Front. Earth Sci. 2025, 19(1): 68–79
https://doi.org/10.1007/s11707-021-0924-7

RESEARCH ARTICLE

GIS-based flood proneness screening: a prelude to stormwater management in rapidly urbanizing catchments

Given J. MHINA (✉)[1], Marina B. JENSEN[2], Thomas BALSTRØM[2]

1 Department of Environmental Science and Management, Ardhi University, Dar es Salaam B201, Tanzania
2 Department of Geosciences and Natural Resource Management, University of Copenhagen, Frederiksberg C 1958, Denmark

Abstract Absence of reliable hydro-climatic information is among the bottlenecks for inadequate and improper management of stormwater runoff in rapidly-urbanizing catchments. This paper explores the influence of catchment heterogeneity in understanding the proneness of urban catchments to stormwater-borne hazards. Using GIS techniques, satellite images, and field surveys, geomorphological features and hydrologic characteristics of the Mbezi River catchment in Dar es Salaam-Tanzania were modeled to understand variations in their influence on flood hazards occurrence throughout the study catchment. The findings reveal that with GIS techniques public, domain Digital Elevation Models (DEMs) can provide preliminary but useful insights to inform stormwater management decisions in cities with limited hydrological data. Specifically, the heterogeneity characterization of the case study catchment indicates that Mbezi River is fern-leaf-shaped: it has a well-drained catchment (drainage density = 1.9 km/km^2), with total relief and elongation ratios of 265 m and 0.25, respectively. Results further revealed that the catchment is comprised of many natural sinks (blue spots) that, upon enhancement, can retain about 18 percent of stormwater runoff that could otherwise contribute to downstream runoff challenges. About 68 percent of the major sinks (with potential volume > 2.4 m^3) are located along the river flood plain where land is publicly owned. Additionally, more than 11.6 ha of land (as property) and 168 buildings are in areas that were mapped to have large natural sinks and they are at risk to flooding when the sinks get filled.

Keywords flood risk mapping, runoff modelling, flood control, runoff routing

1 Introduction

Over the past two decades, there has been an increasing interest in understanding the hydrological response characteristics of urbanizing river catchments (Francis, 2012). Research in this area was sparked with the development and technological application of innovative GIS-based hydrologic models that can describe rainfall-runoff processes in urban river catchments (Zhang and Pan, 2014; Balstrøm and Crawford, 2018). While these model-based investigations now are common in cities of the developed world, hydrological studies of rivers in many cities of the global south continue to be dominated by two older hydrological concepts: the ‘partial-area concept’ (Betson, 1964) and the ‘variable source concept’ (Hewlett and Hibbert, 1967).

Nevertheless, these old-school approaches continue to yield valuable insights. For example, they confirm that the rainfall-runoff process is an absolute function of the rate of rainfall inputs relative to the ability of the landscape characteristics to receive, process and release the excess rainfall (Beven, 2011). Further, work based on these conceptual models show that runoff formation is a composite function of several catchment parameters, including rainfall intensity, infiltration, storage, evaporation, and many other geomorphological characteristics (Kherde, 2016). The efforts of the current study build on this solid theoretical foundation while tapping new methods that promise more fine-grained understandings of the contribution of catchment morphological characteristics on rainfall-runoff processes. Specifically, we use publicly available digital elevation models (DEMs) and GIS-based stormwater applications to generate hypotheses related to the effect of variations in runoff on land use and people.

Proper knowledge of rainfall-runoff processes within river catchments is essential for understanding the quantity and hydrology of the resulting stormwater runoff (Beven,

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Received February 25, 2021; accepted June 21, 2021

E-mail: mhinagiven@gmail.com

2011). Runoff generation (quantity) is a complex, non-linear phenomenon resulting from the interplay of meteorological factors (rainfall and climate characteristics) and physical factors (landscape, soil, slope, plants and animals). Despite the increasing research interest in rainfall-runoff processes, data that could contribute to our understanding of this interaction continues to be inadequate for meaningful analysis. This study reduces this deficit by elucidating the influence of physical factors (catchment heterogeneity) of a river catchment (drainage behavior, shape, and storage characteristics) on the hydrology of its stormwater runoff.

Catchment heterogeneity constitutes another important aspect shaping the ideas in understanding the drainage behavior of stormwater runoff, especially in quickly urbanizing river catchments (Tetzlaff et al., 2010). In addition to land-use activities, heterogeneity of catchments is influenced by the geomorphic formation of the watershed, which defines the factors that affect the movement, interception, and storage characteristics of stormwater runoff in the catchment landscape. Knowledge of these factors facilitates a scrutiny of landscape-based stormwater management options; and when reliable spatial data are available, much of this knowledge can be extracted from DEMs using GIS techniques (Saeedrashed and Guven, 2013; Furze et al., 2017; Baby et al., 2021). However, in cities with inadequately hydrological data and limited access to high-resolution spatial DEMs, acquisition of this knowledge remains a challenge.

Despite the prevalence of knowledge on how the hydrology of stormwater runoff is affected by interception and storage thresholds, rapidly changing runoff generation and drainage behavior in urban catchments escalate the need for versatile methodological investigations (Chen et al., 2009). According to Spence (2010), changes in catchment storage indices have subtle effects on catchment runoff response characteristics depending on how saturation thresholds are attained. In addition to these aspects, new catchment hydrology paradigms are debated with interest to understand the storage-runoff relationships from which stormwater-related hazards arise.

