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Mapping the Gap of Water and Erosion Control Measures in the Rapidly Urbanizing Mbezi River Catchment of Dar es Salaam

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Abstract: In rapidly urbanizing catchments, increase in stormwater runoff may cause serious erosion and frequent floods if stormwater management systems are improper and dysfunctional. Through GIS-based modelling, field investigations, resident's questionnaire survey, and interviews with officials, the study set out to assesses the coverage and efficiency of drainage infrastructure in Mbezi River catchment basin in Dar es Salaam, Tanzania. Between 2003 and 2016, the catchment imperviousness increased by 41%, causing flood incidents, massive erosion, and numerous pollution sources. Residents strive to address stormwater hazards using terraces, hedges, and physical barriers; however, the problems persist, indicating lack of coordination and poor causality understanding between land-use changes and catchment impacts. Small-scale stormwater harvesting was exercised by 75% of the households, pointing to water supply challenges. Municipal stormwater management efforts was limited to roadside drains covering 17% of road lengths in the catchment, and 65% of those did not meet their design standards. Interviews with officials revealed a need for improved co-understanding and collaborative initiatives to bolster integrated water management. The study suggests a need to adopt a new urban stormwater management paradigm, appropriate for both residents and authorities. Without this new discourse, the urbanization led stormwater increase might jeopardize the liveability of the entire catchment.

Keywords: green infrastructure; water supply; flood control; runoff routing; Tanzania

1. Introduction

In rapidly urbanizing catchments, the landscape is often affected due to the formation of impermeable surfaces. These surfaces are one of the primary stressors of hydrologic systems [1–3]. Land-use changes affect runoff quality and flow characteristics, resulting in increased volumes and peak flows, and possibly flash floods, as well as erosion and environmental degradation if appropriate counter measures are not taken [4–6]. With climate change and urbanization, the challenges posed by stormwater and population rise have increased in the recent past [6]. Further, water demands are increasing while supply sources remain the same and some are deteriorating [7]. Unless alternative water supply sources such as rainwater are realized, urban groundwater and surface water reservoirs will likely be stressed and overexploited, adding to critical city-water imbalances [1,8]. Alongside water supply and stormwater management, urban dwellers must cope with increasing amounts of wastewater and solid waste generation [9]. Urban rivers are especially victimized, in terms of drying out due to overexploitation, river bank degradation due to encroachment and erosion, and excessive pollution due to increased raw wastewater discharge and solid waste dumping, altogether causing environmental degradation and loss of ecosystem services [10,11].

In recent years, many small urban centres have rapidly grown into large, crowded cities, of which most of the growth has been in a sprawling fashion [12]. This is especially true for many cities in Sub-Saharan Africa, including Dar es Salaam in Tanzania [13–15]. Among the primary drivers is rural–urban migration [15], in addition to the resettlement of more affluent residents who move from the city centre to outskirts to build better homes ([16], and own observations). The letter pushes the city boundaries to expand into the peripheral landscapes. Added to that, Dar es Salaam is already experiencing increased pluvial flooding and soil erosion [15,17,18], and the water supply situation is fragile [19,20]. Likewise, deteriorated rivers have been reported for many catchments of Dar es Salaam city [21]. It should also be noted that 70% of the city population lives in unplanned settlements with inadequate infrastructure services for sanitation and solid waste [22]. Regarding solid waste, only 39% of the daily production of 3100 tonnes is safely collected [23].

Rapid urbanization in many cities of developing countries is, in most cases, confronted with a deficit in urban water infrastructures [24] due to inadequately implemented plans founded on financial scarcity. The little infrastructure available is based on conventional practices, limiting its focus to drainage efficiency, without considering the overall-catchment water flows and balances or the water quality, in contrast to what is reflected in the Water Framework Directive, which is under implementation in Europe [25]. Thus, where a stormwater runoff service is available, it often consists of direct conveyance into receiving waters at high discharge rates, causing problems of erosion and providing no recharging of surface water and groundwater [26], and, moreover, is not adequately maintained [27].

Considering the inability of conventional infrastructure developments to keep pace with urbanization rate, the need for alternative approaches becomes clear. Here, the so-called source-control stormwater management practice, which has gained popularity in many developed cities, may represent a useful alternative. In source control stormwater management practices, stormwater runoff is dealt with in decentralized detention and retention elements, located close to the runoff generating surface, often as vegetated elements in the landscape, and considering both quantity and quality of the water [28–31]. This practice is known under names such as Water Sensitive Urban Design (WSUD) in Australia [32]; Low Impact Design (LID) in New Zealand [2,31]; Sustainable Urban Drainage Systems (SUDS) in the UK; Best Management Practices (BPM), and recently Green Infrastructure (GI) in the USA [30]; Landscape-based Stormwater Management (LSM) in Denmark; Local Management of Stormwater in Sweden [33]; and Sponge City Concept (SCC) in China [34]. Unlike conventional systems, which involve diverting stormwater runoff out of the city via large, underground pipe-networks, this alternative practice is based on rather simple and isolated solutions that can be implemented independently of each other and with proper function under a minimum of professional skills. Accordingly, this may hold a potential for rapid improvement of the service level in cities in developing countries where urban financial resources are scarce [8].

