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Stormwater Quantity and Quality Management Options in Rapidly Urbanizing Watersheds: The Case of Mbezi River Catchment in Dar Es Salaam-Tanzania

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ABSTRACT: Over the past two decades there has been a growing worldwide concern about the ability of urban infrastructure systems to withstand the increasing impacts of urban population and climate change. Akin to similar concerns, the objective of this paper was to evaluate stormwater quantity and quality management options in rapidly urbanizing watershed of Mbezi River catchment in Dar es Salaam-Tanzania using field investigations, public meetings and GIS techniques. Analysis results of capacity quantification of the proposed stormwater management components indicate that stormwater harvesting alone can disconnect up to 12% of stormwater runoff stream generated in the study catchment. In addition to other components, the proposed landscape-based stormwater management system puts more emphasis on rainwater harvesting, stormwater retention and detention elements to decelerate runoff speed and enhance more residence time for the runoff not only to infiltrate, but also to evapotranspire, while improving the scenery and aesthetic quality of the environment altogether.

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Over the last three decades, the African continent witnessed the rapidest increase in urban population and unprecedented urbanization of cities (Heinrigs, 2020). With the current trends, urbanization in Africa is ranked the fastest in the world; and its cities are predicted to host more than half of the global population by 2050 (UNDESAP, 2015). In many cities of sub-Saharan Africa, combined effect of rapid urbanization and population growth has contributed into urban sprawl and proliferation of informal settlements putting pressure on natural resources while the provision of public infrastructure is increasingly becoming a challenge of concern (Fox, 2014; Thorne *et al.*, 2018). More importantly, rapid increase in population and urbanization has negative implications on urban hydrology in terms of increased quantity of stormwater runoff, shortened peak flows and decreased quality of surface water sources (Shuster *et al.*, 2005). As water supply demands escalate, there is an agent need to replenish our conversional water supply sources through groundwater banking while embarking on alternative sources including stormwater harvesting (Elliott *et al.*, 2019).

Efforts to harness utilities of stormwater runoff have gone through a long evolution of paradigm-shift to meet the escalating demands of human civilization (Burian and Edwards, 2002). According to Fletcher *et*

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al. (2015), gradual changes of paradigm shifts in stormwater management practices (SWMP) are demonstrated by the emergency of terminologies with varying emphasis on how best urban stormwater needs to be managed. However, evidences for SWMP evolution are not apparent yet in many cities of the developing world including those in Sub-Sahara Africa (Barbosa *et al.*, 2012). In Dar es Salaam for instance, despite the escalating rise of stormwater-related challenges like fluvial floods, runoff pollution, river banks erosion, and inadequate supply of water (Justin *et al.*, 2018; Kiunsi, 2013), the potential of stormwater to alleviate such challenges are yet to be sufficiently utilized. At present, stormwater management efforts are focused on conventional approaches which are only meant to drain the city by routing stormwater runoff to nearby receiving waters, mainly through roadside drainage channels.

Based on the interconnectedness and crosscutting nature of urban stormwater challenges, multiple but integrated solutions are often recommended for sustainable management of urban water resources (Liu *et al.*, 2013; Wong and Brown, 2009). Considering the need and nature of stormwater related challenges in Dar es Salaam, this study puts an emphasis on the potentials of adoptability of source-control stormwater management approaches here referred as Landscape-based Stormwater Management (LSM) as a framework for managing quantity and quality of urban runoff in rapidly urbanizing cities. As opposed to the existing practices, LSM has a potential to utilize energy of the inevitable urbanization of cities to navigate into more benign and eco-friendly urban expansion (Backhaus and Fryd, 2013; Jensen *et al.*, 2013). In addition to water-related benefits, LSM is considerably debated to work in synergy with many other urban requirements like, development of green spaces, enhancement of urban ecosystem services, and spatial cohesion to recreational and educational values (Ahern, 2007; Pauleit *et al.*, 2013). However, more context specific studies are needed to tell the location, orientation and efficiency of LSM elements the factors of which are also shaping the focus of the current study using Mbezi river catchment as an exploratory case.

