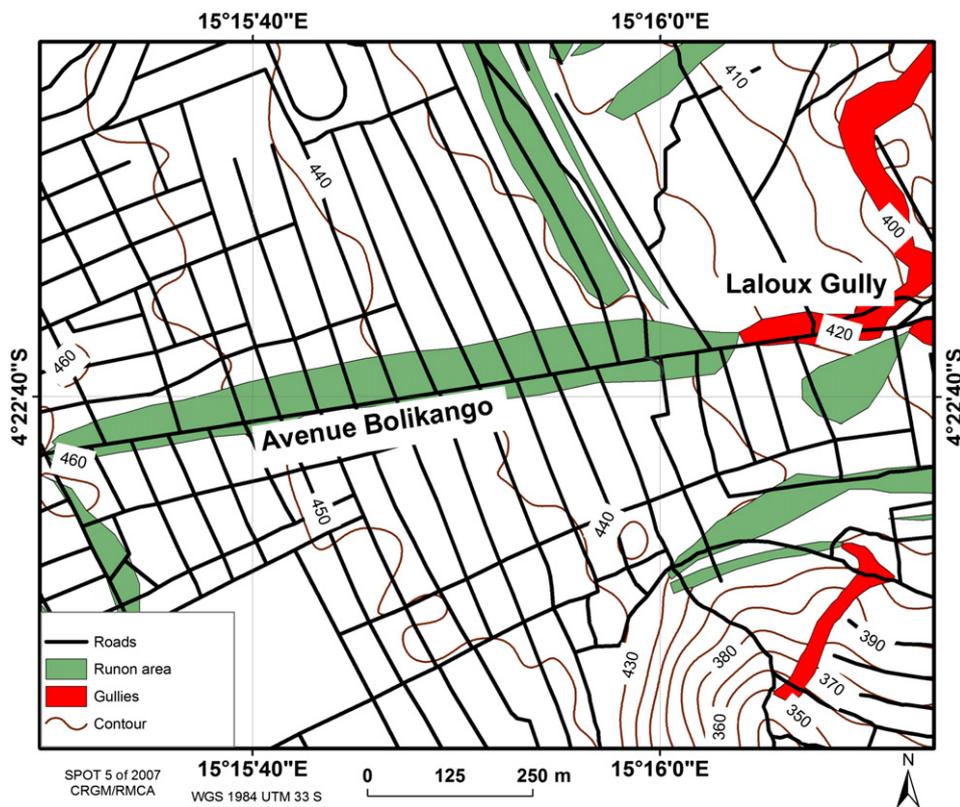


Fig. 3. Influence of the road network on the organization of the runoff pattern in the case of the Laloux gully. A , based on the contour configuration, is only ± 0.025 ha (impossible to indicate on the map), while the real value of $A = 7.8$ ha, due to runoff from Bolikango Street.

Table 1

Cumulative mega-gully length in the sector covered by the WorldView 1 image.

Sources: Panchromatic aerial photograph of 1957 and 1967 from IGN/Congo, and a geotechnical map of Kinshasa from B.E.A.U./Congo.

Documents used	Date of acquisition	Scale or spatial resolution	Cumulative length
Panchromatic aerial photograph	1957	2 m	0.1 km
Panchromatic aerial photograph	1967	2 m	1.0 km
Geotechnical map	1976/77	20 m	13.3 km
Spot image	March 10, 2006 (left) and Mach 31, 2007 (right)	5 m	62 km
World View image	January 26, 2010	0.5 m	102 km

3. Results

3.1. Gully distribution and evolution in Kinshasa

In 2007, Kinshasa counts 308 mega-gullies (≥ 5 m wide) with a cumulative length of 94.7 km. The gully density varies between 0.4 and 2 km km⁻². The mean mega-gully width and depth are 17 and 5 m, respectively. In 2010, in the sector of the town covered by the WorldView 1 image (Fig. 1A), 334 mega-gullies are mapped. The cumulative mega-gully length is ~102 km (Table 1), and the mean gully width and depth are 18 and 6 m, respectively. In this sector, the cumulative gully length was 0.1 km in 1957, 1.0 km in 1967, 13.3 km in 1976/77 and 62 km in 2006/2007 (Table 1).