Progressing from centralized pipe-based discharge of stormwater runoff to a decentralized source-control approach, technocrats and decision-makers need to understand the significance of urban hydrology at a catchment level. By evaluating the entire catchment, it will be possible to make the best use of the existing stormwater infrastructure and combine it with emerging source-control initiatives, thus targeting an overall desirable urban development trajectory [35]. Generally, the argument raised in this context is not about abandoning the existing stormwater management practices but retrofitting them appropriately to counter the impact of urbanization and possibly climate change.

The overall objective of this study was to map the gap of water and erosion control measures in the rapidly urbanizing catchments of Dar es Salaam, Tanzania using the Mbezi River, as a case. The goal is to understand how to initiate a better water management situation given the near future absence of conventional stormwater infrastructure. More specifically, the study was meant to: (i) describe the selected catchment in terms of its urbanization trends and hydrological challenges; (ii) provide an overview and assessment of private and public stormwater infrastructures present in the catchment area with emphasis on flooding and erosion control measures; and (iii) probe the attitudes of officials assigned to deal with stormwater management in Dar es Salaam.

Based on various investigations, the water and erosion situation in a typical catchment of Dar es Salaam is described from both physical-technical and administrative perspectives. The overall assessment can provide a baseline for understanding stormwater infrastructure status quo and to stimulate change.

2. Materials and Methods

The case study area was the Mbezi River catchment, which is one of several watersheds in Dar es Salaam, Tanzania (Figure 1). The catchment covers an area of 56 km^2 of quite undulating topography, and contains mixed settlements with different land use activities. The river is 24 km long, and runs from the western side of the city, passing through the city, and discharges into the Indian Ocean about 12 km north of the city centre. It falls under six different administrative wards of Kinondoni Municipality. The river with its catchment is considered to represent much of the geographical, land use, and administrative variation present in the city.

Delineation of the Mbezi River catchment was based on GIS analysis by running the Basin tool from the Spatial Analyst toolbox of ArcGIS version 10.3.1 (Esri, Redlands, CA, USA). The latter was performed using a digital elevation model (DEM) retrieved from the online data pool, courtesy of the NASA Land Processes Distributed Active Archive Centre (LP DAAC, ASTER GDEM of 30 m spatial resolution, available online at https://asterweb.jpl.nasa.gov/gdem.asp, accessed on 1 January 2016). To map the layout and conditions of natural stormwater flow routes, GIS was further used to model the drainage routes, using the geometric network method as detailed in [36], the simulation of which was later validated by overlaying them against a few georeferenced routes selected and traced from hand-held GPS (Garmin, Olathe, KS, USA) data.

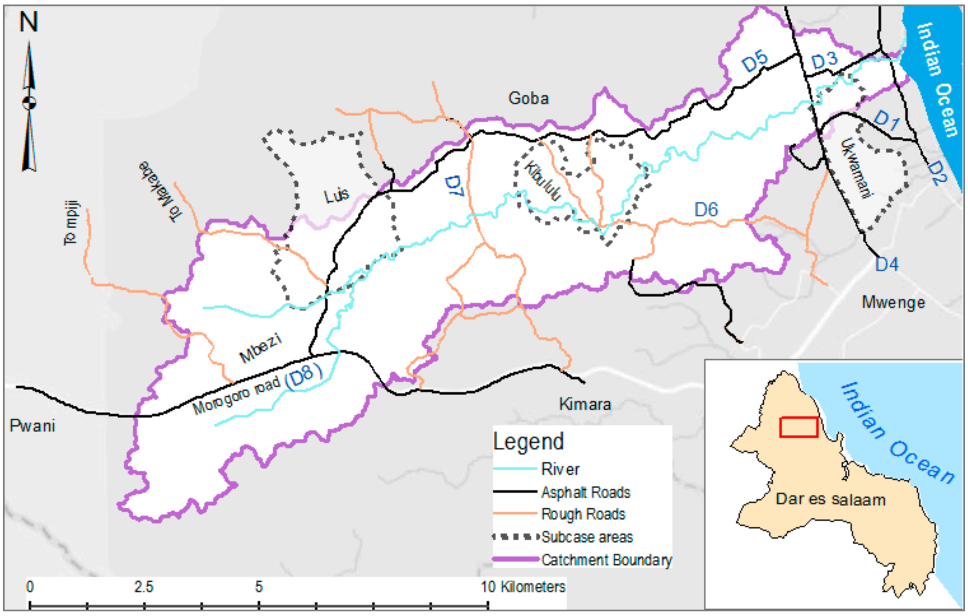


Figure 1. Delineation of Mbezi River Catchment in Dar es Salaam, Tanzania, serving as case study area. The three sub-case study areas (Luis, Kibululu and Ukwamani) are indicated, as are the roads for which drainage channels have been assessed (D1 to D8).

