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Quantifying suitable low-impact development practices in mitigating runoff floods for the Kinyerezi River catchment in Dar es Salaam, Tanzania

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ABSTRACT

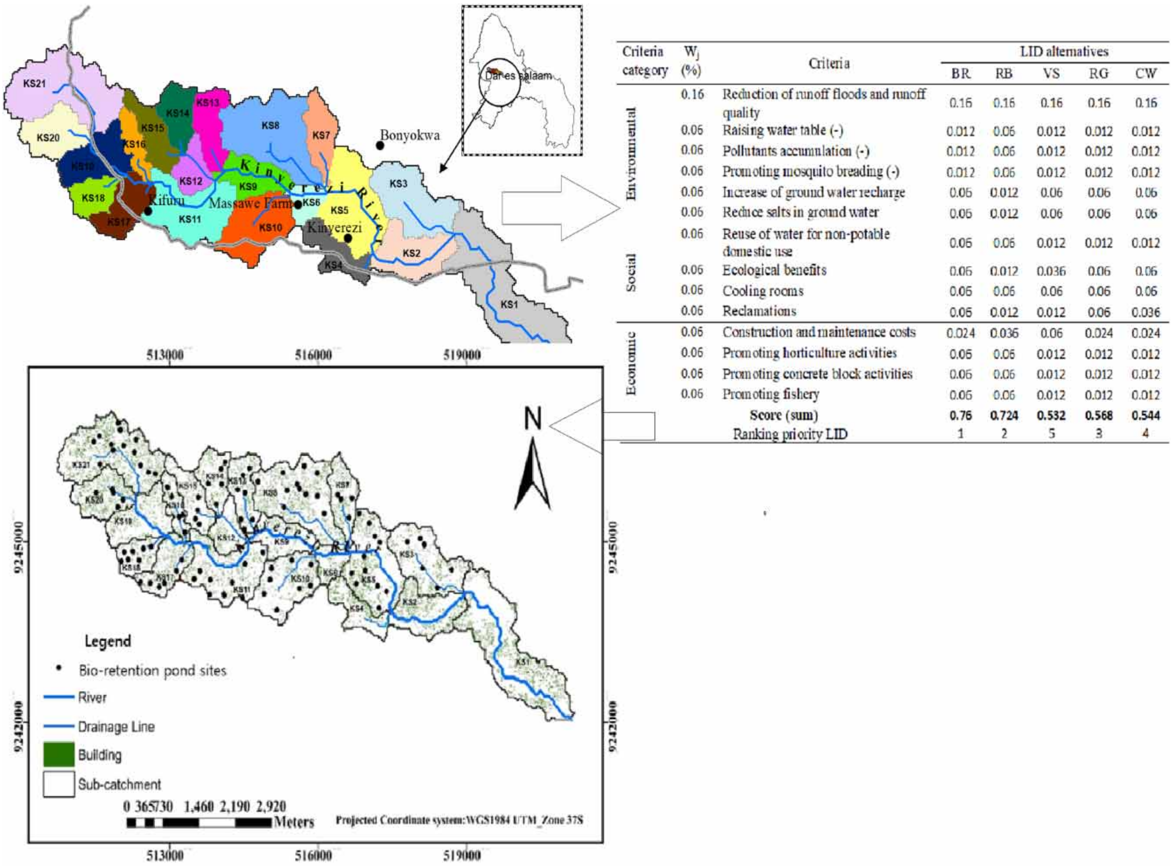
As cities expand, changes in land use increase the runoff quantities. Impermeable catchment areas contribute to peak flows, causing floods in insufficiently capacity river reaches. The rate of urbanization witnessed in the Kinyerezi River catchment in Dar es Salaam has contributed to floods in the Msimbazi River. The low-impact development (LID) practices that include bioretention (BR) ponds, rain barrels (RBs), rain gardens (RGs), vegetative swales (VSs), constructed wetlands (CWs), etc., can be utilized to mitigate a portion of the surface runoff. This study aims to quantify the suitable LID practices for the Kinyerezi River catchment in mitigating a portion of runoff floods. The sub-catchment physical characteristics and soil infiltration rates (*Ks*) were matched with each LID sitting requirements and later by multi-criteria decision-making (MCDM). The results on matching sub-catchment characteristics and LID sitting requirements indicated that BRs, RBs, VSs, RGs, and CWs were the preferable LIDs while MCDM analysis indicated the BRs, RGs, and RBs more appropriate. The BRs, RGs, and RBs were quantified to be 101, 3,698, and 3,698, respectively, within the catchment. BRs are recommended for catchment use while RBs and RGs are recommended for residential buildings. The RBs have the advantage of promoting water-demanding economic activities.

Key words: bioretention ponds, infiltration trenches, Kinyerezi River catchment, low-impact development practices, multi-criteria decision-making (MCDM)

HIGHLIGHTS

- The study improves the knowledge on prioritizing LID practices in sub-catchments by matching LID sitting requirements versus sub-catchment characteristics and MCDM.
- The study improves the knowledge on predicting the quantities of BR ponds and RBs in sub-catchments.

GRAPHICAL ABSTRACT



Criteria category	W_j (%)	Criteria	LID alternatives				
			BR	RB	VS	RG	CW
Environmental	0.16	Reduction of runoff floods and runoff quality	0.16	0.16	0.16	0.16	0.16
	0.06	Raising water table (-)	0.012	0.06	0.012	0.012	0.012
	0.06	Pollutants accumulation (-)	0.012	0.06	0.012	0.012	0.012
	0.06	Promoting mosquito breading (-)	0.012	0.06	0.012	0.012	0.012
	0.06	Increase of ground water recharge	0.06	0.012	0.06	0.06	0.06
	0.06	Reduce salts in ground water	0.06	0.012	0.06	0.06	0.06
Social	0.06	Reuse of water for non-potable domestic use	0.06	0.06	0.012	0.012	0.012
	0.06	Ecological benefits	0.06	0.012	0.036	0.06	0.06
	0.06	Cooling rooms	0.06	0.06	0.06	0.06	0.06
	0.06	Reclamations	0.06	0.012	0.012	0.06	0.036
Economic	0.06	Construction and maintenance costs	0.024	0.036	0.06	0.024	0.024
	0.06	Promoting horticulture activities	0.06	0.06	0.012	0.012	0.012
	0.06	Promoting concrete block activities	0.06	0.06	0.012	0.012	0.012
	0.06	Promoting fishery	0.06	0.06	0.012	0.012	0.012
		Score (sum)	**0.76**	**0.724**	**0.532**	**0.568**	**0.544**
		Ranking priority LID	1	2	5	3	4

1. INTRODUCTION

Rainfall is the major component of the hydrologic cycle and it is the primary source of runoff (Kantharia *et al.* 2024). Flooding is one of the most hazardous natural disasters reported worldwide in urban areas including cities and towns that are developed in floodplain areas (Tanaka *et al.* 2020; Kumar *et al.* 2023). Several researchers have reported on the effect of the increase in urbanization (land use land cover change) resulting in the increase in impermeable areas, reduced hydrological processes that favor infiltrations over surface runoff, and floods (Ekmekcioğlu *et al.* 2021; Mehta *et al.* 2023). This urban development, when combined with extreme rainfall events becomes the major contributor to peak flows. Pluvial floods are dominated by short-term high rainfall intensity and inadequate drainage capacity of the storm systems while fluvial are when the water levels in river channels exceed the bank heights (Apel *et al.* 2016; Tanaka *et al.* 2020).

