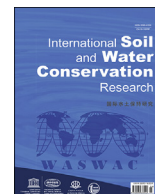




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Original Research Article

The potential of runoff retention structures as a strategy to control urban gully erosion in tropical cities



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ABSTRACT

Rapid and chaotic urbanization leads to the formation of urban gullies in many tropical cities of the Global South. To prevent and limit the destructive impacts of these gullies, runoff retention structures are often constructed. Yet, earlier research indicates that these measures are largely ineffective in reducing urban gully expansion. This study aims to understand why. We conducted detailed field surveys in two representative catchments affected by urban gullies in Kinshasa (Democratic Republic of the Congo) and characterized all existing runoff retention structures. We then used the Soil Water Management Model (SWMM) to evaluate the likely influence of these structures on runoff volumes and peak discharges. Although most parcels (77–88%) in the catchments have at least one runoff retention structure, their overall effect catchment runoff is limited (e.g., only 25–30% reduction of the total runoff volume for an event with a return period of 2 years). One key reason is that many structures are too small and poorly maintained, reducing their already limited storage capacities. Additionally, they are typically unequally distributed within the catchments (with fewer measures upstream) and not proportional to the parcel size, leading to some oversized and many undersized structures. Overall, we demonstrate that, while current efforts are largely ineffective, coordinated implementations of runoff retention structures proportional to parcel size offer promising perspectives for better controlling urban gully erosion.

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1. Introduction

Urban gullies are a rapidly growing concern in many tropical cities of the Global South (e.g., Adediji et al., 2013; Bartley et al., 2020; Kubwimana et al., 2021; Onyelowe et al., 2018; Pathak et al., 2005, p. 28; Poesen, 2018; Vanmaercke et al., 2021). With lengths often exceeding several hundred meters and widths of

several tens of meters (e.g., Lutete Landu et al., 2023), they are typically much larger than their counterparts in rural areas. In addition, they are often characterized by extremely rapid retreat rates (e.g., Ilombe Mawe et al., 2024; Vanmaercke et al., 2016). Because of this, and their occurrence in densely populated areas, urban gullies often lead to casualties as well as extensive damage to infrastructure and private property (Guerra et al., 2006; Makanzu Imwangana et al., 2015; Nsabimana et al., 2023). Furthermore, they have significant socio-economic impacts, especially since they mainly affect poorer countries and populations (Balzerek et al., 2003; Hudec et al., 2005; Kuhn et al., 2023; Makanzu Imwangana et al., 2015; Morokong & Blignaut, 2019; Nsabimana et al., 2023).

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As such, urban gullies are generally the most problematic cases of gully erosion in the world (Bartley et al., 2020; Kuhn et al., 2023; Poesen, 2018; Vanmaercke et al., 2016).

In terms of formation mechanisms, urban gullies somewhat differ from gullies in rural contexts. They are directly linked to the expansion of urban environments and the accompanying increases in impervious surfaces (e.g., roofs, roads, bare, and compacted soils). During rainfall events, such surfaces produce large amounts of runoff (Junior et al., 2010; Makanzu Imwangana et al., 2015; Moeyersons et al., 2015; Zolezzi et al., 2018), which can rapidly accumulate and concentrate along the road network, where—if left uncontrolled—it can incise to form large and destructive gullies (Ilombe Mawe et al., 2024; Lammers et al., 2022; Poesen et al., 2003). Preventing urban gully formation therefore requires proper planning as well as the installation and maintenance of runoff water management infrastructure in cities. However, the frequently chaotic and rapid expansion of many cities in the Global South often does not allow for this (Datta & Shaban, 2016). Projected increases in rainfall intensities are likely to further aggravate the problem (Vanmaercke et al., 2016; Xu et al., 2020).

Kinshasa, the capital of the Democratic Republic of the Congo (DRC), is likely the city most severely affected by urban gullies in the world (Ilombe Mawe et al., 2021; Makanzu Imwangana et al., 2015). As in many tropical cities of the Global South, runoff retention and channelling infrastructures in Kinshasa are largely lacking or poorly maintained. The resulting huge volumes of uncontrolled runoff have led to the formation of more than 570 urban gullies, causing enormous damage to property and people (Ilombe Mawe et al., 2021; Kayembe wa Kayembe, 2020; Kayembe Wa Kayembe and Wolff, 2015; Kuhn et al., 2023; Lutete Landu et al., 2023; Makanzu Imwangana et al., 2014; 2015; Wouters & Wolff, 2010). These large gullies typically have a depth of >10 m, an average width of 30 m and lengths reaching several hundred to thousands of metres. At some locations hard engineering infrastructure, like concrete channels, were implemented by the state to avoid their further expansion. Yet, given their high costs, adequate runoff channelling infrastructure is only implemented along a few major roads (Kayembe wa Kayembe, 2020).

Due to insufficient public investment in runoff control infrastructure, the local population has been proactive in implementing measures to mitigate runoff and to prevent gully erosion. This is already the case since the 1970s with initiatives like reshaping parcel topography (terracing with reverse-slopes), collecting roof rainwater in barrels and tanks, planting grasses and trees and excavating retention basins of various sizes (Lutete Landu et al., 2023; Van Caillie, 1983, 1989). Because the sidewalls and bottoms of these retention basins are usually permeable, allowing for lateral and vertical infiltration, these measures have the potential to reduce runoff volumes much beyond their static storage volume (Travis & Mays, 2008). Overall, such rainwater management techniques, known as Low Impact Development “LID”, have been implemented in various urban areas and can serve multiple purposes, including enhancing infiltration, reducing peak runoff discharges and/or providing domestic water supply (Arjenaki et al., 2021; Jeffers et al., 2022). Meanwhile, numerous studies show that slowing down runoff and promoting its infiltration can be highly effective in preventing and mitigating erosion, including gully erosion (Bartley et al., 2020; Liu et al., 2019; Poesen, 2018; Taye et al., 2015). As such, these LID measures offer substantial potential as a cost-effective strategy to prevent and control urban gully erosion (e.g. Bartley et al., 2020; Dagnew et al., 2015; Frankl et al., 2021; Verstraeten & Poesen, 2000).

Nonetheless, recent extensive field surveys in Kinshasa revealed that the expansion rates of urban gullies where LID measures were implemented upstream did not significantly differ from their

retreat rates observed before the implementation (Lutete Landu et al., 2023). This suggests that such measures remain ineffective. Yet, the reasons behind this remain poorly investigated and understood. This research gap clearly extends beyond Kinshasa. Reviews indicate that the prevention and control of urban gullies have hitherto received very little research attention (Castillo & Gomez, 2016; Bartley et al., 2020; Frankl et al., 2021). In particular, the potential of such bottom-up LID measures to control urban gullies has never been investigated before. Our overall goal is therefore to gain a deeper understanding of the current and potential effectiveness of small-scale runoff retention measures as a strategy to mitigate runoff accumulation and, consequently, urban gully erosion. Our specific objectives are: (1) to characterize rainfall collection and infiltration measures implemented in two representative catchments that drain to urban gullies in Kinshasa; (2) to assess the effectiveness of these measures in reducing runoff volumes; and (3) to propose strategies to enhance the runoff retention potential of such measures, ultimately reducing the risks associated with urban gully erosion.

2. Materials and methods

2.1. Study area

The study was conducted in the southern hilly part of Kinshasa, which is severely affected by urban gully erosion (Makanzu Imwangana et al., 2015). Two representative small urban catchments (in terms of soils, topography and land use) that drain to an urban gully head were selected (Fig. 1; Table A1). The first gully head catchment, Kimwenza (drainage area: 18.9 ha; located in the commune of Mont-Ngafula) is not very densely populated, but has important infrastructure, including a major asphalted road that was already destroyed several times by urban gullies, a university, a library and several large convents, churches and schools. Land cover analysis (see section 2.2) shows that impervious surfaces cover 17% of the catchment. Herbaceous vegetation and trees cover 29% and 19%, respectively. The remaining 35% consists of bare soil.

The second catchment, Kisenso EP5 (drainage area: 5.6 ha; Fig. 1) is located in the commune of Kisenso and has a gully head located just behind an elementary school (‘EP5’). The catchment is densely populated due to the generally low cost of housing and the proximity to the city centre. Land cover analyses (cf. section 2.2) indicate that 36% of the area is covered by roofs or other impervious surfaces. Herbaceous plants and trees cover 2% and 14% of the area, respectively. The rest of the land cover (48%) is bare soil.

As for most of the hilly area in Kinshasa, the soils in the catchments are sandy, derived from soft sandstones and classified as Arenosols (Dewitte et al., 2013; Jones et al., 2013; Lateef et al., 2010; Van Caillie, 1983, 1989). Sand content varies between 95 and 99%, while porosity ranges from 33 to 65% (Moeyersons et al., 2015). The study area has a tropical savannah climate (Aw), with a 4-month dry season (June to September) and a wet season from October to May (Beck et al., 2018). The average rainfall is around 1500 mm yr⁻¹ (Bédécarrats et al., 2016).

2.2. Data collection

We delineated the boundaries of the two catchments (Fig. 1) in the field using handheld GPS, taking into account the presence of roads, drainage channels and other infrastructure that may influence the contributing area of the gully (Makanzu Imwangana, 2014). Next, we used drone images with a 9-cm resolution (taken by a DJI Phantom® 4 RTK by IRDAC SARL on 04-01-2022 for Kimwenza and on 02-06-2022 for Kisenso) to digitize all buildings, parcels and roads in the catchments. Next, we clipped away all

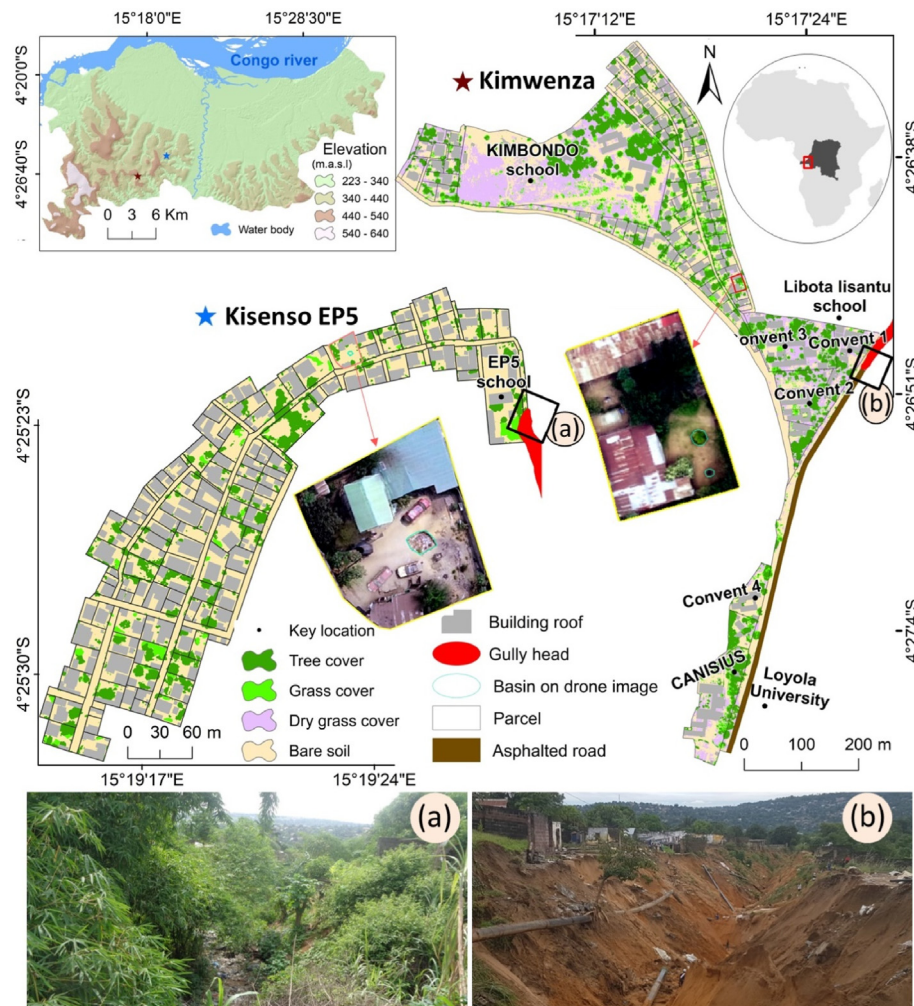


Fig. 1. Characteristics of the two studied catchments (Kimwenza and Kisenso EP5) within Kinshasa (inset). The maps show the spatial extent and the land cover (cf. section 2.2) of the area draining to each gully head. The two zooms show a drone view of parcels with visible runoff retention basins (contours mapped in cyan). The two pictures (a and b) illustrate the respective gully heads. Picture (a) was taken in 2023, while (b) was taken in 2022.

buildings from the images to reduce its large radiometric variability (due to the multiple roof colours and their often bright reflection). We then conducted a supervised classification based on the maximum likelihood algorithm (Erbek et al., 2004) to produce a land cover map for each catchment (Fig. 1).

Intensive field surveys were conducted in both catchments from July to October 2021 to collect information on the presence of runoff infiltration measures and rainwater storage facilities at every parcel. For each identified measure or storage facility, we recorded the geographic coordinates, the type of measure, the dimensions and maintenance status. Regarding the type of measure, we observed a wide variety of sizes, shapes and construction materials. However, for the purpose of this study, we mainly made a distinction between retention basins and water tanks. Retention basins are pits dug into the soil that capture and temporarily store surface water from parcels. They can be simple soil pits that may or may not be vegetated or they can be reinforced with, e.g., sand bags or stone blocks. One of their key properties is that they allow infiltration. This contrasts to water tanks, which store rainwater from roofs in order to be used for domestic consumption. The sizes of both retention basins and water tanks can vary widely. Here we only considered measures with a storage capacity of at least 0.5 m³.

