Mathematical Modelling of Tap Water Leakages in Gweru's Mkoba 7 High Density Households: Implications on Monetary Loss and Environmental Impact?

By

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Abstract

This study sought to investigate, through mathematical modelling techniques of equation generation, equation/data fitting and forecasting, how much water and money per month were lost by ten purposively selected households in Mkoba 7 High Density area due to leaking faulty taps or those not tightly closed after use. The study also sought to investigate, through informal interviews with the house owners, the economic and environmental effects caused by the leaking water. The study employed a quasi-experimental method to collect quantitative data on the number and amount (in litres) of home tap-water droplets during periods of 3 to 17 min when the tap was not tightly closed. The statistical package SPSS 21.0 was used to do computations and data analysis. The data were converted to quantities of litres lost per month and per year and the monetary value that could have been saved or channeled to other necessary expenses by the household in the given month/year. It was found that the data tended to fit ordinary differential equations of first order with assumptions of proportional and constant rates. The leaking water was found to accumulate in certain spots in the houses causing musty smell and moulds, damaging household property and attracting dirt, mosquitoes and flies. The study recommends that since the urban population is increasing while precious water is being lost through negligence or lack of knowledge, Gweru City Authorities should constantly educate households on water saving techniques. It is also recommended that households could save their hard-earned income by finding ways of collecting leaking water for use in the garden or for washing clothes and by ultimately repairing leaking taps or water reservoirs.

Keywords: mathematical modelling, quasi experimental study, equation/data fitting, forecasting, first order differential equations, economic impact, environmental impact.

INTRODUCTION AND BACKGROUND TO THE STUDY

According to Lewis (n.d., p1) WHO stated that in 2004, "…only 16% of people in sub-Saharan Africa had access to drinking water through a household connection (an indoor tap or a tap in the yard). Not only is there poor access to readily accessible drinking water, even when water is available in these small towns, there are risks of contamination due to several factors." United Nations Population Division (2008, p25) also postulated that access to an improved or protected source of drinking water was poorest in sub-Saharan Africa while the urban global population was estimated to increase from 3.4 billion in 2009 to 4,6 billion by the year 2025 and to 6.3 billion by the year 2050. It has also been reported that underprivileged urban populations pay large amounts of money for water, which is often not even suitable for consumption (Lewis, n.d.). This being the case, Zimbabwe faces similar challenges as those faced by developing countries in sub- Saharan Africa.

Water is becoming a scarce resource which should be well distributed, well utilized and well saved in case the next rainy season would be erratic and the country prone to drought. In urban areas it has been documented that water loss through leakage is a major factor that reduces the quantity (Puttaswamaiah, 2005). There has been significant research on burst pipes or leaking distribution pipes elsewhere (Puttaswamaiah, 2005; Svitak, Metelka & Bojkov, 2011) and in Zimbabwe (Makaya & Hensel, 2014; Punungwe, 2008) but probably little research has been done in Zimbabwe on leaking household taps. This could be attributed to the reason that most people do not think much about the dripping tap, leaky hose, whistling toilet, or swampy sprinkler because its 'just a little drip' (Des Moines Water Works, n.d.). For example, in Australia at Yarra Valley, leakage made up 5% of total usage, and for most homes, was a negligible component of their water usage (Roberts, Athuraliya & Brown, 2011). Therefore, as the major challenge in water distribution is in dealing with leakages (Makaya & Hensel, 2014), and given that water conservation policies and planning procedures need to be backed by strong scientific research findings (Punungwe, 2008), this study could also contribute to the body of knowledge on the problem of household leaking taps.

Statement of the problem

Through prior observation, most households in Mkoba 7 high density area appear to be losing a lot of the precious treated water through leaking taps. Households do not seem to know the exact quantity of water they lose, the monetary value and the environmental impact caused by the accumulating water within the household. It also appears that most households simply ignore the leaking taps for a relatively long time and will only act when real 'disaster' happens.

Purpose of the study

The study sought to mathematically model the amount of water lost due to leaking taps by households in Mkoba 7, Gweru. The study also investigated the economic and environmental impact on the households as a result of leaking water accumulating within the household.

