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What controls the expansion of urban gullies in tropical environments? Lessons learned from contrasting cities in D.R. Congo

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ABSTRACT

Urban gullies (UGs) are a growing concern in many tropical cities of the Global South. Addressing this new geo-hydrological hazard requires good insights into the rates and controlling factors of this process. Therefore, we investigate the expansion rates of a representative sample of UGs in Kinshasa (n = 17) and Bukavu (n = 29), two contrasting cities in D.R. Congo. We reconstruct long-term (10–17 years) expansion rates, making a distinction between headcut retreat and sidewall widening, and analyse the environmental factors potentially explaining these rates. Total expansion rates varying between 12.6 and 863 m^2y^{-1}. Most of this expansion happens through sidewall widening. In Kinshasa, which is mainly characterized by sandy soils, contrasts in expansion rates are mainly correlated to the characteristics of the upslope drainage area of the gullies. Especially the road density and a hypothetical runoff index (combining drainage area, land use and soil characteristics) explain a significant part of the observed variation. In Bukavu, such trends are less apparent. This is likely because the clayey nature of the soils provides more resistance against gullying, resulting in overall smaller and less actives UGs. Furthermore, the already low infiltration rates of these soils probably make the relative impact of urbanization on runoff production smaller. Our results also indicate that UGs located in recent landslides have higher gully expansion rates. The mechanisms behind remain poorly understood. Overall, our work opens promising perspectives to model and predict gully expansion rates in urban settings but may also guide efforts aiming to stabilize UGs.

1. Introduction

Urban gullies (UGs) are increasingly highlighted as a growing concern in many tropical cities, especially in the Global South (Guerra et al., 2007; Poesen, 2018; Zolezzi et al., 2018; Bartley et al., 2020; Frankl et al., 2021; Vanmaercke et al., 2021). Such gullies are commonly much larger than those occurring in rural environments (e.g. Makanzu Imwangana et al., 2015). In addition, their formation and expansion can be very quick. Within a few years, they can obtain widths of several dozens of meters and lengths of several hundreds of meters or even kilometers (Makanzu Imwangana et al., 2015; Vanmaercke et al., 2016). As this drastic expansion often happens in densely populated areas, urban gullies are frequently associated with major impacts, including the destruction of properties, buildings, roads and other infrastructure (Lutete Landu et al., 2023). In many instances, this also leads to displaced and wounded people and even casualties (e.g. Balzerek et al., 2003; Guerra et al., 2007; Makanzu Imwangana et al., 2014). As such, UGs form a new geo-hydrological hazard of the Anthropocene (Poesen,

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2018).

Addressing this hazard requires good insights in the factors controlling UG expansion, so that appropriate prevention and mitigation measures can be taken (e.g. Bartley et al., 2020; Lutete Landu et al., 2023). This is especially urgent, given that climate change will likely lead to an overall increase in gully expansion rates as a result of higher rainfall intensities (Nearing et al., 2004; Vanmaercke et al., 2016) and that urbanization in the Global South is expected to accelerate (Seto et al., 2011; UN-Habitat, 2016; United Nations, 2019).

From studies in non-urban contexts, we know that gully expansion is controlled by a combination of factors, including the contributing area, land use, rainfall characteristics and soil properties (e.g. Poesen et al., 2003; Vandekerckhove et al., 2003; Frankl et al., 2012; Vanmaercke et al., 2016, 2021; Guan et al., 2021; Ioniță et al., 2022). More site-specific processes like landsliding can also affect gully erosion rates as they can induce runoff concentration (Wieczorek, 1984; Turner & Schister, 1996; Poesen, 2018; Belayneh et al., 2022) but may also generate loose slope deposits that are susceptible to gullying (Mackey and Roering, 2011; Kubwimana et al., 2014). In many ways, the role of these factors is further complicated in urban environments. For example, roads can concentrate runoff but may also divert it to or from other areas. As such, they can significantly alter the topographical areas draining to potential gullies (Carvalho Junior et al., 2010). Where this leads to an increase in contributing area, this can clearly enhance gully occurrence and expansion (Nyssen et al., 2002; Frankl et al., 2012; Makanzu Imwangana et al., 2014). Urban areas are also typically characterized by a very heterogenous land use, with roofs, roads, foot paths and other nearly impervious surfaces interspersed with bare and vegetated areas that allow water infiltration (Moeyersons et al., 2015). The actual runoff volume that is generated from such areas and that may potentially contribute to gully initiation and development will further depend on elements like rainwater storage infrastructure (Lutete Landu et al., 2023).

Nonetheless, the factors controlling urban gully expansion, and especially their interactions, remain poorly understood (Archibold et al., 2003; Makanzu Imwangana et al., 2014; Moeyersons et al., 2015; Vanmaercke et al., 2016, 2021). For example, urbanization may clearly influence runoff production and, by extent, gully expansion. Yet, the importance of this effect will also depend on the size of the drainage area considered and the occurring soil type. One element contributing to this knowledge gap is the difficulty to collect data on this process. While the growing availability of (high-resolution) remote sensing imagery has made it more feasible to map gullies and their expansion rates (Vanmaercke et al., 2021), this work often remains challenging and time consuming in complex urban environments. In addition, the strong influence of road networks makes it very difficult to automatically delineate the contributing area of gullies from digital elevation models (Carvalho Junior et al., 2010; Makanzu Imwangana et al., 2014). Nonetheless, knowing this contributing area is critical as it will directly influence the runoff volume that can accumulate at a gully head. Delineating contributing areas in the field therefore often remains a necessity, especially in data-scarce regions like tropical cities in the Global South. Also on a more general level, several aspects of gully expansion received hitherto limited research attention. Most studies focussed on gully headcut retreat or the spatial expansion of gullies as a whole (Vanmaercke et al., 2016, 2021). Very few studies make a distinction between gully expansion through headcut retreat or gully widening (Hayas et al., 2019). Yet, the dynamics of both processes may vary strongly.

Here, we aim to address these research gaps by studying the expansion rates of a representative sample of urban gullies in Bukavu and Kinshasa, two cities of the D.R. Congo located in strongly contrasting geomorphic settings that are both affected by UGs. More specifically, we aim to:

(i) quantify the urban gully expansion rates and their dynamics, both in terms of gully headcut retreat and gully widening;
(ii) analyse which environmental factors best explain these expansion rates;
(iii) explore and discuss to what extent these expansion rates can be modelled, taking into account the data limitations that exist for these regions.

2. Materials and methods

2.1. Study area

The cities of Kinshasa and Bukavu, located in the D.R. Congo (Fig. 1), are both characterized by a tropical savannah (Aw) climate with an average annual rainfall depth of ~ 1500 mm (Beck et al., 2018). Yet, they strongly contrast in their topographic and pedological setting. Kinshasa, the capital of the D.R. Congo, was originally located on the alluvial plains of the Congo river. However, over the past decades, the city expanded rapidly and largely uncontrolled to a population of > 12 million people (Bédécarrats et al., 2019). Most of this urban sprawl happened in the surrounding hills, which are mainly characterized by sandy material and Arenosols (Van Caillie, 1983; Lateef et al., 2010; Jones et al., 2013). It is this context that makes the city extremely vulnerable to urban gullying (Van Caillie, 1983; Wouters & Wolff, 2010; Makanzu Imwangana et al., 2015).

Bukavu, on the other hand, is located in the steep mountainous region of the western branch of the East African Rift. The city developed on mainly lava materials that are often deeply weathered into thick regolith and associated Ferralsols and Nitisols (Moeyersons et al., 2004; Jones et al., 2013). Given this steep and clayey context, large deep-seated landslides are also very common in Bukavu, impacting ca. 30 % of the urban area (Moeyersons et al., 2004; Dewitte et al., 2021; Dille et al., 2022). The exact ages of these landslides are often unknown. Yet, it is clear that both very recent (past years) as well as much older (pre-1950 s) landslides occur (Dewitte et al., 2021). The city currently has ca. 1 million inhabitants (Lloyd et al., 2017; Michellier, 2017).

Recent mapping efforts (Lutete Landu et al., 2023) indicated the presence of at least 579 UGs in Kinshasa (Fig. 1**a,** Fig. 2**a-b**) and 102 UGs in Bukavu (Fig. 1**d,** Fig. 2**c-e**). In Kinshasa, the observed lengths of these UGs varied between 10 and 1,920 m (average: 290 m), while their area ranged between 0.003 and 10.45 ha (average: 0.69 ha; Lutete Landu et al., 2003). UG lengths in Bukavu ranged between 30 and 710 m (average: 170 m) and areas varied between 0.01 and 2.08 ha with (average: 0.23 ha; Lutete Landu et al., 2003). While some of the UGs are recent (<5 years), many of them are several decades old. Due to a lack of frequent imagery, their exact age is often hard to determine. Nonetheless, it is clear that nearly all gullies formed after the 1950 s, as a result of largely uncontrolled urban sprawl (Makanzu Imwangana et al., 2015; Dewitte et al., 2021; Lutete Landu et al., 2023).

