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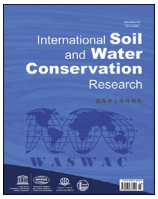

Original Research Article

Effectiveness of measures aiming to stabilize urban gullies in tropical cities: Results from field surveys across D.R. Congo

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ABSTRACT

Urban gullies are a rapidly growing concern in many tropical cities of the Global South. Various measures are already implemented for their stabilization. However, an overview of these measures and their overall effectiveness is currently lacking. We aim at addressing this gap by documenting existing initiatives to stabilize urban gullies in D.R. Congo and assessing their overall effectiveness. To this end we conducted extensive field campaigns in Kinshasa, Kikwit and Bukavu and combined our terrain observations with data on gully expansion rates (derived from series of satellite imagery). In total, we characterized present and past stabilization initiatives for 398 urban gullies. For 69 of these gullies, the effect of a specific measure on gully expansion rates could be estimated. Results show that for the large majority of gullies, various measures have been implemented. Yet, these are mainly ad-hoc measures installed by the affected population. More structural measures based on larger engineering works were observed for only 20–30% of gullies. The huge efforts invested in the installation of measures strongly contrast with their overall low impact. Among all strategies, only the deviation of runoff resulted in significantly lower expansion rates after installation. The numerous initiatives that rely on the sparse means available seem to have limited effects. This does not imply, however, that they are completely ineffective and should be abandoned. Based on our findings, we formulate recommendations for further research on how to effectively prevent and stabilize urban gullies, taking into account the difficult environmental and socio-economic context.

1. Introduction

In many regions worldwide, gully erosion is an important environmental concern (e.g. Poesen et al., 2003; Valentin et al., 2005; Vanmaercke et al., 2011; Vanmaercke et al., 2021). Stabilizing active gullies is often a major challenge, with many of the implemented measures failing or showing only a limited effectiveness (e.g. Bartley et al., 2020; Frankl et al., 2021). Overall, gully erosion and its mitigation is controlled by a wide range of biophysical factors (e.g. Adediji et al., 2013; Bartley et al., 2020; Pathak et al., 2005, p. 28; Poesen et al., 2003; Vanmaercke et al., 2021). As such, these processes have been studied across various environments (e.g. Torri & Poesen, 2014; Castillo & Gómez, 2016). Yet,

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despite their often important impacts, gullies in urban contexts have clearly received much less research attention (e.g. Castillo & Gómez, 2016; Poesen, 2018; Bartley et al., 2020; Frankl et al., 2021; Vanmaercke et al., 2021).

Especially in many tropical cities of the Global South, urban gullies are a growing concern (Adediji et al., 2013; Dos SantosRotta & Zuquette, 2014; Gudino-Elizondo et al., 2022; Guerra et al., 2006; Kayembe Wa Kayembe & Wolff, 2015; Makanzu Imwangana et al., 2014, 2015; Wouters & Wolff, 2010). They typically result from a combination of intensive rainfall, erodible soils, hilly topography, inappropriate drainage infrastructure and/or a lack of spatial and urban planning (De Albuquerque et al., 2020; Gudino-Elizondo et al., 2022; Kayembe Wa Kayembe & Wolff, 2015; Makanzu Imwangana et al., 2014; Zolezzi et al., 2018). Given their typically large sizes (e.g. Makanzu Imwangana et al., 2015), rapid expansion rates (Vanmaercke et al., 2016) and locations in densely populated areas, urban gullies often claim casualties and cause significant destruction of private property, roads, utility lines, sewerage, and other infrastructure (Fig. 1; Balzerek et al., 2003, pp. 94–109; Junior et al., 2010; Dos SantosRotta & Zuquette, 2014). Furthermore, they result in a plethora of associated problems, e.g. the displacement of households, increased poverty and social insecurity, reduced sanitary conditions and impeded traffic (Pathak et al., 2005, p. 28; Dos SantosRotta & Zuquette, 2014). While these impacts currently remain poorly quantified, it is clear that urban gullies already pose a significant threat to hundreds of thousands, if not millions, of people (Ilombe Mawe et al., 2021; Zuquette et al., 2013). These impacts are also likely to strongly aggravate over the next decades as a result of continued rapid urban expansion in sub-Saharan Africa (United Nations department of economic and social affairs population division, 2015; Vermeiren et al., 2016) and expected increases in rainfall intensity (e.g. Hayas et al., 2017, 2019; Polade et al., 2014; Vanmaercke et al., 2016).

One country that is particularly affected by urban gullies is the Democratic Republic of Congo (DRC; Ilombe Mawe et al., 2021). Especially in Kinshasa, urban gullies pose a significant and growing threat (Makanzu Imwangana et al., 2015, Fig. 1). Numerous measures and initiatives have already been implemented from the 1990s onwards to stop their formation and expansion (BTC-CTB, 2007; Kayembe wa Kayembe, 2020; Miti & Aloni, 2005; Wouters & Wolff, 2010; Zolezzi et al., 2018). These initiatives vary greatly in concept, location with respect to the gully and scale. Some can be considered preventive, as they are installed in the catchment draining to the gully with the aim of limiting the peak runoff discharges reaching the gully (Dos SantosRotta & Zuquette, 2014; Rey et al., 2019; Bartley et al., 2020; Frankl et al., 2021). Others can be characterized as 'curative' stabilization measures as they are installed at the gully head or in the gully channel, seeking to prevent further expansion (Bartley et al., 2020; Frankl et al., 2021; Makanzu Imwangana et al., 2014). Some measures rely on 'hard' engineering techniques (e.g. using concrete walls), while others are based on revegetation (Ndona, Truong, & Rachmeler, 2006; Dos SantosRotta & Zuquette, 2014). Likewise, several interventions are the result of large (expensive) mitigation and remediation programs (Miti & Aloni, 2005). Others are the result of 'ad-hoc' initiatives of the threatened population, using locally available means such as sand bags, vegetation, plastic sheets, waste material, car tires or polyethylene bags. Yet, many initiatives seem to fail. Makanzu Imwangana et al. (2015) estimated that, despite implemented measures, around 50% of the urban gullies in Kinshasa continued to expand over their observation period (1957–2010). Considering the tremendous impacts of urban gullies, but also the high costs of gully stabilization programs, there is an urgent need to better understand the effectiveness of measures taken, so that viable and sustainable strategies can be identified.

Nonetheless, such insights are currently largely lacking for several reasons. First, gully erosion in urban environments has clearly received relatively little research attention (e.g. Zolezzi et al., 2018; Poesen, 2018; Bartley et al., 2020; Frankl et al., 2021). Second, most urban gully stabilization initiatives are carried out on an isolated basis, not clearly documented and not evaluated afterwards. Third, assessing the effectiveness of measures is often difficult because gully erosion is typically a very episodic process whereby long phases of stability can be interrupted by sudden expansions due to extreme rainfall events (e.g. Hayas et al., 2017). As such, the success of gully control measures can often only be robustly evaluated after many years (Vanmaercke et al., 2021). Finally, most stabilization efforts consist of a variety of measures, while also other (changes in) environmental factors influence gully dynamics. This makes it difficult to directly quantify the effect of a specific measure on the stability of a gully.

Hence, this study aims to contribute to a better understanding of control measures that are implemented to stabilize urban gullies in DRC. Our specific objectives are: (i) to present an overview of currently implemented measures based on a systematic and field-based documentation of such measures in three representative cities; and (ii) to estimate the overall effectiveness of these measures by exploring their effect on the long-term gully expansion rates.

2. Materials and methods

2.1. Study area

The research was conducted in Kinshasa, Kikwit and Bukavu (Fig. 2). These three cities have a tropical savanna (Aw) climate (Beck et al., 2018) with an average annual rainfall of ~1500 mm and

Fig. 1. Example of a new gully head that formed on the earlier existing "Laloux" gully in Kinshasa and destroyed several houses. **(a)** terrestrial photo of the gully head (November 2019). **(b)** aerial view of the same gully head (Google Earth, April 2019).