Stormwater-induced hazards in rapidly urbanizing cities are increasing expeditiously, and dealing with them is becoming an ever-greater challenge (Sivapalan et al., 2003). Such challenges are becoming even stringent in cities of sub-Saharan Africa, including Dar es Salaam, because they are commonly characterized with ‘ungauged catchment syndrome’ meaning that they neither have reliable stormwater monitoring database nor proper records of hydrologic information available to inform engineering decisions (Ballesteros Cánovas et al., 2011; Beven, 2011). The same syndrome is a major contributor of factors for daunting applicability and development of rainfall-runoff models in cities of the developing world (Debo and Reese, 2003; Parkinson and Mark, 2005). Consequently, the increasing stormwater management challenges are inadequately perceived and inefficiently communicated among the stakeholders (Wagener et al., 2004; Blöschl, 2005).

The main objective of this study was to carry out a GIS-based geomorphological characterization of the Mbezi River catchment in Dar es Salaam, Tanzania to understand its influence on frequent occurrence of flood hazards. In terms of geographical features, land use, administrative capabilities and limitations, and hydrological attributes, this catchment has much in common with urban river catchments throughout sub-Saharan Africa. Hence, this study is intended to be a proof of concept that subsequently can serve as a flood proneness screening procedure in urban river catchments throughout the region. The specific objectives were: 1) to characterize the catchment landforms that influence stormwater hydrology focusing on relief, terrain, drainage density, and drainage pattern; and 2) to carry out an ensemble modeling of the catchment drainage network for Mbezi River and to demystify its hydrologic response behavior during extreme rain events. Ensemble modeling in this case refers to a process where forecasts generated by several models are combined to predict an outcome.

2 Methods and materials

2.1 Selection and description of the case study area

The study was conducted in the Mbezi River catchment located in Kinondoni Municipality (longitude 77°10′ E to 77°17′ E and latitude 15°48′ N to 15°56′ N) in Dar es Salaam, Tanzania. The 24 km Mbezi River has a seasonal flow from west to east before discharging its water into the Indian Ocean. Prior to the selection of the study area, optimization of selection creteria was carried out for eight major river catchments in the study city such that the selected study area could better represent other river catchments.

The 56 km^2 catchment area consists of undulating terrain with an average slope ranging from 7.5% in the upstream to 9% in the downstream area. The mean annual rainfall ranges from 1000 to 1400 mm/year, while mean daily temperature and average humidity range from 17°C to 33°C and 67% to 96%, respectively (Mato, 2002). The highest altitude in the catchment is about 370 m above the sea level, and the evaporation rate is estimated to be over 2100 mm/year (Mjemah and Walraevens, 2015). The major land use in the catchment is residential buildings, but it is also used for livelihood activities like subsistence vegetable gardening and small-scale animal farming.

2.2 Data acquisition and modeling

ArcMap software (version 10.3.1), a digital elevation model (DEM) of 30 m resolution, and rainfall data were required for this study. Although a DEM of such resolution is too coarse for detailed urban runoff studies, for the current study it was sufficient to reveal the flow patterns and the upstream runoff volumes accumulated within the catchment during various precipitation events. The DEM was extracted from a Global Digital Elevation Model (GDEM) that is freely available from ASTER-GDEM and downloaded online at NASA website. Rainfall records for the past 50 years, including intensity-duration curves, were obtained from the Tanzania Meteorology Agency (TMA).

2.3 Conceptualization of the Model

Looking at rainfall-runoff processes from a system perspective, the Mbezi River catchment had been abstracted as a monolithic system with rainfall as the main input. Beven (2011), Kherde (2016) and others have conceptualized the major hydrological processes involved in the rainfall-runoff transformation as illustrated in Eqs. (1) and (2):

$$\Sigma(\text{INFLOW})-\Sigma(\text{OUTFLOW}) = \text{CHANGE IN STORAGE}, \tag{1}$$

$$(P+G)-(E+T+I+R) = \Delta S. \tag{2}$$

Equation (2) presents an overall hydrologic budget for general surface waterflow over the catchment at a given time. P = precipitation or rainfall (mm), G = groundwater flow (mm/unit time), E = Evaporation (mm), T = transpiration (mm), I = Infiltration (mm), R = Runoff (mm/unit time), and storage is ΔS. Storage refers to all sorts of mechanisms that retain water, including the wetting of surfaces, absorption by vegetation (interception), detention in small landscape depressions, and storage in larger bodies of water.

2.4 Preliminary assessment of the catchment landform characteristics

Modeling of the catchment drainage characteristics was preceded by preliminary analyses to understand the morphological characteristics of the catchment. Using ArcMap functions, spatial analysis of the catchment was carried out by assessing the catchment hillshades and shaded relief. Additionally, the drainage density of the study catchment was delineated as a measure of how effectively the watershed was drained via tributary stream channels.

2.5 Modeling of catchment drainage characteristics

Following the Arc-Malstrøm method designed by Balstrøm and Crawford (2018), a catchment drainage model was developed using the ArcMap software's built-in functions. The ArcMap application 'Model Builder' was used to automate four different but interdependent ensemble models to examine the drainage of surface runoff on the study catchment. The first model set out to identify blue spots in the study catchment as a basic input into the next three sub-models which, respectively, 1) located the pour points of the blue spots, 2) modeled the flow routes of blue-spot spillovers; and 3) built a geometric network connecting all the pour points to their respective flow routes. The details on how these sub-models were carried out is summarized in the following subsections.