MATERIALS AND METHODS

Data Acquisition Methodology: To attain the objectives, the catchment for Mbezi River in Dar es Salaam-Tanzania was used as a case study. The study catchment is among the main sub-basins for surface water drainage from the landscape of the Dar es Salaam city to the Indian Ocean. Representing much of the land use changes and settlement heterogeneity, Mbezi river catchment covers around 56 km^2 while the river channel spans about 24km long. In-depth hydroclimatic characterization of Mbezi river and its catchment is referenced in Mhina *et al.* (2021) and Justin *et al.* (2018).

Several methods were adopted for data collection. The main ones involved site surveys, field investigations, GIS modeling, analysis of satellite images, stakeholder's meetings, community consultations, and community design workshops (design charrette). Site Surveys and Field Investigations were undertaken for in-depth understanding of the study case. The two methods were also useful in locating areas prone to floods and soil erosion and in identifying areas suitable for catchment-focused and landscape-based stormwater management solutions.

GIS Modelling was used to delineate the study basin, to extract drainage networks and its corresponding blue spots (naturally occurring depressions). Features of interest were modelled using a digital elevation model (DEM) from an ASTER GDEM of 30m spatial resolution, accessed at https://asterweb.jpl.nasa.gov/gdem.asp by running the hydrology tools of ArcGIS version 10.3.1. as detailed by Balstrøm (2018). Georeferenced satellite image retrieved from Google Earth Professional (Version 7.1.5) was used to estimate the number of buildings and coverage of impervious surfaces in the study catchment. The plan view of buildings footprint, roads and other hardscapes were digitized as polygons on GIS environment and analyzed.

Community workshops and design charrette as guided by Lennertz and Lutzenhiser (2006) to enhance participatory and multi-disciplinary discussion among stakeholders were organized in three locations within the study catchment. The charrette meant to make an in-depth assessment of stormwater-related problems, define abatement options, and co-prioritize the implementation of the decided plans. The agreed plans were then made public through a 21days long exhibition and the feedback was used to improve the earlier plans.

RESULTS AND DISCUSSION

Drainage and geomorphological characteristics, including the shape and boundaries of Mbezi river catchment based on field surveys and GIS modelling are presented in Figure 1. The catchment assumed a dendritic and elongated drainage network undulating from a maximum elevation 254m, mostly in the upstream and northern side of the catchment, with a relief gain of 241m. Spatial location and coverage of naturally occurring depressions (blue spots) are prevalent in the northern side of the catchment in both downstream and upstream areas. Being validated by field surveys, GIS modelling indicated further that the southern side of the catchment is more susceptible to erosion hazards despite having less undulation and gentle slopes. Sub-catchments with the steepest slopes are dominant in the northern side of the catchment a condition that might exaggerate the proneness of the area to erosion hazards as the catchment continue to urbanize.

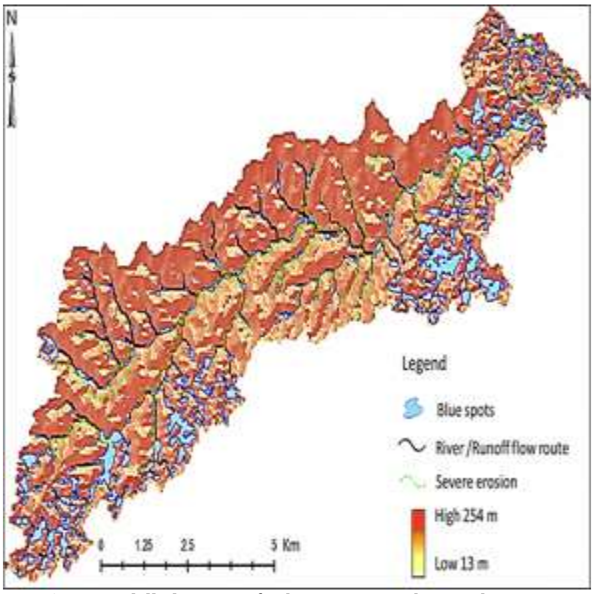

Fig 1: Modelled terrain of Mbezi River catchment showing drainage routes, eroded areas, and spatial coverage of blue spots

Based on field survey results and GIS modelling, preliminary indicators of stormwater-related challenges in the study catchment are perceived and highlights of remedial options are revealed. Having a dendritic drainage pattern with geomorphological features as presented in Figure 1, it is obvious that the flatness of the catchment towards the river mouth being confronted by tidal effect from the Indian ocean increases the proneness of the lower catchment to flood hazards. Complementary arguments are also accentuated in Mhina *et al.* (2021). The location and coverage of blue spots are good indicators of potential areas suitable for stormwater best management features like retention ponds and detention ponds.