It was observed that several retention basins were poorly

maintained and filled with garbage and sediments. This resulted in static storage volumes that were smaller at their moment of survey than at their time of construction. To estimate the initial volumes of these measures, we developed an empirical relationship between the surface area and average depth for well-maintained measures (Fig. A1). We applied this relationship to the partially filled basins and then multiplied the estimated depth by the measured surface area. For a selection of 13 well-maintained retention basins (11% of all basins; 6 in Kimwenza and 7 in Kisenso EP5) that were sufficiently large, we measured the infiltration rate of the basin under saturated conditions. This was done with a double ring infiltrometer, following the procedure described by Ruggenthaler et al. (2016).

2.3. Modelling framework

Evaluating the effect of retention and infiltration measures requires accounting for the various factors and mechanisms that control runoff discharge at the catchment outlet, as well as their spatiotemporal variabilities. For this, we used the Storm Water Management Model (SWMM), a dynamic rainfall-runoff simulation model that was developed to simulate runoff in urban contexts (Babaei et al., 2018; Dongquan et al., 2009; Gironás et al., 2010). We

used SWMM at the scale of single rainfall events, allowing us to ignore evapotranspiration losses.

Both catchments were divided into smaller, homogeneous sub-units corresponding to individual parcels or road sections. The model first simulates the hydrological balance of each of these sub-units, taking into account potential infiltration on bare and vegetated surfaces as well as local water retention (Fig. 3(a)). Next, the hydraulic component of the model routes the runoff that leaves each sub-unit (Fig. 3(b); Arjenaki et al., 2021). This routing through conduits and nodes is done dynamically, based on the full St. Venant equations (Arjenaki et al., 2021). We used a 1-min time step to maintain numerical stability (Lewis, 2017).

As most areas in Kinshasa, neither of the two catchments are equipped with sewers or ditches to evacuate runoff water. Instead, roads typically function as conduits for produced storm runoff. In principle, runoff could also flow from the road into lower lying parcels adjacent to the road. Yet, people living on such parcels typically raise the roadside boundaries of their parcels to avoid runoff from flooding their property. Meanwhile, they dig a channel to evacuate runoff from their parcel towards a point on the road further downslope. This justifies our model assumption that runoff flows from parcels to roads (Fig. 2(a)) and then remains on the roads until it reaches the catchment outlet (Fig. 2(b)). The role of roads in routing runoff was represented in SWMM by conduits with the same length, width and slope steepness as the actual road network, and a depth of 0.5 m.

2.4. Model implementation and input data

Runoff production of sub-units was based on the Soil Conservation Service (SCS) curve number method (Hawkins et al., 2009;

Rossman & Huber, 2016):

$$Q = \frac{P^2}{P + S_{max}} \quad (1)$$

where Q (mm) is the total event runoff associated with a specific rain event, P (mm) is the rainfall depth of that event, and S_{max} (mm) is the maximum storage capacity of the soil. S_{max} was calculated as:

$$S_{max} = 25.4 \left(\frac{1000}{CN} - 10 \right) \quad (2)$$

With CN the Curve Number, which characterizes the hydrological response of a given surface in function of its soil type and land cover (NRCS, 2004).

Rainfall depths were determined based on Intensity-Duration-Frequency (IDF) curves for Kinshasa (Mohymont et al., 2004), assuming an event with a duration of 1 h. Simulations were conducted for seven total rainfall depths: 60, 70, 80, 85, 90, 95, and 100 mm, corresponding to return periods of 2, 5, 10, 20, 35, 50, and 75 years, respectively. All rain events were assumed to have a constant intensity, which typically results in the production of high peak discharges (Alfieri et al., 2008).

To estimate the CN -value of every parcel or road section, we considered four land cover classes: roofs, vegetated surfaces, bare soils and road surfaces. The spatial coverage of these classes were derived from our land cover maps (Fig. 1). CN values for each of these classes were derived from field measurements by Moeyersons et al. (2015). These authors conducted rainfall-runoff experiments for three different rainfall depths at 35 sites across Kinshasa, encompassing the same four land cover classes. For each of their sites, we first approximated the CN value based on values

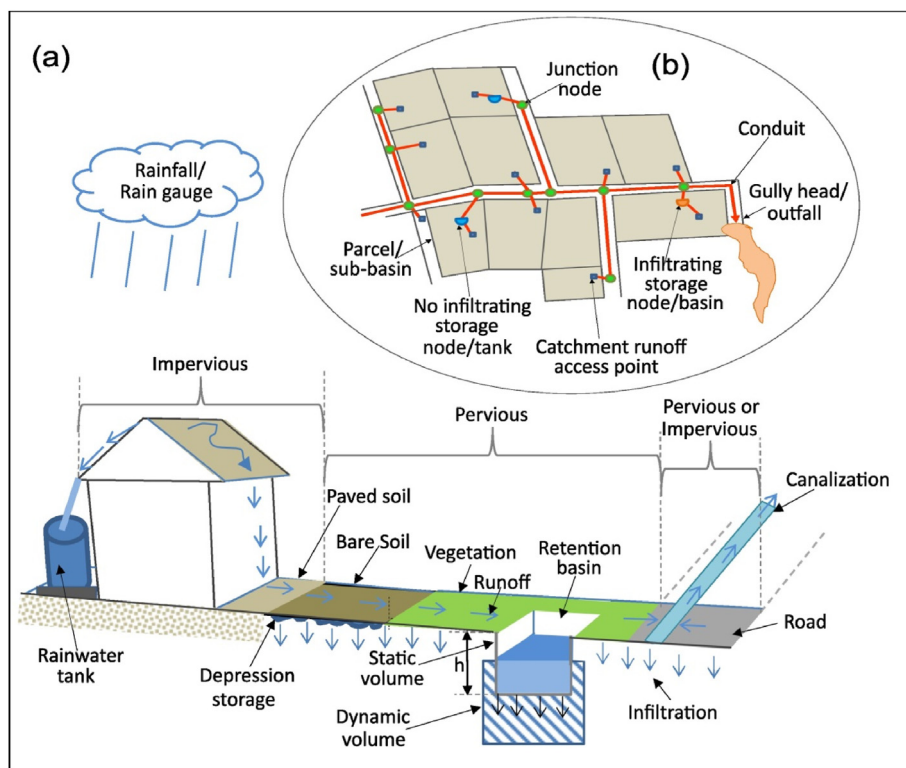


Fig. 2. Overview of the Soil Water Management Model (SWMM) framework as applied in this study. (a) Simulation of the hydrological balance of sub-units. Part of the rainwater is lost to retention and/or infiltration. The rest leaves the parcel as excess runoff. (b) Simulation of the hydraulic routing of the excess runoff from each sub-unit towards the catchment outlet, taking into account the topology of the different nodes, their respective distances, slope steepness and other characteristics.



Fig. 3. Illustrations of observed runoff retention measures used to collect, store and infiltrate rainwater. (a) losing well with blocks; (b) infiltration pit with sand bags; (c) retention basin with vegetation; (d) poorly maintained retention basin filled with sand; (e) partially filled retention basin with sand bags; (f): vegetated retention basin allowing high infiltration rates and avoiding bottom clogging; (g) & (h) plastic rainwater tanks (small and large capacity); (i) cement rainwater tank; (j) open underground tank in masonry collecting rainwater from roofs; (k) closed underground tank in masonry; and l: cellar serving as tank collecting rainwater from the roofs, occupying the entire underground part of the building.

available in literature (Hawkins et al., 2009). The simulated runoff value obtained based on Eq. (1) (and using the same rainfall amount as the field experiment) was then compared to the measured runoff of Moeyersons et al. (2015) ('observed runoff'). The CN values were then adapted iteratively to minimize the average difference between the simulated and observed runoff values over all experiments corresponding to that land cover class. This resulted in a CN value of 99.9 for impervious surfaces, 86.1 for roads, 78.0 for bare soils and 77.7 for vegetated surfaces.

Since evapotranspiration can be considered negligible over our 1-h simulations (Arjenaki et al., 2021), losses due to depression storage and infiltration (F , mm) can be quantified as the difference between rainfall and runoff (Rossman & Huber, 2016; cf. Eq. (1)):

$$F = P - \frac{p^2}{P + S_{\max}} \quad (3)$$

Following earlier applications of SWMM (e.g., Rossman & Huber, 2016), the fraction of F that was lost to depression storage (dp ; which can be interpreted as the initial abstraction term in the basic SCS model; Hawkins et al., 2009) was assumed to be equal to:

$$dp = 0.20S_{\max} \quad (4)$$

Earlier work with SWMM showed that long travel distances on parcels can lead to underestimations of the runoff and overestimations of the infiltration (Rosa et al., 2015). We therefore

checked that the runoff length on a parcel did not exceed 50 m (cf. [Rossman & Huber, 2016](#)). Longer parcels were either subdivided into multiple parcels or virtually reshaped within our model setup to meet this criterion, while maintaining the total parcel size and other characteristics.

Apart from infiltration and runoff, a part of the rainfall can also be stored by retention structures. In our model, we conceptualized this by using two node types ([Fig. 2](#)): ‘junction nodes’ and ‘storage nodes’. Junction nodes link parcels or road sections to other parcels or road sections. Storage nodes have a water retention volume assigned to them and can be infiltrating (e.g. retention basins) or non-infiltrating (e.g. rainwater tank). For parcels with both a rainwater tank and a retention basin, two storage nodes were placed in series, representing situations where rainwater tanks collect water from the roof and the excess water overflows into a retention basin. Very small retention structures (<0.5 m³) were neglected in the simulations. For retention basins allowing infiltration, we used the saturated hydraulic conductivity (mm/hr) measured in the field ([section 2.2](#)). More specifically, we used the average measured infiltration rates of all 13 well-maintained retention basins that were surveyed. Given the sandy nature of the soils, we assumed an average soil capillary suction at the wetting front of 49 mm ([Rawls et al., 1983](#)) and a value of 0.2 for the fraction of soil volume that was initially dry.

Concerning the hydraulic part of the SWMM model, runoff was routed based on Manning's equation which relates conduit flow rate to flow depth, conduit bed slope and roughness ([Liu & Todini, 2002](#); [Yen, 2001](#)). Slope steepness values were derived by combining a SPOT Digital Elevation Model (DEM) with a 5 m resolution ([Makanzu Imwangana, 2014](#)) with a 1 m digital terrain model (acquired by IRDAC SARL using a DJI Phantom 4 RTK topographic drone). This was done to remove potential errors in slope linked to the presence of buildings. Manning's “n” hydraulic roughness coefficients were estimated based on values available in literature ([Yen, 2001](#)). More specifically, we assigned roughness values of 0.010, 0.040, 0.055 and 0.075 to, respectively, impervious surfaces, unpaved roads, bare soils in parcels, and grass-covered surfaces. [Table A2](#) provides further details on the parameters of our SWMM model setup.

2.5. Model validation

Due to a lack of resources and the difficult, often dangerous context of the urban gullies, collecting actual rainfall and runoff observations was nearly impossible. Nonetheless, some measurements could be collected for one rainfall event at the Kisenso EP5 gully head. The event occurred on February 22, 2023 and was registered with a temporal resolution of 10 min by a meteorological station of the *Centre de Recherche en Ressources en Eau du Bassin du Congo “CRREBaC”* at the University of Kinshasa (2.4 km from the EP5 gully). The total rainfall depth of the measured event was 47 mm in 190 min (mean intensity: 36.3 mm/h), corresponding to an estimated return period of one year ([Moeyersons et al., 2015](#)).

A temporary weir at the EP5 gully head, constructed by the NGOs *Centre d'Etudes Environnementales pour le Développement Durable “CEEED”* and *Terraforma Rainwater Collective*, allowed to manually record the water heights (H_w , [m]) approximately every 10 min and convert them into the runoff discharges (Q , [m³/s]) using the following equation ([Brunner, 1995](#)):

$$Q = C_w \cdot L_w \cdot (H_w)^{3/2} \quad (5)$$

where C_w is the weir coefficient (set to 1.7, based on its dimensions and shape; [Brunner, 2010](#)) and L_w is the weir width (1.56 m). By running the SWMM model for Kisenso EP5 using the observed

rainfall and comparing our simulation results with the observed hydrograph, a validation of our model results was possible for this one event.

2.6. Scenario analyses

Once set up, we used SWMM to simulate 16 scenarios to assess the effect of rainfall retention measures on total runoff volume and hydrographs at the gully head. Each scenario resulted in 14 simulations, as they were each time conducted for seven rainfall events (cf. [section 2.4](#)) and for both catchments ([Fig. 1](#)). The first (baseline) scenario assumed that no runoff retention measures were present. The (actual) second scenario considered all retention measures and their properties as we observed them in the field. The third (potential) scenario assumed that all observed measures were well-maintained (i.e. having their original capacity, cf. [Fig. A1](#)). For scenarios four, five, and six, we assumed that each parcel had a retention basin with a static volume equal to the average expected runoff from a parcel of the same size. This for a rainfall event with a return period of 2, 5, and 10 years, respectively. The volumes were estimated using a linear regression between parcel size (m²) and simulated runoff volume (m³) generated by these rainfall events across all parcels in both catchments. Scenarios 2–6 were further divided into two versions: one considering only the static storage capacity of the measures, and another based on the estimated ‘dynamic’ capacity, which includes infiltration within the retention basins. The results of each scenario were compared with the baseline scenario to evaluate the corresponding runoff reduction.

3. Results

3.1. Field observations

We surveyed 114 parcels in Kimwenza and 120 in Kisenso EP5 in the field ([Table A1](#); [Fig. 1](#)), mapping and characterizing 306 functioning runoff retention measures. These included 120 retention basins ([Fig. 3\(a\)–\(f\)](#)) to infiltrate runoff and 186 large (>0.5 m³) rainwater tanks for domestic use ([Fig. 3\(g\)–\(l\)](#)). Overall, these measures varied greatly in size, maintenance status and building materials ([Fig. 3](#)).