2.5.1 Identification of the blue spots

Model-builder framework as a visual programing data model was used to automate workflow series of hydrology tools (Fig. 1) to simulate the way runoff would flow across the catchment. Hydrologic modeling tools in ArcMap

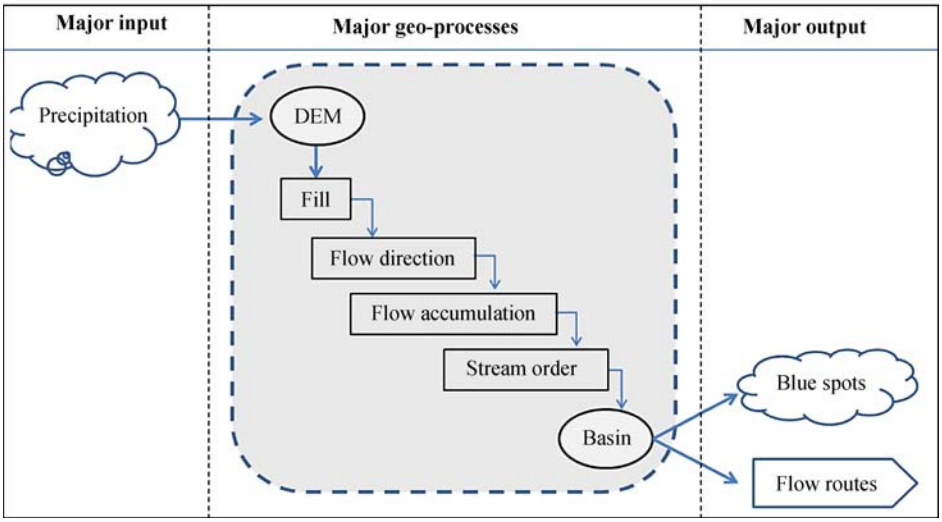

Fig. 1 Major tools and process involved in the identification of blue spots.

Spatial Analyst are equipped with procedures on how each tool is operationalized. The tools are useful for the identification of sinks, flow direction and flow accumulation, as well as delineating watershed and stream networks.

Using the DEM as an input to the Flow Direction tool, the direction in which runoff would flow out of each cell was established. To ensure proper drainage routing, depressions with values lower than the surrounding values were corrected using the Fill tool. Flow accumulation and local watersheds for every blue spot were delineated using Flow Accumulation and Watershed tools, respectively.

Digitized building footprints were available for the study area and, in principle, they could have been raised to infinite elevation levels and 'stamped' onto the Digital Terrain Model (DTM), thus enabling the model to indicate how their presence affected water flow paths. However, this 'enhancement' was rejected because the DTM's poor resolution lead to underestimations of sinks volumes when buildings and sinks were located within the same 30 m cell.

2.5.2 Pour points identification

A pour point is the location at which runoff drains out of a sink or depression on a given landscape. Basically, it is an outlet location of a blue spot (Fig. 2). In the Model-builder application, the pour point model was built to locate pour points for every identified blue spot. The major inputs for modeling the location of pour points were the DEM and layers of blue spots together with flow accumulation. Modeling is an iterative process; therefore, all the processes were automated and made flexible such that input variables are versatily to receive different input data sets.

2.5.3 Runoff flow path and network creation

To trace the downhill movement of runoff from each blue spot, another model was built. Using flow direction and pour point layers as inputs, a Cost Path tool was run to simulate the flow path of water from one blue spot to the next. Its output raster was then converted into a polyline feature class. Again, the model was customized such that its input variables could accept changes to re-automate the procedures repeatedly.

Finally, a geometric network was created such that a raindrop falling at any one location within the catchment, under ideal circumstances (see the Model assumptions section, just below), can be traced all the way to its final destination.

2.6 Model calibration and validation

As part of model calibration, the model of stream network features were burnt onto the existing streams. The validation of the model was done by comparing the modeled features with features in the real catchment basin. A field validation survey was carried out at seven major areas that were identified to contain large and deep blue spots. Field observations like flood marks, flood debris and the nature of the buildings were recorded in a field data log, along with summaries of discussions with residents of the visited areas. To map the risk of fluvial and pluvial floods, building footprints in the catchment were all digitized from Google Earth Pro Version 7.1.5 and their spatial locations were compared with blue spot locations.

2.7 Model assumptions

To simulate the impact of rapid urbanization within the catchment, we considered a hydrologic response model that assumes perfect runoff flow conditions proposed by Horton and used by Dunne et al. (1995). This model assumes that all the rainfall is converted into runoff and storage. The basis of the assumption rests on the fact that in stormwater management, surface water hydrology focuses on extreme rainfall and runoff events over relatively short periods. For such short-time events, several parameters in Eq. (2) become insignificant. Groundwater flow, evaporation, and transpiration are very slow-occurring processes that require longer residence time to generate an impact. Since the typical rainfall-runoff duration is very short in urban catchments, the effect of G, E, and T were simply ignored. Given these assumptions, Eq. (2) is rearranged and simplified to represent ideal runoff conditions as summarized in Eq. (3).

$$P - I - R = \Delta S, \tag{3}$$

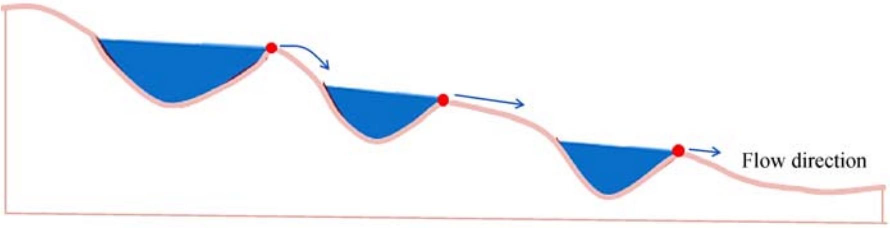

Fig. 2 This conceptual representation of a vertical landscape section explains the relationship between blue spots (blue) and pour points (red dots).

where P stands for precipitation or rainfall, R for runoff, and ΔS for storage.