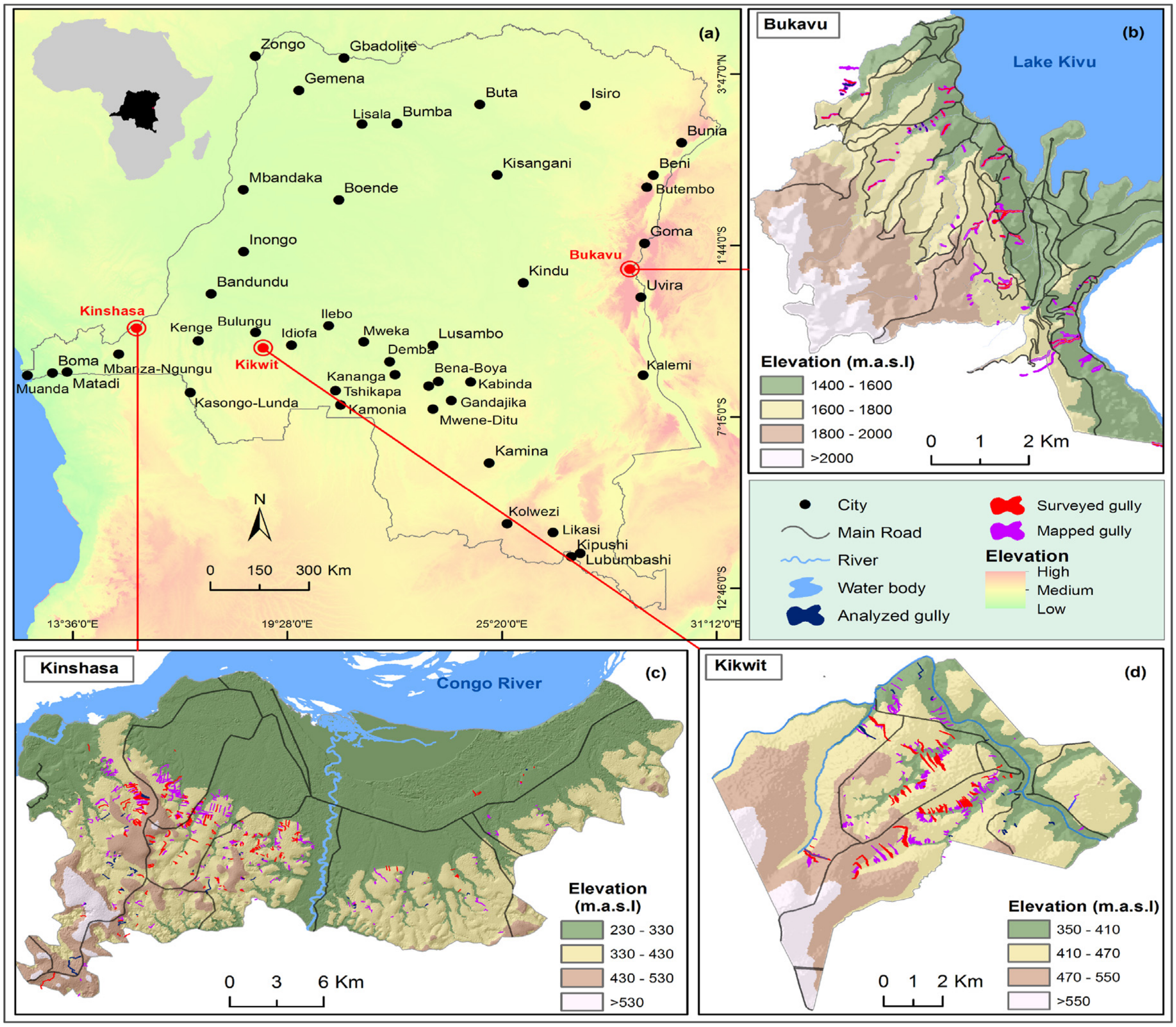

Fig. 2. **(a)** Location of the three studied cities (Kinshasa, Kiwit and Bukavu) within D.R. Congo. The insets (**b**, **c** and **d**) show the spatial extent and topography of each city. Polygons in these insets correspond to urban gullies that were mapped via satellite imagery ('mapped'), mapped and surveyed in the field ('surveyed'), or mapped, surveyed and analyzed to determine retreat rates before and after implementation of gully control measures ('analyzed').

a dry season lasting three to four months (June–September).

Kinshasa, with an estimated population of 10.6 million inhabitants (Bédécarrats et al., 2016), has an area of ~1200 km^2 and is located at an altitude of 300–675 m a.s.l. The soils are sandy and can be characterized as Arenosols (Jones et al., 2013; Lateef et al., 2010). The lowest part of the city corresponds to a flat plain where the older districts are located. Most of the (typically anarchic) post-independence expansion of the city occurred in the hilly areas (Bédécarrats et al., 2016; Lasserre, 1979). It is here that most of the gullies occur (Makanzu Imwangana et al., 2015; Wouters & Wolff, 2010). Overall, the city is severely affected by gullying with several hundreds of urban gullies observed (Wouters & Wolff, 2010; Makanzu Imwangana et al., 2015; Kayembe wa Kayembe, 2020). These gullies are typically very large in size, often reaching widths of >30m, depths of >10 m and lengths of several hundreds to thousands of meters (Makanzu Imwangana et al., 2015). While some of these gullies are already several decades old (Makanzu Imwangana, 2014, p. 209; Van Caillie, 1989), the rapid and anarchic urbanization continues to lead to the formation of new urban gullies, especially in peri-urban zones (e.g. Sambiéni et al., 2018).

Kikwit has a population of ~500,000 inhabitants (Tatem, 2017). The town has an area of ca. 90 km^2 and is located on the Kwango Plateau, which mainly consists of sandstones and argillites (Linol et al., 2015). The weathering of this material results in sandy regolith and Ferrasols (Jones et al., 2013) with a clay content that is typically higher than in Kinshasa (Moeyersons et al., 2015). Due to the plateau context (ca. 470 m a.s.l.), large parts of the city are relatively flat. Yet, this plateau is incised at some places, leading locally to very steep slopes. It is mainly on these slopes that urban gullies occur. These can be very large, reaching sometimes depths of 30–40 m and widths of >60m (Salomon, 1997).

Bukavu is located in eastern DRC at an altitude of around 1700 m a.s.l.. It has a surface area of ca. 60 km^2 and an estimated population of nearly one million inhabitants (Michellier, 2017; Tatem, 2017). The city has a hilly landscape and is built on weathered lavas of Late Miocene to Pleistocene origin (Moeyersons et al., 2004; Pouclet et al., 2016). The weathering of these lavas is highly variable. Regolith thickness can vary from a few centimeters to >10 m along the same slope profile (Dille et al., 2019). The dominant soils are clayey Nitisols that developed on this regolith (Jones et al., 2013; Moeyersons et al., 2004). While common and often linked to the steep terrain context, urban gullies in Bukavu are typically somewhat smaller than in Kinshasa and Kikwit. This is likely attributable to the clayey soils and the irregular depth of the regolith. The presence of large landslides (covering more than 20% of the urban area) can locally favor the development of gullies (Dewitte et al., 2021).

2.2. Methods

2.2.1. Inventory of urban gullies

As a first step, we created comprehensive spatial-temporal inventories of urban gullies in the three cities. For Kinshasa, this was done by building on an earlier mapping of urban gullies that were formed during the period 1957–2010 (Makanzu Imwangana, 2014, p. 209). We updated and completed this inventory by mapping the extent of urban gullies, using available very high-resolution Google Earth imagery for the years 2002, 2004–2006, and 2008–2020. For Kikwit, no previous mapping was available. As such, the spatial extent of all visible urban gullies was mapped using Google Earth imagery with images from 2004, 2011, 2012, and 2015–2020. For Bukavu, we started from a field-based mapping conducted by Nshokano Mweze (2015) and updated and completed this, using Google Earth imagery from 2003 to 2004, 2010–2014, and 2017–2020. Urban gullies in Bukavu were generally smaller and more difficult to map as compared to those in Kikwit and Kinshasa. We therefore verified the most recent extent of 39 gullies in the field and corrected where necessary. For the three cities, Pléiades images from 2014 to 2015 were used as orthorectified reference supports. The Pléiades satellites (Pléiades 1A and 1B) are two of the latest generation satellites that produce images at very high resolution (0.5 m for Panchromatic images and 2 m for four multispectral bands; Stumpf et al., 2014).

Overall, these inventories provide a comprehensive overview of (recent and old) urban gullies in Kinshasa, Kikwit and Bukavu. Yet, the observation periods and number of moments for which the gully limits could be delineated varied strongly, depending on the age of the gully and the available imagery.

2.2.2. Field surveys

Taking into account time, security and accessibility constraints, a representative selection of gullies (in terms of gully ages and sizes) was visited in the field between December 2019 and April 2020. These field surveys were conducted to obtain more information on the expansion history of the gullies as well as to document (past and current) gully control measures. Data were collected based on direct terrain observations as well as by interviewing knowledgeable persons living near the gullies. These included local community leaders, people directly involved in the implementation of measures and people (at risk of) being affected by the gully. The data were registered using the KoboCollect tool (KoBoToolbox, 2022; Lakshminarasimhappa, 2021), which allowed to systematically record all relevant information.

With respect to the expansion history, we aimed to determine the age of each gully (i.e. the initiation date) and its most recent activity. If the gully was recently active, we tried to reconstruct as precisely as possible the different expansion phases. This was mainly done by inquiring about previous positions of the gully head and gully width as well as dates of significant expansion. Evidently, such testimonies are subject to uncertainties. However, given the drastic expansion rates of most gullies (with linear retreat rates often exceeding 50 m during one large rainfall event) and the significant impacts they have (e.g. the destruction of houses), it can be expected that the acquired information was sufficiently reliable to reconstruct at least major phases of gully expansion. Studies in other contexts have also shown the value of such interviews when reconstructing gully dynamics (e.g. Nyssen et al., 2006).

For documenting gully control measures, we differentiated between measures present in the gully channel or at the gully head, measures present in the area draining to the gully channel, and measures that were previously applied but were destroyed by subsequent phases of gully expansion. Information about measures was obtained through a combination of direct field observations and interviews. For each of the implemented measures, we recorded the type and exact location of the measure, the date when the measure was implemented, the date when the measure was destroyed (if applicable), information on who implemented the measure and its estimated cost as well as photographs and information on the dimensions and state of the measure. For several measures, these collected data were subject to some uncertainties and/or incomplete. In addition, some measures may have remained unrecorded; especially destroyed measures or smaller measures implemented further upstream in the drainage areas (which often cover several hectares; Makanzu Imwangana et al., 2015). Nonetheless, we are confident that our inventory provides a representative sample of measures that are currently implemented.