On the other hand, some studies have reported on the use of low-impact development (LID) practices as an emerging alternative method for mitigating surface runoff and floods in urbanized areas (Abduljaleel & Demissie 2021). LID practices are runoff detaining or storage facilities constructed to capture stormwater runoff near generation points and provide ample time for infiltration, evaporation, and transpiration processes through vegetation of the captured surface runoff (Joksimovic & Alam 2014). LID practices have been reported to contribute in adapting and mitigating urban climate change including the reduction in cooling and heating demand, ameliorating risks of floods, reducing hot spots that create urban heat islands, and improving urban health (Senosiain 2020). LID practices such as bioretention (BR) ponds, rain gardens (RGs), rain barrels (RBs), vegetative swales (VSs), green roofs (GRs), infiltration trenches (ITs), permeable pavements (PPs) as well as detention ponds (DPs), and constructed wetlands (CW) have been reported by Xian *et al.* (2021) and Rizzo *et al.* (2018) that they can reduce runoff floods in different cities. Jaber (2015) reported the bioretention ponds and permeable pavements in clay soil to reduce the runoff volume by 50 and 65%, respectively. Likewise, Heidari & Kavianpour (2021) evaluated the effectiveness of RBs, BR ponds, and PPs in arid and semi-arid regions in Varamin-Tehran, Iran and the RBs were the most effective by reducing the peak discharge and total volume by 12.7 and 40.71%, respectively.

The population growth of Dar es Salaam has resulted in a 42% increase in the city's built-up land space from 1989 to 2015 (Igulu & Mshiu 2020). The increase in land development coupled with a decrease in permeable surfaces led to an increase of stormwater runoff pluvial and fluvial flooding in the city (Sakijege 2013). Dar es Salaam city experiences frequent floods along the Msimbazi River, whose flows originate from different tributaries including the Kinyerezi River (Ngassapa *et al.* 2018). For example, the city has been hit by numerous floods from the Msimbazi River in recent years, including in 2007, 2011, 2014, 2015, 2018, 2019, and 2020 (Mzava *et al.* 2021). The floods in 2011 and 2018 impacted 12,000 individuals, resulting in 58 fatalities according to World Bank (2019). The cost of property loss exceeded Tanzanian Shilling 7.5 million, and the Tanzanian government responded by relocating affected communities from Jangwani to Mabwepande at a cost of approximately Tanzanian Shilling 1.83 billion (Anande & Luhunga 2019). Currently, the Kinyerezi River catchment is under development of villas, apartment complexes, office buildings, hotels, residential buildings, and commercial premises that is believed to increase runoff generation within the catchment hence contributing to floods in the Msimbazi River (Mkilima 2018). Some studies in Dar es Salaam have proposed different runoff flood control alternatives to overcome the consequences witnessed in Rivers. Kibugu *et al.* (2022) pointed out measures to mitigate floods in the Msimbazi River including proper design and preservation of drainage facilities downstream of the catchment, as well as preventing the dumping of human-produced debris in open channels and streams. Mkilima (2018) assessed the runoff discharge generated from the Msimbazi River sub-catchments and recommended construction of reservoirs/detention basins for each Msimbazi River sub-catchment outlet.

In making informed decisions in various aspects, the multi-criteria decision-making (MCDM) approach has been reported by different researchers for comprehensive decision-making on the suitability of LIDs through incorporating various factors such as environmental, educational, social, technical, and economic aspects in determining suitable LID types within the sub-catchments (Kaykhosravi *et al.* 2019; Movahedinia *et al.* 2022). Sheikh & Izanloo (2021) used an MCDM approach to evaluate the alternatives for LID practices in Bojnord, Iran where criteria such as hydrological, social, and economic were considered, and the data were collected using the questionnaire survey and modeling technique. Similarly, Jia *et al.* (2013) applied the MCDM approach to developing indices for urban runoff LID selections by considering best management practices (BMPs) site suitability, runoff control benefits, and cost and maintenance of BMPs. Moreover, Heidari (2022) compared and employed an MCDM approach for characterizing the best LID techniques for stormwater management in urban areas under different stakeholder scenarios. Equally, Garcia-Cuerva *et al.* (2016) employed the MCDM method by considering the environmental, social, and educational benefits of LID practices in locating the priority sites for Walnut Creek Watershed in central North Carolina. Likewise, Raei *et al.* (2019) applied the MCDM method by considering physical, technical, economic, and multi-stakeholder aspects for locating and sizing LIDs while considering also hydrologic and hydraulic impacts for a catchment located in the northeastern part of Tehran, Iran. However, quantifying and sitting appropriate LID practices on sub-catchments continues to be a challenge.

Despite numerous flood studies for Dar es Salaam city, there have been no previous reports on quantifying or enhancing LID practices to mitigate runoff flood events along the rivers draining in the city. Therefore, this study aims to quantify the LID practices to suit the Kinyerezi River catchment in mitigating a portion of runoff floods for the Kinyerezi River. This method is easy, straightforward, and popular approach that is widely used in ranking the appropriate LID practices compared with other approaches such as the use of indices and optimization of LID sizes. The method solves decisions that cannot be completed manually and helps the administration in choosing the best decision in any particular instance (Siahaan *et al.* 2017). The use of this approach improves the knowledge on prioritizing and quantifying LID practices especially BR ponds and RBs for a particular sub-catchment.