Specific model assumptions

1) The delineation of location and sizing of blue spots (sinks) or major water storage areas (ΔS) is based on the assumption that there are no buildings in the landscape,

2) The runoff in the catchment is considered to assume Horton's flow, as neither infiltration nor evaporation occurs at relevant levels during a severe storm,

3) The parameters used in the modeling process is lumped and the catchment is more or less homogeneous in terms of soil, vegetation and geology,

4) The rainfall intensity is assumed to be uniform all over the Mbezi River's small catchment.

3 Results

The results of our catchment landform characterization in terms of basin shape, watershed boundaries, and topographic relief as delineated from the DEM are presented in Fig. 3. The characterization further indicated that the catchment is elongated and fern-leaf-shaped, with a drainage area of about 63 km^2 and an elongation ratio of about 0.25. Looking at the shaded relief map (Fig. 3), the catchment relief rises gradually from sea level to an altitude of about 254 m in the far end of the catchment. The overall watershed is comprised of many sub-catchments with sizes ranging from half a hectare ($\approx$ 4000 m^2) to 2.7 km^2. On average, the watershed landscape is made up of heterogeneous terrain that slopes at different gradients.

Results of catchment slope analysis are presented in Fig. 4, where it can be observed that the northern part of the catchment is relatively lower than the southern area, which is characterized by undulation and gentle slopes (Fig. 4). During the field surveys, it was observed that this part of the catchment was less eroded compared to the southern side of the river catchment. Regardless of high total relief of 254 m, the most dominant surface slope – the one prevalent in the middle parts of the study catchment area – ranges between 4° and 17°. The sub-catchments with the steepest slopes (above 40°) are dominant in the upper and middle catchment areas.

Field observations and the landscape characterization indicate that catchment vulnerability to flash floods, landslides, and soil erosion increases proportionally to slope steepness. The risk and susceptibility to these hazards thus increases from upstream to downstream areas of the study catchment. Regardless of the vegetation cover alongside Mbezi River, which is also receding as severe soil erosion and deep gullies become more extensive on steep slope areas and, as a result, many buildings fell off their eroded foundations. This observation was common in the southern parts of both the upper and lower catchment, where the slope is between 30° and 49° (Fig. 4).

Figure 5 presents a drainage density map for the Mbezi River catchment. The analysis of the DEM shows that the study catchment has an average drainage density of 1.9 km/km^2. This is equivalent to a drainage pattern where four tributary streams are formed during every kilometer run. Based on Strahler stream orderling system (Gleyzer

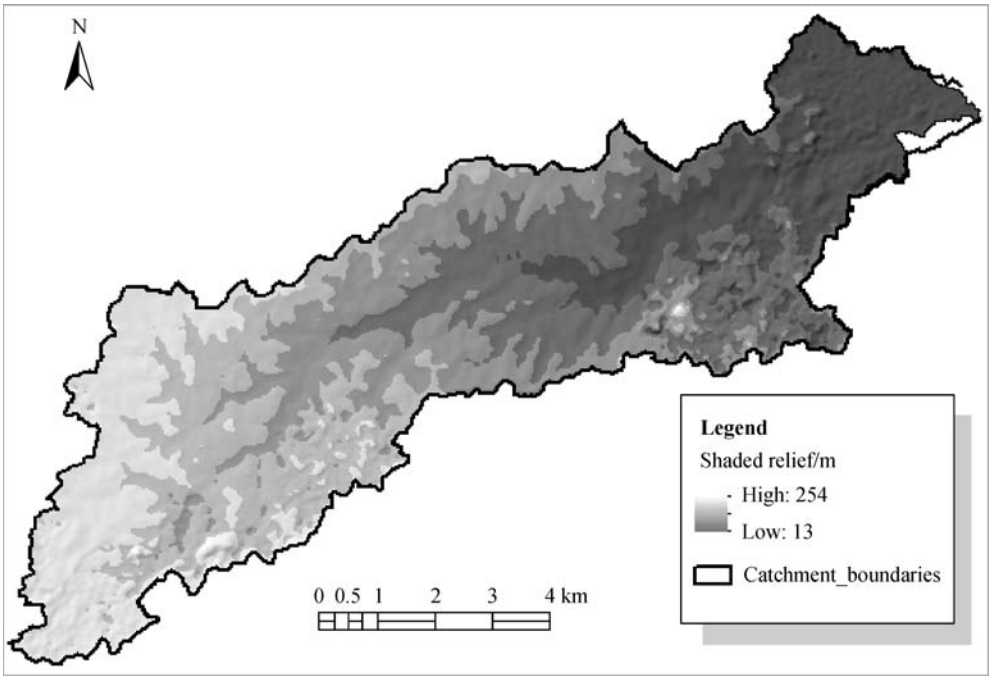

Fig. 3 Shaded relief map of Mbezi River catchment at 45° azimuth angle. The darkgrey and pale-black colors indicate low-lying areas and raised relief, respectively.