2.2.3. Estimating the effectiveness of implemented gully control measures

We assessed the overall effectiveness of implemented measures by estimating their effect on the Linear Retreat Rates (RRL, [m/y]) and areal or Surfacic Retreat Rates (RRS, [m^2/y]) of gullies. For this, we compared the retreat rate before the measure was installed with the retreat rate after installation. Below, we explain how we did this for RRS. For RRL the calculations were analogous, but instead of the surface area of a gully at a given moment (S_i) we used its length measured along the thalweg (Fig. 3).

The average surfacic retreat rate before the measure was installed (RRS_b, [m^2/y]) could be approximated as:

$$RRS_{b,approx} = \frac{S_2 - S_1}{T_2 - T_1} \qquad \text{(Eq. 1)}$$

with S_1 the surface area [m^2] of the urban gully at the oldest date for which this could be determined (T_1). T_2 is the date that is as close as possible to the installation date of the considered measure (T_M) and for which the surface area (S_2) of the gully could be determined. Similarly, the average surface retreat rate after the measure was installed (RRS_a, [m^2/y]) was approximated as:

$$RRS_{a,approx} = \frac{S_3 - S_2}{T_3 - T_2} \qquad \text{(Eq. 2)}$$

with S_3 the surface area of the gully [m^2] at the most recent date for which this could be determined (T_3). S_1, S_2 and S_3 were derived from the polygons mapped from very high resolution satellite imagery (cf. section 2.2.1). As such T_1, T_2 and T_3 (and by consequence S_1, S_2 and S_3) are largely determined by the availability of imagery. Where possible, these data were complemented with information collected during the field surveys (cf. section 2.2.2). For example, in some cases, the exact formation date of a gully could be determined. In such a case, T_1 corresponds to this initiation date and S_1 was set to the size right after the initiation event.

If the difference between the date that the measure was installed (T_M) and the nearest date for which the extent of the gully could be determined (T_2) is small, equations (1) and (2) give good approximations for the retreat rates before and after measure installation. However, as this time difference increases, this can lead to significant over- or underestimations. We therefore modified Eqs. (1) and (2) to correct for this effect (cf. Fig. 3). In cases where $T_M < T_2$, we calculated the retreat rate before the measure (RRS_b) as:

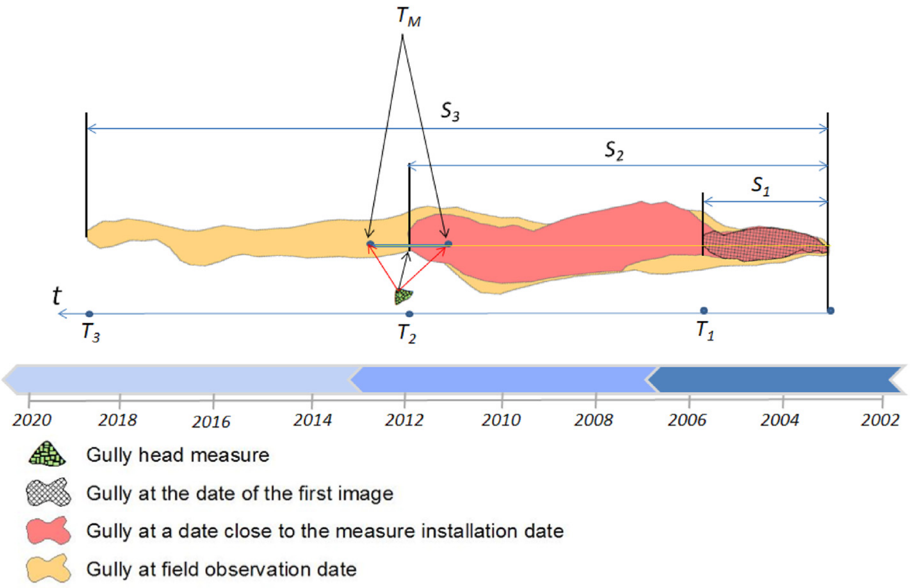

Fig. 3. Methodology of calculation the gully retreat rate before and after a control measures was installed (see Eqs. (1)–(6)). S_1, S_2, S_3 are respectively the surface area of the gully at the oldest date (T_1), at a date as close as possible to the installation date of the measure (T_M), and at the most recent date for which the gully extent could be determined (T_3).

$$RRS_b = \frac{\left(S_2 - RRS_{b,approx} \times \Delta t\right) - S_1}{T_M - T_1} \qquad \text{(Eq. 3)}$$

with Δt the absolute time difference between T_M and T_2 (i.e. $|T_M - T_2|$). In cases where $T_M > T_2$, RRS_b was calculated as:

$$RRS_b = \frac{(S_2 + RRS_{a,approx} \times \Delta t) - S_1}{T_M - T_1} \qquad \text{(Eq. 4)}$$

Correspondingly, in cases where $T_M < T_2$, the retreat rate after measure installation (RRS_a) was calculated as:

$$RRS_a = \frac{S3 - \left(S_2 - RRS_{b,approx} \times \Delta t\right)}{T_3 - T_M} \qquad \text{(Eq. 5)}$$

In cases where $T_M > T_2$, RRS_a was calculated as:

$$RRS_a = \frac{S3 - (S_2 + RRS_{a,approx} \times \Delta t)}{T_3 - T_M} \qquad \text{(Eq. 6)}$$

Evidently, the accuracy and robustness of these quantifications (Eqs. (3)–(6)) is better if Δt is small and if T_2-T_1 and T_3-T_2 are large. For the latter two, we considered a minimum period of one year. Overall, Δt varied between 0.1 and 5.5 years (average 0.7 years). T_2-T_1 varied between 1.0 and 13.9 years (average 5.6 years), while T_3-T_2 varied between 1.1 and 11.9 years (average 4.8 years).

The overall effectiveness of a certain type of measure was then evaluated by comparing the distributions of RRS_b and RRS_a across gullies where the measure was installed. Since retreat rates were generally not normally distributed, the significance of observed differences was tested through non-parametric paired-samples Wilcoxon tests.

It should be noted that this approach comes with limitations, as also other factors may influence these retreat rates (e.g. rainfall dynamics, topography, characteristics of the contributing area and the presence of other measures). Hence, caution in the interpretation of these results is required. Furthermore, some initiatives not only involved the installation of a specific control measure but also the infilling of at least part of the gully. In some cases, this resulted in negative RRS_a values. To allow comparison, we assumed RRS_a to be zero in such cases.

3. Results

3.1. Overview of the collected data

In total, we mapped 934 individual urban gullies, comprising a total area of 610.8 ha and a total gully length of 241.56 km (Table 1; Fig. 2). The majority of these gullies are very large, with an average length of 260 m and an average width of 32.6 m. The gullies in Bukavu are typically smaller than in Kinshasa and Kikwit. Of these 934 mapped gullies, 398 (43%) were surveyed in the field (Table 1). For 89% of these gullies, at least one control measure was observed.

3.2. Overview of gully control measures

A wide variety of control measures aiming to stop or slow-down gully expansion were observed in the field (Fig. 4). These include large-scale projects using hard engineering structures, measures based on vegetation as well as various local initiatives attempting to slow down gully development with the sparse means available. Building on our terrain observations and reviews of gully erosion control measures in other environments (e.g. Bartley et al., 2020; Frankl et al., 2021; Haregeweyn et al., 2015; Pathak et al., 2005, p. 28; Taye et al., 2015), we classified these measures into different groups (Table 2). This grouping, which focuses on the main purpose of the measures, allows for an adequate generalization and a more systematic analysis.

A distinction is made between measures installed inside or at the gully head and measures installed in the drainage area of the gully head (Table 2). For the first group, further distinctions are made between measures that aim to reinforce the channel of the gully (Fig. 4a1-c1), the gully walls (Fig. 4d1-g1), the gully head (Fig. 4h1-l1) or measures that aim to slow down runoff and promote sediment deposition within the gully (Fig. 4m1-p1). Initiatives taken in the drainage area are grouped into measures aiming to limit runoff production on private properties/parcels (Fig. 4a2-d2), limit and slow down runoff from roads (Fig. 4e2-j2), or

Table 1
Overview of the mapped, surveyed and analyzed gullies (cf. Fig. 2).

	Bukavu	Kikwit	Kinshasa
Mapped gullies			
# mapped gullies	102	253	579
Minimum gully area (ha)	0.01	0.02	0.003
Maximum gully area (ha)	2.08	10.29	10.45
Average gully area (ha)	0.23 (±0.32)	0.73 (±1.10)	0.69 (±1.0)
Total mapped gullied area (ha)	23.3	185.81	401.7
Minimum gully length (km)	0.03	0.03	0.01
Maximum gully length (km)	0.71	1.43	1.92
Average gully length (km)	0.17 (±0.14)	0.23 (±0.21)	0.29 (±0.24)
Total length of mapped gullies (km)	17.6	58.4	165.6
Minimum gully width (m)	1.8	4.3	2.2
Maximum gully width (m)	73.6	150.9	183.9
Average gully width (m)	20.7 (±14.9)	40.2 (±25.6)	31.3 (±20.0)
Gullies surveyed in the field			
# surveyed gullies	66	66	266
# gullies with at least one control measure in the gully or at the head	66	62	227
# gullies with at least one control measure in the upslope catchment	66	52	223
Gullies used for analyzing measure effectiveness			
# gullies for which retreat rates could be calculated	14	12	43
Observation period of retreat rates	2003–2020	2004–2020	2002–2020
Average of total areal retreat rate of gullies (RR_S: $m^2\ y^{-1}$)	62.7 (±94.6)	656.4 (±691.3)	569.7 (±1560.2)
Average of total linear retreat rate of gullies (RR_L: $m\ y^{-1}$)	3.7 (±2.9)	16.3 (±16.1)	13.1 (±14.0)
# gullies that were (partially) refilled	0	0	6

deviate and evacuate runoff in a secure way (e.g. through a reinforced channel; Fig. 4k2). While most measures clearly belong to one of these groups, some observed measures belong in different categories. For example, vegetation planted in the gully channel can be expected to both reinforce the channel (e.g. through its root network) but also to slow down runoff and promote sediment deposition (through its above ground biomass). In such cases, the measure was included in both categories.

