



Identification of potential sites for surface runoff harvesting in the semi-arid area for developing cities. A case study of Dodoma urban, Tanzania

Ombeni J. Mdee¹ · Malugu M. Tembo¹

Received: 14 April 2021 / Accepted: 3 October 2021 / Published online: 18 October 2021
© Saudi Society for Geosciences 2021

Abstract

The rapid growth of socioeconomic activities brings the overpressure to the water sources in the semi-arid areas. This paper identifies potential sites for surface runoff harvesting from seasonal rainfall. The potential sites were determined using the analytic hierarchy process (AHP) and weighted linear combination (WLC) techniques with four parameters including runoff depth, drainage density, slope, and lineament density under the GIS environment. The runoff depth was estimated using the Soil Conservation Service method with the three factors such as land use, rainfall, and soil parameters. The normalized weights obtained from the AHP technique were multiplied with the individual weights for each parameter using the WLC technique to acquire the weighted classes (WCs) for defining suitable for surface runoff harvesting. The covered area of about 5.5% for a very high suitable site was obtained followed by 76.4% of the highly suitable site with the WC ranged from 433 to 500% and 372 to 433%, respectively. The covered area of about 18.1% for the medium to a very low suitable site for harvesting surface runoff with the WC between 271 and 372%. The developed potential site map would provide access for harvesting the surface runoff to improve the water shortage during long dry periods, minimize flooding, or reduce the land use across the drainage network in the semi-arid areas.

Keywords Surface runoff · Drainage density · Runoff depth · Lineament density · Slope · Land use

Introduction

Water scarcity has been increasing globally especial in semi-arid areas due to the high variability of climate (Uwizeyimana, et al., 2019), scarce and intermittent rainfall (Nthuni, et al., 2014; Sayl, et al., 2019), or unforeseeable periods of flood and drought (Adham, et al., 2018). Water availability is the basic need of human development and population growth (Zaki, et al., 2019). Also, farming and livestock activities depend only on the water ponds accumulated during wet seasons in the semi-arid areas (Shemsanga, et al., 2016). The shortage of water affects every aspect of socioeconomic

life including health, agriculture, food security, and other technical aspects.

The semi-arid regions are characterized by the low frequency of rainfall events with high intensity, short periods, and highly temporal-spatial distribution (Camarasa-Belmonte and Soriano, 2014). During rainfall, a fraction of the precipitation evaporates, some infiltrate or intercepted by vegetation, and others become surface runoff (Vikneswaran and Razak, 2015). The amount of surface runoff generated depends on several factors including rainfall intensity, initial soil moisture condition, land use and land cover, soil texture, topography, and basin characteristics. Surface runoff harvesting is the collection, accumulation, and storing of the rainwater into an artificial or man-made reservoir for future reuse (De Winnaar, et al., 2007). Rainwater harvesting is considered to be a sustainable method to collect water for use in domestic and agriculture activities and industry (Sayl, et al., 2019; Matomela, et al., 2020). Several techniques such as deep tillage, contour farming, and ridging have been used for in situ surface runoff harvesting (Hatibu and Mahoo, 1999).

Responsible Editor: Broder J. Merkel

Communicated by Broder J. Merkel

✉ Ombeni J. Mdee
ombenijohn@gmail.com

¹ College of Earth Sciences and Engineering, University of Dodoma, P.O. Box 259, Dodoma, Tanzania

The increase in population and economic growth becomes the driving force for the expansion of urban built areas in the developing cities (Li, et al., 2015). The expansion of built areas with several infrastructures leads to change in water balance parameters and urban land uses (Ligtenberg, 2017). The infrastructures built including buildings, roads, airports, and other impervious structures such as parking and so forth. The generated surface runoff either runs away from residential or premises, trapped for use, lost in the atmosphere through evaporation, or runs in the river or streams. Also, a high amount of surface-runoff is generated in the urban areas are due to the low infiltration that is turning into flooding during the heavy storm (Du, et al., 2015).

The identification of surface runoff sites for rainwater collection was determined normally using the geographical information system (GIS) and remote sensing (RS) tools. The factors affecting rainwater harvesting were synthesized in the GIS and RS tools with different methods and multi-criteria techniques to identify the potential sites. Several factors used include rainfall intensity, runoff coefficient, soil texture, drainage pattern, topography, vegetation cover, and socioeconomic conditions as described

in Wu et al. (2018) and Terêncio et al. (2017). The potential sites were identified using the hydrological modelling (HM) integrated with GIS/RS as described in De Winnaar et al. (2007), multi-criteria analysis (MCA) integrated with HM and GIS-RS described in Weerasinghe et al. (2011), and Elewa et al. (2012) and MCA integrated with GIS as described in Kadam, et al. (2012). The climate-flood model was developed to understand the annual runoff characteristics based on the climatic variables including rainfall depth, air temperature, sunshine, evaporation, humidity, wind speed cloud cover, soil temperature, solar radiation, and atmospheric pressure (Ekwueme & Agunwamba, 2020). The Soil and Water Assessment Tool (SWAT) model was used with inputs from geospatial datasets and precipitation data to simulate the watershed for enhancing water resource management (Guiamel and Lee, 2020). The selection of the method depends on the data availability, accuracy, and requirement of the specific area (Ammar, et al., 2016). Table 1 shows the methods used and parameters applied by different scholars to identify the potential sites for surface runoff harvesting. However, the combination of MCA and GIS has proved potential to

Table 1 Potential sites identification based on different methods and parameters from several scholars

S/N	Methods used	Parameters	Sources
1	Remote sensing and GIS-based SCS-CN method	Rainfall data, land use/land cover, elevation, slope and stream network, and soil texture	Al-Ghobari, et al. (2020)
2	Integrating remote sensing, watershed modelling system (WMS) and GIS	Volume of annual flood, basin area, basin length, maximum flow distance, drainage frequency density, lineaments frequency density, basin slope, and stream order and soil	Sayl, et al. (2019)
3	Integrated use of remote sensing and GIS	Slope, drainage, land use/cover, lineaments, soil, rainfall data	Mugo and Odera (2019)
4	GIS-based multi-criteria approach	Rainfall, soil, slope, land use/land cover and drainage density, surface runoff, and infiltration zone	Singhai, et al. (2019)
5	GIS-based approach	Land use and land cover, rainfall, slope, soil digital elevation model, slope and drainage density	Haile and Suryabhagavan (2019)
6	GIS-based method	Slope, runoff depth, land cover/use, soil texture, and stream order	Adham, et al. (2018)
7	Analytical Hierarchy Process	Runoff, soil texture, land use/cover, distance from road distance from agricultural field, and slope	Wu, et al. (2018)
8	A GIS-based integrated fuzzy logic and analytic hierarchy process model	Slope, soil, land cover/use, rainfall data, and distance to the river	Al-Abadi, et al. (2017)
9	Use of AHP with GIS environment	Rainfall, slope, soil clay content, lineament density, geology, and drainage density	Al-shabeeb (2016)
10	Remote sensing and GIS environment	Population density, rainfall distribution, DEM, demographic data, administrative unit, and topographical feature	Nthuni, et al. (2014)
11	GIS approach combined with Multi-criteria decision-making techniques	Rainfall, slope, distance to wadis, soil, distance to the urban center, and distance to road	Al-Adamat, et al. (2010)
12	SCS-CN Method	Land use/land cover, rainfall data, drainage, soil, and contour	Amutha and Porchelvan (2009)
13	GIS-based approach	Distance to home, distance to crop, DEM, soil, and land use/cover	De Winnaar, et al. (2007)

logical, objective, and non-biased approach to the selection of the suitable area for surface runoff harvesting (Isioye, 2012).

Research goals, motivation, and paper organization

According to the population census of 2012, the number of people in the Dodoma urban was 410,956 (URT The United Republic of Tanzania, 2013). However, the population has steadily increased in recent years following the shifting of the national capital from Dar es Salaam to the Dodoma region in 2016. The increased population in Dodoma urban has been marked to increase water demand (Shemsanga, et al. 2018; SHLC (Centre for Sustainable Health and Learning Cities and Neighbourhoods, 2020) and changes in land use. The current water demand in Dodoma is 45 Million liters per day and the supply is only about 20 million liters per day (DUWASA, Dodoma Urban Water Supply and Sanitation Authority, 2019). The water authority of Dodoma urban depends on the groundwater sources both in deep and shallow wells (Shemsanga, et al. 2018). This source of water is limited to the beneficiaries' water supply network or the situation becomes critical, especially during the drought period (WB (The World Bank, 2019).

The area is overpopulated and increases land use, especially the construction of public buildings and residences. Knowing that the land use was already given without showing the provision of routines for surface runoff (URT, 2019), this makes the paper to be valuable to the study area and provides information to the other developing cities for considering the identification of surface runoff routes during land use map preparation. Therefore, the motivation of this paper is to reduce the pressure of pumping groundwater resources in the study area, especially during the wet season and encourage the practice of rainwater harvesting in the urban built-up areas. The objective of this study is to identify the potential sites for surface runoff harvesting and estimate the available surface area in emerging urban cities for minimizing floods.

The research works identified the potential sites for surface runoff harvesting based on the general procedures of the analytic hierarchy process (AHP) under the GIS environment. The AHP method was analytically triggered with a weighted linear combination method to identify the very high suitability area when the slope is less than 5°, high drainage density, low lineament density, and higher runoff depth.

This paper is organized as follows: the introduction part consists of the assessment of water needs, land uses, and socioeconomic activities; the methodology part consists of the description of the study area, and identification of the six factors that affected the harvesting of surface runoff. The curve numbers were determined using hydrological soil groups, land use, and rainfall data, while the normalized

weights were determined using runoff depth, drainage density, slope, and lineament density; the results and discussion part consists of the spatial distribution of runoff depth; then, potential sites were identified using the AHP method with normalized weights. Also, the surface areas for potential sites were calculated using the triangulated irregular network, and natural ponds were identified using Google Earth images; the conclusion part supports the harvesting practices of surface runoff in the semi-arid areas.