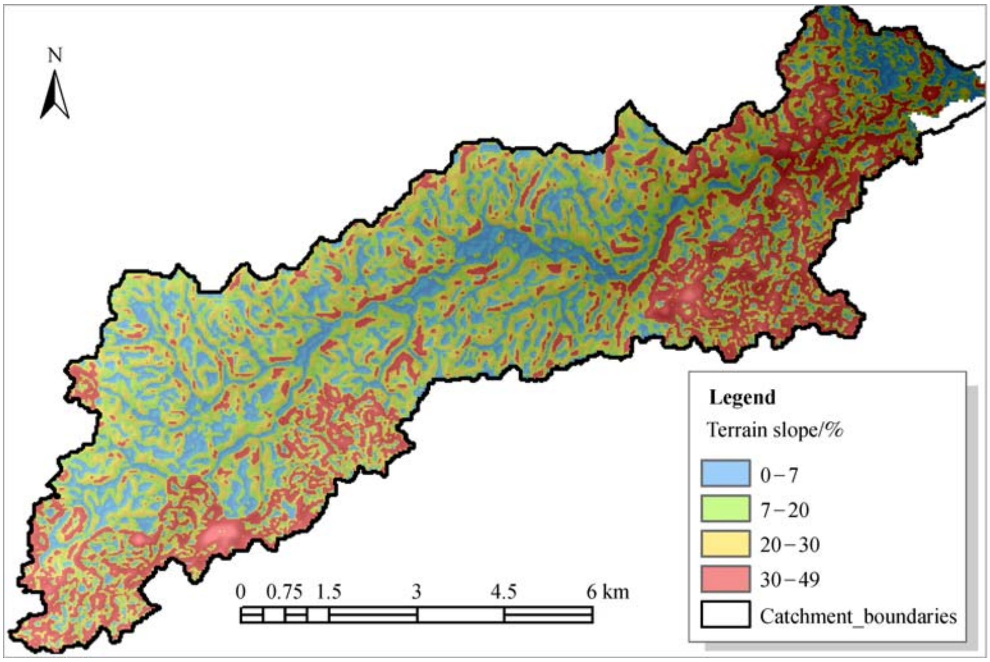

Fig. 4 Slope analysis map of Mbezi River catchment.

et al., 2004), the study catchment has 18 first-order streams, 4 second streams and 1 (one) third-order stream summing up to a total length of 12, 8.5, and 9 km, respectively. With reference to Fig. 5, the catchment is essentially divided into three drainage density zones. The first is the wet zone (blue color), characterized by high flow accumulation, a high groundwater table (by physical observation), and great flooding potential. The second zone is the green buffer (green color), characterized by only moderate moisture but active erosive processes. The outer zone (brown color), is the driest and most distant part of the catchment.

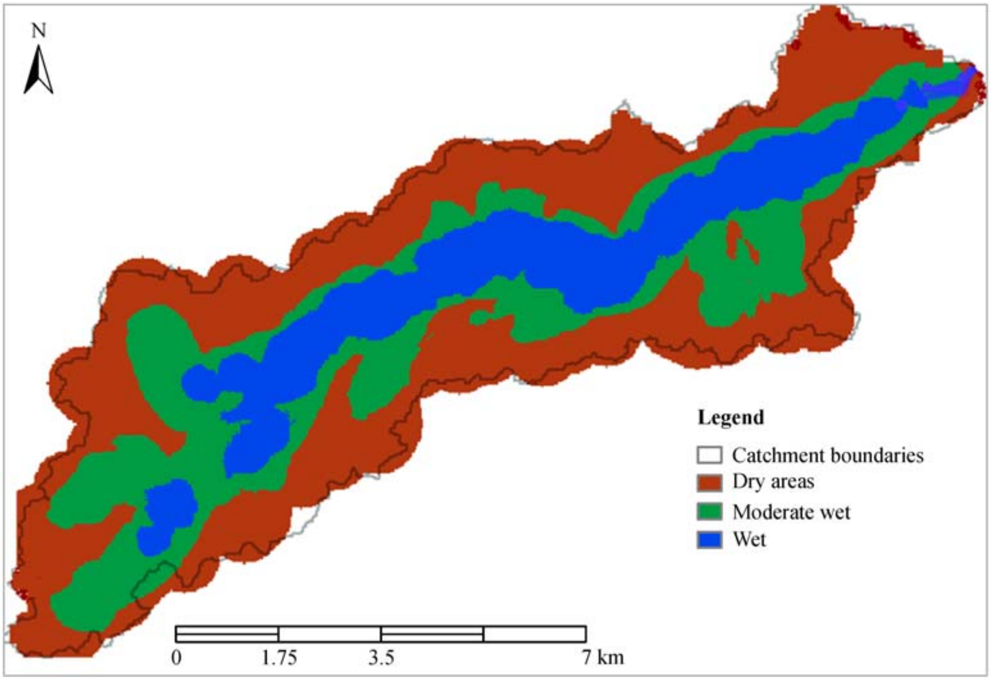

Fig. 5 Drainage density map of Mbezi River catchment basin.

3.1 Hydrological behavior of the study catchment

The hydrological response of the Mbezi River catchment to a five-year (100 mm) rain event, which was assumed to rain evenly over the watershed and under perfect rainfall conditions, is presented in Fig. 6. As noted earlier, rainfall intensity-duration frequency curves (IDF) provided by Tanzania Meteorologic Agency indicate that for the past 20 years, a rainfall intensity of 100 ± 5 mm in Dar es Salaam lasts for 15 min and has a return period of 5 years. Comparing the study results from the two rain events used for modeling, there was no significant difference ($p < 0.03$) in catchment hydrologic response between 100 mm and 30 mm rain events in terms of runoff volume retained in the natural depressions (blue spots) of the Mbezi River catchment.

The hydrology and hydraulics of the spillover volume from the modeled blue spots of Mbezi River catchment conforms to a sequent drainage pattern in which the watershed is drained consistently along the overall catchment slope. The Mbezi River, which acts as main drain the catchment, is fed by a number of tributaries that emerge from various locations depending on the local initial surface slopes. In accordance with Seo et al. (2015), the spatial arrangement of runoff spillover routes on the sub-catchments watershed demonstrates a typical dendritic (tree-like) drainage pattern of streams network (Fig. 6).