2.2. Reconstruction of gully expansion rates

In this research, we selected 46 UGs for further analyses (17 in Kinshasa, 29 in Bukavu). As our objective was to study gully expansion dynamics over longer periods (>10 years), this selection was mainly based on the availability of Google Earth images that allowed quantifying such expansion rates (see below) as well as the possibility to visit these gullies and their contributing area on the terrain (taking into account security and accessibility constraints). The exact formation dates of these gullies was mostly unknown. Yet, field interviews and analyses of historical aerial photos indicates that most of our gullies were formed before the early 2000 s and sometimes even before the 1970 s (Makanzu Imwangana et al., 2015; Dewitte et al., 2021; Table SI.1**).**

In Kinshasa, the most recent observed lengths of these UGs ranged between 80.2 and 859 m (average: 334 m), while their area varied between 0.20 ha and 2.92 ha (average: 0.97 ha). In Bukavu these lengths

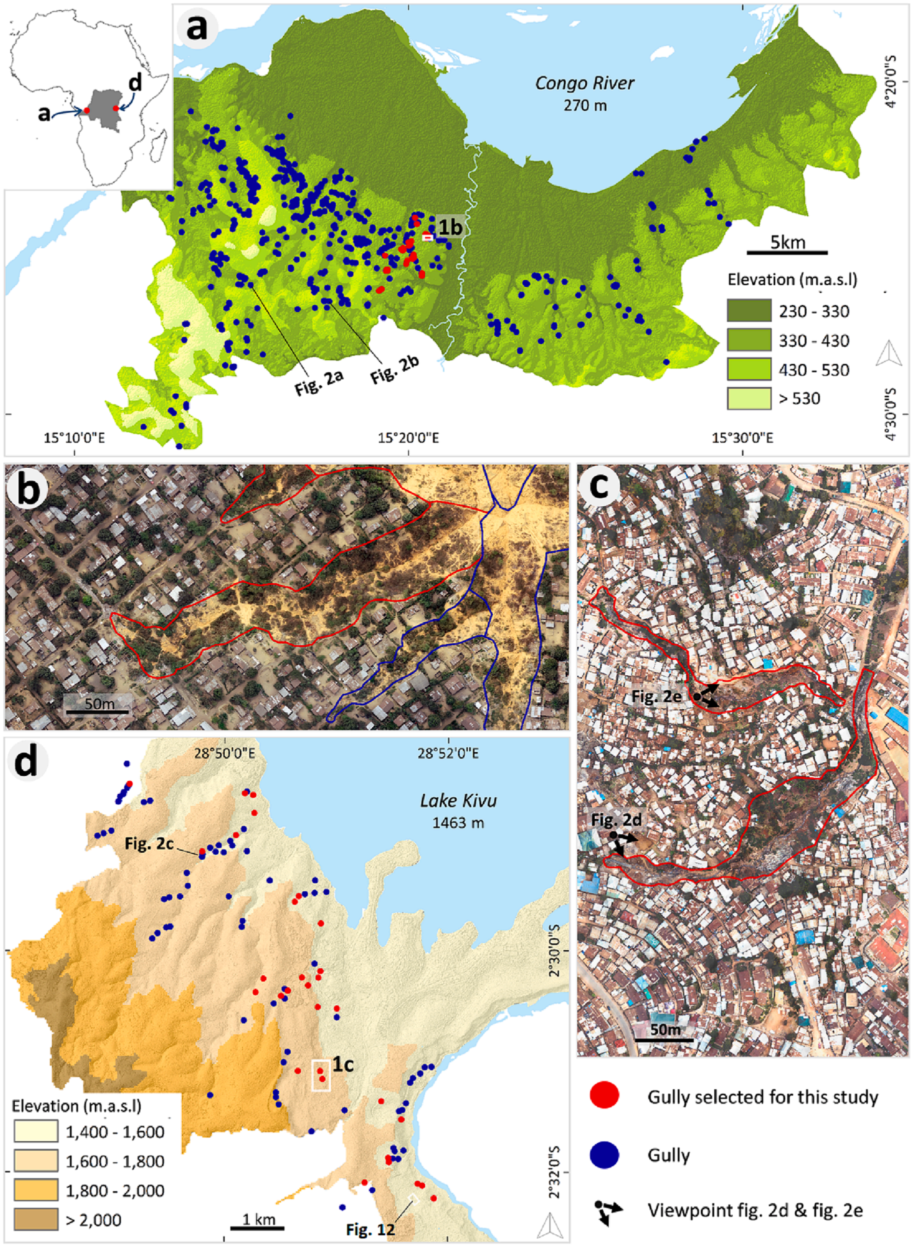

Fig. 1. Spatial distribution of urban gullies in Kinshasa (a) and Bukavu (d). Gullies in red were selected for this research. Gullies in blue indicate other urban gullies, mapped by Lutete Landu et al. (2023). Topography and hillshading were derived from the Digital Surface Models of Dewitte et al. (2021) for Bukavu and Makanzu Imwangana et al. (2015) for Kinshasa. (b) and (c) show UAV images of urban gullies and their surrounding urban fabric in Kinshasa (b, image from August 2022) and Bukavu (c, images from October 2018; Dille et al., 2022). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

varied between 59.4 and 621 m (average: 246 m), while their areas ranged between 0.037 and 1.58 ha (average: 0.390 ha; Table. SI.1). As such, the size distribution of our selected UGs is similar to the range reported by Lutete Landu et al. (2023). Also in terms of age as well as topographic, pedological and land use conditions, our selection can be considered representative for UGs occurring in Kinshasa and Bukavu (Lutete Landu et al., 2023; Fig. 1).

To reconstruct the expansion dynamics of the selected gullies, we mapped their spatial extent on the oldest available Google Earth image of sufficiently high quality (having an estimated effective resolution of 0.3 to 1 m) and then remapping them on later images of similar resolution. For Bukavu, the first images were taken on 14/09/2004 or 15/08/2003 (depending on the location of the gully), while the subsequent images were taken on 18/07/2011, 31/08/2016 and 09/02/2020 (i.e. the image date that corresponded as close as possible to the timing of our fieldwork; see **section 2.3.1**). This allowed us to reconstruct the total expansion over a period of > 15 years (2003/4 to 2020), as well as for three sub-periods: 2003/2004–2011(P1, ~8 years), 2011–2016 (P2, ~5 years) and 2016–2020 (P3, ~4 years). Similarly, for Kinshasa, the imagery was taken on 30/06/2010, 28/04/2014, 27/04/2017 and 18/04/2021. This allowed us to quantify long-term expansion rates over a total period of ca. 11 years (2010–2021), as well as for 3 shorter sub periods: 2010–2014 (P1, ~4 years), 2014–2017 (P2, ~3 years) and 2017–2021 (P3, ~4 years).

On each of these indicated image dates, we manually mapped the spatial extent of the gully as well as the position of its thalweg (Fig. 3, SI.1). We considered the starting point of each gully to be its head. The endpoint was either the confluence of the gully with another gully or

Fig. 2. Terrestrial photos of some of the urban gullies selected for this research in Kinshasa (**a**, **b**) and Bukavu (**c, d**, **e**). The locations of these photos is indicated in Fig. 1. Note the contrast in soil type and resulting gully morphology. Gullies in Kinshasa incise loose, largely homogeneous sandy soils, resulting in wide gully channels. Soils in Bukavu are clayey and more cohesive, often resulting in a more narrow gully channels. The red arrow in **(c)** indicates a reddish paleosol separating a relatively recent volcanic outflow from a clay soil below it, which resulted from the alteration of an older lava layer. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

river or its outlet into a flat area (resulting in signs of sediment deposition). In some cases, it was observed that gully heads bifurcated or that new gullies formed along the sides of existing UGs. If the length of the thalweg of such new gully head was longer than 30 m, it was mapped as a separate gully.

By comparing the mapped lengths and spatial extents of the gullies at different dates, we reconstructed the linear and areal expansion rates over the time periods indicated above. In doing so, we made a distinction between headcut retreat and sidewall widening (Fig. 3). While some earlier studies differentiate both processes based on morphological characteristics like curvature (e.g. Wu et al., 2018), the irregular shape of many of our gullies did not allow such approach. We therefore drew a line at the position of the gully head on the oldest of the two considered images, perpendicular to the mapped thalweg (Fig. 3**c**). The expansion that occurred upslope of this separation line was defined as headcut retreat, while the expansion downslope of this line was defined as sidewall expansion. As such, linear gully headcut retreat rate (*GHRRL*) was calculated as:

$$GHRRL = \frac{LH}{period} \tag{1}$$

with *LH* the length of the gully thalweg on the most recent image, upslope of the separation line and *period* the time difference between the two considered images. Similarly, the areal gully headcut retreat rate (*GHRRA*) was calculated as:

$$GHRRA = \frac{A3}{period} \tag{2}$$

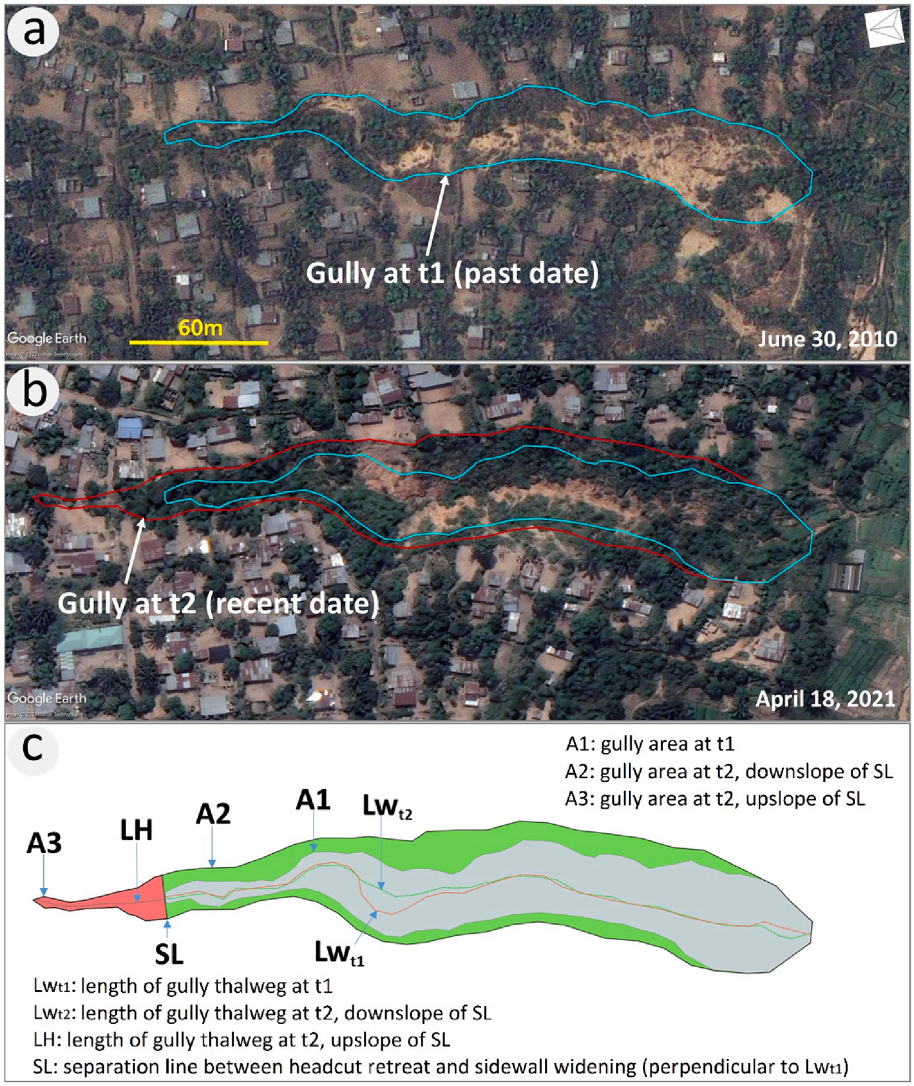

Fig. 3. Example of how gully expansion rates were assessed for an urban gully in Kinshasa. **(a)** Mapped extent of the gully on the first (oldest) Google Earth image (t1). **(b)** Mapped extent on the last (most recent) Google Earth image (t2). **(c)** Illustration of how headcut retreat (red) and sidewall widening (green) were quantified based on the mapped gully areas and thalwegs at t1 and t2 (see text for details). Fig. SI.1 provides additional examples. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

with *A3* the area of the mapped gully polygon on the recent image, upslope of the separation line. The areal gully sidewall widening retreat rate (*GSWRRA*) was calculated as:

$$GSWRRA = \frac{A2 - A1}{period} \quad (3)$$

with *A1* the area of the gully as mapped on the old image and *A2* the area of the gully polygon on the recent image downslope of the separation line. To calculate the corresponding linear gully sidewall widening retreat rate (*GSWRRL*), *A1* and *A2* were divided by the lengths of their corresponding thalwegs:

$$GSWRRA = \frac{\left(\frac{A2}{Lw_{t2}}\right) - \left(\frac{A1}{Lw_{t1}}\right)}{period} \quad (4)$$

With Lw_{t1} the length of the gully thalweg as mapped on the old image and Lw_{t2} the length of the thalweg on the recent image, downslope of the separation line. Finally, we calculated the total areal gully retreat rate (TGRRA) as the sum of the areal sidewall expansion and headcut retreat rate:

$$TGRRA = GHRRA + GSWRRA \quad (5)$$

Evidently, challenges and differences in interpretation induce uncertainties on the mapped gully areas and lengths (e.g. Maugnard et al., 2014). These will also propagate into the calculated expansion rates. Also in our case, mapping the exact boundaries of the gullies was at some points difficult, e.g. due to the presence of vegetation. In addition, inaccurate georeferencing and/or orthorectification sometimes caused small positional shifts in Google Earth imagery of different dates. To estimate to what extent these difficulties caused uncertainties on our calculated expansion rates, a representative subset of ten gullies (5 Kinshasa, 5 in Bukavu) were mapped a second time by another researcher who received sufficient training to do so. This was done for both the oldest and most recent images considered. Using these polygons and following the procedures above, we calculated alternative values for the long-term *GHRRA*, *GSWRRA* and *TGRRA* and compared them to those obtained by the original mapper.

2.3. Factors potentially controlling urban gully expansion rates

2.3.1. Drainage area

The mapping of the areas draining to each gully head was done in two steps. First, we automatically delineated these areas from digital surface models (DSM), using standard GIS flow routing procedures (i.e., the r.watershed and r.water.outlet algorithms of GRASS). To explore the impact of DSM resolution, this was done based on a 30 m DSM, derived from GLO-30 m (ESA, 2019) as well as more detailed DSMs. The detailed DSMs had a resolution of 1 m and 5 m DSM for Bukavu and Kinshasa, respectively (Dewitte et al., 2021; Makanzu et al., 2015, Fig. 1). This allowed to obtain a first rough estimate of the size and morphology of the drainage areas. Next, the actual drainage areas were verified during terrain surveys in 2020 and 2021 and, where needed, remapped with a handheld GPS (Fig. 4). Building on the procedure of Makanzu Imawangana et al. (2014), we used marks of runoff flowing towards the gully heads as well as subtle topographic and flow orientation differences associated with the presence of roads to determine the actual drainage areas. We also reconstructed the drainage areas in the past, based on the position of gully heads at the starting date of the measuring period (as derived from Google Earth) and used information from field interviews with inhabitants about past flow patterns of runoff.

2.3.2. Slope

The two DSMs of 1 m (Bukavu) and 5 m (Kinshasa) were used to extract mean soil surface slope values of the drainage areas. In addition, we obtained the difference in elevation between the most recent and oldest positions of the gully head. For this, we selected nine representative pixels at each side of the gully head (without buildings or vegetation) and calculated the average altitude of these points. This was done for both the oldest and most recent position of the gully head (Fig. 4). The slope gradient over which the gully headcut retreat occurred was then calculated as the difference in altitude of the two head positions, divided by the horizontal distance between them (measured along the thalweg).

2.3.3. Geological context and the presence of landslides

Given the strong spatial homogeneity (cf. section 2.1) and the absence of fine-scale resolution datasets, contrasts in lithology and soil properties were not further considered in Kinshasa. Also Bukavu has a relatively homogeneous lithology. Nonetheless, the parent material shows strong contrasts in (shear) strength and weathering conditions due to the presence of large landslides (Dewitte et al., 2021). The presence of these landslides as well as their relative age (recent vs old; Dewitte et al., 2021) were therefore considered as potential controlling factors of UG expansion rates in Bukavu.

2.3.4. Land use, hypothetical runoff and roads

Land use in the upslope drainage area may have an effect on gully expansion rates, as they influence the volumes of runoff that arrive at the gully head. To account for this, we quantified hypothetical runoff volumes (R) for each gully based on the rational method (Blanco et Lal, 2008):

$$R = RCg.A.P \quad (6)$$

where R is the hypothetical runoff volume (m^3), A is the drainage area (m^2), and P is the rainfall depth (m) of the rainfall event causing the runoff. As we lack the timeseries data to study gully expansion rates at the event scale and as we are mainly interested in explaining observed contrasts in long-term average expansion rates of gullies within the same city, we assumed P to be constant and equal to 20 mm in the two cities.

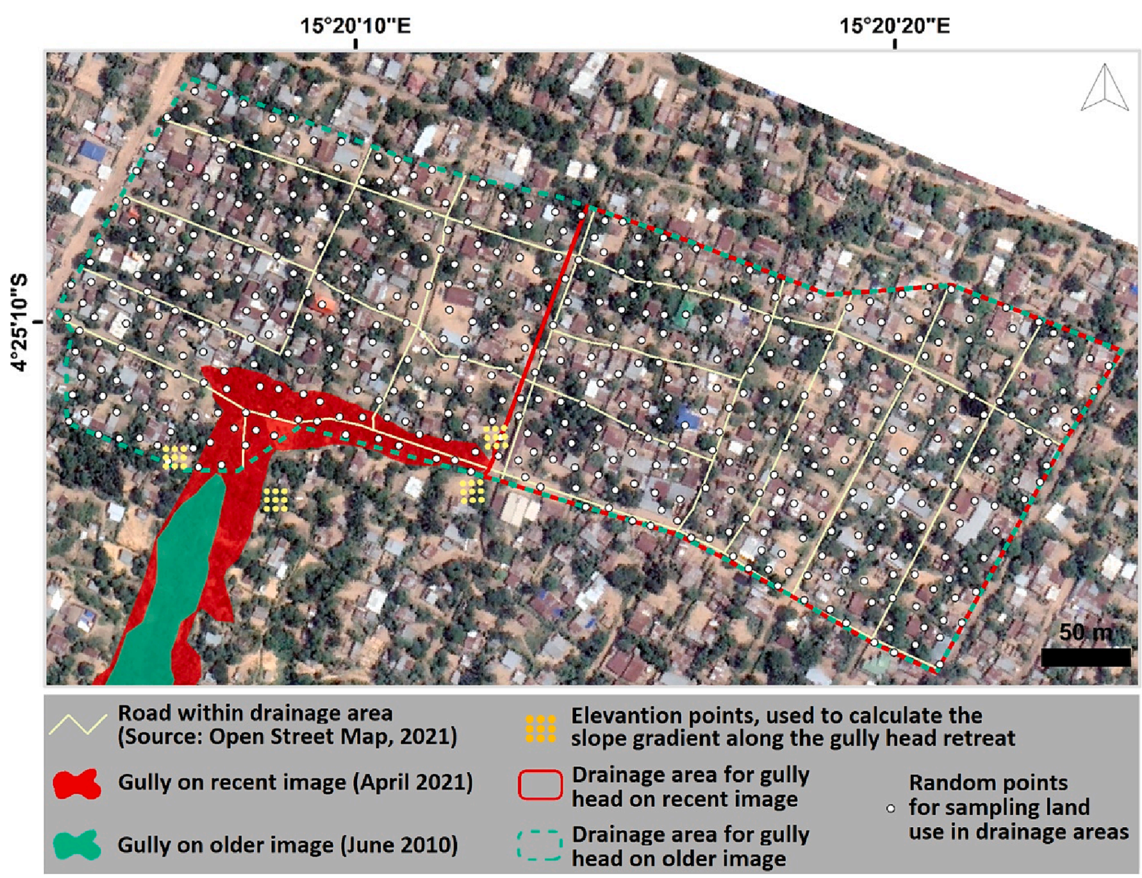

Fig. 4. Illustration of the determination of drainage area, slope gradient and land use for an urban gully in Kinshasa. The background image was derived from Google Earth.