Meanwhile, erosion hotspot areas are not only indicators of areas to locate erosion-checking features but also useful in identify priority areas suitable for erosion control (Zhang *et al.*, 2010). A list of stormwater-related challenges, in the order of their severity, as ranked by stakeholders during community workshops and design charrette using a severity scale (1-10) is presented in Figure 2.

Complementing what GIS modelling revealed, soil erosion and fluvial flooding were reported to be prevalent in the middle and lower parts of the study catchment with increased severity towards the downstream. Like in other informal settlements in the city, residents in the lower catchment of the study case experience back-to-back but complementing challenges such that flooding is largely experienced during the rainy season while water scarcity becomes more severe in dry season. Among other things, insights from the design charrette and community consultations revealed a need for integrated and catchment-wide SWM strategy guided by co-developed and enforceable regulations articulating roles and responsibilities of stakeholders from the household level to the municipal level.

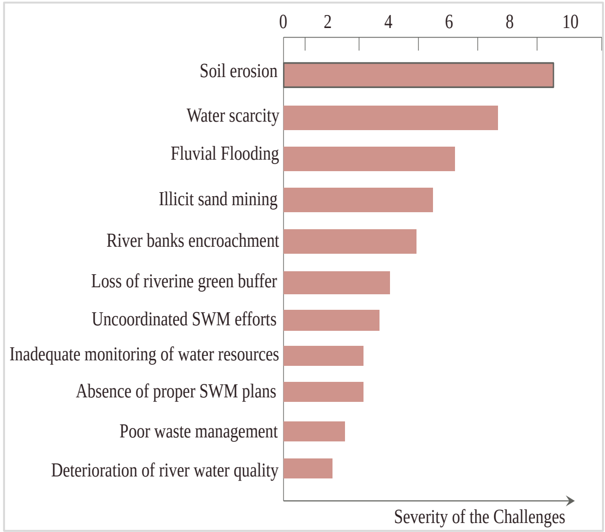

Fig 2: Severity of stormwater-relate challenges as ranked by stakeholder

Having the challenges known, co-development of counter-measures to address them was also deliberated through community workshops and design charrette resulting in what was perceived and agreed as a catchment plan (Table 1). An in-depth analysis and classification of the proposed measures resulted into a set of 12 SWM elements to be operationalized in five clusters (spatial scales) within the study catchment to constitute a catchment SWM system. Results of SWOT analysis of the proposed SWM element are summarized in Table 1. For adoptability and management, the proposed elements were further categorized into three levels of enforcement cascading from household level, sub-ward level to municipal level. The spatial scales, in this context, provide a window of opportunities from which various stormwater management actors can exercise duties in operationalization of various SWM elements in the catchment SWM plan.

Table 1: SWOT analysis of the proposed SWM elements for catchment-based SWM plan

Spatial scale	Proposed SWM elements	Strengths and opportunities	Weakness and threats	Responsible organ
Building level	Rainwater harvesting (RWH)	Versatile & well-known, Rising water needs, pliable in built-up areas	Rapid deterioration of rain water quality, high initial costs of RWH systems (especially for piping and storage)	Households/ Public buildings
	Permeable pavers (PP)	Existence of local skills on pavement making, Presence of local pavement factories	Comparatively shorter life span of PP, Elevated fabrication costs, prone to clogging, traditional pavers are relatively cheap	
Land parcel/ Plot level	Bio retention cells and Swales	Rising desire for grass lawns/gardens Ability to improve runoff quality	Some areas might have high water table to require soil permeability improvement	
	Grass/gravel lawns	Multiplicity of aesthetic benefits, Ability to improve runoff quality	Relatively expensive to maintain, Pests and weeds control might result into runoff pollution	Households
	Infiltration trenches and aquifer recharge wells	Scalable & versatile for retrofit projects Rising needs for ground water	Limited in areas with high water table and impermeable soils Require high capital costs Infiltrability fades with time	
Neighbour-hood level [1]	Infiltration trenches	Scalable & versatile for retrofit projects	Might require high capital costs Infiltrability fades with time	Households Adjoining neighbours Community groups
	Green/soft boundaries and grassed swales	Aesthetic appeal and ecological benefits, Ability to improve urban ecosystems services	Need for constant enforcement of the rules and regulation Requires a collective public initiative and proper organization	
	Retention ponds	Water scarcity problems, Soil erosion challenges	Requires relatively large area, may attract other public risks if not well designed and attended	
Valley/ tributary level	Green terraces	Ability to improve ecosystems services	Requires collective efforts and public initiatives	Ten cell leaders Sub-ward leaders NEMC Municipal planners
	Detention and retention ponds	Rising water needs, Increase of erosion challenges	They are area intensive, they might cause other public risks if not well designed/attended	
	Check dams and Step pools	Widening of gullies, escalation of fluvial floods	Requires relatively high capital costs depending on the nature of the site and intended functions	
River course level	Green buffer	Ability to improve aesthetics & sceneries, ability to improve urban ecosystems services	Need for constant enforcement of the rules and regulation Requirement for a collective public effort	Sub-ward leaders, adjoining land property owners, Municipal planners, NEMC
	Detention and retention ponds	Water scarcity problems, Soil erosion challenges	May attract other risks if not well designed and attended	