Table 2 shows the classification of mega-gully types for the two inventories. Axial mega-gullies induced by regressive erosion (Graf, 1977) occur in respectively 43.8% and 54.8% of the cases. Leak mega-gullies induced by progressive erosion (Moeyersons, 1991) occur in respectively 51.0% and 34.4% of the cases. Between 89.2 and 94.8% of all mega-gullies have a direct relation with an urban structure such as a road or a street. The remaining gullies are fed by urban sectors where construction works occur. In the area covered by the WorldView image, the number of mega-gullies has more than doubled between 2007 and 2010 (Table 3).

Analysis of the 1957 aerial photographs shows that the area which is currently occupied by the high town was mainly covered by palm plantations and primitive dry forest. No mega-gully could be detected; only some rills along the new buildings of the Lovanium University (Mont Amba site in Fig. 1). Amphitheatres associated with spring were the only visibly active landforms where rotational slumps, evidenced by patches of inclined trees, could be detected.

The aerial photos of 1957 also show three deforested enclaves in the high town (Fig. 1). The first one is the old nucleus of the district of Djelo Binza, where in the late 1990s the large mega-gully of Mataba developed. Van Caillie (1983) mentions the existence of a small gully in 1976. According to our interpretation of the 1957 photograph, this precursor of the Mataba mega-gully (Fig. 1) developed from a street corner. Another enclave is Mont Amba where in 1957 the first buildings of the present University of Kinshasa rose up. The photograph shows that runoff, produced by the buildings and the campus had already induced sheet erosion (Van Caillie, 1983). The third enclave is Mont Ngaliema, but no gully features appeared in 1957. Fig. 1 evidences the spatial and temporal correlations between the urban growth and the extension of the gully distribution. From the diachronic observations (Fig. 1), it can be concluded that road building and urban development precede mega-gully development by 5 to 10 years.

Table 2

Mega-gully (≥ 5 m) types.

	1957–2006/2007		2006/2007–2010	
	# of gullies	%	# of gullies	%
Axial mega-gully	135	43.8	183	54.8
Leak mega-gully	157	51.0	115	34.4
No classified mega-gullies	16	5.2	36	10.8
Total	308	100	334	100

3.2. S–A and S–Lc relations

The S–A graph (Fig. 4) shows the 308 gullies mapped in 2007 together with the 334 gullies mapped in 2010. The trend lines are sub-horizontal and have both low R²-values of 0.0034 and 0.0134 respectively, showing that no significant relation between S and A exists. A parallel line to these trend lines cannot be used as a relevant envelope.

On the other hand, the graph in Fig. 4 shows a clear gully free zone for the lower combinations of S and A. This zone can be approximately delimited by a straight line envelope described as:

$$S = 0.00008A^{-1.459} \quad (4)$$

This line is drawn along seven gullies of 2007 and two gullies of 2010, all located at the left margin of the cluster. Two remarks can be made:

1. The 2007 and 2010 clouds can be delimited by the same envelope line of Eq. (4). This shows that the topographic control did not change within these three years in spite of the marked increase in mega-gullies during that period.
2. Eq. (1) is valid for the two gully types described in Section 2.3.

The equation can help in creating weak harmless runoff based on the slope gradient of the runoff axis. Table 4 is derived from Eq. (1) and indicates the surface which can be safely drained to a point with a given topographic gradient, without danger of gullying.

Fig. 5 shows the S–Lc graph for the 308 mega-gullies of 2007. Similarly to the topographic control, the trend line does not reveal any significant relationship. The trend line is sub-horizontal and shows a low R²-value of 0.0022. However, the graph shows a clear gully free zone for lower values of S and Lc. This zone is delimited by a straight line envelope, described as:

$$S = 22.991Lc^{-1.999} \quad (5)$$

Like in the S–A graph, the majority of the gullies are in the center of the cluster with only a few concentrating along the (S–Lc) envelope (Fig. 5).

4. Discussion

4.1. Validity of the S–A relation

According to Fig. 6, the sands covering the area of Kinshasa are among the most susceptible substrates on earth for gullying. This

Table 3

Characteristics of the mega-gullies (≥ 5 m) in the sector covered by the WorldView 1 image.

