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A STUDY OF RAINWATER HARVESTING PRACTICE IN SEMI-ARID AREAS IN THE DODOMA REGION, TANZANIA: PLANNING PHASE

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ABSTRACT

Basins offer potential source points to collect runoff water during rainfall, especially in areas that are associated with highly variable rainfall and long dry periods. The Dodoma region is surrounded by hills and valleys, which offers an efficient and reliable water harvesting opportunity. This study identifies seven (7) potential basins with seventy-nine (79) pour points for sub-basin development by using topography and river network maps created from the ArcGIS software application. Each of the basin's features were analysed based on the drainage area, which included the minimum, mean and maximum elevations, and soil type. However, when rainfall was analysed, it indicated a break during the rainy season that resulted in a long dry period. This study uses Google Earth to validate identified pour points and results indicated the possibility of conducting site visits for further implementation of the sub-basins. Therefore, the study presents the possibility of harvesting rainwater in semi-arid areas, which could be used for agriculture activities and by local communities around the basin.

Keywords: rainwater harvesting, semi-arid area, sub-basin, topography.

1. INTRODUCTION

Methods of rain water harvesting have been developing since ancient times, and the practice of rain water collection is one of the best possible ways to conserve water and educate society about the importance of water (Mati et al., 2005). The semi-arid zones of Africa are subject to flooding during the rainy season and a long dry period, providing an opportunity for the practice of rainwater harvesting. During the rainy season, a great deal of water goes to waste, eventually reaching lakes or the ocean through trenches and rivers, which results in farmers and local communities complaining about the lack of water. The practice of rain water harvesting is the collection of water through the use of scientific techniques and from the areas where the rain falls to a storing point (URT, 2002; Nyamadzawo *et al*., 2013). In regard to different functions, harvested rainwater can be used for agriculture activities, livestock, fisheries, or soil and water conservation (ACPC, 2011). There is growing interest in the large range of low-cost agricultural water management technologies, especially in semi-arid areas of developing countries because the unreliable water supply threatens the availability of water for crops (Merrey *et al*.,2006). Still, approximately 69 % of southern African land occurs where permanent rivers are few and far apart (Mati et al., 2005). However, other South African countries report the use of water management technologies, such as pumping, the use of boreholes, construction of river diversion weirs and use of conservation agricultural technologies, such as mulching, the use of infiltration ditches, and strip farming, to enhance agricultural development and eventually ensure food security (IWMI, 2006).

More than 50 % of the agricultural land in Tanzania falls under semi-arid areas and receives less than 750 mm of rainfall annually, which include areas of Dodoma, Tabora, Shinyanga, Arusha, Manyara and Singida (Senkondo *et al*.,1998; Hatibu, 1999). In Tanzania, rainwater can pass through valleys, gullies, and ephemeral rivers and may be harvested using a number of techniques including in situ, farm ponds or ponds, building roofs, and surface and sub-surface dams. However, basins or ponds are particularly popular in rural and urban areas, as this technique can be cost-effective using local materials and labour, which water storage capacity ranges from 5,000 to 50,000 m^3 (ACPC, 2011; Bake, 1993). Water storage in ponds requires a pump and pipes or trenches to direct water into the farms or fetching water for domestic purposes. However, farmers make excavated bunded basins "majaluba", semi-circular or simply ploughed land, which may hold rainwater. Crops utilize this water during long dry periods, which affect only a small part of the farm.

Drought in semi-arid zones indicates a prolonged period without a considerable amount of rainfall that hinders plant growth (ACPC, 2011). In the Dodoma region, agriculture activities often encounter an amount of rainfall that is much lower than that in a normal year, and hence, plants do not get enough water to cover the atmospheric demand throughout the growing period, or there is enough water for early plantation but later stages are exposed to a soil water deficit (ATPS, 2013). In a different scenario, the total amount of rainfall is comparable to normal years, but plants are exposed to stress at some stage of growth because of irregular or uneven rainfall distribution. However, it is possible to control the situation by identifying different numbers of sub-basins for rainwater collection. Therefore, this paper provides a planning phase stage of identifying sub-basins/ponds with proposed design and pour points/outlets as one of the simplest and least expensive techniques in

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the areas that are characterized with hills and valleys would be beneficial, especially in the Dodoma region, to harvest rainwater and utilize it during extended dry periods of the wet season.

2. MATERIALS AND METHODS

2.1 Description of the study

The Dodoma region is located in the centre of Tanzania, which is exposed to a semi-arid climate at 6°48' South latitude and 39°17' East longitude and has an average altitude of 1125 metres above sea level. Dodoma has been Tanzania's capital since the 1970's and is the place of the Union Parliament. The Dodoma region is divided into five administrative areas, including Dodoma rural, Dodoma urban, Kondoa, Mpwapwa and Kongwa districts, as indicated in Figure-1.

