


Characterizing hydrological-sensitive areas of the Kinyerezi river sub-catchments in Dar es Salaam, Tanzania using the topographic index approach

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ABSTRACT

Several areas experience frequent floods due to anthropogenic activities. Among them, is the Dar es Salaam city, which experiences frequent floods along the Msimbazi River, whose flows originate from different tributaries including the Kinyerezi River. This study aims to evaluate the hydrological-sensitive areas of the Kinyerezi River sub-catchments using topographic index values (λ^*) that enable the identification of areas with a higher probability of generating surface runoff. A digital elevation model was utilized to delineate the Kinyerezi River sub-catchment characteristics using ArcGIS 10.4. Soil infiltration rates (K_s) on selected open places were determined using a Guelph permeameter. Soil particle size distributions were analyzed and the λ^* values were evaluated. The results showed the particle size distribution contains sand and silt-clay ranging from 46 to 84% and 16 to 53%, respectively. The K_s ranged from 0.6 to 7.8 mm/h while the sub-catchment KS3 scored the highest λ^* value of about 10.7. Hence, there is a higher probability for generating surface runoff. Sub-catchment KS16 scored the smallest λ^* value of 5.7, perceived to generate less surface runoff. Low-impact development practices capable of capturing runoff and enabling infiltration, evaporation, and detention should be employed in sub-catchments with higher λ^* values.

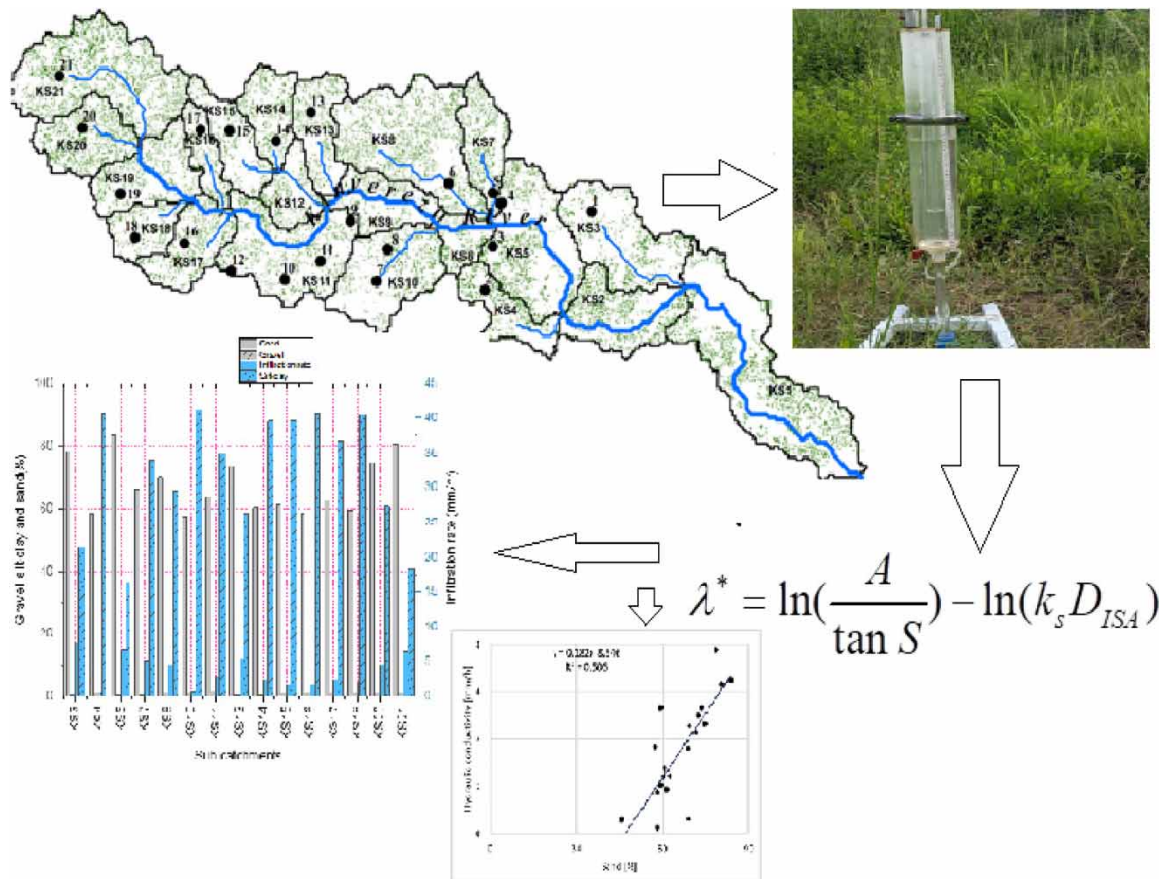
Key words: Guelph permeameter, floods, infiltration rate, Kinyerezi River catchment, surface runoff, topographic index value

HIGHLIGHTS

- The study improves knowledge and awareness of the sensitive sub-catchments of the Kinyerezi River catchment.
- The soil infiltration rate ranges are given for the Kinyerezi River sub-catchments and can be adopted by engineering practitioners in the design of stormwater management infrastructures in the catchment.
- Gives the gravel, sand, and silt-clay contents for soils from the Kinyerezi River sub-catchments that may help engineering practitioners in deciding the type of stormwater management to adopt for the catchment.