2. MATERIALS AND METHODS

2.1. Study area

Dar es Salaam city receives an average annual rainfall of 800–1,400 mm and has a mean annual temperature that ranges from less than 18 to higher than 33 °C (Machiwa *et al.* 2021). The Kinyerezi River catchment is situated at 6050′36.55S and 39008′36.45E, located in the western part of Dar es Salaam city (Figure 1). The runoff produced

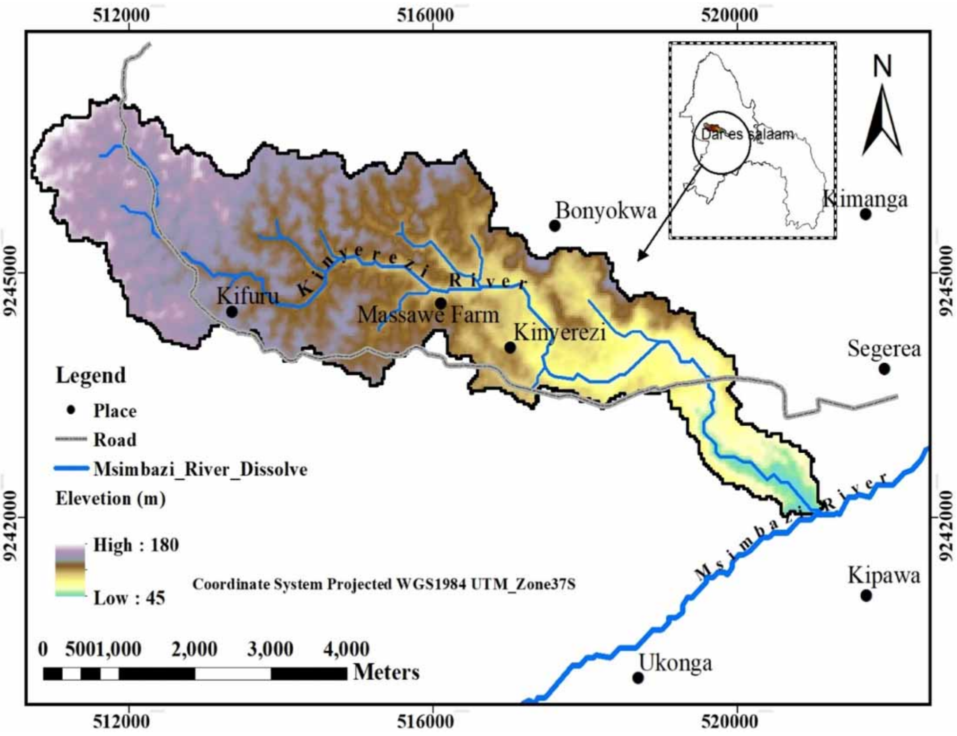


Figure 1 | Kinyerezi River catchment (ArcGIS10.4).

by its sub-catchments flows into the Kinyerezi River and thereafter it joins the Msimbazi River. It is fair to note that, currently, the Kinyerezi River catchment is undergoing significant urbanization, with the construction of real estate such as villas, apartment complexes, office buildings, hotels, and shopping malls (Mkilima 2018).

2.2. LID practices

LID practices are widely used in mitigating runoff floods in urbanized areas (Abduljaleel & Demissie 2021). Generally, the application of any LID practice is likely to have benefits, drawbacks, technical requirements, costs, and implementation limitations. The site slopes, soil infiltration rates (*Ks*), and hydrological soil groups (HSGs) are among the important sub-catchment physical characteristic requirements used to select a particular LID for implementation (Warganda & Sutjiningsih 2017). In this study, the sub-catchment physical characteristics were matched with the requirements for sitting nine (9) commonly used LID techniques. The LID types that did not fit the sub-catchment physical characteristics were considered as ineffective in mitigating runoff floods in the Kinyerezi River sub-catchments and therefore were not considered for further analysis. The LID types considered for this study included BR ponds, RGs, RBs, VSs, GRs, ITs, PPs, DPs, and CWs.

BR ponds are shallow depressions composed of surface, soil, and storage layers meant to improve water quality and attenuate peak runoff volume originating from catchments (Sheikh & Izanloo 2021). The BR ponds are applied in sub-catchments with drainage areas greater than 4.5 hectares (ha), terrain slope less than 20%, and native soil infiltration rates greater than 12.7 mm/h (Martin-Mikle *et al.* 2015). In situations where the infiltration rate is less than 12.7 mm/h, underdrain (200 mm diameter) is introduced (OrmondCity 2013) while RGs are a type of bioretention pond consisting of just the soil layer with no underlying gravel bed below. The RGs are suitable for sites with slopes less than 20%, with any HSG and soil *Ks*, and are useful for collecting runoff from small sub-catchments such as rooftop runoff, runoff from yards and sidewalks, and runoff from roads and small parking lots (Martin-Mikle *et al.* 2015).

RBs are containers that collect rooftop rainwater during storm events and are installed for small sub-catchments such as residential or commercial buildings and the collected water is used for landscaping irrigation, vehicle washing, gardening, or other economic activities (Sheikh & Izanloo 2021). VSs are trapezoidal or triangular channels/depressed with sloping sides covered with vegetation for conveying collected runoff and allow it to infiltrate into the native soil beneath it. VSs are suitable for sites with *Ks* greater than 12.7 mm/h, site slope not exceeding 4% and with HSG A or B and are used for collecting runoff from the roadway, commercial, or residential buildings (OrmondCity 2013).

GRs are another variation of BR ponds that uses vegetation overlaid on rooftops to delay and retain rainfall runoff. The vegetated roof covers are designed to reduce stormwater volumes through storage of precipitation in a soil media layer and increase evapotranspiration. The roofs must be reinforced concrete to carry the soil and vegetation loads (OrmondCity 2013). ITs are shallow ditches (0.9–1.5 m depth) filled with gravel and stones that intercept runoff from upslope areas and provide time for the captured runoff to infiltrate into the native soil. The trenches are suitable for sites with small drainage areas and are constructed alongside the streets, parking lots, roadways, and sidewalks, particularly in low-density and medium-density residential areas (Sheikh & Izanloo 2021). The native soil for trenches should have a minimum *Ks* of 12.7 mm/h and HSG A or B with site slope not exceeding 25% (OrmondCity 2013). PPs are excavated areas filled with gravel and paved over with a porous concrete or block pavers. They allow stormwater to infiltrate into underlying soils promoting pollutant treatment, ground recharge, and reducing runoff volume (Sheikh & Izanloo 2021). PPs suite for parking lots, residential buildings, and sidewalks with subgrade HSG A or B and sub-soil *Ks* of more than 13 mm/h. The permeable pavement site slopes should not exceed 5% (OrmondCity 2013).

DPs are the earthen structures (minimum depth of 0.15 m) constructed either by impoundment of a natural depression or excavation of existing soil at nodes (junctions) where more than one drainage stream meets (Mkilima 2018). The ponds are designed to store stormwater runoff temporarily (24–48 h) during rainfall until it infiltrates. DPs are suitable for large catchment areas (not exceeding 300,000 m^2) with soil *Ks* greater than 12.7 mm/h and site slope not exceeding 15% (OrmondCity 2013). A CWs pond is a large shallow retention pond designed to permit the growth of wetland plants and permanent pooling of water throughout the wet season. The pond sites should have low steep (slope 1%) and low infiltration rates (Kennedy 2007).