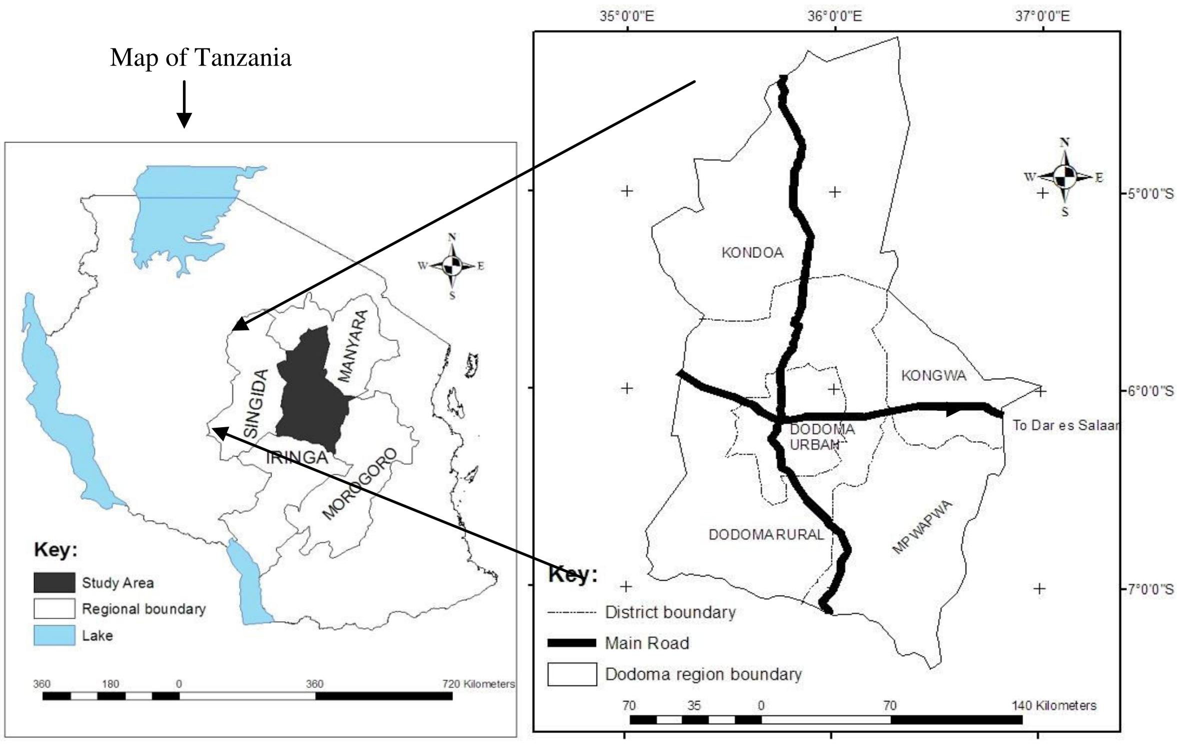

Figure-1. Location of the study area.

It has an approximate population of 2,083,588 people with the percentage distribution of 2.1 in 2012 census counts within a coverage area of 41,311 km^2. The estimated total number of households is 453,844 with an average household size of 4.6 people. Inhabitants mostly depend on agriculture crops such as grapes, sorghum, groundnut, millet, castor oil seeds and maize crops (URT, 2013). The soil types are characterized by a variety of textures, ranging from coarse sands to heavy clays. Acidic clay soils with low soil permeability are widespread in most areas of the Dodoma region, which has a high water table (approximately 1 metre below ground level), especially during the rainy season (De Pauw *et al*., 1983), which supports the use of the basins for the practice of water harvesting and makes it overall more significant.

The main drainage channels are usually dry throughout the year, except during rainfall when rivers collect most of the runoff from the hills and store it in the sandy river beds. These river beads have shallow and poor vegetative cover with a number of gullies or the water drains into swamps where it evaporates or feeds groundwater reservoirs. The main natural vegetation types that are recognized in the study area include woodland - a stand of trees, up to 18 m in height with open or continuous branching but not thickly interlocked; bush land - an assemblage of woody plants, mostly of shrub habitat, with a shrub canopy of more than 2 m but less than 6 m in height; grassland - land dominated by grasses, sometimes with widely scattered or grouped trees and shrubs; and permanent swamp vegetation - various plants by communities associated with permanent standing water such as aquatic grass species, trees or shrubs.

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2.2 Nature and data type

The data used in this study includes land use, rainfall, soil and topography maps. The nature and data types are presented in Table-1. Land use was identified based on activities conducted on the land such as agriculture, grazing, deforestation, small scale mining, buildings or roads. Oldeman *et al*. (1991) developed the Global Assessment of Soil Degradation (GLASOD), which indicates global land use. The rainfall data from 1999 to 2010 were collected from the Tanzania Meteorological Agency (TMA) to analyse the rainfall situation. However the author believes the rainfall data trend can be possible presented by the bundle of data for many years, but there is difficultness to obtain the data and this study serves only planning phase situation. The soil features were determined based on the available online Food and Agricultural Organization (FAO) soil map of Africa acquired from global data sets that were used under ArcGIS to clip the study area soil textures. Lastly, the Digital Elevation Model (DEM) of Africa acquired from global data sets that are available online from USGS was used under the ArcGIS 9.3 software to analyse the topographic features of the study area.

Table-1. Data types, sources and format.

S/N	Data Type/Spatial map	Source	Data format	Pixel size
1	Land use	GLASOD	Features/string	-
2	Rainfall	TMA	Image	-
3	Soil features	FAO	Raster	1 km
4	Topography	USGS	Raster	90 m

The study also indicates the available rain gauge stations, which were used to measure the rainfall around the constructed dams and remaining part of the study area as presented in Figure-2. The dams were constructed in the 1930s to 1950s for the purpose of harvesting runoff to control flooding or used for domestic livestock and domestic purposes. The geographic locations of the existing dams were adopted from Husebye and Torblaa (1995).