Plot level: - The smallest spatial scale (unit) at which at-source control of SWM practices can be implemented. It is also known by other names like, lot level or land parcel scale
Neighborhood: - Refers to the specific geographical areas defined by the natural terrain to drain stormwater towards a common outlet. It is therefore not synonymous with the urban planning neighborhood concept.
Tributary level: - A spatial scale meant to collect runoff from its hydrologically contributing neighborhood

With reference to Table 1, it is apparent that various landscape-based SWM elements can be adopted in different locations to address different challenges in different problem areas within the study catchment. Potential areas for implementation of catchment scale landscape-based SWM elements as analyzed from GIS models and field surveys were mapped and presented in Figure 3. The map (Figure 3), highlights not only the location of areas prone to soil erosion and pluvial flooding but also defines suitable areas to abate the said challenges. Additionally, Figure 3 maps the location of potential areas for surface runoff retention and detention to enhance runoff attenuation, ecosystem services and groundwater replenishment. As such a combination of different landscape-based SWM elements can be operationalized differently at different spatial scales in the catchment depending on the field conditions.

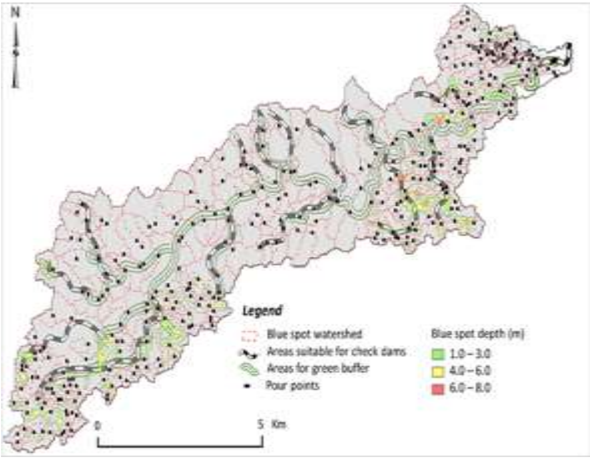

Fig 3: Proposed landscape-based stormwater management elements for catchment-scale stormwater quantity and quality management

Efficiency of the Proposed Stormwater Quality and Quantity Management Options: The efficiency of the proposed catchment-based SWM plan to address stormwater quantity and quality challenges in the study catchment was defined by the capacity of its individual components. Based on the study findings, it was possible to quantify the potential of retention basins and roof top rainwater harvesting in managing rainwater in the study catchment. The capacity of retention basins to manage surface runoff was assessed in terms of volume of the modeled blue spots (Figure 3) while the potential of rooftop rainwater harvesting to manage quality and quantity of stormwater was defined in terms of accessibility to rainwater harvesting infrastructure. Analysis of the modelled blue spots (Figure 3) revealed the presence of about 13 natural depressions (sinks) which are large enough (2548 m^3 on average) and located in areas with potentials to be modified into retention ponds. In addition to storage capacity, other factors considered in validating the highlighted pond sites included soil stability (via erosion profiles), soil type, and landuse activities of the surrounding areas. However, field surveys indicated further that the storage capacity of such natural depressions is increasingly jeopardized by erosion-deposition processes and the nature of the ongoing development of the study catchment. The potential of rooftop rainwater harvesting was assessed in terms of availability of surfaces from which rainwater can be harvested. From satellite images it was analyzed that 11.5 percent of the study area was covered by roofs of buildings with potential for rainwater harvesting. The analysis pointed out further that when 50% of households present in the study catchment is sensitized to harvest at least two cubic meters of rain, then the harvested water is enough to meet water supply demands needed by households in the study catchment for three days. Apart from improving water security, when half of the household population in the catchment is engaged in rainwater harvesting about 10.2% of stormwater runoff is disconnected from joining the downstream flood waters.