Objectives of the study

The objectives of the study were:

- To investigate the amount of water lost due to leaking household taps by counting and recording the number of water droplets in a given time period and measuring (in liliters) the amount of water that leaked from each tap,
- To model the drops and the amount of water using ODE, data fitting and forecasting,

- To convert the lost water to monetary value using Gweru City Council rates, and
- To analyse the environmental impact caused by the leaking and accumulating water.

Review of Related Literature

Due to the rise in populations of African countries, especially in urban areas, demand for clean water is quite high (UNESCO-WWAP, 2012). Rapid population growth, which is also a characteristic of Sub-Saharan Africa region, has increased water demand for domestic, agricultural and industrial purposes and is causing water scarcity" (Punungwe, 2008, p1). Urban water supply systems in Zimbabwe are stressed because there is low conversion of rainfall to runoff, resulting in an imbalance between available water resources and demand (Mazvimavi, 2003 in Punungwe, 2008). It is estimated that by the year 2025, Zimbabwe will be water stressed (Wilson, 1990 cited in Punungwe, 2008). Therefore there is need to minimize water loss through both short term and long term means.

Research shows that, "A relatively small (3 millilitres) leak in a service pipe, or a dripping tap, under normal working pressure can waste 340 litres (90 US gallons, 75 UK gallons) per day, the amount required to supply the needs of a family of three" (WHO, n.d., p. 107). There is, however, no agreed measurement of a 'drop of water'. The volume of a drop is affected by variables like the size and shape of the outlet the drop is coming through. For example, there are five "faucet drops" in a millilitre, but twenty "eyedropper drops." Even a drop of rain can vary in size depending on factors such as surface tension. What one person considers 'slow dripping' might seem 'fast dripping' to someone else. If one wants to measure a leak, one can count drops for 30 seconds (Des Moines Water Works, n.d.) or count drops for 60 seconds over a certain period of time of say half an hour.

A study carried out in Zimbabwe revealed that in the city of Harare, 36% of the total water supply was being lost monthly. Of the 36% lost water, 33% was lost as leakage water every month. With the Greater Harare area having nearly 200,000 connections, each connection was losing an average of $5.50 every month. Thus, the City of Harare was losing, due to distribution networks, over one million dollars monthly. Therefore, the City of Harare was urged to be proactive in reducing leakages since leakage losses negatively affect service delivery (Makaya and Hensel, 2014). The study however did not investigate the amount of water and money lost due to leaking household taps.

Effects of leaking water taps have been documented. (www.slideshare.net/meenakshidpfoc/what-are-the-effects-of-leaking-pipes/). These include

- indoor flooding which results in spending more money in cleaning and repairing damaged items,
- moulding: fungi which can grow below the sink, under the carpet or on the walls are dangerous to health as they can cause allergies, fever, coughing, sneezing and asthma attacks,
- floors which can become weak,
- metal pipes which can get rusty and weak, and
- deformation of the house, tiles, roof or ceiling.

Leaking water that can accumulate on areas of the house can cause musty smell in the home (http://waterleakdetectors.wordpress.com/2013/04/0/how-water-leaks-can-cause-health-problems/). If the accumulated water is not immediately removed from the floor, it can become contaminated, dirty and may become breeding place for mosquitoes and flies.

Modelling of pipe water leakages in Harare using logistic regression/spatial model (Punungwe, 2008) and South African Night Flow Analysis Model (Makaya & Hensel, 2014) have been done. However, at the time of this research, the researcher failed to get relevant sources on mathematical modelling of water lost due to leaking household taps in Zimbabwe.

Materials and Methods

The researcher had observed the leaking taps during church visits to some of the households in Mkoba 7 High Density Suburb of Gweru City, Zimbabwe. He became interested to found out how much water was being lost due to the leakages. He also became interested to investigate if the collected data could be modelled mathematically. The researcher had intended to purposively sample fifteen households in Mkoba 7 High Density Suburb. However, only ten house owners gave the researcher access onto their premises to observe the leaking taps and take out measurements. The researcher assumed little variation of the data and considered the small sample to produce meaningful results of the model because:

> To accurately estimate a model where the data contain a lot of random variation, it is necessary to have a lot of data. On the other hand, if the data have little variation, it is possible to estimate a model more or less accurately with only a few observations (Hyndman & Kostenko, 2007, p13).