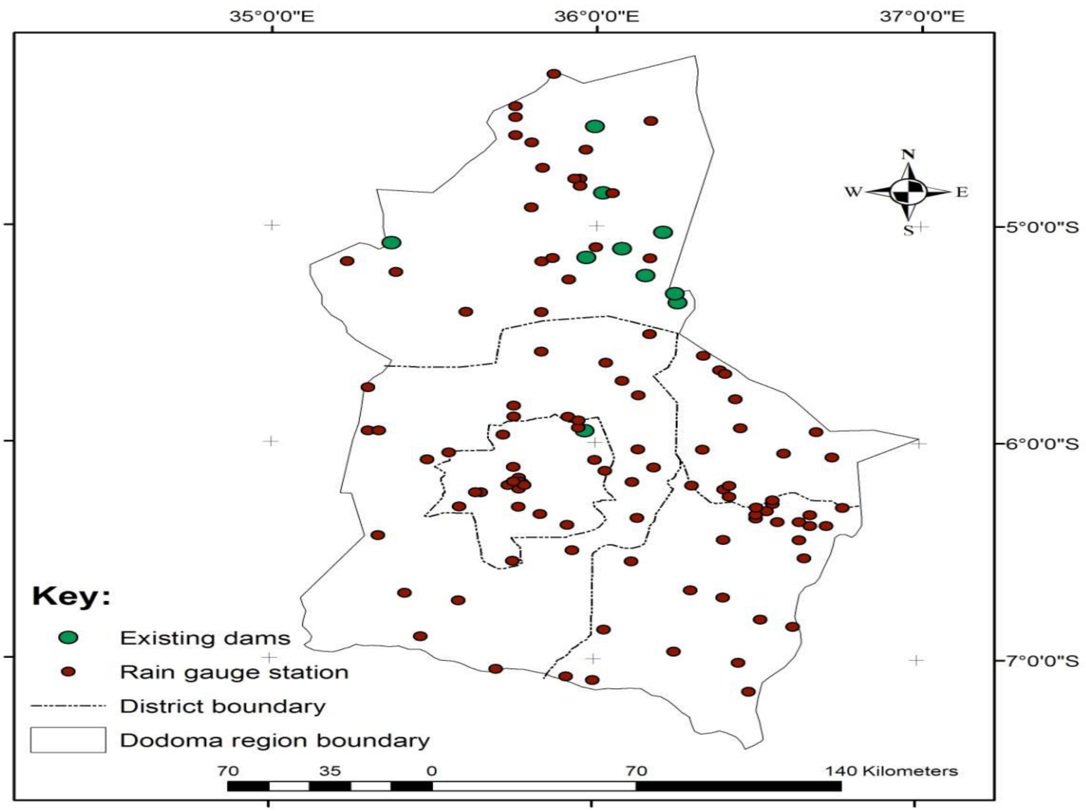

Figure-2. Rain gauge stations with constructed dams.

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2.3 Data analysis

A catchment or basin is a land area from which all rainfall would drain by gravity into a common outlet point (Mahoo *et al.,* 2000; GIS, 2008). The basin area collects runoff, which can be stored as rain water in sub-basins. The procedure first started by developing the basins within the study area using the hydrology tool in ArcGIS 9.3 software and through generation of a flow direction and accommulation raster maps and delineation basins with a specific pour point. The basins were used to provide the boundary and maximum points of contribution of the rainfall to the specific area. Secondly, each basin was used to generated sub-basins by generating both flow direction and flow accommulation raster mpas. However the occurance of topography features, i.e., contour map and river network / drainage maps is used to develop sub-basins. Generally sub-basin identification can be obtained during site visiting by applying the following procedures;

- Identify the lowest and highest elevation values.
- Analyse the behaviour of the contour lines, i.e., landscapes with a gently sloping or flat areas result in contour lines that must be spaced far apart; when the landscape has steep areas or dramatic changes in the rise and fall, the contour lines are spaced very close together. A depressed area or valley is represented by a series of contour lines “pointing” towards the highest elevation. A higher area or hill is represented by a series of contour lines “pointing” towards the lowest elevation.
- Align arrow perpendicular to a series of contour lines that decrease in elevation to determine the direction of the drainage, i.e., any drop of runoff seeks the path of least resistance and travels downward. The path is the shortest distance between contours and hence a perpendicular route.
- Mark different points at the middle of the highest elevation, which causes half of the runoff to drain towards one side and other half to drain towards another side of the drainage area
- Connect the marked points with a line to complete the boundary of the sub-basins to determine the total drainage area at a given pour point.

However, the model presented in Figure-3 summarizes the process of sub-basins development, which can be used to harvest rainwater. The development of sub-basins can be constructed locally based on the establishment of the different pour points.

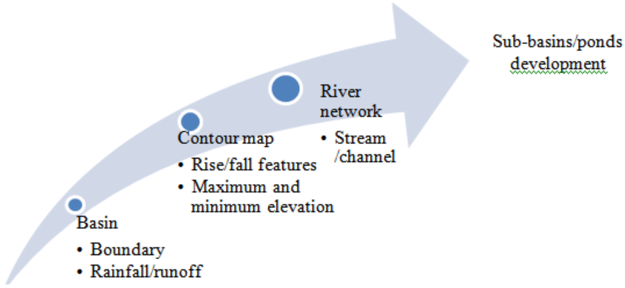

Figure-3. The development of sub-basins/ponds.