Technical considerations and general discussion: Generally, the nature of stormwater-related issues accentuated in this study (Figure 2) stands to challenge the status quo of stormwater management (SWM) in Dar es Salaam. Among other things, the study presents a range of measures proposed to avoid, or at least, to minimize stormwater related impacts while reducing water demands and potential pollution of receiving waters. Similar SWM concern, is widely reported in literature (Burns *et al.*, 2012; Shishegar *et al.*, 2018; Vasconcelos *et al.*, 2022). In effort to address these challenges, many scholars (Keeley *et al.*, 2013; Kvamsås, 2021; Walsh *et al.*, 2016) recommend the adoption and application of combined strategies derived from both structural and non-structural stormwater best management practices (BMPs). While the focus and discussion of the current study is limited on the adoption and applicability of structural aspects of urban stormwater BMPs (Table 1), the importance of non-structural measures is highly appreciated but falls beyond the scope of the study. Adoption and wider application of stormwater BMPs in many cities of the developing world is impeded by many factors (Drosou *et al.*, 2019; Ureta *et al.*, 2021). Limited information to address adoption doubts, operation and maintenance-related challenges and validity of benefits that stormwater BMPs present to leverage decision making stand among the impeding factors (Hager *et al.*, 2019). Despite the use of public domain DEM with low resolution (30m x 30m), it was possible to derive useful information to advise SWM decisions in the study catchment (Figure 3). The rationale of the findings underscores the usefulness of knowledge about catchment drainage patterns and hydrological behaviour of the underlying landscape being crucial for landscape-based SWM planning. GIS models used in this study has demonstrated to be useful not only in delineation of catchment runoff patterns but also in giving crucial information for locating, sizing, and quantification of different landscape-based SWM components in the study area (Figure 3). The approach is similarly useful in highlighting, mapping and visualization of watershed hydrological characteristics for communication and informed SWM decision-making. In addition to the appropriateness of the proposed landscape-based SWM elements (Table 1), the study findings highlight the need for a city-wide

SWM approach to enable the operationalization of stormwater BMPs. Insights of the study results demonstrate the recognition of river catchments (basins) as functional units of urban water resources management (Katusiime and Schütt, 2020). It is argued further that municipal SWM plans should be comprised of decentralized, but integrated, landscape-base and catchment-focused SWM sub-plans with well-known set of cascading practices implementable right from plot (lot) scale to a catchment level (Table 1). Preferably, catchment-based SWM hierarchy should be designed to proceed from: rainwater harvesting and reuse practices, towards engineered and natural infiltration surfaces, via flow control and delay elements, all of which are categorized as "at-source" control measures, and finally the overflow runoff should be conveyed safely to the receiving environment. Despite the achievement in meeting the study objectives, the use of case study research design, in addition to the limitations of public domain DEM and satellite images, might have constrained the generalizability of the reported findings. Based on the information acquired, stormwater quantity management potential of only two elements (rainwater harvesting and retention ponds) out of the proposed landscape-based SWM components are reported. Ideally, the assessment of runoff management potential of other SWM components could have tagged more value into the rationale of the study. It should be noted, however, that the availability and accessibility of high-resolution datasets stands among the challenges hindering the use of rainfall-runoff process models a decision support tool for water resources management in many cities of the developing world (Hughes, 2013; Nkwunonwo *et al.*, 2020).

Conclusion: The findings demonstrates that adoption and wider application of catchment-focused and landscape-based stormwater best-management practices (BMPs) may support the transition of cities towards sustainable water resources management. The need for multi-objectives SWM approaches and multi-disciplinary SWM initiatives to keep pace with the rapidly changing urban hydro-climatic environment is emphasized. Despite the limitations, it is articulated that BMPs are capable of retaining a commendable runoff volume while lessening runoff pollution of receiving waters.

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