In Kimwenza, 77% of the parcels had at least one retention basin or rainwater tank, while 42% had at least one of both. Four percent had two or more retention basins, while 23% had no measures (or owners refused to provide further information). In Kisenso EP5, these percentages corresponded to 88% (at least one measure), 33% (at least one retention basin and rainwater tank), 2% (two or more retention basins) and 12% (no measures or no information).

The average size of rainwater tanks was 8.5 and 5.5 m³ for Kimwenza and Kisenso EP5, respectively. For retention basins, this was 10.5 and 2.5 m³, respectively ([Table A3](#)). Of these retention basins, 16.7% (Kimwenza) and 31.3% (Kisenso EP5) were well-maintained, while the rest were totally or partially filled ([Table A3](#); [Fig. A1](#)). The infiltration tests in well-maintained basins resulted in an average steady-state infiltration rate of 423 mm/h (± 242 mm/h) in Kimwenza and 267 mm/h (± 145.7 mm/h) at Kisenso EP5.

The spatial distribution of the retention basins and water tanks in Kisenso EP5 indicates that retention basins tend to be more numerous close to the gully head ([Table A3](#); [Fig. 4](#)). This is especially true for larger infiltration basins. The opposite situation is observed for rainwater tanks, with the largest ones typically occurring somewhat further from the gully head. In Kimwenza, this trend is less apparent. This can be attributed to the large size of several parcels in the direct vicinity of the gully head.

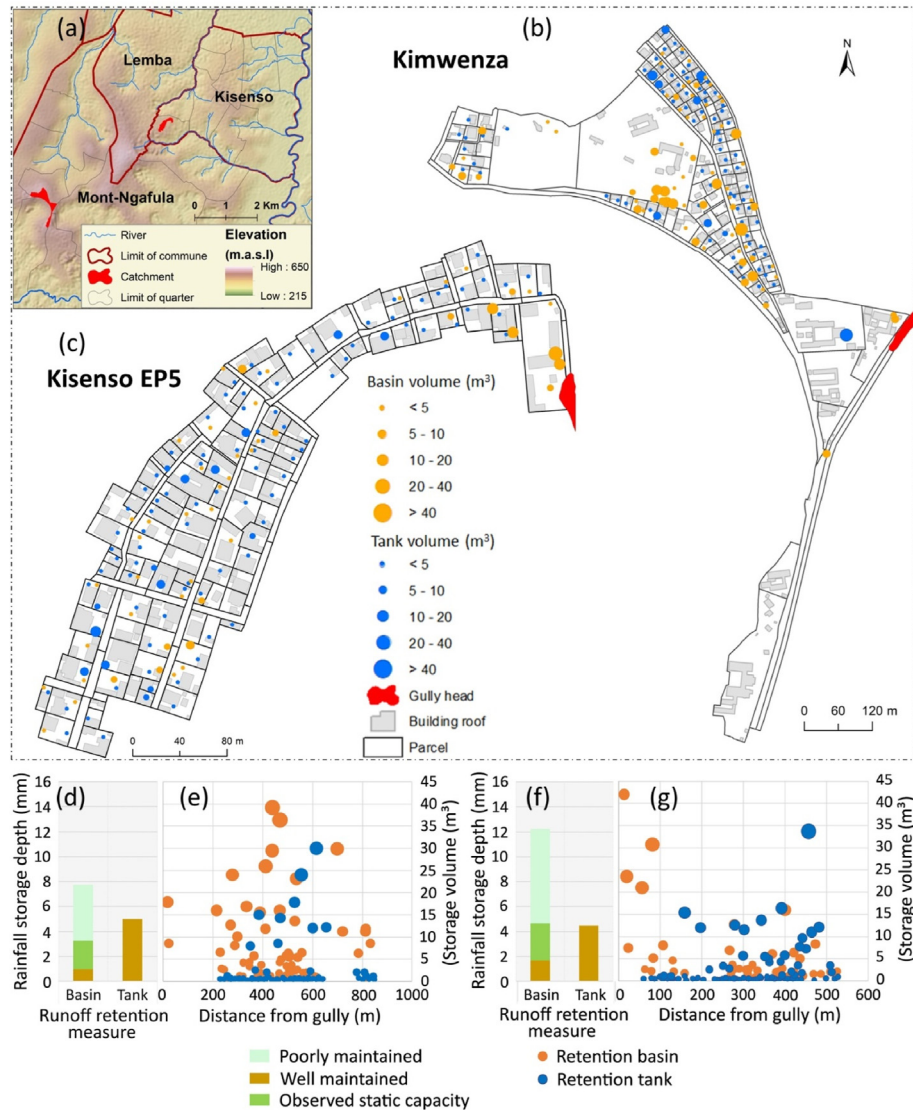


Fig. 4. Runoff retention measures characteristics. (a) Shows the topographic setting of the catchments. (b) and (c) show the distribution and characteristics of retention measures within the Kimwenza and Kisenso EP5 catchments. (d) and (f) show the corresponding total static rainfall storage depth (i.e. the total volume of measures, divided by the catchment area) of poorly maintained measures (i.e. retention basins filled with sediments), the total storage depth of well-maintained measures (i.e. retention basins still having their initial storage capacity + rainwater tanks), and the static storage capacity lost due to the infilling of poorly maintained basins. (e) and (g) show the static storage volume and type of each measure as a function of their distance from the gully head.

3.2. Comparison of measured and modelled runoff

While comprehensive rainfall-runoff monitoring was impossible, one runoff event was monitored at the Kisenso EP5 catchment outlet (section 2.6). Fig. 5 shows the modelled and measured hydrographs. The measured runoff peak occurs later and is lower than the one simulated with SWMM. The observed peak discharge is $0.20 \text{ m}^3 \text{ s}^{-1}$, while the simulated peak is $0.26 \text{ m}^3 \text{ s}^{-1}$. Also the falling limb of the simulated hydrograph shows higher discharges, resulting in a total measured runoff volume of 321 m^3 compared to a simulated volume of 576 m^3 over the same period. The coefficient of determination (r^2) between measured and observed values is 0.45.

This comparison indicates that while there are discrepancies, the SWMM model produces realistic results. Furthermore, the recorded event occurred about 1.5 years after our field surveys (section 2.2), during which many additional water retention structures were constructed (Fig. A2). These additional measures

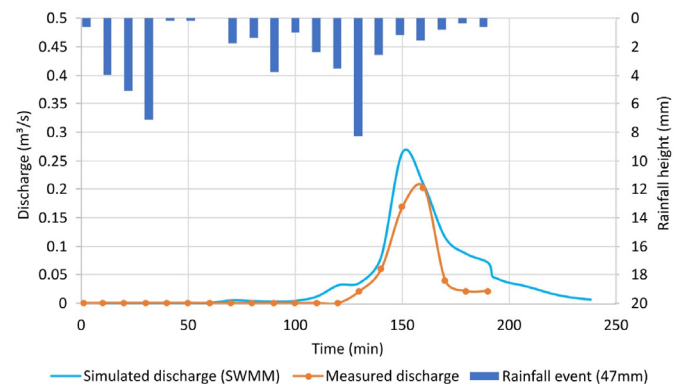


Fig. 5. Comparison between measured and simulated runoff discharge with SWMM at the Kisenso EP5 gully for a rainfall event that occurred on February 22, 2023 (see section 2.6 for details). Time step is 10 min.

likely contribute to the apparent overestimation by our model, which will be discussed further in section 4.1.

3.3. Storage versus parcel runoff volumes

As might be expected, the simulated runoff volume produced by individual parcels increases with their size and rainfall amount (Fig. 6(a)). Land cover characteristics induce some scatter on these trends, but this remains limited (R^2 -values >0.94), which may be because of the overall limited differences in land cover between parcels.

The storage capacity installed on parcels shows more contrasting trends (Fig. 6(b)). Observed storage volumes generally increase with parcel size but are typically below expected parcel runoff volumes (Fig. 6(a)). Among parcels with at least one retention basin and/or water tank, only 15% have sufficient capacity to store runoff from a 2-year return period rainfall event. This drops to 8% for a 10-year event and 6% for a 75-year event. When considering all parcels, these percentages drop further to 10%, 6%, and 4%, respectively. However, a few small parcels have water retention capacities that exceed expected runoff even for the largest events. Many of these are located near the gully head (Fig. 4).

3.4. Effect of runoff retention measures at the catchment scale

3.4.1. Effect on peak and total runoff

Our modelling results indicate that measures observed in the field only have a limited effect on the total runoff arriving at the gully head (Fig. 7(a) and (b)). Depending on the return period of the rainfall event (2–75 years), their expected runoff reduction varies between 24% and 14% in Kimwenza and between 30% and 16% in Kisenso EP5. Under a scenario where these measures are well-maintained (cf. 'Potential volume'), runoff reductions increase to 33–21% at Kimwenza and to 36%–24% in Kisenso EP5.

Fig. 7(c) & (d) shows the scenario analysis results, where each parcel has a retention basin with a static capacity equal to the average expected runoff from a 2, 5, or 10-year return period rainfall event for a parcel of that size. In Kimwenza, these basins have median sizes of 11, 15, and 19 m³, respectively, while in Kisenso EP5, the sizes are 10, 13, and 17 m³. These scenarios demonstrate the significant potential of such measures for reducing total runoff at the catchment scale. Installing measures designed to capture runoff from a 2-year rainfall event can reduce runoff by 74% in Kimwenza and 87% in Kisenso EP5 for events with the same return period. This effectiveness decreases for larger events; however, even for a 75-year event, the reduction remains substantial:

33% in Kimwenza and 47% in Kisenso EP5 for measures designed for a 2-year event. Installing larger storage capacities further increases effectiveness, especially during larger events. For instance, retention measures capable of storing runoff from a 10-year event could potentially reduce total expected runoff from a 75-year event by 72% in Kimwenza and 83% in Kisenso EP5.

Nevertheless, reducing peak runoff discharge is likely more important than reducing total runoff volume to stop further urban gully expansion. Fig. 8 therefore shows the hydrographs from these simulations. The results indicate that currently installed measures slightly delay and reduce peak discharges, but their overall effect is limited, especially during large rainfall events. For a 75-year return period event, peak discharge would be reduced by only 10% in Kimwenza and 4% in Kisenso EP5. Improving maintenance and restoring measures to their original capacity would offer slight improvements, reducing peak discharge by 12% in Kimwenza and 14% in Kisenso EP5.

Installing retention measures on every parcel, proportional to parcel size, has a larger effect on peak discharges. For measures designed to retain runoff from a 2-year event, the impact is significant mainly for rainfall events with a return period below 5 years. For larger events, the peak discharge is slightly delayed but remains similar to that of the currently installed structures. However, installing structures capable of retaining runoff from a 5 or 10-year event has a much larger effect, potentially reducing peak discharges by 50% even during a 75-year return period rainfall event.

3.4.2. Hydrological balance

Fig. 9 illustrates the hydrological balance of the two catchments under the different scenarios and for rainfall events with return periods of 2, 20, or 75 years. Parcels are the primary source of runoff at the catchment outlets under both actual and potential (well-maintained) storage capacities. Roads typically contribute less than one third of the total runoff, with their relative contribution decreasing as rainfall intensity increases. However, there are notable differences between the catchments. In Kimwenza, 50%–70% of rainfall is retained as depression storage or infiltrated within the parcels themselves. In Kisenso EP5, where parcels are smaller and building density is higher (Fig. 1), infiltration rates are typically 10–12% lower.

Currently installed measures store and absorb only 10–15% of the total rainfall amount. As these measures do not affect depression storage and infiltration rates on the parcels themselves, they reduce the parcel runoff component with an equal amount. A similar trend is observed when every parcel has a retention basin to

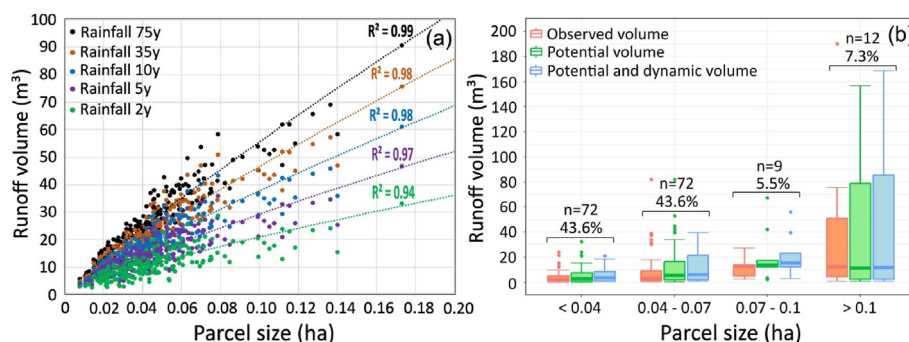


Fig. 6. (a) Simulated parcel runoff production with SWMM as a function of parcel size for rainfall events with different return periods (2–75 years) for all parcels ($n = 234$) in both catchments. (b) Distribution of the total available water retention volume (retention basins + tanks) in parcels with at least one measure installed, grouped per parcel size (percentages indicates the share of parcels in each size class). A further distinction is made between the observed storage volume, the potential static volume that could be stored if all measures were well maintained (i.e. no infilling with sediments) and the potential dynamic storage volume, which also considers the potential infiltration in well-maintained retention basins that may occur over the duration of the simulated rainfall events (1 h).

