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The origin and control of mega-gullies in Kinshasa (D.R. Congo)

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ABSTRACT

This study aims to investigate the relation between mega-gully (>5 m width) distribution and urbanization in Kinshasa (D.R. Congo), to establish what governs mega-gully location and plan form and to illustrate the concepts behind mega-gully treatment. For this purpose, the diachronic distribution of mega-gullies has been mapped in Kinshasa. All mega-gullies have been reported in ArcGis 9.3 on the orthorectified SPOT 2007 image. A newly elaborated DEM enables the mega-gullies to be placed in their natural topographical context. The GIS inventory on the SPOT 2006/2007 anaglyph indicates the mega-gully situation in the high town of Kinshasa 5 years ago: 308 mega-gullies with a cumulated length of 94.7 km, a mean drainage density of 0.4 km km^{-2} and an average width and depth of 17 m and 6 m respectively. On the WorldView 1 (WV1) coverage, the number of mega-gullies has more than doubled between 2007 and 2010 from 160 to 334. The study shows that mega-gullies only develop within the urbanized perimeter of the high town of Kinshasa and only 5 to 10 years after incipient urbanization. The study also indicates that neither the location, the plan form or the downslope course of mega-gullies in Kinshasa are controlled by the natural topography. Forty-three point eight percent of the mega-gullies in Kinshasa are 'axial', occupying urban structures which function as artificial runoff drainage lines: roads, tarred or not, with or without side-road trenches, gutters in all forms and materials from concrete to sand, also foot paths and further all artificial runoff drainage lines. The study reveals that every mega-gully is directly or indirectly induced by human activities, but that every gully also finally ends to grow after an initial phase of sudden development. Mega-gully treatment follows two principles, often combined. The first is to stop the alimentation of the mega-gully head with water. The second includes a complete stabilization of the channel and walls inside the mega-gully. This study emphasizes that gully prevention can basically be achieved by control of the runoff discharges in the artificial stream network, as well as beside the roads.

1. Introduction

Urban gullying has progressed over the last few decades to become a worldwide problem (Guerra et al., 2006, 2013). In Africa, most case studies come from towns in the west-African Savannah belt (Balzerek et al., 2003; Ugodulunwa and Laka, 2008) and from southern Africa (Rowntree et al., 1991). But also many towns in central Africa are severely affected by gullying. This is not only the case in Kinshasa, capital of the Democratic Republic of the Congo (Makanzu Imwangana, 2010), but many other towns and cities in the wider region. The total annual material damage in the DRC, Rwanda and Burundi is estimated at >€200 million/year (Vandecasteele et al., 2010). Apparently, urban gullying is a problem in the whole central-African tropical belt.

In Kinshasa (Fig. 1), the first signs of gullying were reported by De Ploey (1975) and by Van Caillie (1983) when the western plain along the Malebo Pool became completely urbanized in the early 70s and the built up area started to extend into the hilly landscape to the South (Fig. 1).

Van Caillie (1983) correlated the vertical incision of drainage lines with slopes steeper than 0.12 to 0.20 m m^{-1}. According to his observations, the only way to stop gully development is to stop the supply of the gully head by runon. For this reason, he studied the factors governing the origin of runoff in the house parcels, drained towards the gullies. He concluded that a good vegetation cover close to the ground surface allowed for 100% water infiltration. He further advised the construction of water tanks, soak away pits and water retarding structures in every parcel in order to prevent runoff delivered by the roofs of the houses and impervious surfaces. He claimed that water conducting sewage structures should not end on a steep and unprotected slope but should join the river channel in the centre of the valley.

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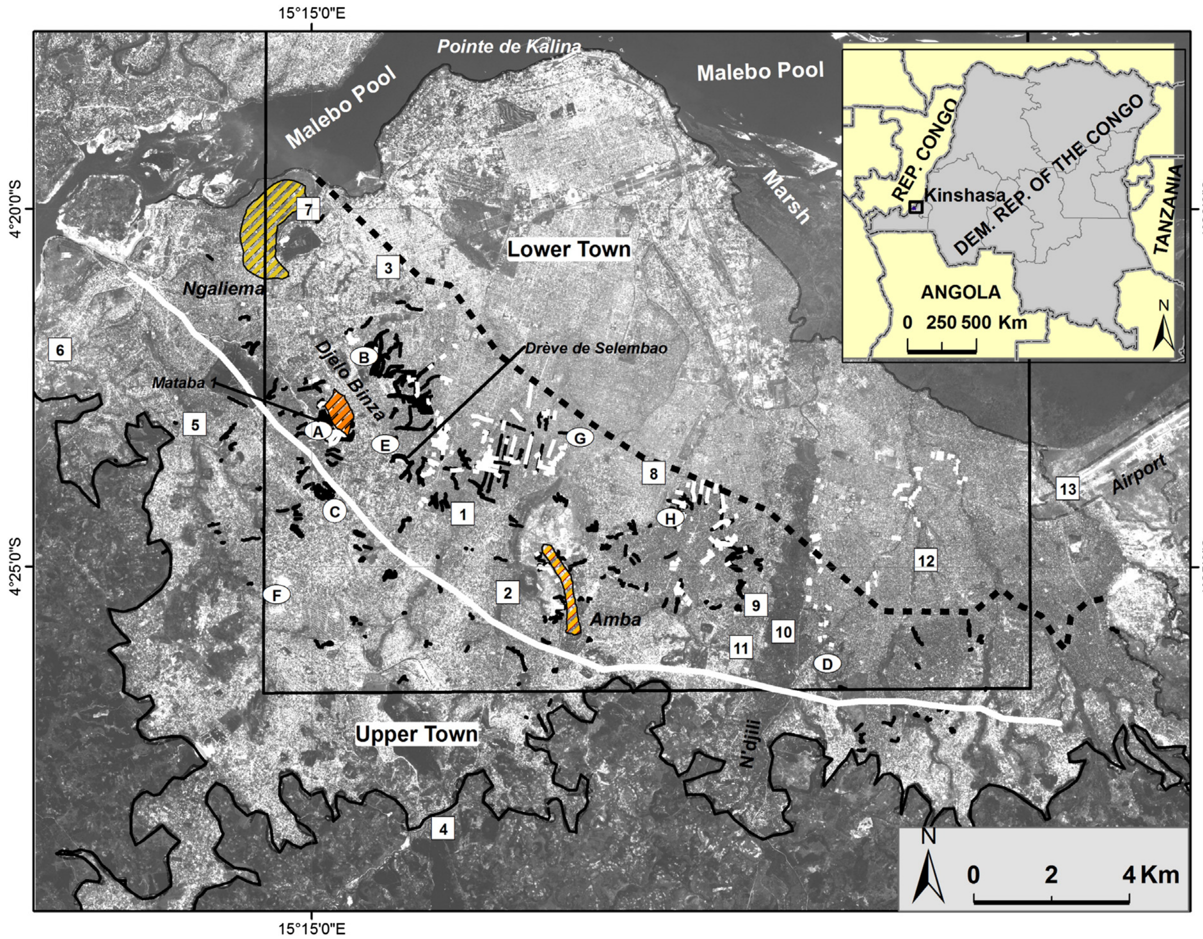

Fig. 1. The mega-gully situation in Kinshasa. The hilly region is delimited to the North by the black dashed line. White line: built up extension to the South in 1976; white patches: gullies 1976 (Van Caillie, 1983); black line: southern limit of the hills, following the string of erosion cirques. This line coincides with the southern extension of the built up area in 2007, black patches: mega-gullies in 2007; 1–13: river basins of Table 4; A: Mataba; B: Laloux; C: Kinkusa; D: N'djili; E: Drève Selembao; F: Maman Mobutu; G: Kémie; H: Kinsenso. The black frame indicates the WorldView 1 coverage of 2010.