2.3. Selecting the suitable LID practices by the MCDM approach

The MCDM approach combines environmental, economic, and social criteria when choosing the best LID practices (Sheikh & Izanloo 2021). Environmental criteria associated with implementation of LIDs included reducing runoff floods and improving runoff quality, raising the water table, increasing pollutant accumulation, promoting mosquito breeding, and reducing salts in groundwater. Economic criteria included construction, operation, and maintenance costs, as well as other economic activities. Social criteria of LIDs included reusing water for non-potable domestic use, ecological benefits, reclamations, and cooling rooms, particularly for green roofs as reported by Kaykhosravi *et al.* (2019) and Movahedinia *et al.* (2022).

There are two commonly used sets of MCDM methods: multi-attribute decision-making (MADM) and multi-objective decision-making (MODM). MODM involves providing a mathematical framework for designing a set of decision alternatives or objectives (Kahraman 2008), while MADM methods involve scoring, compromising, and concordance (outranking) of the given attributes (Sheikh & Izanloo 2021). Since the aim of the study was to propose appropriate LID alternatives, MADM methods were adopted. In this study, the simple additive weighting (SAW) method which is a straightforward and popular approach within the MCDM group was used (Siahaan *et al.* 2017). The SAW method was used to rank the best LID practices from a group of nine (9) options. This was done by considering environmental, social, and economic criteria. The method involved creating a decision matrix with '*m*' alternatives for LID practices and '*n*' criteria for environmental, social, and economic considerations (Vaseghi *et al.* 2020). These criteria were ranked on a scale of 1–5, with 1 being the least important, 2 being the least medium, 3 being medium, 4 being medium important, and 5 being the most important (Heidari 2022). The ranking was based on consultation with the Kinyerezi River catchment stakeholders on the desired advantages and benefits they wish to get from the proposed LID practices.

The consultation involved a wide range of social, economic, environmental criteria, and limitation. The views of the stakeholders on LIDs were discussed and brainstormed on the present study's objective. Brief explanations about the LIDs, their impacts on reducing flood consequences, reclamations, and economic impacts were introduced to the Kinyerezi River catchment stakeholders. The consultation involved 21 residents of the Kinyerezi River catchment specifically nearby sites where Swilla *et al.* (2023) tested the soil infiltration rates, 3 local government leaders, 6 civil engineers who are construction experts with vast experience, and 2 consulting engineering firms. Criteria ranking was unformed by the views of the consultated stakeholders. To proceed, the normalized decision matrix (n_{ij}) was prepared by applying Equations (1) and (2). This gave the values ranging from 0 to 1 (Sheikh & Izanloo 2021).

$$n_{ij} = \frac{k_{ij}}{k_j^{\max}},\ i = 1, \ldots m,\ j = 1, \ldots n \quad \text{for beneficial (positive) criteria} \tag{1}$$

$$n_{ij} = \frac{k_j^{\min}}{k_{ij}},\ i = 1, \ldots m,\ j = 1, \ldots n \quad \text{for non-beneficial (negative) criteria} \tag{2}$$

There are six methods of weighting perspectives, which include Shannon entropy, Delphi, equal weighting (assigning equal weight for all criteria), hydrologic priority, social priority, and economic priority (Sheikh & Izanloo 2021). The Shannon entropy evaluates values by measuring the degree of differentiation. The higher the degree of dispersion of the measured value, the higher the degree of differentiation of the index, and the higher weight should be given to the index, and vice versa (Zhu *et al.* 2020). The Delphi method is devised to obtain a consensus among experts by evaluating Cronbach's statistical index value that is used to assess the reliability or internal consistency of a summation of entities by considering the number of panelists, variances of each panelist's responses, and the variance of the sum of responses for each panelist. The index value close to 0 means that the ratings of the experts are completely unrelated to one another, while values close to 1 mean that the ratings are strongly associated (Mafi-Gholami *et al.* 2015). In this study, the hydrological priority approach was applied based on the Kinyerezi River resident's views on LID practices implementations; therefore, higher weights (w_j in percent) were assigned to environmental criteria and the equal weighting approach was utilized in assigning weights to social and economic criteria.

Equation (3) is used to determine the weighted normalized matrix (v_{ij}), and the total of all v_{ij} for each LID alternative (A_i) is calculated using Equation (4).

$$v_{ij} = w_j x n_{ij} \tag{3}$$

$$A_i = \sum v_{ij} \tag{4}$$

The larger the A_i value, the more superior the LID substitute.

3. RESULTS AND DISCUSSION

3.1. Catchment delineation and sub-catchment physical characteristics

The digital elevation model (DEM) dataset for the Kinyerezi River catchment was downloaded from the official website of open topography using the link: https://opentopography.org/, entity ID rt1676707346732 and dataset COP30 with 30 × 30 m resolutions. The catchment was delineated into 21 sub-catchments (Figure 2) and the sub-catchment average slopes, percentage imperviousness, and sub-catchment areas were generated using ArcGIS 10.4 software.

3.2. Land use/land cover and sub-catchment average slopes

The 2021 satellite images of the Kinyerezi River catchment land use/land cover was obtained from the official website of the United States Geological Survey (USGS) at https://earthexplorer.usgs.gov/. The images had a resolution of 30 × 30 m and were processed in ArcGIS 10.4 toolbox. The land use/land cover types of the study area were paved roads, built-up land, vegetation, and open lands as indicated in Figure 3(a) with the percentage imperviousness approximated to be more than 38%. The sub-catchment average slopes were classified into five categories: flat (0–5%), gentle slope (5–10%), moderate slope (10–15%), high slope (15–15%), and very high slope (>20%) as indicated in Figure 3(b).