Fig. 5 shows the relative frequency with which measures of a certain category (cf. Table 2) were observed. Overall, measures aiming to reinforce the gully head or slow down runoff in the gully channel were observed most frequently (Fig. 5a). In terms of materials used, these mainly rely on vegetation, household waste and sand bags. This already suggests that most measures are implemented on an ad-hoc basis with limited means. Indeed, measures relying on larger engineering structures (e.g. canalisation of the gully channel, terracing or supporting the gully walls, concrete spillways) were typically observed at less than 10% of the surveyed gullies. Some differences can be observed between Kinshasa, Kikwit and Bukavu. Yet, the observed patterns are overall similar across these cities.

Of the measures taken in the upstream catchment (Fig. 5b), small dams along roads, vegetation in parcels and small infiltration structures within parcels were most frequently observed. Also here, measures involving large engineering works (i.e. canalisation in the upstream area) were observed at only 20–30% of the gullies. Overall, Kinshasa and Kikwit show a somewhat larger variety of implemented measures. Especially measures intended to limit and slow down runoff along roads appear to occur somewhat less frequently in Bukavu.

In many cases, measures implemented in or at the gully head were destroyed by subsequent phases of gully expansion (Fig. 5c). These measures could generally no longer be observed in the field and the reported frequencies rely on information provided by local stakeholders. Therefore, these frequencies are likely (severe) underestimations. This is especially the case for Kikwit, where our fieldwork faced severe time constraints. Nonetheless, these data provide some indications on the potential (in-)effectiveness of some measures. Overall, attempts to stabilize the gully head with household waste or sand bags, retention structures in the gully and planted vegetation in gully were the most frequently reported types of failed measures.

3.3. Estimated effectiveness of gully control measures

For 69 gullies surveyed in the field, retreat rates could be reconstructed for the period before and after the installation of at least one measure (Table 1). As explained in section 2.2.3, these reconstructions depended on the availability of remote sensing imagery and knowledge of the installation date of the measures. Note that for some gullies, several measures were installed and corresponding retreat rates could be estimated for these different measures.

Fig. 6 shows a pairwise comparison between gully retreat rates before and after a certain category of measures was installed, with the results grouped for the three cities. Overall, retreat rates after the implementation of a category of measures are generally somewhat lower than before. Nonetheless, this effect is small and shows a wide spread. Grouped over all cities and measures installed in the gully or at the head, the median RRS before installation is 128.9 $m^2\ y^{-1}$ and 97.2 $m^2\ y^{-1}$ after installation. This difference is not significant according to a Wilcoxon test ($p = 0.09$; Fig. 6a). For measures taken in the upstream catchment, the difference is also not significant ($p = 0.29$) with a median RRS of 154.5 $m^2\ y^{-1}$ before and 98.6 $m^2\ y^{-1}$ after installation (Fig. 6b). For linear retreat rates, the effect appears even more limited. For measures applied in the gully or at the head (Fig. 6c), the median linear retreat rate decreases from 7.6 $m\ y^{-1}$ to 7.0 $m\ y^{-1}$ ($p = 0.37$). For measures taken in the catchment (Fig. 6d), median linear retreat rates decrease from 7.7 $m\ y^{-1}$ to 7.4 $m\ y^{-1}$ ($p = 0.41$). With respect to the different categories of measures installed in the gully or at the head, measures aiming to reinforce the gully channel or wall seem to show the strongest reduction in RRS (Fig. 6a). Yet, the differences are not significant and overall somewhat smaller for RRL (Fig. 6c). Also for other categories of measures, no significant reduction can be observed. This is also the case for measures aiming to reinforce the gully head, despite being the most commonly applied category of measure (Fig. 5a).

Fig. 4. Illustrations of measures taken to stabilize large urban gullies in D.R. Congo. **a1:** gully channel canalised with concrete; **b1:** vehicle wrecks placed in the gully channel; **c1:** planted vegetation in gully channel; **d1 & e1:** terraced gully walls; **f1:** supporting walls; **g1:** vegetation (vetiver) planted on gully walls; **h1:** sand bags to reinforce the gully head; **i1:** concrete spillway at the gully head; **j1:** plastic (geomembrane) or metal sheets to reinforce the gully head and start of the channel; **k1:** dumping household waste in and at the gully head; **l1:** vegetation (e.g. grasses, shrubs, crops) planted at the gully head; **m1:** small dikes of car tires in the gully channel; **n1:** sandbags placed in the gully channel (often in small piles); **o1:** gabion check dams in the gully channel; **p1:** diverse small sediment trapping structures in the gully (e.g. fences); **a2 & b2:** runoff retention and infiltration pits at parcels; **c2:** rainwater storage tank (also used for local consumption); **d2:** vegetation at parcels; **e2** small infiltration pits along roads; **f2:** large water retention basin on a road; **g2:** small sandbag dams along a road; **h2:** small (stone) dams along the roads; **i2:** piled-up household waste along the road; **j2:** grasses and shrubs planted along the road; **k2:** runoff deviation channels in the upstream area.

Table 2
Overview of control measures taken to stabilize urban gullies in D.R. Congo.

Measure purpose	Type of measures	Description	Reference
A. MEASURES IN THE GULLY CHANNEL OR AT THE GULLY HEAD			
1. ***Reinforcing the gully channel***	Canalisation of the gully channel	Reinforced channel or pipe (in masonry, concrete or metal) allowing safe evacuation of runoff without causing further erosion. Some channels end with a drop structure that avoids incision at the downstream end of the gully (scouring).	Fig. 4a1
	Vehicle wrecks	Vehicle wrecks placed in the gully to slow down runoff, promote sedimentation and (especially) avoid further channel incision. Such wrecks typically end up being buried and may increase the resistance of the channel against erosion.	Fig. 4b1
	Vegetation in the gully channel	Fast-growing plants (mainly bamboo) planted in the gully channel to slow down runoff, reduce channel incision and avoid undercutting of gully walls	Fig. 4c1
2. ***Reinforcing gully walls***	Terracing of gully walls	Reshaping the walls of gullies to reduce their overall slope, increase their stability and/or provide opportunity for vegetation to colonize the gully walls.	Fig. 4d1 & e1
	Supporting walls	Masonry or concrete walls to protect gully sidewalls against slope failure or incision by water. These walls typically have an angle that mimics the equilibrium slope of the gully walls.	Fig. 4f1
	Vegetation on walls	Mostly herbaceous (e.g. Vetiver grass), shrubby and arborescent vegetation, planted to stabilize gully walls.	Fig. 4g1
3. ***Reinforcing gully head***	Sand bags at gully head	Typically multiple layers of sand bags, stacked onto each other at the gully head. These bags are mainly intended to stop or slow down further headcut retreat by runoff entering the gully. Such sand bags are often the first measure that is implemented once a gully head has formed or retreated.	Fig. 4h1
	Concrete spillway	Drop structure made of masonry or concrete, constructed at the gully head to protect it from further incision by runoff flowing into the gully.	Fig. 4i1
	Plastic or metal sheets	Waterproof covers (geomembranes) placed at the gully head to protect it from concentrated runoff erosion. The extent of these covers varies from only the steepest part of the gully head to larger areas that include parts of the upslope and downstream reaches.	Fig. 4j1
	Household waste	Organic and inorganic waste (including plastics) collected by households and local communities to fill (mainly) the gully head. This is done to increase the resistance of the soil against further incision, to absorb the energy of runoff flowing into the gully, but also to reclaim land that is already lost to gully expansion.	Fig. 4k1
	Vegetation planted at the gully head	A wide variety of plants (including herbaceous and tree-like species, ruderal plants, bananas and other crops), planted with the main purpose of slowing down runoff and increasing the stability of the gully head.	Fig. 4l1
4. ***Slow down water in the gully***	Vegetation planted in the gully channel	Fast-growing plants, mainly bamboo, planted in the gully channel to slow down runoff, reduce channel incision and avoid undercutting of the gully walls.	Fig. 4c1
	Retention structures in the gully	Various structures placed across the gully channel to slow down water and promote sediment deposition. Examples include piles of sandbags, small earthen dikes (check dams), old car/truck tires and gabion dikes.	Fig. 4 m1, n1, o1
	Sediment trapping structures	Smaller structures aimed to slow down runoff, but mainly to promote sedimentation and, hence, channel infilling. Examples include grids made of bamboo plants, placed in the gully channel perpendicular to the flow direction.	Fig. 4 p1
B. MEASURES IN THE CATCHMENT DRAINING TO THE GULLY			
1. ***Limiting runoff from parcels***	Small infiltration structures at parcels	Soil pits that are dug on individual parcels to prevent runoff from leaving the property. These structures have various dimensions (typically 4–7 m^3), construction materials and levels of maintenance. While some structures are only intended to trap runoff, others also aim to infiltrate the trapped water into the soil.	Fig. 4a2 & b2
	Rainwater storage tanks	Tanks to collect rainwater from roofs so that it can be used for household consumption. Their volumes (typically 1–4 m^3) are generally smaller than that of infiltration pits.	Fig. 4 c2
	Vegetation in parcel	Vegetation planted inside parcels with the specific purpose of improving infiltration and limiting runoff.	Fig. 4d2
2. ***Limiting and slowing down runoff along roads***	Small infiltration pits along roads	Pits that are dug in roads (often in series, alternating between both sides of the road) to trap runoff and facilitate infiltration. This to reduce the runoff peak that may arrive at the gully head. These holes are similar in size to infiltration pits on parcels.	Fig. 4e2
	Water retention basin	Large open pits (typically with a surface area of ca. 20 m^2 and a depth of ca. 2 m) dug into roads to retain runoff and limit peak discharges at the gully head. Overall, they are much larger than infiltration pits along roads or on parcels.	Fig. 4f2
	Small dams along roads	Small structures constructed along major drainage lines (i.e. mainly roads) to slow down runoff. These dams can be constructed from various materials (e.g. sand bags, car tires, earth dikes, stone walls). They are low (typically <0.5 m) and/or block only part of the road so that traffic is still possible.	Fig. 4g2 & h2
	Household waste	Organic and inorganic waste, piled up in large quantities on the road with the purpose of slowing down runoff. The (implicit) assumption behind this measure is that the waste blocks and absorbs part of the water and contributes to road stability.	Fig. 4i2
	Vegetation along the road	Vegetation (mainly grass) planted along the road (mostly on the sides) to slow down runoff, promote infiltration and provide additional resistance against erosion.	Fig. 4j2
3. ***Deviating runoff in a secure way***	Canalisation in the upstream area	A reinforced channel (network) to divert runoff away from the gully and safely evacuate it downstream. Sometimes built next to the gully, these channels aim to stop water contributing to the gully head. Forms and dimensions may vary.	Fig. 4k2