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GRAPHICAL ABSTRACT



1. INTRODUCTION

Urbanization contributes significantly to the rise in floods in cities because previous surfaces are often replaced with impervious ones, leading to increased stormwater runoff that can flood drainage streams and rivers (Kong *et al.* 2017). Catchment runoff is influenced mainly by land use and soil types, which in turn affect runoff volume and flow rates (Blair *et al.* 2014). Zakizadeh *et al.* (2022) reported that managing stormwater runoff involves monitoring the amount of runoff entering the system and taking preventative measures accordingly. According to the Tanzanian National Bureau of Statistics (2022), Dar es Salaam is one of the fastest growing cities in Africa region with an annual growth rate of 2.1%. This has attributed to the increase in the city’s built-up area of 42% from 1989 to 2015 as reported by Igulu & Mshiu (2020). The Msimbazi Valley’s built-up area from 1990 to 2019 expanded by 26.2% (Machiwa *et al.* 2021). These facts and many others, have increased flood disaster risks as reported by Sakijege (2013). Among the historical flood events experienced in Msimbazi River floods are in the years of 2007, 2011, 2014, 2015, 2018, 2019, and 2020 (Mzava *et al.* 2021). These events call for sustainable city development approaches that substantially promote natural hydrological processes.

Real estate development is surging in the Kinyerezi River catchment including the construction of villas, apartment complexes, office buildings, hotels, and shopping malls (Mkilima 2018). Rapid infrastructure development is reducing the infiltration capacity of pervious surfaces and creating impervious surfaces that favour more stormwater runoff generation. The Kinyerezi River discharges runoff into the Msimbazi River, but it is unsure about the sub-catchments within it that generate high volumes of runoff. In this study, these sub-catchments are known as the hydrological-sensitive area (HSA). The aim of this study is to identify the HSAs, by evaluating sub-catchment topographic index (λ^*) values. The λ^* value is proportional to the HSA and implies that there is a high probability of runoff generation from the respective sub-catchment (Martin-Mikle *et al.* 2015).

Several studies have employed λ^* values to identify sub-catchments of HSA. Agnew *et al.* (2006) justified the method as being stronger in identifying sub-catchment HSAs. Martin-Mikle *et al.* (2015) used λ^* values to

determine the values of HSA for mixed-use watershed in central Oklahoma, USA. Xue *et al.* (2014) applied the method in establishing HSA values based on λ^* values for the spatial-temporal variability of surface runoff probability in different periods for the Meishan watershed, China. Similarly, Aksoy *et al.* (2016) utilized the topographic Wetness Index and the SAGA (System for Automated Geoscientific Analyses) wetness index approach to map flood-prone areas at the regional scale, in Turkey.

2. MATERIALS AND METHODS

2.1. Study area

The Kinyerezi sub-catchment is located on the eastern coast of Tanzania in Dar es Salaam City. The flows from this sub-catchment contribute to the flows of the Msimbazi River. The study area covers an area of 19,167,000 m² and the altitude ranges from sea level to 144 m above mean sea level, Figure 1. The Dar es Salaam City experiences rainfall ranging from less than 800 to above 1,400 mm, the mean annual temperature ranges from 18 to 33 °C and the mean annual evaporation rate is 2,104 mm (Machiwa *et al.* 2021).