Year	2007	2010
Number of gullies	160	334
Cumulative length (km)	62.1	102.1
Mean width (m)	19	18
Mean depth (m)	7	6

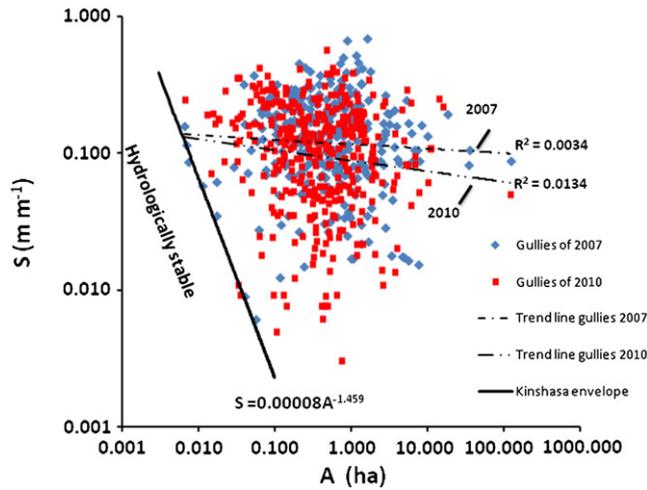


Fig. 4. Topographic control of the mega-gullies for the entire 2007 and 2010 mega-gully population.

susceptibility is related to anthropogenic conditions enhancing runoff production. In natural conditions runoff generation is limited. Permeability measurements by means of a cylindrical ring infiltrometer show that the hydraulic conductivity of the Kinshasa sands often exceeds 0.354 m h^{-1} (Makanzu et al., 2013b). This allows absorbing heavy rainfall in the region. Without roads or other urban structures, the runoff production would be very limited or even null and the risk for gullying would be minimal. The area A in the S – A relation is a proxy for the peak runoff discharge with maximum erosive force. As the average runoff coefficient in an urbanized area should be higher than that in a rural area, Eq. (4) is only valid for the high town of Kinshasa. In a rural area without roads, the S – A envelope for gullying should be located very far to the right of the envelope as established in Fig. 4. On the other hand, the S – L_c relation of Eq. (5) takes account of the degree of presence of roads and is applicable to both urban rural areas where, the growth of the road networks can be taken into account.

4.2. Gully management

Contrary to the examples in the US (Montgomery and Dietrich, 1994) and Northern Rwanda (Moeyersons, 2003) with a clear negative S – A relation as shown in Fig. 2, the cluster of mega-gullies of Kinshasa is broad and the trend line is nearly horizontal and statistically insignificant. On the other hand, the envelope is well defined by a number of points (Fig. 4). This striking regional difference between the US and Northern Rwanda and Kinshasa can be explained in two ways.

Firstly, there is a difference of gully activity. In Northern Rwanda and the US, the majority of the existing gullies are close to their equilibrium state after the early stage of more intensive regressive erosion (Graf, 1977). In Kinshasa, on the contrary, gullying started only in the 1960s

Table 4
Threshold condition of gully erosion in Kinshasa.

$S \text{ (m m}^{-1}\text{)}$	$A \text{ (m}^2\text{)}$	$L_c \text{ (m)}$
1.00	16	5
0.84	18	5
0.58	23	6
0.36	31	8
0.18	51	11
0.09	83	16
0.07	96	18
0.05	117	21
0.03	155	26
0.02	249	36
0.01	401	51

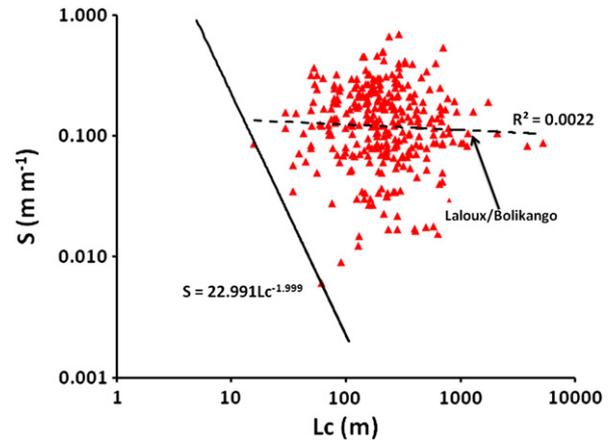


Fig. 5. Road control of the mega-gullies of 2007, showing the relation of the slope gradient at the gully head (S) with the cumulative road length in the runon area (L_c). The solid line is the gully erosion envelope, the dashed line is the trend line.