2.3.1 Dry sub-basin design

The design of a dry sub-basin should consider engineering constraints and design parameters to achieve the required storage capacity and existing topography (ASCE, 1998). Pond design parameters include water volume, depth, drainage surface area, detention period and cost. It is recommended that the horizontal to vertical length ratio or side slope should be 3 to 1 or greater to facilitate sedimentation processes and decrease the possibility of short-circuiting (ASCE, 1998). The contour profile is critical to the design of a pond and to determine available storage and the movement of water through the pond. Proper location of land mass during sub-basin construction can be used to manipulate flow characteristics, which can increase the distance that water travels and help segregate first flush inflow from later flows within a storm event (EPA, 1999).

The most important concern of rain water management confinement and the creation of retention ponds is safety. Clay or any material with binding properties are supposed to be well compacted to the floor and wall sides of the sub-basins by the use of compact machine. A failure to act in some situations may cause structural failure. Inspections must be made, at least annually, to ensure the safety of rainwater ponds and includes frequent removal of floating debris and accumulated petroleum products, maintenance of outlet structures and vegetation mowing and control. Outlet spillways can be located at a place on the top surface and range from 3 to 15 m wide or wider with typical pipe diameter ranging from 10 cm to 75 cm (Brater and King, 1976; ASCE, 1998). Researchers report that the main factors causing small sub-basin to be highly expensive compared to large sub-basins is the earthmoving cost, while associated costs such as clearing, site preparation, pipe, concrete, and seeding and mulching are often only incidental or normal (ASCE, 1998). The labour and equipment rental are dependent on the type of basin desired, but additional materials may be needed and are often unavoidable costs such as clay material for compacting the floor and sides and a trash rack for removing suspended debris. According to Hyde (1998), small sub-basins are generally constructed at a cost range from $10,000 to $20,000 per acre and larger sub-basins ranged from $1,000 to $5,000 per acre. Therefore, this

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study proposed the geometry of a trapezoidal excavated shape of the sub-basin, which can be easily constructed with reasonable cost, and the water volume was estimated by using Equation 1 (Brater and King, 1976; Chow, 1959). Based on the knowledge and skills of the author after researching the available cited material, the geometry of a trapezoidal excavated shape of the sub-basin was designed by using AutoCAD 2007 (Figure-4) with the plan view and section view presented in Figure-4.

$$V=\frac{(A_b+A_t)*H}{2}=\frac{[(L_tW_t+L_bW_b)]}{2} \quad (1)$$

A_t = water surface area at the design depth, m^2; A_b = bottom surface area, m^2; H = design depth, m; L_t and W_t= basin top length and width, m; L_b and W_b= basin bottom length and width, m.

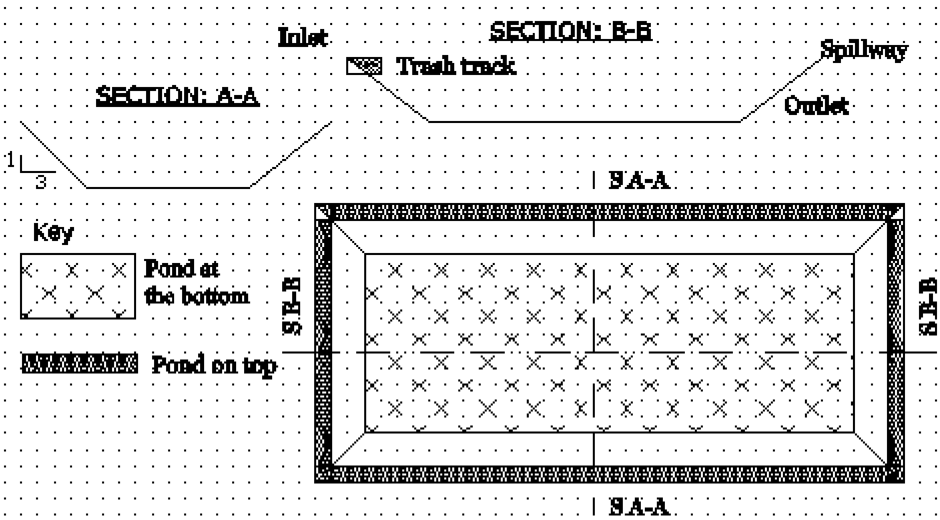

Figure-4. Proposed sub-basin/pond design.

Determination of the capacity of rainwater harvested (C) within a sub-basin/pond depends on the soil excavation (S), seepage and evaporation losses, non-usable water (dead storage) and number of ponds (N) and presented in Equation 2.

$$C=\frac{S*N}{1+\alpha} \quad (2)$$

Whereby α is equal to the water losses and dead storage.

The distribution of ponds is mostly influenced by the community pattern in the area and the number of suitable sites for economic development. However the water balance of a pond is presented in Equation 3 to express a rainfall falling directly into a pond (P), runoff harvested (R), seepage/infiltration and evaporation losses (B), consumption in agriculture and household activities (A) and rainwater storage remain in the pond (Marsh and Woo, 1972).

Storage remain = (P + R) - B - A (3)

3. RESULTS AND DISCUSSIONS

Globally, the high variability of rainfall in semi-arid areas leads to communities relying on indigenous knowledge for harvesting rain water. Rather than collect water within the settlements, the communities can start by preventing runoff and promoting infiltration of the rain falling directly on the field or collect into sub-basins. The rain situation in the study area is characterized by short-term rainfall with high variability from place to place (Njau*et al.,* 2014). In the Dodoma region, rain begins in late October and continues until early May with the seasonal maximum rainfall occurring from December to January, while only a negligible amount of rainfall is observed between June and October, as indicated in Figure 5. The annual rainfall and monthly rainfall were examined from 1999 to 2010, and the data support this observation. According to Kassile (2013), there is no statistically significance evidence for the variability of rainfall data in the Dodoma region from 1980 to 2010 with an average temperature of 22.6 °C per year. Nevertheless, there is a variation in the distribution of rainfall for both short and long rainy seasons. The highest rainfall amount was 790 mm in 2009 and the lowest was 318 mm in 2010 with annually average of 581.6 mm.

