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ORIGINAL ARTICLE

Rainwater harvesting potential assessment for non-potable use in urban areas

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Abstract

Water is an important natural resource which could be utilized for different purposes. Now a day's water became a scarce resource which needs be conserved. One of the most effective ways to conserve water at urban areas is installing a rainwater harvesting system for the strain of the shower, laundry, plant growth, and construction requirement. This study aimed to determine the rainwater harvesting potential and analyse the importance of a rainwater harvesting system for non-potable use in urban areas. The evaluation of rainwater harvesting was done through surveying and analysis of roof catchment, channel networks, and rainfall data. The assessment of rainwater potential was followed by quantifying the runoff volume and characterization of the rainwater harvesting system components. The investment required for rainwater harvesting within the study site was very small, since it only requires the development primary and secondary sedimentation tanks, and pump cost for lifting the water from the tank to the distribution system. The results of this study indicated that installing a rainwater harvesting system is economical to handle the water scarcity problem within the university. In Debre Tabor University, the available water to be collected from 13 dormitory buildings and also the open area was about 41,511 m^3. This revealed that there's an enormous amount of water which is sufficient enough to fulfil the demand for non-potable uses. Hence, the adoption of rainwater harvesting system in urban areas is appropriate method and plays an excellent role in resolving water scarcity problem.

Keywords Rainwater harvesting · Water scarcity · Non-potable uses · Thomas and fiering model

Introduction

Water is an important natural resource which could be utilized for different purposes. This is often because of the transformation of one sort of water to a different during a specified manner. Though two-thirds of the planet is full of water, the usable water for irrigation and drinking purpose is minimal with only two percent of the available water. The proper management of the available water is incredibly important for the sustainable utilization of water for various purposes (Ursino 2016; Abu-Zreig 2019; Chaimoon 2013). The most important share of usable water is found underground within the aquifers. A rise of groundwater storage within the aquifers has been detected as the spot measure of water richness. Nowadays rainwater harvesting plays a thoughtful role in reducing surface and underground water scarcity problems in tropical and dryland areas (Naseef and Thomas 2016; Lee et al. 2016; Ghisi et al. 2009).

A technology of collecting and storing rainwater from land surface catchments, and rooftops using different and easy techniques like jars and pots and sophisticated techniques as underground check dams are termed as rainwater harvesting (Sivanappan 2006). Rainwater harvesting can be used as the best tool for combating the water scarcity problem. Rainwater harvesting will have a significant role in reducing domestic water consumption for the increasing water demand with an increasing population growth and other related factors (Diaper et al. 2001). The harvested water could be used for potable and non-potable purposes (Chiang et al. 2013). The harvested water from rain is the main source of drinking water supply, irrigation, gardening, construction purpose, and recharging groundwater. The commonly used rainwater harvesting system has three main components namely the geographic region, conveyance, and the collection system (Fewkes 2006).

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Rainwater harvesting could be a technique employed to effectively trap the surface runoff. In technical terms, water harvesting could be a system that collects rainwater from where it falls around its periphery instead of allowing it to travel as runoff (Chiu et al. 2015). By constructing water harvesting structures in the appropriate sites it's possible to extend the groundwater recharge and level of the geological formation so we can effectively use the water for irrigation and drinking purpose within the off-monsoon season. Also, these structures act as a barrier to eating away and forestall flooding. Percolation Ponds, Subsurface Dykes, Farm Ponds, Check Dams, Bunds, etc. are a number of the kinds of water harvesting structures that are widely in use (Durga et al. 2005). most typically rainwater harvesting is employed for non-potable water uses (Nicholson et al. 2009; Mehrabadi et al. 2013; Souza and Ghisi 2012).

The purpose of this study was to evaluate the rainwater harvesting potential and analyze the importance of a rainwater harvesting system for non-potable uses as a strategic tool for reducing water scarcity in Debre Tabor University. Moreover, this study tried to analyze the rainfall, measure the roof catchments to be used as a catchment, and evaluate the cost–benefit-analysis about the employment of the rainwater harvesting system.