The maximum altitude of the catchment is 370 m above mean see level, while the average slope ranges from 7.5% in the upstream to 9% in the downstream. The area has a tropical coastal climate with mean daily temperature ranging from 17 to 33 °C and average humidity of 67–96% [37]. The mean annual rainfall ranges from 1000 to 1400 mm/year, distributed on two seasons, November to January ("short rains") and March to May ("long rains") [38], and the potential evaporation rate exceeds 2100 mm/year [39]. The dominant land use is residential, with a mixture of licensed and unlicensed plots, and small-scale vegetable farming. Being unplanned, the plot sizes are not standardized but varying, reflecting the purchasing power of the landowner, from approximately 225 to 625 m^2 and with a building-to-plot-size ratio of more than 60% (field survey 2014, data not shown). Most of the buildings are permanent structures constructed of cement-sand blocks (100 mm × 210 mm × 440 mm from local markets), roofed with corrugated iron sheets. There are two main roads across the catchment, New Bagamoyo Road (D4) and Morogoro Road (D8), as well as a number of feeder rough roads (see Figure 1). Public drainage infrastructures are only provided for the major roads, labelled D1 to D8 in Figure 1. The study focused on the major roads and three selected sub-case areas, representing, respectively, the upper (Luis), middle (Kibululu) and lower (Ukwamani) parts of the catchment (Figure 1).

Luis (total area 7.8 km^2) is a fully developed semi-informal (a mixture of licensed and unlicensed plots) settlement with relatively high-income residents (100–250 USD per month [40]); Kibululu (total area 4.6 km^2) is an informal settlement with comparatively larger open plots and relatively high-income residents [40]); and Ukwamani (total area 4.2 km^2) is a totally unplanned, informal and highly congested settlement, mostly with low income residents (<100 USD per month [40]). The over-all area of the three sub-cases within the catchment boundary constitutes about 21% of the total catchment area.

Based on the informality of the settlement, records on new building development do not exist. Therefore, satellite images of 2016, together with historical images from 2003, 2007, 2010 and 2013 available in Google Earth Pro (version 7.1.5, Google, Mountain View, CA, USA), were used to describe the urbanization trends over the past 13 years for the three sub-cases. From each satellite image, nine representative segments of 1 km^2 each were delineated, three from each sub-case area to identify the number of buildings in each segment as seen from the satellite images. The three segments were thus selectively delineated to include the densely, moderate, and sparsely built areas from each subcase, and the average number of buildings per 1 km^2 was documented.

To describe the hydrological challenges along Mbezi River, catchment surveys catalogued the major sources of pollution in terms of noting illicit wastewater and solid waste dumping locations, and marking of the major erosion-affected areas. To obtain information on flooding problems and local practices for stormwater management and erosion control, a questionnaire was administered to landowners, selected randomly among the three sub-cases. The sub-case areas were purposefully selected to ensure fare distribution and representativeness of the randomly selected landowners over the catchment. The survey thus covered 27 landowners from Luis, 31 from Kibululu and 23 from Ukwamani. The total number of households included in the survey corresponds to 3.6% of all households in the catchment, since most of the 81 landowners represented more than one household. When administering the questionnaire, practices for stormwater harvesting were also noted. The questionnaire responses on stormwater and erosion control measures were categorized into four hydraulically cascading units: tributary level, neighbourhood level, plot level and building level. The building level was included because many erosion gullies originate below the roof runoff down spouts. "Neighbourhood" refers to a local watershed that includes a network of runoff routes from buildings and their corresponding plots, roads and footpath networks that drain stormwater towards a common tributary or valley.

The coverage and efficiency of man-made stormwater infrastructure along major roads (D1 to D8 in Figure 1) as provided by the municipality were were geo-referenced, and their dimensions and slope recorded. The slope was calculated as ratio between vertical rise between points and their horizontal distance using total station theodolite (SOKIA SX series). The hydraulic capacity and design goals of the drains were assessed with reference to the area of sub-catchment contributing to every drainage channel. The performance for an installation to meet its design goals was based on criteria suggested by [36], as summarized in Table 1.

Table 1. Criteria for assessing man-made infrastructure drainage service. Modified from [41].

Assessment Criteria	Criteria Description and Main Features
Service coverage	Spatial extent and land area coverage of the service
Service level	Accessibility/availability degree and convenience of service to users
Effectiveness	Degree of achievement of service design goal
Condition of repair	Physical condition/capacity of service quality, service advancement level
Service standard	Status/hierarchy/level/class of service quality; service advancement level

To obtain more information about the attitudes and opinions of officials responsible for stormwater infrastructures in Dar es Salaam, a total of 27 interviews were conducted with relevant authorities, including officials from the six sub-wards constituting Mbezi River catchment whereby each sub-ward was represented by two native members from the environmental committee, the chair person, and one executive officer, as well as three officials from the National Environmental Management Council (NEMC), Kinondoni Municipal Council, and Tanzania Road Agency. The interviews were semi-structured, focusing on probing how the local authorities perceived stormwater related challenges and which options they considered for resolving the challenges.