In spite of the efforts to follow these early recommendations, gullying in the high town progressively intensified during the subsequent years and started to induce correlative mud and water problems in and along the rivers in the low town. UNIKIN researchers repeatedly sounded the alarm (Lelo, 2008; Lukidia et al., 1996 and 2008; Makoko and Mananga, 1986; Miti and Aloni, 2005; Miti et al., 2004; Ntombi and Makanzu Imwangana, 2006; Ntombi and Tumwaka, 2004), and although no recent gully inventory of Kinshasa exists, the gully situation there is felt to have never been worse than it is today.

In the meanwhile, many studies have led to a complementary understanding of why towns are much more affected by gullying than rural areas (Osintseva and Kwasnikowa, 2013). First of all, runoff is considered to increase in towns as a result of the creation of hard surfaces with low or no permeability like buildings, roads and other urban constructions (Berthier et al., 2004; Rodriguez et al., 2003). Secondly, roads and ditches disrupt and replace the natural drainage pattern and thus may concentrate runoff in places where there was no problem before but where, today, a gully develops (Moeyersons, 1991a,1991b). As a town generally shows a dense road network, the chance of gully development in a town should be higher than that in a rural area. In this context, roadside gully formation is now a major environmental problem in rapidly developing regions and towns (Jungerius et al., 2002; Nyssen et al., 2002; Osmar et al., 2010). Finally, roads, gutter systems and other water conductors considerably increase the hydrologic connectivity between hill top and valley bottom. This leads to a quicker and more important stream flood response to a rainstorm.

In spite of all these studies, people often question whether gullies in Kinshasa are the consequence of urbanization. The question of gully treatment is also at stake. There are cases of successes and failures. Finally, the question of possible prevention of gully initiation is not really addressed in Kinshasa. For all these reasons, this article aims:

1) To evaluate the seriousness of the gully problem in terms of gully dimensions, gully density and gully dynamics.
2) To demonstrate the relationship between gullying and urbanization in time and space.
3) To establish whether gully location is related to the urban infrastructure, mainly roads, gutters, trenches, sewers, tracks and other linear elements.
4) To illustrate the different concepts behind gully treatment and technologies applied and to demonstrate the successes and failures of treatment methods.

It is hoped that the work in Kinshasa might contribute to a better understanding of the urban gully problem in the wider region.

Because gullies are often hidden behind buildings and vegetation, and therefore, difficult to identify, remote sensing techniques have been used as much as possible to localize and measure gully dimensions and to create a complete gully inventory in order to answer questions 1 to 3. In addition, field surveys provided the necessary information in the study of gully treatment.

2. Materials and methods

2.1. The study area

Kinshasa is located on the southern banks of the Malebo Pool (272 m ASL), an enlargement of the Congo River (Fig. 1). The town experienced its early development in the rather flat plain (280–300 m ASL) along the shore and the marshes of the Pool (Fig. 1). At the end of the sixties, the whole plain between Pointe de Kalina in the West and the Tshangu basin close to the airport in the East (13, Fig. 1) was occupied. The southern limit of the town at that time (Fig. 1) coincides with the northern edge of an undulating and widely dissected plateau, the summits of which are between 350 and 710 m ASL (De Maximy, 1978; De Maximy and Van Caillie, 1978). The plateau has a surface area of 240 km^2 and is delimited to the south by a continuous sequence of spring amphitheatres as indicated (Fig. 1). This explains the irregular and curbed plan form of the southern plateau border. The Northern edge of the plateau is believed to be an ancient cliff or bluff of the Malebo Pool (De Maximy, 1978). The whole area, including the plateau and adjacent northern and southern plains is underlain by a sub horizontal series of reddish shale and soft sandstone of questionable Mesozoic age (Egoroff, 1955). Geologists hesitate to correlate this substrate either with the so-called sandstone of Inkisi, 'grès polymorphe' or with another geological series. On the plateau, this series is overlain by a 50 to 100 m thick mantel of sands belonging to the series of ochrous sands, dating either back to the end of the Cretaceous or to mid-Tertiary times (Cahen, 1954) and considered by De Ploey (1963) as a Kalahari Sand type. The hills of the high town of Kinshasa 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 act as an aquitard compared to the overlying sands. Therefore, all hills of the plateau contain a perched water table with corresponding perennial springs at their foot (Van Caillie, 1983).

The gully problem in Kinshasa started with the urbanization of the plateau. In 2007, the whole plateau was built up (Fig. 1). Today the town is extending further southwards through the belt of spring amphitheatres into the lower lying plain. The gullies in the high town of Kinshasa are a result of the vertical incision by concentrated wash, but the incision might sometimes reach the water table and lead to drainage of the latter. Some of these gullies are indeed 'famous' for their size, for the damage they cause and for their sudden development. A relationship between the gully form and the hydro-geological conditions in the high town seems to exist. Gullies in Kinshasa have a V-like cross-section as long as they remain above the perched water table. In some instances they widen and show a flat floor when they reach the latter in their lower course. In this sector and sometimes kilometres further away in the lower part of the city, aggradation and water problems occur in relation to the gully incision in the upper town.

According to the classification of Köppen and Geiger (1930) and of Guetter and Kutzbach (1990), Kinshasa enjoys a climate of type $Aw_{4,}$ characterised by hot and wet conditions. At the meteorological station of Kinshasa/Binza, the mean annual precipitation amounts to 1432 mm (Makanzu Imwangana, 2010). The annual precipitation in the Kinshasa region extends from October to May with a short interruption from the end of December to mid-February (Bultot, 1971). Kinshasa is the only place in central Africa where statistics indicate that the global change is expressed by rainstorms, increasing in size and rainfall intensity (Ntombi et al., 2004 and 2009).

The natural vegetation of the Kinshasa region is composed of dry dense forest, savannahs and semi-aquatic and aquatic formations in the valleys and around the Malebo Pool (Kikufi and Lukoki, 2008; Pain, 1984). In the town of Kinshasa, nothing is left of this luxuriant vegetation besides a few grasses like *Laudetia demeusi* and *Schyzochysium semiberle* (Tshibangu et al., 1997).

