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Investigation on Rooftop Rainwater Harvesting Potential and Roof Catchment Area Measurement Techniques in Addis Ababa, Ethiopia

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Abstract
This study was conducted by aiming quantification of the potential of rooftop rainwater harvesting (RT-RWH) in general and (1) comparing alternative methodologies for measuring roof catchment areas, (2) analyzing demand-supply gap between harvested rainwater and toilet flushing water demand in particular for the study area. A comparison was made between the roof catchment area measurement techniques such as; Google Earth (GE), Master Plan and field survey. The coefficient of determination (R^2) was used as a comparison tool for deciding which measurement techniques are better, so as to recommend for accurate usages for practical purposes for roof catchments areas measurements. Hence, R^2 values of field measurement versus Master Plan, field measurement versus GE, and Master Plan versus GE were found to be 0.997, 0.959 and 0.971 respectively. In the meantime, it was proved that measuring roof catchment areas by the Master Plan is better than GE for the case of this study area. In addition to this, the water harvesting potential of the study area was estimated and compared with the toilet flushing water demand (which accounts for the major portions of domestic water demand of the study area). The annually harvested rainwater of the study area was estimated to be 1**25,172m^3** and the respective annual toilet flushing water demand was **6,090,314m^3**. This result showed that **18.13%** of water consumption of toilet flushing of the study area could be covered by the harvested rainwater, which is an indispensable figure to alleviate and minimize the ever-increasing water scarcity of the study area to some extent.
Keywords: Rooftop-Rainwater Harvesting; Google Earth; Field Survey; Master Plan; Potential Assessment
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1. Introduction

Sustainable utilization of natural resources and their protection is of fundamental significance for smart development (Urbaniec et al., 2017; Lopez and Roderiguz, 2019). To attain this, it is very crucial to implement alternative sources of water and energy in all capacities of the economy, particularly in housing, which is characterized by a high demand for water and energy (Stec et al., 2017; Kordana and Slys, 2017). It is assessed that domestic use of fresh water is about 10% of the total global water demand (Bocanegra et al., 2014).

Though studying the typical consumption of water in residential buildings, it can be observed that over 50% is used for purposes where the quality of drinking water is not required (Agnieszka and Martina, 2019). Water resources are also affected by climate change and the increase of the urbanization process, which also causes substantial hydrological alterations in catchment areas. These alterations have an adverse influence predominantly on the quantity and quality of rainwater, causing an increase in the speed and volume of runoff, a decrease in infiltration, an increased risk of flooding, and the hydraulic overload of sewage systems (Pochwat et al., 2017; Kazmierczak and Kotowski, 2014; Pochwat, 2017).

Besides meeting demand, rainwater harvesting systems can improve rainwater management in urban areas, and a reduction of drained volume and peak flow in sewage systems (Teston et al., 2018; Palla et al., 2017; Zhang et al., 2018). It is very important because the drainage systems are the most capital-intensive type of sewage system Starzec et al., (2018) and it is necessary to reduce the costs of their construction and functioning by implementing LID (Low Impact Development) practices. Low impact development techniques include mainly decentralized devices and objects, whose operation is to imitate natural hydrological processes, such as infiltration, evaporation, and retention of rainwater, which take place in the catchment. One of the LID practices is the collection and use of rainwater (RWHS) (Agnieszka and Martina, 2019).

While looking for alternative sources of water, special attention was paid to rainwater, which usually is characterized by a low degree of pollution, which does not require advanced cleaning processes (Takagi et al., 2018; lani et al., 2018; Zhang and Hu, 2014).

Collecting and using rainwater may decrease the use of municipal and groundwater. Since the rainwater collected from roofs is relatively cleaner than the rainwater collected from other impermeable surfaces such as roads, roofs are the largest impervious surface in residential areas to be used as catchment areas and allow the harvest of water that would otherwise enter into the storm-water drainage system. This may reduce storm-water runoff and the necessity for downstream storm-water management and treatment. Harvested rainwater is used mainly for irrigation and toilet flushing (Ling and Benham, 2014). According to Hamid and Nordin (2011), there are five components of any RWHS:

i. Catchment area
ii. Gutters and downspouts
iii. Storage system
iv. Delivery system
v. Filtration and Treatment system

The quantity of rainwater that can be collected from a surface such as a roof is dependent on its size and texture. Moreover, the material of the catchment surface will affect the rainwater quality through the contaminants that might be present on the surface (Ling and Benham, 2014). In the systems intended for non-potable uses such as irrigation and toilet flushing, screens and first flush diverters are sufficient for treatment thereby reducing the cost of the system.

The history of water harvesting in Ethiopia dated back as early as the pre Axumit period (560 BC). It was a time when rainwater was harvested and stored in ponds for agricultural and water supply purposes. Anthropologists Fattovich (1990) has documented evidence of the remains of ponds that were once used for irrigation during this period. A roof water harvesting set up is still visible in the remains of one of the oldest palaces in Axum; the palace of the legendary Queen of Sheba. Other evidence includes the remains for one of the old castles in Gondar, constructed in the 15-16th century, which used to have a water harvesting set up and a pool that was used for religious rituals by the kings.

Many publications have portrayed the economic and ecological advantages of rainwater harvesting systems (Rahman et al., 2010; Mehrabadi et al., 2013; Karim et al., 2015; Vialle et al., 2015). In fact, Ethiopia is endowed with tremendous water resources, access to potable water supply is still a critical question. One of the key reasons for this is financial barriers related to water supply production (water treatment) costs. However, alternative sources that could alleviate and minimize the water supply for non-domestic purposes from RWHs are not critically taken into considerations.