Description of the study area

The Dodoma urban is the capital city of Tanzania, located in the central part of Tanzania having an elevation between 925 and 1691 m above sea level with an average elevation of 1100 m as shown in Fig. 1. The high elevation area has been allocated in the North and South of the Dodoma urban. About 49% of the area is situated in an elevation ranging between 1074 and 1163 m. For more than 2 decades, three dams were built and used to store the surface runoff for domestic, livestock, and farming activities. These dams including Imagi, Mkalama, and Hombolo as shown in numbers 1, 2, and 3 at the geographical locations of $-6.2051, 35.7529$; $-6.1992, 35.7727$; and $-5.9469, 35.9679$, respectively. Dodoma urban receives a single rainfall period between October and May ranging between 400 and 900 mm with an average total annual rainfall of 550 mm (Kassile, 2013). The average temperature of Dodoma urban is 24.7 °C with November being the hottest month in a year and July the month with the lowest average temperature.

Materials and methods

Data types and sources

The identification of potential sites for surface runoff harvesting was evaluated using a combination of different data set as presented in Table 2.

Factors affecting the rainwater harvesting

The originality of this study is to use simple methods and freely available data to solve the problem related to planning the land use without thinking about the surface runoff routes, especially in the developing cities, where high knowledge and finance conditions are major barriers. Figure 2 shows the flow of needed parameters to develop the surface runoff that can be harvested or leave the place opens to avoid flooding or restricts water flows. Three parameters were used to estimate the runoff depth

Fig. 1 Location of Dodoma urban with the spatial elevation map (Google Earth photo as of 09 March 2021)

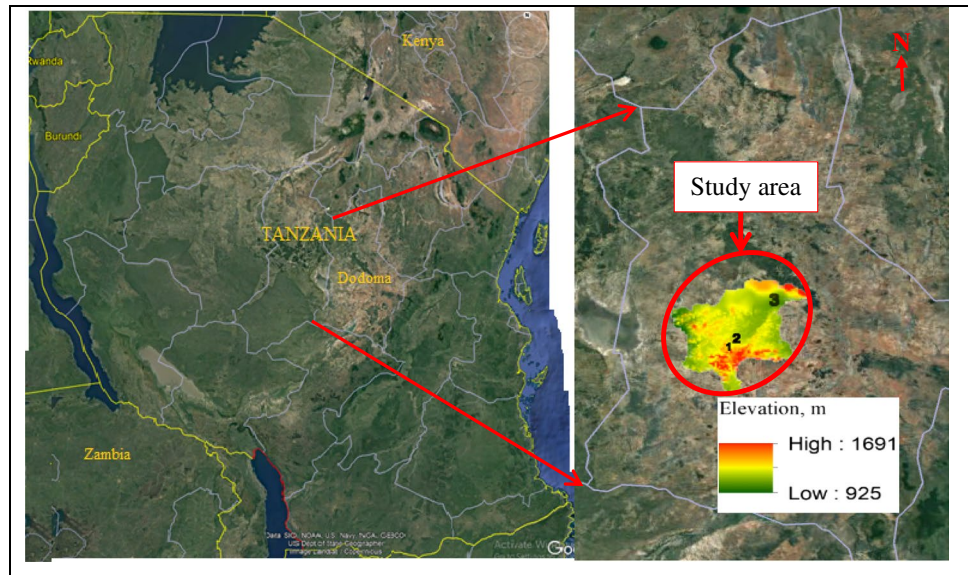
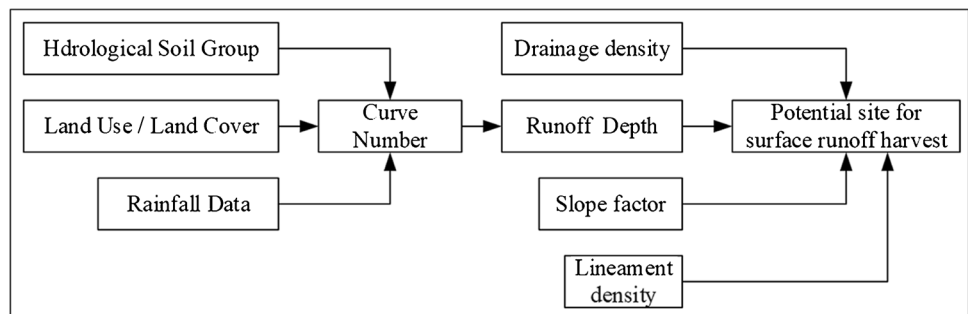


Table 2 Data type, resolution, and uses from different literature sources

S/N	Parameter	Resolution	Uses	Source
1	DEM map	30 m	To develop the slope and drainage density	USGS (United States Geological Survey, 2006)
2	Land use land cover Map	30 cm-5 m/pixel 463.3 m	Input factor for runoff depth	WB (World-Bank, 2017); USGS (2020)
3	Landsat-8 OLI image	-	To develop lineament density	USGS (2020)
4	Soil	1 km	To develop hydrological soil groups	FAO (Food Agriculture Organization of the United Nations (2003)

Fig. 2 Simplified flowchart showing the procedures for identifying potential sites for rainwater harvesting



which is the main source of surface runoff harvesting, and then three physical parameters include drainage density, slope, and lineament density were applied to identify the percentage of surface runoff that can reach a particular time. The land use or cover type and soil groups were used to estimate the adjusted curve number. Then, the adjusted curve number was combined with rainfall using Soil Conservation Service (SCS) method to obtain the runoff depth. Again, runoff depth, drainage density, slope, and lineament density were combined using weighted linear combination (WLC) to identify the potential surface runoff sites.

Runoff depth factor using SCS method

The runoff depth was estimated using the SCS method based on the land use/land cover, soil, and rainfall data. The SCS method was developed by the Natural Resources Conservation Service of the United States Department of Agriculture (USDA) in 1954 to estimate the runoff depth (Gajbhiye, 2015). The method originated from the assumption of the ratio of runoff depth to precipitation minus initial abstraction is equal to the ratio between the infiltration to soil potential maximum retention as expressed in Eq. (1) (Li, et al. 2015). The method

considers that the initial abstraction had a proportional constant to soil potential maximum retention (Patil, et al. 2008). The method has been used to estimate the runoff depth in a wide climatic zone ranging from temperate humid zone to arid areas (Boughton, 1989).

$$\left. \begin{aligned} Q &= \frac{(P-\lambda S)^2}{(P-\lambda S)+S} \text{ for } p > \lambda S \\ Q &= 0 \text{ for } p < \lambda S \end{aligned} \right\} \quad (1)$$

where Q is the runoff depth, mm; P is the precipitation, mm; S is the soil potential maximum retention; and λ is the proportionality constant that is depending on the climate and the geology of the region under study (Patil, et al. 2008). The value of λ parameter ranges between 0.1 and 0.3 inclusively. Most of the reach works used an average value of $\lambda = 0.2$ (Al-Ghobari, et al., 2020). However, some of the researchers used a maximum value of $\lambda = 0.3$ (Satheeshkumar, et al. 2017). Comparison of different values of $\lambda = 0.1, 0.2,$ and 0.3 was conducted by Farran and Elfeki (2020). The findings were relatively agreed with the other literature data for using $\lambda = 0.2$ and adopted in this study.

The soil potential maximum retention (S) was determined indirectly by using the curve number (CN) of hydrological soil cover. The value of CN depends on soil type, land use, and the antecedent moisture condition (AMC) (Satheeshkumar, et al. 2017). The relationship between the S and CN is given in Eq. (2).

$$S = \frac{25400}{CN} - 254 \quad (2)$$

The anteceded moisture condition (AMC) indicated the degree of wetness of the soil before the storm. This AMC has a great effect on the quantity of water to be retained or overflow on the surface of the earth (Rawat and Singh, 2017). To take care of the AMC, SCS has developed a manual to adjust the curve number based on the rainfall of 5 days preceding the storm event as grouped into three types (Farran and Elfeki (2020). Normally the calculation of the CN is first done by assuming AMC type two condition, i.e., 5 days antecedent rainfall of dormant season ranged between 12.7 and 27.9 or growing season ranged between 35.6 and 53.3 mm (Farran and Elfeki (2020). The adjusted CN_a as expressed in Eq. (3) depends on the rainfall condition type one of less than 12.7 in the dormant season and less than 35.6 mm in the growing season that suits this study area.

$$CN_a = \frac{CN}{2.2754} - 0.01275CN \quad (3)$$

Soil texture factor

The FAO soil map of Africa acquired from global data sets that are available online was used under the GIS to clip the soil texture and soil composition (Table 3).

Slope factor The slope of different classes significantly affects the surface runoff and the infiltration amount (Garg, et al. 2013). A slope of less than 5° is recommended for surface runoff harvesting (Mugo and Odera, 2019). This implies that the selection of the suitability of an area for runoff harvest is a function of a slope. A slope in the study area was developed using the DEM obtained from USGS. The DEM in the study area clipped using the study area boundary shapefile and slope tool in the spatial analyst tool to calculate five classes of slope in degree as shown in Fig. 3. The DEM was filled to make sure all pixels contain values. The larger part of the study area had a percentage slope ranging between 0 and 1.7° of about 69% followed by 1.7 and 2.8° of about 14%. Typical slope classes from different literature sources were presented in Table 4.

Drainage density Drainage density measures the distribution of streams in the study area to determine the amount of runoff losses due to infiltration. The higher the drainage density, the higher the potentiality for surface runoff harvesting (Sayl, et al. 2019). Typical drainage density classes from different literature sources are presented in Table 5. The stream order raster map generated in the ArcGIS was used in the line density analysis to estimate the magnitude per area within the radius of each pixel. Figure 4 shows the drainage density that varied between 26 and 104 m/m^2 .