3.3. Sub-catchment physical characteristics and LID sitting requirements

The HSG from the Food and Agriculture Organization (FAO) website classifies the Kinyerezi River catchment as HSG C, which has *Ks* ranging from 1.3 to 3.8 mm/h with a clay content of about 20–40% (Mkilima 2018). This is in good agreement with the soil infiltration rates for the Kinyerezi River sub-catchments reported by Swilla *et al.*

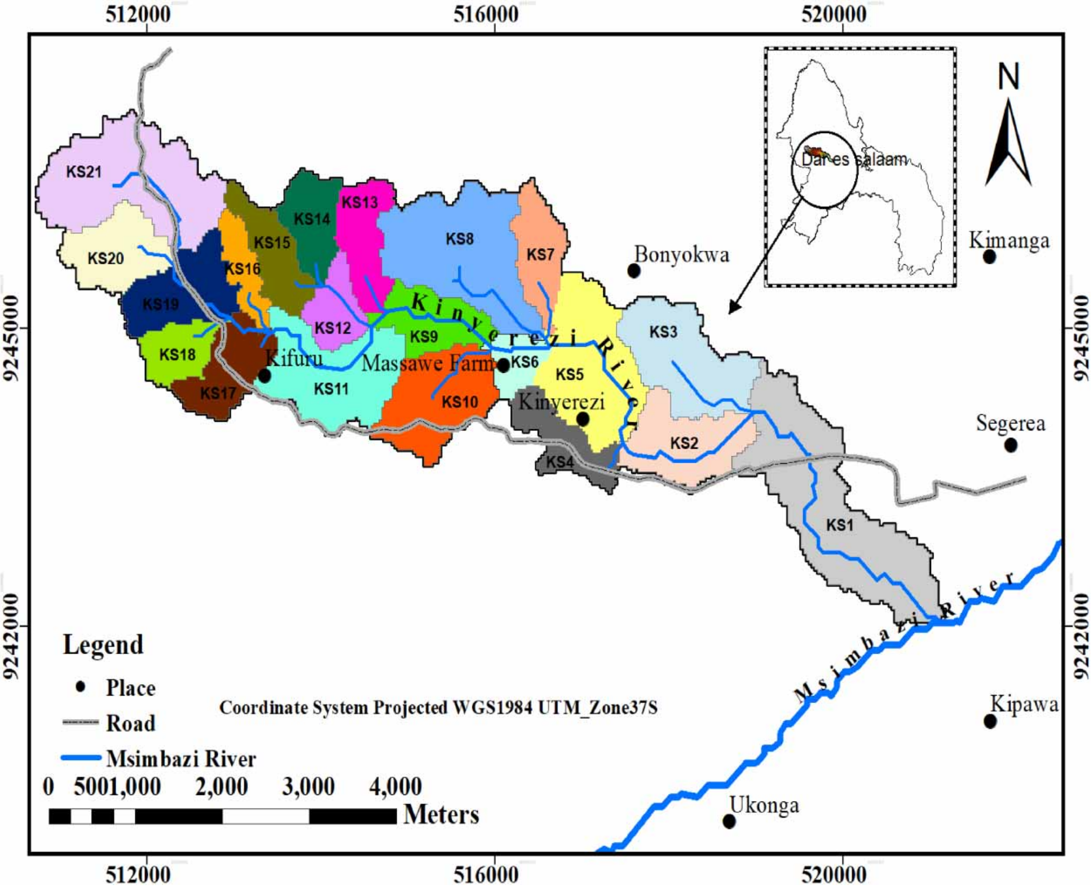


Figure 2 | Delineation of Kinyerezi River catchment (labeling was based on Swilla *et al.* (2023)).

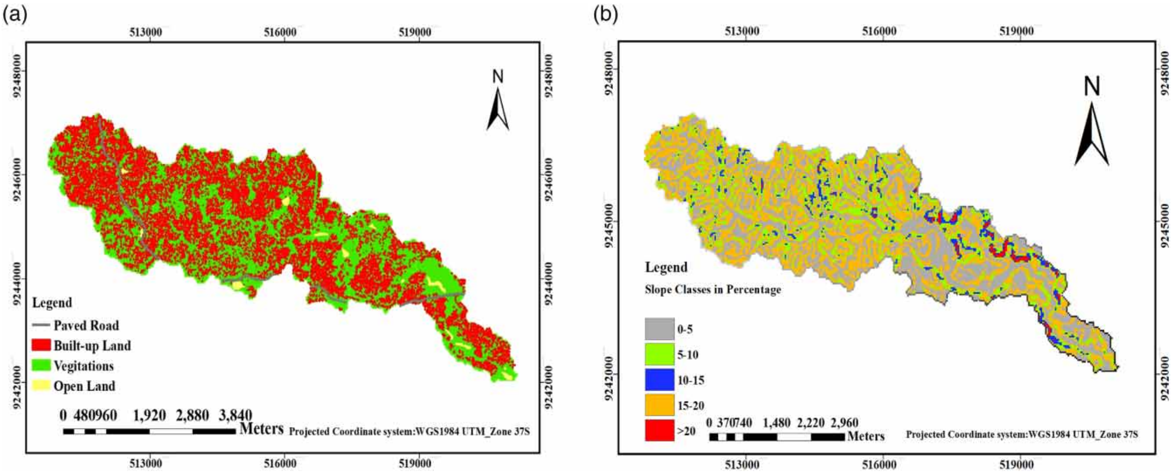


Figure 3 | (a) The land use/land cover. (b) The sub-catchment average slopes (ArcGIS10.4).

(2023) which was between 0.22 and 7.76 mm/h with an average of 3.42 mm/h. These sub-catchment characteristics do not favor the LID practices that require soil infiltration rates greater than 12.7 mm/h and HSG A or B. The average slopes for the Kinyerezi River sub-catchments ranged from 0 to 13.2% with the sub-catchment areas greater than 32 ha. These sub-catchment characteristics were matched with each LID sitting requirements described in the sections above as illustrated in Table 1.

Table 1 | Sub-catchment physical characteristics and LID sitting requirements

		Kinyerezi River sub-catchment physical characteristics (Swilla *et al.* 2023)				
LID	**LID sitting requirements**	**Have site slopes $<25\%$**	**Have HSG C**	**Have roads, buildings, and parking lots**	**Have *Ks* $<$ 12.7 mm/h**	**Large sub-catchment areas $>$32 ha**
BR	For site slope $<20\%$, any *Ks* value, any HSG, and used in catchment scale	√	√	√	√	√
RB	For the building's rooftop rainwater harvesting	N/A	N/A	√	N/A	N/A
VS	For site slope $<4\%$, any HSG, any *Ks*, for roadway, commercial, or residential	√	√	√	√	X
RG	For site slope $<20\%$, any *Ks*, any HSG, and a small catchment	√	√	√	√	X
GR	For reinforced concrete roofs	X	X	X	X	X
IT	For site slope $<25\%$, *Ks* $>$ 12.7 mm/h, HSG A or B, roadways, parking, or sites with hydrocarbon pollutants	√	X	√	X	X
PP	For site slope $<5\%$, *Ks* $>$ 13 mm/h, HSG A or B, for parking, or residential	√	X	√	X	X
DP	For site slope $<15\%$, *Ks* $>$ 12.7 mm/h, HSG A or B, large catchments	√	X	√	X	√
CW	For site slope $<1\%$, low *Ks* and require large space	√	√	√	√	√