While estimating the quantity of rainwater harvested from rooftop; the amount of rainfall, and rooftop catchment area measurement techniques are the main factors that affect its definitive quantity. This day, roof catchment area can be measured via Masterplan, Google Earth, Onsite measurement techniques, etc. However, selecting the best techniques among them in multimodal aspects is still a question for designers and engineers incorporating in water sectors.

Therefore, in this study, the potential of rooftop rain-water harvesting and its respective roof catchment area measurement techniques in Addis Ababa, Ethiopia were targeted and studied.

2. Materials and Methods

The research was conducted in East Africa, Ethiopia, the capital Addis Ababa, at Akaki Kality sub-city specifically at the Tulu-Dimitu condominium area. Tulu-Dimitu is located in the southeast direction of Addis Ababa, at a geographic coordinate of 8^0 54’11” North and 38^0 49’60” East. It is situated about 20km far from the center of Addis Ababa see Fig-1.

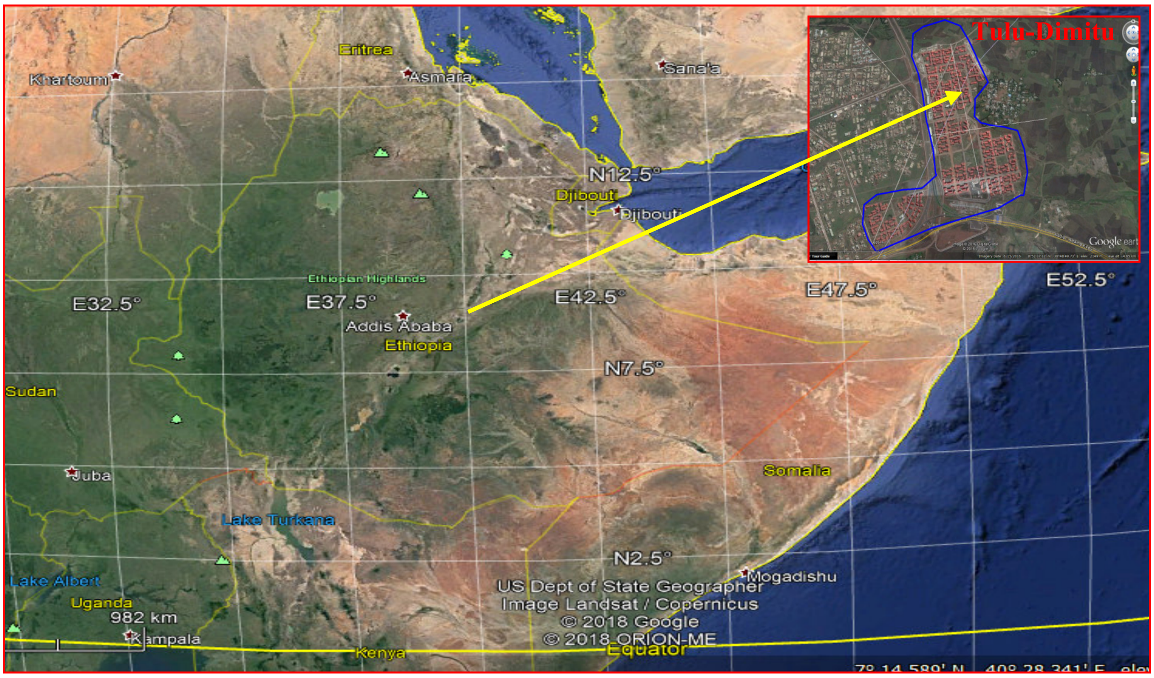

Fig 1: Location map of the study area
(Source: Google Earth&Google Map, 2019)

2.1 Demography, Climate, Precipitation, and Topography

Tulu Dimitu is a condominium area and the condominium was constructed to serve 36,785 inhabitants. The numbers of inhabitants per house are different. The master plan of the condominium site describes that the number of inhabitants per; studio, one-bedroom, two-bedroom, and three-bedrooms was, 2, 3, 4 and 6 respectively. The condominium has 10653 housing units and 489 Blocks. The mean and median annual rainfall is between 991 mm and 950 mm respectively. The highest amount of rainfall was recorded in the month of August and the rainy season start from April to October. The Monthly temperature recorded in 2016 was within 6.9-29 ºC. The landform is generally low-lying and somehow-undulated. Figure 1 indicated an overview of the area.

2.2 Techniques of data collection

The data's indispensable for conducting this research was collected as primary and secondary methods of data types. Primary data were collected by making a site visit or observation to the intended area which can help to generate ideas about the physical view of the intended area and to carry out a professional hypothesis with regard to how the system is going to be assessed and designed. The secondary data was also collected from different government sector offices as well as from software and via different kinds of literature.

2.2.1 Field measured roof catchment area

In this measurement method, the ground base area of buildings was considered as equivalent to that of roof catchment areas. During calibrations of roof catchment areas, end to end, rear to rear and edge to edge measurements were conducted as indicated in Figure 2.

Fig 2: Carrying out the measurement of field roof catchment area by using tape or meter (A), recording the measured length (B)

2.2.2 Precipitation data

The daily precipitation data for Tulu Dimitu condominium from 2006 to 2016 was obtained from the national metrology agency of Ethiopia at Akaki rain gauge station located at geographic coordinates of 8º52'11.28" North and 38°47'10.32" East with an elevation of 2057 m.a.s.l.