Lineament density

Lineament density was obtained using the total length of the observed lineaments divide by the total area of the basin as shown in Fig. 5. The lineament density indicates the suitability of an area for surface runoff harvest or groundwater recharge. High lineament density is suitable for groundwater recharge and the low lineament density is suitable for surface runoff harvest (Maina and Raude, 2016). Typical lineament density classes from different literature sources were presented in Table 6. The Landsat 8 operational land image

Table 3 Soil texture in the study area as taken from (FAO, 2003)

Sequence	Counts	Sand %	Silt %	Clay %	Soil texture
407	1941	54	21	25	Sand-clay-loam
414	507	65	15	20	Sand-loam
420	166	68	14	18	Sand-loam
483	3	48	19	33	Sand-clay-loam

Fig. 3 Slope factor with five classes in degree

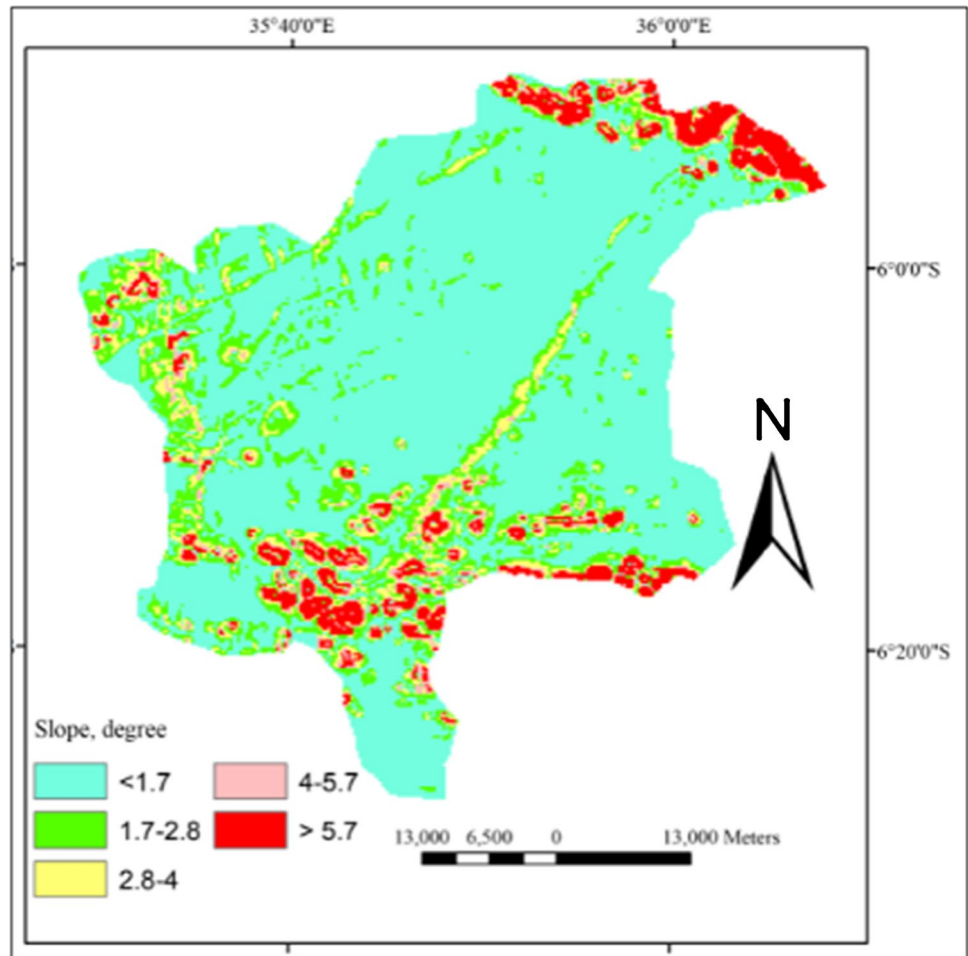


Table 4 Typical slope classes from different literature sources

Slope classes from different literature sources							
Class interval	Weight	Class interval	Weight	Class interval	Weight	Class interval	Weight
< 3%	4	0°-1°	5	< 2	1.0	< 5%	9
3% ≤ S < 5%	3	1°-2°	4	2-5	0.75	5-15%	7
5% ≤ S < 10%	2	2°-3°	3	5-10	0.50	15-25%	6
> 10%	1	3°-4°	2	10-30	0.25	25-35%	5
-	-	4°-5°	1	> 30	0.0	35-45%	3
-	-	> 5°	0	-	-	> 45%	1
Al-shabeeb (2016)		Dai (2016)		Haile & Suryabhagavan (2019)		Mugo and Odera (2019)	

was imported into Catalyst Professional software for the demarcation of lineaments as described in Mugo and Odera (2019). The obtained lineament under the GIS environment is used to define the lineament density.

Land use and land cover

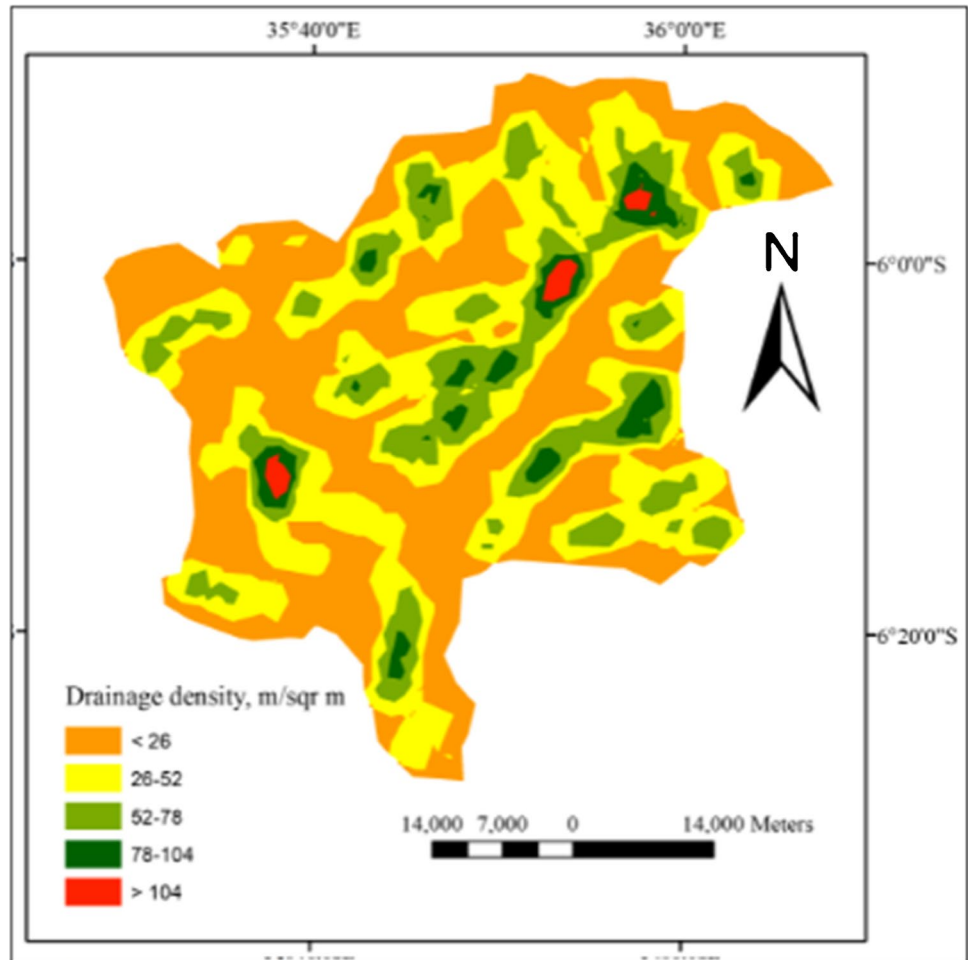
The land use and land cover (LULC) data were loaded in the ArcGIS environment. The land use classes and

corresponding coverage area were obtained as shown in Fig. 6. A total of eight land use classes were identified which are barren or sparsely vegetated, cropland or natural vegetated, deciduous broadleaf forest, grassland, savanna, open shrublands, and urban built up. The covered areas of cropland and urban built-up increased each year resulted to decrease other five LULC classes.

Table 5 Typical drainage density classes from different literature sources

Drainage density classes from different literature sources							
Class interval	Weight	Class interval	Weight	Class interval	Weight	Class interval	Weight
> 2.55	4	> 222	90	> 2	1.0	0–21	4
2.55–1.5	3	221–161	70	1.8–2	0.75	21–40	7
1.5–0.75	2	161–121	50	1.7–1.8	0.50	40–80	8
< 0.75	1	120–61	30	1.5–1.7	0.25	80–139	9
		< 61	10	< 1.5	0.0		
Al-shabeeb (2016)		Elewa et al. (2012)		Haile & Suryabagavan (2019)		Mugo and Odera, (2019)	

Fig. 4 Drainage density with five classes



Data analysis

Curve number identification

Six classes of land use/land cover were reclassified to fit the standard classes provided by HSG (Neilsen and Hjelmfelt, 1998) and integrated with the soil classes to define the curve number as shown in Table 7. The land covered with dense forest experienced less curve number compared with the bare or man-made land features. The adjusted CN values

were obtained using Eq. 3 and spatially interpolated using the raster calculator to obtain Fig. 7. The CN ranged between 65 and 99.6 with an average of 71.5.