3. Results

3.1. Urbanization Trends and Water Related Challenges

Mbezi River catchment boundary and its natural stormwater drainage routes, as revealed by hydrology tools of ArcGIS, are presented in Figure 2. It shows a well-drained catchment with up to four stream orders [42]. While the simulated fourth and third order streams, as well as most of the second order streams, overlaid perfectly with existing streams, most of the first order and a few of the second order streams could not be located on their predicted positions. In addition, several non-predicted first order streams were observed during ground truthing. Overall, the GIS-based map delineated the catchment and localized the natural runoff routes well and could serve as a base map. The banks of the main river were the most affected by erosion, followed by areas along the first and second order streams (Figure 2).

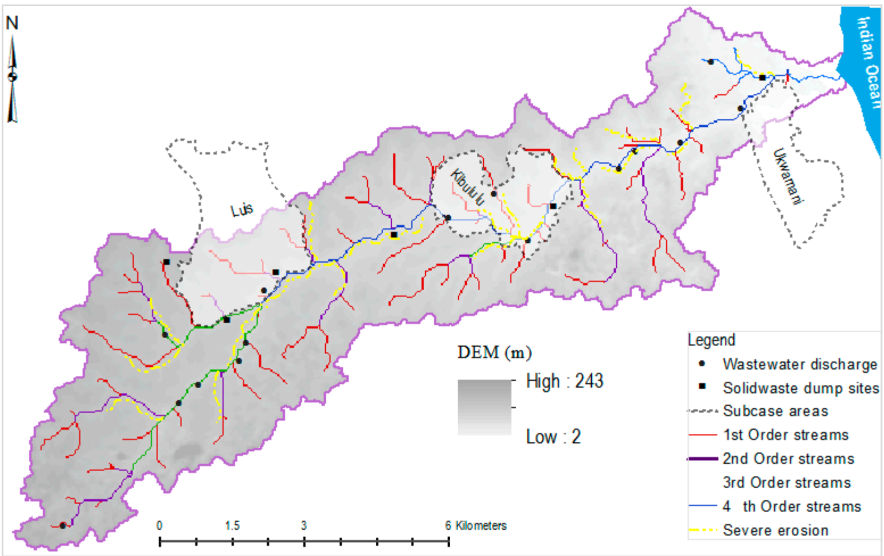


Figure 2. Delineation and topography of Mbezi River catchment, occurrence and ranking of streams, based on GIS, and locations of erosion and pollution sources based on field investigations.

Figure 3 presents the rate of urbanization in the three sub-case areas from 2003 to 2016, based on analysis of Google Earth historical images. In recent years, there has been no significant development in the downstream part of the catchment (Ukwamani), reflecting this area being fully built, while urbanization has occurred at an increasingly rapid rate in the two sub-case areas further upstream in the catchment where space is still available. The Luis area showed the most rapid rate of urbanization, with 124 new building per year in the period 2013 to 2016. Currently, there is a large urbanization difference in terms of building density between the sub-case areas in the upstream and those downstream, ranging from a maximum of 980 to 2780 buildings per km^2, respectively (Figure 3). To further visualize the rates of urbanization, Figure 4 presents pairs of historical satellite images taken from selected parts of each sub-case area, each covering an area of 0.35 km by 0.6 km. It can be seen that, in the upstream catchments of Luis and Kibululu, the vegetation cover seemed to be gone already in 2003, even though the number of buildings was much lower than in 2016. Regarding the downstream part, represented by Ukwamani, the level of urbanization appears to be about the same in 2003 as in 2016. The average plot sizes appeared to be relatively larger in Luis and Kibululu compared to that of Ukwamani. From the trends presented in Figure 3, the area of the surface sealing (in terms of roof footprints) in the overall catchment rose by 41%, from 8.62 km^2 in 2003 to 12.15 km^2, in 2016.

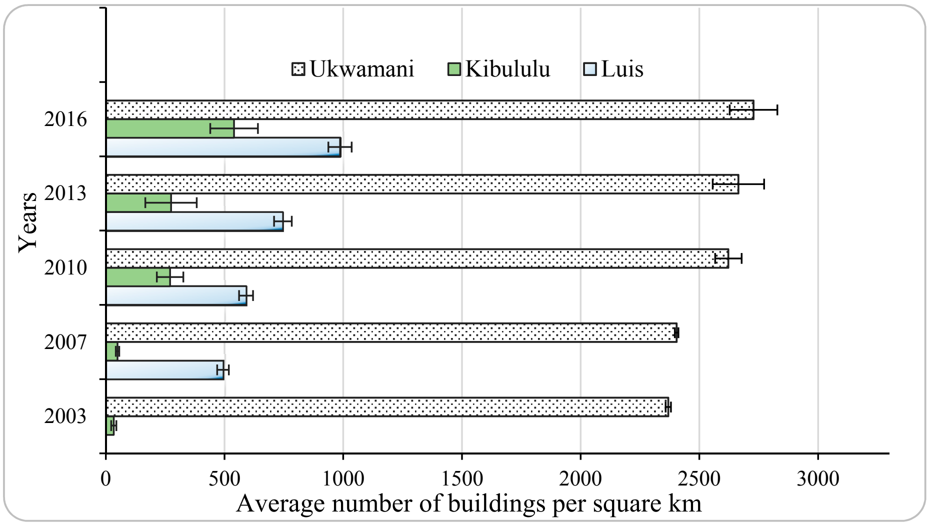


Figure 3. Bar graph comparing number of buildings per km^2 in sub-case areas for the past 13 years. The whiskers indicate the standard deviation of three individual samples from the mean value. No image was available for Luis 2003.