Regarding measures taken in the gully catchment (Fig. 6b & d), the strongest reduction was observed for gullies where measures to safely evacuate runoff were implemented. Only for this type of measure, a significant reduction in RRS was observed ($p = 0.02$). Nonetheless, such measures were applied in only 17–32% of the surveyed gullies (Fig. 5b). Measures aiming to limit runoff from parcels or limit and slow down runoff from roads appear to have little effect.

Fig. 7 makes a further distinction per studied city. Data limitations (especially for Kikwit and Bukavu) hamper an in-depth analysis, but overall the same patterns emerge: most measures appear to have only a limited effect. This trend is also confirmed

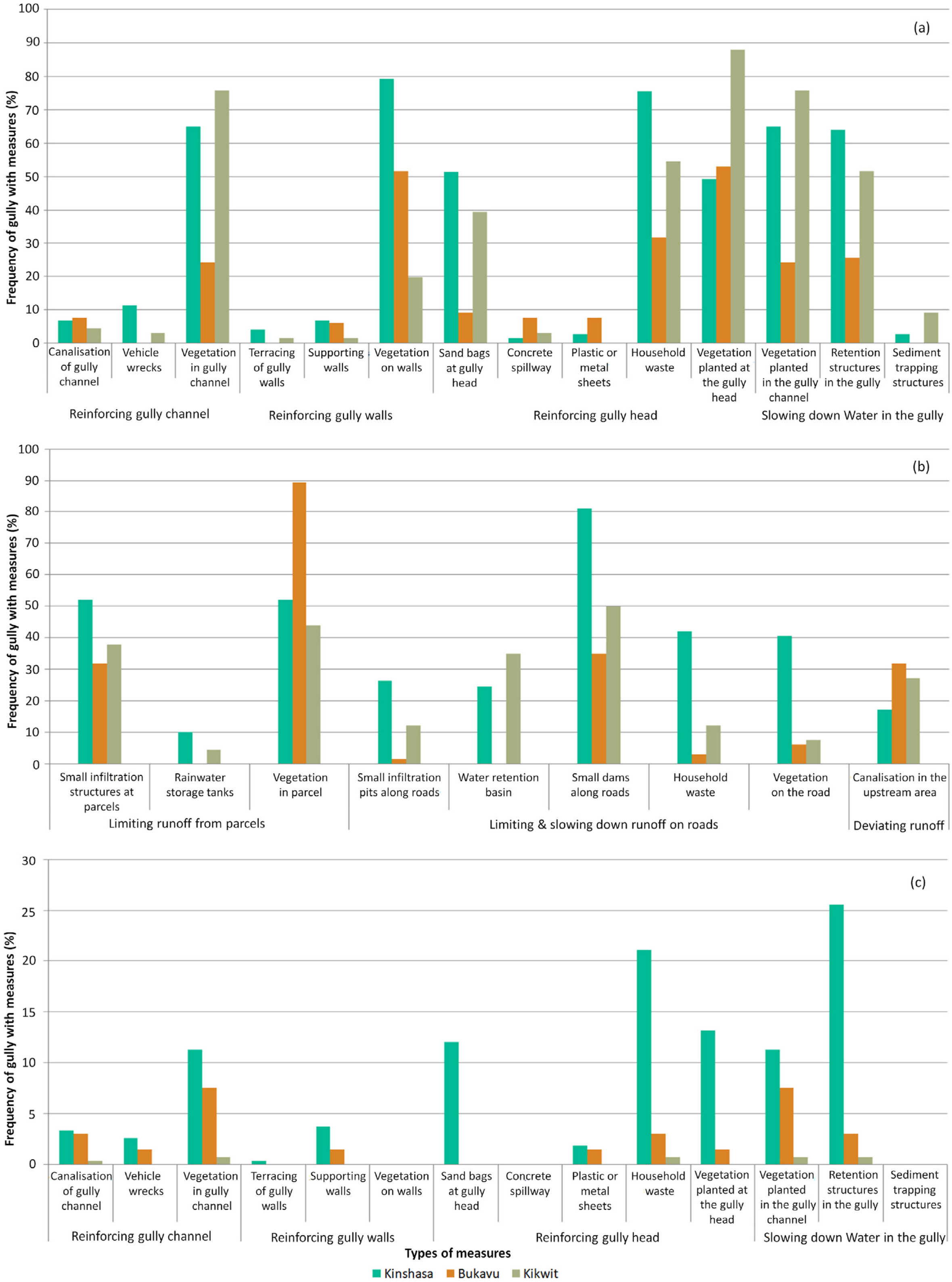

Fig. 5. Frequency of control measure types, calculated as the percentage gullies surveyed within a city for which that type of measure was present. **(a)** measures implemented in the gully or at the gully head. **(b)** measures implemented in the catchment draining to the gully. **(c)** measures that where implemented in the gully or at its head but subsequently destroyed by further gully expansion. Note: the scale of the Y axis for (c) is different from (a) and (b).

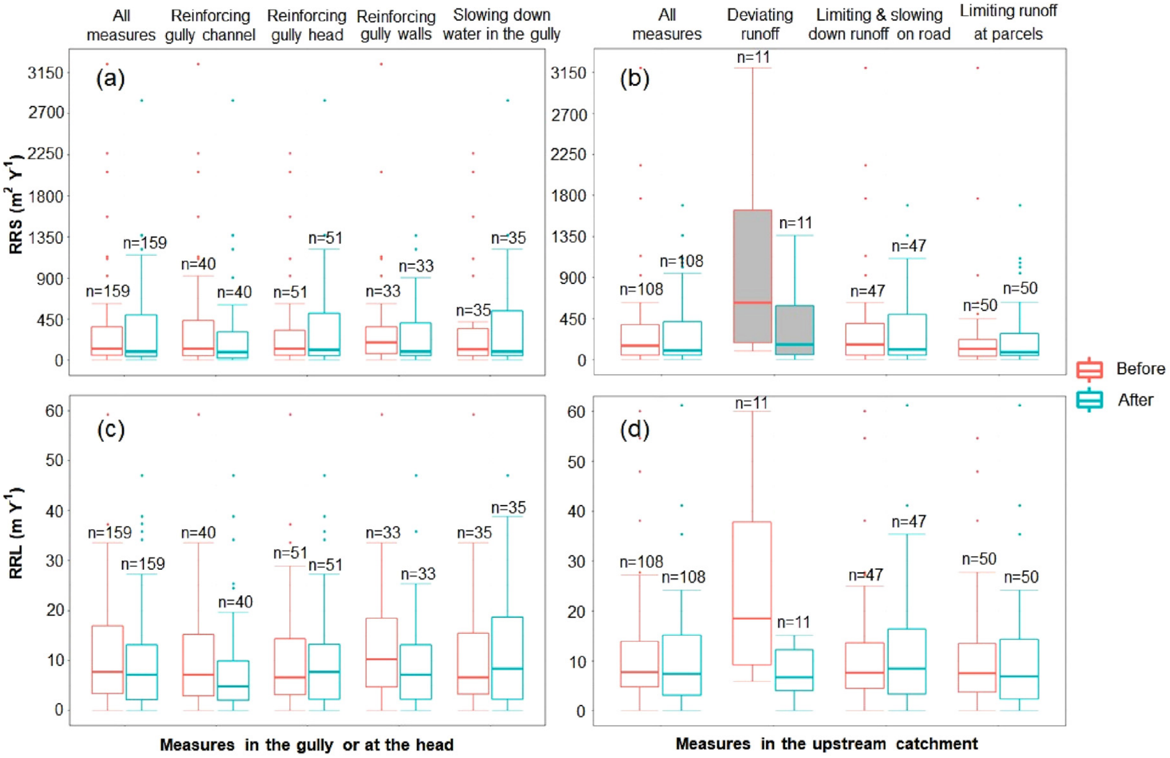

Fig. 6. Comparison of areal (RRS) and linear (RRL) gully retreat rates before and after the installation of control measures. Measures are shown per category, grouped across the three cities (cf. Table 2). **(a)** Comparison of RRS for measures installed in the gully or at the head. **(b)** Comparison of RRS for measures installed in the upstream catchment. **(c)** Comparison of RRL for measures installed in the gully or at the head. **(d)** Comparison of RRL for measures installed in the upstream catchment. Boxplots filled in grey indicate a significant statistical difference in retreat rates before and after measure installation ($p < 0.05$).