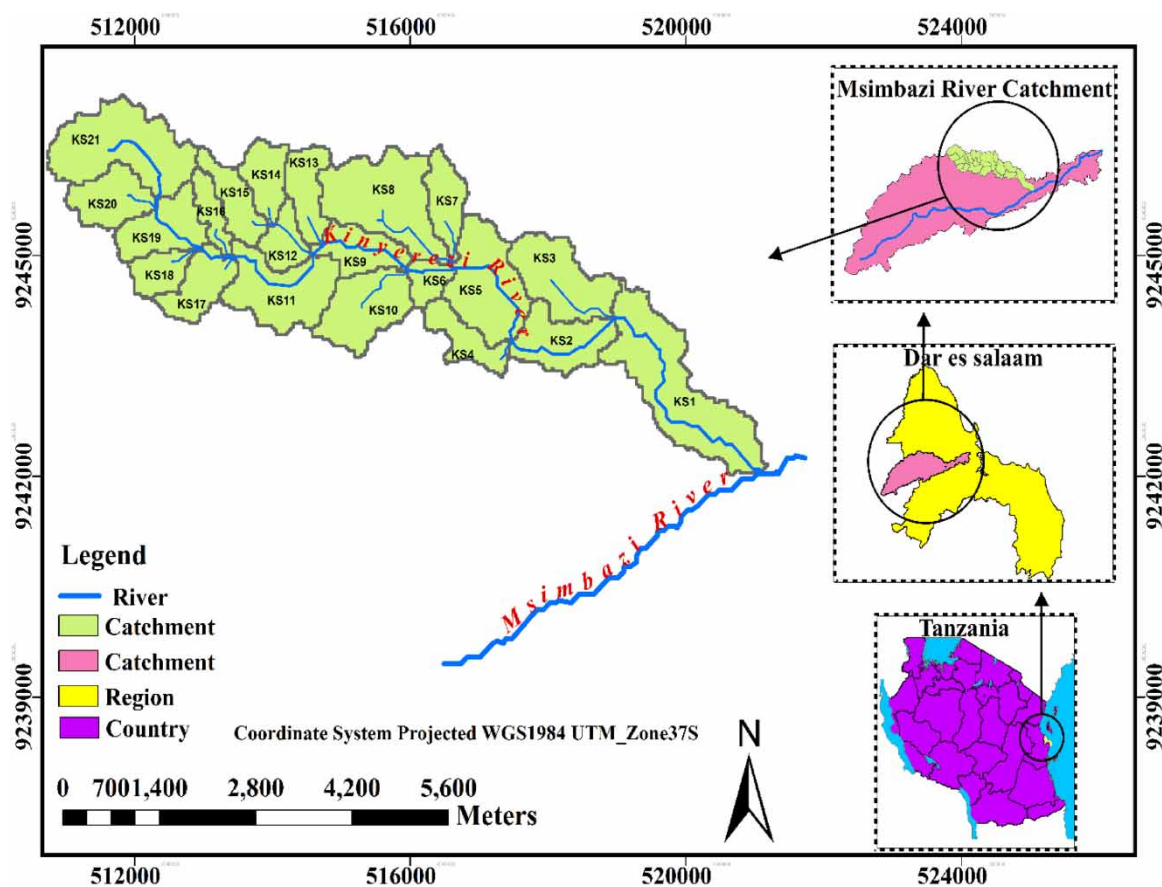


Figure 1 | Dar es Salaam map with the delineated Kinyerezi River sub-catchments (ArcGIS 10.4).

2.2. Determination of hydraulic conductivity (K_s)

Soil hydraulic conductivity (K_s) also known as infiltration rate is an essential parameter for evaluating the HSA of sub-catchments. Infiltration testing is conducted to a depth at the same depth as the bottom of the low-impact development (LID) practices that are expected to be installed (Cahill & Godwin 2018). However, in many cases, the test itself determines how deep the LID practice should extend. In general, the bio-retention facilities are recommended to have a total depth of 1.2 m that contains a surface layer depth of 0.3 m, a soil layer depth of 0.6 m and a storage layer depth of 0.3 m (Choi & Kim 2020) therefore, infiltration rate testing to a depth of 1.5 m gives suitable results for LID implementation. In addition, Armin & Associates Ltd (2013) reported on the LIDs such as infiltration trenches, detention ponds, and bio-retention ponds to require a total depth of 1.5 m that includes LID depth and depth from the bottom to the restrictive layers.

Field visits were made to verify the existence of hydrologic drainages and test the hydraulic conductivity (K_s) in selected places for 15 sub-catchments, namely KS3, KS4, KS5, KS7, KS8, KS10, KS11, KS13, KS14, KS15, KS16, KS17, KS18, KS20 and KS21 using a Guelph permeameter. The sub-catchments for testing K_s were chosen depending on the presence of defined runoff drainage lines, the availability of open places and the size of the sub-catchments above 354,000 m². This was perceived to offer adequate space for LID development. In this regard, six sub-catchments, namely KS1, KS2, KS6, KS9, KS12, and KS19 were not included since had no defined hydrologic drainage lines. The selected sub-catchments were considered adequate for the study and the Guelph permeameter (Model 2800K1) was used to determine the infiltration rate during the wet season of the year 2023 and the borehole locations utilized for testing soil infiltration rates are indicated in Figure 2.