Materials and methods

Location of study area

The project area is located in Debre Tabor University, Debre Tabor, Ethiopia male technology faculty student's dormitory and it lies between 11° 51′ 15.71″ to 11° 51′ 29.52″ North latitude and 38° 02′ 21.1″ to 38° 02′ 35.31″ East longitude (Fig. 1). It covers a total area of 39,819.51 m^2 from this 10,177.74 m^2 area is covered by buildings and the rest 29641.77 m^2 is covered with grass. This study is intended to propose and design the collection and treatment system of rainwater from the technology faculty male students' dormitory and office area. The study area includes 2-drainage channels, open surface, and other building blocks (B-53, B-54, B-55, B-56, B-57, B-58, B-61, B-62, B-63, B-64, B-67, B-68, and B-144) (Fig. 2). Hence this study area has been used for the determination of the amount of water to be collected and rainwater harvesting system design.

Description of Thomas and Fiering model

Stochastic simulation of hydrologic statistics has been widely used for solving various problems related to the design and management of water resources systems for several decades (Kim et al. 2004). Stochastic monthly streamflow models are often employed in simulation studies to judge the likely future performance of water resource systems (Stedinger and Taylor 1982). Synthetically generated flows have many uses to the water resources planner. They're of equal importance as historic flows in simulation and optimization schemes to study several feasible alternatives of designing, design, and operation of water resources projects (Wijayaratne and Chan 1987). The role of stochastic methods in water resources was first explored by Thomas and Fiering (1962) within the context of system design and operational studies through the generation of synthetic sequences of stream flow through town simulation.