The sub-catchment average slopes, *Ks*, and HSGs are the important sub-catchment physical characteristics for selecting a particular LID type for implementation (Warganda & Sutjiningsih 2017). The ITs, PPs, and DPs require HSG A or B with soil infiltration rates greater than 12.7 mm/h, contrary to the Kinyerezi River sub-catchments which have infiltration rates less than 12.7 mm/h with HSG C, hence these LIDs are considered ineffective in mitigating runoff floods in the sub-catchments (Swilla *et al.* 2023). Additionally, GRs require consideration during the design of reinforced concrete roofs for buildings, as they impose loads due to soils and vegetation planted on it. Contrary to the Kinyerezi River catchments that already have residential buildings with iron sheet roofs; therefore, GRs cannot be the choice. Matching the sub-catchment physical characteristics with LID sitting requirements indicated the BRs ponds, RBs, VSs, RGs, and CWs as the preferable choice for mitigating runoff floods in the Kinyerezi River sub-catchments and therefore were subjected to the MCDM approach.

3.4. LID prioritization by the MCDM approach

The Kinyerezi ward has a population of about 62,480 residents (NBS 2022), regardless of ranking 21 residents residing near the sites where Swilla *et al.* (2023) tested the *Ks*, 3 local government authority leaders within the catchment, 6 civil engineering construction experts, and 2 consulting engineering companies were consulted. The preferable LID practices in mitigating runoff floods in the catchment that were obtained by matching sub-catchment characteristics with LID practices sitting requirements were subjected to a ranking by MCDM based on the views of the catchment residents, local government authority leaders, civil engineering construction experts, and consulting engineering companies. The catchment residents and local government authorities' views slightly varied from that provided by civil engineering construction experts and consulting engineering companies (Table 2), for this case the resident's views were considered in first place since are the ones who would interact much with the proposed LID practices.

Based on the frequencies (F) of respondents for each LID practice criteria, in this study all criteria with a frequency greater than 24 (75%) were the 'most important' to be considered, whereas between 19 and 24 (60–75%) being 'medium important', 15 and 19 (45–60%) 'medium', 10 and 15 (30–45%) 'least medium', and less than 10 (less than 30%) being the 'least important'.

The environmental criteria considered were reduction of runoff floods and runoff quality, raising the water table, accumulation of pollutants, promoting mosquito breeding, reducing salts in groundwater, and increasing

Table 2 | Stakeholders views on the LID implementation criteria

		Positive respondents' answers				
LIDs and category	**LID capabilities**	**KRR**	**KLGL**	**CEE**	**CEC**	**Frequency (F)**
Environmental BRs, VSs, RGs, and CWs	Reduction of runoff floods and runoff quality	21	3	6	2	32
	Raising water table (–)	21	3	5	1	30
	Accumulating pollutants (–)	21	3	5	1	30
	Promoting mosquito breading (–)	21	3	6	1	31
	Increase in groundwater recharge	18	3	5	1	27
	Reduce salts in groundwater	21	3	5	1	30
Social BRs, RBs, CWs, and RGs	Reuse of water for non-potable domestic use	21	3	6	2	32
	Ecological benefits	8	3	1	2	14
	Cooling rooms	2	1	1	2	6
	Reclamations	7	3	1	1	12
Economic BRs, RBs, CWs, and RGs	Construction and maintenance costs	14	3	3	1	21
	Promoting water-demanding economic activities	21	3	6	2	32

groundwater recharge. The economic criteria considered were construction, operation, and maintenance costs, as well as promoting economic activities. Social criteria included the reuse of water for non-potable domestic use, ecological benefits, cooling rooms (for GRs), and reclamations (Sheikh & Izanloo 2021). Criteria such as raising the water table, accumulation of pollutants, and promoting mosquito breeding were considered as non-beneficial (negative) criteria.

The stakeholders were separately consulted and all agreed that environmental issues, the reuse of captured runoff, and LID that promotes economic activities should be considered. The Kinyerezi River catchment residents and local government leaders insisted that construction and maintenance costs of LIDs should be considered while civil engineering construction experts and consulting engineering companies could not see it as an important criterion to be considered. The ecological benefits and reclamations of LIDs were not a priority for the Kinyerezi River catchment residents but seemed to be very important for local government leaders, civil engineering construction experts, and consulting engineering companies. Based on the views of the consulted stakeholders, the criteria were ranked on a scale of 1–5, with 1 being the least important, 2 being the least medium, 3 being medium, 4 being medium important, and 5 being the most important (Heidari 2022) as presented in Table 3.

Table 3 | Ranking LID criteria in order of their preferences

		LID alternatives				
Criteria category	**Criteria**	**BRs**	**RBs**	**VSs**	**RGs**	**CWs**
Environmental	Reduction of runoff floods and runoff quality	5	5	5	5	5
	Raising water table (−)	5	1	5	5	5
	Accumulating pollutants (−)	5	1	5	5	5
	Promoting mosquito breading (−)	5	1	5	5	5
	Increase in groundwater recharge	5	1	5	5	5
	Reduce salts in groundwater	5	1	5	5	5
Social	Reuse of water for non-potable domestic use	5	5	1	1	1
	Ecological benefits	5	1	3	5	5
	Cooling rooms	1	1	1	1	1
	Reclamations	5	1	1	5	3
Economic	Construction and maintenance costs	5	3	2	5	5
	Promoting horticulture activities	5	5	1	1	1
	Promoting concrete block activities	5	5	1	1	1
	Promoting fishery	5	5	1	1	1

*(−) sign implies non-beneficial (negative) criteria.

Based on the views of the consulted stakeholders, the LIDs that detain runoff (BRs, VSs, RGs, and CWs) and environmental factors such as raising the water table, accumulation of pollutants, and promoting mosquito breeding were scored 5. Other environmental criteria, such as increasing groundwater recharge and reducing salts in groundwater, were also considered preferable and were ranked 5, except RBs which was ranked 1. For social criteria, reuse of water for non-potable domestic use was ranked 5 for BRs and RBs, while ecological benefits were ranked 5 for BRs, RGs, and CWs. Reclamation was ranked 5 for BRs and RGs all of which are important for social sustainability in the Kinyerezi communities. The proposed LIDs should also promote water-demanding economic activities in the Kinyerezi River catchment according to the resident's views and increase households' income. BRs and RBs were ranked 5th due to their ability to detain water, which can then be used for horticulture, concrete block making, car washing fishery activities, etc. The VSs, RGs, and CWs were ranked 1 due to their inability to detain water that can be utilized in economic activities. Construction and maintenance costs are also an important economic criterion, with a ranking of 5 for all LIDs except RBs and VSs, whose costs were considered less important. The assigned ranks were normalized to obtain values from 0 to 1 as presented in a normalized decision matrix in Table 4 (Sheikh & Izanloo 2021).