Earlier studies reported that events of gully headcut retreat typically only occur for rainfall events of at least 20 mm/day (Hayas et al., 2019; Poesen, et al., 2003). Likewise, Moeyersons et al. (2015) reported a value of 24.9 mm per event as a critical rainfall threshold for gully initiation in Kinshasa.

RCg is a composite runoff coefficient that depends on the areal percentages of the *n* different land use types (%LU) in the drainage area and a typical runoff coefficient (*RCi*) corresponding to each land use:

$$RCg = \sum_{i=1}^{n} (\%LU_i \times RC_i) \tag{7}$$

In terms of land use types, we considered unmetalled roads, asphalted roads, roofs, vegetation and bare soils. To assess their areal extent, we generated random points (50 per ha of drainage area) and recorded the land use type at each point, based on Google Earth imagery (Fig. 4). To take into account changes in land use, this was done for different time periods (using the same points), i.e. for 2010 and 2021 in Kinshasa, and 2004 or 2003 and 2020 in Bukavu.

The exact runoff coefficients corresponding to these land use types (*RCi*) are unknown. Yet, they can be expected to also vary with the overall soil type. Hence, *RCi* values per land use and per city were assigned based on available literature (Table. SI.2). For Kinshasa, these values are mostly derived from field experiments using simulated rainfall (Moeyersons et al., 2015).As both the land use and the drainage area above the gully head (A) evolved over the measuring periods, we calculated the average hypothetical runoff ($R_{average}$) for the measuring period as:

$$R_{average} = \frac{1}{2}\left(R_{recent\ LULC\ recent\ A} + R_{past\ LULC\ past\ A}\right) \tag{8}$$

where $R_{recent\ LULC\ recent\ A}$ is the hypothetical runoff based on the most recent drainage area and land use mapping (2021 in Kinshasa and 2020 in Bukavu) and $R_{past\ LULC\ past\ A}$ the hypothetical runoff based on the older drainage area and land use mapping (2010 in Kinshasa and 2004 or 2003 in Bukavu).

Likewise, we assessed the difference in hypothetical runoff due to land use changes during the corresponding study period:

$$R_{difference} = \left(R_{recent\ LULC\ past\ A} - R_{past\ LULC\ pastA}\right) \tag{9}$$

where $R_{past\ LULC\ past\ A}$ is the same as in Eq. (8) and $R_{recent\ LULC\ past\ A}$ is the hypothetical runoff based on the recent land use mapping, but using the same contributing area as that for the past land use (2010 in Kinshasa and 2004 & 2003 for Bukavu). This allowed us to isolate the effect of changes in land use on runoff from the effect of changes in contributing area. Moreover, while the drainage area of a gully head typically decreases as the head retreats, this is not the case for other cross-sections downstream of the gully head. As such, mainly changes in runoff due to land use changes can be expected to explain gully widening rates.

Apart from their effect on contributing areas (**section 2.3.1**) and runoff coefficients (cf. Eq. (7) and Table. SI.2), roads may also influence the characteristics of runoff arriving at a gully in other ways. For example, they may concentrate and transfer runoff more efficiently to a gully head. To consider such effects, we calculated the road density in each catchment draining to a considered gully, based on Open Street Maps data (Dille et al., 2022; © OpenSteetMap contributors):

$$Road\ density = \frac{Cumulative\ length\ of\ roads\ in\ drainage\ area\ in\ the\ past}{Intitial\ Drainage\ area\ in\ the\ past} \tag{10}$$

These calculations were conducted based on data for the oldest considered phase of gully extent, i.e. 2004–2003 for Bukavu and 2010 for Kinshasa.

2.4. Statistical analyses

To test the relevance of different factors in explaining UG expansion, we conducted linear least-square regressions between the considered explanatory factors (**section 2.3**) and the observed areal gully headcut retreat rates, gully widening rates and/or total gully expansion rates. We used the coefficient of determination (R^2) as a proxy to evaluate the goodness of the fit, as well as a linear regression *t*-test to see if the slope of the regression differed significantly from zero. For this, we assumed a significance level of 0.05. Both in Kinshasa and Bukavu, there were gullies that can be considered outliers (for reasons that will be further explained below). To account for their effect, regressions were fitted with and without these outliers.

3. Results

3.1. Urban gully expansion rates

Overall, gully expansion rates are much larger in Kinshasa than in Bukavu (Fig. 5**a & 5b**). While linear gully headcut retreat rates (GHRRL) generally exceed linear sidewall expansion rates (GSWRRL), this is clearly not the case for areal expansion rates. In both cities, the areal gully sidewall widening rates typically largely exceed the areal gully headcut retreat rate. Indeed, the average GSWRRA is 205 $m^2.y^{-1}$ in Kinshasa and 112 $m^2.y^{-1}$ in Bukavu, while the average areal gully headcut retreat rate (GHRRA) is only 166 $m^2.\ y^{-1}$ in Kinshasa and 20 $m^2.\ y^{-1}$ in Bukavu. Both processes also show different temporal dynamics (Fig. 5**.c–f;** Table. SI.3). In both cities, GHRRA strongly decreased in the most recent time period (P3). Yet, GSWRRA values consistently remained high and even slightly increased in Bukavu.

A comparison of areal expansion rates with those obtained by a second mapper who followed the same procedure indicates that our results are subject to some uncertainty. Observed deviations in estimated expansion rates between both mappers varied between 0.7 and 89 % with an average of 21 %. Nonetheless, these deviations are relatively minimal as compared to the overall range of expansion rates, resulting in a very high correlation between the two mapping results (Fig. SI.2).

3.2. Factors controlling gully expansion rates

3.2.1. Drainage area and slope steepness

Drainage areas obtained from DSMs were typically much smaller than those obtained in the field (Fig. SI.3 & SI.4). This was true for both the 30-m and the high-resolution (1 to 5 m) DSM, although the deviations were slightly smaller for the latter. We based the rest of our analyses on the field-derived drainage areas, as these can be expected to be most accurate.

Overall, drainage areas measured in the field show no significant correlation with expansion rates measured over the total study period (Fig. 6). This is true for both Kinshasa and Bukavu and holds for the areal gully sidewall widening rates (GSWRRA), areal gully headcut retreat rates (GHRRA) and total areal gullyhead retreat rates (TGRRA).

One gully in Kinshasa had a much larger drainage area than the others. Field surveys indicated that the drainage area of this UG was initially much smaller, but that the construction of a dike across a road (to stop runoff towards another gully head) led to a drastic increase in drainage area. This point (indicated in red on Fig. 6) can therefore be considered an outlier. Excluding it from the regression results in a significant and positive correlation between drainage area and GSWRRA (Fig. 6**a**). However, the trends with GHRRA and TGRRA remain insignificant.

The slope gradient of the soil surface at the gully head shows insignificant correlations with GSWRRA and GHRRA in both Kinshasa and Bukavu (Fig. SI.5). Also the slope steepness of the upslope drainage area is not significantly correlated to gully expansion (Fig. SI.5, Table SI.4 & SI.5).

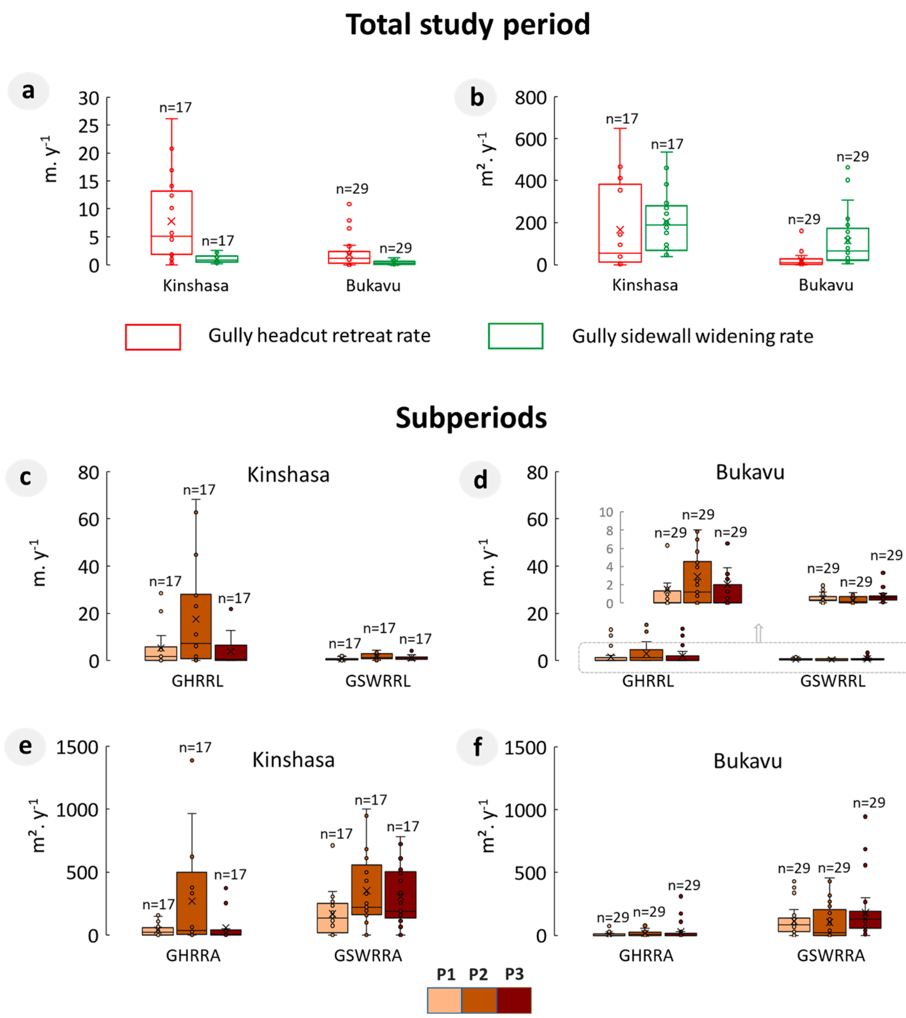

Fig. 5. Urban gully expansion rates in Kinshasa and Bukavu. **(a)** and **(b)** show respectively the linear and areal headcut retreat and sidewall widening rates over the entire measuring period (2010–2021 for Kinshasa, 2003/4–2020 for Bukavu). **(c)** and **(d)** show the linear gully headcut retreat (GHRRL) and gully sidewall expansion rates (GSWRRL) over the three considered time intervals in Kinshasa (P1: 2010 to 2014, P2: 2014 to 2017, P3: 2017 to 2021) and Bukavu (P1: 2003/4 to 2011, P2: 2011–2016, P3: 2016–2020). **(e)** and **(f)** show the corresponding areal gully headcut retreat (GHRRA) and sidewall expansion (GSWRRA) rates. n indicated the number of gullies. Further details can be found in Table SI.3.