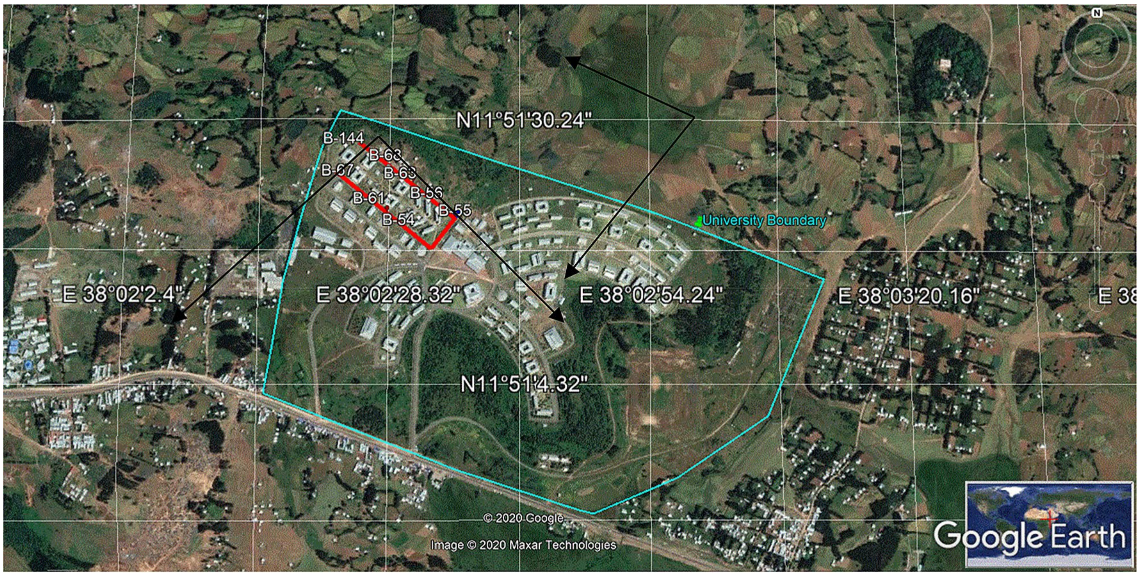

Fig. 1 Location map of Debre Tabor University

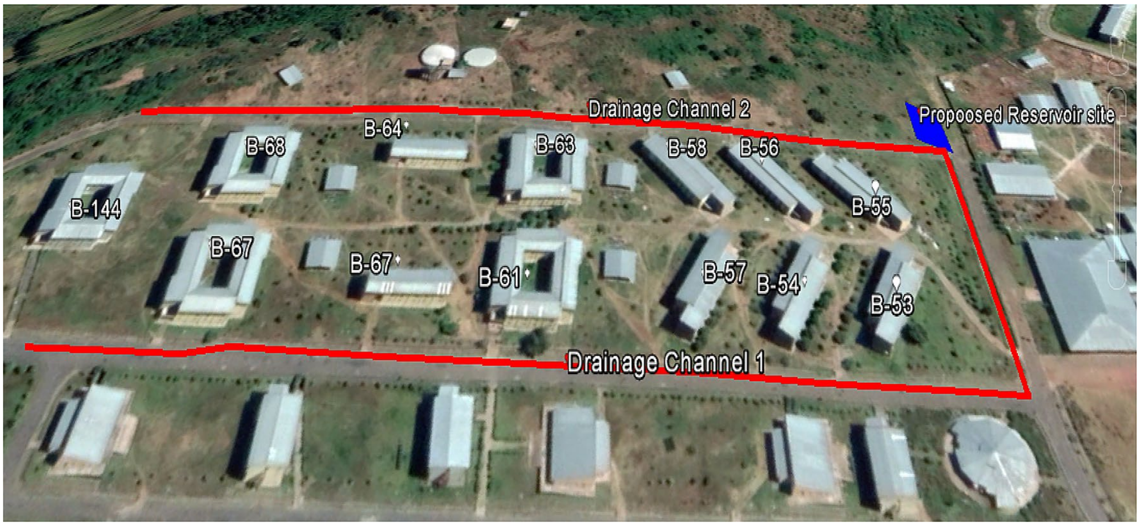

Fig. 2 Buildings and channels considered for analysis

They developed a stochastic data generation model incorporating the serial correlation behaviour of hydrologic data. This serial correlation model was an example of Markovian type models; that's a lag-one Markov model.

For the primary style of models, the Thomas Fiering (T-F) model may be thought to be a typical stochastic approach for forecasting in hydrology (Harms and Campbell 1967; Joshi and Gupta 2009; McMahon and Miller 1971; Thomas and Fiering 1962). Harms and Campbell (1967) extended the TF model to preserve the traditional distribution of annual flows, the lognormal distribution of monthly flows,, and therefore, the autocorrelation of both annual and monthly flows. Modelers later disaggregated the annual flow requirement, usually data from a terminal reservoir, into the monthly flow requirements by establishing the correlation between annual and monthly flows (Kurunç et al. 2005).

The generated data sequences, particularly monthly statistics like streamflow or rainfall are widely employed in water resources planning and management to know the variability of future system performance (Yousif et al. 2016). Stochastic data generation aimed toward generating synthetic data sequences that are statistically the same as the observed data sequences. Therefore, the generated data is vital for more accurate solutions to numerous complex planning, design, and operational problems in water resources development.

Data analysis

In this study the required data were collected through measurement and from secondary data sources. The total areal coverage of the study site was measured from google earth, whereas the area of each building and drainage channels were collected through direct measurement using measuring tape. The area of buildings, drainage channels and open surfaces were used as a catchment area which is used to compute the amount of runoff generated from the rainfall reaching to the surface. The long-term rainfall data of Debre Tabor meteorology station were collected from Amhara National Meteorology station. The number of peoples who will use water from the harvested water were collected from each student dormitory administrators and faculty dean.

Thomas and Fiering (1962) used the Markov process model for generating monthly flows (by serial correlation of monthly flows) using the subsequent recursion equation:

$$q_{i+1} = \overline{q_{j+1}} + b_j\left(q_i - \overline{q_j}\right) + \varepsilon_i \delta_{j+1} \sqrt{1 - r_j^2}, \quad (1)$$

where:

q_i, q_{i+1} = discharges (rainfall depth) in the i and $i+1$ months, respectively.

$\overline{q}_j$, $\overline{q}_{j+1}$= mean monthly discharges in the j and $j+1$ month of the annual cycle.

b_j = regression coefficient for estimating the discharge (rainfall depth) in the $j+1$ month from that in the j month.

ε_i = a random normal deviate at the time i with a zero mean and unit variance.

σ_{j+1} = standard deviation of discharges in the $j+1$ month.

r_j = correlation coefficient between the discharges (RF depth) in the j and $j+1$ months.

The above Equation is called 'Lag-one single period Markov Chain Model, where the period may be the day, month or year.

The quantification of runoff volume to be collected from the catchment area has been employed in this study. The rainfall depth and the catchment area were used to compute the runoff volume for the study site (Ghisi et al. 2006; Lade and Oloke 2013). The treatment plant was designed to support the inflow and outflows of the system (Santos and Taveira-Pinto 2013):

$$\text{Net harvesting potential } (\text{m}^3) = \text{Catchement area } \left(\text{m}^2\right) \times \text{rainfalldepth(m)} \times \text{runoff coefficient,}$$

where:

- The catchment area is in m^2 which is determined by direct measurement and from Google Earth
- Rainfall depth is in the meter which is the average value of generated depth by Thomas Fiering model.
- Runoff coefficient is taken as 0.85, 0.95, and 0.75 for channels, building a roof and free space between buildings and channels, respectively.