Figure 7 presents the spatial location of blue spots in relation to the elevation and catchment slope, in three dimensions. A closer look at Fig. 7 shows that natural depressions (sinks) in the landscape of the upper and lower parts of the catchment have more potential to retain rain; such depressions are largely absent from the central catchment areas. This is partly because these areas are being leveled by anthropogenic activities. Field observations indicate further that the central areas of the study catchment are characterized by a series of little hills with gentle slopes but contain deep and relatively narrow erosion-caused ditches that concentrated runoff flow from the upstream catchments. Landscapes in the upper and lower catchment, where most of the blue spots are found, were characterized by similar undulating terrain but with relatively gentle surface slopes and wide plateaus (Fig. 7).

The volume of identified blue spots ranged from 2000 m^3 to 3.24×10^6 m^3, with a standard deviation of 2.6×10^7 m^3. About 12 per cent of blue spots with capacity greater than 1000 m^3 were located in the southeastern part of the upper and lower river catchments (Figs. 6 and 7). A validation field visit for the model outputs revealed that the large and deep blue spots (red and orange patches on Fig. 6) were located in areas that were either naturally low-lying or lower due to various livelihood activities like sand mining and as borrow pits.

Under ideal rainfall-runoff conditions, the Mbezi River catchment area can generate up to 6.3×10^6 m^3 of runoff in response to a 5-year rain event (100 mm in 15 min). The modeled capacity of the blue spots' collective volume can hold up to 41 per cent of the runoff generated during such an event. The overflow is normally drained to the Indian ocean through the Mbezi River. The average depth of the blue spots was 1.91 m (ranging from 1 to 4 m), with a standard deviation of 0.56.

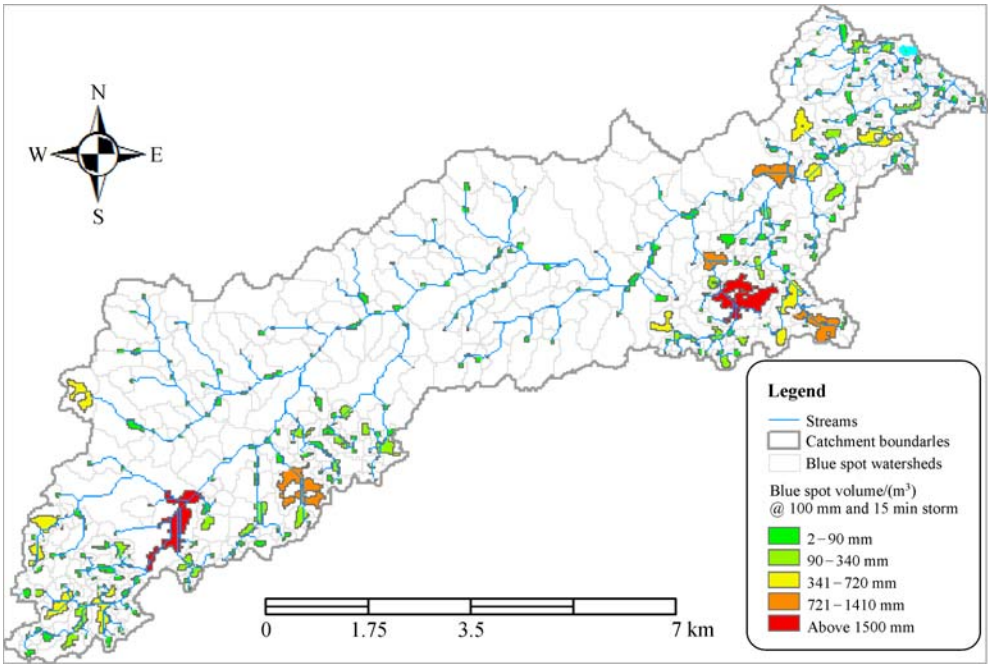

Fig. 6 Drainage pattern and runoff storage potential of the Mbezi River catchment.

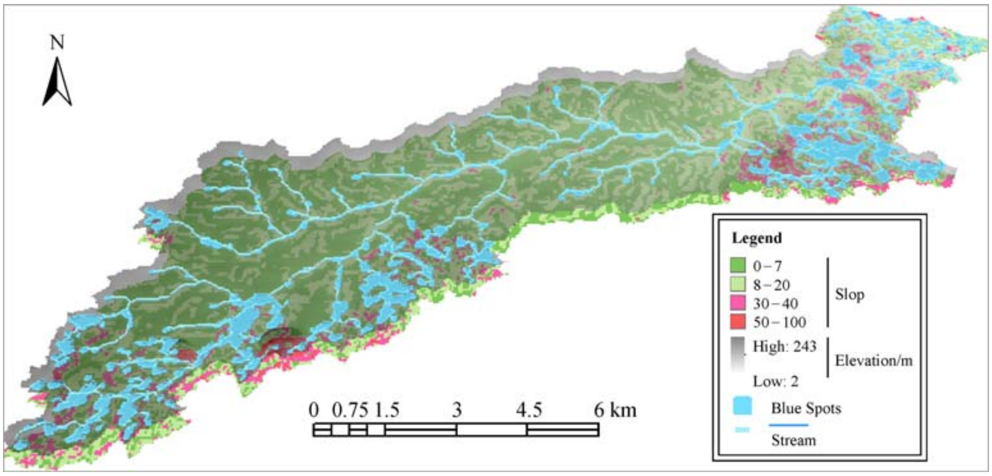

Fig. 7 Blue spots in the Mbezi River catchment, presented in 3D.