The researcher visited the households on different days and for Households 1-5, he physically counted the number of droplets, measured the time taken (in minutes and seconds) and the amount of water (in milliliters and liters) that was lost. For Households 6-10 water droplets were not counted but the volume of collected water as well as time of observation were measured. The researcher used City of Gweru (Mkoba Suburb) rates for urban household water usage to calculate the amount of money (in US $) that each household could have saved if there were no leakages. The researcher could not establish if the payment rate for water consumption in the City of Gweru was constant or varied from suburb to suburb or depended on type or purpose of settlement. Maybe rates for some type of households were higher than for others. However for the suburb of Mkoba 7 the rates were observed and found to be the same.

Mathematical Modelling techniques/approaches used

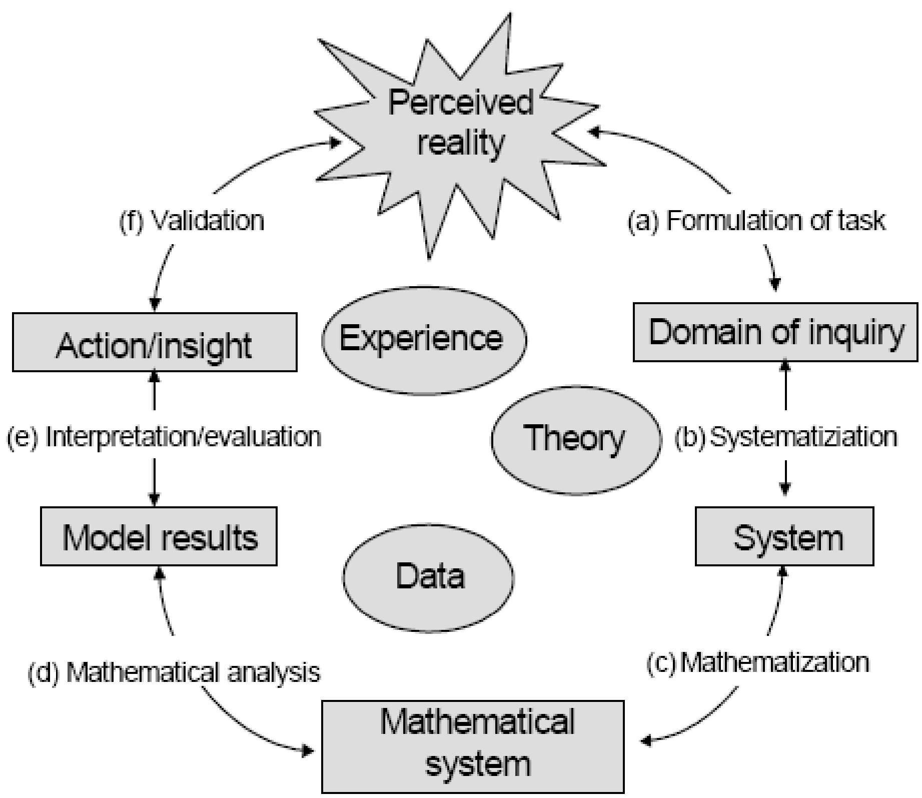
Mathematical modelling techniques of equation generation, equation/data fitting and forecasting were used. In these approaches, data was available (from a process of measurement) to assist in the modelling. The researcher then dealt with the question of how functions or equations could be computed or generated so that they would reflect the relationships between variables in the data. The aim was to produce a model or function $g = f(x,y)$ (Dangelmayr & Kirby, 2005). After producing the model $g = f(x,y)$ a set of input figures were tried resulting in the forecasted figures.

Since the goal in all modelling problems is added value (Dangelmayr & Kirby, 2005), the researcher tried the form of *f* using ODE and assumptions of constant or non constant rates. The assumption of constant rates finally produced reasonable models. The researcher adopted and followed the modelling algorithms suggested by Dangelmayr and Kirby (2005, p10) and these were:

- Identify the problem and questions,
- Identify the relevant variables in a problem,
- Simplify until tractable,
- Relate these variables mathematically,
- Solve,
- Does the solution provide added value?, and
- Make fine adjustments/Tweak the model and compare solutions.

The procedure that was followed can also be represented diagrammatically as in Fig 1 and can be labelled as complex modelling (Frejd, 2014).

Fig 1: Modelling Procedure Followed



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The Modelling Cycle: Adopted from Frejd 2014, Figure 3, p. 15.