Field observations revealed a number of direct discharges of polluted water as well as piles of solid waste blocking many natural drainage routes, as illustrated in Figure 5. Further, some drainage routes were levelled out for building projects (data not shown). Concerning erosion, this was especially widespread in the middle catchment area. In all cases, erosion was caused by runoff creating deeper and wider gullies as routes merged on their downstream routes. According to the questionnaire survey more than 45% of the respondents settled in riparian areas used the erosion gullies and eroded parts of the river for solid waste dumping, assuming it to be a solution to erosion problems on their land properties.

According to local residents, the impact of urbanization on the catchment is being increasingly felt. Information from Luis and Ukwamani sub-ward executive officers documented that nine houses, built illegally within the 60 m of river flood plain, were destroyed by floods between the years 2013 and 2015. In addition, it was noted during field survey that foundations of 12 houses built beyond the 60 m of the flood plain in Kibululu were severely eroded in 2016, and nine more houses in the Ukwamani sub-case were in jeopardy. In 2014, three people were reported drowned in the same area following a heavy rainfall. Furthermore, survey of the river morphology indicated that 12.5 km of the river (48% of its total length), including five bridges, are seriously eroded.

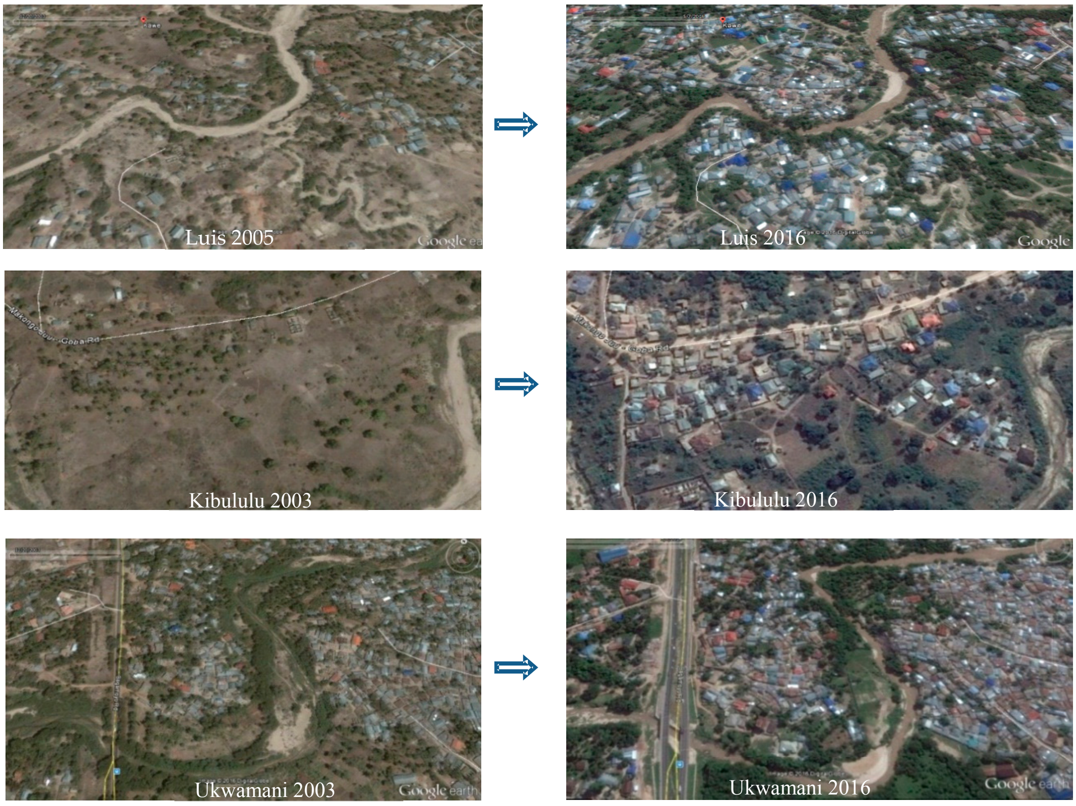


Figure 4. Urbanization trends from 2003 to 2016 in sub-case areas: Luis (**top row**); Kibululu (**middle row**); and Ukwamani (**bottom row**). Photos from: 2003 (**left column**); and 2016 (**right column**).