2.2.3 Population and related data

The number of blocks, houses, inhabitants and in general the overall site descriptions of the condominium plan the so-called (Master Plan) data were gathered from Addis Ababa housing development agency. The overview of the master plan is indicated in Figure 3.

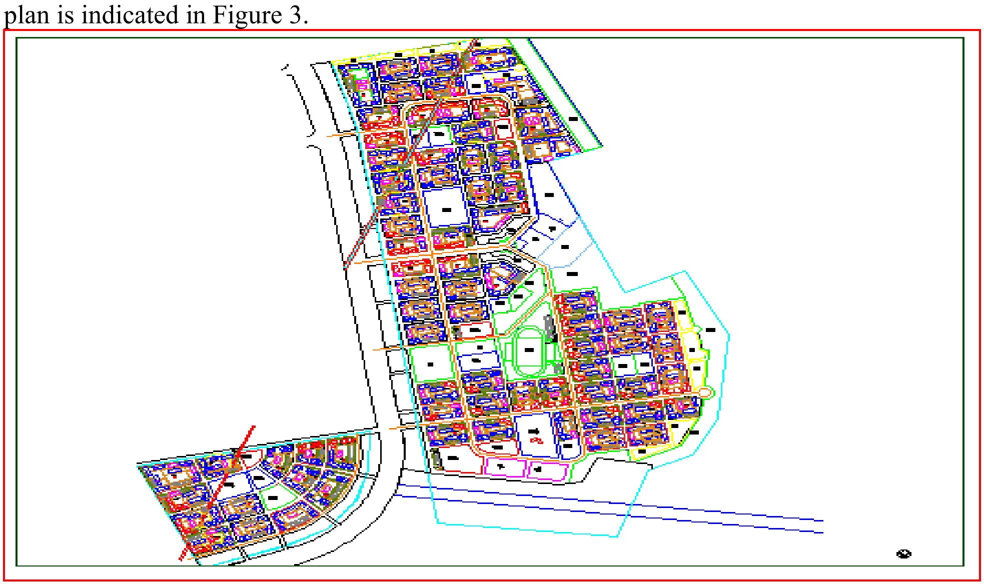

Fig 3: Master Plan of the study area

2.2.4 Block sampling techniques

In this case, a systematic method of sampling was applied. Measuring the rooftop catchment areas of all 489 buildings is bulky, tedious and budget and time-consuming. Therefore, a representative sample was to be taken from similar typology buildings. Basically taking more samples would provide a better result. However, it depends on different factors. If there exist similarities or homogeneities between data, taking the population or the whole data would not be economical and it provides unnecessary duplications of results. Therefore, in this study, buildings of having similar shapes were clustered in the same groups. Ten representative samples of buildings having complex roof areas were taken out of 489 buildings as per the technical point of view. Because taking all block measurements would not be that much necessary since it's a duplication. Therefore for computations of total measured roof catchment areas, ten sampled buildings field measured roof catchment areas were multiplied by the total number of buildings from distinct typologies Figure 4 shows the adopted ten samples of buildings from different typologies.

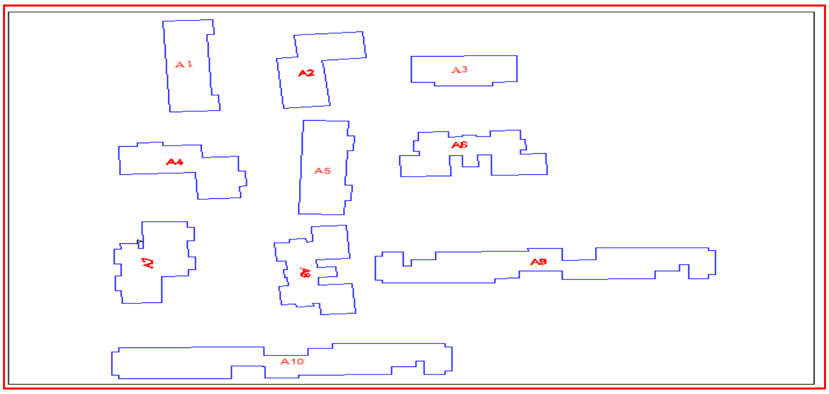

Fig 4: Roof catchment plans of sampled buildings

2.2.5 Roof catchment area measurement using Google Earth

Despite the degrees of uncertainty it might provide, Google Earth can be used as an alternative method for measuring roof catchment areas of buildings. The following seven steps were carried out in order to measure roof catchment areas of buildings by using Google Earth.

Step-1: Enhancing satellite image clarities of buildings to the maximum zoom extents.

Step-2: Click the add path menu and via it, fill style, color, and other properties then click ok

Step-3: Once again by clicking the add path menu, start tracing of the building's roof area. While finishing, click ok.

Step-4: Right-clicking on one of the places option on the drop-down lists found on the right side of the Google earth menu. Then click add folder, give folder name, then drag and put the created layer features into the created folder.

Step-5: From the file, menu click to save my places as, and save it either in KML or KMZ format

Step-6: Open the Google earth file of having layer features of roof catchment areas into global mapper software. From the global mapper file menu, choose export vector format, then save it in either DXF or DWG format.

Step-7: Collecting areas of buildings using AutoCAD software via, selecting the building's roof plan, click properties and take the areas of the selected roof plan listed under the properties option.