Results and Discussion

It was observed that the City of Gweru used different rates for different types of households and also according to type of suburb. High density suburbs paid lower rates than medium density and low density suburbs. Residential rates were also lower than Commercial rates. It was also noted that water leakage also depended on type of tapes used, workmanship and amount of force applied during use or handling, among other variables. Pressure of water flowing through the tap as well as size of the drops could also vary from time to time.

Numerical data that were collected are presented as follows:

Household 1: Tap for Toilet Water Tank
Date of Visit: 01/06/15
Time of Observation: 2103hrs to 2148hours

2103hrs to 2105hrs – 60 drops in 2minutes or 120sec
2105hrs to 2107hrs 23min – 60 drops in 2.383min or 123sec
2111hrs 26min to 2114hrs 48min – 60 drops in 3.366min or 202 sec
2115hrs to 2116hrs 09min – 30 drops in 1.15min or 69 sec
2117 hrs to 2120hrs – 60 drops in 3min or 180 sec
2141hrs to 2142hrs – 60 drops in 1min or 60 sec
2144hrs to 2146 hrs – 60 drops in 2min or 120 sec
2146hrs 03min to 2148hrs 22min – 60 drops in 2.316min or 139sec
Total: 450 Drops in 16.88 min or 1013 sec

This gives about 26.6272 drops per min or 0.44422 drops per sec

Modelling drops and amount of water:

According to MIT (n.d., p2), "The simplest model is that water leaks at a constant rate, independent of the height in the tank. That model is, however, too simple to show interesting behavior" because there could be other variables affecting water leakage such as the height of tank which is proportional to pressure at the bottom. The height is proportional to the amount (L) in the tank which is also proportional to the number of drops (N). Therefore assuming that water leaks at a rate proportional to the number of drops then dN/dt=N, with initial conditions N(0)=0.44422

$\Rightarrow \int \frac{1}{N} dN = \int dt \Rightarrow \ln N = t + c$ where c is a constant

$\Rightarrow N = e^{t+c} = e^t . e^c = Ae^t$ where $A=e^c \Rightarrow A=0.44422$ when t=0.

Therefore after 3600 sec (ie 1 hour) $N= 0.44422.e^{3600}$ = ??? [If one drop was making some noise, what amount of noise would be made by such a number of drops!!!]

An empty container was left to collect the leaking water and in the morning of the following day at 0620hrs, 2.5 liters of water had accumulated in the container. Thus on average, water was leaking at the rate of 2.5 liters per about 9hrs 17min, that is about 0.2693litres per hr.

Assuming that water is lost at a rate proportional to the amount (L), then dL/dt =L with initial conditions L(0) = 0.2693 $\Rightarrow \int \frac{1}{L} dL = \int dt \Rightarrow$ L=Ae^{t}. Therefore after 24 hours (ie 1 day), L= 0.2693.e^{24} = 7 133 520 590 litres, enough for about 35 million people simultaneously flushing their toilets after use!

This would be an 'astronomical' loss difficult to comprehend. However, if we disregard the 'exponential' assumption and consider the simplest model of a constant rate, we would just lose about 0.2693x24=6.4632 litres per day = (6.4632x30) =193.896 liters per month = (193.896x12) =2326.752 litres per year. [If this is just for one household in Mkoba 7 and there are about 900 of them, how much water is lost? How much water does Gweru City lose considering that there are about 20 such villages only in Mkoba?] Mkoba area alone would be losing 2326.752x900x20 = 41 881 536 liters of water, enough for about 2 094 076 people taking a five minute 20 litre shower each or 4 188 153 people at a big church gathering taking a 10 litre bucket bath each!

Household 2: Garden Tap
Date: 05/06/15
Time of observation: 0630hrs – 0811hrs (1 hr 41min)

0630- 0632hrs - 60 drops	0638- 0639hrs - 36 drops
0640- 0641hrs - 34 drops	0642- 0643hrs -33 drops
0644- 0645hrs -33 drops	0646- 0648hrs -64 drops
0654- 0656hrs - 60 drops	0657- 0659hrs - 56 drops
0659- 0701hrs - 60 drops	

After 0701hrs the researcher stopped counting drops and just observed them until 0811hrs.
Total: 436 drops in 14min, giving a rate of 31.1428 drops per min.