The amount of water to be consumed for different non-portable use were determined by considering the number of students and academic staff members living in each building. It was assumed that the common water demand of 55 l/p/d and 35 l/p/d for college students and office members, respectively. The population to be supplied from the collected water will be 3064 students with 55 l/p/d and 1620 staff and floating population in offices with 35 l/p/d demand.

The cost–benefit analysis of the project has been performed considering the cost of construction and maintenance of rainwater harvesting project and the cost of water to be paid for each unit m^3 of water demanded by the users. Hence, the water harvested will prevent the cost of water to be invested without having a rainwater harvesting scheme. The analysis has been done considering 10 years utilization time of the rainwater harvesting project. In analysing the cost–benefit of the project 20% of the initial cost of the project, and operation and maintenance cost is expected to be returned. In addition, 10% of the initial cost of the project is expected to be invested as operation and maintenance cost (Matos et al. 2015).

Results and discussion

Statistical comparison of historical and generated rainfall depth

The daily historical record of rainfall depth of Debre Tabor meteorological station data of 25 years period (1992–2016) was used for prediction of the next 34 years using Thomas and Fiering model. The future prediction of average rainfall depth (mm) for each month for the next 34 years were done and compared with the historical record at Debre Tabor rain gauge station (Table 1).

The comparison between historic and predicted monthly rainfall using Thomas Fiering model showed that the model has an excellent accuracy of predicting the future rainfall with a Pearson correlation value of 0.99 (Table 1 and Fig. 3). Hence, the predicted rainfall depth could be used for estimating the amount of water to be harvested from the catchment in the coming 34 years.

Table 1 Statistics of observed and predicted rainfall (mm) using the Thomas-Fiering model

Month (j)	Historic (1992–2016)			Predicted (2017–2050)		
	Mean rainfall (μ) in (mm)	Std. deviation (σ)	Correlation (ρ)	Mean rainfall (μ) in (mm)	Std. deviation (σ)	Correlation (ρ)
Jan	8.86	17.52	− 0.12	11.15	11.75	0.14
Feb	4.40	8.24	0.05	6.74	5.24	0.37
Mar	30.67	22.53	0.03	23.71	22.22	− 0.15
Apr	47.04	31.43	− 0.08	42.41	27.00	− 0.21
May	108.74	64.96	0.10	88.25	69.40	− 0.06
June	164.41	50.97	0.24	143.33	51.56	0.31
July	406.72	68.27	0.54	359.85	75.07	0.65
Aug	411.15	91.70	0.09	369.67	93.63	0.07
Sept	195.33	40.73	− 0.08	188.44	39.88	− 0.17
Oct	73.14	75.66	− 0.14	66.80	59.13	0.07
Nov	28.14	26.22	0.01	28.65	22.70	0.08
Dec	14.55	17.85	0.06	11.64	15.90	0.25
Annual	1493.15			1340.64		

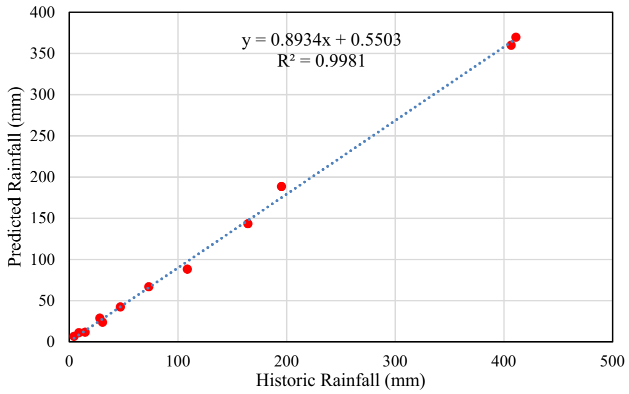

Fig. 3 Comparison between mean monthly observed and predicted rainfall depth using the T-F model

Computation of runoff volume

The amount of runoff volume to be collected from the rooftop is required to design a rainwater harvesting system. The runoff volume and water demand of the study area has been presented in Table 2.

In the study catchment a total of 24671.43 m^3 volume of water could be collected annually from the average monthly rainfall values. The water collected is sufficient enough to supply the required water demand (Table 2).