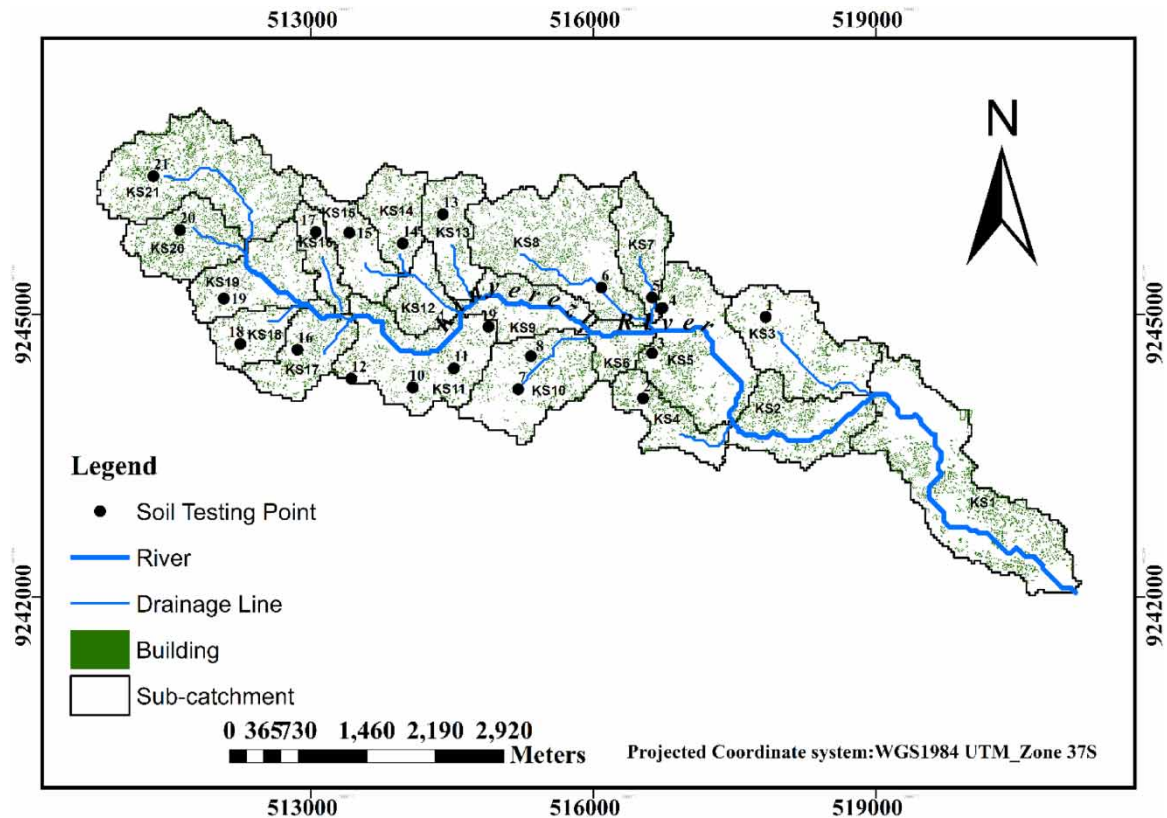


Figure 2 | Hydraulic conductivity (infiltration rate) testing boreholes (ArcGIS 10.4).

Boreholes were drilled using a 10-cm diameter hand-operated auger to 1.5 m to measure infiltration rates and sample soils. The permeameter was inserted into it – Figure 3(a) and 3(b) – and water poured slowly into the permeameter reservoir while keeping the down tape closed. After opening the tape, the water level fall in the reservoir was recorded every 2 min. The steady rate of fall, R , was determined until R did not change significantly over three consecutive time intervals (Reynolds & Elrick 1985).

Soil hydraulic conductivity (infiltration rate) was determined by inputting used permeameter reservoir cross-sectional area (A) of 51 cm², constant water head height (H) measured for each borehole during the test, 5 cm used borehole radius (a), soil texture-structure category and steady rate of fall (R) into the ‘calculator spreadsheet’. The average infiltration rate was calculated for the sub-catchments to determine topographic index values. Soil samples were collected from each borehole at a depth of 1.5 m and their particle size distributions were analyzed in the lab.

2.3. Evaluating topographic index value for sub-catchments

A Digital Elevation Model (DEM) for the Kinyerezi River catchment was freely downloaded from the official website of open topography using the link: <https://opentopography.org/> with entity ID rt1676707346732, data set COP30 and 30 × 30 m resolution. The clipped DEM was delineated into 21 sub-catchments in ArcGIS