Analytic hierarchy process for potential site identification

This study used the AHP method that was used frequently by scholars and ranked first followed by the other decision methods, according to Mardani et al. (2015). The features of runoff depth, drainage density, slope, and lineament

Fig. 5 Lineament factor with two classes

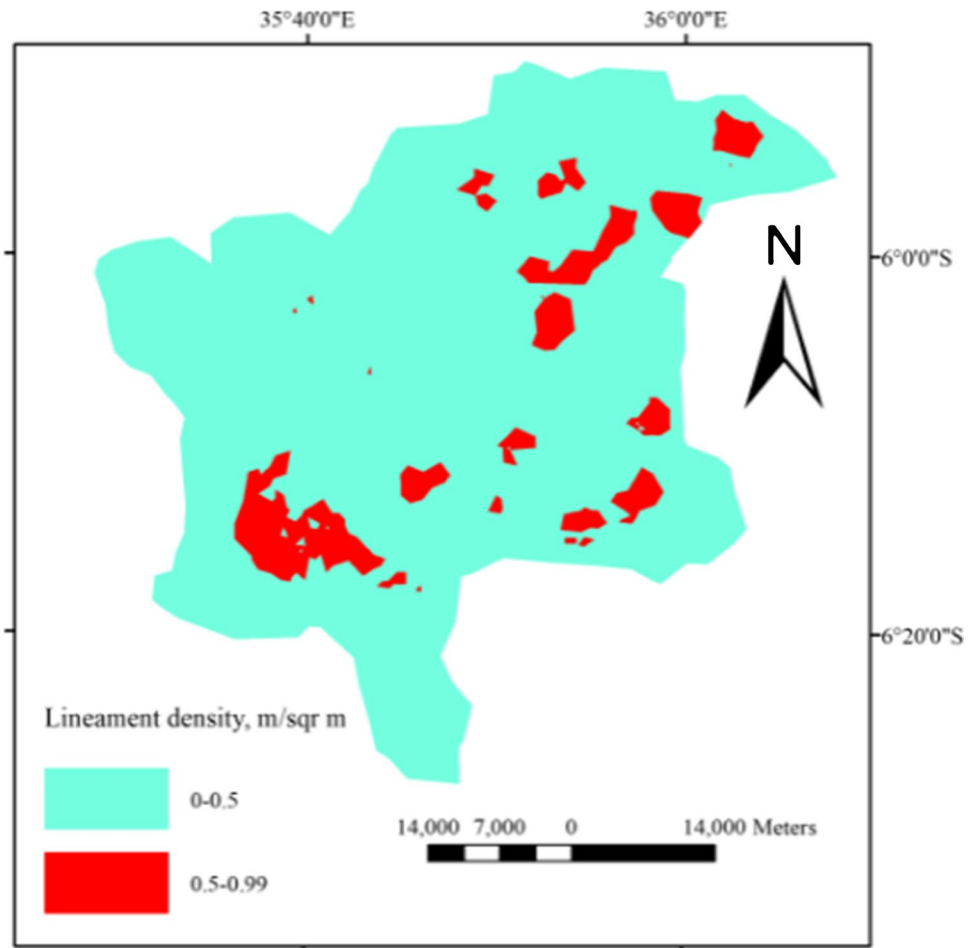


Table 6 Typical lineament density classes from different literature sources

Lineament density classes from different literature sources							
Class interval	Weight	Class interval	Weight	Class interval	Weight	Class interval	Weight
0–1.5	4	< 3	90	2.5–3	0.25	0–0.2	9
1.5–2.5	3	4–6	70	1.5–2.5	0.50	0.2–0.5	7
2.5–3.5	2	7–13	50	0.75–1.5	0.75	0.5–1.0	5
> 3.5	1	14–29	30	< 0.75	1.0	1.0–2.4	3
-	-	> 30	10	-	-	-	-
Al-shabeeb (2016)		Elewa et al. (2012)		Haile & Suryabhagavan (2019)		Mugo & Odera (2019)	

density factors were assigned weights based on Saaty’s scale from 1 to 9. The value of 9 shows the highest influential and the value of 1 shows the lowest weight of influential (Saaty, 2004). Weights on the features of thematic layers were assigned based on the opinion of experts and tested using a consistency ratio (Al-Adamat, et al. 2010; Ammar et al. 2016). Pairwise comparison of the assigned matrix for factors was conducted using the AHP technique to obtain a matrix as shown in Table 8. The values of the matrix were based on the influence of one factor compared to another. For instance, a runoff depth influences to surface runoff

compared to the slope is 3, but the slope influences as reciprocal to runoff, i.e., slope factor equal to 0.33. Then, normalized eigenvectors were obtained as 53%, 27%, 14%, and 6% for runoff depth, slope, drainage density, and lineament density, respectively.

The values of the matrix were tested using the consistency ratio (RC) to measure the acceptance level. The RC was computed using the consistency index and random consistency index (RCI) as expressed in Eq. 4. When the value of RC is between 0 and 0.1, the consistency is acceptable (Zhang, et al. 2014); otherwise, the subjective

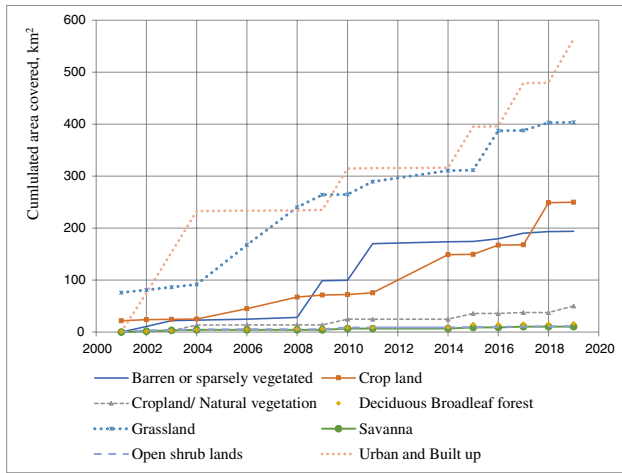


Fig. 6 Land use and land cover from the year 2001 to 2019 using satellite image data

Table 7 Lookup table for land use/land cover and soil types with the corresponding curve number

Land use/land cover	Curve number, CN			
	HSG A	HSG B	HSG C	HSG D
Artificial surface—buildings	77	86	91	94
Artificial surface—roads + air-port	83	89	92	93
Agricultural land	68	79	86	89
Forest	55	72	81	86
Bare land	69	80	87	86
Water bodies	100	100	100	100

judgment is revised for all factors. The computed value of principal eigenvector (γ_{max}) as the product of each element of eigenvector and reciprocal matrix sum of columns and *RCI* was equal to 0.9 for four factors.

$$RC = \frac{\gamma_{max} - n}{(n - 1) \times RCI} \tag{4}$$

The maximum principal eigenvector (γ_{max}) was 4.158 as calculated using the assigned weights of four factors in the comparison pairwise matrix. For checking the probability of randomness of the generated matrix ratings, the consistency index is 0.052 with the formula adopted from Jha et al. (2014). Then, the consistency ratio (*RC*) was 5.8% that lied within the acceptance level to provide the results using the AHP technique. The four thematic layers/maps together with their corresponding normalized weights were integrated into the GIS environment to select the potential harvesting site for surface runoff. The WLC method was used to sum all four factors as equal to

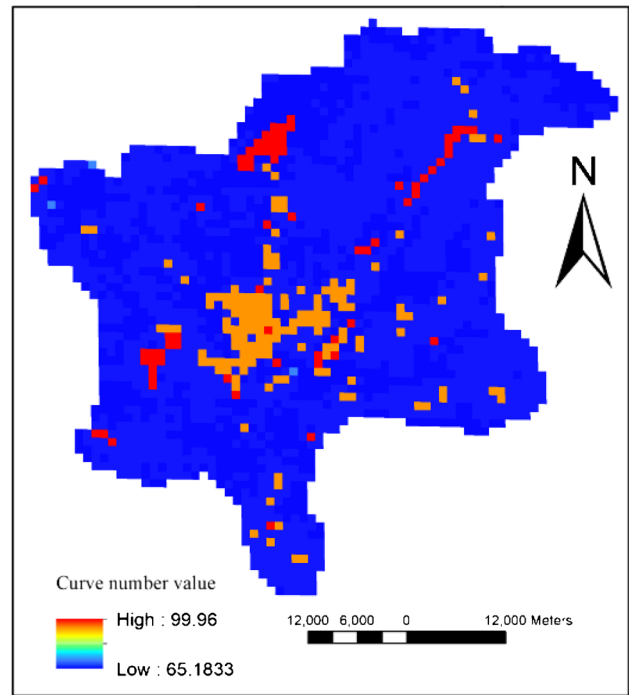


Fig. 7 Spatial distribution of adjusted curve number

Table 8 Pairwise matrix comparison of factors affecting potential sites identification

Factor	Runoff depth	Slope	Drainage density	Lineament density
Runoff depth	1	3	3	9
Slope	0.333	1	3	5
Drainage density	0.333	0.333	1	3
Lineament density	0.111	0.2	0.333	1

weights for each factor times the normalized eigenvectors to define each weighted class (*WC*) for potential site identification.

Results and discussion

This session covers the assessment of six factors affecting the surface runoff, variation of assigned scales to factors, and normalized weights, and then potential site map was developed and overlaid to the natural streams.

Assessment of factors for potential site identification

Assessment of rainfall factor

The measured rainfall data from 1981 to 2011 as adopted from Hamisi (2013) is shown in Fig. 8. The mean value of total annual rainfall was 550 mm at the percentage of time equal to or exceeded 50%.

Assessment of land use/land cover factor

Figure 9 shows the five classes of land use/land cover including agriculture activities covered the area of 58% followed by forest and other natural areas of about 33.6%. The other land use/land cover consists of artificial surfaces based on the constructions of buildings, roads, railway, and airport of about 5.9%; wetlands and inland water of about 2.4%; and bare land of about 0.1%.

Assessment of soil factor

Two main soil textures were identified which are sandy-clay-loam and sandy-loam as shown in Fig. 10. The land is dominated by a sand-clay-loam soil texture of about 92.1%. The soil texture was used to define the HSG in the study area. The study area was covered with the HSG group C that is associated with the following features: (i) soil having moderately high potential runoff when thoroughly wet; (ii) contain 20–40% clay and 50% sand; (iii) soil texture: loam, silt-loam, sand-clay-loam, clay-loam, and silt-clay or sand clay; (iv) saturated hydraulic conductivity between 1 and 10 μm per second.