The temporal variation of runoff volume showed that there will be high amount of inflow during July and august due to the highest rainfall in these wet months. On the other hand, the water demand is very low during July, August and September months due to the reduced number of students in these months for inter annual students break time (Fig. 4). To supplement the water demanded by the population throughout the year without water scarcity, it's required to collect the surplus water within the time of year by preparing an appropriate tank which can store the runoff from the catchment. The tank capacity was computed using sequent peak volume of tank analysis method without considering evaporation, since the size of thank is very small, i.e., evaporation will be negligible in amount (Ghisi et al. 2009). The desired tank volume was fixed from the maximum volume deficit and estimated to be 379 m^3 which might be divided into two tanks as primary and secondary rectangular sedimentation tank. Hence the primary sedimentation tank volume was fixed as 353.4 m^3, whereas the secondary sedimentation tank was proposed to have a capacity of 10 m^3.

Cost and benefit comparison

It is essential to evaluate the cost–benefit analysis of rainwater harvesting projects implementation for sustainable design and construction in water scarcity areas. For this study site the cost of the rainwater harvesting scheme were done considering the above recommended tank sizes in "Computation of runoff volume".

The total cost required for the development of the rainwater harvesting structure was estimated as 579649.7 ETH Birr (Table 3) for material, equipment, and labor cost. Hence the profit of the project has been estimated considering the total amount of water to be stored and a unit price of water per m^3. The current unit price of water per m^3 which was taken for calculation were 7 ETH-birr. Therefore, if the annual average water volume to be collected (Table 2) sold, it will have annual benefit of 172, 698 ETH birrs. For evaluating the cost and benefit of the rainwater harvesting project it was considered 10% of the initial investment (57964.97 ETB), and annual

Table 2 Computation of volume of water to be collected from the catchment (2017–2050)

Month	Average rainfall depth (m)	Area (m^2)			Water to be collected (m^3)	Water demand (m^3)
		Channels	Building roof	Free space		
January	0.012	53.29	11,013	27144.84	190.14	2081.4
February	0.007				112.04	2081.4
March	0.023				377.23	2081.4
April	0.052				834.34	2081.4
May	0.110				1775.06	2081.4
June	0.159				2580.41	2081.4
July	0.407				6595.05	693.8
August	0.417				6752.67	693.8
September	0.215				3474.10	693.8
October	0.078				1257.42	2081.4
November	0.028				461.26	2081.4
December	0.016				261.45	2081.4
Total volume (m^3)					24,671	20,814

Table 3 Quantity and cost of the rainwater harvesting project

S. No	Description of work	Unit	Quantity	Cost (birr)	Amount (birr)
1	Quantity of earthwork with specified before	m^3	537	205	110,085
2	Site clearance	m^2	208	21	4,368
3	Quantity of RR masonry work	m^3	75	262.5	19,688
4	Quantity of cement bags	Bags	651	145	94,395
5	Quantity of sand	m^3	74	875	64,750.0
6	Quantity of aggregates	m^3	20	562.5	11,250
7	Steel bar 8 mm Dia	Berga[a]	158	250	39,500
8	Purchasing of 10,000 L tank from Bahir Dar	No	2	30,000	60,000
9	Purchasing of 0.5 HP capacity pump from Bahir Dar	No	1	5000	5,000
10	Transportation cost for the above-said items 8 and 9 from Bahir Dar				5,000
	Adding above all the items				414,035.5
	Adding 15% VAT on above-said items				62,105.33
	Adding 25% for miscellaneous items				103,508.9
	Total cost				579,649.70

[a] Berga means 12 m long steel

operation and maintenance cost (10% of initial cost which is 57964.97 ETB) needs to be returned in each year for ten consecutive years.

The cost–benefit analysis of the rainwater harvesting project showed that it is much beneficial for non-potable purposes. From 10 years cost recovery schedule the net benefit gained found that 567,682 ETB (Table 4 and Fig. 5). Therefore, the construction of a rainwater harvesting project can save an extra cost which could be invested for water consumption.