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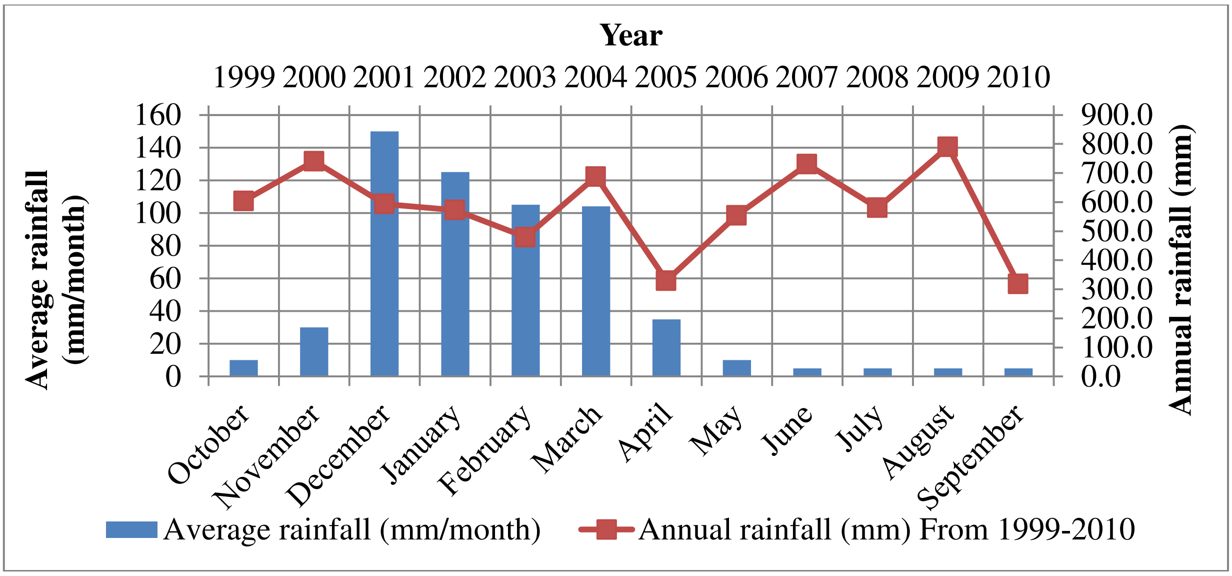

Figure-5. Variation of rainfall in the Dodoma region.

3.1 Sub-basin development

There are many operational meteorological satellites and rain gauges that can be used for monitoring precipitation, i.e., rainfall and snow over different parts of the globe. The meteorological satellites have different spatial and temporal resolutions to provide a stream of valuable rainfall data. However, the occurrence of rain gauges provides rainfall data more easily and timely, especially in the local environment which communities lack skills and knowledge of meteorological satellites operation. The rain gauges of the study area are presented in Figure-2,which can be used within the basins. The rain gauge stations often experience improper maintenance and road accessibility. Tanzania receives a reasonable amount of rainfall, which is susceptible to land degradation and results in refilling the existing construction of dams and mainly affects the semi-arid areas (Darkoh, 1982). The average annual rainfall of 581.6 mm can offer reasonable amount of runoff to be stored at the sub-basins. According to Reynard *et al*. (1997), analyzed the amount of annual runoff in the southern Africa part by using Probability Distribution Model and the author observed 117 mm/year at north east part, 17 mm/year to the west side and 754 mm/year to the south side part respectively from Dodoma urban district after map intepretation.

This study identified seven (7) basins using the hydrology package in ArcGIS software as discussed in section 2.3 and presented in Figure-6. The geographical locations of the identified basins indicated that they are within the drainage line where there is a possibility of runoff to be collected. The slope direction was analysed using a spatial analyst tool under ArcGIS 9.3. The slope is measured clockwise in degrees from 0° to 360°, and the value of each cell in an aspect dataset indicates the direction that the cell's slope faces for the water drainage network.