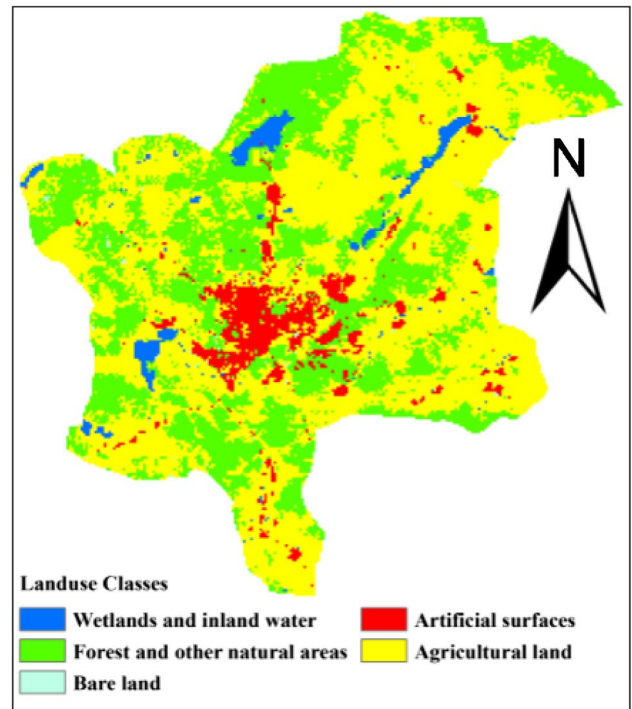
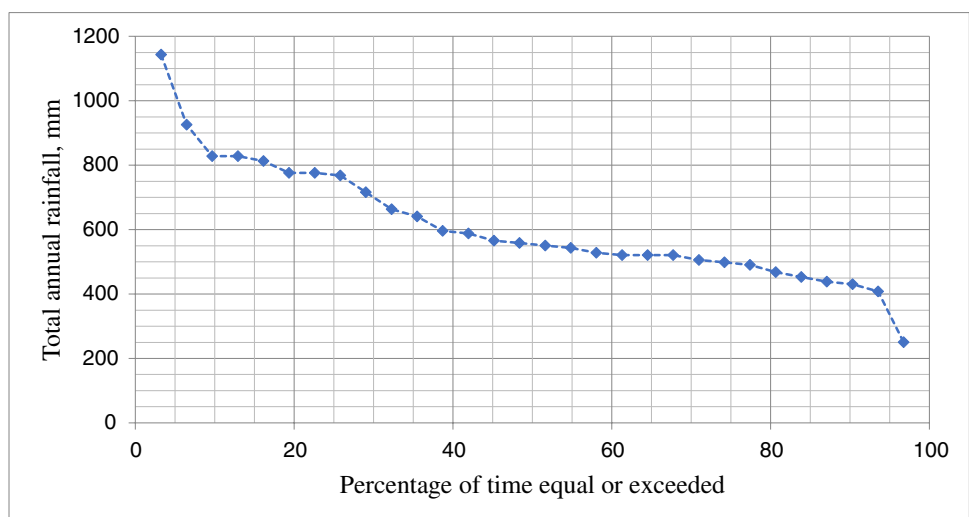


Fig. 9 Land use/land cover of Dodoma urban with six classes

Assessment of runoff depth factor

The assessment of runoff depth was conducted using the average amount of rainfall, land use/land cover classes, and soil textures. The runoff depth was developed using Eq. (1) after estimating the curve numbers as shown in Fig. 11. The mean total annual rainfall of 550 mm at the 50% of time equal or exceeded and $\lambda = 0.2$ were used in this study. The highest runoff depth was generated in the area around the city center and the wetland area. Using

Fig. 8 Total annual rainfall from 1981 to 2011 at the Dodoma region



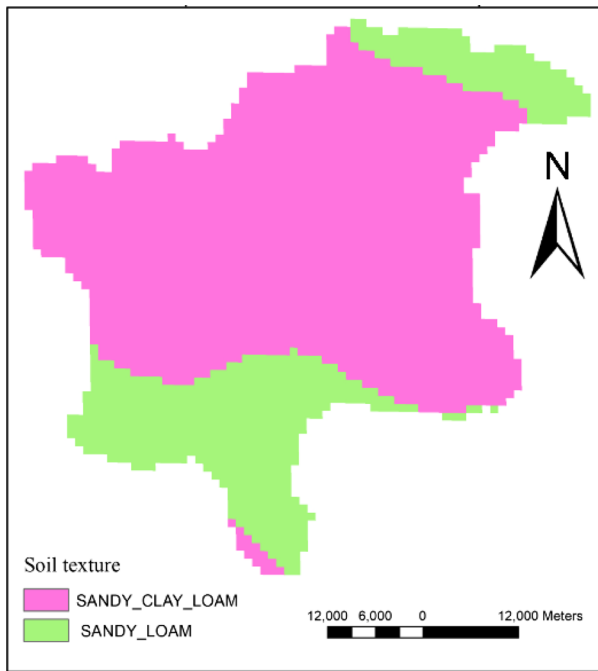


Fig. 10 Classification of soil textures in Dodoma urban

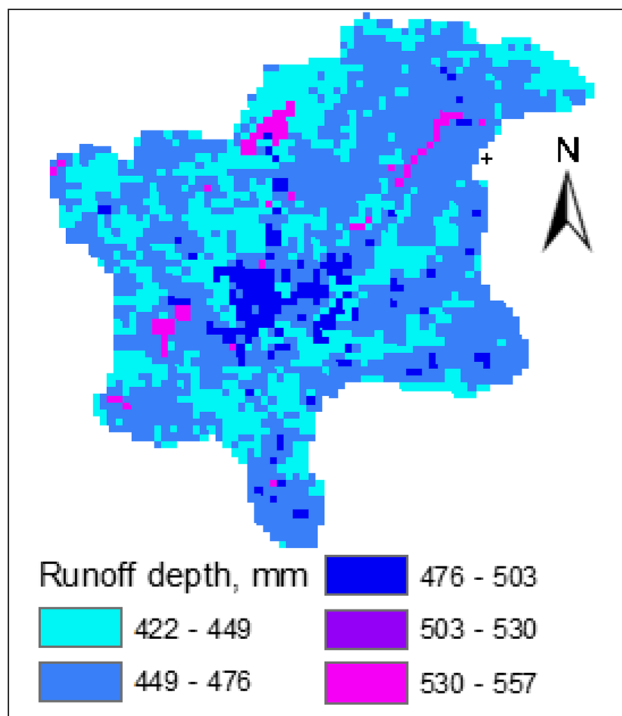


Fig. 11 Runoff depth map with the five classes

natural breaks classification, the runoff depth ranged between 422 and 557 mm with an average of 451 mm. About 91% of the area had a runoff depth ranged between 422 and 480 mm.

Variation of assigned weights for factors affecting rainwater harvesting

The runoff depth, drainage density, slope, and lineament density maps were assigned weight as described in Table 9. Ideally, each map is supposed to have five classes, but the values for each map determined the number of classes; further descriptions are obtained in “Factors affecting the rainwater harvesting” section and “Assessment of runoff depth factor” section. This study indicated that the runoff depth had only three classes, drainage density for five classes, slope for five classes, and lineament density of two classes as shown in Fig. 12. A scale of 5 indicated the most influential and 1 indicated the least influential. Then, lineament density had more area-based influence with the covered area of 91.2% followed by slope factor with the covered area of 69%.

Normalized weights for factors affecting potential sites

Figure 13 shows the four normalized weight values for four factors arranged by adjacent intervals in a scale to indicate the spatial distribution. Three normalized weight classes of runoff depth ranged between 159 and 265% with an average of 212% and a standard deviation of 43.3%. Five normalized weight classes of percentage slope ranged between 27 and 135% with an average of 81% and a standard deviation of 38.2%. Five normalized weight classes of drainage density ranged between 14 and 70% with an average of 42% and a standard deviation of 19.8%. Two normalized weight classes of lineament density ranged between 24 and 30% with an average of 27% and a standard deviation of 3%.

Table 9 Assigned weights for four factors with verbal judgement

Factor	Feature	Weight	Verbal judgement
Slope, degree	< 1.7	5	Very high suitability
	≥ 1.7 < 2.8	4	High suitability
	≥ 2.8 < 4	3	Medium suitability
	≥ 4 < 5.7	2	Low suitability
	≥ 5.7	1	Very low suitability
Drainage density, m/m ²	> 104	5	Very high suitability
	78–104	4	High suitability
	52–78	3	Medium suitability
	26–52	2	Low suitability
	< 26	1	Very low suitability
Runoff depth, mm	540–557	5	Very high suitability
	480–540	4	High suitability
	420–480	3	Medium suitability
Lineament density, m/m ²	0–0.5	5	Very high suitability
	0.5–1.75	4	High suitability

Fig. 12 Spatial distribution of assigned weights and covered areas for the (a) runoff depth (b) drainage density (c) slope and (d) lineament density