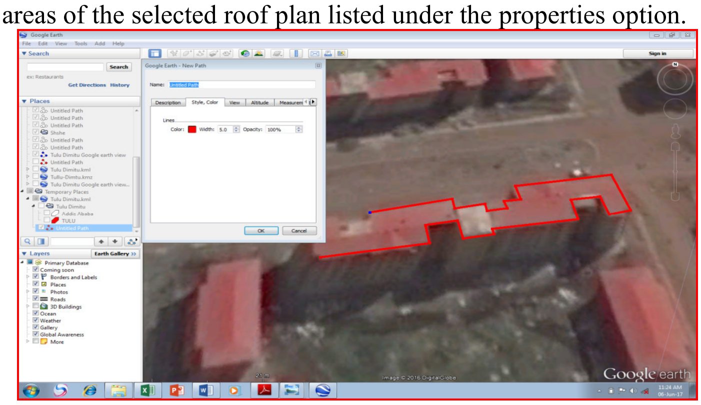

Fig 5: Roof catchment area measurement using Google Earth

2.2.6 Roof catchment area measurement using the master plan

In this method, simply the areas of buildings were gathered through, clicking the roof plans of buildings under the master plan drawing on AutoCAD, also click the property option, then taking the respective areas, as indicated in Figure 6.

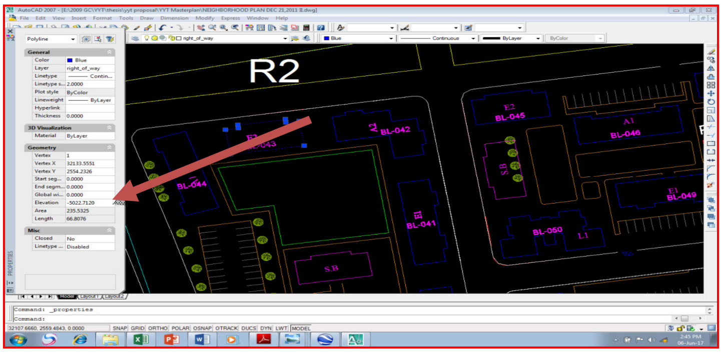

Fig 6: Roof catchment area measurement using Master Plan via AutoCAD

2.2.7 Precipitation analysis

Determinations of the quantity of harvested rainfall in a certain area have to be carried out seriously since it has an effect on increasing or decreasing the quantity of harvested rainwater and at the same time, it can also increase or decrease the total costs incurred for implementing the system. Two methods are commonly used for the calculations of rainwater harvesting. Those methods are mean and median rainfall. The analysis of the two methods is elaborated consecutively.

2.2.8 Mean rainfall

The collected eleven years (2006-2016) of rainfall data were analyzed on a monthly basis. Once the mean rainfall value of each year at a monthly level was computed, then the mean values of eleven years of rainfall at monthly basis were also computed by using the following formula. And Table 1 shows the computed mean monthly rainfall of eleven years of data.

$$\mathbf{R} = \sum_{i=1}^{n} \frac{\mathbf{P}}{\mathbf{n}} \qquad (1)$$

Where, R= mean monthly rainfall,
P= Total monthly rainfall, and,
n = number of months

Table 1: Computed mean Monthly rainfall of the study area

Year	**Monthly mean rainfall in mm**											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
2006	2.6	44.2	56.3	79.7	22.0	84.3	276.4	262.6	148.1	38.0	0.0	3.2
2007	34.2	24.7	25.6	96.8	64.6	132.7	254.2	221.8	148.5	14.3	1.3	0.0
2008	0.0	0.0	0.6	34.2	62.4	140.2	253.5	252.3	191.4	7.2	64.8	0.0
2009	60.2	0.0	10.0	118.7	47.7	63.5	235.3	322.4	71.3	32.8	4.0	16.8
2010	0.0	63.8	126.2	170.0	95.2	164.8	334.4	169.8	154.1	5.2	14.8	7.8
2011	0.0	2.5	45.2	20.7	128.7	60.0	204.3	304.0	194.5	0.0	4.7	0.0
2012	0.0	0.0	29.0	61.0	26.1	80.6	228.0	243.9	122.9	0.0	0.0	0.0
2013	0.0	0.0	77.0	89.1	73.4	111.5	179.6	242.4	142.5	20.6	0.0	0.2
2014	0.0	39.4	76.0	13.9	95.2	52.6	176.8	281.6	115.3	52.3	0.0	0.0
2015	0.0	0.0	13.7	170.0	96.5	158.0	187.8	247.5	70.0	0.0	14.5	0.0
2016	0.0	0.0	39.3	184.5	134.2	105.7	233.9	183.7	113.1	16.2	9.3	0.0

2.2.9 Median rainfall

In computing of median rainfall, first, the rainfall data of eleven years were arranged in ascending order. The middle term was selected as the median values. The median rainfall of eleven years data was shown in Table 2.