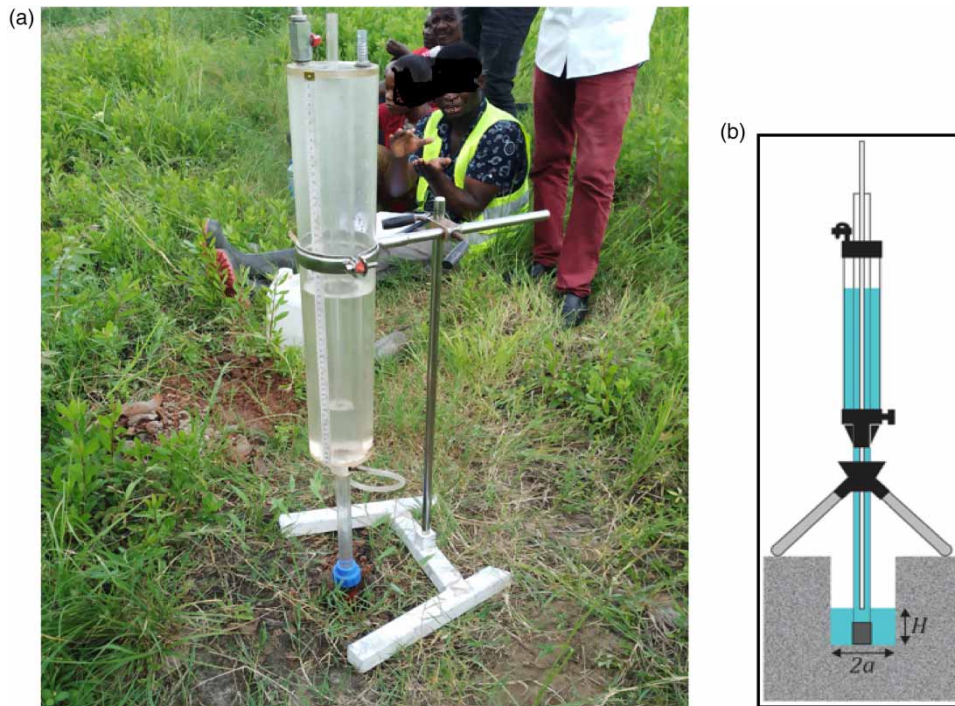


Figure 3 | (a) Field Guelph permeameter setup, with the water head height (H) and borehole radius in (b) (Soilmoisture Equipment Corp 2012).

10.4 (Figure 1). The outlet of the Kinyerezi River catchment was considered as the outfall of the catchment and the runoff drains into the Msimbazi River. Other sub-catchment characteristics that were extracted in ArcGIS 10.4 hydrology tools included areas (A), average slopes (S), and percentage imperviousness. The sub-catchment topographic index values (λ^*) were evaluated using Equation (1)

$$\lambda^* = \ln\left(\frac{A}{\tan S}\right) - \ln(k_s D_{ISA}) \quad (1)$$

where K_s is the average soil hydraulic conductivity. Where there is no restrictive layer, the maximum depth to the water table or bedrock (D) in the sub-catchment is set at 2 m. The D_{ISA} was determined using Equation (2)

$$D_{ISA} = D - (D \times ISA) \quad (2)$$

where ISA represents the sub-catchment's impervious surface area.

Relatively higher λ^* values (greater than standard deviations above the watershed mean) imply a greater likelihood of HSA – i.e., sub-catchments with a high probability of high runoff generation (Martin-Mikle *et al.* 2015; Giri *et al.* 2018) and the lower λ^* value (less than 8) are considered to have very low probabilities of generating excess surface runoff (Agnew *et al.* 2006).

3. RESULTS AND DISCUSSION

3.1. Effect of clay, silt-clay, and gravel on hydraulic conductivity

An attempt to evaluate the effect of the percentage of silt-clay, sand, and gravel on the hydraulic conductivity was made. Given the fact that the particle sizes of silt-clay are the smallest followed by those of sand and gravel. Figure 4 shows the correlations (R^2) of about 0.613 with a negative trend line between silt-clay and hydraulic conductivity. This indicates that hydraulic conductivity increases with the decrease in the percentage of silt-clay particles. When the percentage of silt-clay is greater than 50% the hydraulic conductivity is approximately zero suggesting low or no flow of water. Figure 5 indicates a positive correlation (R^2) trend of about 0.606 between the percentages of sand to the soil infiltration, it confirms that the soil infiltration rate is affected by

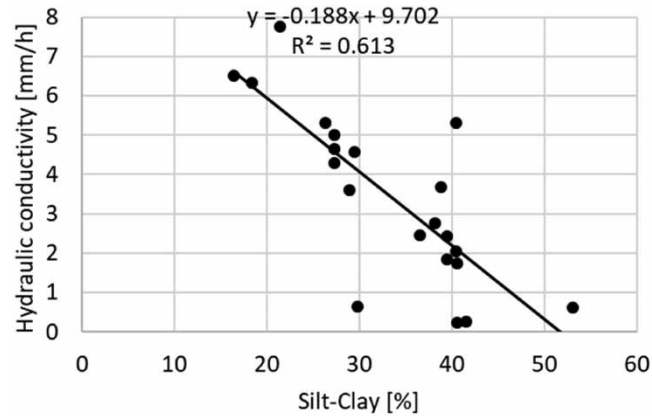


Figure 4 | Correlation between silt-clay and hydraulic conductivity.