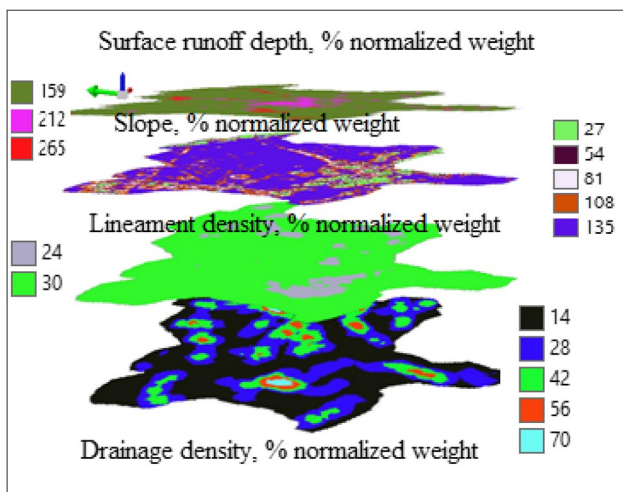
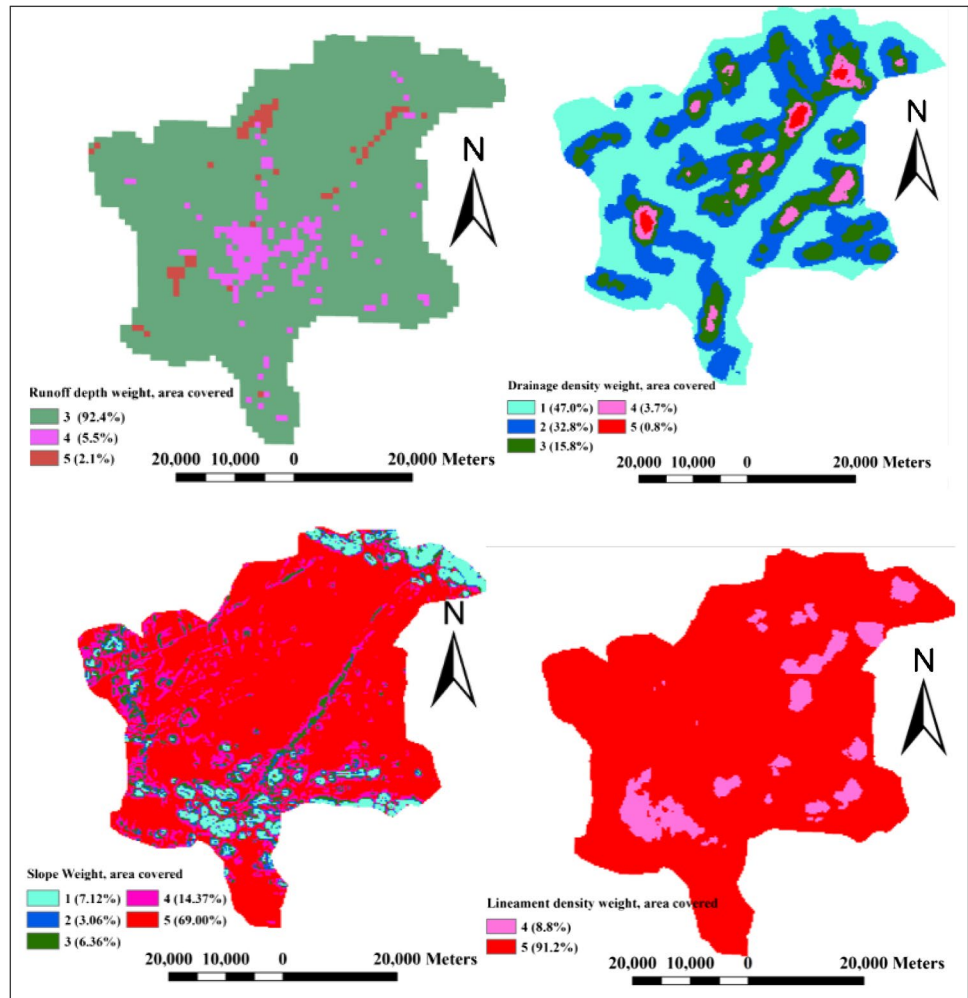


Fig. 13 Stepwise maps of normalized weight for drainage density, lineament density, percentage slope, and surface runoff depth

Table 10 Normalized weights and percentage covered areas for four variables

S/N	Factors	Normalized weight, %	Covered area, %
1	Runoff depth	159	92
		212	6
		265	2
2	Slope	135	69
		108	14
		81	7
		54	3
		27	7
3	Lineament density	30	91
		24	9
4	Drainage density	70	1
		56	4
		42	16
		28	33
		14	47

Table 10 shows the order of the normalized weight and covered area for four factors. Based on the large percentage of covered areas, the runoff depth with the low normalized weight of 159% had a covered area of 92%; slope with the high normalized weight of 135% had the covered area of 69%; lineament density of high normalized weight of 30% had the covered area of 69%; and drainage density with the low normalized weight of 14% had the covered area of 47%.

Potential surface runoff site identification

The four normalized weight maps of runoff depth, percentage slope, lineament density, and drainage density were synthesized with the WLC method using a raster calculator as shown in Fig. 14. Five weighted classes were obtained using natural breaks techniques to classify the potential sites. Most of the area in the north and south constituted a low

percentage of a potential site for harvesting. The suitable area for surface runoff harvesting is placed in the area with a slope of fewer than 2.8° and drainage density greater than 52. The large areas are suitably located in the middle of the study area. Sensitivity analysis was performed to identify the influential variables to the suitability of the RWH site when its weight is relatively changed by a small amount (Sayl, et al. 2020).

The sensitivity analysis was conducted by taking one class of normalized weight for runoff depth variable at a time and generated the potential sites for surface runoff harvesting while using the same values of lineament density, slope, and drainage density. The potential sites for surface runoff harvesting were increased with an increased covered area of runoff depth. Although, the very high suitability of potential sites were identified with a high class of normalized runoff depth. About 5.5% of the covered area was very

Fig. 14 Potential sites identification for RWH harvesting with the normalized weights of lineament density, slope, drainage density and (a) with all three classes of runoff depth, (b) with runoff depth of normalized weight of 159%, (c) with runoff depth of normalized weight of 212%, and (d) with runoff depth of normalized weight of 265%

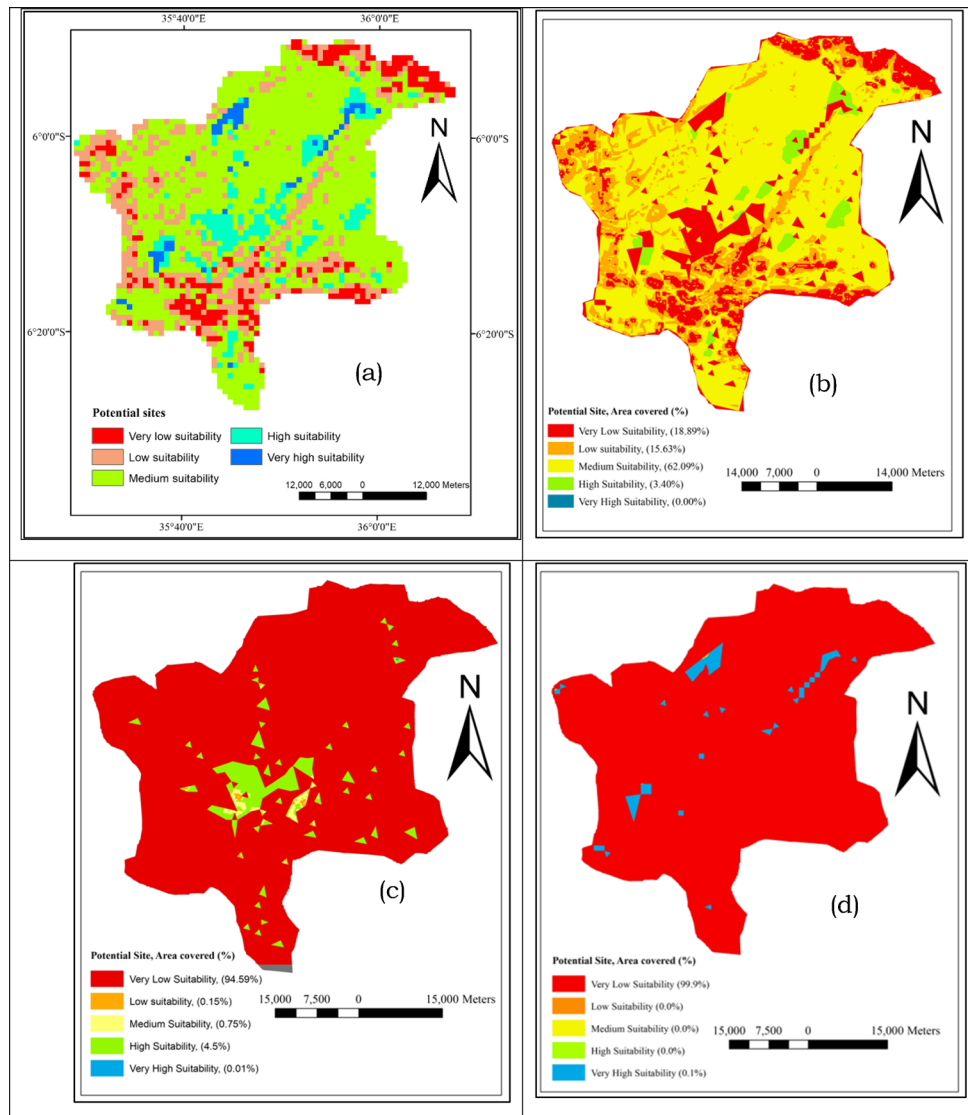


Table 11 Covered area with different suitability classes

Weighted classes, %	Site suitability for surface RWH	Area coverage, %
433–500	Very high suitability	5.5
372–433	High suitability	76.4
325–372	Medium suitability	8.9
271–325	Low suitability	7.5
224–271	Very low suitability	1.7

high suitability sites, followed by 76.4% of the covered area as high suitability as shown in Table 11.

The potential site map was exported and overlaid to the Google Earth map (accessed on March 2021) indicated the number of ponds and major streams intersected with the area of very high and high suitability for harvesting the surface runoff. Figure 15 shows the main streams with the flow directed from Ntyuka and Nala to the Hombolo dam through Makutopora, Mkalama, Nzuguni, Swaswa, and Ng'ong'ona streams and also the main ponds including

Nzige, Matumbulu, Ntyuka, Mkalama, Nala, Kigongwe, Makutopora, and Hombolo.

Surface runoff network and surface area estimation

The surface runoff network and surface area were estimated using triangulated irregular network (TIN) technique. The water surface with the triangular facets used the WLC class interval map as presented in Fig. 16. Each triangle indicates the surface runoff direction and slope gradients for surface runoff potential sites. The percentage of shape area and shape length of each triangle was summarized in Fig. 17. The values of WLC decreased with the slope for different triangles. The flatter of the ground surface consists of small slope values with the less surface runoff; but, the steeper the ground surface consists of the higher slope values that had the high surface runoff. Less than 400 triangles had a slope of greater than 10% and shape area less than 0.04%. The higher slope values are used to define the triangles of highest steepness to collect water in the surface runoff potential sites.