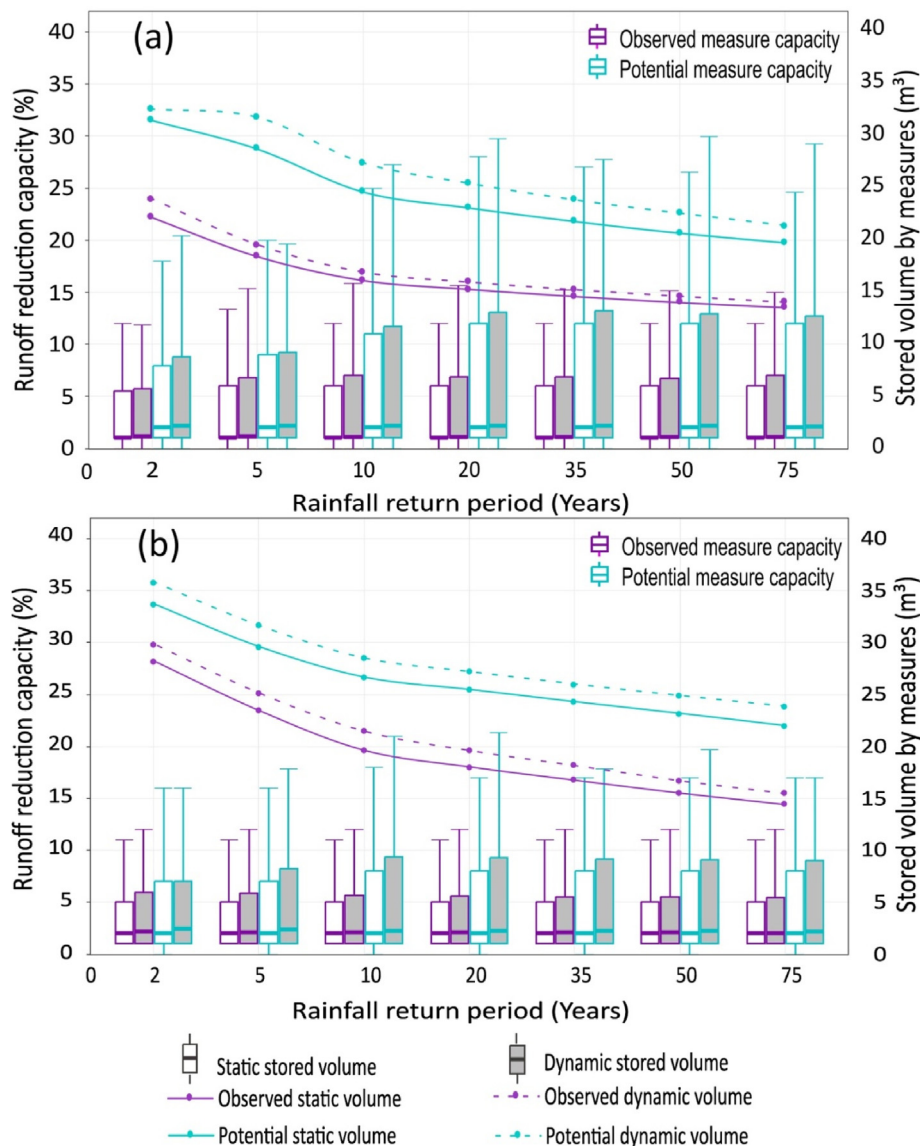


Fig. 7. Distribution of simulated runoff volumes stored in water retention basins and tanks, and the cumulative effect of all storage measures on reducing total runoff in the gully catchment for various rainfall return periods. (a) and (b) illustrate results for Kimwenza and Kisenso EP5, respectively, showing both observed storage capacities and potential capacities assuming optimal maintenance of all measures. (c) and (d) present scenario analyses for Kimwenza and Kisenso EP5, where each parcel is equipped with retention basins having a static storage capacity equivalent to expected parcel runoff from rainfall events with return periods of 2, 5, or 10 years, as estimated from Fig. 6(a).

statically store runoff volumes from rainfall events with 2, 5, or 10-year return periods. However, these measures can significantly reduce parcel runoff beyond their designed capacity. For instance, retention basins with a static capacity equal to the runoff produced by a 10-year event can eliminate parcel runoff entirely during a 20-year event. Even for a 75-year event, such measures reduce parcel runoff to less than 5%.

4. Discussion

4.1. Model errors and reliability

Due to the challenging context of our research, only one runoff event could be monitored in the field (section 2.6). Comparing the measured and simulated runoff for this event showed that our simulations overestimated both total runoff and peak discharge

(section 3.2; Fig. 5). This, along with the lack of additional validation data, necessitates caution in interpreting our simulations. Nonetheless, we believe this comparison is mainly encouraging and overall supports the validity of our findings.

First, despite the overestimation, our simulations produced a hydrograph of the correct order of magnitude, with errors comparable to those obtained in less data-scarce urban catchments (e.g., Kourtis et al., 2017; Sun et al., 2014). This is particularly true for peak discharge, which is most critical for gully expansion (Frankl et al., 2021; Hayas et al., 2019; Vanmaercke et al., 2021).

Second, the monitored event occurred about 18 months after our mapping campaign. Since then, several additional retention measures, including dams and basins along the main road (Fig. A2), have been installed but were not considered in our simulation (which reflected the situation in October 2021). These new measures were likely a response to the catastrophic flooding and gully

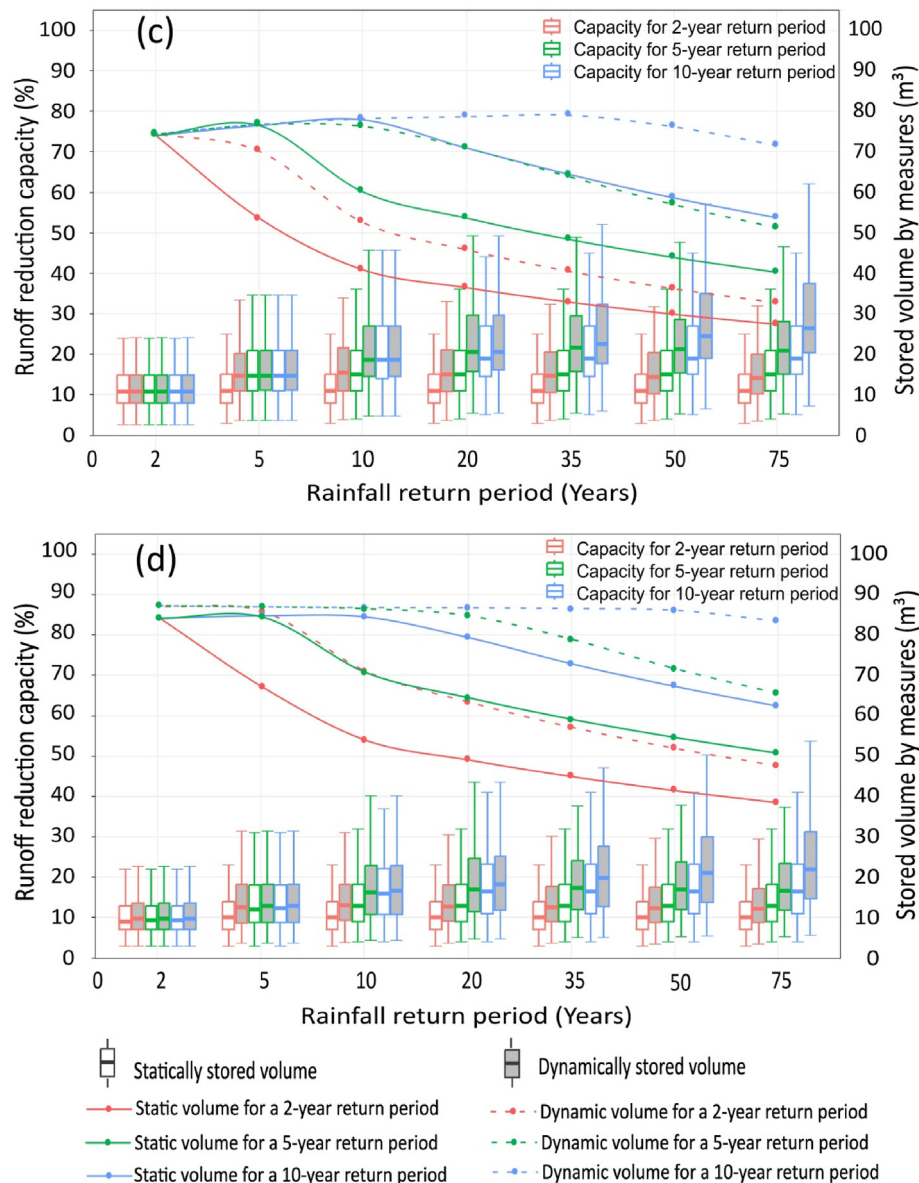


Fig. 7. (continued).

expansion events that hit Kinshasa in December 2022, killing >120 people (BBC, 2022). The observed new measures have a combined capacity of 29.8 m³. Although a systematic resurvey of the catchment was not possible and many more measures were likely implemented on parcels, this already represents an increase of the total static storage capacity in the basin by at least 6% as compared to the situation in October 2021 (Table A3). Given their strategic location along the main drainage line and near the catchment outlet and their ability to also infiltrate water, these measures likely already account for an important portion of the 30% overestimation of peak discharge. Furthermore, our research only included measures with a capacity greater than 0.5 m³.

Third, due to limited resources, also the measured rainfall depths and runoff discharges are subject to uncertainties. For example, the actual peak discharge might not have been captured, only the water stage before and after (Fig. 5), potentially making the overestimation again slightly smaller than suggested.

Lastly, some deviations may be due to systematic model errors. While these might lead to overestimations of peak and total

discharge, they will likely affect the different scenarios similarly. As our focus is on relative runoff reductions, errors in absolute discharge may therefore largely cancel each other out.

4.2. Why current efforts seem to fail

Our findings indicate that parcel runoff is the predominant source of runoff at urban gully heads (Fig. 9), reinforcing the idea that reducing runoff from areas upstream of the gully head should be a primary approach to control urban gully erosion (Bartley et al., 2020; Frankl et al., 2021; Vanmaercke et al., 2021). Nonetheless, despite the significant efforts conducted, current measures appear to have limited effect on reducing total runoff volumes (Fig. 7) and peak discharges (Fig. 8). This is likely explained by a combination of reasons.

Overall, the total installed capacity is too low to have a strong effect on runoff reduction. The total actual capacity observed during our field surveys was 1518 m³ in Kimwenza and 512 m³ in Kisenso EP5. Yet, the total parcel runoff produced by these two basins

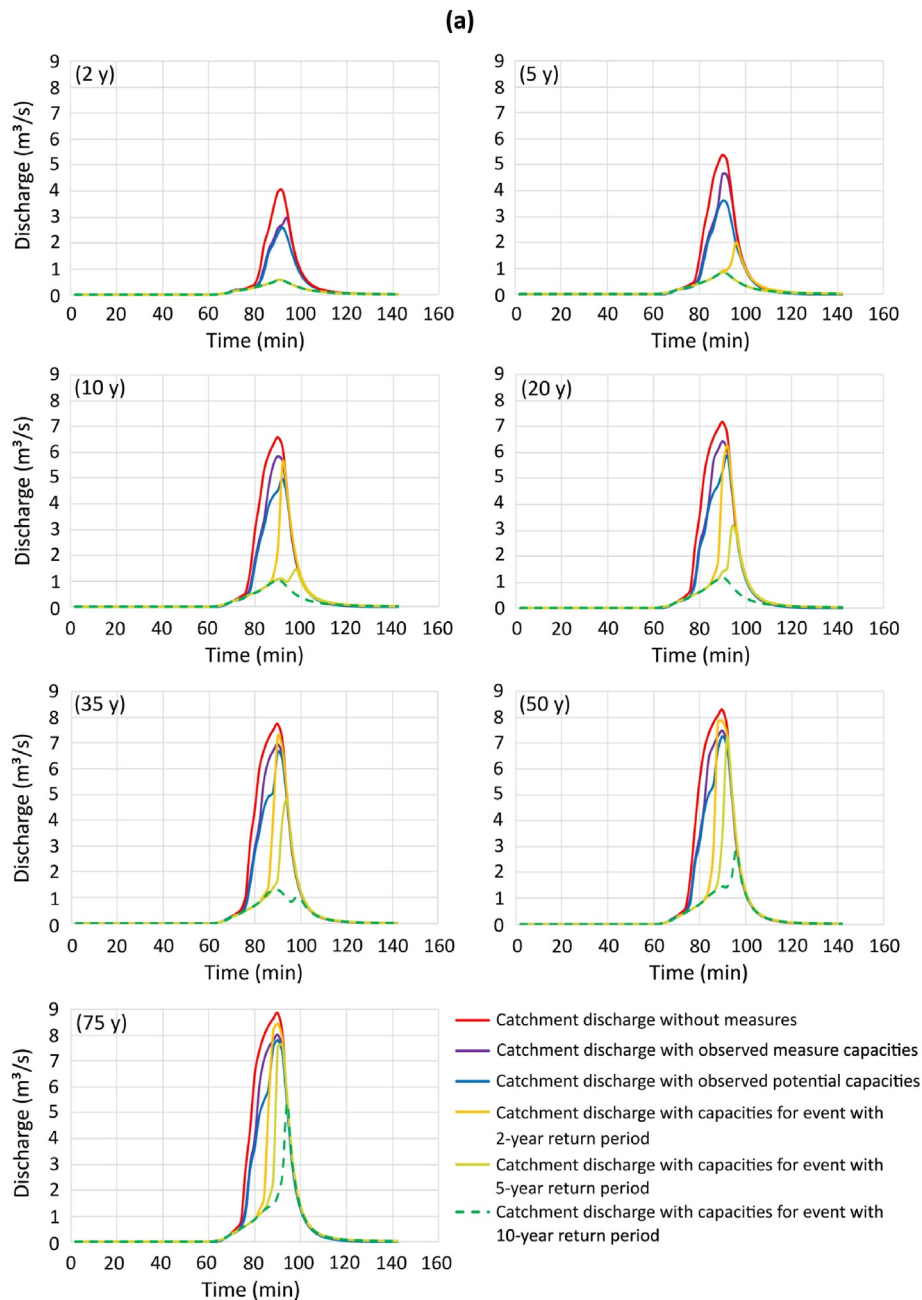


Fig. 8. Hydrographs for (a) Kimwenza and (b) Kisenso EP5, simulated for rainfall events with different return periods (2–75 years). Each time, simulations were run for different scenarios: assuming no runoff retention measures, considering the observed storage capacities, considering the potential storage capacities if all measures were well-maintained and assuming that each parcel had a retention basin with a static storage capacity equal to the expected parcel runoff volume produced by a rainfall event with a 2, 5 or 10-year return period.

during a rainfall event with a 2-year return period is 2580 m³ and 1359 m³, respectively.