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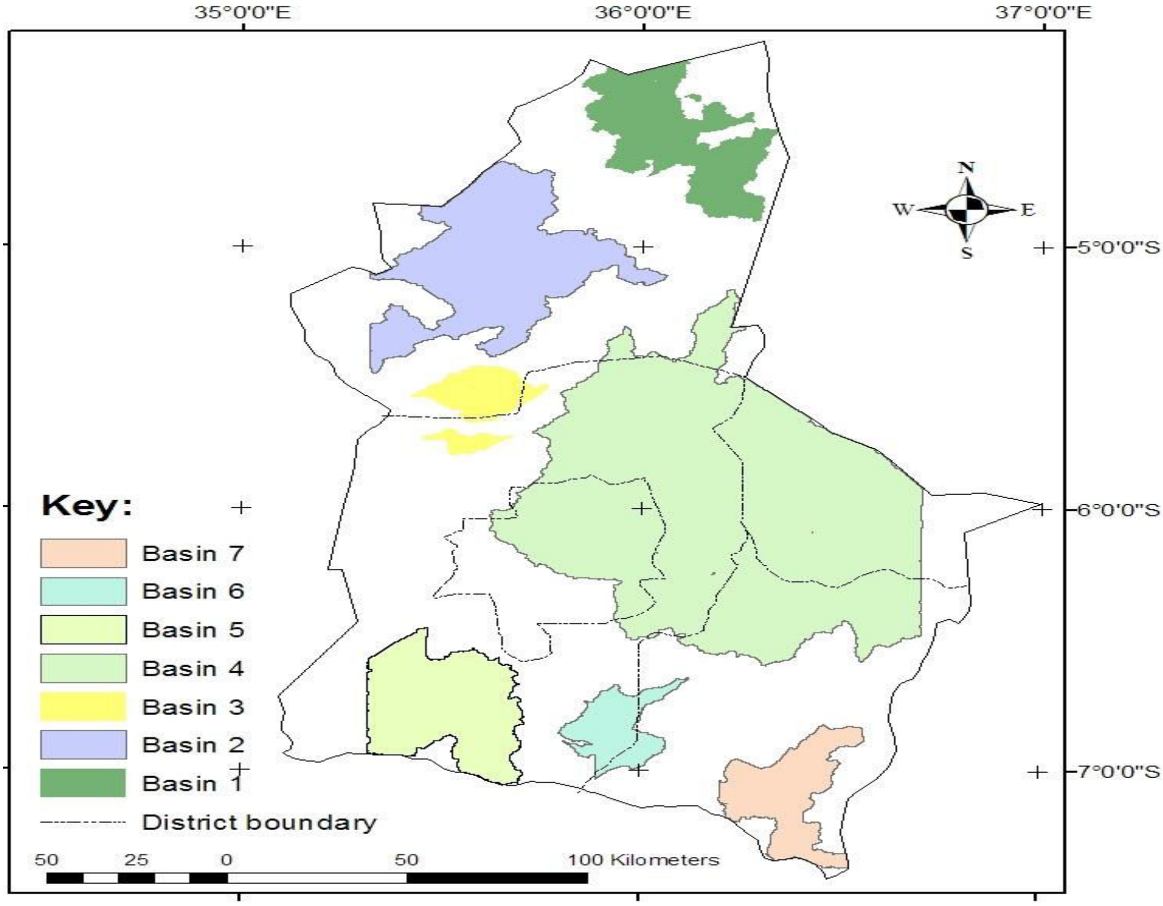

Figure-6. Study area basins.

An independent analysis of the 7 basins, as supported by Figure-7, suggests that basin terrain characteristics might partially explain the performance of basin creation for the practice of rain water harvest. For the basins, an increase of a few metres in the ground height, results in a larger gain in the area coverage with rapid changes and increases in the 0 to 10 and 90 to 100 percent of the coverage area. The largest percentage coverage area occurred in basin 1 to basin 7 at 1121, 1134, 997, 1002, 936, 705, 546 m above mean sea levels, is 4.8, 0.6, 3.4, 0.4, 17, 26.6, and 0.7 respectively. Another notable observation is that basin number 7, terrain is much steeper compared with other basins with less than half of the basin area characterized as flat land.

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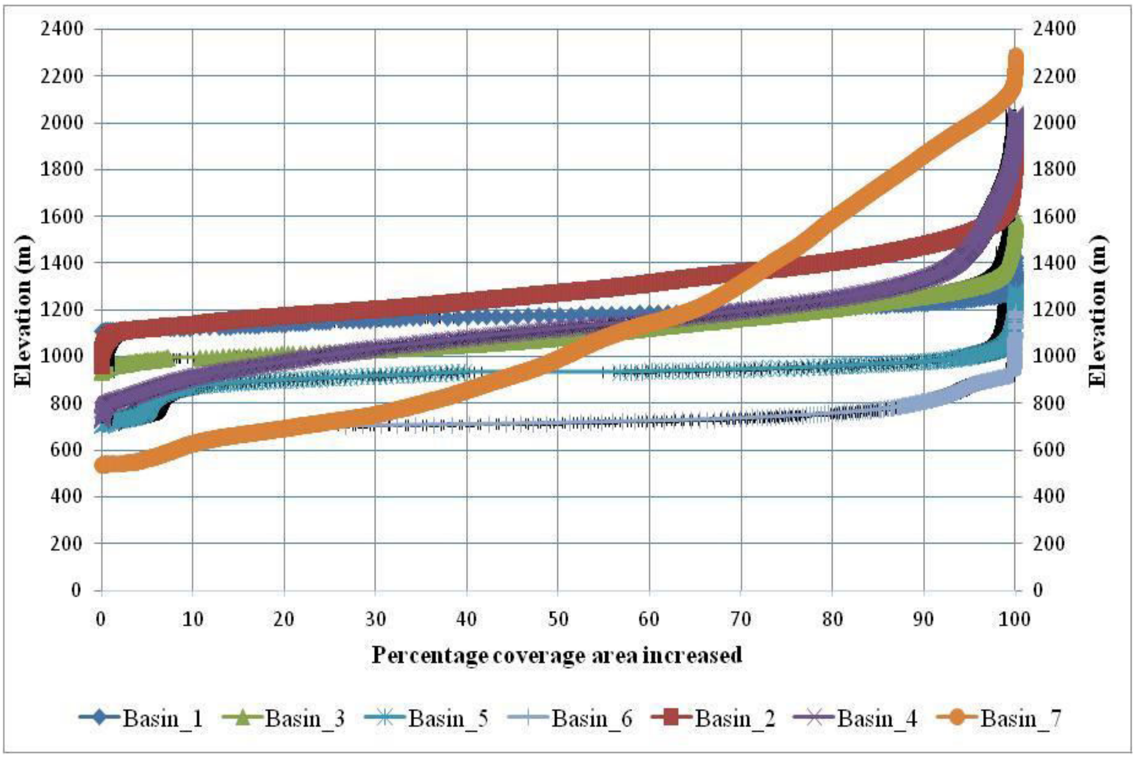

Figure-7. Distribution of ground elevation with respect to an increased percentage of coverage area.