Table 2: Computed monthly median rainfall

	Monthly median rainfall in mm											
S.No	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1	0.0	0.0	0.6	13.9	22.0	52.6	176.8	169.8	70.0	0.0	0.0	0.0
2	0.0	0.0	10.0	20.7	26.1	60.0	179.6	183.7	71.3	0.0	0.0	0.0
3	0.0	0.0	13.7	34.2	47.7	63.5	187.8	221.8	113.1	0.0	0.0	0.0
4	0.0	0.0	25.6	61.0	62.4	80.6	204.3	242.4	115.3	5.2	0.0	0.0
5	0.0	0.0	29.0	79.7	64.6	84.3	228.0	243.9	122.9	7.2	1.3	0.0
6	**0.0**	**0.0**	**39.3**	**89.1**	**73.4**	**105.7**	**233.9**	**247.5**	**142.5**	**14.3**	**4.0**	**0.0**
7	0.0	2.5	45.2	96.8	95.2	111.5	235.3	252.3	148.1	16.2	4.7	0.0
8	0.0	24.7	56.3	118.7	95.2	132.7	253.5	262.6	148.5	20.6	9.3	0.2
9	2.6	39.4	76.0	170.0	96.5	140.2	254.2	281.6	154.1	32.8	14.5	3.2
10	34.2	44.2	77.0	170.0	128.7	158.0	276.4	304.0	191.4	38.0	14.8	7.8
11	60.2	63.8	126.2	184.5	134.2	164.8	334.4	322.4	194.5	52.3	64.8	16.8

2.2.10 Quantity of harvested rainwater determination

After conducting roof catchment area measurement via master plan, Google Earth and field survey, the next step is estimating the harvested rainwater quantity on the monthly level. In this regard, first, the sampled blocks were converted to the population and then an appropriate run-off coefficient was selected as per the roof material and finally multiplied with the mean and median rainfall depths respectively. The following formula was applied for the estimation of the quantity of rainwater harvested for the study area

$$\mathbf{S = R \times K \times A_v} \qquad (2)$$

Where, S = Monthly rainwater supply (m^3)
R=average monthly rainfall (mm)
K=coefficient of runoff
A_v=average roof catchment area (m^2)

2.2.11 Estimations of water consumptions for toilet flushing

Since one of the aims of this study is to use the harvested rainwater for toilet flushing purposes, thus the harvested quantity of rainwater has to be compared with the toilet flushing water demand. Therefore, for toilet flushing water demand estimation, Ethiopian Building Code Standard (EBCS-9), version for plumbing services, was adopted and computed via the formula presented here.

Toilet flushing demand = Number of houses*
Water consumption per water closet **(3)**

3 RESULTS AND DISCUSSIONS

3.1 Comparisons of roof catchment area measurement techniques

Three methods were used in measuring the roof catchment areas of the buildings. According to the measurement conducted by Google Earth and Master Plan, 489 buildings were found and buildings of having the same roof shape were categorized into ten groups for the ease of simplicity. In the field measurements, ten representative samples of buildings were taken under ten groups based on a technical point of view. The measured areas by the three methods are shown in Table 3 and Figure 7 respectively.

Table 3: Measured roof catchment areas by three methods

Typology	Google Earth (M^2)	Master Plan (M^2)	Field Survey (M^2)
A_1	339	299	275
A_2	255	236	214
A_3	252	218	206
A_4	330	304	281
A_5	360	320	295
A_6	348	340	314
A_7	336	335	313
A_8	413	367	351
A_9	666	652	632
A_{10}	659	676	643

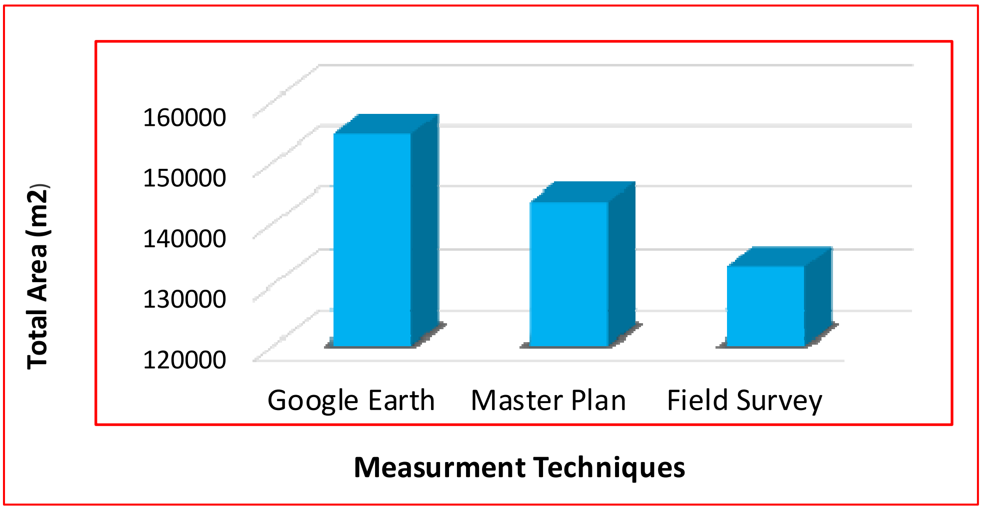

Fig 7: Total measured roof area by the three methods

3.1.1 Field measurement versus Google Earth and master plan comparisons

A comparison was made by considering field measurement as a reference point so as to compare its result with the results obtained from a master plan and Google Earth. Linear regressions were used for constructing a mathematical relationship that expresses one in terms of another. In comparison, the higher the regression value portrays the strong the relationship, on the contrary, the lower the regression values represent the weak the relationship. In this study, the correlation values of field measurement versus master plan, field measurement versus Google Earth, and master plan versus Google Earth were found to be 0.997, 0.959 and 0.971 respectively. Therefore, in this study master plan was found to be better than Google Earth. Figure 8 shows the relationships between the respective methods.