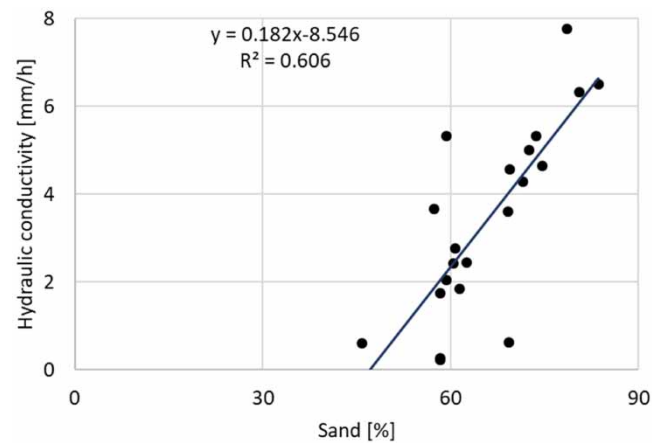


Figure 5 | Correlation between sand and hydraulic conductivity.

proportional sand content where the hydraulic conductivity increases with the increase in percentage of sand. Figure 6 shows no correlation between the percentage of gravel and the hydraulic conductivity and it is likely that gravel does not have any capillarity effect due to large particle sizes and is not affected by the location of the water table. It is fair to note that this study has not considered the moisture content and the groundwater level was not observed to 1.5 depth.

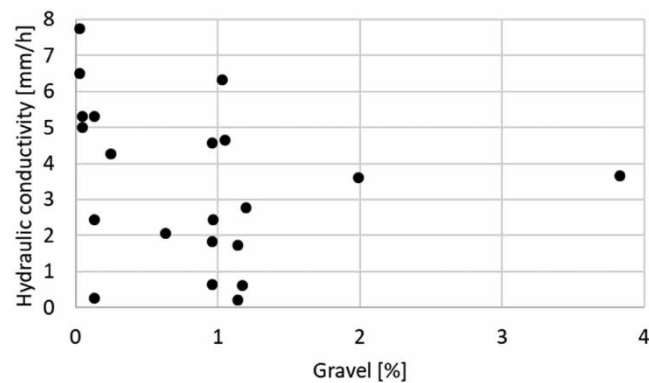


Figure 6 | Zero correlation between gravel and hydraulic conductivity.

3.2. Sub-catchment percentage silt-clay, sand, and gravel variation when compared to hydraulic conductivity

The variation of silt-clay, sand, and gravel when compared to hydraulic conductivity was done for the sub-catchments. Boreholes in sub-catchments KS5, KS21, and KS3 have relatively higher sand contents of about 84, 81, and 79% respectively (Figure 7). The corresponding infiltration rates are estimated at 6.5, 6.3, and 7.8 mm/h, respectively as tested from the field. KS3 has higher proportions of sand and silt than clay, which promotes runoff infiltration. The silt-clay content varied from 16 to 41%, while KS10 had a silt-clay content of about 30–53%. The percentage of gravel varied from 0% in KS 3 and KS5 to 4% in KS11.

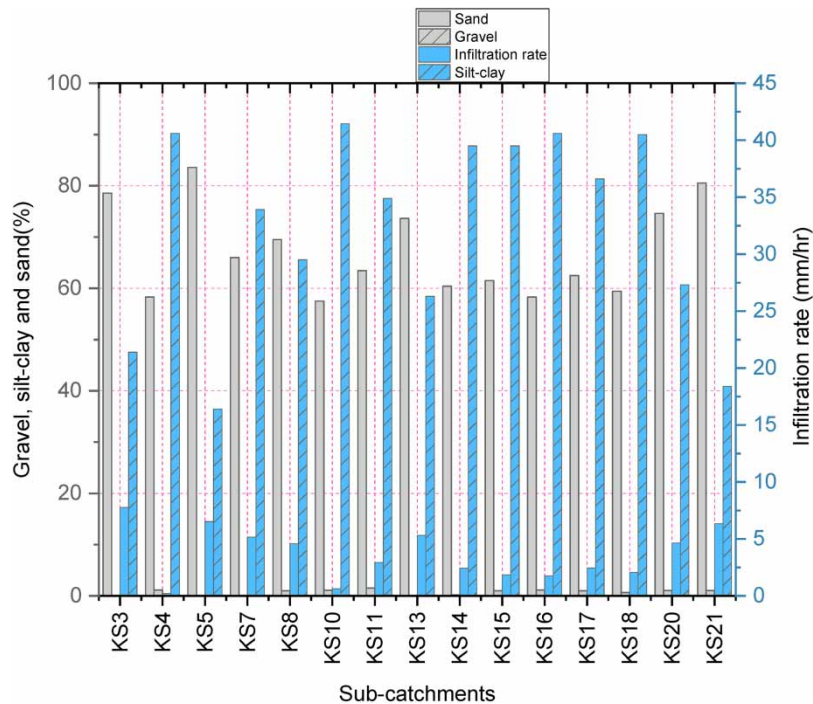


Figure 7 | Infiltration rates and proportional soil contents (Origin Pro).