Fig. 15 Existing intermittent streams and ponds near the suitable areas for surface runoff harvesting in Dodoma urban

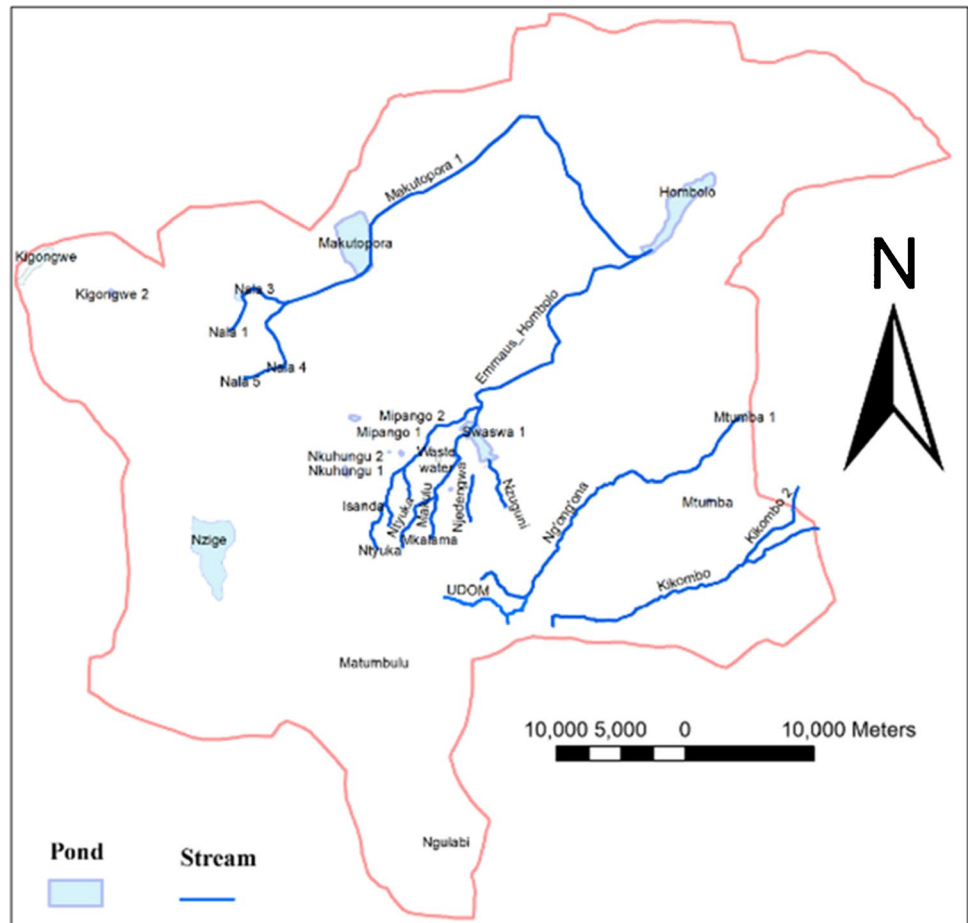


Fig. 16 Surface runoff triangulated network with the WLC class intervals

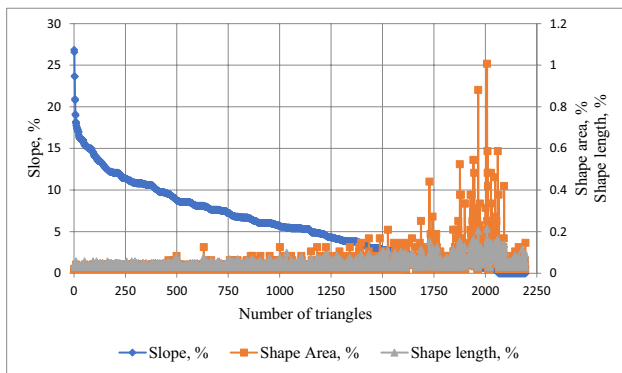
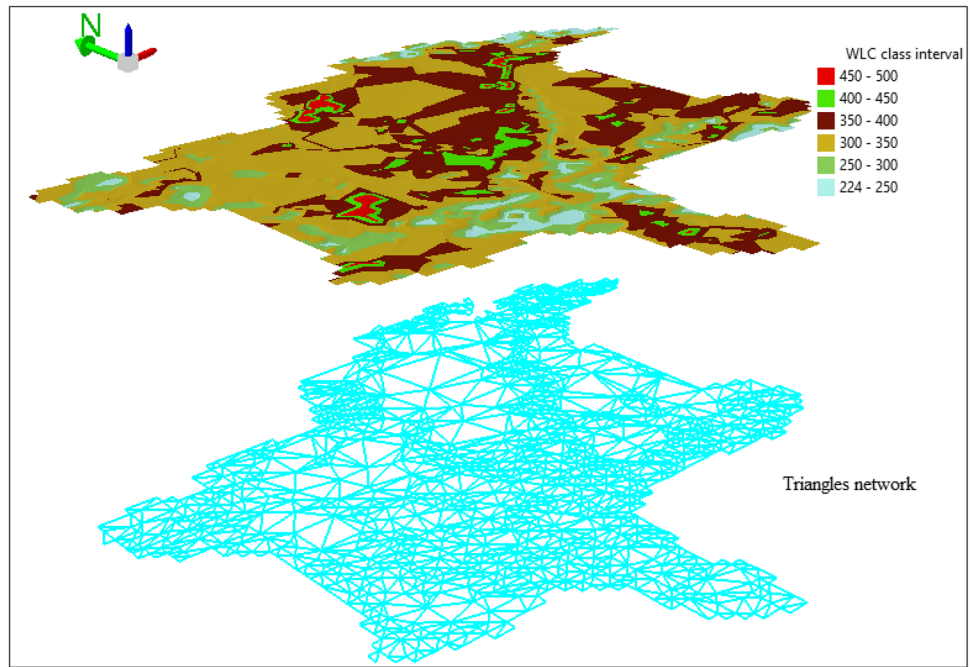


Fig. 17 Variation of triangle polygons with the slope, shape area, and shape length

Conclusion

This study was conducted to identify potential sites for surface runoff harvesting for socioeconomic activities in the Dodoma urban. The Dodoma urban was selected for investigation due to single water source dependence and rapid growth with the increasing water needs for constructions and agriculture activities. Dodoma urban is dominated by agricultural land (58%) and forestry area (33%) with a sand-clay-loam soil texture. Clay content ranging between 18 and 33% makes Dodoma urban suitable for surface runoff harvesting.

In this study, runoff depth, drainage density, lineament density, and the slope were analyzed using AHP in

an ArcGIS environment to identify a suitable location for surface runoff harvesting. The runoff depth was estimated using the SCS method based on the establishing curve numbers using land use, soil, and rainfall data. Runoff depth was the most influential factor in the selection of the site followed by slope, drainage density, and finally the lineament density. About 5.5% of the area showed a very high suitability site and 76.4% high suitability site for surface runoff harvesting. The remaining land portion of about 18.1% showed low to medium suitability for surface runoff harvesting, and most of these places correspond to the region with a high slope. The natural ponds were identified within the study area and corresponding to the identified potential sites for harvesting the surface runoff.

This study addresses a vital supplemental source in the areas of intermittent streams and scarce or unpredictable rainfall intensity. The identified potential map for surface runoff could be harvested in small and medium storage facilities. But historical data is used to classify the land use, rainfall, and soil for runoff depth prediction. The local anomalous features were neglected due to the low resolution of the DEM map when calculated the lineament density, slope, and drainage density; should the current and future changes have a linear corresponding from the past, the suitable areas for surface-runoff harvesting would be significantly different. Subsidy individuals or water authorities could fasten the implementation of surface runoff harvesting. Further studies should set criteria to determine the specific catchments, estimate the quantity of surface runoff harvesting, and conduct economic analysis.

Author contribution The authors contributed to the study conception and design. Material preparation and data collection were conducted by Malugu M. Tembo. The data analysis and first draft of the manuscript were performed by Ombeni J. Mdee and Malugu M. Tembo. Number of comments was addressed to improve the quality of manuscript by authors and reviewers.

Funding The authors acknowledge the financial support from the University of Dodoma through junior academic staff members capacity-building portal year 2020.

Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare that they have no competing interests.