Amount that was collected after 1 hr 41 min was 323.86mls. This translates to 0.192392litres/hr=4.617408lit/day= 138.52lit/month=1662.2668lit/year. If water is lost at a rate proportional to the amount collected (L), then dL/dt=L, $\Rightarrow \int \frac{1}{L} dL = \int dt \Rightarrow$ L=Ae^{t}. Therefore after 24 hours (ie 1 day), L= 192.392.e^{24} mls= 5 096 295 185litres per day. However, if we ignore the exponential loss and consider a constant rate then Household 2 would lose just 0.192392x24 =4.617408 litres per day. If they had a 6 month old baby, this would be enough water to bath him/her in one day!

Household 3: Kitchen Tap
Date: 06/06/15
Time of Observation: 1906hrs – 2006hrs

1906.00hrs- 1906.38hrs – 60 drops (38sec)	1908.00hrs- 1908.44hrs – 60 drops (44sec)
1909.00hrs- 1909.47hrs – 60 drops (47sec)	1910.00hrs- 1910.49hrs – 60 drops (49sec)
1913.00hrs- 1913.48hrs – 60 drops (48sec).	Total: 300drops in 226sec or 3.766min.

The number of drops translates to 1.32743 drops per sec. After 1913.48hrs the researcher stopped counting drops but continued to observe what was happening until 2006hrs. The amount of water droplets that was collected after 1 hour was 800mls or 0.8litres. After one day, this kitchen tap would lose about 19.2litres of water ≈ 20l. Imagine that some girls in the rural areas travel about 5-10km to the nearest river to fetch this amount of water, carrying the full bucket on the head all the way back home!

Household 4: Shower Tap
Date: 13/06/15
Time of Observation: 0846hrs-0952hrs

0846hrs-0848hrs 10sec- 60 drops	0850hrs-0852hrs 18sec- 60 drops
0853hrs-0854hrs 9sec- 30 drops	0855hrs-0857hrs 23sec- 60 drops
0858hrs-0859hrs 12 sec- 30 drops	0900hrs-0902hrs 28sec- 60 drops

After 0902hrs 28 sec the researcher stopped counting but continued to observe what was happening. The total was 300 drops in 700 sec or 11.67min. This translates to 0.42857 drops/sec or 25.7142857 drops/min. The drops were left to accumulate in a container and after 1hr 6min they were collected, measured and found to have a capacity of 95.23ml. This translates to 86.5727ml/hr or 0.08657litres/hr. This was concluded to be a slow dripping shower tap.

Household No 5: Bath Tap tightened after use but still leaking
Date: 15/06/15
Time of Observation: 2139-2143hours (4 min)

2139-2140 - 58 drops	2140-2141- 60 drops
2141-2142 - 65 drops	2142-2143- 70 drops

Total number of drops = 253 in 4min.

This translates to 63.25 drops/min or 1.054166 drops/sec. The water that had leaked was collected, its capacity measured and found to be 125 mls. This translates to a rate of 31.25 mls/min = 1875 mls/hr=1.875lit/hr=45lit/day=1350lit/month.

For Households 6-10 the researcher did not count the drops but carried out similar observations and measurements for the taps in the toilet, garden, kitchen, shower room, and bath tab as for Households 1-5 respectively. The results are presented in Table 1 below.

Table 1: Amount of Water lost by Households 6-10

Household	Date of Visit	Time Taken To Observe/Measure	Amount of Water Lost
6	27/06/15	1954-2024 hrs (30 min)	128.5ml
7	05/07/15	0715-0730 hrs (15 min)	70.2ml
8	09/07/15	1900-2245 hrs (225 min)	457.1ml
9	12/07/15	2022-2029 hrs (7 min)	42.9ml
10	18/07/15	1209-1211 hrs (2 min)	50ml

The information for all the households under study is presented together in Table 2 for ease of comparison.

Table 2: Comparison Table for all the Households

	Amount of water lost due to leaking taps (in litres)			
	In 1 hr	In 1 day	In 1 month	In 1 year
Household 1	0.2693	6.4632	193.896	2326.752
Household 2	0.192392	4.6174	138.5222	1662.266688
Household 3	0.8	19.2	576	6912
Household 4	0.08657	2.07768	62.3304	747.9648
Household 5	1.875	45	1350	16200
Household 6	0.257	6.168	185.04	2220.48
Household 7	0.2808	6.7392	202.176	2426.112
Household 8	0.1218	2.9232	87.696	1052.352
Household 9	0.3677	8.8248	264.744	3176.928
Household 10	1.5	36	1080	12960

It is concluded that different taps in the different households leaked at different rates, the smallest being 0.08657 lit/hr and the largest rate being 1.875 lit/hr. The effect is that the tap for Household 5, for example, could be letting the largest amount of 16 200litres of clean water go down the drain by the end of one year. There could be other households in the Mkoba 7 residential area with leaking rates far higher than these.