The population of Kinshasa grew between 1957 and 2007 from 404,173 to nearly 8,000,000 inhabitants (Hôtel de ville de Kinshasa, 2007). This corresponds to an increase by a factor 20 over the last 50 years. In the meantime, the surface of the urbanized area grew from 94 to 443 km^2 (Makanzu Imwangana et al., 2012).

2.2. Gully mapping

Several remote sensing documents and products derived from them have been used in this study. Orthorectified products and maps make part of a GIS ArcGis 9.3 project.

2.2.1. The black and white aerial photograph coverage of 1957

The hilly plateau area of the high town has been studied on 321 aerial photographs. The scale of the photographs is about 1:20,000. A mirror stereoscope Sokkisha, Tokyo 8426, with magnifying oculars enables objects of the order of 2 m to be distinguished. With the magnification of the oculars of the stereoscope, the ground surface is visible between the palm oil trees, but not in the patches of semi-natural forest.

2.2.2. The geotechnical map of 1976/1977

The geotechnical map of 1976/77, (1/20.000), which is part of the 'Carte Géomorphologique et Géotechnique de Kinshasa' (Van Caillie, 1988), was used for gully mapping. The map shows 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.

2.2.3. A SPOT image of 2006 and 2007, and the derived anaglyph

ENVI software has been used to join two SPOT 5 panchromatic images (with 5 m of spatial resolution) into an anaglyph of the Kinshasa region. The left and right SPOT pictures date from 10/03/2006 and 31/03/2007 respectively. Both SPOT images have been cut into panchromatic stereo-pairs of the size of an ordinary aerial photo-pair. These stereo-pairs have been studied by means of a mirror stereoscope Sokkisha, Tokyo 8426, with magnifying oculars. All gullies visible in 2007 in the high town of Kinshasa have been mapped. The map has been controlled by a cyan-red anaglyph, viewed directly on the computer screen using red-cyan glasses. Field truth confirms that gullies of 5 m wide can be easily detected on the 3D anaglyph. Undoubtedly, this 5 m limit leads to an underestimation of the number of gullies, of their length and of the gravity of the gully situation in Kinshasa.

Although Google Earth imagery dating from 2008 has a 1 m precision, the SPOT anaglyph allows a much better 3D perception than the Google Earth imagery. This is an advantage in the case of gullies which are completely invaded by quickly developing annual herbs, bushes and small trees. On 2008 Google Earth imagery such gullies are very often untraceable, but can be nicely distinguished on the 2006–2007 anaglyph.

Furthermore, it is also an advantage that the precision of the aerial photographs of 1957 is greater than that of the 2006/2007 anaglyph. This situation excludes that gullies of 5 m wide, already present in 1957 would have been missed.

We are aware of the fact that the limit between rills and gullies is generally set lower than at a width of 5 m (Poesen et al, 1996). In order to take into account the fact that we miss all gullies below 5 m wide, the mapped gullies in this article are called mega-gullies. All mega-gullies have been inventoried in a shape file of an ArcGis 9.3 GIS work place laid upon the orthorectified SPOT image of 2007. As such, the inventory misses a number of gullies less than 5 m wide, mapped by Van Caillie (1988) on the eastern bank of the Ndjili, in the low town (Fig. 1). It concerns small river bank gullies (Poesen, 1993).

On the gully inventory shape file, every mega-gully is represented as a polygon and the length of every mega-gully has been measured. An error in the GIS measurements of the surface and the length of gullies occurs because these automatic functions rely on the shape file, which is a projection of the 3-D landscape on a horizontal 2-D image. The correction factor should be $(\cos\alpha)^{-1}$, α being the local slope angle. On slopes of 35°, about the steepest slopes in Kinshasa, underestimation of length and surface can amount in the worst case to 20%, but as the longitudinal gully gradient in Kinshasa often remains below 10°, errors are only of the order of an insignificant 1%.

2.2.4. The WorldView image of 2010

An orthorectified panchromatic satellite image WorldView 1 (WV1) taken in 2010 (26 January) has been added to the ArcGis 9.3 project. Although the WV1 2010 image has a spatial resolution of 0.5 m, this high precision could not be exploited when it comes to comparison with the year 2007, because the SPOT 2006/2007 anaglyph only allows an observation precision of 5 m. So, mapping from the WV1 2010 image was restricted to gullies and gully sections larger than 5 m (Table 1). Furthermore, the comparisons between both satellite images and the aerial photos of 1957 on the one hand and the geotechnical map (Van Caillie, 1988) on the other are only possible for gully length, because the latter only holds data on this item.

The WV1 2010 image has the disadvantage of covering only 124.2 km^2 of the high town (Fig. 1). Therefore, diachronic comparisons for the period 1957–1976–2007–2010 are only possible for this area.

2.3. Topographical position of the mega-gullies

In order to recognize gullies developed on and along urban structures which have disappeared, the relation of the gullies to the natural topography has been analyzed. Gullies, the location of which is not influenced by preexisting structures, should be particularly expected in the stream axis of convergent slopes, to a lesser degree on slopes with parallel slope lines and not at all on spurs with divergent slopes. Furthermore, gullies should normally flow parallel to the slope lines, in other words in the direction of the steepest slope. But the majority of structures like roads, trenches, gutters, sewers and tracks, along and upon which gullies develop, do not follow but cross the natural slope lines. This aberration is expressed by the angle of 'obliquity', between the slope line and the structure axis, seen in plan form.

The relationship between gully location and natural topography has been studied on a new DEM of Kinshasa with spatial resolution of 5 m. This numerical model is established by means of ENVI 4.6 software, based on the two SPOT 5 panchromatic images and is calibrated by 25 ground DGPS Pathfinder Pro Series and 25 GPS Garmin control points. One of the problems to be overcome with numerical models obtained in this way is that the topographic end product does not reflect the topography of the land surface but that of the top of all objects, like houses, high trees, towers and all objects of a certain height. Therefore, a frequencies Fourier filter has been applied to the raw numerical model. The 10 m equidistance contour map, deduced from this model has been used to categorize every mega-gully mapped on the SPOT 2006/2007 anaglyph in relation to its natural topographical context.

Two subdivisions have been made. The first subdivision concerns the type of slope the gully is located on. Three classes have been considered: gully location on a spur with divergent slope, location on a slope with parallel slope lines and location in a topographic hollow or convergence. These three categories have been introduced with the idea of eliminating 'unnatural' gullies, especially as gullies on a spur theoretically have no natural runon area and, therefore, should be considered as 'artificially' induced.

Table 1
The documents used.

Documents used	Date of acquisition	Precision of observation
Black and white aerial photograph	1957	2 m
Geotechnical map	1976/77	20 m
Spot image	March 10, 2006 (left) and	5 m
	March 31, 2007 (right)	5 m
WorldView image	January 26, 2010	0.5 m

The second subdivision is made on the base of the trajectory of the gully in relation to the slope lines. Basically, the straight line which connects the gully head with its end at the hill side can be parallel to the local slope line or can cross the local slope line at a certain angle. The latter type of gully, called 'oblique' gully should be influenced in its course by structural elements, as stated above. Gullies have only been identified as 'oblique' when there was a clear angle of 5 to 10° between the gully trajectory line and the slope line. This visual categorization probably leads to an underestimation of the number of oblique gullies.