On the other hand, KS4 has the lowest infiltration rate (0.2 mm/h) with a proportional sand content of about 58%, this is likely due to the presence of a large pond, which saturates the surrounding soils and limits infiltration.

The infiltration rates obtained align with those adopted by Young *et al.* (2023) during the pilot phase of their water-sensitive decentralized stormwater management project for Mburahati Secondary School in Dar es Salaam. Similarly, the infiltration rates are close to that was reported by Winsemius *et al.* (2018) during the development of the hydrological and hydrodynamic model of the Msimbazi River basin-Dar es Salaam in which the soil infiltration rates adopted ranged from 10.4 to 33.33 mm/h.

The Hydrological Soil Group (HSG) from the Food and Agriculture Organization (FAO) website classifies the Kinyerezi River catchment as HSG group C, which has K_s between 1.3 and 3.8 mm/h with a clay content of about 20–40% (Mkilima 2018). The results obtained in this study agree well with the FAO soil classification, except for KS10. Similarly, the average hydraulic conductivity is within the range of the results reported by Lu *et al.* (2017) in the study on better-fitted probability of hydraulic conductivity for silty clay sites, in China.

3.3. Topographic index values

To identify HSA sub-catchments, the λ^* values were determined using the expression proposed by Martin-Mikle *et al.* (2015) and Qiu *et al.* (2017) as represented in Equation (1). The sub-catchment's average K_s – i.e., 3.42 mm/h was utilized as recommended by Agnew *et al.* (2006) and Qiu *et al.* (2020). Depth (D) to the restrictive layer taken as 2 m, the contributing drainage area (A), impervious surfaces area (ISA) and average sub-catchment slope (S) were used to evaluate λ^* value as illustrated in Table 1 using Equations (1) and (2).

Table 1 | Evaluation of sub-catchments λ^* values

| Sub-catchment | K_s | A (ha) | S (%) | %impervious | ISA (ha) | D_{ISA} | λ^* | Ranking |
|---------------|-------|--------|-------|-------------|----------|-----------|-------------|---------|
| KS2 | 3.42 | 93.3 | 9 | 35 | 32.6 | -63.3 | 9.6 | 8 |
| KS3 | 3.42 | 120.1 | 13 | 35 | 42.0 | -82 | 10.7 | 1 |
| KS5 | 3.42 | 142.2 | 10 | 29 | 41.2 | -80.5 | 10.2 | 3 |
| KS7 | 3.42 | 58.6 | 10 | 24 | 14.0 | -26 | 9.2 | 10 |
| KS8 | 3.42 | 173.6 | 12 | 12 | 19.9 | -37.9 | 10.4 | 2 |
| KS10 | 3.42 | 108.2 | 9 | 8 | 8.8 | -15.7 | 10.1 | 4 |
| KS11 | 3.42 | 131.6 | 10 | 10 | 12.6 | -23.2 | 9.68 | 7 |
| KS13 | 3.42 | 61.6 | 13 | 11 | 6.7 | -11.4 | 8.5 | 12 |
| KS14 | 3.42 | 54.5 | 10 | 32 | 17.4 | -32.9 | 8.9 | 11 |
| KS15 | 3.42 | 58.2 | 10 | 9 | 5 | -8.1 | 7.8 | 13 |
| KS16 | 3.42 | 35.4 | 11 | 38 | 13.4 | -24.9 | 5.7 | 15 |
| KS17 | 3.42 | 67.7 | 10 | 33 | 22.3 | -42.7 | 9.74 | 5 |
| KS18 | 3.42 | 44 | 11 | 18 | 7.9 | -13.8 | 7.0 | 14 |
| KS20 | 3.42 | 75.1 | 10 | 17 | 13.0 | -24.1 | 9.3 | 9 |
| KS21 | 3.42 | 179.2 | 11 | 15 | 26.3 | -50.7 | 9.72 | 6 |