3.2 Vulnerability of the Mbezi River catchment to flooding

The red patches (dots) in Fig. 8 present a pattern of settlement development in the catchment as digitized from Google Earth (satellite images of 2016). The blue-green (aqua-marine) color in Fig. 8 indicates the locations and sizes of blue spots. As can be observed from Fig. 8, the upper and lower parts of the catchment are heavily built (many red dots) while the central catchment areas are relatively less congested.

By overlaying the map of built areas (digitized buildings) within the catchment on the map of modeled blue spots, it was observed that about 168 buildings are located in large blue spots (see the zoomed area in Fig. 8). During field visits for validation of the model results, only two houses located on blue-spot areas were reliably identified. These two houses, in Mbezi Luis sub-ward, had raised foundation plinths with flood marks ranging from 0.8 to 1.3 m. The house owners reported that they had lived in the area for 15 years and and had witnessed at least

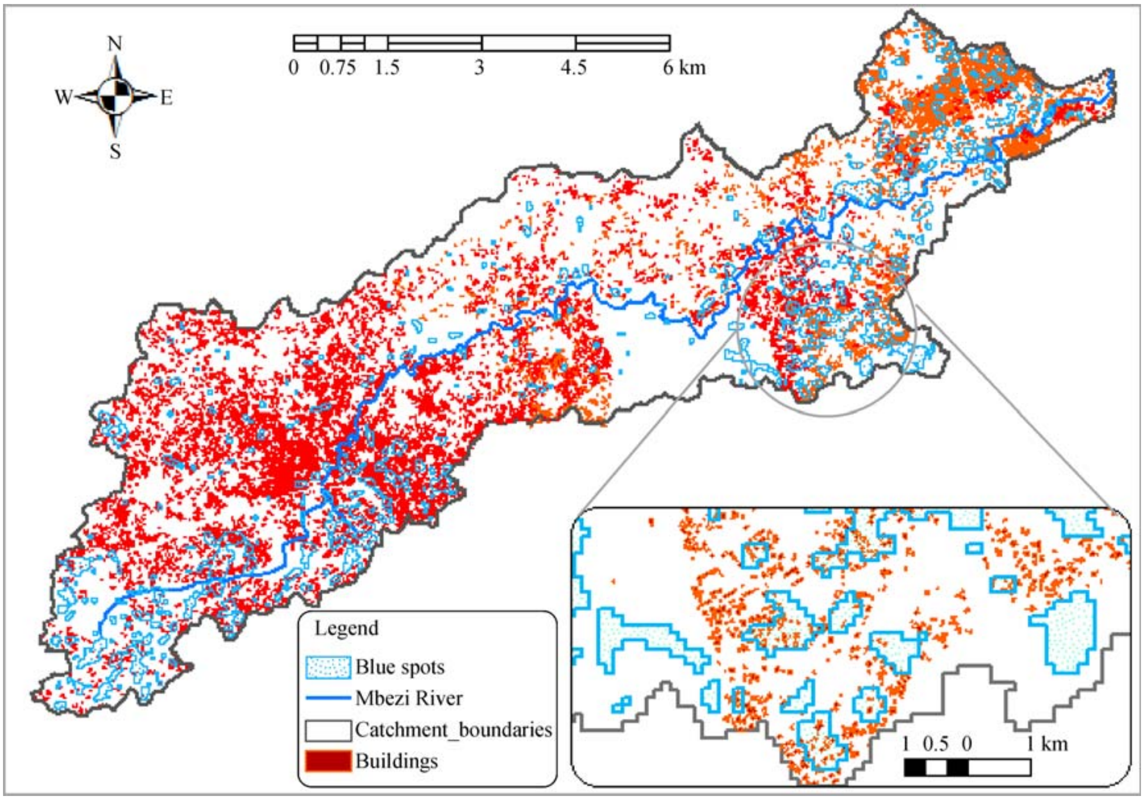

Fig. 8 Proneness of Mbezi River catchment to flash floods.

three flood event in the past 6 years. Other areas modeled as covered with blue spots had neither significant signs of flooding nor records of floods occurring during the past 6 years. However, most of those areas were severely affected by soil erosion. In response to such hazards, a lot of flood coping strategies were observed in areas that were marked to be in blue spots, especially in lower parts of the catchment.

Fluvial flooding is common and mostly reported in the downstream part of the catchment (Kawe ward). According to three members of the sub-ward environmental committee, including the chairperson, during the past ten years about 28 houses were completely demolished by flood-caused erosion and another 13 houses were at immediate risk if the erosion trend continued unchecked (see Fig. 9). In response to this phenomenon, various flood risk coping mechanisms were observed during the field visits, including concrete dykes, gabion walls, piles of sand bags (Fig. 9) and retention walls made from used car tires.

4 Discussion

The current study indicates that the Mbezi River catchment is a well-drained, elongated, fernleaf-shaped watershed with a relatively high drainage density (1.9 km/km^2). Among other factors, high drainage density is often a precursor of flash floods and a good indicator of erosion hotspots (Pallard et al., 2009). Watersheds with high drainage densities are often characterized by flashy hydrographs with steeper rising and recession limbs (Pallard et al., 2009). During the study, areas with severe soil erosion were widely observed during field surveys; however, the measurement of flow hydrographs was beyond the scope of the current study.

The study results reveal further that the Mbezi River catchment has a natural drainage outline (Fig. 6) with potential for Landscape-based Stormwater Management (LSM), as elaborated by Dhalla and Zimmer (2010). Despite the conflicting layout between the natural drainage pattern and the urbanization trend of the catchment (Fig. 8), it is evident that if the catchment drainage potential is harnessed by adopting LSM options (Dhalla and Zimmer, 2010), about one-third of ‘on-catchment’ runoff could be retained, thereby ameliorating some of the prevailing stormwater-borne challenges (Fig. 9) into water utility amenities.