2.4. Field observations and inquiries concerning gully treatment

Since 2008, we have conducted occasional inquiries and field observations on the different ways gullies in Kinshasa are treated. From the 1st of February to the end of April 2012, a more systematic field investigation and inquiry among the residents of 9 districts around the Kinshasa/Binza meteorological station took place. Apart from observations and questions about gully treatment, we investigated the age, year and month, of the mega-gullies visited.

3. Results

3.1. The mega-gully situation in Kinshasa in 2007 and mega-gully dynamics

Three hundred and eight mega-gullies have been mapped (Fig. 1) on the 2006/2007 SPOT image anaglyph. Two hundred and ten mega-gullies are almost completely devoid of vegetation, while 98 show a continuous cover of arborescent and grassy vegetation (Table 2). The former are considered as 'active', while the latter are interpreted as 'stable'. Our field observations in Kinshasa show that mega-gullies are not becoming stable as a result of their colonization by vegetation but vice versa. At many instances, e.g. in the historical mega-gully of Mataba 1, we could observe that the reactivation of a mega-gully, even under continuous arborescent cover, is only governed by the renewed vertical incision by runoff in the centre of the V cross section. After the vertical incision to the order of 1 m, translational sliding starts to affect the mega-gully walls. Soil slabs of only 1 m thick easily transport even big trees: the few roots that penetrate deeper into the soil just snap when the slab moves. The presence of shrubs and trees inside mega-gullies only indicates fragile stability.

Further characteristics of the 2007 mega-gully inventory of the high town of Kinshasa are given in Table 3. Data on depth and volume are derived from gully width. They have been calculated assuming an average gully wall slope of 35°. Gully walls in Kinshasa have been measured to vary between ~45° and ~25°, the major part showing a slope between 37° and 33°. Gully depth equals (Tan 35°)(width/2) for a triangular section.

The cumulated length of the 308 gullies in the high town of Kinshasa amounted to about 94.7 km in 2007, meaning an average yearly increase of 2 km of cumulated mega-gully length over the last 50 years. This corresponds with a mean gully density of about 0.4 km km^{-2} in the high town. But gully distribution inside the high town is far from equally spread. In the northern part of the high town values easily amount to 1.5 or 2 km km^{-2} while in the southern part gullies are almost absent (Table 4).

The mean values in Table 3 have to be interpreted with caution because of the high spread between maximum and minimum values. Table 5 illustrates that the cumulated volume of the ten most voluminous mega-gullies amounts to 5,497,636 m^3, which accounts for 49.8% of the approximate total volume of the 308 gullies mapped. The mean width and depth reach 57 and 20 m respectively for the ten biggest mega-gullies and only 17 and 6 m for the whole mega-gully population.

The map (Fig. 1) and the data in Tables 2 to 5 point to the extreme gravity of the gully problem in Kinshasa, with a lot of economic consequences. The price of the houses, yearly destructed by gullying amounts to 1.5 million US$ per year. Furthermore, 10 million US$ was the price of

Table 2
Vegetation cover and mega-gully stability.

	Topographical position			Obliquity	
	Divergent	Parallel	Convergent	Yes	No
Unvegetated mega-gully					
# of gullies/# of oblique gullies	46/36	53/43	111/98	177	33
Mean length m	265	256	239		
Approximate mean gully volume m^3	18,920	12,894	23,202		
Vegetated mega-gully					
# of gullies/# of oblique gullies	31/28	39/34	28/15	89	9
Mean length m	444	428	422		
Approximate mean gully volume m^3	27,844	106,229	68,663		

the redevelopment of the district of Drève de Selembao in 2004. Gully treatment costs in the Mataba district rose to 7.8 million US$ in 2006.

But the diachronic mega-gully evolution shows that the mega-gully situation in the high town of Kinshasa is still quickly deteriorating and therefore, extremely serious. The comparison of the mega-gully characteristics between 2007 (SPOT anaglyph) and 2010 (WV1) suggests a dramatic evolution (Table 6) in the area, covered by the WV1 satellite image. Within these 3 years, the approximate mega-gully volume of this area covered by the WV1 has doubled and their average volume has increased by 20% (Table 6). The evolution of the accumulated mega-gully length in this area from 1957 to 2010 is spectacular over the last years (Fig. 2). It is remarkable that the increase of the cumulated length of mega-gullies (width > 5 m) between 2007 and 2010 from 62,092 m to 102,076 m is essentially due to the development of new mega-gullies. In 2007, the area covered by WV1 accounts for 160 mega-gullies and in 2010 the number rises to 334.

3.2. Diachronic gully spreading and urban extension

Aerial photographs of 1957 show that spring alcoves were the only visibly active landforms in the forested or agro-forested hills, occupied today by the high town of Kinshasa. Rotational slumps evidenced by patches of inclined trees are visible in many instances in spring amphitheatres. But not one single gully could be found on the aerial photographs in the forested zone.

The aerial photos of 1957 also show three deforested enclaves in the high town. The first is the old nucleus of the district of Djelo Binza, where in the late nineties the famous mega-gully of Mataba developed. In 1976 Van Caillie (1983) mentions the existence of a small gully. According to our own interpretation of the 1957 photograph in question, this gully first developed from a street corner. At the corner, the lowest point of the road, street water that came from the two road sections, could spill over. From that point the gully follows in an upstream direction the path of the steepest of both road sections. The other enclave is Mont Amba where in 1957 the first buildings of the present UNIKIN rose up. The aerial photograph in question shows that runoff, produced by the buildings and the campus already produced a sheet erosion problem, emanating, according to Van Caillie (1983), from the Funa river. The third enclave is Mont Ngaliema, but there were no problems in 1957. The three 1957 urban extensions are indicated on Fig. 1

Table 3
Some characteristics of mega-gullies in Kinshasa, reference year 2007.

	Cumulated	Mean	Maximum	Minimum
Surface (m^2)	1,969,148	6,393	89,921	146
Length (m)	94,732	308	2129	25
Width (m)		17	117	3
Depth (m)		7	41	1
~Volume (m^3)	11,034,595	35,827	1,469,805	124

Table 4 shows the unequal mega-gully drainage density inside the high town of Kinshasa in 2007. Fig. 1 clearly shows that gully density is highest along the northern border of the high town, with a progressive decrease to the South. The southern part of the high town even seems to be mega-gully free close to the southern border along the fringe of active spring amphitheatres. Fig. 1 shows the distribution of gullies and the extension of the urbanized area in 1976 (Pain, 1984). Except for the three 1957 enclaves, the urbanization of the northern fringe of the high town started in the late sixties and extended to the position of 1976 as indicated (Fig. 1). According to Van Caillie (1983), the distribution of gullies at that time, remains clearly within the 1976 urbanized perimeter. Moreover, gully concentration at that time was highest on the northern edge of the high town, where urbanization started 8 to 10 years previously. The 2007 urban extension reaches the southern limit of the plateau of the high town. In the meantime the mega-gully distribution extends further South than the 1976 southern urbanization limit, but did not yet reach the southern border of the high town (Fig. 1). At the same time, the northern fringe of the high town, where urbanization started around 1968, and also Djelo Binza and the UNIKIN campus experience a still increasing mega-gully drainage density.