and gullies of all stages are present. In every humid period, new gullies start to develop and most gullies have not yet approached equilibrium.

Secondly, in Kinshasa, some artificially stabilized mega-gullies are located in the middle of the data cloud (Fig. 4) or even in the right margin. An example is the Laloux mega-gully (Fig. 4). Without the stabilization of its head (Fig. 7), it would be close to the envelope. This example shows that the wide form of the S – A data cloud is partly due to the success of local initiatives of gully head stabilization. Numerous gully heads away from the envelope (Fig. 4) include cases where inhabitants as well as local NGOs are able to halt regressive gully erosion by piling up household refuse and rubbish in the gully heads, or by the construction of embankments and levees by means of sand bags. Also constructing gully head protection as in Fig. 7 is an efficient way to limit gully head retreat.

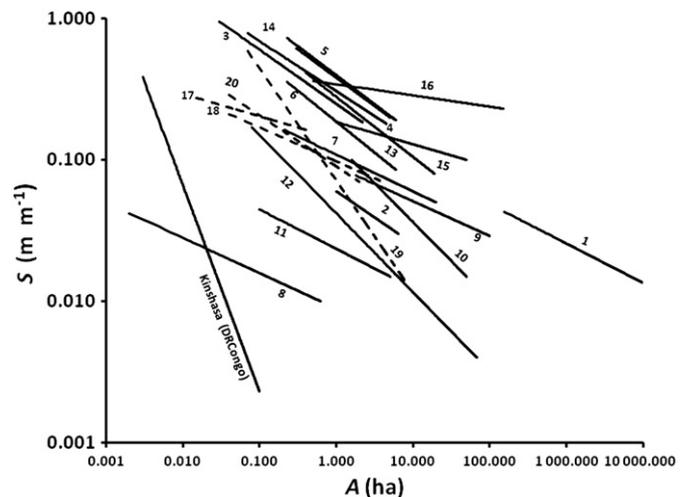


Fig. 6. Geomorphologic thresholds for gully erosion in the world. Solid lines are the envelopes according to Montgomery and Dietrich (1994) and applied in (1) Colorado/US (Patton and Schumm, 1975); (2) Northwestern France (I.G.N., 1983); (3) Coss Bay/Oregon, (4) Stanford Hills/California, (5) Southern Sierra Nevada, (6) Tennessee Valley/California and (7) Northern Humboldt Range/Nevada in the US (Montgomery and Dietrich, 1988); (8) Central Belgium (Rills) (Govers, 1991); (9) South Downs/UK (Boardman, 1992); (10) Central Belgium (Fields) (Poesen et al., 1996); (11) South Portugal (Aerial photographs) and (12) Central Belgium (Aerial photographs) (Vandaele et al. (1995); (13) North Ethiopia (Highlands of Tigray) (Nyssen et al., 2002); (14) Southwestern Rwanda (Moeyersons, 2003); and (15 and 16) Southwestern Uganda (cropland, 15; grassland, 16) (Wanyama et al., in preparation). Dotted lines are the trend lines representing the envelopes according to Vandekerckhove et al. (1998, 2000) in South east Spain (17) and Northeast Portugal (18); and Achten et al. (2008) in Makombe plateau (19) and Inland plains (20) in Southeastern Tanzania.



Fig. 7. Mitigation measures at the head of the axial mega-gully of Laloux. In 2009, metallic sheets, intended to protect the gully against further vertical incision and head retreat by runoff from Avenue Bolikango (Laloux Gully, Figs. 1 and 3), were destabilized due to sapping. In 2011, an insufficient amount of sand bags was put in the head to replace the metallic sheets that had partially collapsed. In the foreground the top of a sand dam is visible. This dam caused temporary sedimentation in the mega-gully bottom. In 2012, the metallic sheets were all take away and a huge staircase-like gutter has been constructed.