Figure 5. Solid and liquid waste dumping along Mbezi River. The photos were taken with permission on 24 June 2016.

3.2. Stormwater Infrastructures on Private and Public Initiative

According to questionnaire responses, stormwater control measures at building, plot and neighbourhood levels in the Mbezi River catchment are exercised individually, depending on household income, with no common stormwater management plan to manage runoff at tributary and valley levels. Such measures are used by plot owners in safeguarding their assets against soil erosion, pluvial flooding and scarcity in water supply. Table 2 summarizes the most frequently used flood and erosion control measures as well as stormwater harvesting methods, and their main drawbacks, according to the residents. Most measures concerned erosion control, especially terraces fortified with strong grasses, sand bag barriers, and in only a few cases were drainage channels observed. Stormwater harvesting was practiced by approximately 54% of the households visited, with a typical storage capacity of 1–1.5 m^3, obtained either as a single vessel or as aggregate of several smaller vessels. Ready-made above-ground plastic containers and below ground water storage facilities made from cement-sand blocks were the most common types of water storage method for middle-income people while low-income mostly used 20 L plastic buckets. Nearly 65% of the measures for flood and erosion control (presented in Table 2) were concentrated in low laying areas (downhill) where the problems were most serious and less in the upland (plateau) from which it originates. Further, about 80% of these measures were employed at building level and plot level, with very little effort to implement measures at either neighbourhood or tributary levels.

Table 2. Overview of stormwater management measures implemented by residents in the Mbezi River catchment, and their drawbacks according to questionnaire survey. The most commonly used measures are listed first.

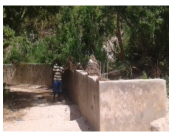
Control Method Used	Appearance	Application Level	Intended Use/Functions	Drawback or Challenges According to Interviewees
Terracing with vetiver grass (*Vetiveria zizanoides)* and elephant grass (*Pennisetum purpureum)*		Plot level	Erosion reduction Fodder crop for dairy farmers (elephant grass)	Wilting due to long dry season Takes long to establish
Sand bag barrier		Plot and neighbourhood level	Bank erosion control and	Temporary solution (lasts for two seasons at most)
Tree hedging		Plot and neighbourhood level	Erosion control and scenic improvement	Wilting due to long dry season
Used car tires barrier		Plot level	Erosion control	Short-term solution and space consuming
Dykes along the water courses		Tributary level	Protection against fluvial flooding and erosion control	Expensive to build and maintain; design and construction require expertise Risk of transferring problems to neighbours
Drainage ditches		Plot and neighbourhood level	Protection against pluvial flooding	High construction cost; needs sufficient space and expertise to construct
Gabions and concrete retention walls		Tributary level	Control of bank erosion and protection against minor floods	Expensive and needsexpertise to install

Table 2. *Cont.*

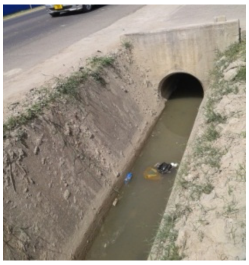
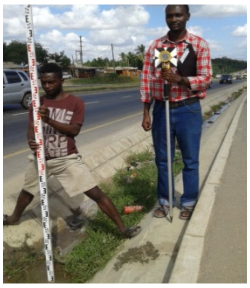
Control Method Used	Appearance	Application Level	Intended Use/Functions	Drawback or Challenges According to Interviewees
Roof top runoff harvesting		Building level	Water supply and erosion control	High installation cost (vessels, pipes, expertise); rapid deterioration of water quality; long-term storage requires disinfectants
Runoff harvesting in ponds		Tributary level	Water supply	Requires large land; and expensive to maintain; needs expertise and permits

Regarding stormwater infrastructures along roads provided by the city, the field survey concluded that the service coverage in the area was low. Approximately 17% of all roads were equipped with a municipal drainage channel, corresponding largely to the major asphalt roads and segments of a few earth roads. The assessed municipal roadside drainage channels were mostly found to be in poor condition of repair, as described in Table 3. Comparing the observed condition with the design standards, the effectiveness of roadside drains in the catchment is also low. Having been designed to handle the same design storm (five-year return period), roadside drains along Morogoro (D8) and Tangi bovu-Goba (D5) roads were the only drains that met the anticipated hydraulic capacity standards when considering attached catchment area. The drain layouts in these two roads were similar to the rest, except that the roads ran almost along the mountain ridges, such that the drains had relatively smaller catchment from which the runoff could be collected. Based on the condition of repair, operation, and hydraulic capacity, all drains along the remaining roads could hardly meet their intended design goals.

Table 3. Extent and conditions of public stormwater infrastructures along the four main roads along and across the Mbezi River. The location of drainage channels (D1 to D8) is shown in Figure 1. All the channels were trapezoidal in shape, concrete lined, non-traversable, and not covered. S = channel slope (%); L = channel length (m). All roads had drainage channels on both sides of the road, and they were all investigated.