However, the basins, contour map and drainage lines were manually integrated to identify the outlet of the sub-basins as explained in section 2.3. The pour points can be used to guide farmers where to locate sub-basins for the practice of rain water harvesting. The development of sub-basins, commonly known as the micro-catchment technique, is a long tradition of harvesting rainwater in semi-arid regions with a size range of 10 to 100 m^2 and is surrounded by an earth material approximately 0.3 to 0.4 m high (Hatibu *et al*., 2000). Therefore, Table-2 indicates the geographical locations for potential sub-basins, which can be easily utilized for agricultural activities and by local communities. Oldeman *et al.* (1991) identified agriculture, overgrazing and deforestation activities as one of the main land uses within the study area.

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Table-2. Pour points of sub-basins for the practice of rainwater harvesting.

Basin ID number	Pour point		Basin ID number	Pour point	
	X	Y		X	Y
1	36.0818	-4.4784	4	36.0291	-6.1620
	35.9135	-4.5270		36.1841	-6.0970
	35.9743	-4.5632		36.1075	-6.0237
	35.9731	-4.5994		35.9175	-5.9987
	35.9187	-4.4461		35.8508	-6.0829
	36.0650	-4.5254		35.7775	-5.9462
	36.1016	-4.6237		35.8525	-5.9029
	36.1233	-4.6579		36.2775	-6.0512
	36.2200	-4.8545		36.2475	-5.9945
	35.9616	-5.0379		36.2116	-5.8729
	35.7616	-5.1962		36.1566	-5.8262
2	35.7100	-5.0454		36.0858	-5.6920
	35.7083	-4.9737		36.0241	-5.6220
	35.7266	-4.9095		35.8875	-5.4787
	35.7233	-4.7204		36.0716	-5.3795
	35.6983	-4.6779		36.0041	-5.4212
	35.7400	-4.9412		36.0283	-5.5420
	35.8383	-5.1062		36.2150	-5.6987
	35.7558	-5.2020		36.3900	-5.9062
	35.6100	-5.2854		36.4366	-6.1520
	35.6016	-5.2137		36.5391	-6.1779
	35.5658	-5.2270		36.5925	-6.1420
	35.4466	-5.1287		36.6258	-6.0337
	35.5266	-5.2420		36.5808	-6.5395
	35.6041	-5.2929	5	35.4650	-6.5687
	35.7116	-5.3295		35.3758	-6.7587
	35.5375	-5.3604		35.3558	-6.8087
	35.3341	-5.4854		35.4383	-6.8637
3	35.5608	-5.6704		35.4408	-6.9304
	35.5500	-5.7229	6	35.6875	-7.0504
	35.4508	-5.7395		35.8800	-6.9029
	35.4241	-5.5745		35.9908	-6.8479
4	36.3300	-6.3604		35.8900	-7.0362
	36.1116	-6.3962		35.9650	-6.7145
	36.1966	-6.4420	7	36.2200	-7.1262
	36.2958	-6.2895		36.2550	-7.1912
	36.3300	-6.2104		36.4825	-7.3729
	36.3000	-6.1604		36.5425	-6.5220
	36.2416	-6.1479		36.4916	-6.4887
	36.1533	-6.2154		36.4500	-6.4745

Basically possible deep percolation is high when the soil is wet and rapidly decreases when the rate of dry soil increases. This study assumed a simple constant value for deep percolation based on the permeability rate (mm/hr) for different types of soil textures and used the soil textures obtained in the identified basins (Table-3), which had heavy clay soil textures with a permeability rate of less than 2.5 mm/hour to sandy loam with a maximum rate of 120 mm/hour (FAO, 1995).

Table-3. Soil characteristics within the identified basins.

Basin ID	**Elevation** (m)			**Coverage area** (km^2)	**Soil texture**
	Min	**Mean**	**Max**		
Basin 1	1110	1181	1452	1807	Sandy loam, sandy clay loam and loam at a percentage of 6.6 %, 92.9 % and 0.5 %, respectively
Basin 2	963	1296	1898	3064	91.8 % is covered with sandy loam and 8.2 % with sandy clay loam textures
Basin 3	936	1111	1605	633	80.6 % is covered with sandy loam and 19.4 % is only covered with sandy clay loam
Basin 4	732	1132	2044	1094	42.4 % is covered with clay loam, 39.2 % is covered with sandy clay loam, 16.3 % is covered with loam and 2.1 % covered with sandy loam
Basin 5	710	928	1290	1918	79.3 % is covered with sandy clay loam,10.4 % and 10.3 % is covered by clay loam and loam, respectively
Basin 6	705	740	1199	657	99.3 % is covered with sandy clay loam and 0.7 % with loam
Basin 7	537	1117	2289	1119	100 % covered with loam

The pour points were again validated with Google Earth to identify the potential of sub-basin establishment, which indicated a high potential when observing the upper part, left side and bottom part of the study area. However, the right side was determined to have only temporal flows and few streams start at the centre to the South East.Still, the pour points that are within the identified basins were overlaid with drainage lines and elevation data (Figure-8). Result indicates a higher potential for harvesting rain water both on land and stream networks. This study was supported by a research study conducted in the Nakuru district using GIS techniques that located 908 runoff ponds or sub-basins (Mati *et al.*, 2005). Therefore, the proposed sub-basin design in Figure-4 can hold 3,037 m^3, which is the greater than 90 % of the volume needed for collecting runoff using Equation 1 with a width and length of 15 m and 45 m at the bottom and 45 m and 135 m on top of the sub-basin, respectively and application assumption is presented in section 2.3.