Poor maintenance of many of the installed retention basins are already a major reason for this shortage. This is especially the case in the Kisenso EP5 catchments, where numerous retention basins were installed but already filled up (Fig. 4(f)). While the total potential capacity in the Kimwenza catchment was somewhat lower, most of these structures were better maintained, leading to a very similar observed static storage capacity (Fig. 4(d)).

Yet, more importantly, a large fraction of parcels have no significant retention structures installed. For example, only 34%

(Kisenso EP5) to 45% (Kimwenza) of the parcels had at least one retention basin installed (Fig. 6, Table A3). For rainwater tanks the situation is better, with 75% (Kimwenza) to 84% (Kisenso EP5) of the parcels having such measure installed. This links to the necessity to store rainwater for domestic use in these overall poor and unplanned neighborhoods (Bédécarrats et al., 2016; Ditona Tsumbu et al., 2020; Lateef et al., 2010; Nzuzi, 2008). Yet, such rainwater tanks are clearly less effective in preventing parcel runoff, as they have limited storage capacity, typically only capture runoff from roofs, and are not designed to infiltrate potential excess water.

Moreover, even in the parcels where measures are installed, the

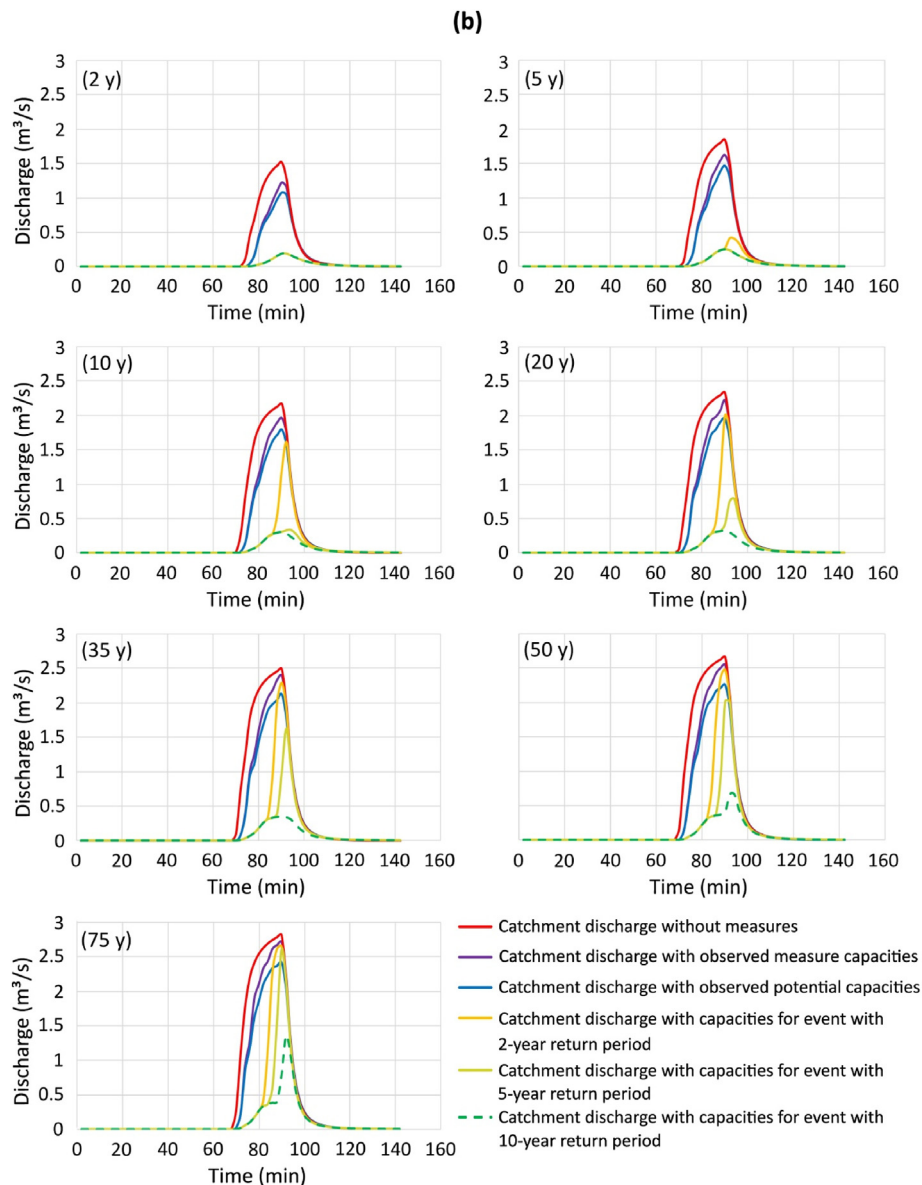


Fig. 8. (continued).

volume of these tanks and basins are not proportional to the parcel size. The majority of parcels possess inadequate capacity to capture the runoff generated by significant rainfall events. Yet, a minority of parcels have measures with capacities greatly exceeding the runoff volumes that can realistically be expected (Fig. 6). This disproportionality may be linked to a lack of quantitative insight into the storage capacities required. Our field surveys indicated that most people construct retention basins on their own parcels according to their own judgement, commitment and capacity.

Nonetheless, also the broader socio-economic context should be considered. The majority of the population living in the areas affected by urban gullies in Kinshasa have an income below \$1.9/day (Kayembe wa Kayembe, 2020; PNUD, 2019), making the implementation of larger measures that require significant investments nearly impossible. For them, a small, hand-dug retention basin (infiltration pit) is often the only measure that is feasible.

Social segregation may further aggravate the problem. Overall, we observe that many of the largest runoff retention basins are installed on parcels close to the gully head, while the (often

somewhat larger) parcels further away are less likely to have such larger basins (Fig. 4(b), (c), (g)). This is especially the case in the densely populated Kisenso EP5 catchment. On the other hand, parcels further away from the gully head are overall more likely to have rainwater tanks. These tendencies likely relate to socio-economic status. Kayembe wa kayembe (2020) argues that settlement development on the hills of Kinshasa follows a certain socio-spatial segregation imposed by decreasing land price from the relatively flatter hilltops to the steeper downslope zones. The latter are also more susceptible to gully formation (Makanzu Imwangana et al., 2014). While the overall richer population upslope may be able to install water tanks to foresee in their own domestic water consumption, they do not necessarily perceive the gully expansion as a risk that concerns them. As such, they may be less inclined to implement additional measures that capture the excess runoff from their parcels. The poorer population downslope is confronted by the consequences of this, urging them to install –sometimes oversized– runoff retention basins. At that stage, however, these measures are of little avail.

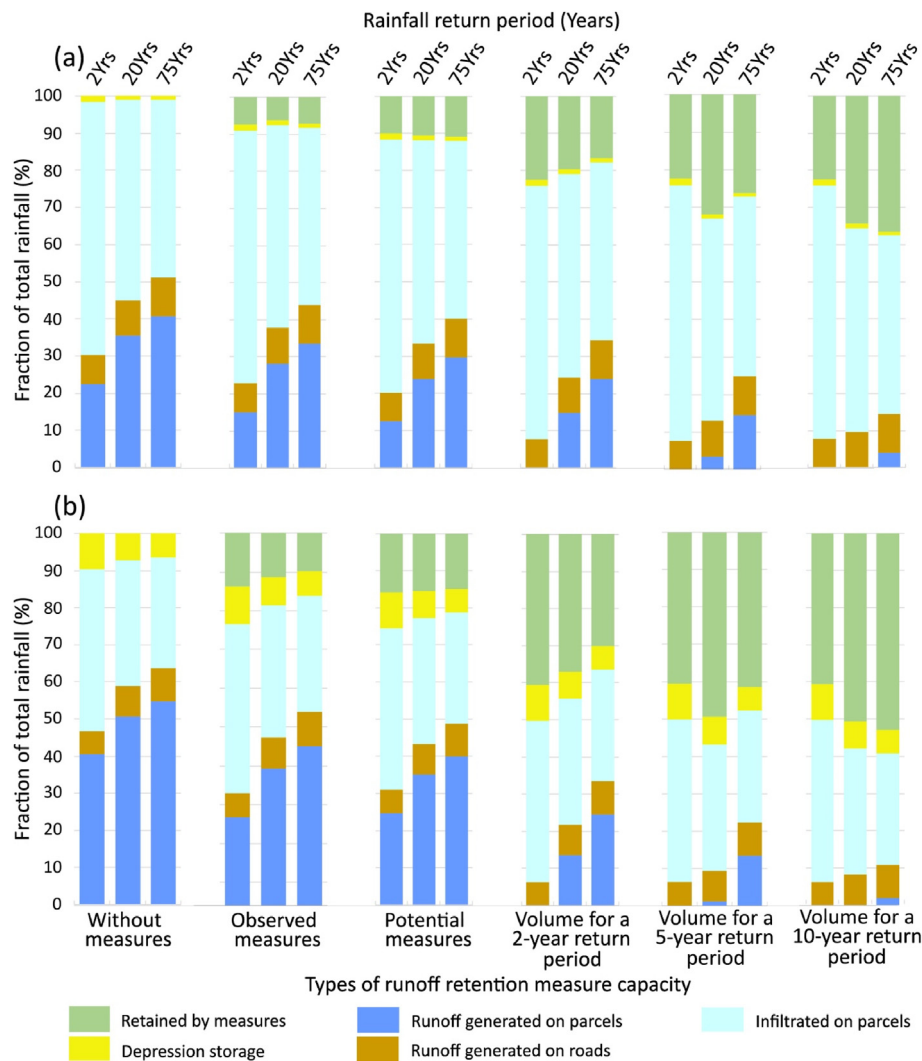


Fig. 9. Hydrological balance for (a) Kimwenza and (b) Kisenso EP5 under different scenarios of runoff retention measures and for rainfall events with a return period of respectively 2, 20 or 75 years. 'Retained by measures' indicate the water that is statically stored by measures or infiltrated in the soil by retention basins. 'Depression Storage' was calculated based on Eq. (4). 'Infiltrated on parcels' was calculated as the difference between Eq. (3) and Eq. (4). 'Runoff generated on road/parcels' indicate the remaining rainfall that is not infiltrated, retained as depression storage or captured by installed retention measures.

In this regard, also the contrasts with the Kimwenza catchment is revealing. While both catchments had a very similar observed static storage capacity per unit area (Fig. 4(d) and (f)), the effect of these measures in reducing peak discharges was generally larger (Fig. 8) in Kimwenza. A key reason for this is that this catchment mainly consists of large parcels, owned by schools and convents (Fig. 1). Many of these parcels already have large runoff retention structures installed (Fig. 4(b) and (e)). A greater awareness of the need to retain rainwater on parcels, but also more financial and material means available to install such structures (e.g. Fig. 3(l)) likely explain this. As a result of this, installed retention structures are more equally spread across the Kimwenza catchment and more proportional to parcel sizes (Fig. 4(b)), resulting in an overall greater effectiveness (Fig. 8(a)).

It should be noted that some international organizations and local NGOs already help address the need for more runoff retention structures by implementing additional water retention structures. For example, FOLECO, GIZ and CTB/BTC have installed large (>50 m³) retention basins on avenues as well as dykes to slow down runoff (Makanzu Imwangana, 2014; Kayembe Wa Kayembe & Wolff, 2015; Kayembe wa Kayembe, 2020). More recently,

organizations like CEEDD and the Terrafrima Rainwater Collective focus on installing water tanks of 3–9 m³ that are directly connected to losing wells to infiltrate excess water. Yet, despite great support from the population, these initiatives currently appear too limited to have a significant impact (Lutete Landu et al., 2023).

4.3. Towards more successful runoff reduction strategies

Our results indicate that strategies where every parcel has measures to prevent runoff from leaving its boundaries offer great potential to reduce the problem (Figs. 7–9). Nonetheless, several elements need careful attention when implementing such strategies.

First, it appears key that runoff retention measures are implemented proportional to the parcel size. Whereas, the total volume of currently implemented measures in the catchments is significant, they have only a limited effect on total runoff volume (Fig. 7) and peak discharge (Fig. 8). A major reason for this is that a few large parcels have little to no retention measures (Fig. 6(b)) and are thus responsible for a disproportionately large part of the runoff production. On the other hand, some smaller parcels have

capacities that are generally much larger than the runoff volume they may actually capture. This results in a loss of efficiency and may even create a false sense of security. Policies that provide clear regulations on the minimum required storage volumes per parcel will likely be needed for this. Our work provides quantitative insights that may help developing such policies (e.g. Fig. 6(a)).

Second, it will be important that implemented runoff retention basins are well-maintained. Due to various water erosion processes, many retention basins quickly fill up with sediments (Bartley et al., 2020; Makanzu Imwangana et al., 2015; Van Caillie, 1989, Fig. 4(d)). This may not only reduce the static but also the dynamic storage capacity, as such infilling may lead to the formation of depositional crusts that strongly limit infiltration. Regularly removing the sediments and breaking up such crusts is therefore required. Planting vegetation in and around retention basins may also help, as they can increase infiltration capacities (Bartley et al., 2020; Frankl et al., 2021; Sambieni et al., 2018; Vannoppen et al., 2015; Zegeye et al., 2018). Rainwater tanks generally suffer less from sedimentation problems as they typically only capture water from roofs and are typically better maintained. However, their potential to actually reduce parcel runoff volume is likely much more limited. First, they are typically smaller (Fig. 4(d)) and only capture rainfall from roofs. Second, due to their importance for domestic use, they may already be (partially) filled before a rainfall event. Measures that directly couple the overflow of a rainwater tank to a small retention basin protected with blocs (losing well, e.g. Fig. 3(a)), may offer a good solution here. Nonetheless, implementing such measures often remains costly for parcels owners (Burns et al., 2015; Campisano et al., 2017; Hermann & Schmida, 2000; Kim & Yoo, 2009).