Conclusion

Water scarcity became a critical problem in urban areas. This is mainly due to the shortage of surface water and groundwater in aquifers. Now adays the use of different technologies for solving water scarcity problem is mandatory. Therefore, rainwater harvesting is a good choice to provide adequate storage of water from rooftop and urban catchment for showering and gardening by providing simple treatment like sedimentation. Hence, this paper tried to evaluate the effectiveness of the rainwater harvesting system in terms of quantity and cost. In the proposed study site about 379 m^3 volume of water is

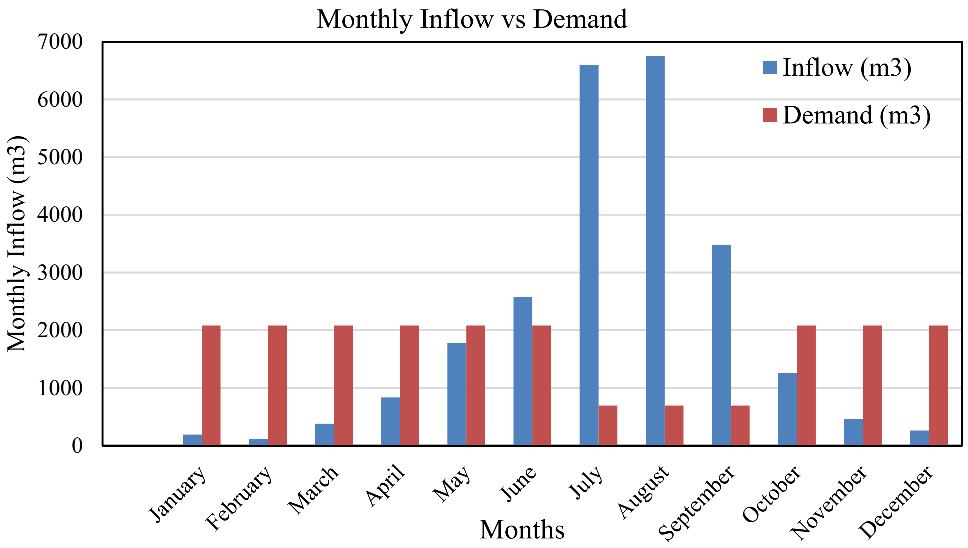

Fig. 4 Temporal variation of runoff volume and demand

Table 4 Cost–benefit analysis

Year	Cost to be recovered (ETB)	Benefit gained (ETB)	Cumulative cost to be recovered (ETB)	Cumulative benefit (ETB)	Net cumulative benefit (ETB)
2019	115,930	172,698	115,930	172,698	56,768
2020	115,930	172,698	231,860	345,396	113,536
2021	115,930	172,698	347,790	518,094	170,304
2022	115,930	172,698	463,720	690,792	227,073
2023	115,930	172,698	579,650	863,490	283,841
2024	115,930	172,698	695,580	1,036,189	340,609
2025	115,930	172,698	811,510	1,208,887	397,377
2026	115,930	172,698	927,440	1,381,585	454,145
2027	115,930	172,698	1,043,369	1,554,283	510,913
2028	115,930	172,698	1,159,299	1,726,981	567,682
Total	1,159,299	1,726,981			567,682

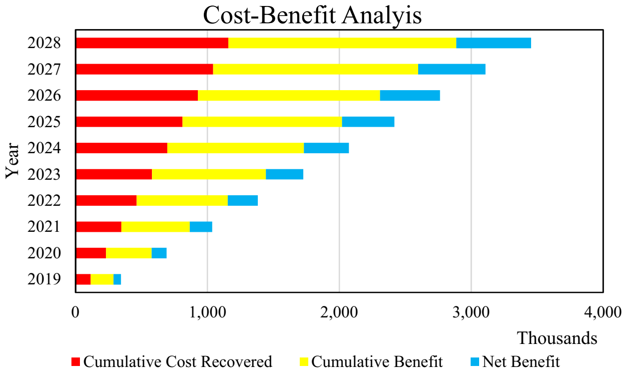

Fig. 5 Cost–benefit analysis of a rainwater harvesting project

designed to be collected from the urban catchment. The water to be collected was considered for non-potable uses which doesn't need further treatment. The cost of rainwater harvesting project is mainly for construction as an initial investment, and operation and maintenance cost. The cost–benefit analysis was done considering the amount of water to be collected and the cost which will be invested for getting the water as compared to the investment for rainwater harvesting project. Ten years of cost recovery has been taken for checking economic sustainability of the project. The development of rainwater harvesting project in Debre Tabor university will have about 567,682 ETB profit. Therefore, the implementation of rainwater harvesting projects in urban areas is cost effective for reducing water scarcity problem.

Compliance with ethical standards

Conflict of interest There is no conflict of interest between authors.

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