However, gully treatment is only a casual post-consequence action. The $S-Lc$ relation opens perspectives in gully prevention in Kinshasa. Lc could be considered to equip the road infrastructure with runoff diverters. When only protection against axial gully erosion is at stake, the maximal distance between the diverters is defined in Table 4 by considering the road or other conveyor axis gradient. In the case of leak gully prevention, the distance between the diverters is governed by the steepest section of the natural slope aside the road. This slope is usually much steeper than the road and numerous diverters might be needed.

4.3. Gully risk mapping

It is possible to use Table 4, which lists the limiting values of the $S-Lc$ and/or $S-A$ envelopes for mega-gully risk mapping in Kinshasa. But the mapping cannot be automated because the definition of A depends on the road pattern and other situations in the field. For the moment, a

risk assessment is necessary. An example of Maman Mobutu Hill (Fig. 1) is given in Fig. 8.

When Eq. (4) is applied to the hill of the sector of Maman Mobutu, negating the presence of roads and considering only the topography given by the contour map, none of crossroads 1 to 7 has an upstream area. This is due to the general divergent character of the slope. When Eqs. (4) and (5) are applied in relation to the presence of roads and the role they play, it becomes evident that cross-roads 1 to 7 (Fig. 8) receive appreciable runoff delivered by the side-roads of the Avenue de la Colline. If A is calculated for every cross-road by taking account of drainage due to the roads, points 1 to 7 fall on the right part of the $S-A$ cloud (Fig. 9). Also in the $S-Lc$ graph, points 1–7 fall into the sector of hydrological instability (Fig. 9). This result shows that the Avenue de la Colline is theoretically prone to gully erosion till close to the hill summit.

The lower part of the Avenue de la Colline was indeed affected by regressive gully erosion in 2010 and the road at points 6 and 7 and 35 houses around (Fig. 8) were destroyed. Local mitigation activities