Third, important trade-offs exist between effectiveness and feasibility. Measures with a static capacity equal to the parcel runoff produced by an event with a 2-year return period can drastically reduce runoff production for rainfall events with return below 5 years. Yet, for larger events, the effect quickly drops (Figs. 7 and 8). As such, larger storage capacities are better. Yet, such measures require a significant commitment. For example, assuming a basin depth of 1 m and subtracting the areas already occupied by buildings, a retention basin able to capture the runoff of a 5-year event would require on average 4.7% ($\pm 2.3\%$) of the available free parcel area in Kimwenza and 9.1% ($\pm 5.6\%$) in Kisenso EP5. For a 10-year event, these percentages rise to 5.9% ($\pm 2.7\%$) to and 11.1% ($\pm 6.5\%$), respectively. This may quickly make such measures impractical (e.g. Fig. 10(a)), leading to a lower likelihood that they are indeed consistently implemented and maintained. In addition, having infiltration basins with ponding water can lead to various other nuisances and safety issues.

Further reflection is therefore needed on how to best install retention basins. Constructing retention basins of greater depth may strongly reduce the parcel area required and is already commonly done in our study area (Fig. 3, Table A3). Nonetheless, such basins may become dangerous to construct and maintain and typically require larger investments. Reshaping the parcel so that large parts are lowered with a few decimetres could potentially provide an alternative (Fig. 10(b)). In such case, a majority of the parcel may potentially be used to store and infiltrate runoff during significant rainfall events, while the parcel area may remain available for other purposes under dry conditions.

Measures aiming to store and infiltrate runoff are also better combined with initiatives to further enhance infiltration and slow down runoff. Examples include planting vegetation in strategic areas, using permeable pavements, and connecting different retention measures to optimize runoff control (Travis & Mays, 2008; Reaney et al., 2014; Zanandrea & Silveira, 2018). Parcels

with high a hydraulic connectivity can particularly benefit from such additional measures. Also in this regard, results for Kimwenza and Kisenso Ep5 indicate telling differences. While installed retention measures have an overall larger effect on reducing peak discharges in Kimwenza (Fig. 8), their effect in terms of relative total runoff reduction is smaller than in Kisenso Ep 5 (Fig. 7). One key reason for this is the denser vegetation cover in Kimwenza (Fig. 1, Table A1), resulting in overall much higher on-parcel infiltration rates and, hence, less runoff production (Fig. 9). This probably also makes runoff retention structures more effective in reducing peak discharges, as the amount of remaining runoff to capture is relatively smaller. Since reducing these peak discharges is generally most critical to stabilize gullies (e.g. Bartley et al., 2020; Vanmaercke et al., 2021), this suggests that combining such retention structures with vegetation measures that promote infiltration may lead to even more efficient stabilization and prevention initiatives.

Finally, the road network must also be considered. While roads contribute a limited percentage of overall runoff (Fig. 9), the total volumes can be significant. Moreover, their high hydraulic connectivity (Bracken & Croke, 2007) means they play a key role in channeling runoff from parcels to the gully head, thus contributing to gully initiation and expansion (Ilombe Mawe et al., 2024; Makanzu Imwangana et al., 2014). Therefore, roads need to safely evacuate all runoff they produce or the water that cannot be retained on parcels, preferably through concrete channels that safely direct water to the bottom of hillslopes. Such infrastructure is costly and often lacking (e.g., Makanzu Imwangana et al., 2015). Yet, effective rainfall retention measures on parcels can clearly reduce the required dimensions and, by extent, the costs. Also retention basins, dams, vegetation or other measures along the road network can be helpful here. Affected communities already regularly implement such initiatives (e.g., Lutete Landu et al., 2023; Fig. A2), and as our comparison suggests (cf. section 3.2), they may be clearly effective in reducing peak discharges.

4.4. Limits and scope of research

While our research provides important insights into the potential of runoff retention measures for preventing and mitigating urban gully erosion, it also comes with limitations. First, as already discussed (sections 2.6 & 4.1), the accuracy of our simulations could only be tested for one event. Further validation and finetuning of our model setup across different catchments and rainfall events is therefore highly recommended.

Related to this, it is important to point out that our findings cannot be straightforwardly extrapolated to other cities affected by urban gullies. Especially contrasts in soil types and hence in infiltration capacity may play an important role here. Infiltration not only greatly influences the expected parcel runoff (Section 2.4; Moeyersons et al., 2015) but also the effectiveness of runoff retention basins through its effect on dynamic storage capacity (Figs. 6(b) and 7). Due to the presence of very sandy soils, infiltration capacities in Kinshasa are overall very high (Jones et al., 2013; Lateef et al., 2010; Moeyersons et al., 2015; Van Caillie, 1989). Nonetheless, urban gullies also occur in cities where soils have lower infiltration rates due to their higher clay content (e.g. Lutete Landu et al., 2023). This may significantly reduce the effectiveness of retention basins in such cities. Yet, quantitative assessments of this are hitherto lacking.

In our analyses, we also only considered hypothetical rainfall events with return periods of 2–75 years. This because the initiation and expansion of urban gullies is caused by such large events

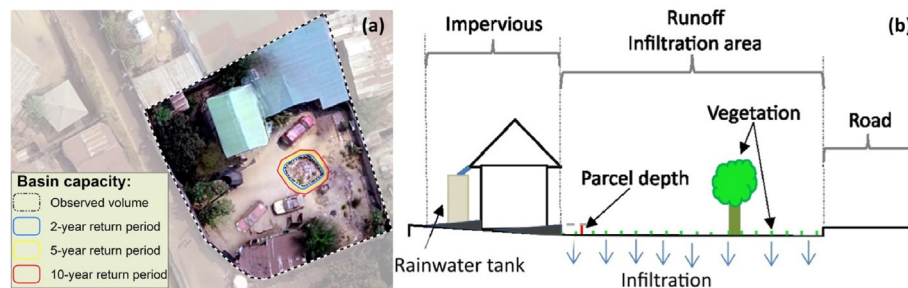


Fig. 10. (a) Example of a typical parcel in Kisenso EP5 (see Fig. 1) with a retention basin installed. Assuming a depth of 1 m, the installed basin can be expected to store the parcel runoff produced by a 2-year rainfall event. Yet, enlarging its size to cope with rainfall events with return periods of 5 or 10 years would require a further, significant space investment. (b) Lowering parts of the parcel area to temporarily store and infiltrate runoff during rainfall events may be an alternative strategy to avoid that parcel runoff concentrates on roads.

(Moeyersons et al., 2015; Mohymont et al., 2004). However, to fully understand the dynamics of runoff production, it is recommended to also consider the effect of actual, successive rainfall events. Indeed, due to soil saturation effects, a series of events may potentially generate more runoff than the sum of individual events (e.g. Minet et al., 2011). Moreover, runoff retention measures may be less effective as they may still contain water from previous events (cf. section 4.2).

Finally, also the link between runoff discharge at a gully head and the resulting potential gully expansion will merit further research. From first principles, it is clear that gully formation, gully headcut retreat and gully widening are all strongly controlled by the discharge of the concentrated flow and the duration of the event (e.g. Frankl et al., 2011; Hayas et al., 2019; Vanmaercke et al., 2016, 2021). Yet, quantifying the exact effect of runoff on gully expansion remains extremely challenging (Ilombe Mawe et al., 2024). Nevertheless, this is critical to design and implement efficient gully prevention and stabilization measures, as it determines which amount of runoff may be acceptable.

5. Conclusions

Urban gullies are a rapidly growing concern in the Global South. A promising strategy to address them is implementing retention basins and water tanks to limit runoff production and concentration. This study presents the first analysis on the potential of runoff retention measures in reducing urban gully erosion, based on detailed field observations in two representative catchments in Kinshasa as well as a novel modelling framework.

Our results show that although 85% of parcels have rainfall retention measures, their overall effect on catchment runoff production is limited (i.e., <30% reduction for a 2-year event, to <15% reduction for a 75-year event; Fig. 7). One reason is the limited capacity of many installed measures, partly due to poor maintenance. More importantly, many parcels have no or insignificant capacity installed. Especially larger parcels and parcels further away from the gully head tend to have undersized measures (Fig. 6(a)). In contrast, many parcels close to the gully head, typically inhabited by poorer populations, often have larger retention basins, as these residents are most directly threatened by gully expansion. Yet, these measures fall short of really stopping the accumulated runoff produced by other parcels upslope.

Nonetheless, our scenario analyses show that installing runoff retention measures can be extremely effective in reducing runoff accumulation. Ensuring that every parcel has a retention basin with a static capacity proportional to its size can reduce catchment-scale

runoff production by 70–80% (Fig. 7). Therefore, developing policies that encourage such measures is highly recommended. However, the exact design details require careful consideration. Effectiveness depends on the storage capacity of the measures and the return period of the rainfall event (Figs. 7 and 9). Larger structures are generally more effective but also more costly and difficult to implement.

Overall, our work demonstrates that coordinated initiatives to retain runoff on parcels can be a key strategy to control urban gullies. Furthermore, it provides a suitable framework to develop similar strategies for the numerous other cities in the tropical Global South affected by Urban Gullies. Nevertheless, further testing and fine-tuning of this framework is recommended.

CRedit authorship contribution statement

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

Declaration of competing interest

The authors have no conflict of interest to report.

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APPENDICES

Table A1

Characteristics of the two studied urban gully catchments. See text for more information. 'SWMM' stands for 'Soil Water Management Model'.

	KIMWENZA		KISENSO EP5	
Area (ha)	18.9	100%	5.6	100%
Herbaceous plant cover (ha)	5.5	29%	0.1	2%
Tree cover (ha)	3.6	19%	0.8	14%
Impervious area (ha)	3.2	17%	2.0	36%
Bare area (ha)	6.6	35%	2.7	48%
Slope, mean $\pm$ st. dev. (%)		12.3%		9.4%
	Parcels	Roads	Parcels	Roads
Runoff producing entities, #	114	9	120	12
Area, min.-max. (ha)	0.01–5.4	0.01–1.41	0.01–0.3	0.004–0.31
Area, mean $\pm$ st. dev. (ha)	0.14 $\pm$ 0.53	0.34 $\pm$ 0.48	0.04 $\pm$ 0.03	0.05 $\pm$ 0.08
Area, total (ha)	15.83	3.08	4.77	0.84
Length, min. – max. (m)	14.9–299.9	32.5–987	11.8–91.7	13.4–618
Length, mean $\pm$ st. dev. (m)	36 $\pm$ 41.3	381 $\pm$ 353.9	23.8 $\pm$ 8.5	128 $\pm$ 168.4
Length, total (m)	4098	3426	2859	1667
Width, min.-max. (m)	7.0–180	3.0–20	5.6–34	1.6–7.0
Width, mean $\pm$ st. dev. (m)	21.9 $\pm$ 15.2	7.3 $\pm$ 5.3	15.6 $\pm$ 5.2	4.8 $\pm$ 1.6
Impervious area, min. – max. (%)	0–70.1	0–42	0–79.4	0
Impervious area, mean $\pm$ st. dev. (%)	29.0 $\pm$ 14.4	4.7 $\pm$ 14.1	46.6 $\pm$ 18.2	0
Impervious area, total (%)	18.8	19.4	42.3	0
Tree cover, min.-max. (%)	1.2–62.3	1.4–26.9	0–51.8	0.3–26.2
Tree cover, mean $\pm$ st. dev. (%)	18.9 $\pm$ 11.7	13.7 $\pm$ 8.7	12.3 $\pm$ 11.9	8.5 $\pm$ 8.0
Tree cover, total (%)	20.9	7.9	14.6	11.0
Herbaceous area, min.-max. (%)	2.6–53.1	8.5–68.3	0–24.7	0–0.7
Herbaceous area, mean $\pm$ st. dev. (%)	21.6 $\pm$ 10.8	33.7 $\pm$ 20.5	1.5 $\pm$ 3.5	0.1 $\pm$ 0.3
Herbaceous area, total (%)	31.8	15.7	2.5	0.2
Bare area, min. – max. (%)	1.9–76.2	12.1–90.1	12.9–77.2	73.8–99.7
Bare area, mean $\pm$ st. dev. (%)	30.5 $\pm$ 15.3	47.9 $\pm$ 23.6	39.6 $\pm$ 12.6	91.3 $\pm$ 7.9
Bare area, total (%)	28.5	57.0	40.6	88.8
Slope steepness, min.-max. (%)	1.7–35.3	1.5–21.0	1.5–16.2	1.6–15.3
Slope steepness, mean $\pm$ st. dev. (%)	12.1 $\pm$ 7.4	10.6 $\pm$ 5.1	7.3 $\pm$ 3.0	6.4 $\pm$ 3.1
SWMM parameters				
Manning coefficient, min.-max. (Yen, 2001)	0.055–0.075	0.01–0.04	0.055	0.040
Manning coefficient, mean $\pm$ st. dev.	0.057 $\pm$ 0.01	0.03 $\pm$ 0.01	0.055 $\pm$ 0.0	0.04 $\pm$ 0.0
Curve Number, min.-max.	77.9–93.4	80.3–100	77.9–95.5	85.8–86.1
Curve Number, mean $\pm$ st. dev.	84.3 $\pm$ 3.2	87.0 $\pm$ 6.2	88.2 $\pm$ 4.01	86.1 $\pm$ 0.06

Table A2

Overview of the various parameters of the SWMM model

	Kimwenza	Kisenso EP5
# of raingages	1	1
# of sub-catchments	193	159
# of junction nodes	96	82
- Initial depth of junction (m)	0	0
- Invert elevation of junction (m)	variable	Variable
- Maximum depth of junction (m)	0	0
# of storage nodes	105	105
- Invert elevation of node (m)	variable	Variable
- Initial depth of junction (m)	0	0
- Maximum depth of junction (m)	variable	Variable
- Seepage loss	Yes/No	Yes/No
# of conduit links	201	187
- Conduit length (m)	variable	variable

Table A2 (continued)

	Kimwenza	Kisenso EP5
- Conduit width (m)	variable	Variable
- Maximum depth of conduit (m)	0.5	0.5
- Roughness of conduit	0.01	0.01
- Shape of conduit	rectangular	Rectangular
# of outfall nodes	1	1
Storage infiltration parameters (Green-Ampt)		
- Suction head (mm)	49	49
- Conductivity (mm/h)	423	267
- Initial deficit	0.2	0.2
Rain gage parameters		
- Rain format	Volume	Volume
- Time interval	0:30	0:30
- Snow Catch Factor	1	1
- Data Source	Time series	Time series
- Series Name	Yes	Yes

Table A3

Characteristics of the water retention structures in the two gully catchments.