Table 4 | Normalized decision matrix

		LID alternatives				
Criteria category	**Criteria**	**BR**	**RB**	**VS**	**RG**	**CW**
Environmental	Reduction of runoff floods and runoff quality	1	1	1	1	1
	Raising water table (–)	0.2	1	0.2	0.2	0.2
	Accumulating pollutants (–)	0.2	1	0.2	0.2	0.2
	Promoting mosquito breading (–)	0.2	1	0.2	0.2	0.2
	Increase in groundwater recharge	1	0.2	1	1	1
	Reduce salts in groundwater	1	0.2	1	1	1
Social	Reuse of water for non-potable domestic use	1	1	0.2	0.2	0.2
	Ecological benefits	1	0.2	0.6	1	1
	Cooling rooms	1	1	1	1	1
	Reclamations	1	0.2	0.2	1	0.6
Economic	Construction and maintenance costs	0.4	0.66	1	0.4	0.4
	Promoting horticulture activities	1	1	0.2	0.2	0.2
	Promoting concrete block activities	1	1	0.2	0.2	0.2
	Promoting fishery	1	1	0.2	0.2	0.2

The weights for each criterion were assigned using hydrologic priority and equal weighting approaches based on interviewers' views (Sheikh & Izanloo 2021). The top priority of the study was to reduce runoff floods and improve runoff quality, which was assigned a weight of 16% and the other criteria were given equal weights of 6% each. The weighted normalized matrix was calculated and the sum of all weighted normalized for each LID alternative is presented in Table 5.

After ranking, the BR ponds took the first place, followed by RBs in second place, and RGs in third place. The CWs were ranked fourth while the VSs were ranked fifth. Since the Kinyerezi River have large sub-catchments with drainage areas greater than 4.5 ha, the BRs are suggested as the preferable choice (Martin-Mikle *et al.* 2015). For capturing runoff from multiple small-scale catchment areas such as rooftop runoff, runoff from yards, sidewalks, driveways, and small parking lots with sub-catchment areas less than 4.5 ha, the RBs and RGs are preferable choices (Martin-Mikle *et al.* 2015). The RBs have multiple benefits to the community if are to be practiced in residential or commercial buildings in large scale. The CWs require large site areas with slopes not exceeding 1% (Kennedy 2007), while in the Kinyerezi River, the sub-catchments have limited open spaces with average slopes greater than 1%; therefore, CWs are ineffective in mitigating runoff floods in the catchment. Based on the MCDM, the preferable efficient LID alternatives in mitigating runoff floods in the Kinyerezi River catchment are BR ponds, RGs, and RBs that can reduce the runoff volume, improve the runoff water quality as well as promote water-demanding economic activities in the areas.

Table 5 | Weighted (W_j) normalized decision matrix

			LID alternatives				
Criteria category	**W_j (%)**	**Criteria**	**BR**	**RB**	**VS**	**RG**	**CW**
Environmental	0.16	Reduction of runoff floods and runoff quality	0.16	0.16	0.16	0.16	0.16
	0.06	Raising water table (–)	0.012	0.06	0.012	0.012	0.012
	0.06	Pollutant accumulation (–)	0.012	0.06	0.012	0.012	0.012
	0.06	Promoting mosquito breading (–)	0.012	0.06	0.012	0.012	0.012
	0.06	Increase in groundwater recharge	0.06	0.012	0.06	0.06	0.06
	0.06	Reduce salts in groundwater	0.06	0.012	0.06	0.06	0.06
Social	0.06	Reuse of water for non-potable domestic use	0.06	0.06	0.012	0.012	0.012
	0.06	Ecological benefits	0.06	0.012	0.036	0.06	0.06
	0.06	Cooling rooms	0.06	0.06	0.06	0.06	0.06
	0.06	Reclamations	0.06	0.012	0.012	0.06	0.036
Economic	0.06	Construction and maintenance costs	0.024	0.036	0.06	0.024	0.024
	0.06	Promoting horticulture activities	0.06	0.06	0.012	0.012	0.012
	0.06	Promoting concrete block activities	0.06	0.06	0.012	0.012	0.012
	0.06	Promoting fishery	0.06	0.06	0.012	0.012	0.012
Score (sum)			**0.76**	**0.724**	**0.532**	**0.568**	**0.544**
Ranking LID priorities			1	2	5	3	4

3.5. Quantifying the RBs in the catchment

The generated sub-catchment areas (in ha) for each sub-catchment and the percentage imperviousness (% of built area) of the Kinyerezi River sub-catchments were used to evaluate the impervious areas/built areas (in ha). The field visit in the Kinyerezi River catchment revealed the different RB sizes that were currently in use by the residents for domestic rooftop rainwater harvesting. The RB capacities varied from 500, 1,000, 2,000, 3,000, 4,000, and 5,000 liters. The 3,000-liter RB capacities were used by many residents within the catchment. The Kinyerezi River catchment is classified as a high-density residential area with plot areas ranging from 301 to 600 m^2 according to PO-LALG (2018). For high-density residential areas, 10 RBs can be accommodated in 1 ha (Zahmatkesh *et al.* 2015). The 10-RB/ha were multiplied by the built area (in ha) for each sub-catchment in determining the number of 3,000-liter capacity RBs in each sub-catchment and for the whole Kinyerezi River catchment.

3.6. Quantifying the RGs in the catchment

Much of the existing design guidelines indicate that common residential RG sizes range from 9.3 to 28 m^2 depending on the *Ks* of soils (Jennings *et al.* 2015). It was considered that all residential buildings capable of purchasing a 3,000-liter capacity RB are capable of constructing a residential RG of about 28 m^2 sizes (with 0.9 m depth) in the Kinyerezi River catchment. The soil *Ks* within the Kinyerezi River catchment was reported by Swilla *et al.* (2023) to be small; therefore, bigger sizes of RGs are preferable for increasing the runoff capture ratio. Based on this phenomenon, the total number of RGs were considered to be the same as the total number of rain barrels in the Kinyerezi River catchment.