However the author acknowledge the consideration of the location, catchment size, run-off coefficient, seepage/infiltration and evaporation can possible reduce the collection of volume of rainwater. Equation 2 can be used for determine the capacity of water storage when the farmer/community manage to remove the volume of soil or measure the area of the valley identified. Still the water storage can be estimated by using water balance summarized in Equation 3. According to Senkondo *et al.* (2004), the rain water harvesting technique increases production for the farmers.

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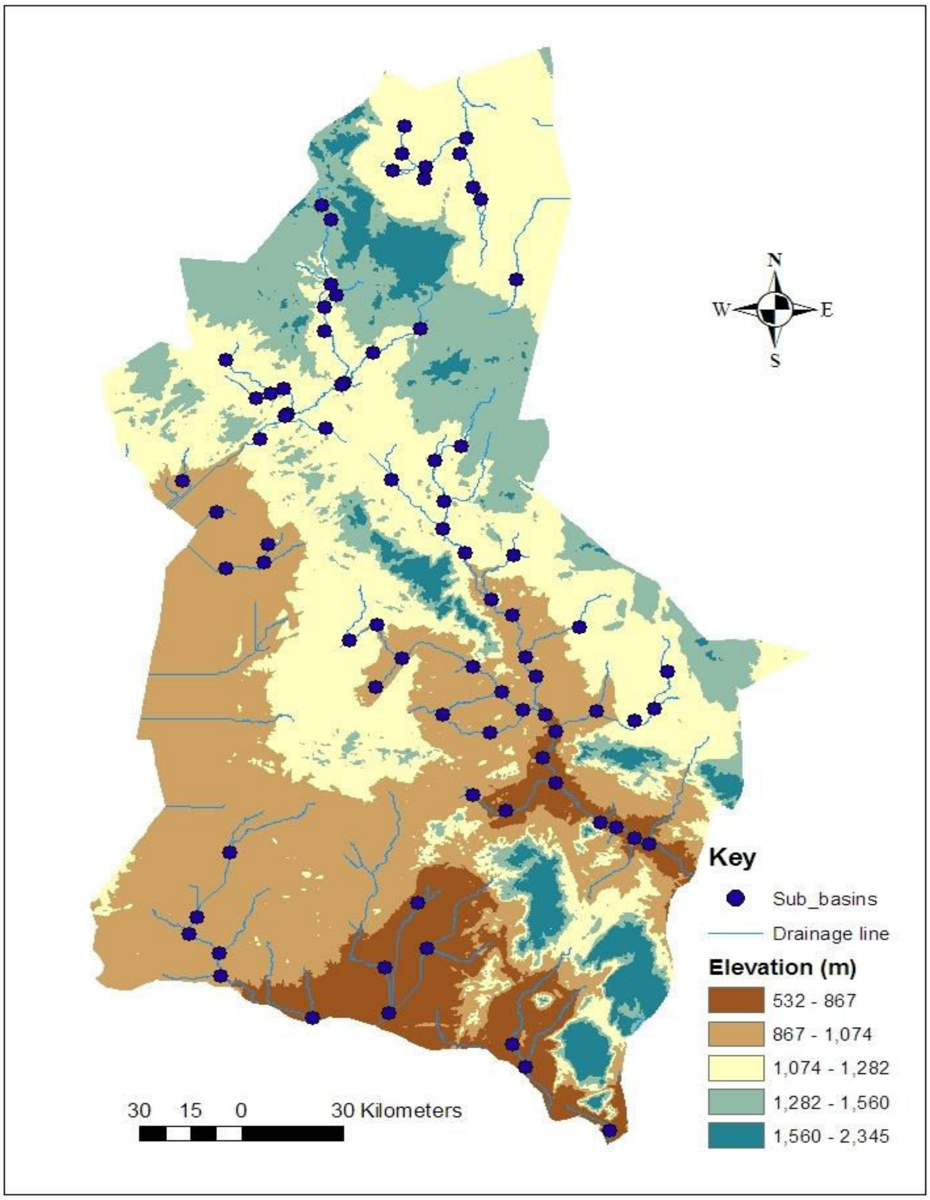

Figure-8. A map of the pour points, drainage lines and elevation data.

4. CONCLUSIONS AND RECOMMENDATIONS

ArcGIS software is globally applied to explore untapped water, especially in the African continent. However, due to the local anomalies, a different number of studies within each local area should be conducted to investigate potential untapped rainwater. Therefore, this study identified 79 potential pour points to establish sub-basins for agriculture and household applications. The author believes that it is necessary to collect and store rainwater to meet the water needs in the preceding dry period, especially in the Dodoma region, which is characterized by semi-arid climate conditions. In addition, the runoff response during rainfall is very rapid, and the water often flows as a flood and proceeds to unwanted areas. This study recommends the development of sub-basins within the plantation areas to fill the gap of long dry periods between the first and the second occurrence of rainfall. Furthermore, the sub-basin design can provide a benchmark for decision making during planning phase; however, it requires further study including site visitation and more engineering before implementation.

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