	KIMWENZA		KISENSO EP5	
# of storage units	157		149	
# of parcels with storage unit	88	77%	110	92%
# of parcels with storage unit >0.5m ³	76	68%	86	72%
Volume of storage unit, total (m ³)	1518.4	100%	512.3	100%
Volume of storage unit >0.5m ³ , total (m ³)	1490.6	98%	502.5	98%
Area of storage units, total (m ²)	515.3	100%	252.8	100%
	Retention basins	Rainwater tanks	Retention basins	Rainwater tanks
# storage units	72	85	48	101
Proportion of parcels with storage (%)	44.7	74.6	34.2	84.2
Volume, min.-max. (m ³)	0.1–81.6	0.06–718.2	0.18–42.0	0.04–33.7
Volume, mean $\pm$ st. dev. (m ³)	8.5 ($\pm$ 12.4)	10.6 ($\pm$ 77.8)	5.5 ($\pm$ 8.3)	2.5 ($\pm$ 4.9)
Volume, total (m ³)	614.4	904.0	261.7	250.6
Area, min.-max. (m ²)	0.4–26.8		0.4–28.0	
Area, mean $\pm$ st. dev (m ²)	7.2 ($\pm$ 6.4)		5.3 ($\pm$ 5.7)	
Area, total (m ²)	515.3		252.8	
Depth, min.-max. (m)	0.1–3.5		0.3–2.3	
Depth, mean $\pm$ st. dev (m)	1.0 ($\pm$ 0.6)		0.9 ($\pm$ 0.5)	
Distance from gully head min.-max. (m)	17.1–832.9	86.6–847.9	13.6–525.4	60.3–527.5
Median distance from gully head (m)	470.8	485.9	321.6	312.5
# of storage units with infiltration data	17		7	
# of well-maintained storage units with infiltration data	6		7	
Storage unit infiltration rate, min.-max. (mm.h ⁻¹)	182–885		66–581	
Storage unit infiltration rate, mean $\pm$ st. dev (mm.h ⁻¹)	423 ($\pm$ 242)		267 ($\pm$ 146)	
Proportion of well-maintained measures (%)	16.7	100	31.3	100
Proportion of fully filled measures (%)	5.6		8.3	
Proportion of partially filled measures (%)	77.8		60.4	
Proportion of undersized storage (%)	95.8		98	100

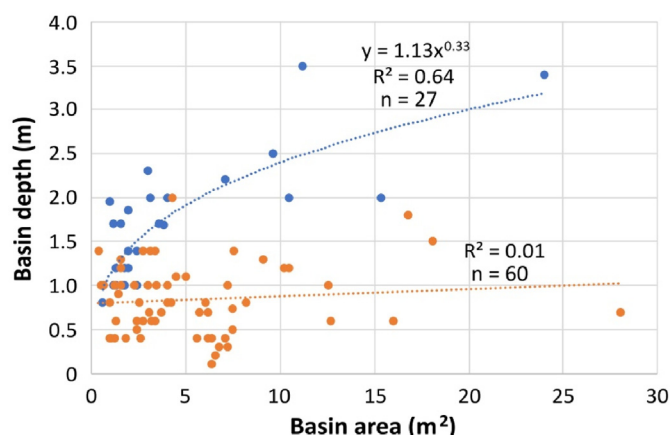


Fig. A1. Relationship between the average depth and the surface area for well-maintained retention basins (blue) and for poorly maintained basins (orange).

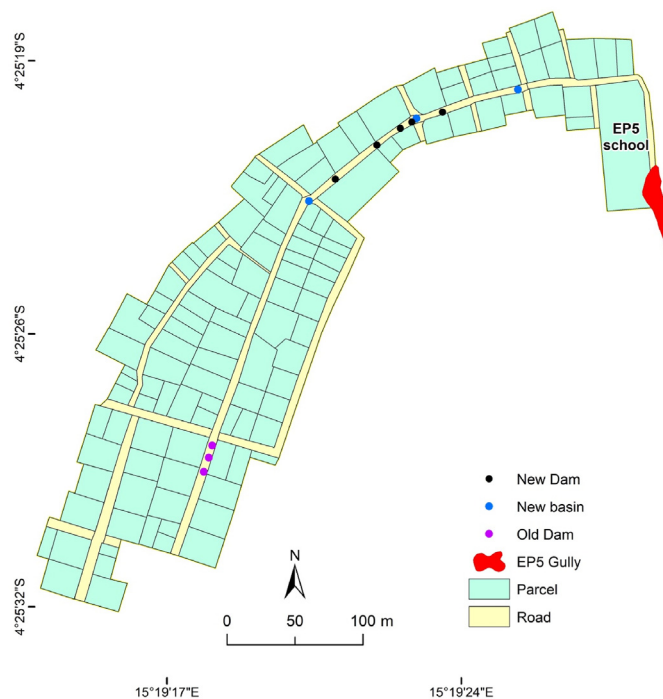


Fig. A2. Some newly observed measures in the Kisenso EP5 catchment, installed between our systematic field surveys (July–October 2021) and the recorded runoff event (February 2023). In 2021, only a few old check dams were present along the road in the upstream part of the catchment. Yet, since then, at least 8 additional dams and retention basins were constructed along the lower part of the main road. Potentially new measures on parcels could not be documented.

References

- Adediji, A., Jeje, L. K., & Ibitoye, M. O. (2013). Urban development and informal drainage patterns: Gully dynamics in Southwestern Nigeria. *Applied Geography*, 40, 90–102.
- Alfieri, L., Laio, F., & Claps, P. (2008). A simulation experiment for optimal design hyetograph selection. *Hydrological Processes: International Journal*, 22(6), 813–820.
- Arjenaki, M. O., Sanayei, H. R. Z., Heidarzadeh, H., & Mahabadi, N. A. (2021). Modeling and investigating the effect of the LID methods on collection network of urban runoff using the SWMM model (case study: Shahrekord City). *Modeling Earth Systems and Environment*, 7(1), 1–16.
- Babaei, S., Ghazavi, R., & Erfanian, M. (2018). Urban flood simulation and prioritization of critical urban sub-catchments using SWMM model and PROMETHEE II approach. *Physics and Chemistry of the Earth, Parts A/B/C*, 105, 3–11.
- Balzerek, H., Fricke, W., Heinrich, J., & Moldenhauer, K. M. (2003). Man-made flood

- disaster in the Savanna town of Gombe/NE Nigeria. The natural hazard of gully erosion caused by urbanization dynamics and their peri-urban footprints. *Erdkunde*, 57(2), 94–109. <https://doi.org/10.3112/erdkunde.2003.02.02>
- Bartley, R., Poesen, J., Wilkinson, S., & Vanmaercke, M. (2020). A review of the magnitude and response times for sediment yield reductions following the rehabilitation of gullied landscapes. *Earth Surface Processes and Landforms*, 24, 3250–3279. <https://doi.org/10.1002/esp.4963>
- BBC. (2022). DR Congo floods leave more than 120 dead in Kinshasa. Available online: <https://www.bbc.com/news/world-africa-63967016>.
- Beck, H. E., Zimmermann, N. E., McVicar, T. R., Vergopolan, N., Berg, A., & Wood, E. F. (2018). Present and future Köppen-Geiger climate classification maps at 1-km resolution. *Scientific Data*, 5(1), 1–12.
- Bédécarrats, F., Lafuente-Sampietro, O., Leménager, M., & Sowa, D. L. (2016). Building commons to cope with chaotic urbanization? Performance and sustainability of decentralized water services in the outskirts of Kinshasa. *Journal of Hydrology*, 573, 1096–1108.
- Bracken, L. J., & Croke, J. (2007). The concept of hydrological connectivity and its contribution to understanding runoff-dominated geomorphic systems. *Hydrological Processes: International Journal*, 21(13), 1749–1763.
- Brunner, G. W. (1995). HEC-RAS river analysis system. *Hydraulic reference manual*. Davis CA: Hydrologic Engineering Center Version 1.0. .
- Brunner, G. W. (2010). *Hydraulic reference manual*. Davis, CA: US Army Corps of Engineers, Hydrologic Engineering Center.
- Burns, M. J., Fletcher, T. D., Duncan, H. P., Hatt, B. E., Ladson, A. R., & Walsh, C. J. (2015). The performance of rainwater tanks for stormwater retention and water supply at the household scale: An empirical study. *Hydrological Processes*, 29(1), 152–160.
- Campisano, A., Butler, D., Ward, S., Burns, M. J., Friedler, E., DeBusk, K., ... Han, M. (2017). Urban rainwater harvesting systems: Research, implementation and future perspectives. *Water Research*, 115, 195–209.
- Castillo, C., & Gomez, J. A. (2016). A century of gully erosion research: Urgency, complexity and study approaches. *Earth-Science Reviews*, 160, 300–319.
- Dagnew, D. C., Guzman, C. D., Zegeye, A. D., Tibebe, T. Y., Getaneh, M., Abate, S., Zemale, F. A., Ayana, E. K., Tilahun, A. S., & Steenhuis, T. S. (2015). Impact of conservation practices on runoff and soil loss in the sub-humid Ethiopian highlands: The debre mawi watershed. *Journal of Hydrology and Hydromechanics*, 63(3), 210–219. <https://doi.org/10.1515/johh-2015-0021>
- Datta, A., & Shaban, A. (2016). *Mega-urbanization in the global south: Fast cities and new urban utopias of the postcolonial state*. New York: Routledge.
- Dewitte, O., Jones, A., Spaargaren, O., Breuning-Madsen, H., Brossard, M., Dampha, A., ... Zougmore, R. (2013). Harmonisation of the soil map of Africa at the continental scale. *Geoderma*, 211, 138–153.
- Ditona Tsumbu, H., Cammaerts, D., Adant, I., Sambieni Kouagou, R., Lelo Nzuzi, F., & Deliége, J. F. (2020). Acceptabilité sociale d'un système décentralisé d'approvisionnement en eau potable: le cas d'étude des Associations d'Usagers de Réseaux d'Eau Potable (ASUREP) à Kinshasa, République Démocratique du Congo. *International Journal Water Science and Environment Technologies*, (2).
- Dongquan, Z., Jinling, C., Haozheng, W., Qingyuan, T., Shangbing, C., & Zheng, S. (2009). GIS-Based urban rainfall-runoff modeling using an automatic catchment-discretization approach: A case study in Macau. *Environmental Earth Sciences*, 59, 465–472.
- Erbek, F. S., Özkan, C., & Taberner, M. (2004). Comparison of maximum likelihood classification method with supervised artificial neural network algorithms for land use activities. *International Journal of Remote Sensing*, 25(9), 1733–1748.
- Frankl, A., Nyssen, J., De Dapper, M., Haile, M., Billi, P., Munro, R. N., Deckers, J., & Poesen, J. (2011). Linking long-term gully and river channel dynamics to environmental change using repeat photography (Northern Ethiopia). *Geomorphology*, 129, 238–251. <https://doi.org/10.1016/j.geomorph.2011.02.018>
- Frankl, A., Nyssen, J., Vanmaercke, M., & Poesen, J. (2021). Gully prevention and control: Techniques, failures and effectiveness. *Earth Surface Processes and Landforms*, 46(1), 220–238.
- Gironás, J., Roesner, L. A., Rossman, L. A., & Davis, J. (2010). A new applications manual for the storm water management model (SWMM). *Environmental Modelling & Software*, 25(6), 813–814.
- Guerra, A. J., Sathler, R., Mendes, S. P., Silva, S. L. S., Guerra, T. T., Araujo, I. H. M., Lima, F. S., Fullen, M. A., Booth, C. A., Mendonça, J. K. S., Furtado, M. S., Souza, U. D. V., & Ribeiro, F. V. (2006). *Urban gully assessment in Sao Luis City (Maranhao State), Brazil, using penetrometer data and soil properties*.
- Hawkins, R. H., Ward, T. J., Woodward, D. E., & Van Mullem, J. A. (2009). *Curve number hydrology: State of the practice* (p. 106). American Society of Civil Engineers.
- Hayas, A., Peña, A., & Vanwalleghem, T. (2019). Predicting gully width and widening rates from upstream contribution area and rainfall: A case study in SW Spain. *Geomorphology*, 341, 130–139.
- Hermann, T., & Schmida, U. (2000). Rainwater utilisation in Germany: Efficiency, dimensioning, hydraulic and environmental aspects. *Urban Water*, 1, 307–316.
- Hudec, P. P., Simpson, F., Akpokodje, E. G., & Umenweke, M. O. (2005). Anthropogenic contribution to gully initiation and propagation in southeastern Nigeria. *GSA Reviews in Engineering Geology*, 16, 149–158. [https://doi.org/10.1130/2005.4016\(13](https://doi.org/10.1130/2005.4016(13)
- Ilombe Mawe, G., Lutete Landu, E., Makanzu Imwangana, F., Hubert, A., Dille, A., Bielders, C. L., ... Vanmaercke, M. (2024). What controls the expansion of urban gullies in tropical environments? Lessons learned from contrasting cities in DR Congo. *Catena*, 241, Article 108055.
- Ilombe Mawe, G., Lutete Landu, E., Makanzu Imwangana, F., Nzolang, C.,