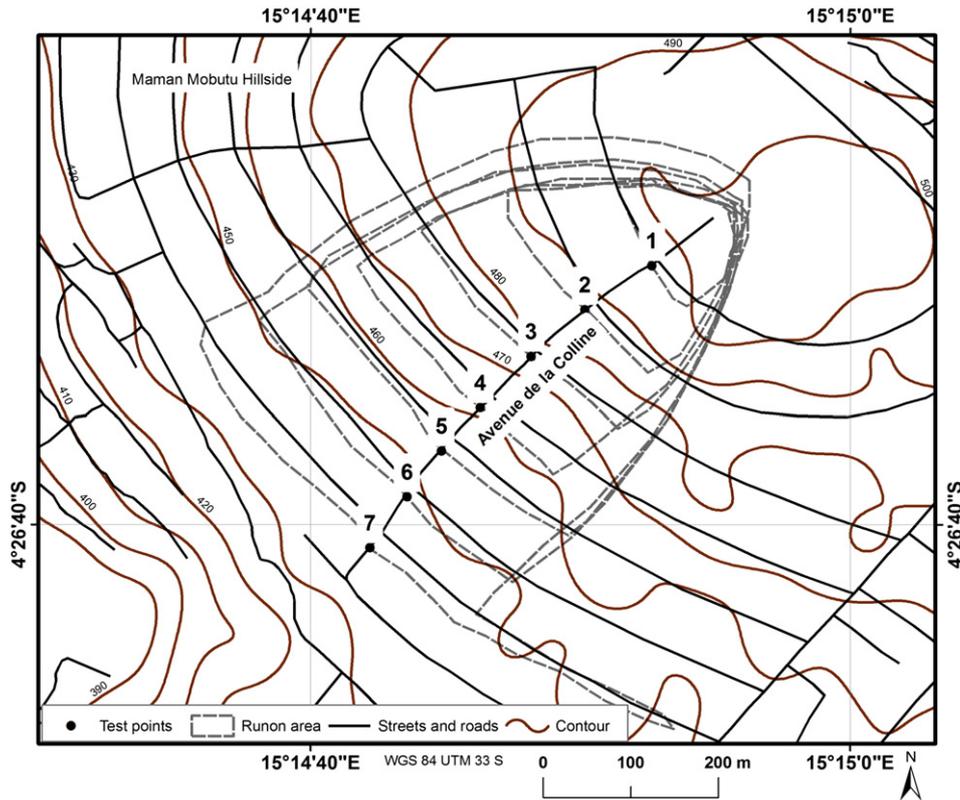


Fig. 8. Part of the Maman Mobutu sector (Fig. 1). The runon area at test points 1–7 is nearly zero if the delineation is only based on the natural topography, showing a slightly divergent slope. Due to the road configuration, water is concentrated towards the Avenue de la Colline. Each test point receives a certain amount of runoff from the street network, covering an important runon area A.

resulted in the construction of walls/dams across the avenue below cross-roads 2 to 5, which became ‘road reservoirs’. Then the gully heads were not affected anymore by peak discharges due to rain storms. After each storm, the reservoirs were slowly emptied by means of pumps and siphons so that the gully head just upstream of the point was not anymore subjected to runoff peak discharges but by harmless flow. The point by point risk assessment shows that without this action the mega-gully of the Avenue de la Colline would have reached the top of the hill.

Given the small critical values of Table 4, all slopes in the high town of Kinshasa are potentially susceptible to mega-gully formation when they become urbanized. Only the small sub-horizontal hilltops are not susceptible to gullying.

5. Conclusions

Mega-gullies in Kinshasa develop like other natural gullies in nature and reach equilibrium when the area above the gully head has shrunk and collect a small amount of water insufficient for further headward retreat (Graf, 1977). However, Table 4 shows that remaining runon areas are so small, meaning that mega-gullying may transform the broad area of the high town of Kinshasa into badlands.

Besides the S–A gullying limit, there also exists an S–Lc limit. Here again, the cumulative road length is small (Table 4). The topographical control for gullying and the control by cumulative road length in the runon area are given by Eqs. (4) and (5), respectively.

The analysis shows that S–A and S–Lc combinations critical to gullying are only reached in the presence of a road network that enables abundant runoff production on the hard surfaces and to the axial concentration of water. This result is corroborated by the analysis of aerial photographs taken in 1957, showing that no mega-gullies exist under forest and palm plantations. The mega-gully of Mataba, the oldest mega-gully of Kinshasa, originated along a road through the forest. Gully mitigation by head protection with primitive means has been successful and thus is encouraged as long as it can be environmentally justified.

The Lc-values in Table 4 are regarded as a criterion for gully prevention. Runoff diverters, installed along a road at distances <Lc decrease axial runoff and render runoff delivered by the diverters harmless.

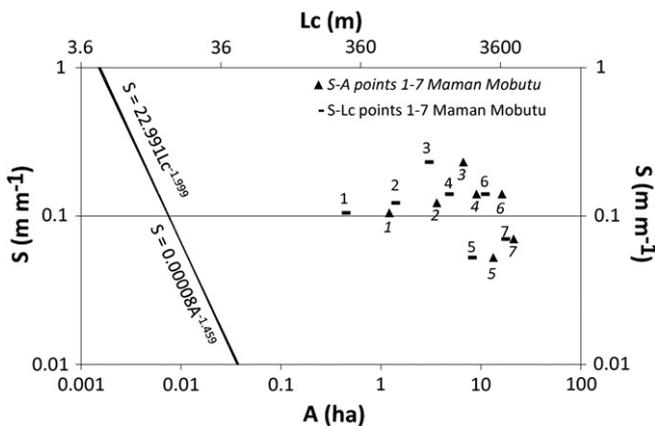


Fig. 9. S–A (primary axes) and the S–Lc (secondary axes) relations of points 1 to 7 (Fig. 8) located far to the right of the envelope of topographic control $S = 0.00008A^{-1.459}$ and that envelope of road control, $S = 22.991Lc^{-1.999}$. The scale of the Lc secondary axis is adapted to make both envelopes to coincide.

Further research is needed to put this theoretical gully prevention method into practice.

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