3.2.2. *Land use dynamics, estimated runoff production and road length*

Both cities underwent important land use changes over the past decades, in particular an increase in roof-covered areas at the expense of bare soils (Fig. 7). In both cities, the drainage areas at the gully head slightly decreased over the observation period. Yet, with the exception of the earlier mentioned outlier in Kinshasa (**section 3.2.1**), these changes remain overall limited (Fig. 7**c**).

€The average hypothetical runoff volume (Eq. (8) resulting from these drainage areas and land uses tend to be positively correlated to gully expansion. When excluding the earlier mentioned outlier, this trend is significant in Kinshasa for both TGRRA (Fig. 8) and GSWRRA, but not for GHRRA (Fig. SI.6). In Bukavu, these trends remain insignificant (Fig. 8**,** SI.6).

Changes in hypothetical runoff volume, resulting from changes in LU and drainage areas over the study period (Eq. (9), correlate less clearly with gully expansion (Fig. 9). Only for Kinshasa, a significant positive correlation exists with gully widening (Fig. 9**a**).

The total road length in the gully drainage area show significantly positive relationships with gully sidewall and total areal gully expansion in Kinshasa (Fig. 10). For Bukavu, these relationships are insignificant.

3.2.3. *Interactions with landslides*

Further analyses for Bukavu revealed that gully expansion rates strongly interact with landsliding (Fig. 11). Three groups of UGs can be identified. The first group concerns UGs formed in recent landslides (i.e. landslides that occurred around the 1950 s or later; Dewitte et al., 2021). These gullies are typically larger (Fig. 11**e**) and show higher total expansion rates (Fig. 11**d**). The TGRRA of these gullies is also positively correlated to both average hypothetical runoff volume (Eq. (8); Fig. 11**b**) and the total road length (Fig. 11**c**). Only one point deviates from this trend (indicated with a red arrow in Fig. 11). Field observations revealed that this gully was associated with the rupture of a water pipe (Michellier et al., 2020) and currently cuts through compact volcanic rocks at its bottom. This likely explains its relatively lower TGRRA. As such, we considered this point to be an outlier. The second group consists of UGs in (very) old landslides (pre-1950 s, but likely thousands of years old; Dewitte et al., 2021). The TGRRA of these gullies remains limited, regardless of their corresponding hypothetical runoff volume or road length. The third group are UGs that are located outside landslide-affected areas. Likewise, they have overall low expansion rates, but also lower hypothetical runoff volumes and upslope road lengths. This is mainly attributed to their overall smaller drainage areas (Fig. 11**e**).

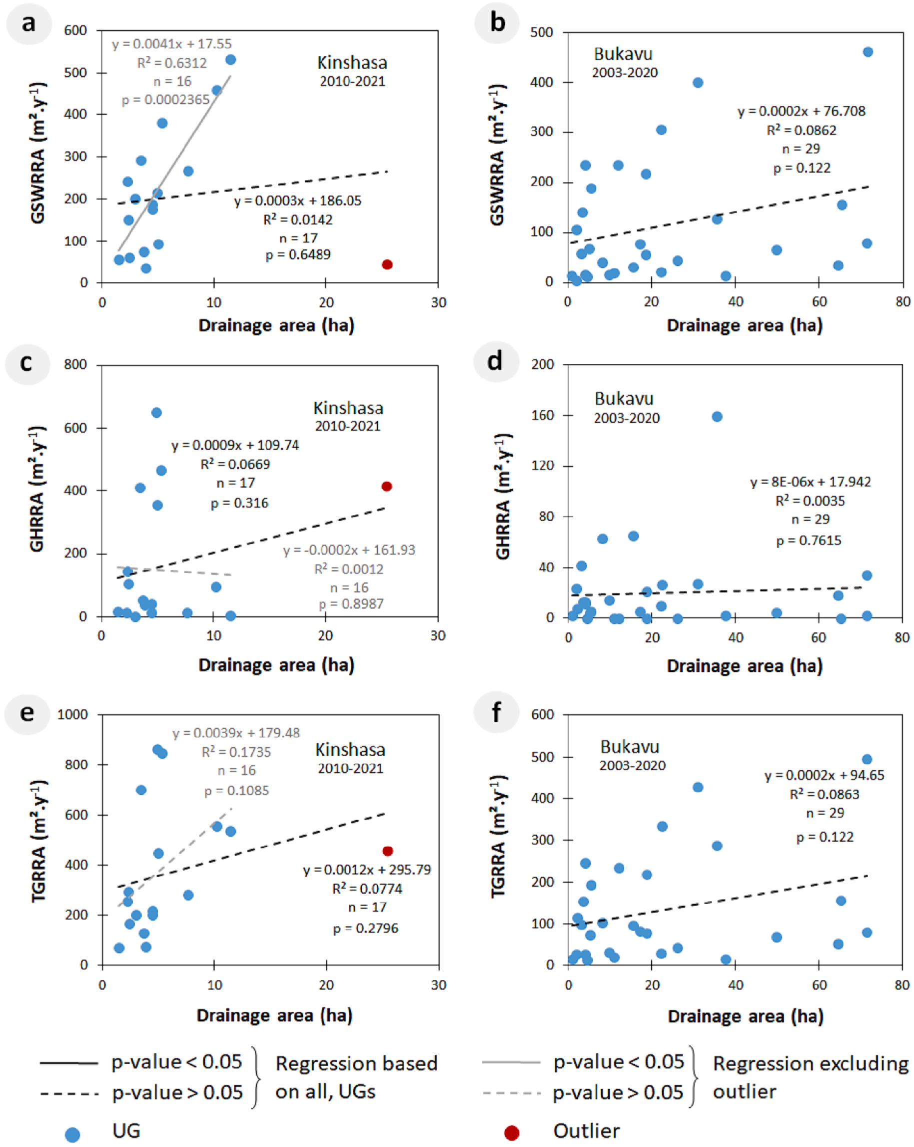

Fig. 6. Relationships between drainage area measured in the field and the urban gully (UG) expansion rate over the entire measuring period. GSWRRA: areal gully sidewall widening retreat rate. GHRRA: areal gully headcut retreat rate. TGRRA: total areal gully retreat rate. One point in Kinshasa (indicated in red) was considered to be an outlier (see text for further details). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4. Discussion

4.1. Rates, dynamics and mechanisms of urban gully expansion

As our calculated gully expansion rates are based on the visual interpretation of satellite images, they are evidently prone to uncertainties. These uncertainties are difficult to exactly quantify, but a comparison of mapping results by two separate mappers suggests relative errors of ca. 20 %. For some cases, the errors can be larger. Nonetheless, they remain limited when compared to the overall range of observed expansion rates (Fig. SI.2). This uncertainty is also comparable to that of other studies using aerial imagery to map gully extents in non-urban settings (e.g. Maugnard et al., 2014).

Overall our observed expansion rates are clearly higher than those of gullies in non-urban context. For example, based on a compilation of headcut retreat rates for > 900 gullies worldwide, Vanmaercke et al. (2016) report a median linear headcut retreat rate of 0.89 m/year and an areal headcut retreat rate of 3.12 m^2/year. Meanwhile, we observed a median GHRRL of 5 m/year and a median GHRRA of 52.4 m^2/year (Table SI.3) at Kinshasa. For Bukavu, the median headcut retreat rates are somewhat lower (median GHRRL: 1.1 m/year, median GHRRA: 9.8 m^2/year), but still larger than these global values. Yet, these values are likely no exceptions. For example, Makanzu Imwangana et al. (2015) already reported estimates of long-term (>10 year) retreat rates of up to 50 m/y in Kinshasa. Likewise, linear retreat rates of UGs in Butembo (D. R. Congo) are in the order of 10 m/y (Mahamba et al., 2023).

However, our results indicate that –at least in terms of areal expansion– gully sidewall widening is an even more important process than headcut retreat. This is in line with other recent studies, pointing to the relevance of this hitherto somewhat neglected process of gully expansion (e.g. Hayas et al., 2019). Also here, the widening retreat rates we observed in Bukavu and Kinshasa (Fig. 5) are generally above those reported for gullies in non-urban contexts (e.g. Martinez-Casasnovas, 2003; Frankl et al., 2011; Hayas et al., 2019). In addition, gully widening seems to have different temporal dynamics than headcut retreat. Whereas the latter tends to slow down in the last subperiod, gully widening rates remained consistently high over the three considered time periods in both Kinshasa and Bukavu (Fig. 5).