It can be concluded that the occurrence of mega-gullies in the high town of Kinshasa spread out with the extension of the built up area. Firstly, during the whole process of urbanization of the high town gully distribution remains restricted to the urbanized perimeter. Secondly, it takes some years of urbanization before the first mega-gullies appear. This is evidenced by the relative absence of mega-gullies in the southern part of the high town, where urbanization only started about five years ago. On the other hand, the oldest urbanized districts like Djelo Binza and Mont Amba and furthermore the whole northern part of the high town have experienced an increase in mega-gully density which, as a matter of fact, has not yet ended. Every rainy season, new mega-gullies are reported, not only in the northern half of the high town, but also more and more in a southerly direction. An example of the latter is the mega-gully in the district of Maman Mobutu (Fig. 1) which led to the destruction of 69 houses in 2008.

3.3. Mega-gully location and plan form related to urban structures and natural topography

During the mapping exercise on the SPOT 2006/2007 anaglyph, attention has been paid to the possible relation between plan form and visible urban structures. But before discussing the results in Table 7, it is necessary to report on 3 different relations which could be found between mega-gullies and urban structures.

It appears that 135 mega-gullies are visibly located on urban structures like roads, gutters, tracks, even a corridor in a forest. Most of the time the information of the recent SPOT images is enough to find the relation, but sometimes it is useful to consult the Google Earth images. In some cases it is necessary to go back to the 1957 aerial photographs to gather more information.

Because not only roads are involved, but also other structures as mentioned above, we prefer to expand the term road side gully (Jungerius et al., 2002; Nyssen et al., 2002; Osmar et al., 2010) to the term 'axial' mega-gully, because all structures mentioned are in fact artificial runoff axes. Therefore, an axial mega-gully is located upon the trajectory of this structure, faithfully following it, even when it is angular or when it obliquely ascends a slope. As far as indicated by the consulted imagery and field checks, a typical axial mega-gully originates on this axis at the point of the steepest slope. It very often concerns the base of the convex hill just above the valley, where the local slope can reach 0.7 m m^{-1}. From this point the mega-gully develops by headward retreat, faithfully following the axis of its supply, be it a road or another structure as indicated above. Apparently, axial mega-gullies never reach

Table 4
Mega-gully drainage density in the stream basins in the high town of Kinshasa.

#	Stream basin	Vegetation situation of mega-gully		Total	Gully drainage density (km km^{-2})
		Vegetation free	Continuous cover		
1	Bumbu	39	20	59	0.95
2	Funa	34	4	38	0.49
3	Lubudi	8	36	44	2.05
4	Lukaya	2	0	2	0.01
5	Lukunga (+Binza)	50	19	69	0.34
6	Lutendele	6	0	6	0.02
7	Mampenza	1	0	1	0.05
8	Matete_N'djili	17	14	31	1.30
9	Mumfu_N'djili	3	2	5	0.92
10	N'djili (Aval)	16	3	19	0.14
11	N'kwambila_N'djili	12	0	12	0.36
12	Tshangu	20	0	20	0.08
13	Tshuenge	2	0	2	0.02
	Total number	210	98	308	–

the top of the hill and thus an intact part of the structure upon or along which the mega-gully develops remains intact and visible. An example is given in Fig. 3. Table 7 shows that a slight majority of axial mega-gullies occur in a completely unnatural position of divergent slopes. Furthermore, it is indicated that 123 mega-gullies obliquely descend the slope. The 12 axial mega-gullies showing no obliquity are developed on roads which descend the hill following the slope lines.

A second class of mega-gullies often shows a trajectory with all characteristics indicating a structurally determined location, but where no upslope remnants of the structure occupied by the mega-gully are left. It concerns mega-gullies originating on the place where a road or other artificial runoff axis laterally loses important quantities of water along its trajectory. From the leakage or the point of release, this water runs over a natural slope. If the natural slope side of the structure is steeper than the longitudinal gradient of the structure, a mega-gully can develop from the point of lateral release in a downslope direction (Fig. 3 and 4). These are cases of progressive erosion (Moeyersons, 2003). The term 'leak' mega-gully is proposed here. The 'leak' mega-gully head often remains at a distance of metres to decametres from the road or other structure where lateral water losses occur. In that case the latter is not endangered. But if the leak mega-gully head originates at the very side of the structure, the latter will be attacked by regressive erosion emanating from the mega-gully head and a leak and an axial mega-gully develop at the same time from the same point, the first in a downslope direction by progressive erosion, the latter along the road in an upslope direction by regressive erosion. The fusion of both types of mega-gullies can finally obliterate the different origin of both mega-gully sections (Fig. 3 and 4). Table 7 shows that the majority of leak mega-gullies occur in topographical hollows. The influence of urban structures is best expressed by the obliquity of the leak mega-gullies. Twenty-seven of the 157 leak mega-gullies are not oblique, but 3 of these 27 are located on a diverging spur slope. This topographical situation on a spur instead of in a topographical hollow evidences their artificial origin.

Table 5
The 10 most and 10 least voluminous mega-gullies of Kinshasa in 2007.

FID/ID	Name	Type	Length (m)	~Volume (m^3)
306	Mataba 1	Active	963	1,469,805
307	Mataba 2	Active	582	1,398,757
133	Laloux Droit	Active	2129	472,312
195		Stable	1074	464,635
138		Stable	437	426,869
3	Laloux Gauche	Active	1196	312,777
1		Stable	861	295,722
139		Active	705	226,195
151		Stable	1340	216,738
92	Drève Selembao	Active	742	213,825
22		Active	26	267
27		Active	25	228
46		Active	31	204
19		Active	65	194
52		Active	61	187
86		Active	72	182
38		Active	29	156
59		Active	106	145
55		Active	35	139
29		Active	30	124

Finally, 16 mega-gullies could not be classified, but 13 show clear obliquity.

Table 7 shows in the first place that 77 of the 308 mega-gullies are located on a spur, 92 on a parallel slope and 139 in a topographic hollow. Under natural conditions no gullies are to be expected on a spur where theoretically all runoff should be diffuse and divergent. The vast majority should be found on convergent slopes. These data indicate that the topography only has a restricted influence on the mega-gully location.

Seventy of the spur mega-gullies are axial and leak mega-gullies and this indicates their artificial origin. The 7 remaining gullies developed on the wall of the sand quarry of the Kemi, an affluent of the Funa River. Also most of the mega-gullies on a parallel slope are probably artificial. Of the 92 mega-gullies, 90 are either leak or axial gullies. The remaining 2 developed below a big housing estate. There are also strong indications for the artificial nature of the 139 gullies in topographical hollows. Only 7 of them have no relation with a runoff concentrating/conducting structure, but they are also located downslope of a housing estate.