3.7. Quantifying BR ponds in the catchment

The Kinyerezi River catchment is under significant development and more attention was required for selecting the available open spaces for the BR ponds. The open spaces for sitting BRs ponds for each hydrological drainage line were spotted using Google Earth pictures of 24 June 2023 and their existence and suitability were verified by field visiting (Zahmatkesh *et al.* 2015; Ekmekcioğlu *et al.* 2021). The preferable sites were chosen in such a way that the distance from septic tanks/water wells should be greater than 30 m, the distance from building foundations be greater than 5 m and there should be a hydrological drainage streams (OrmondCity 2013). Fourteen (14) sub-catchments namely KS3, KS5, KS7, KS8, KS10, KS11, KS13, KS14, KS15, KS16, KS17, KS18, KS20, and KS21 had spotted sites suitable for the BR ponds making a total of 101 sites as indicated in Figure 4. In this regard, six sub-catchments namely KS1, KS2, KS6, KS9, KS12, and KS19 were not included since had no defined hydrologic drainage lines. Table 6 shows the sub-catchment areas, percentage imperviousness, the identified number of BR ponds, RGs, and RBs for the Kinyerezi River sub-catchment.

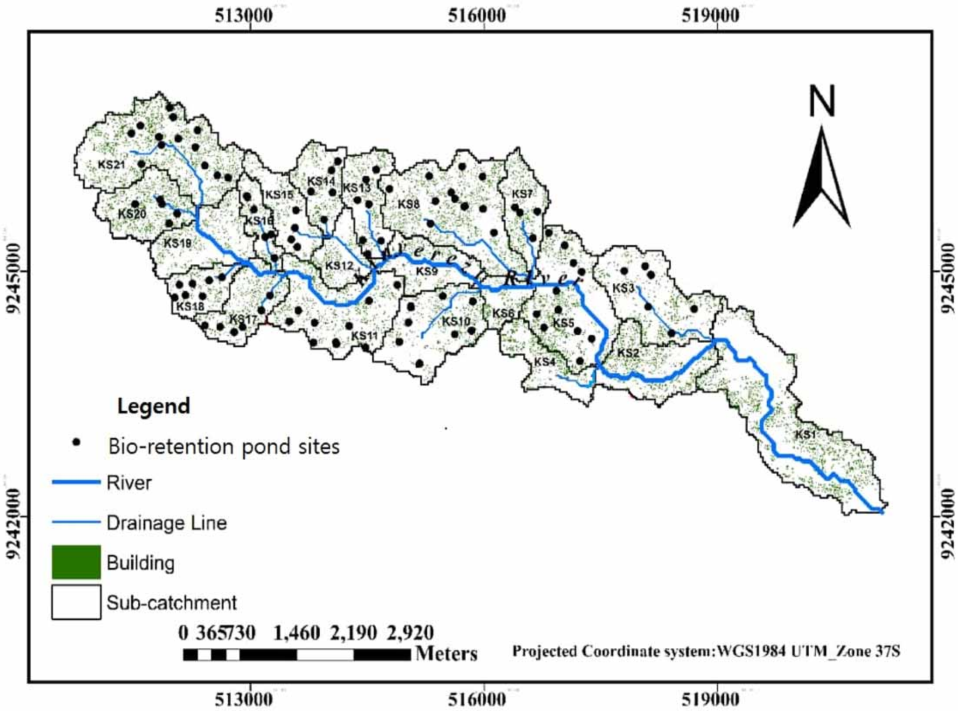


Figure 4 | Proposed BR pond sites in the Kinyerezi River sub-catchments (ArcGIS 10.4).

Table 6 | Number of BRs ponds, RGs, and RBs for the Kinyerezi River catchment

Sub-catchments	A (ha)	% Imperviousness (% of built areas)	Impervious area (ha)	10-RB/ha	No. of 3,000 L sizes RB	No. of 28 m^2 sizes RG	No. of BR
KS1	233.7	10.3	24.0711	10	241	241	–
KS2	93.3	35	32.655	10	327	327	–
KS3	120.1	35	42.035	10	420	420	6
KS4	55.2	31	17.112	10	171	171	–
KS5	142.2	29	41.238	10	412	412	11
KS6	32.1	14.8	4.7508	10	48	48	–
KS7	58.6	24	14.064	10	141	141	4
KS8	173.6	11.5	19.964	10	200	200	11
KS9	65.7	29	19.053	10	191	191	–
KS10	108.2	8.2	8.8724	10	89	89	9
KS11	131.6	9.6	12.6336	10	126	126	9
KS12	43.2	28	12.096	10	121	121	–
KS13	61.6	10.9	6.7144	10	67	67	7
KS14	54.5	32	17.44	10	174	174	5
KS15	58.2	8.7	5.0634	10	51	51	4
KS16	35.4	38	13.452	10	135	135	5
KS17	67.7	33	22.341	10	223	223	5
KS18	44	18	7.92	10	79	79	7
KS19	83.5	10.5	8.7675	10	88	88	–
KS20	75.1	17.4	13.0674	10	131	131	5
KS21	179.2	14.7	26.3424	10	263	263	13
Total					3,698	3,698	101

The Tanzania government under PO-LALG (2022) has developed Urban Greening Guidelines that illustrate the design, selection, and construction of LID practices. For this study, to reduce the number of the proposed BR ponds in the catchment and to canter with the small soil infiltration rate reported by Swilla *et al.* (2023) for the catchment, the authors opted for bigger sizes of BR ponds. The spotted sites were considered suitable if could accommodate the BR ponds of sizes greater than 800 m^2 with a 1.2 m depth that contains a surface layer depth of 0.3 m, a soil layer depth of 0.6 m, and a storage layer depth of 0.3 m as indicated in Figure 4 (Choi & Kim 2020).

4. CONCLUSION AND RECOMMENDATION

This study aimed to quantify the LID practices to suit the Kinyerezi River catchment in mitigating runoff floods for the Kinyerezi River. The preferable LID practices for the catchment were identified by matching the sub-catchment physical characteristics with the LID practices sitting requirements and by the MCDM approach. The results on matching the sub-catchment physical characteristics indicated that BRs, RBs, VSs, RGs, and CWs were appropriate LID practices for the catchment while the MCDM analysis indicated that BR, RG, and RB are preferable. The BRs, RGs, and RBs were quantified to be 101, 3,698, and 3,698, respectively. BRs are recommended for catchment use while RBs and RGs are recommended for residential buildings. The RBs have the advantage of promoting water-demanding economic activities at the household level. The reported *Ks* values which are less than 12.7 mm/h and global HSG C of the Kinyerezi River catchment was used to disqualify a number of LID practices. The *Ks* values were tested in few sites; within the catchment, it is fair to note that short distance testing intervals may result in *Ks* values greater than 12.7 mm/h and other HSGs rather than C; this was considered as the limitation for this study. The field visit revealed different RB sizes (500–5,000 m^3) that are currently in use by the residents in the catchment; however, in this study, only 3,000 liters capacity were quantified, and this was also considered as a limitation.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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