The topographic index value for the Kinyerezi River sub-catchments varies from 5.7 to 10.7 with a mean topographic index value of 9.1 and a standard deviation of 1.3. Sub-catchments KS3 and KS8 have the highest λ^* values of about 10.7 and 10.4, respectively, are greater or equal to 10.4 (mean + standard deviation), implying that are the most HSAs, with a high probability of major runoff generation in the Kinyerezi River catchment (Martin-Mikle *et al.* 2015). KS3 is large with a catchment area of about 120.1 ha, highly urbanized with a percentage impervious of about 35% and the highest average slope of about 13% therefore, due to the high slope much runoff is generated and runs into the Kinyerezi River hence increasing floods in the Msimbazi River. KS8 was ranked second in runoff generation, with λ^* value of about 10.4. It has a catchment area of approximately 173.6 ha, a percentage impervious 12% and an average slope of about 12% (Figure 8). This sub-catchment

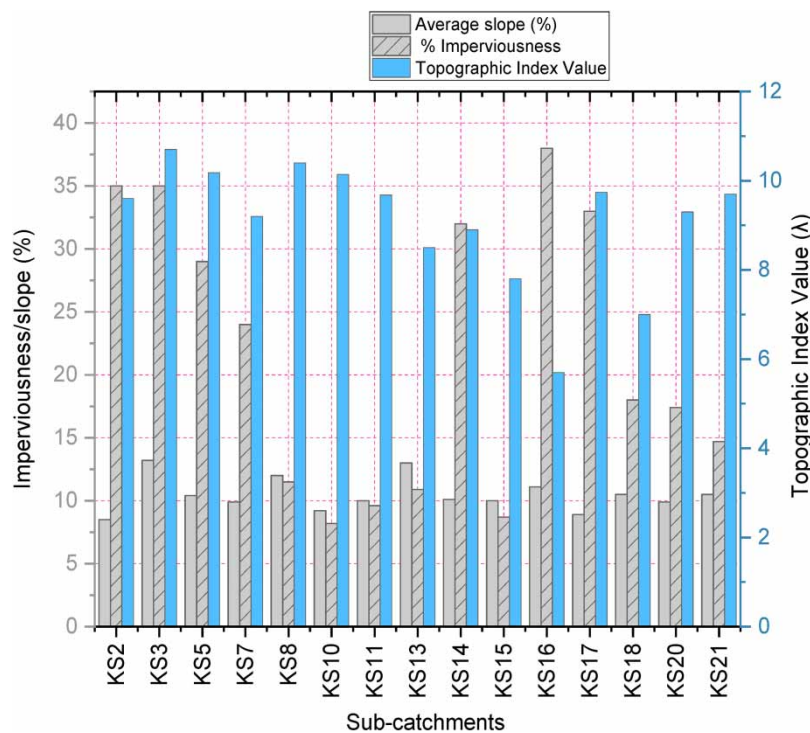


Figure 8 | Sub-catchment λ^* values proportions of impervious ground surface and slope (OriginPro).

generates much runoff with minimum infiltrations due to the high slope of the catchment hence discharging runoff into the Kinyerezi River.

Sub-catchments KS16, KS18, and KS15 are small, with the lowest λ^* values about 5.7, 7.0, and 7.8, respectively, that are less than 8 therefore, are considered to have low probabilities of generating excess surface runoff (Agnew *et al.* 2006). The sub-catchments have small catchment areas of about 35.4, 44, and 58.2 ha, respectively, with high average slopes ranging from 10 to 11% hence, runoff generated within these sub-catchments runs into the Kinyerezi River with negligible impacts. Sub-catchments KS2, KS5, KS7, KS10, KS11, KS13, KS14, KS17, KS20, and KS21 have λ^* values about 8–10.4 hence considered moderate probabilities of generating runoff within the Kinyerezi River catchment.

Agnew *et al.* (2006) evaluated the spatial monthly distribution of λ^* values from January to December to capture seasonal variability in HSA, and found values between 7.7 and 10.3, noting that λ^* was a consistent and reliable indicator of HSA. Similarly, Xue *et al.* (2014) used λ^* on HSAs in the Meishan watershed to evaluate the spatiotemporal variability of surface runoff probabilities and the value ranged from about 13 to 17.

4. CONCLUSION AND RECOMMENDATIONS

The hydrologic sensitivity of sub-catchments is mainly influenced by their soil infiltration rates, slopes, catchment areas, and impervious areas. Those in the Kinyerezi River sub-catchment were tested and the soil samples were collected for particle size distribution analysis. The proportion of sand contents ranged from about 46 to 84% while silt-clay contents ranged from about 16 to 53%. Soil infiltration rates were between 0.6 and 7.8 mm/h. The highest λ^* values about 10.7 and 10.4, were found in sub-catchments KS3 and KS8 respectively and imply that are the most hydrologically sensitive, with a high probability of runoff generation. Sub-catchments KS2, KS5, KS7, KS10, KS11, KS13, KS14, KS17, KS20, and KS21 have their λ^* values ranging from 8 to 10.4; hence, implying moderate probability of runoff generations.

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DATA AVAILABILITY STATEMENT

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

CONFLICT OF INTEREST

The authors declare there is no conflict.

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