An analysis of the City of Gweru water charges accounts revealed that a ‘fixed charge’ was billed at US$3.00 per month while a ‘metered charge’ was billed at US$0.60 per kilolitre per month for every household in Mkoba. Using the rate for the ‘metered charge’ the cost of leaking water was calculated. Table 3 shows information to answer the question “How much money could have been saved by each household?”

Table 3: How much money could have been saved by each household?

	Amount of money (in US$) that could have been saved	
	In 1 month	In 1 year
Household 1	0.12	1.39
Household 2	0.08	0.99
Household 3	0.35	4.15
Household 4	0.04	0.45
Household 5	0.81	9.72
Household 6	0.11	1.33
Household 7	0.12	1.45
Household 8	0.05	0.63
Household 9	0.16	1.91
Household 10	0.65	7.78

Table 3 shows that Household 4 was the most economical one since it was losing only 45 cents per year (the smallest amount). An amount of $9.72 is the largest sum of money that could have been saved by Household 5 followed by $7.78 that could have been saved by Household 10 in a year. However there could be other households in Mkoba 7 which are losing more than $10.00 a year which they could have used to buy groceries for a fortnight or for a month. Every penny (cent) counts, no matter how small. 'A stitch in time saves nine.' Zimbabweans like their sub-Saharan counterparts cannot afford to lose even a single cent since "sub-Saharan Africa is the world's poorest and least-developed region, with half its population living on less than a dollar a day" (UNESCO-WWAP, 2012).

Interview Data:
The researcher wanted to find out from the house owners their knowledge on leaking taps, and implications on monetary loss and environmental impact. Some of the house owners (H1-H5) who were interviewed had this to say:

H1*: We don't see the leaking tap. Water just goes down the drain and does not affect my property. It is the Council that loses water, so let it be.*

H2: *We see them but we can't do anything. We tell them to come and repair but they don't.*

H3: *The toilet chamber leaks-it causes flies and mosquitoes to breed. It also causes flies to spoil food since the toilet is close to the kitchen.*

H4*: My carpet got damaged by water that leaked from the kitchen tap, overflowed from the sink and got into the other rooms.*

H5*: My bathroom-tap leaks even after closing it tightly. Sometimes when I am not around children do not clean the bath room and the water that accumulates on the floor becomes dirty and attracts mosquitoes. However, I am aware that I will have to pay more bills at the end of the month. But what can I do since I do not have money to repair the tap now.*

It is not clear whether residents of Mkoba 7 were aware of the monetary effects of leaking household taps and how they could solve the problems. Health aspects such as unpleasant smell and the effect of moulds were not mentioned.

It also seems the issue of leaking household taps is under researched probably because such leakage is negligible, difficult to measure, sensitive to go to people's homes to carry out surveillance unless it is done by City Council

Conclusions
This study concludes that:

1. Some households lack knowledge on the amount of their water that is lost due to leaking taps.
2. Households lack education on the environmental and economic impact of their leaking tap water.
3. By using water wisely, households can help the environment to be clean.
4. Stationary water that has leaked may become breeding place for mosquitoes and flies.

5. Using water-saving techniques could save households significant amount of money each year.
6. The amount of household leaking water may be insignificant but may have long term effects such as destruction to property, health problems and monetary loss.

Recommendations

The study recommends that:

1. The City of Gweru should educate house owners on water efficiency and voluntary use reduction and subsidize use of water-efficient taps, toilets and showerheads.
2. The City of Gweru should educate house owners on the environmental and economic impact of their leaking tap water.
3. Households should engage in community projects that use water wisely and help the environment to be clean.
4. Stationary water that has leaked should be reused in the garden.
5. Households should save money by carrying out leak detection surveys, meter testing and repairs.
6. There is need to carry out more research using mathematical modelling and other techniques in order to provide more data on the amount of household leaking taps and their effects.

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