ID	Dimensions (m)	Appearance	Observation/Condition of Repair of the Drainage Channels
D1	S = 1.3 L = 176.1		Poorly maintained, many segments clogged with solid waste Inadequate hydraulic capacity (design flow less than potential runoff from its catchment area) The drain catchment area is likely to be further urbanized.
D2	S = 0.9 L = 246.8		Inadequate hydraulic capacity Several parts have excessively steep side slopes; Some segments are illegally blocked to pond runoff for car washing and tree nurseries The downstream part is severely eroded due to poorly designed outfall

Table 3. *Cont.*

ID	Dimensions (m)	Appearance	Observation/Condition of Repair of the Drainage Channels
D3	S = 0.6 L = 887.2		Some sections have excessively deep and steep side slopes with no safety guides The adjacent roadway is above the drainage shoulders Inadequate flow capacity (design flow less than anticipated runoff)
D4	S = 1.4 L = 1396		Newly built but poorly attended water stagnation and deposited debris cause vegetation growth Areas adjacent to drain shoulders are severely eroded inadequate flow capacity (design flow less than anticipated runoff) A long section of the road floods during wet season.
D5	S = 1.9 L = 14300		Newly built and some parts are still under construction The design seemed to be intended only for the road runoff, excluding runoff from the adjacent catchment area Drain outfalls cause significant soil erosion downstream
D6	S = 2.4 L = 320		Good condition of repair well maintained Some parts have excessively steep horizontal slopeAdequate flow capacity (design flow more than anticipated runoff)
D7	S = 1.1 L = 125		The hydraulic capacity is compromised by sand deposits; Poorly maintained, leading to excessive vegetation growth Inadequate flow capacity (design flow less than anticipated runoff) Runoff from catchment areas adjacent to the road seemed not to be considered in the drainage design
D8	S = 1.8 L = 1280		Some sections are excessively deep, with steep side slopes Several parts of shoulders are above normal ground level, causing erosion along the drains themselves Adequate design flow more than anticipated runoff)

Since all the roadside drains found in the Mbezi River catchment are lined with concrete, they are considered to be of a good service standard. However, the way the drains' outflows are designed and constructed seems to cause severe soil erosion to the land parcels adjacent to the roads. In addition to erosion, property owners along the roads complained that stormwater from drainage outflows were among the causes for flooding of their homes. An overall analysis revealed that the design of the roadside stormwater drainage channels was road-centred, with limited consideration to the impacts of concentrated stormwater flow at outflows.

3.3. Challenges and Solutions According to Officials

The interviewed officials recognize inadequate stormwater management a problem in Dar es Salaam. Almost all the interviewees considered stormwater management exclusively a question of runoff drainage, neglecting the problem of soil erosion as well as the wider benefits of source-control, link to water supply, and reestablishment of green vegetation cover. None of the officials interviewed were pleased with the current stormwater management initiatives in their areas of jurisdiction in terms of the budget assigned and the overall emphasis given to it. In terms of priorities, however, the majority of the interviewees at sub-ward level ranked stormwater management below other issues, such as absence of good quality roads and water scarcity.

In response to what should be done to obtain successful stormwater management, the officials pointed to the importance of a collective commitment for all stormwater stakeholders, from the municipal level to the local community. Enforcement of existing regulations and the possible formulation of new bylaws at sub-ward level for protecting rivers and streams were highlighted too. For better and collective understanding on how rivers and streams could be conserved, officials recommended demarcation of flood plains to prevent encroachment. Officials' recommendations were further extended to recharging and protecting groundwater, as groundwater has become an increasingly accepted water supply source.

4. Discussion

The results reveal an unfortunate matchup between catchment urbanization (Figures 3 and 4) and the evolution of stormwater related problems (Figure 2), indicating the need for change in management of the Mbezi River catchment area. If new stormwater management schemes are not adopted, it is likely that many of the assets in the already built-up areas will eventually be lost, since erosion gullies will multiply, and flooding events will become both more frequent and more intense. In addition, the freshwater supply is critical, as expressed by the many stormwater harvesting measures (Table 2). With rivers running dry and water being polluted by wastewater discharge and solid waste dumping (Figure 2), the residents are experiencing back-to-back problems with flood and erosion risks in the wet season and water scarcity in the dry season. Referring to studies done in other parts of the world, such problems require informed water resources planning and catchment-based urban stormwater management [43,44]. The goal of this study was to establish an empirical basis for implementing such new practices.

Even with limitation of a public domain DEM with a resolution of only 30 m $\times$ 30 m, the GIS catchment delineation was an accurate reflection of the hydraulic boundaries and river characteristics as observed in the field, with the exception of specific position of first order rivers (Figure 2). This approach seems feasible for highlighting, mapping and understanding watershed hydrological behaviours for easy communication, thus creating a good point of departure for informed stormwater management decision-making. Obviously, access to better resolution DEM can provide more detailed catchment information and should be adopted when possible [45,46]. Further, the GIS-based map allowed for easy documentation of field observations, such as wastewater discharge and solid waste dumping sites (Figure 2), and could also be used for erosion mapping.