Analysis of the study findings also reveals that the ongoing and inadequately controlled urbanization (Mhina et al., 2018) is undermining the catchment’s drainage system and more assets are becoming vulnerable to flood-related damage. If the situation continues along its present trajectory, gully erosion will enlarge and flood events will be both more frequent and more intense.

As the catchment continues to urbanize, the need for versatile stormwater management practices intensify. However, catchment-based stormwater management looks promising. Studies done in other parts of the world emphasize that catchment-based stormwater management planning requires, among other things, a complete picture of the geology, the hydrology, and the climatic characteristics of the catchment (Weitman et al., 2009; Lee and Yigitcanlar, 2010). This is why the current study sought to carry out a GIS-based geomorphological characterization of the Mbezi River catchment in Dar es Salaam: as an attribute in understanding the geomorphometric indices of urban rivers.

Despite the limitations of public domain DEMs (Tian et al., 2018; Tavares Da Costa et al., 2019), data from the DEM used in the current study were adequate for the derivation of reliable drainage characteristics maps (Figs. 3 and 6). However, some minor shifts of drainage features occurred on the derived maps when compared to those observed during the validation of the findings on the ground and on the google earth images. According to Papasaika et al. (2011), terrain characteristics, primary data

Fig. 9 Impacts of fluvial floods in the Kawe Ukwamani area. (a) shows some of the endangered buildings. (b) shows some of the community coping strategies against floods. The black line in (b) shows the height of the flood marks.

acquisition technology, and processing procedures are among the sources of DEM errors. Such errors are liable for impaired quality and heterogeneity of DEMs.

Several studies (Furze et al., 2017; Tian et al., 2018) have reported on the use of data fusion techniques that improve the accuracy of public domain DEMs. However, these techniques require advanced GIS skills, which are rarely possessed by ordinary stormwater managers. To this end, the need for advanced GIS skills impedes the applicability of GIS models as a tool to inform decision making. The latter observation is among the reasons why the current study used an original (unmodified) DEM. It is expected that many stormwater managers can use the research methods presented here to analyze catchments that are of interest to them. The approach used in drainage characterization of the current study is found to be both practical and useful in highlighting, mapping and visualizing drainage patterns of river catchments, and a commonly-used approach could facilitate communication among stormwater management stakeholders. Additionally, the derived drainage maps can usefully inform stormwater management decisions. To this end, access to a DEM of better resolution could provide more detailed catchment information and should be used when possible (Siart et al., 2009; Florinsky et al., 2018).

Geomorphological analysis of river catchments is crucial to the derivation of utilizable potentials of rainwater (Chadha and Neupane, 2011). In this study, the morphological characterization of the catchment serves as a flood proneness screening procedure; the assessment on how the catchment responds to rain events is done by looking at the layout of the drainage network (Fig. 6), including the location of blue spots (Fig. 8). Knowledge of the spatial distribution of blue spots, including water levels and holding capacity, can serve watershed-based water resource planners and managers in a variety of ways. Practically, blue spots are indicators of potential sites for inundation. They help planners not only to identify and delineate low-lying areas with high flood risk to floods, but also to highlight the assets and properties exposed to such floods (Minea, 2013). In addition, knowledge about low-lying areas of the landscape informs the process of identifying potential areas suitable for implementation of LSM elements (e.g., retention and detention ponds). In other words, blue spots exist in areas with great runoff accumulation in response to storm event (Apel et al., 2009; Mason et al., 2011). The latter information might be valuable to urban and infrastructure planners, disaster responders and risk managers.

Many studies have reported on the power of GIS and the ability of high-resolution geospatial data in understanding the hazards of changing urban hydrology (Chen et al., 2009; Ghimire et al., 2013; Baby et al., 2021). However, the achievement of this knowledge is more compatible with the technological advancement of the first world and highly celebrated in cities of the global north. At present, the application of this knowledge, despite the desperate need, is far beyond the reach of third world cities.

Most rainfall-runoff models are data intensive, complex and difficult to use (Zhang and Pan, 2014), while most cities have inadequate monitoring data of their own and, at best, limited access to high-resolution geospatial data (Makungo et al., 2010). Adding on the existing knowledge on how GIS techniques can be used to determine the location and magnitude of hydrological hazards, the scholarship of the current study goes beyond the delineation of such hazards focusing to inform the location and options of LSM using a public domain DEM.

5 Conclusions

This paper has demonstrated the influence of catchment morphological characteristics in understanding the proneness of urban river catchments to stormwater-born hazards. The findings reveal that GIS-based terrain descriptors extracted from public domain DEMs are trustfully capable of availing reliable hydrological information to aid communication among stormwater management stakeholders. In reference to the study case, the analysis of such terrain descriptors revealed further that the Mbezi River catchment is prone to flash floods and the proneness has a potential to intensify with the increasing impairment of catchment drainage routes caused by inadequately controlled urbanization.

Given the fact that many smaller river basins in developing cities are un-gauged (Blöschl, 2005), modeling to aid decision making is crucial. For models to be useful and fit for integration into municipal fiscal plans, especially in technology- and data-challenged cities, they need to be simple in terms of input requirements, manipulation, operation, and interpretation of the simulated results. In such circumstances, models that can be customized to make use of open-source (public domain) input data and still provide useful information in decision making are most preferred.

The overall findings of this study underscore the need for policy interventions that ensure that stormwater management is adequately integrated into both urban planning codes and the management of water resources. More specifically, a source-control stormwater management practice needs to be integrated into the design of stormwater management systems for both erosion control and water provision.

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