when considering individual measures (cf. Fig. 8). Nonetheless, there are noteworthy contrasts between the cities. In Kikwit, for example, retreat rates are typically larger after the installation of measures. In Bukavu, measures appear to have a larger effectiveness. However, retreat rates in Bukavu are also overall much lower than those in Kinshasa and Kikwit.

4. Discussion

4.1. Urban gullies: a rapidly growing concern

A first observation that stems from our documentation of urban gullies is the large scale of the problem. Through our mapping, we identified over 934 urban gullies across the three studied cities, comprising a total gully length of nearly 242 km (Table 1). These are certainly not the only affected cities in DRC. Overall, the problem of urban gullying is not new (e.g. Van Caillie, 1983, p. 554). Makanzu Imwangana et al. (2015) reported that the number and total length of large gullies in Kinshasa grew exponentially since the late 1960s to a total of 308 gullies in 2007 (combined length: 94.7 km). Our data for 2020 indicates that this exponential growth is still ongoing. Over the period 2007–2020, the number of urban gullies has increased with ca. 88%. The total length increased with ca. 74% (Table 1). For the other two cities, no earlier systematic mapping existed. Yet, available evidence indicates that the trend is similar (e.g. Nshokano Mweze, 2015). To a large extent, this exponential increase is attributable to the rapid and often chaotic urban expansion (e.g. Bédécarrats et al., 2016; Makanzu Imwangana et al., 2015). It is expected that this expansion will continue over the next decades (Boke-Olén et al., 2017; Ezeh et al., 2020). As such, unless drastic measures are taken, the number and extent of urban gullies is expected to further increase. Furthermore, a meta-analysis of gullies worldwide showed that gully expansion rates are strongly controlled by rainfall intensities (Vanmaercke et al., 2016). Given that also these rainfall intensities are expected to increase over the following decades (Polade et al., 2014), this will likely further aggravate the trend.

4.2. A variety of control measures

Overall, it emerges from our surveys that huge efforts are made to stabilize active gullies. Across the three cities, 85–100% of the gullies visited in the field had at least one control measure implemented in the gully or at the head (Table 1). A slightly smaller, yet still dominant number of gullies (78–85%) also had at least one measure taken in the gully catchment. Our field surveys revealed a wide variety of implemented measures and strategies (Fig. 4; Table 2). Based on our classification, we observed 13 different types of measures implemented in gullies and/or at the gully head (14 when we distinguish between vegetation installed in channels to reinforce the gully bed or to slow down runoff and promote sedimentation). In the gully catchments, we observed nine distinct types of measures.

For each of these types, numerous variations exist in terms of scale and materials used. For some gullies, extensive engineering efforts have been undertaken. These include canalisations in the upstream area, the construction of concrete drop structures, reinforcing gully walls and/or constructing a reinforced channel in the gully bottom (Fig. 4). However, such efforts typically come at great costs. Miti and Aloni (2005) estimated that civil engineering works to rehabilitate 70 urban gullies in Kinshasa between 1990 and 2003 cost >104 million US$ (ca. 93 million €). This corresponds to an

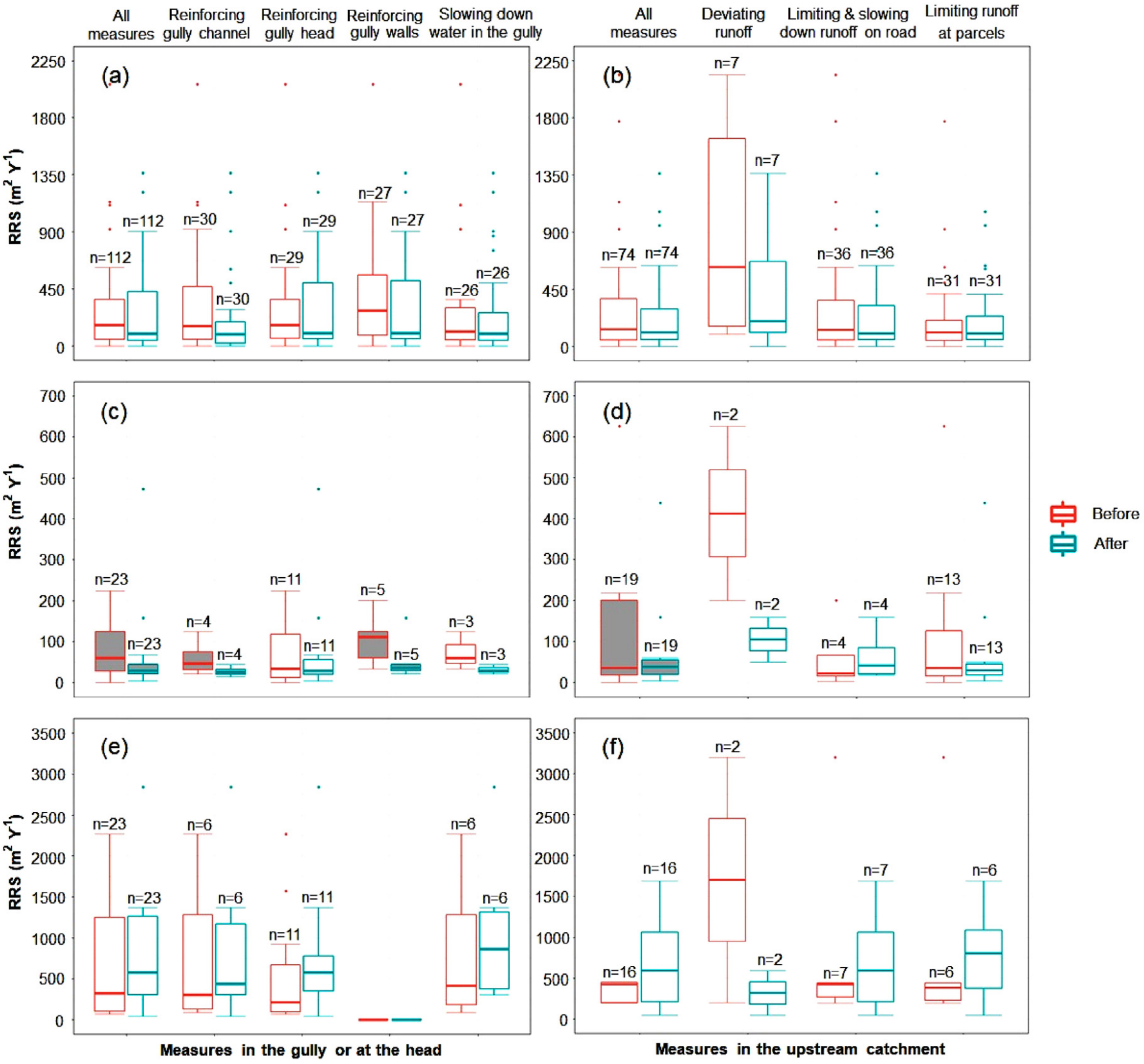

Fig. 7. Comparison of areal retreat rates (RRS) before and after the installation of measures per city and per type of measure (cf. Table 2). The left figures show the results for measures taken in the gully channel or at the gully head for Kinshasa **(a)**, Bukavu **(c)** and Kikwit **(e)**. The right figures show the results for measures taken in the catchment draining to the gully for Kinshasa (**b**), Bukavu **(d)** and Kikwit (**f**). Boxplots filled in grey correspond to measures where the differences in retreat rate were significant ($p < 0.05$).

average cost of 1.5 million US$ per gully (ca. 2.2 million US$ or 1.97 million € when accounting for inflation). Yet, more recently, costs exceeding 10 million US$ (ca. 8.93 million €) per gully are no exception (Kayembe wa Kayembe, 2020; Kayembe Wa Kayembe & Wolff, 2015). These high costs probably also explain why such large scale measures remain relatively scarce. Across the three cities, such large engineering measures were typically present in less than 10% of the surveyed gullies (Fig. 5a). Structural measures to safely deviate runoff within the upstream catchments were slightly more common, but still relatively rare, especially in Kinshasa (Fig. 5b). As such, most observed measures are local initiatives that use the scarce means available (e.g. household waste, vegetation, sand bags, car tires, vehicle wrecks and pits). Research in other environments showed that such low-cost measures can be effective (e.g. Dos SantosRotta & Zuquette, 2014; Joseph & Der Westhuizen, 2021; Poesen, 1989). However, the urban environment, (often extreme) poverty, very erodible soils, lack of vegetation and exceptionally large scale of many of the gullies pose a particularly challenging context (cf. Table 1; Makanzu Imwangana et al., 2014; 2015; Vanmaercke et al., 2016; Poesen, 2018).