- Nandefo, R. W., Poesen, J., Bielders, C., Dewitte, O., & Vanmaercke, M. (2021). Quantifying the impacts of urban gully erosion at the scale of the Democratic Republic of Congo, EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-8831. <https://doi.org/10.5194/egusphere-egu21-8831>
- Jeffers, S., Garner, B., Hidalgo, D., Daoularis, D., & Warmerdam, O. (2022). Insights into green roof modeling using SWMM LID controls for detention-based designs. *Journal of Water Management Modeling*, 13.
- Jones, A., Breuning-Madsen, H., Brossard, M., Dampah, A., Deckers, J., Dewitte, O., Gallali, T., Hallett, S., Jones, R., Kilasara, M., Le Roux, P., Micheli, E., Montanarella, L., Spaargaren, O., Thiombiano, L., Van Ranst, E., Yemefack, M., & Zougmore, R. (eds.) (2013). *Soil Atlas of Africa*. Luxembourg: European Commission, Publications Office of the European Union, 176 pp. ISBN 978-92-79-26715-4, <https://doi.org/10.2788/52319>.
- Junior, O. C., Guimaraes, R., Freitas, L., Gomes-Loebman, D., Gomes, R. A., & Martins, E. (2010). Urbanization impacts upon catchment hydrology and gully development using multi-temporal digital elevation data analysis. *Earth Surface Processes and Landforms*, 35(5), 611–617. <https://doi.org/10.1002/esp.1917>
- Kayembe wa Kayembe, M. (2020). *Ville et érosion ravinante intra-urbaine: Kinshasa: facteurs, conséquences et interventions*. Editions L'Harmattan.
- Kayembe Wa Kayembe, M., & Wolff, E. (2015). Contribution de l'approche géographique à l'étude des facteurs humains de l'érosion ravinante intra-urbaine à Kinshasa (R.D. Congo). *Geo-Eco-Trop*, 39(1), 119–138.
- Kim, K., & Yoo, C. (2009). Hydrological modeling and evaluation of rainwater harvesting facilities: Case study on several rainwater harvesting facilities in Korea. *Journal of Hydrologic Engineering*, 14, 545–561.
- Kourtis, I. M., Kopsiaftis, G., Bellos, V., & Tsihrintzis, V. A. (2017). Calibration and validation of SWMM model in two urban catchments in Athens, Greece. In *International conference on environmental science and technology (CEST)*.
- Kubwimana, D., Ait Ibrahim, L., Nkurunziza, P., Dille, A., Depicker, A., Nahimana, L., Abdelouafi, A., & Dewitte, O. (2021). Characteristics and distribution of landslides in the populated hillslopes of Bujumbura, Burundi. *Geosciences*, 11(6), 259.
- Kuhn, C. E. S., Reis, F. A. G. V., Zarfi, C., & Grathwohl, P. (2023). Ravines and gullies, a review about impact valuation. *Natural Hazards*, 117(1), 597–624.
- Lammers, R. W., Miller, L., & Bledsoe, B. P. (2022). Effects of design and climate on bioretention effectiveness for watershed-scale hydrologic benefits. *Journal of Sustainable Water in the Built Environment*, 8(4), Article 04022011.
- Lateef, A. S. A., Fernandez-Alonso, M., Tack, L., & Delvaux, D. (2010). Geological constraints on urban sustainability, Kinshasa city, democratic Republic of Congo. *Environmental Geosciences*, 17(1), 17–35.
- Lewis, A. (2017). *Storm water management model reference manual volume II hydraulics*. Cincinnati: US Environmental Protection Agency.
- Liu, X., Li, H., Zhang, S., Cruse, R. M., & Zhang, X. (2019). Gully erosion control practices in Northeast China: A review. *Sustainability*, 11(18), 5065. <https://doi.org/10.3390/su11185065>
- Liu, Z., & Todini, E. (2002). Towards a comprehensive physically-based rainfall-runoff model. *Hydrology and Earth System Sciences*, 6(5), 859–881.
- Lutete Landu, E., Ilombe Mawe, G., Makanzu Imwangana, F., Bielders, C., Dewitte, O., Poesen, J., ... Vanmaercke, M. (2023). Effectiveness of measures aiming to stabilize urban gullies in tropical cities: Results from field surveys across DR Congo. *International Soil and Water Conservation Research*, 11(1), 14–29.
- Makanzu Imwangana, F. (2014). Etude de l'érosion ravinante à Kinshasa. Thèse de doctorat en Sciences. *Faculté des Sciences, Université de Kinshasa*, Article 209p.
- Makanzu Imwangana, F., Dewitte, O., Ntombi, M., & Moeyersons, J. (2014). Topographic and road control of mega-gullies in Kinshasa (DR Congo). *Geomorphology*, 217, 131–139. <https://doi.org/10.1016/j.geomorph.2014.04.021>
- Makanzu Imwangana, F., Vandecasteele, I., Trefois, P., Ozer, P., & Moeyersons, J. (2015). The origin and control of mega-gullies in Kinshasa (D.R. Congo). *Catena*, 125, 38–49. <https://doi.org/10.1016/j.catena.2014.09.019>
- Minet, J., Laloy, E., Lambot, S., & Vanlooster, M. (2011). Effect of high-resolution spatial soil moisture variability on simulated runoff response using a distributed hydrologic model. *Hydrology and Earth System Sciences*, 15(4), 1323–1338.
- Moeyersons, J., Makanzu Imwangana, F., & Dewitte, O. (2015). Site- and rainfall-specific runoff coefficients and critical rainfall for mega-gully development in Kinshasa (DR Congo). *Natural Hazards*, 79(1), 203–233.
- Mohimont, B., Demarée, G. R., & Faka, D. N. (2004). Establishment of IDF-curves for precipitation in the tropical area of Central Africa-comparison of techniques and results. *Natural Hazards and Earth System Sciences*, 4(3), 375–387.
- Morokong, T., & Blignaut, J. N. (2019). Benefits and costs analysis of soil erosion control using rock pack structures: The case of mutale local municipality, Limpopo Province, South Africa. *Land Use Policy*, 83, 512–522. <https://doi.org/10.1016/j.landusepol.2019.02.010>
- NRCS. (2004). Hydrologic soil-cover complexes. *National Engineering Handbook, Part, 630*(Chapter 9). U.S. Dept. of Agriculture, Washington, DC.
- Nsabimana, J., Henry, S., Ndayisenga, A., Kubwimana, D., Dewitte, O., Kervyn, F., & Michellier, C. (2023). Geo-hydrological hazard impacts, vulnerability and perception in bujumbura (Burundi): A high-resolution field-based assessment in a Sprawling city. *Land*, 12(10), 1876.
- Nzuzi, F. L. (2008). *Kinshasa, ville et environnement. Kinshasa, ville et environnement*. Paris: Editions L'Harmattan.
- Onyelowe, K. C., Van, D. B., Ikpe, O. C., Ubachukwu, O. A., & Van Nguyen, M. (2018). Assessment of rainstorm induced sediment deposition, gully development at Ikot Ekpene, Nigeria and the devastating effect on the environment. *Environmental Technology & Innovation*, 10, 194–207.
- Pathak, P., Wani, S. P., & Sudi, R. (2005). Gully control in SAT watersheds. *Global theme on agroecosystems report no. 15*. Patancheru 502 324, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics.
- PNUD. (2019). *Rapport sur le développement humain 2019. Au-delà des revenus, des moyennes et du temps présent : les inégalités de développement humain au XXIe siècle*. Bureau de la coordination des affaires humanitaires de l'ONU.
- Poesen, J. (2018). Soil erosion in the anthropocene: Research needs. *Earth Surface Processes and Landforms*, 43(1), 64–84. <https://doi.org/10.1002/esp.4250>
- Poesen, J., Nachtergaele, J., Verstraeten, G., & Valentin, C. (2003). Gully erosion and environmental change: Importance and research needs. *Catena*, 50(2–4), 91–133.
- Rawls, W. J., Brakensiek, D. L., & Miller, N. (1983). Green-Ampt infiltration parameters from soils data. *Journal of Hydraulic Engineering*, 109(1), 62–70.
- Reaney, S. M., Bracken, L. J., & Kirkby, M. J. (2014). The importance of surface controls on overland flow connectivity in semi-arid environments: Results from a numerical experimental approach. *Hydrological Processes*, 28(4), 2116–2128.
- Rosa, D. J., Clausen, J. C., & Dietz, M. E. (2015). Calibration and verification of SWMM for low impact development. *JAWRA Journal of the American Water Resources Association*, 51(3), 746–757.
- Rossman, L. A., & Huber, W. C. (2016). *Storm water management model reference manual volume I—Hydrology*, 3. US Environmental Protection Agency.
- Ruggenthaler, R., Meißl, G., Geitner, C., Leitinger, G., Endstrasser, N., & Schöberl, F. (2016). Investigating the impact of initial soil moisture conditions on total infiltration by using an adapted double-ring infiltrometer. *Hydrological Sciences Journal*, 61(7), 1263–1279.
- Sambieni, K. R., Moyene, A. B., Toyi, M. S., Sambieni, E., Natta, A. K., Occhiuto, R., & Bogaert, J. (2018). La biodiversité des parcelles habitées en zone périurbaine à Kinshasa: déterminants socio-biophysiques et représentations. *International Journal of Biological and Chemical Sciences*, 12(3), 1164–1183.
- Sun, N., Hall, M., Hong, B., & Zhang, L. (2014). Impact of SWMM catchment discretization: Case study in Syracuse, New York. *Journal of Hydrologic Engineering*, 19(1), 223–234.
- Taye, G., Poesen, J., Vanmaercke, M., Van Wesemael, B., Martens, L., Tekla, D., Nyssen, J., Deckers, J., Vanacker, V., Haregeweyn, N., & Hallet, V. (2015). Evolution of the effectiveness of stone bunds and trenches in reducing runoff and soil loss in the semi-arid Ethiopian highlands. *Zeitschrift für Geomorphologie*, 59(4), 477–493. <https://doi.org/10.1127/zfg/2015/0166>
- Travis, Q. B., & Mays, L. W. (2008). Optimizing retention basin networks. *Journal of Water Resources Planning and Management*, 134(5), 432–439.
- Van Caillie, X. (1983). Hydrologie et érosion dans la région de Kinshasa. Analyse des interactions entre les conditions du milieu, les érosions et le bilan hydrologique. PhD. Thesis. *Department of geography and geology*. KU Leuven, Belgium.
- Van Caillie, X. (1989). Erodabilité des terrains sableux du Zaïre et contrôle de l'érosion. *Cahiers. ORSTOM, Sér. Pédol.*, 25(1–2), 197–208.
- Vanmaercke, M., Panagos, P., Vanwallegem, T., Hayas, A., Foerster, S., Borrelli, P., Poesen, J., Rossi, M., Torri, D., Casali, J., Borselli, L., Vigiak, O., Maerker, M., Haregeweyn, N., De Geeter, S., Zgibicki, W., Bielders, C., Cerdà, A., Conoscenti, C., de Figueiredo, T., ... (2021). Measuring, modelling and managing gully erosion at large scales: A state of the art. *Earth-Science Reviews*, Article 103637.
- Vanmaercke, M., Poesen, J., Mele, B., Van Demuzere, M., Bruynseels, A., Golosov, V., Rodrigues Bezerra, J. F., Bolysov, S., Dvinskikh, A., Frankl, A., Fuseina, Y., Guerra, A. J. T., Haregeweyn, N., Ionita, I., Makanzu Imwangana, F., Moeyersons, J., Moshe, I., Nazari Samani, A., Niacsu, L., ... (2016). Earth-Science Reviews How fast do gully headcuts retreat. *Earth-Science Reviews*, 154, 336–355. <https://doi.org/10.1016/j.earscirev.2016.01.009>
- Vannoppen, W., Vanmaercke, M., De Baets, S., & Poesen, J. (2015). A review of the mechanical effects of plant roots on concentrated flow erosion rates. *Earth-Science Reviews*, 150, 666–678.
- Verstraeten, G., & Poesen, J. (2000). Estimating trap efficiency of small reservoirs and ponds: Methods and implications for the assessment of sediment yield. *Progress in Physical Geography*, 24(2), 219–251.
- Wouters, T., & Wolff, E. (2010). Contribution à l'analyse de l'érosion intra-urbaine à Kinshasa (R.D.C.). *Belgeo [En ligne]*, 3 | 2010, mis en ligne le 15 décembre 2012, consulté le 30 septembre 2016. URL : <http://belgeo.revues.org/6477>
- Xu, C., Rahman, M., Haase, D., Wu, Y., Su, M., & Pauleit, S. (2020). Surface runoff in urban areas: The role of residential cover and urban growth form. *Journal of Cleaner Production*, 262, Article 121421.
- Yen, B. C. (2001). Hydraulics of sewer systems. In L. M. Mays (Ed.), *Stormwater collection systems design handbook*. New York: McGraw-Hill.
- Zanandrea, F., & Silveira, A. L. L. D. (2018). Effects of LID implementation on hydrological processes in an urban catchment under consolidation in Brazil. *Journal of Environmental Engineering*, 144(9), Article 04018072.
- Zegeye, A. D., Langendoen, E. J., Tilahun, S. A., Mekuria, W., Poesen, J., & Steenhuis, T. S. (2018). Root reinforcement to soils provided by common Ethiopian highland plants for gully erosion control. *Ecohydrology*, 11(6), 1–11. <https://doi.org/10.1002/eco.1940>
- Zolezzi, G., Bezzi, M., Spada, D., & Bozzarelli, E. (2018). Urban gully erosion in sub-Saharan Africa: A case study from Uganda. *Land Degradation & Development*, 29, 849–859. <https://doi.org/10.1002/ldr.2865>