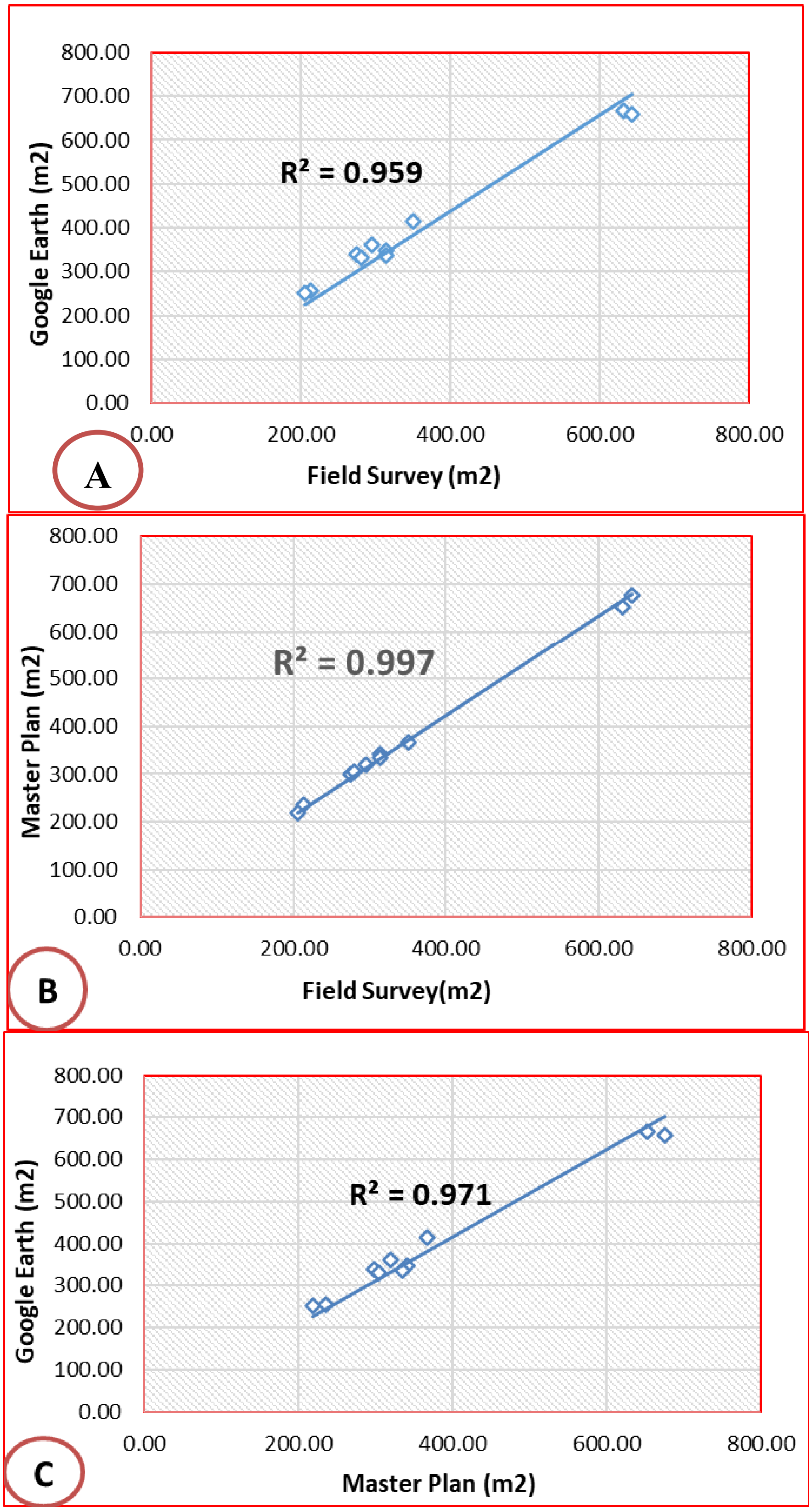

Fig 8: Correlation of Field Survey Vs GE (A), Field survey Vs Master Plan (B), and Master Plan Vs GE **(C)**

3.1.2 Mean and median rainfall comparison

The collected daily rainfall data of eleven years were analyzed in terms of mean and median as per monthly and yearly basis. Usually, the amount of rainfall computed by using the median is less than the mean. The same thing appeared in this study, the median rainfall was found to be less than the mean rainfall. A yearly mean and median rainfall of **991.35** and **949.70 mm** were found respectively. A little bit different in rainfall could have a great effect on the overall system design of rainwater harvesting. Figure 9, A, B, and C shows the difference between the harvested rain-water on the basis of mean and median rainfall patterns with the three methods.