It can be concluded that the location of 281 mega-gullies out of the 308, mapped in 2007, is predestinated by the presence of a road, a gutter or other runoff concentrating/conducting urban structure. The other remaining 27 developed on or downslope of places of human activities, like quarrying and parcelling. It should also be noted that these 27 mega-gullies are significantly shorter and less voluminous than the 281 other mega-gullies, which do not show a trajectory commanded by the natural topography, even in the case of leak gullies (Table 7).

3.4. An inventory of gully treatment in Kinshasa

Gully treatment in Kinshasa has become reality since the first hillslope incisions affected the northern part of the high town of Kinshasa at the end of the sixties. Mega-gullies, once stabilized, are very quickly invaded by arborescent and scrub vegetation and are as such easily detectable on the SPOT 2006/2007 anaglyph. Field observations show two different concepts behind mega-gully treatment.

3.4.1. Interruption of the supply of the mega-gully head by water

The objective is to prevent headward erosion and further vertical incision in the bottom of the mega-gully. Two techniques are used. Firstly, small and big retention basins are constructed in the runon area. Some of these small basins are intended as a reservoir for rain water from

Table 6
Mega-gully evolution between 2007 and 2010.

	Cumulated		Mean		Maximum		Minimum	
	2007	2010	2007	2010	2007	2010	2007	2010
Surface (m^2)	1,356,138	2,524,610	8476	7559	75,787	140,086	146	120
Length (m)	62,092	102,076	388	306	2129	2190	30	24
Width (m)	–	–	19	18	75	110	5	5
Depth (m)	–	–	7	6	26	38	2	2
~Volume (m^3)	6,646,615	17,142,622	41,541	51,325	472,312	2,690,075	124	106

house roofs. Other small basins are just deep pits inside the parcel. In other cases, check dams some metres high and some tens of metres long retain runoff at a short distance upstream of a mega-gully head.

The second technique is to divert runoff away from the gully head. In most cases this is realized by the construction of a solid gutter in concrete. This gutter, descending the slope aside of the mega-gully, is often constructed in the form of a staircase in order to break the kinetic energy of the flow. Occasionally big and costly engineering works are involved. In other cases, such as at Laloux, the creativity of the local habitants has resulted in the use of an existing road as a deviation structure.

3.4.2. Protection of the interior of the mega-gully

They aim to store the material entering the mega-gully head from upslope. As such they protect the mega-gully head and the downslope mega-gully bottom against the vertical incision and the storing preserves the downstream part of the town from water and mud problems. It concerns small dams built in the head and centre of the mega-gully. These dams act as check dams, collect deposits behind and create a gully with a flat bottom with level differences at the dam locations. Of course, once the space behind the dam is filled up, sediments are no longer retained and delivery to the lower part of the gully starts again. Gully wall stabilization is another way to protect the interior of the mega-gully.

3.4.3. Technology and materials

Sustainable constructions in the sands in Kinshasa need solid foundations, preferably rocks, boulders, bricks, concrete and masonry. But due to the restricted financial possibilities, Kinshasa became an open-air museum of artisanal mega-gully treatment by means of low-cost materials:

Firstly, mega-gully wall stabilization and head protection against the vertical incision is often realized through the massive dumping of household residues. These residues contain a large quantity of tear up of plastic bags and packing plastics. These remnants, once dumped, are obviously more stable than the natural sand deposits at Kinshasa. Because of the plastics, these deposits resist in all investigated cases vertical incision by concentrated runoff. The initiative of waste dumping comes from FOLECO (Fédération des ONGs Laïques à vocation Economique du Congo). Household residues have been very successfully applied to the complete immobilization and even filling up of many mega-gully heads.

Another technique used in gully wall stabilization is the massive piling up of polypropylene bags, filled with sand, against the wall to be protected. Most of the system holds for 10 to 15 years, the time needed for deterioration of the polypropylene. Tyres are also frequently used, in particular to construct stairs allowing people to descend a steep mega-gully wall.

Furthermore, mega-gully walls are stabilized by micro terracing and by fixing the terraces with vegetation.

Modern ways of obtaining wall stability are the use of sustaining walls in masonry or gabions. In Kinshasa, this method has only been applied in mega-gullies since the 21st century.

Dams and check dams are most of the time constructed with a mixture of tyres and sand bags. In Selembao, the project financed by the World Bank uses gabions to collect the water from the top of the hill into a huge staircase gutter of concrete and masonry.

But local technology and creativity are very inventive when it comes to the protection of the mega-gully head against the further vertical incision by the water current and hence against gully head retreat. On the axial gully on the road from UNIKIN to Kimwenza, canvas or plastic sheets are used to collect water entering a mega-gully head and to let it run over the sheet into the mega-gully at some distance from the mega-gully head (Fig. 5). In the case of Laloux gauche (Fig. 6) an immense construction of metallic sheets was erected to guide the runoff from the Avenue Bolikango over the gully head to the lower part of the gully. It is crucial that the structure collects all runoff entering the mega-gully head, and that the structure is not attacked by regressive erosion. This erosion starts from potholes which develop at the point where the structure delivers the collected runoff into the unprotected gully bottom.

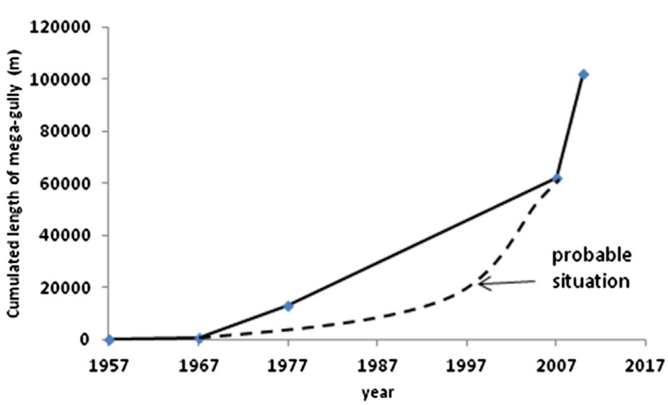

Fig. 2. Cumulated length of mega-gullies in the sector of the town covered by WV1 image. The 1977 value, on the base of Van Caillie (1988) is too high because gullies smaller than 5 m are included. The dashed line gives a better interpretation.

Table 7
Mega-gully location and plan form related to topography and urban structures.