Overall, the types of measures observed (cf. Table 2; Fig. 4) broadly correspond to gully remediation strategies as observed in other, non-urban, contexts and build on the same principles (e.g. Frankl et al., 2021; Haregeweyn et al., 2015; Pathak et al., 2005, p. 28; Taye et al., 2015). For example, a review of gully remediation efforts worldwide shows that successful remediation typically requires a combination of measures in the gully as well as in its catchment (Bartley et al., 2020). Likewise, a combination of engineering structures with vegetation measures is recommended. Whereas the first can be very helpful in the beginning, their effectiveness typically declines over time. Vegetation needs time to develop a sufficiently dense cover and root network, but often offers a more long-term solution (e.g. Bartley et al., 2020; Frankl et al., 2021; Poesen, 1989; Stokes et al., 2014). As our surveys indicated, a combination of measures is typically installed in both the gully channel and its catchment, with measures based on vegetation being omnipresent (Fig. 5).

Yet, there are also noteworthy differences. As mentioned, large engineering structures (e.g. to reinforce the gully head or channel or to deviate runoff) remain relatively rare (cf. Fig. 5). Nonetheless,

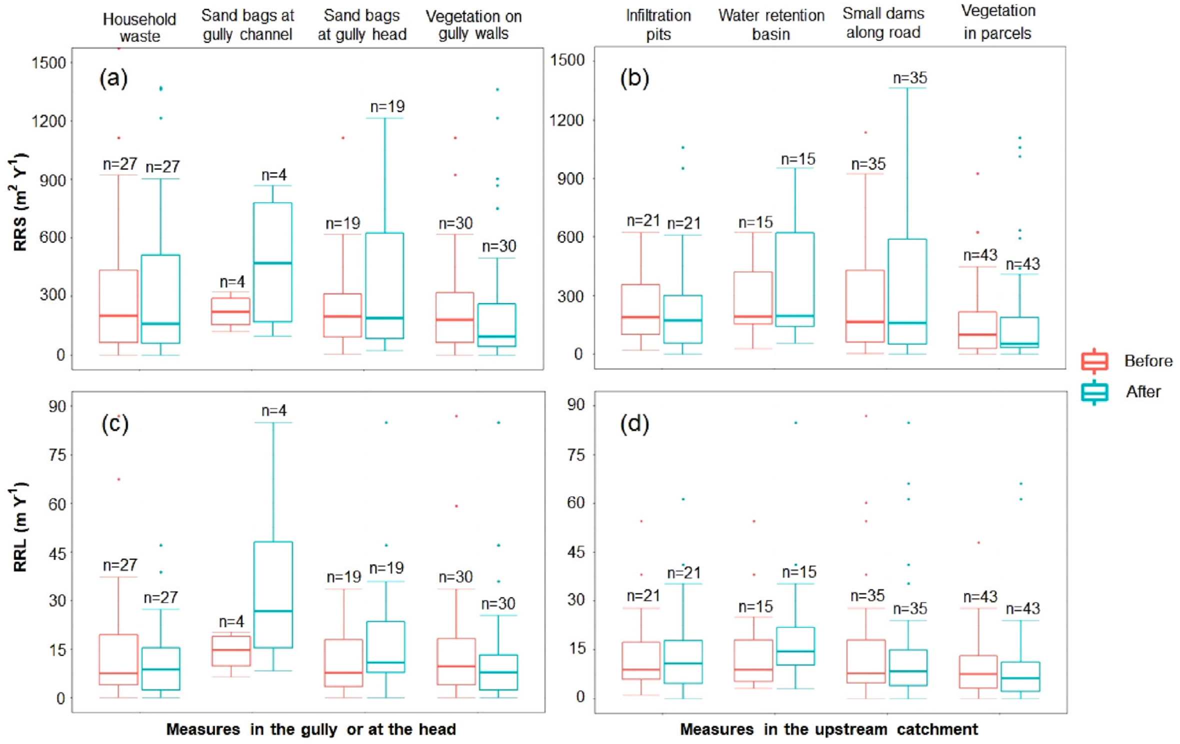

Fig. 8. Comparison of areal (RRS) and linear (RRL) gully retreat rates before and after the installation of individual control measures, grouped across the three cities (cf. Table 2). **(a)** RRS for measures installed in the gully or at the head. **(b)** RRS for measures installed in the upstream catchment. **(c)** RRL for measures installed in the gully or at the head. **(d)** RRL for measures installed in the upstream catchment.

they appear to be more frequently applied than in non-urban contexts (e.g. Bartley et al., 2020; Frankl et al., 2021; Stokes et al., 2014). The higher stakes and impacts associated to gullying in urban environments likely explain this. Likewise, attempts to stabilize gully heads with (household) waste are rarely reported in non-urban contexts (e.g. Bartley et al., 2020; Frankl et al., 2021), but are one of the most commonly applied measures, especially in Kinshasa (Fig. 5). Another noteworthy difference is the relative absence of "check dams". Check dams are one of the most commonly applied measures to control gully erosion in non-urban environments (e.g. Bartley et al., 2020; Frankl et al., 2021; Nyssen et al., 2004). Yet, in our study, we observed only few. Some measures mimic the principle of check dams (e.g. low dams along roads, retention structures in gullies; cf. Figs. 4 and 5), but they are generally small and often block only a part of the flow route. This may be attributable to several reasons. Along roads, larger measures would often hamper traffic. Within gullies, the massive gully dimensions (cf. Table 1) and associated water volumes as well as the loose sandy material (at least in Kinshasa and Kikwit) often hamper the successful implementation of check dams. Furthermore, check dams often risk being bypassed or ruptured (Poesen et al., 2006; Boix-Fayos et al., 2008; Nyssen et al., 2017). This forms a particularly important risk in urban contexts. Cases have been reported where earthen dams were constructed in the gully channel that were ruptured during subsequent runoff events (cf. Fig. 5c). This can result in flood waves downstream that cause further havoc and sometimes claim casualties.

Some differences in control measures exist between the cities. The environmental and socio-economic context may help to explain these. In Bukavu, for example, most measures in the gully catchment are taken at either the level of individual parcels (e.g. vegetation, small infiltration pits) or through larger (government or other donor) initiatives (e.g. canalisation of the upstream area; Fig. 5b). Initiatives that focus on limiting or slowing down runoff along roads were reported much less frequently than in Kinshasa and Kikwit. Also efforts to stabilize the gully channel, wall or head are less frequently implemented in Bukavu, with the possible exception of planting vegetation (Fig. 5a). Our field surveys revealed that such informal measures are typically implemented through community initiatives, organized by the people directly at risk. We hypothesize that such initiatives are less common in Bukavu because there may be a lower "sense or urgency" among the population. Urban gullies in Bukavu are typically smaller than in Kinshasa and Kikwit (Table 1), probably due to contrasts in soil type, regolith and topographic conditions (Dewitte et al., 2021; Dille et al., 2019; Van Engelen et al., 2006). Also their overall retreat rates are lower (e.g. Fig. 7). This may result in lower perceived risks of being impacted. Furthermore, the clayey and often shallow soils and regolith of Bukavu makes the digging of retention basins and other measures focusing on water infiltration more labor intensive and less effective as compared to Kinshasa and Kikwit, where soils and regolith are mainly sandy (Fehr, 1993; Moeyersons, 2003; Moeyersons et al., 2015).

4.3. Effectiveness of control measures

The large efforts observed (cf. Fig. 5) and the fact that control measures are generally based on commonly accepted gully control strategies (cf. Table 2; section 4.2) strongly contrasts with their overall effectiveness (Fig. 6). While retreat rates are overall slightly smaller after measure installation, the differences are generally not significant and most gullies are far from stabilized.

It should be noted that these results may also suggest a slightly stronger impact of the control measures than their real effectiveness. Indeed, gully expansion rates are mainly high at the beginning of a gully's lifecycle and decrease over time (e.g. Frankl et al., 2021;

Poesen et al., 2006; Vanmaercke et al., 2016). Given that the retreat rates 'after' the installation always occur later in the natural 'life cycle' of the gullies, a part of the observed declines is therefore not necessarily attributable to the control measures. Fully disentangling the effects of measures from expected 'natural' declines in gully expansion rates remains a key challenge, even in less complex contexts (e.g. Frankl et al., 2021). Nonetheless, we observed that the gullies for which retreat rates could be analyzed are still relatively young (cf. Table 1; Makanzu Imwangana et al., 2015) and showed clear indications of still being active (e.g. little to no natural vegetation on the gully walls, evidence of recent channel incisions). As such, we expect that at least a significant part of the observed declines in retreat rates can be attributed to measures (Fig. 6).