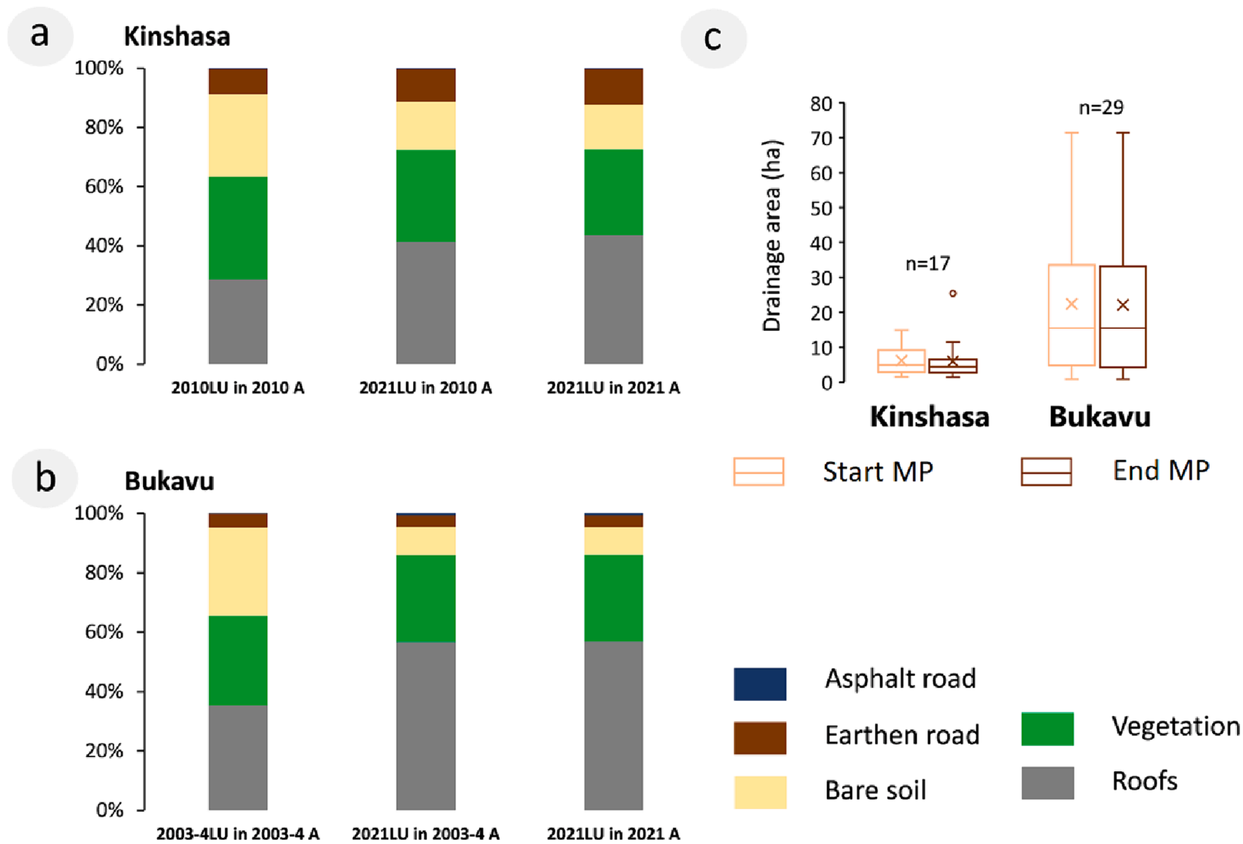

Fig. 7. Evolution in land use (LU) and gully drainage area (A) of the considered gullies over the entire measuring period (MP). **(a)** and **(b)** indicate the areal fraction of each land use type, measured over all urban gullies. **(c)** indicates the distribution of drainage areas at the start and end of the total MP. For Bukavu, the MP started in 2003/2004 and ended in 2020. For Kinshasa, the MP started in 2010 and ended in 2021.

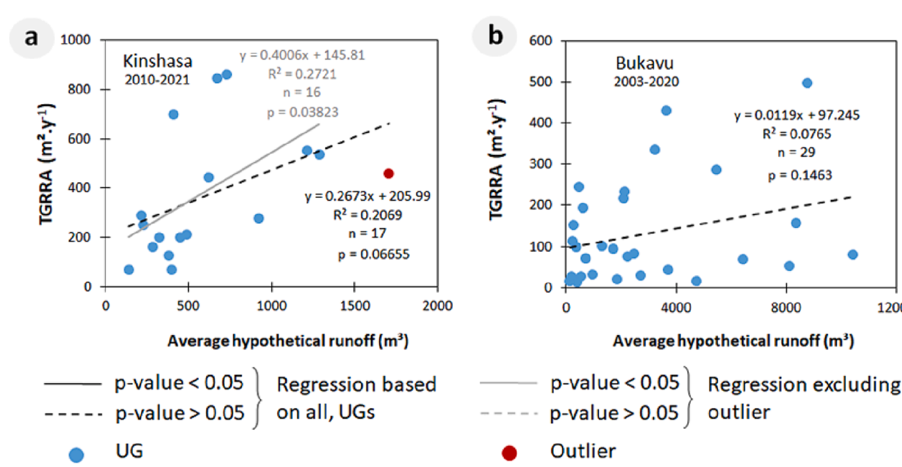

Fig. 8. Relationships between the average hypothetical runoff volume arriving at the gully head (Eq. (8) and the average total areal gully retreat rate (TGRRA) of the urban gully (UG) over the entire measuring period. One point in Kinshasa (indicated in red) was considered to be an outlier (see **section 3.2.1** for further details). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Several elements may explain these results. Both in urban and non-urban environments, gullies typically show the highest headcut retreat rates at the beginning of their life cycle and tend to stabilize over time (e.g. Nachtergaele et al., 2002; Makanzu Imwangana et al., 2015; Vanmaercke et al., 2016; Frankl et al., 2021). One reason for this is that, as a headcut retreats, its contributing area – and hence runoff supply to the gully head – typically decreases. Available information indicates that the majority of the UGs we studied were already 10–50 years old before the start of the measuring period (Table SI.1). As such, most of these gullies are likely already at a late stage of their life cycle. Furthermore, headcut retreat may come to a halt as a result of bedrock or other resistant layers in the soil profile. This was observed for at least some UGs in Bukavu (Fig. 2**c, 11**). In addition, stabilization measures are implemented at most of these gullies in an effort to prevent further damage and impacts (Makanzu Imwangana et al., 2015; Lutete Landu et al., 2023). Many of these efforts are concentrated at the gully head (Lutete Landu et al., 2023), which may further contribute to the observed decrease of headcut retreat rates.

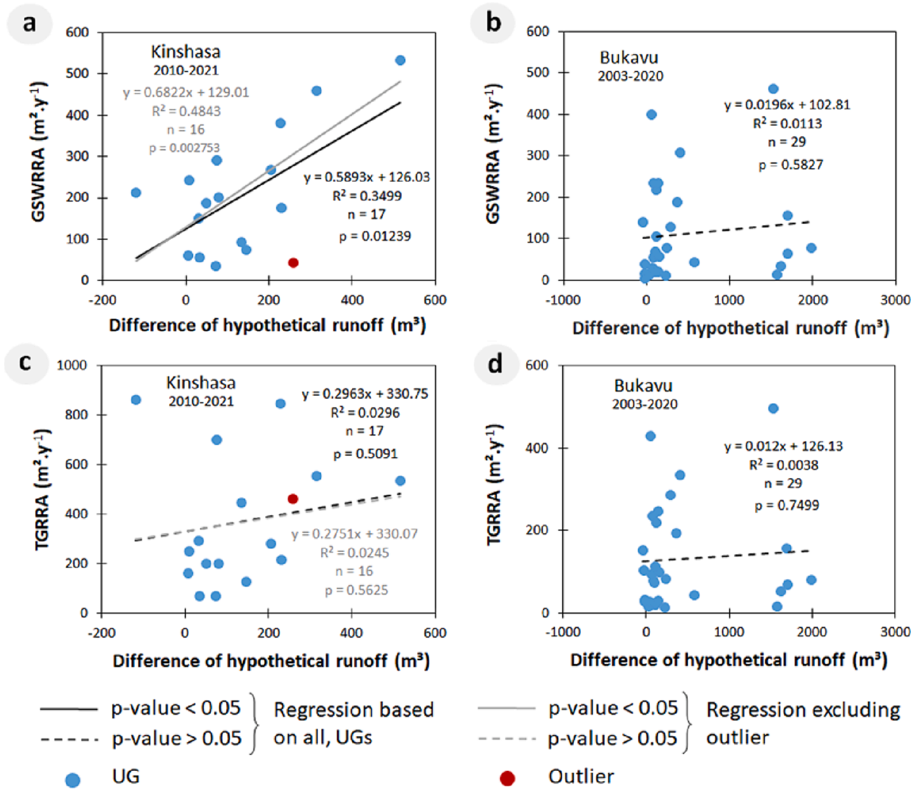

Fig. 9. Relationships between the difference in hypothetical runoff volume at the gully head (Eq. (9) and average expansion rate of the urban gully (UG) over the entire measuring period. GSWRRA: areal gully sidewall widening retreat rate; TGRRA: areal total gully retreat rate. One point in Kinshasa (indicated in red) was considered to be an outlier (see section 3.2.1 for further details). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

On the other hand, several elements may help explain the consistently higher gully widening rates (Fig. 5). In contrast to the gully head, the area draining to a given gully cross-section will not decrease. Hence, no negative feedback between gully width and runoff supply should be expected. Research in non-urban contexts further showed that the maximum width of a gully is likely in equilibrium with the largest peak discharges that pass through the gully channel (e.g. Hayas et al., 2019). As these peaks usually only occur during extreme rainfall events, it may take a long time before such equilibrium is attained. Continued urbanization, resulting in overall higher rainfall-runoff responses over time, may further postpone such equilibrium (Figs. 7, 9**a**). Likewise, the deepening of gully channels may contribute to further widening by increasing the rate of mass wasting processes acting on the gully walls (Hayas et al., 2019). Finally, as the length of the gully increases due to headcut retreat, so does the amount of sidewalls that may continue to expand. Hence, even if sidewall expansion slows down or stops at a given location, it may continue at another location along the gully walls. Given the large lengths of the UGs studied here (80.2–859 m; Table SI.1), this is likely a dominant feedback in explaining the importance of sidewall expansion: linear sidewall expansion rates are overall limited. However, the occurrence of this process along the whole gully length results in very significant areal sidewall expansion rates over the whole measuring period (Fig. 5).