Despite uncertainties in the method, analysis of historical satellite images returned approximate urbanization rates (Figures 3 and 4) that can be used to guide both solution strategies and to prioritize where to invest resources. Both the urbanization rates and urbanization hotspots can be revealed, as can the observed differences between upper and middle parts and the strong tendency to encroach river banks. The severity of the situation in the Mbezi River catchment is to some extent acknowledged by both residents (Table 2 and questionnaire) and municipal officials (interviews). However, a lack of full understanding is evident from the fact that anti-erosion measures are implemented downstream rather than upstream, and that drainage channels along major roads are designed in a way that triggers formation of erosion gullies (Table 3). Similar challenges are reported by Debo et al. [27,47] for many municipal stormwater management plans in developing countries, and is thus a well-known problem. The field investigations conducted in this study helped to illuminate the severity of the situation and to clarify the degree of commitment and kinds of perceptions held by both residents and municipal officials alike. Apart from the documented level of urbanization and its respective challenges, the middle and upper catchment areas contained sites with potential for adoption of various source control stormwater management (Figure 4) to minimize the challenges.

In the Mbezi River catchment, individual property owners are forced to respond to the impacts of urban sprawl because the upper level administrative organizations stay silent as long as no large-scale flood event occurs to evoke political interests. Unfortunately, the unconnected stormwater control measures in practice are neither guided nor controlled by any reliable approach. Rather, the management decisions are governed by economic constraints and random or undocumented ideas (solutions) emerging from the community itself. However, the combination of the status of stormwater problems, the urgency of urbanization problem and the commitment shown by residents can be mobilized into sustainable adoption of source control stormwater management practices. Both the continued encroachment of river banks and the malfunctioning of the public drains have been viewed as common hydrologic characteristic in many urban catchments [6,47–49], a phenomenon also observed in the current study.

If stormwater management based on source-control by use of detention and retention elements in the terrain surface and located in close proximity to the runoff generating surfaces can be implemented, it is likely that both erosion and flood events can be minimized, since water is infiltrated or only slowly released to downstream flow routes. Such an approach allows for recharging of groundwater reservoirs for water supply, and facilitates the reestablishment of a vegetation cover. Similar arguments have been accentuated by [29].

While a number of source-control stormwater management concepts have been suggested by various scholars [11,31,50], successful implementation is highly dependent on the concepts being framed so as to form a nexus between urbanization dynamics and people's livelihoods. This can enable local residents to take the lead, with support from their ward and municipality authorities. The main challenge is to ensure appropriate coordination of elements in the catchment so that emphasis is placed on upstream rather than downstream solutions. Ideally, a storm water management scheme should be developed, but simple principles linked to construction of buildings and roads may be sufficient. For example, retention of a minimum rain depth of, e.g., 40 mm at plot level could be introduced, supplemented with infiltration-based road drainage practices through vegetated swales and gravel-filled infiltration trenches. It should be noted however that source control stormwater management approaches consist of several runoff management elements with limitations that might be varying from one location to another.

Findings of the study reveal the transdisciplinary and cross-cutting nature of stormwater management problems. It is also evident from the literature that source-control stormwater management approaches have a profound potential to alleviate stormwater management problems [31,50]. However, it needs to be integrated with the implementation of other supportive measures such as policy formulation, introduction rules, and enforcement of regulations pertaining to urban water resources management.

5. Conclusions

To counteract the negative consequences of unplanned urbanization of catchments in terms of flooding, erosion and water scarcity, the goal of this study has been to establish an empirical foundation for introducing a new stormwater management practice, balanced against the available resources and targeting multiple purposes. GIS-based study based on DEM of 30 m resolution was used to delineate the catchment and to form a base map for further registrations as well as for support of discussions with stakeholders.

Analysis of historical satellite images in three sub-case areas was used to estimate urbanization rates, which are necessary for proposing the most effective targeted approach. Through field observations, the catchment delineation and position of first, second, third and fourth order streams predicted by GIS analysis were confirmed, and sites of direct discharge of wastewater, solid waste dumping and degree of erosion were registered. From a questionnaire survey among residents in sub-case areas, problems of flooding, erosion and water scarcity were revealed, as well as the current mitigation practices, most of which appeared ineffective.

Additional field analysis of current extent and quality of implemented drainage practices and discussion of findings with the competent municipal officials points to a willingness to improve both coverage and quality. However, these discussions also showed a lack of resources and skills as to how to perform integrated water management. Overall, the study confirms the critical situation in such catchments, pointing to a need for introduction of sound stormwater management practice based on retention and detention in a re-vegetated landscape, and linked to water supply in terms of direct harvesting and groundwater recharging.

While most such practices can be initiated and managed by the local residents, some supervision and coordination for large scale elements would be beneficial, especially to ensure upstream approach and large-scale stormwater harvesting in shared ponds. The findings of this study underscore the need for policy intervention for ensuring that stormwater management is adequately integrated into 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 provision of water. To achieve this goal, modifications are needed in the stormwater design code and in water policy.

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