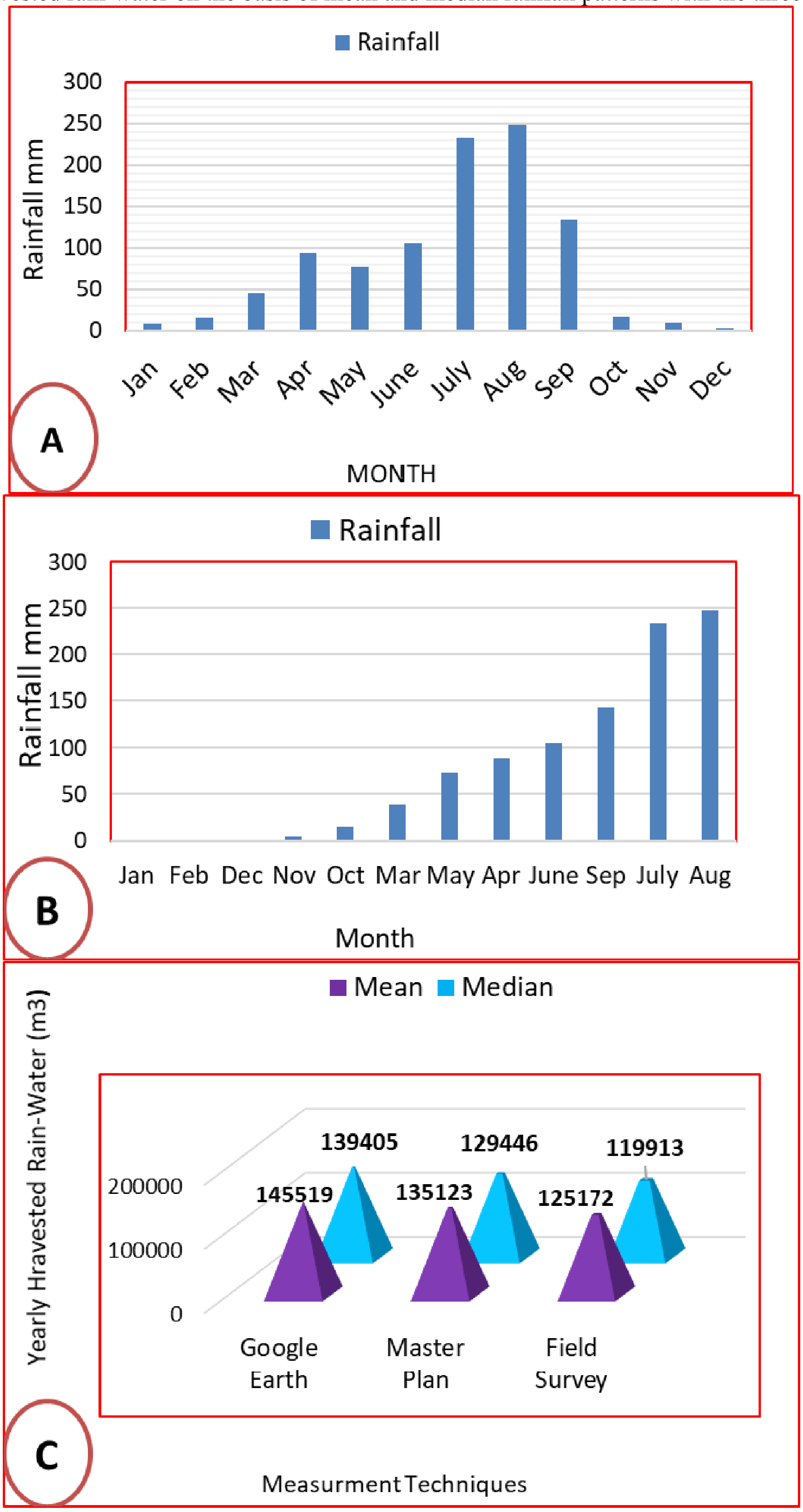

Fig 9: A (Mean Rain-fall), B (Median Rain-fall), and C (Harvested Rainwater with the three methods)

3.2 Harvested rainwater versus toilet flushing water demand

A field measurement result portrays that **132,910m²** of roof catchments areas were obtained from a total of 489 buildings. Then with a runoff coefficient of **0.95**, mean annual rainfall of **991.33mm** and with the respective total area, the harvested quantity of rainwater was found to be **125,172m³** per annum. However, this quantity of rainwater couldn't be considered as the net harvested rainwater, because some portions of rainwater should be losses as a first flush. And therefore a percentage factor of **0.0623%** was taken by referencing a standard which says in **9.23m²** area **1.5 gallons** of rainwater should be used as a first flush, then in **132,910m²** area **75.34m³** of rainwater was obtained as a first flush. Hence, **75.34m³** of the harvested rainwater was reduced from **120933m³,** and a net harvested rainwater was found to be **125,172m³.**

The water demand estimations of toilet flushing were carried out on the basis of household-level as per EBCS-9. And here, with a total number of houses of **10653** and with **180l/hh/d** of toilet water demand, **690,314m³** toilet flushing water demand was estimated. And finally, the harvested rainwater was covered **18.13%** of toilet flushing water demand. Figure 12 shows the difference or gaps between toilet water demand and harvested rainwater.