	Topographical position			Obliquity	
	Divergent	Parallel	Convergent	Yes	No
Axial mega-gully					
# of gullies/# of oblique gullies	51/43	42/40	42/40	123	12
Mean gully length (m)	414	420	340		
~Mean gully volume (m^3)	29,140	59,121	30,357		
Leak mega-gully					
# of gullies/# of oblique gullies	19/16	48/35	90/79	130	27
Mean length (m)	234	260	254		
~Mean gully volume (m^3)	14,122	48,800	35,511		
No classified mega-gullies					
# of gullies/# of oblique gullies	7/7	2/2	7/4	13	3
Mean length (m)	80	72	174		
~Mean gully volume (m^3)	974	415	3848		

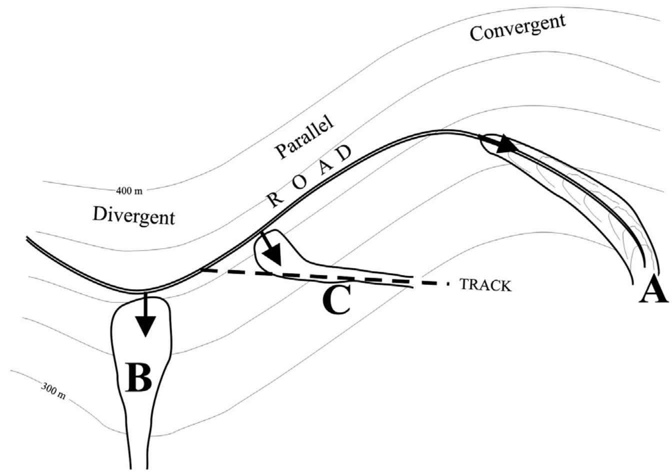

Fig. 3. A: axial oblique mega-gully on convergent slope; B: not oblique leak mega-gully on divergent slope; C: oblique leak mega-gully on parallel slope. Arrows indicate alimentation of mega-gully. More explanation in text.

3.4.4. Successes and failures of mega-gully treatment

The mega-gully mapping on the SPOT 2006/2007 anaglyph revealed the presence of 98 completely vegetated mega-gullies (Table 2). To our knowledge the vast majority of these mega-gullies in Kinshasa have been stabilized intentionally by human intervention. Only in two cases, temporal Google Earth imagery or field information did not allow a decision to be made as to the method of treatment. Therefore, these two mega-gullies are considered to be stabilized by natural evolution. This can be understood in the sense that mega-gully head retreat has resulted in the reduction of the runon area and hence the reduction of available water for further regressive erosion (Graf, 1977; Rutherfurd et al., 1997). These two mega-gullies were not treated because of their location somewhat away from habitation. As such they did not form a risk.

We found that the method of complete protection of the interior of the mega-gully, a combination of check dams made of sand bags, and the use of tyres, sand bags and household refuse in wall stabilization, is successful in 76 cases. In only 7 cases, mega-gully stabilization was obtained by the prevention of runon to the mega-gully head, most times by a combination of deviation of runon and temporary storage in small basins. The 13 cases where a combination of both methods was successful refer mostly to the district of Kisenso, where the Belgian Technical Cooperation was active and where mainly sand bags and to a lesser degree tyres have been used for the construction of check dams and mega-gully wall stabilization. In some gully sectors micro-terraced mega-gully walls have been revegetated.

But the success of gully treatment is not restricted to the completely vegetated mega-gullies. The mapping also revealed mega-gullies which are still active in their lower course as indicated by landsliding, while their head is stabilized. This situation was encountered in 57 of the 210 active mega-gullies. Although impossible to know the technique used to stabilize every mega-gully head, the most important successes come from the prevention of runon, massive dumping of household refuse, piling up of sand bags and tyres, replanting, often used in combination. A typical example of such combined techniques is the mega-gully head of Mataba 1, where the decisive factor of success was probably the sideward deviation of runon along a gutter in armed concrete, nearly 1 km long.

4. Discussions

4.1. The role of urbanization and road construction on gully development

This study confirms observations from elsewhere in the world that the risk of gully development is high in urbanized areas. This stems from the erosional influence of increased flow concentration caused by urban occupation. This has been recently shown in SW-Nigeria (Adediji et al., 2013) and in China (Sun and Wang, 2013). In many instances, researchers have focused on the role of paved as well as earth roads in producing and concentrating runoff and hence in reorganizing the natural drainage in Europe (Boardman, 2013; Waldykowski and Krzemien, 2013), in SE-Australia (Munoz-Robles et al., 2010), in northern Israel (Svoray and Markovitch, 2009) and in Kenya (Jungerius et al., 2002). We prefer the term of 'axial' gully instead of 'road'-gully, because in Kinshasa gully development is observed not only upon roads, but upon all structures which produce and/or concentrate runoff, including sewers. Furthermore, only 43.8% of the gullies are axial, although 94.8%

Fig. 4. New quickly developing leak mega-gully along the road of Kimwenza, 4 km south of UNIKIN (Fig. 1). Progressive erosion from the side of the road with already pronounced gully head. Regressive erosion on the road. GoogleEarth, 30/06/2010. The gully complex is only a few months old at the moment when the picture was taken.

Fig. 5. Tyres, sand bags, canvas, fences of wooden sticks, auto parts and rubbish, to protect the axial mega-gully on the road of Kimwenza, 3 km south of the UNIKIN campus, 2009. The axial mega-gully developed from the plunge pool head of a progressive leak mega-gully behind the back of the photographer. Finally, in 2010, a Chinese contractor has filled up the axial part of the mega-gully and repaired the road. The plunge pool head has been stabilized by a huge massive retaining wall with a concrete gutter to assure a safe outlet of the water in the future.

are alimented in water by these axial structures. The other 50.0% of the gullies is of the type of progressive erosion gully (Moeyersons, 1991b) which has been called here 'leak' gullies. The existence of the equivalent of a 'leak' gully has never been mentioned in other studies of urban gullying.

4.2. Mega-gully treatment assessment

In the light of the 153 failures in the treatment of 306 mega-gullies, this section gives a qualitative assessment of problems or disadvantages of some of the techniques, methods or materials used.

1. Small and big retention basins in the runon area and in the mega-gully head often show a quickly decreasing storage capacity after the five or ten heaviest showers of the rainy season. Except for rain water from house roofs, sediment concentration in diffuse runoff is high. Experimental work By Savat (1975) shows a sediment concentration for calcareous loess of the order of several dozens of $g \cdot l^{-1}$, due to the splash effect. Our own observations during rain showers in Kinshasa indicate at least the same order of magnitude of sediment concentration. The result is ultra-rapid sedimentation and filling up of these structures. Therefore, these structures need to be cured continuously during the rainy season. In addition, the field inquiry revealed that a number of mega-gullies were reactivated by the rupture of retention basins

2. Deviation of runoff upstream of the mega-gully head is a fundamentally sound principle. It was also forwarded by Van Caillie (1983). But in reality, the sewer, constructed to intercept runoff, often undergoes axial gullying as mentioned in Section 3.4.1. Famous cases of a literal displacement of the mega-gully problem are the mega-gullies Mataba 2 and Laloux gauche which reached almost the same size as the protected mega-gullies Mataba 1 and Laloux droit, within a few rainy seasons. Table 5 shows that these 4 mega-gullies figure amongst the ten biggest mega-gullies of Kinshasa.

The Project at Drève de Selembao, funded by the World Bank shows that the lateral deviation or the interception of runoff before entering the mega-gully head can also be successful. Apparently, much depend on the attention given by the engineer and the entrepreneur to the quality of the construction. As many of these gutters break at the base of the hill where the slope is steepest, attention should be paid to the outlet of the construction. It should rest on a large and very solid platform which cannot be undermined by the arriving water and mud. Van Caillie (1983) advises prolonging the gutter, trench or sewer until the river channel.