Also other elements induce uncertainty in our analyses. Due to the infrequent availability of satellite imagery, the effect of measures on gully expansion could only be determined for a relatively limited number of gullies (Table 1). Likewise, the estimated retreat rates before and after installations are prone to uncertainties. These mainly relate to the timing of the imagery with respect to installation date of the measures and/or the relatively short observation period over which these retreat rates were determined (cf. section 2.2.3). Furthermore, at most gullies, multiple control measures are jointly implemented, while other environmental factors (e.g. size and characteristics of the catchment area, rainfall conditions) also influence retreat rates. This makes it hard to attribute changes in retreat rates to one specific measure and limits the level of detail with which our results can be interpreted. Nonetheless, our analyses comprise a quantitative evaluation of 267 measures (of which 159 taken in the gully or at the head and 108 taken in the upstream catchments; cf. Fig. 6), measured at 69 individual gullies (cf. Table 1). As such, it represents the first comprehensive effort to evaluate the effect of gully control measures in tropical urban contexts.

A noteworthy observation is that the relative impact of measures is typically larger in terms of areal retreat rate than in terms of linear retreat rates (Fig. 6). This indicates that many measures may limit further widening of gullies but not necessarily stop gully head retreat. For measures concentrating on the gully walls and channels this is to be expected (cf. Table 2). For example, reinforcing the gully channel may effectively prevent undercutting of the sidewalls and hence further lateral expansion. Also for measures installed in the upstream catchments, our results suggest that measures are typically more effective in terms of areal than in terms of linear retreat rate reduction (Fig. 6b and d). This corresponds to our understanding that most measures aim to limit the peak discharge that arrives at the gully (cf. Table 2) and that gully widening is mainly controlled by these peaks (e.g. Bingner et al., 2016; Frankl et al., 2011; Hayas et al., 2019; Salvador Sanchis et al., 2009). Yet, it also indicates that stabilizing the gully head is often a key challenge. This is also evident from the results for measures concentrating on the gully head: overall, these had no clear effect on the areal retreat rate (Fig. 6a). Linear retreat rates were typically even higher after the installation of such measures (Fig. 6c). Even large-scale engineering efforts like reinforcing the gully head with concrete spillways sometimes fail; for example because they can be undercut or bypassed by runoff (Makanzu Imwangana et al., 2015; Poesen, 2018; Liu et al., 2019).

Regarding measures installed inside the gully or at the head, no measure type resulted in a significant decline in areal retreat rates after installation (Fig. 6a). Yet, the strongest overall decrease was observed for measures aiming to reinforce the gully walls. For measures installed in the gully catchment (Fig. 6b and d), only the deviation of runoff through canalisation efforts resulted in a significant reduction. Indeed, runoff deviation from the gully head immediately stops its activity. However, when this is done in an insecure way (e.g. barricading the road that channels the runoff to the gully with low walls or earthen dykes), one risks simply moving the problem to another, typically parallel road. This helps explain why many urban gullies are parallel to each other in Kinshasa and Kikwit. Our field observations show that such sequences of new gullies forming typically stop once secure measures are installed (e.g. sufficiently large and maintained canalisations along roads) that deviate the runoff towards the valleys. Nonetheless, such measures involve large-scale engineering works, are very costly (cf. section 4.2) and are therefore currently only implemented at a limited number of gullies (Fig. 5). In other words, the most effective measures also appear to be the most expensive ones. The numerous community-based initiatives relying on local resources clearly seem to have limited effects.

This does not imply that such small initiatives are completely ineffective and should be abandoned. Implementing large-scale civil engineering projects to stabilize all urban gullies will likely remain impossible for the coming years to decades, given the large and rapidly growing number of gullies (cf. section 4.1), the high costs of such large engineering projects (cf. section 4.2) and the extremely poor economic context of most areas affected (Poesen, 2018; Wouters & Wolff, 2010). As such, rather than discarding cheap initiatives, further research is needed to investigate which of these may work and how they can be improved or combined in order to have a beneficial impact.

One rather controversial example of such a locally applied measure is the use of (organic and inorganic) household waste to reinforce and stabilize the gully head. Such measures can have significant negative side effects, including sanitary concerns, odor hindrance and water pollution. During our fieldwork, we also encountered cases where these waste dumps became unstable during large rainfall events, leading to collapses. In at least one reported case, this also claimed casualties. Nonetheless, efforts to stabilize gully heads with household waste represent one of the most commonly applied gully control measures, especially in Kinshasa (Fig. 5). Yet, in some cases, it may slow down gully expansion and even lead to the reclamation of land that was previously lost.

Vegetation is typically considered key in stabilizing gullies over longer timescales (e.g. Bartley et al., 2020; De Baets et al., 2007; Frankl et al., 2021; Reubens et al., 2007; Stokes et al., 2014; Talema et al., 2019; Vannoppen et al., 2016). Also in poor and tropical urban contexts, measures based on vegetation may offer perspective and are already widely applied (Fig. 5). Yet, overall, these measures seem to have little effect on the retreat rates (Figs. 6 and 7). This may partially be attributed to the short observation periods. Nonetheless, many efforts to stabilize gullies with vegetation appear to fail (cf. Fig. 5c). As already highlighted by other studies (e.g. De Baets et al., 2007; Stokes et al., 2014; Talema et al., 2019; Vannoppen et al., 2016), more research is needed to identify suitable species and strategies to stabilize gullies by vegetation. Most likely, such initiatives will need to be combined with other measures in order to provide sufficiently stable conditions for the vegetation to develop (Chen & Cai, 2006; Pathak et al., 2005, p. 28; Poesen, 2018; Zegeye et al., 2018). Likewise, they need to take into account the specific environmental and socio-economic context (Poesen, 1989, 2018; Poesen et al., 2006; Rey et al., 2019; Stokes et al., 2014).

Another promising avenue are strategies aiming to reduce runoff production from parcels, e.g. through the installation of water harvesting tanks and/or infiltration pits. On an individual basis, the storage capacity of such individual measures is relatively limited. Indeed, our field surveys indicated that infiltration pits, tanks and basins can store on average 4, 5.6 and 15.3 m^3, respectively. However, when installed on a sufficiently large number of parcels, such measures have the potential of significantly reducing the total runoff production within catchments. From a principle point of view, this is probably the most promising strategy as it aims to limit runoff production before this runoff can concentrate and accumulate (e.g. Bartley et al., 2020). As such, it is also the most viable strategy to prevent urban gullies. While most current initiatives focus on stabilizing active gullies, their prevention clearly received much less attention (e.g. Makanzu Imwangana et al., 2015; Poesen, 2018). We observed that such measures on parcels are already frequently implemented (cf. Fig. 5b). Yet, they seem to have little effect on the gully retreat rates (Fig. 6b and d). To some extent, this may be due to the limitations of our research approach. Given time and accessibility constraints, typically only the catchment area in the vicinity of the gully head could be surveyed. As such, we could not conduct a complete mapping of all control measures installed at parcel levels. We therefore recommend more in-depth research of the potential effects of these measures, based on more complete documentation for at least some gully catchments.

Finally, it should be noted that contrasts in effectiveness appear to exist between the three cities studied (cf. Fig. 7). While the majority of data was collected for Kinshasa, many of the measures appear to be relatively more effective in Bukavu. We expect that, to some extent, this may be attributable to the overall smaller retreat rates. Likewise, most measures appeared to have no clear effect on retreat rates in Kikwit. This may be due to the fact that urban gullies in Kikwit are younger as compared to Kinshasa and therefore still in a more active development phase (e.g. Frankl et al., 2021; Poesen et al., 2006).

Yet various other environmental, infrastructural, governmental and socio-economic conditions may also play a role here. Further research is therefore required to better understand the factors influencing the success or failure of gully remediation efforts in tropical urban contexts. To give one example, differences in rainfall characteristics may play an important role, given that rainfall intensity is a key driver of gully expansion (e.g. Vanmaercke et al., 2016). First explorative analyses revealed no significant contrasts in rainfall conditions between the three cities that could explain the observed differences in retreat rates and measure effectiveness. Nonetheless, the potential role of rainfall in explaining observed differences in measure effectiveness merits a more in-depth investigation based on sufficiently long and reliable rainfall series.

5. Conclusions

Urban gullies form an important and rapidly growing concern in D.R. Congo as well as in other tropical countries. Numerous efforts have already been undertaken to stabilize such gullies. Yet, hitherto, little to no information was available as to the diversity of strategies that are being implemented and on how effective these strategies are. Based on extensive field surveys and detailed GIS analyses, we conducted the first comprehensive assessment of the most commonly implemented gully control measures and their effectiveness.

Our results indicate that implemented measures only have a limited effect on gully expansion rates. Only the deviation of runoff away from the gullies led to a statistically significant reduction in areal expansion rate. Yet, such measures are typically very expensive and currently only applied on a limited scale. The wide variety of other initiatives appears to have much more limited effects. Yet, these measures are typically based on well-known principles and are widely supported and maintained by local communities. Their failure to slow down gully expansion seems therefore mainly attributable to their exceptionally large size when compared to their counterparts in non-urban environments. Furthermore, the extremely difficult and specific environmental context (i.e. intensive tropical thunderstorms, highly erodible soils, degraded vegetation cover) and the scarce means available cannot be ignored.

Many cheap measures may nevertheless offer promising strategies for stabilizing urban gullies, possibly in combination with larger infrastructural measures. Moreover, the extensive scale at which urban gullies occurs and will continue to occur, make them a necessity. More research is therefore needed to investigate how such measures can be successfully implemented in tropical urban contexts. This is especially the case for measures based on vegetation and measures aiming to limit the runoff production from individual parcels.

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.

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