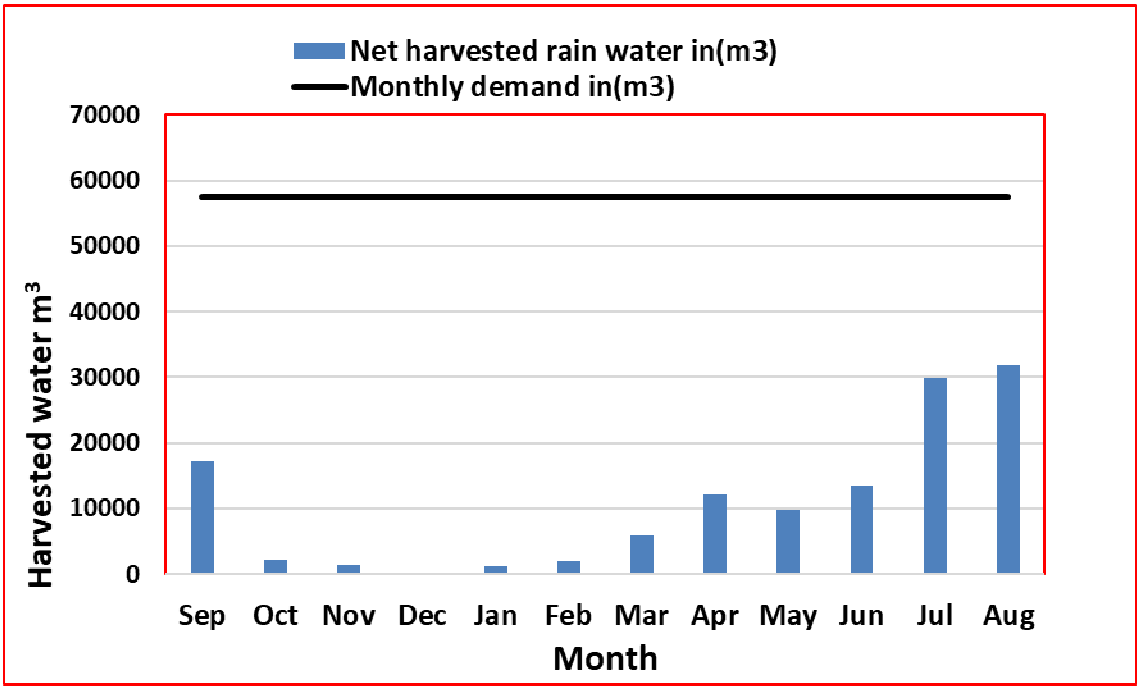

Fig 10: Harvested rainwater Vs toilet flushing water demand

Table 4: Harvested rainwater Vs toilet flushing water demand

Determinations of demand gaps between toilet flushing and harvested rainwater												
Quantity of monthly harvested rainwater calculation					Quantity of rainwater diverted as a first flush		Net harvested rainwater m³	Water consumption for toilet flushing estimation			Demand Vs. supply gap determination	
Month	Field measured roof area m²	Mean rainfall mm	Runoff coefficient	Harvested rainwater m³	% age factor	Quantity m³		Number of houses	Demand m³/d	Monthly demand m³	Deficit m³	%age coverage of harvested rainwater Vs. toilet flushing water demand
Sep		133.80		16322		10.17	16312				-41214	28.36
Oct		16.90		2062		1.28	2060				-55466	3.58
Nov		10.31		1258		0.78	1257				-56269	2.18
Dec		2.55		311		0.19	311				-57215	0.54
Jan		8.82		1076		0.67	1075				-56451	1.87
Feb		15.87		1936		1.21	1935				-55591	3.36
Mar	132,172	45.35	0.95	5532	0.0623%	3.45	5529	10653	0.18	57526	-51997	9.61
Apr		94.42		11518		7.18	11511				-46015	20.01
May		76.91		9382		5.85	9376				-48150	16.30
Jun		104.90		12797		7.97	12789				-44737	22.23
Jul		233.10		28436		17.72	28418				-29108	49.40
Aug		248.40		30302		18.88	30284				-27243	52.64
Σ		991.33		125,233		75.34	125,172			690,314	-569457	**18.13**

4. CONCLUSIONS

Rainwater harvesting system, where rainfall runoff collected and utilized, is a prominent solution to address the issue of water scarcity by conserving the available water resources and the energy needed to deliver water to the water supply system. The impact of climate change on water resources can also be reduced by rainwater harvesting. Rainwater harvesting is becoming an important part of sustainable water management around the world.

This study was conducted by focusing assessments of the potential of rooftop rainwater harvesting in general and determinations of the demand-supply gap between harvested rainwater and toilet flushing water consumption, quantifying alternative methodologies for measuring roof catchment and sizing of the storage tank in particular. The results of the study were shown that 18.13% of water consumptions by toilet flushing could be covered by the harvested rainwater.

A comparison was made between Google earth and master plan by taking field measurement as a reference and linear regressions as a comparison tool for deciding which measurement techniques are the best fit so as to calibrate the areas of roof catchments.

However, the main aim of this study was to use the correlation between the aforementioned methods of roof catchment area measurements as per its necessity with the allowable practical site conditions with cost-effective ways, then GE can be used as a cost-effective tool for roof catchment area measurement with the computed correlation coefficient value for the areas where master plan are poorly implemented. In addition to this, the water harvesting potential of the study area was estimated and compared with the toilet flushing water demand (which accounts for the major portions of domestic water demand of the area). The annually harvested rainwater of the study area was estimated to be 125,172m3 and the respective annual toilet flushing water demand was 6,090,314m3. This result showed that 18.13% of water consumption of toilet flushing's of the study area could be covered by the harvested rainwater, which is a very important figure to alleviate and minimize the ever-increasing water demand to some extent.

5 RECOMMENDATIONS

In order to enhance and improve the utilization of rainwater for domestic purpose, the following recommendations were made:

- Roof catchment area measurement using the master plan is better than Google earth for the areas where the master plan is nicely implemented to the ground or to the real world.
- Google Earth is the best tool for roof catchment area determinations, for the areas do not have a master plan.
- Since Ethiopia has huge potentials of rainwater, it has to be implemented on large-scale to alleviate the risk shortages of water.
- The government or any issued organizations have to carry out the feasibility study on rainwater harvesting systems in line with other water resources, so as to implement it at a large scale in a committed manner.
- While new master plans proposed, they shall better take in to account constructing suitable positions for elevated storage tanks as per their plan.
- Rainwater harvesting has to be considered in any newly proposed water supply projects so as to minimize or conserve surface and groundwater sources for future utilizations.

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