4.2. Controlling factors of gully expansion

Variables relating to the slope steepness showed insignificant, mostly negative correlations with gully expansion (Fig. SI.5). This may be considered counter-intuitive as steeper slopes could result in faster runoff accumulation, higher flow shear stresses and hence a higher erosion potential (Ioniță et al., 2022; Vanmaercke et al., 2021). Nonetheless, various other studies have reported negative or insignificant correlations between topographic steepness and gully expansion (Vanmaercke et al., 2016). Also drainage areas showed only weak correlations with gully expansion rates (Fig. 6). Nevertheless, drainage area is often used as a predictor of gully expansion (e.g. Poesen et al., 2003; Vanmaercke et al., 2016; Hayas et al., 2019; Vanmaercke et al., 2021; Ioniță et al., 2022). This because drainage areas will directly influence the runoff volume that can potentially accumulate at a gully head. Both for drainage area and slope steepness, their effect is likely confounded by other factors that exert a larger control (Table SI.4 & SI.5).

In Kinshasa, this seems confirmed by the fact that our hypothetical runoff index (which integrates the effects of drainage area, soil type and land use; Eqs. (6)–(8)) shows a significant positive correlation with total gully expansion (at least, when removing the outlier; Fig. 8**a**). Interestingly, expected changes in this hypothetical runoff due to land use changes over the observation period also explain a significant proportion of the gully widening rates in Kinshasa (Fig. 9**a**). This indicates that the continued widening of gullies is indeed linked to further urban densification (Fig. 7**a**), resulting in overall higher runoff coefficients (cf. **section 4.1**).

Nevertheless, total road length explains an even higher proportion of the gully expansion rates in Kinshasa (Fig. 10). This is in line with earlier work, indicating that roads play a direct role in the formation of UGs (e.g. Makanzu Imwangana et al., 2014; 2015). Logically, total road length also showed strong intercorrelations to our hypothetical runoff index (Table. SI.4 & SI.5). Yet, this is not the case for road density, which likewise shows a significant albeit somewhat weaker correlation with total gully expansion (Fig. 10**e**). This suggests that roads may have an influence on gully expansion, beyond their overall high runoff coefficients (Table SI.2). While the total amount of runoff that arrives at a gully head will be influenced by the size and land use of the entire drainage area, unpaved roads likely play an additional important role as highly efficient runoff pathways. As such, a combination of both

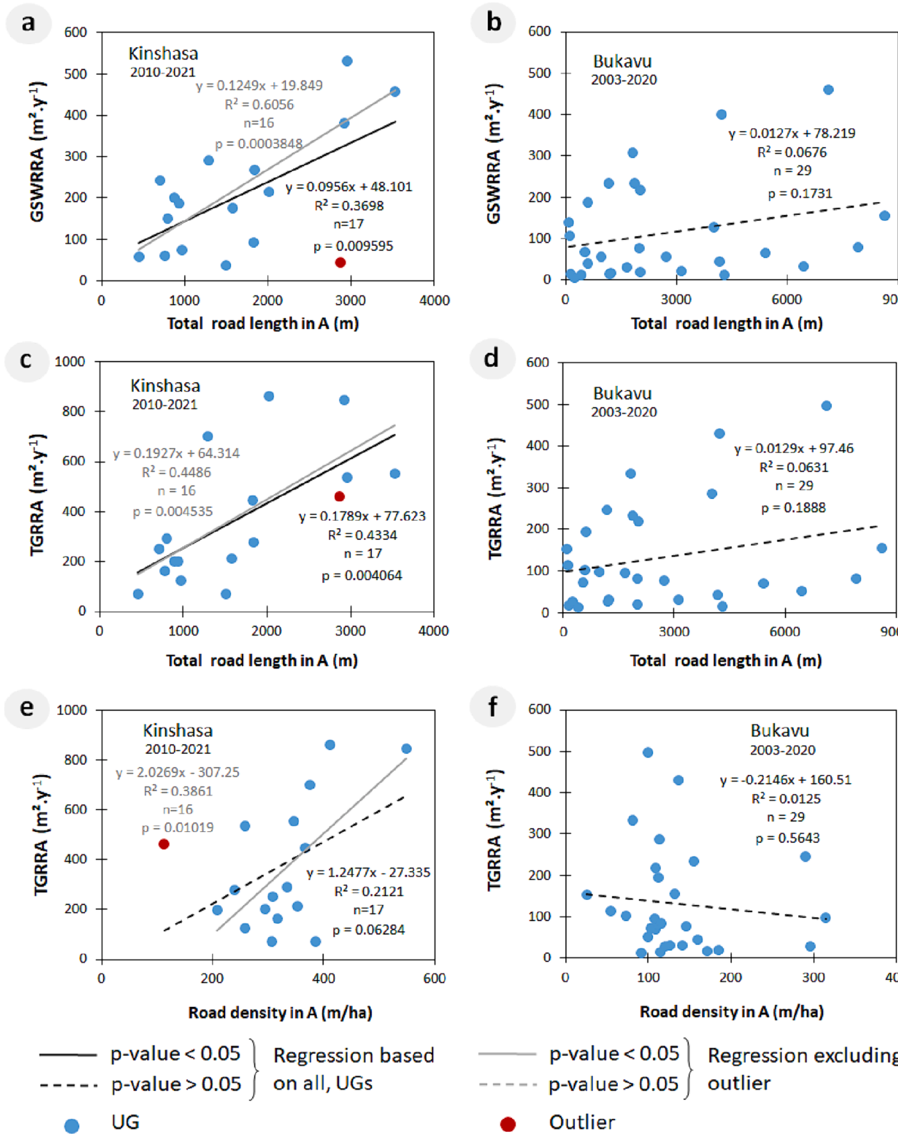

Fig. 10. Relationships between total road length or road density in the drainage area and urban gully (UG) expansion rate. GSWRRA: areal gully sidewall widening retreat rate; TGRRA: total areal gully retreat rate. One point in Kinshasa (indicated in red) was considered to be an outlier (see section 3.2.1 for further details). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

variables might potentially explain more of the observed variation in retreat rates. Unfortunately, our sampling size (n = 17, or 16 without outlier) was too small to provide statistical proof of this.

In Bukavu, however, both the hypothetical runoff volume (Fig. 8**b**) and road length (Fig. 10) show much weaker correlations with gully expansion rates. Uncertainties on both the expansion rates as well as the hypothetical runoff volumes may play a role here. Yet, we hypothesize that this is mainly attributable to soil characteristics. Whereas Kinshasa has highly erodible sandy soils, Bukavu is characterized by dominantly clayey soils. These are clearly more resistant to erosion, which is evident from the overall gully expansion rates (Fig. 5). In addition, these clayey soils can be expected to have overall much higher runoff coefficients, regardless of their land use (Table SI.2). Hence, unlike the sandy context of Kinshasa, a densification of the urban area (Fig. 7**b**) does not necessarily translate into a strong increase in runoff and –subsequently– an increase in gully expansion rates (Fig. 9).

Apart from these differences in erodibility and runoff productions, the soils in Bukavu are also characterized by a larger heterogeneity. One striking result is that UGs located in recent landslides have much higher gully expansion rates (Fig. 11). This can likely not be attributed to age effects, as these gullies have an overall similar age range as those in (very) old landslides or none-landslide areas (Table SI.1). In some cases, the gully may even predate the recent landslide (Dewitte et al., 2021). Interestingly, the expansion rates of these gullies in recent landslides also show positive correlations with hypothetical runoff volume and total road length (Fig. 11). We hypothesize that the materials of recent landslides are less compacted and therefore more apt to be eroded. Also in non-urban contexts, extensive gullies can form in earthflows and landslides (e.g. Wieczorek, 1984; Turner & Schister, 1996; Mackey and Roering, 2011; Kubwimana et al., 2021; Belayneh et al., 2022). A relevant implications of this process combination is that UGs can potentially destabilize hillslopes and (re)activate landslides. For example, they can undercut hillslopes or reroute and concentrate runoff, leading to significant changes in subsurface hydrology (Dille et al., 2022). Nevertheless, these interactions between landsliding and gullying remain poorly understood and warrant further research (Poesen, 2018).