References

- Adham, A., Sayl, K. N., Abed, R., Abdeladhim, M. A., Wesseling, J. G., Riksen, M., ... & Ritsema, C. J. (2018). A GIS-based approach for identifying potential sites for harvesting rainwater in the Western Desert of Iraq. *International Soil and Water Conservation Research*, 6(4), 297–304
- Al-Abadi AM, Shahid S, Ghalib HB, Handhal AM (2017) A GIS-based integrated fuzzy logic and analytic hierarchy process model for assessing water-harvesting zones in Northeastern Maysan Governorate, Iraq. *Arab J Sci Eng* 42(6):2487–2249
- Al-Adamat R, Diabat A, Shatnawi G (2010) Combining GIS with multicriteria decision making for siting water harvesting ponds in Northern Jordan. *J Arid Environ* 74(11):1471–1477
- Al-Ghobari H, Dewidar A, Alataway A (2020) Estimation of surface water runoff for a semi-arid area using RS and GIS-based SCS-CN method. *Water* 12(7):1924
- Al-shabeeb AR (2016) The use of AHP within GIS in selecting potential sites for water harvesting sites in the Azraq Basin—Jordan. *J Geogr Inf Syst* 8(1):73–88
- Ammar A, Riksen M, Ouassar M, Ritsema C (2016) Identification of suitable sites for rainwater harvesting structures in arid and semi-arid regions: a review. *International Soil and Water Conservation Research* 4(2):108–120
- Amutha R, Porchelvan P (2009) Estimation of surface runoff in Malattar sub-watershed using SCS-CN method. *Journal of the Indian Society of Remote Sensing* 37(2):291
- Boughton WC (1989) A review of the USDA SCS curve number method. *Soil Research* 27(3):511–523
- Camarasa-Belmonte AM, Soriano J (2014) Empirical study of extreme rainfall intensity in a semi-arid environment at different time scales. *J Arid Environ* 100:63–71
- Dai, X. (2016). Dam site selection using an integrated method of AHP and GIS for decision making support in Bortala, Northwest China (Master's thesis, University of Twente).
- De Winnaar G, Jewitt GPW, Horan M (2007) A GIS-based approach for identifying potential runoff harvesting sites in the Thukela River basin, South Africa. *Physics and Chemistry of the Earth, Parts a/b/c* 32(15–18):1058–1067
- Du S, Van Rompaey A, Shi P (2015) A dual effect of urban expansion on flood risk in the Pearl River Delta (China) revealed by land-use scenarios and direct runoff simulation. *Nat Hazards* 77(1):111–128
- DUWASA, Dodoma Urban Water Supply and Sanitation Authority. (2019). Supply of clean water. Available from: <https://www.duwaso.go.tz/pages/supply-of-clean-water> [accessed on 24 February 2021].
- Elewa HH, Qaddah AA, Ayman AE (2012) Determining potential sites for runoff water harvesting using remote sensing and geographic information systems-based modeling in Sinai. *Am J Environ Sci* 2012(8):42–55
- Ekwueme BN, Agunwamba JC (2020) Modeling the influence of meteorological variables on runoff in a tropical watershed. *Civil Engineering Journal* 6(12):2344–2351
- FAO (Food Agriculture Organization of the United Nations) (2003). Digital soil map of the world and derived soil properties. Land and Water Development Division.
- Farran MM, Elfeki AM (2020) Evaluation and validity of the antecedent moisture condition (AMC) of Natural Resources Conservation Service-Curve Number (NRCS-CN) procedure in undeveloped arid basins. *Arab J Geosci* 13(6):1–17
- Gajbhiye S (2015) Estimation of surface-runoff using remote sensing and geographical information system. *International Journal of u-and e-Service, Science and Technology* 8(4):113–122
- Garg V, Nikam BR, Thakur PK, Aggarwal SP (2013) Assessment of the effect of slope on runoff potential of a watershed using NRCS-CN method. *International Journal of Hydrology Science and Technology* 3(2):141–159
- Guiamel IA, Lee HS (2020) Watershed modelling of the Mindanao River Basin in the Philippines using the SWAT for water resource management. *Civil Engineering Journal* 6(4):626–648
- Haile G, Suryabhagavan KV (2019) GIS-based approach for identification of potential rainwater harvesting sites in Arsi Zone, Central Ethiopia. *Modeling Earth Systems and Environment* 5(1):353–367
- Hamisi, J. (2013). Study of rainfall trends and variability over Tanzania (Doctoral dissertation).
- Hatibu, N., & Mahoo, H. (1999). Rainwater harvesting technologies for agricultural production: a case for Dodoma, Tanzania. Conservation tillage with animal traction, 161.
- Isioye, O. A. (2012). A multi criteria decision support system (MDSS) for identifying rainwater harvesting site (S) in Zaria, Kaduna state, Nigeria. *International Journal of Advanced Scientific Engineering and Technological Research*, 1(1).
- Jha MK, Chowdary VM, Kulkarni Y, Mal BC (2014) Rainwater harvesting planning using geospatial techniques and multicriteria decision analysis. *Resour Conserv Recycl* 83:96–111
- Kadam AK, Kale SS, Pande NN, Pawar NJ, Sankhua RN (2012) Identifying potential rainwater harvesting sites of a semi-arid, basaltic region of Western India, using SCS-CN method. *Water Resour Manage* 26(9):2537–2554
- Kassile T (2013) Trend analysis of monthly rainfall data in central zone. *J Math Stat* 9(1):1
- Li J, Liu C, Wang Z, Liang K (2015) Two universal runoff yield models: SCS vs. LCM *Journal of Geographical Sciences* 25(3):311–318
- Ligtenberg, J. (2017). Runoff changes due to urbanization: a review.
- Maina, C. W., & Raude, J. M. (2016). Assessing land suitability for rainwater harvesting using geospatial techniques: a case study of Njoro catchment, Kenya. *Applied and Environmental Soil Science*, 2016.
- Mardani A, Jusoh A, Nor K, Khalifah Z, Zakwan N, Valipour A (2015) Multiple criteria decision-making techniques and their applications—a review of the literature from 2000 to 2014. *Economic Research-Ekonomska Istraživanja* 28(1):516–571
- Matomela N, Li T, Ikhumhen HO (2020) Siting of rainwater harvesting potential sites in arid or semi-arid watersheds using GIS-based techniques. *Environmental Processes* 7(2):631–652

- Mugo GM, Odera PA (2019) Site selection for rainwater harvesting structures in Kiambu County-Kenya. *The Egyptian Journal of Remote Sensing and Space Science* 22(2):155–164
- Neilsen, R. D., & Hjelmfelt, A. T. (1998). Hydrologic soil group assignment. *Proceedings of Water Resources Engineering*, 1297–1302.
- Nthuni SM, Lübker T, Schaab G (2014) Modelling the potential of rainwater harvesting in western Kenya using remote sensing and GIS techniques. *South African Journal of Geomatics* 3(3):285–301
- Patil JP, Sarangi A, Singh AK, Ahmad T (2008) Evaluation of modified CN methods for watershed runoff estimation using a GIS-based interface. *Biosys Eng* 100(1):137–146
- Rawat KS, Singh SK (2017) Estimation of surface-runoff from semi-arid ungauged agricultural watershed using SCS-CN method and earth observation data sets. *Water Conservation Science and Engineering* 1(4):233–247
- Saaty TL (2004) Decision making—the analytic hierarchy and network processes (AHP/ANP). *J Syst Sci Syst Eng* 13(1):1–35
- Satheeshkumar S, Venkateswaran S, Kannan R (2017) Rainfall–runoff estimation using SCS–CN and GIS approach in the Pappiredipatti watershed of the Vaniyar sub basin, South India. *Modeling Earth Systems and Environment* 3(1):24
- Sayl, K. N., Muhammad, N. S., & El-Shafie, A. (2019, June). Identification of potential sites for runoff water harvesting. In *Proceedings of the Institution of Civil Engineers-Water Management* (Vol. 172, No. 3, pp. 135–148). Thomas Telford Ltd.
- Sayl K, Adham A, Ritsema C (2020) A GIS-based multicriteria analysis in modeling optimum sites for rainwater harvesting. *Hydrol Earth Syst Sci* 7(3):51
- Shemsanga C, Muzuka ANN, Martz L, Komakech H, Mcharo E (2018) Indigenous knowledge on development and management of shallow dug wells of Dodoma Municipality in Tanzania. *Appl Water Sci* 8(2):1–20
- Shemsanga, C., Muzuka, A. N. N., Martz, L. W., Komakech, H. C., & Omambia, A. N. (2016). Statistics in climate variability, dry spells, and implications for local livelihoods in semi-arid regions of Tanzania: the way forward.
- SHLC (Centre for Sustainable Health and Learning Cities and Neighbourhoods) (Dodoma) (2020) Building a sustainable city to meet neighbourhood needs. [Available from: <http://www.centreforsustainablecities.ac.uk/research/dodoma-building-a-sustainable-city-to-meet-neighbourhood-needs/> [accessed on 6 February 2021].
- Singhai A, Das S, Kadam AK, Shukla J, Bundela D, Kalashetty M (2019) GIS-based multi-criteria approach for identification of rainwater harvesting zones in upper Betwa sub-basin of Madhya Pradesh, India. *Environment, Development Sustainability* 21(2):777–797
- Terêncio DPS, Fernandes LS, Cortes RMV, Pacheco FAL (2017) Improved framework model to allocate optimal rainwater harvesting sites in small watersheds for agro-forestry uses. *J Hydrol* 550:318–330
- URT, The United Republic of Tanzania. (2013). 2012 Population and Housing Census. Population Distribution by Administrative Areas. Dar es Salaam, Tanzania: National Bureau of Statistics
- URT, The United Republic of Tanzania. (2019). Ministry of Lands, Housing and Human Settlements Development. Dodoma National Capital City Master Plan (2019–2039). Dar es Salaam, Tanzania.
- USGS (United States Geological Survey) (2006). The HYDRO1k data for Africa. *Earth Resources Observation and Science (EROS)*: Available from: [<http://edc.usgs.gov/products/elevation/gtopo30/hydro/africa.html>]; 2006 [accessed on December 2012].
- USGS (United States Geological Survey). Science for a changing world [Available from: <https://earthexplorer.usgs.gov> [accessed on 23 December 2020].
- Uwizeyimana D, Mureithi SM, Mvuyekure SM, Karuku G, Kironchi G (2019) Modelling surface-runoff using the soil conservation service-curve number method in a drought prone agro-ecological zone in Rwanda. *International Soil and Water Conservation Research* 7(1):9–17
- Vikneswaran, M., & Razak, M. A. Study on surface-runoff harvesting for sustainable UPNM campus. *Int J Appl Eng Res* 10 (95) 2015.
- WB (World-Bank) (2017). Dodoma (Tanzania) - Land Use/Land Cover Maps (ESA EO4SD-Urban) [updated 2018. Available from: <https://datacatalog.worldbank.org/dataset/dodoma-tanzania-land-useland-cover-maps-esa-eo4sd-urban>. [accessed on 14 November 2020].
- WB (The World Bank) (2019). Tanzania Water Security for Growth (P168238). Available from: <http://documents1.worldbank.org/curated/en/914081568201887071/pdf/Concept-Project-Information-Document-PID-Tanzania-Water-Security-for-Growth-P168238.pdf> [accessed on 23 March 2021]
- Weerasinghe H, Schneider UA, Loew A (2011) Water harvest and storage-location assessment model using GIS and remote sensing. *Hydrology and Earth System Sciences Discussions* 8(2):3353–3381
- Wu RS, Molina GLL, Hussain F (2018) Optimal sites identification for rainwater harvesting in northeastern Guatemala by analytical hierarchy process. *Water Resour Manage* 32(12):4139–4153
- Zaki SR, Redwan M, Masoud AM, Moneim AAA (2019) Chemical characteristics and assessment of groundwater quality in Halayieb area, southeastern part of the Eastern Desert. *Egypt Geosciences Journal* 23(1):149–164
- Zhang, H., Sekhari, A., Ouzrout, Y., & Bouras, A. (2014). Optimal inconsistency repairing of pairwise comparison matrices using integrated linear programming and eigenvector methods. *Mathematical Problems in Engineering*, 2014.