3. Protective structures in the mega-gully head to prevent the further vertical incision and gully head retreat are very numerous. In all cases where applied, the dumping of plastic household residues or the piling up of sand bags is very successful. But problems mostly occur when sheets, canvas or other protections are used. As shown in the case of Laloux gauche (Fig. 6), the metallic sheets do not hold for two reasons. Firstly, at the lower end of the gutter, the water discharge erodes the mega-gully bottom. The developing plunge pool extends in the mega-gully in a downslope direction and the deepening of the mega-gully provokes a landslide on the gully walls and a widening of the mega-gully. Secondly, the lowest iron plate becomes destabilized and falls in the plunge pool, the second last plate forms at its outlet a new plunge pool and the whole structure collapses gradually as a domino-effect (Fig. 6). At the end, when the upper plates start to destabilize, the masonry, destined to concentrate the water from the avenue into the collector, starts to collapse and the gutter structure is attacked by runoff from the sides. Fig. 6 also shows the situation in 2012 when a Chinese contractor replaced the metallic sheets by a staircase gutter in concrete.

4. Finally the timing and achievement of the ground works before the start of the rainy season are important. Many failures occur because ground works do not start quickly enough or do not end before the start of the new rainy season.

Of the 306 treated mega-gullies, only 98 have been stabilized and a further 53 are only stabilized at their head. The rapidity of the gully development, the restricted local possibilities in finances, workers, temporary unavailability of tools, even of polypropylene bags, and the absence of good organization, are all equally responsible for this meagre success.

Moreover, no work has ever been carried out in Kinshasa to anticipate where and when mega-gully development will occur in the future.

Fig. 6. Axial mega-gully head of Laloux gauche. A construction of metallic sheets, intended to protect the mega-gully head against further vertical incision and head retreat by runon from Bolikango Street (Laloux gauche, Fig. 1) is destabilized from below. The 2011 picture shows that an insufficient amount of sand bags has been put in the mega-gully head to replace the metallic construction which has partially gone. In the foreground the top of a sand dam, is visible. This dam causes temporary sedimentation in the mega-gully bottom. Finally in 2012 the metallic sheets were all gone and a huge staircase-like gutter has been constructed.

Prevention is simply not on the agenda. Among measures to reduce the threat of gullying we consider:

1. Preventing a critical concentration of runoff on roads, tracks, gutters and other structures where runoff is produced or concentrated. This can be achieved by installing on the roads artificial 'leaks', runoff diverters, (Section 3.3 and Figs. 3 and 4) numerous enough to prevent leak gullying. For this purpose, combinations of runon area and slope, critical for mega-gully incision in an urban environment, should be searched for.
2. Measures to reduce runoff generation and sediment production in the fields. In this way retention basins will not be needed any longer and gutters, trenches and other water conductors will not be silted up anymore.

4.3. Timing and duration of geomorphological activity

Diachronic Google Earth images of the same scene show that gullies with a length of hundreds of metres can develop within a timeframe of one rainy season. But field evidence shows that the real geomorphological activity for mega-gullies is quite often a question of a few hours. This is the case for the gully which developed in the district of Maman Mobutu (Fig. 1) on the night of the 5th of April 2008 over some three hours. During that single event headward regression amounted to nearly 300 m. The fact is that the rapidity of the process often surprises the local inhabitants and this means that gully treatment always runs behind the facts.

Mega-gullying in Kinshasa seems to closely follow the natural development of gullies, showing a quick start but retarding evolution over time (Graf, 1977; Rutherfurd et al., 1997). The gully mapping on the 2006/2007 SPOT anaglyph in combination with interviews and field inquiries enables the annual axial retreat of 45 mega-gullies to be described as a function of their age (Fig. 7).

5. Conclusions

Firstly, given the high average mega-gully density with values >2 km km^{-2} in the oldest urbanized parts of the high town, mega-gullying in Kinshasa is manifestly a problem. Elsewhere in the world higher densities occasionally occur in rural areas (Bouchnak et al., 2004; Hughes and Prosser, 2003; Hughes et al., 2001), but the high average mega-gully width in Kinshasa of >17 m compensates for the lower density values. Taking into account this width, it can be calculated that 0.83% of the surface of the high town of Kinshasa in 2007 is only occupied by mega-gullies, larger than 5 m. Still more worrying is the accelerated development of new mega-gullies in Kinshasa during recent years (Fig. 2).

Mega-gullies in Kinshasa developed in the high town only since urbanization started. There is a time delay of 5 to 10 years between the first construction of buildings, houses and streets and the appearance of the first mega-gullies. Apparently a critical density of houses and road networks is needed to start mega-gullying.

The combined checking of a mega-gully location with natural topography and mega-gully plan form with preexisting urban structures, mainly artificial runoff lines like roads, trenches, sewers, gutters, and tracks, shows that 43.8% of mega-gullies in Kinshasa develop along and upon these artificial axes of drainage lines. The term 'axial' gully is proposed. When such a drainage line experiences lateral losses of water, a new mega-gully incision can result. We propose the term 'leak' mega-gully (Figs. 3 and 4). It appears that the trajectory of leak mega-gullies is also mainly imposed by the same artificial drainage lines.

It can be concluded from the study of the inventory of the 308 mega-gullies in 2007 that not one single mega-gully in the high town of Kinshasa can be described as a 'naturally induced' erosion form. The whole mega-gully stock is artificial and induced by human activities.

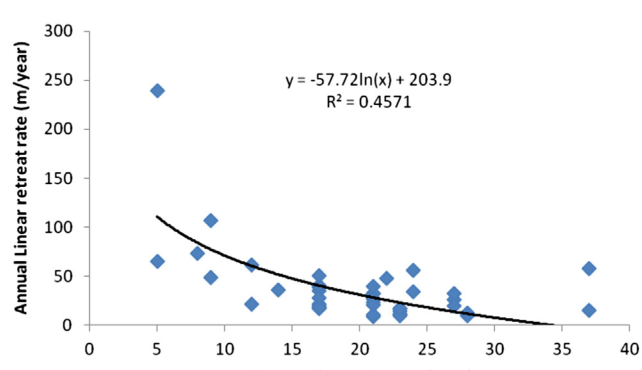

Fig. 7. The annual retreat of 45 mega-gullies, as based on field information. A decrease in annual retreat with mega-gully age is obvious.

This study shows in the first place that mega-gullies in Kinshasa are treated in an artisanal way. The lack of sufficient material and financial means, the absence of sufficient attention to the problem are certainly decisive factors in the many failures.

The reality in the field shows that Van Caillie's idea (1983) of stopping runoff before it arrives on the street is, today, an insufficient measure. This study shows that in spite of all efforts, mega-gullies nevertheless develop upon streets and roads. These structures obviously produce enough runoff on their own to produce mega-gullies.

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