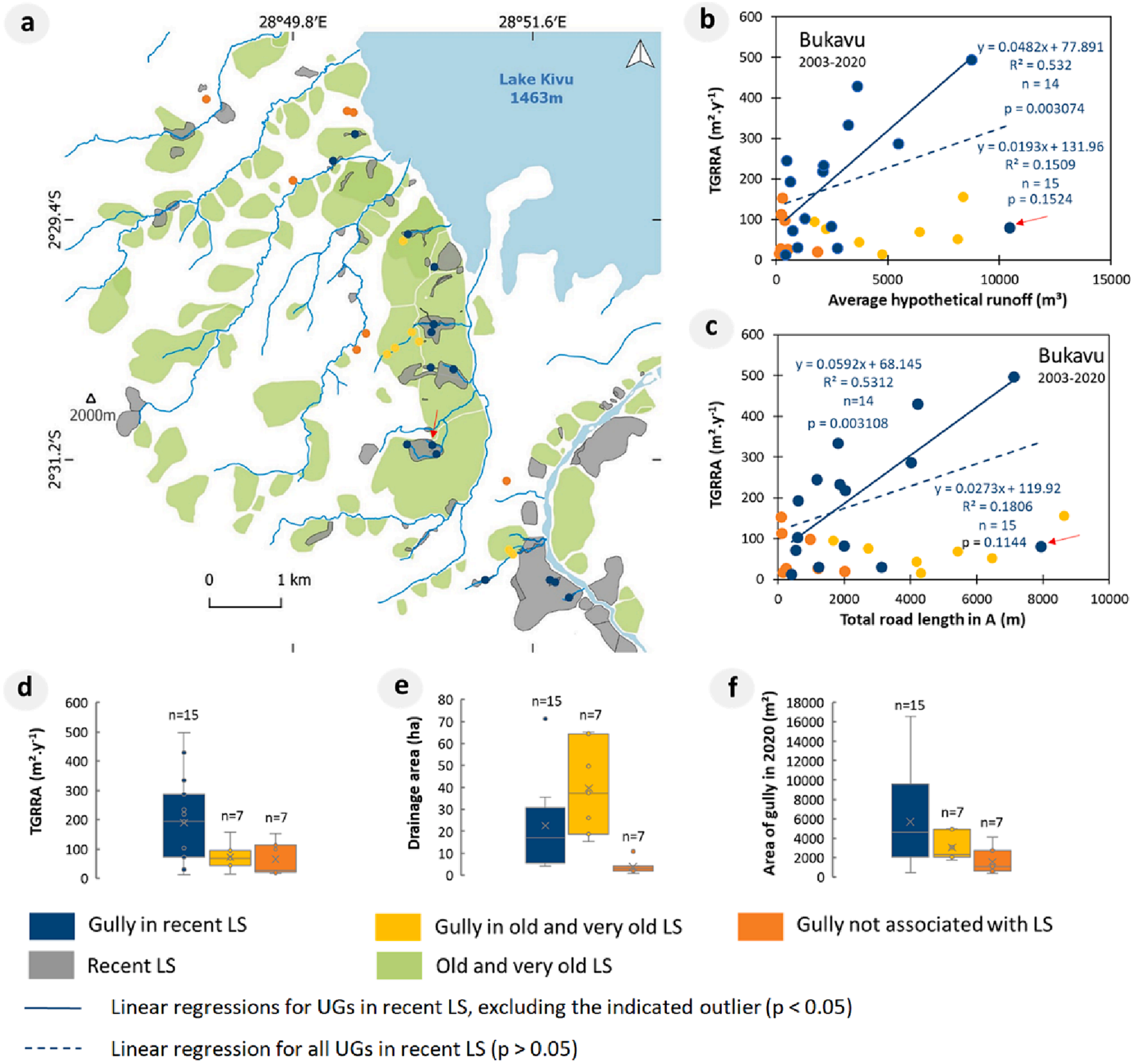

Fig. 11. The effect of landslides (LS) and other factors on total areal gully retreat rate (TGRRA) for urban gullies (UGs) in Bukavu. (a) Map of the selected UGs with respect to mapped (very) old and recent landslides (derived from Dewitte et al., 2021). (b) and (c) indicate the relations between TGRRA and average hypothetical runoff volume and total road length in the drainage area. (d), (e) and (f) indicate the distributions of TGRRA, drainage area and gully size in 2020, subdivided by whether the gully is located in a recent landslide, a (very) old landslide or in a non-landslide area. The red arrow indicates an outlier (see text for details). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4.3. Implications and scopes for model development

Overall, our results demonstrate the complexity of gully expansion in urban environments. Yet, they also open promising perspectives to better simulate this process and its interaction with both natural and anthropogenic factors. In the homogeneous sandy soils of Kinshasa, a significant proportion of the observed variability can be explained by characteristics of the road network and (changes in) land use. As such, simple estimates of runoff based on the rationale method (cf. Eqs. (6)–(8)) provided encouraging results, given the clearly data-poor contexts in which UGs typically occur. Evidently, this index can be improved in various ways. In particular by: (i) further finetuning and validating the assigned runoff coefficients (Table SI.2), (ii) better integrating the different effects of roads (i.e. as surfaces producing runoff, but also as pathways that facilitate runoff concentration and as features that modify the shape and size of drainage areas); (iii) accounting for the actual rainfall conditions, rather than assuming a hypothetical value; and (iv) incorporating the potential effect of rainwater storage facilities (e.g. retention basins, water tanks) that may reduce runoff accumulation (Lutete Landu et al., 2023). Also in more complex contexts like Bukavu, proxies like road length and hypothetical runoff have significant potential. Nonetheless, in these contexts, contrasts in soil conditions and especially interactions between UGs and landslides will need to be accounted for as well.

One important bottleneck in the development of tools and models that can predict the formation and expansion of UGs is accurately assessing the drainage area of (potential) UGs. While the size of drainage area itself only showed weak to moderate correlations with gully expansion rates (Fig. 6), delineating this area remains critical to quantify the land use, road length/density and runoff production of the catchment draining to the gully. Earlier research demonstrated that changes in drainage area due to urbanization and road construction can play a direct role in the initiation of UGs (e.g. Carvalho Junior et al., 2010). Yet, even with high resolution DSMs, automatically delineating drainage areas is highly challenging. In our case, we observed very large contrasts in the drainage areas obtained from 1-5 m DSMs and those obtained in the field (cf. Fig. SI.3 & SI.4). These differences were even larger when using a 30-m resolution DSM, which are often the only DSM available for the Global South (Vanmaercke et al., 2021). These deviations result from the complexity of roads and other factors that may influence the drainage area. Moreover, our fieldwork indicated that drainage areas can drastically change over time due to, for example, temporal blockages and deviations (e.g. Fig. 6, A.7). Such erratic changes are very hard to account for, but also deviate from the often implicit assumption that the topographic contributing areas of gullies are constant (e.g. Torri & Poesen, 2014; Vanmaercke et al., 2021). As such, there is a need for strategies and methods that allow characterizing the contributing areas of UGs in more accurate and robust ways. Overall, these findings also demonstrate the relevance of detailed field observations when aiming to understand gully expansion rates, especially in complex urban settings. Finally, as many other studies (e.g. Torri & Poesen, 2014; Vanmaercke et al., 2016; 2021), our work only focussed on the drainage area at the gully head. This makes sense for gully headcut retreat. However, gully widening may also be partially driven by runoff coming from areas downslope of the gully head. We therefore recommend to also include the total contributing area (measured at the outlet of the gully) in future analyses.

4.4. Implications for prevention and mitigation

Both in Kinshasa and Bukavu, the overwhelming majority (>85 %) of UGs already has one or more control measure implemented, aiming to stabilize the gully. Yet, most of these measures appear to have only a very limited effect (Lutete Landu et al., 2023). Our findings may help in better understanding why this is the case. For example, many of these control measures aim at stabilizing the gully head (e.g. by reinforcing it with concrete). In many cases, this may be necessary as rapid gully head retreat can clearly wreak havoc. Yet, our results indicate that gully widening may often be a much more persistent problem. While linear rates of gully widening are overall slower than gully headcut retreat, their areal rates are clearly higher and tend to continue over longer time periods (Fig. 5). Given that most UGs form along the trajectory of roads with people living at both sides, large numbers of people may be directly affected by the impacts of gully widening (Ilombe Mawe et al., 2022; Lutete Landu et al., 2023). Stabilizing the gully sidewalls over their whole length is therefore often a necessity. Yet, this may require significantly more efforts than only stabilizing the gully head, especially given that many of these gullies regularly develop to lengths of > 1 km (Lutete Landu et al., 2023). This emphasizes the need to intervene rapidly, once a gully is formed. Further gully headcut retreat may not only cause more damage, but also make it more difficult to stop gully widening.

Furthermore, our results demonstrate that expansion rates of UGs are clearly linked to the runoff production in their upstream drainage area. The latter is linked to the land use in these areas. For example, we demonstrated that gully widening rates in Kinshasa are likely linked to the densification of housing in these areas (Fig. 9**a**). This is important to consider as urbanization and the impervious areas in Congolese cities is expected to further increase in the future (World Bank Group, 2021). It is likely here that the most promising strategies to prevent and stabilize UGs can be found, e.g. by implementing initiatives that trap runoff on individual plots rather than allowing runoff to flow towards roads (Lutete Landu et al., 2023). However, our results further demonstrate that also foreseeing and maintaining proper road drainage infrastructure will be essential in this regard (Figs. 10, 11 **&** A.7; Makanzu Imwangana et al., 2014, 2015; Lutete Landu et al., 2023).

5. Conclusions

By combining visual analyses of optical satellite images with field observations and simple empirical modelling strategies, this study provides insights into the dynamics and controlling factors of urban gully expansion in the tropical Global South.

Overall, the studied gullies expand more rapidly than gullies in non-urban environments. Most of this expansion happens through gully widening, rather than through headcut retreat. This has important implications for disaster risk reduction, as urban gully expansion often comes with severe impacts (e.g. the destruction of houses). Yet, efforts aiming to stabilize urban gullies often only concentrate on the gully head.

In Kinshasa, which is mainly characterized by sandy soils, expansion rates mainly correlate to estimated runoff production and upslope road length. This demonstrates a strong anthropogenic control on gully expansion rates. These trends are less apparent in Bukavu, which is likely attributable to soil and lithological characteristics. Due to their clayey nature, soils in Bukavu are more resistant to gullying. Furthermore, these soils are already by nature more likely to produce runoff. This may make the relative impact of urbanization smaller. In this setting, the most actively retreating gullies occurred in recent landslides. The mechanisms behind this are not yet fully understood and warrant further research. Especially since important interactions between (urban) gullying and landslides may exist.

Our work also demonstrates that it may be possible to simulate and predict average urban gully expansion rates, taking into account problems of data scarcity. Future studies may further improve our hypothetical runoff approach by integrating actual rainfall data as well as better incorporating the effects of roads. Yet, a critical factor in such modelling exercise is correctly delineating the area that drains to a gully. Field verification and/or more robust methods than traditional flow routing algorithms will be essential in this.

CRediT authorship contribution statement

Guy Ilombe Mawe: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Eric Lutete Landu:** Writing – original draft, Methodology, Data curation. **Fils Makanzu Imwangana:** Writing – original draft, Supervision, Resources, Project administration, Funding acquisition. **Aurélia Hubert:** Writing – original draft, Supervision, Project administration. **Antoine Dille:** Writing – original draft, Visualization, Data curation. **Charles L. Bielders:** Writing – original draft, Methodology, Investigation, Funding acquisition, Conceptualization. **Jean Poesen:** Writing – original draft, Supervision, Funding acquisition, Conceptualization. **Olivier Dewitte:** Writing – review & editing, Writing – original draft, Supervision, Resources, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Matthias Vanmaercke:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.catena.2024.108055.

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