AN ALTERNATIVE RAINWATER HARVESTING SYSTEM DESIGN METHODOLOGY

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Abstract

Many African cities are growing so rapidly that water supply and reticulation infrastructure cannot keep up with demand. It is therefore important to identify alternative sources of water that can meet current and emerging needs and improve the resilience of supply. One solution is onsite rainwater harvesting systems which capture rainwater from roofs and other surfaces and store this. Stored water can then be used instead of municipal water supplies for drinking, cleaning, irrigation and flushing toilets. While these systems can be highly effective and significantly reduce mains water consumption, they are not widely used in South Africa and there is limited guidance on the design of rainwater harvesting systems. This chapter presents, and critically evaluates, an alternative rainwater harvesting design methodology based on the Rainwater Use Model (RUM). The RUM methodology is compared to conventional methodologies by applying this to a case study building and carrying out rainwater harvesting calculations for different scenarios. Results suggest that the RUM methodology may be more accurate than conventional methods which appear to be optimistic. By enabling different aspects of a rainwater harvesting system to be tested under different conditions the model provides useful guidance on the sizing of components and their optimization as an integrated system The chapter will be of interest to Architects, Engineers, Planners and members of the public interested in developing more resilient and sustainable water resources in buildings and human settlements.

Keywords: Rainwater harvesting, estimating tools, calculators

INTRODUCTION

Many African cities are growing so rapidly that water supply and reticulation infrastructure cannot keep up with demand (WWAP, 2017). The World Resources Insitute indicates that there are significant drought and water stress risks in many parts of Africa and classify most of Southern Africa as ‘high’ or ‘very high’ risk (World Resources Institute, 2020).

An effective way of addressing water risks and increasing the resilience and reliability of water supplies in built environments is to draw on alternative supplies such as an onsite rainwater harvesting system, which captures rainwater so it can be used for drinking, washing, irrigation and other functions.

This chapter aims to contribute to knowledge about how rainwater harvesting systems can be designed. In particular, it aims to provide a better understanding of how systems can be designed to respond to their particular climate and rainfall patterns as well as the water needs within and around buildings.

It has the following structure. Firstly, a context for the study is provided by describing water scarcity and its prevalence in Africa. Secondly, the methodology applied in the study is outlined. Thirdly, results are presented. Fourthly, results are discussed and conclusions and recommendations are drawn.

CONTEXT
The United Nations Environmental Programme (UNEP) estimates that 450 million people in 29 countries suffer from water shortages (UNEP, 2008). Within Africa, many countries experience either physical or economic water scarcity. Economic water scarcity is where access to water is limited by human, institutional or financial capital, even though water may be available locally. Scarcity here may, therefore, be a result of a lack of water infrastructure, or the capacity and finances to keep this running. Other countries experience physical water scarcity which is where countries reach a point where there is insufficient water.

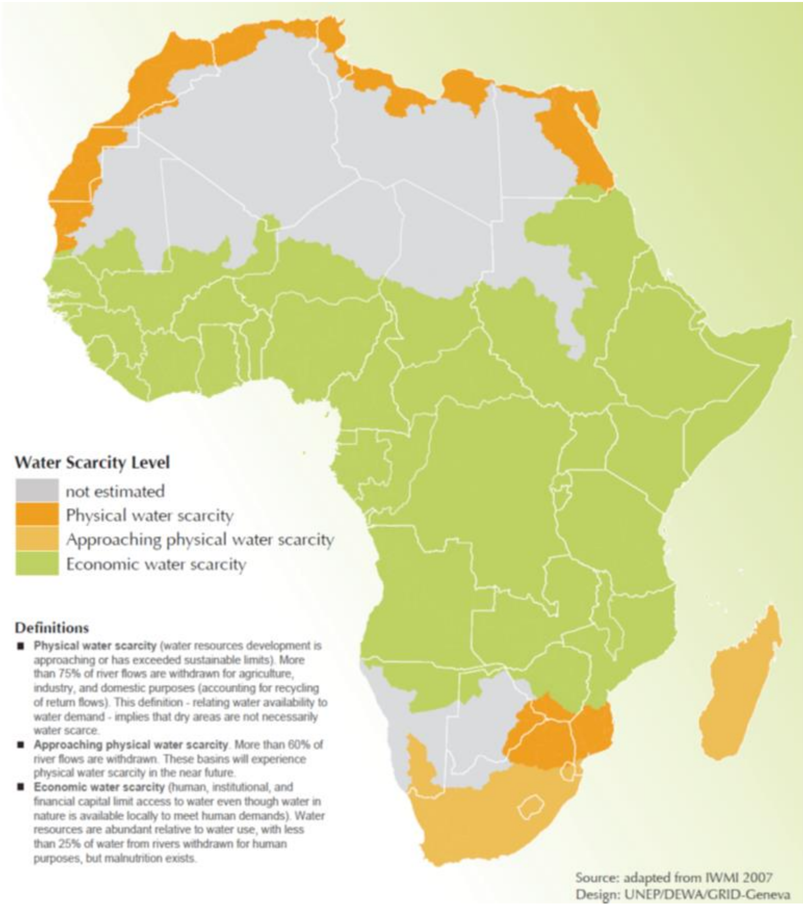

Figure 1: *Areas of physical and economic water scarcity in Africa (UNEP, 2014)*

Physical and economic water scarcity in Africa is shown in Figure 1. Areas on light orange, are nearing physical water scarcity, and areas with deep orange experience water scarcity (UNEP, 2014). Figure 1 shows that some areas of South Africa already experience physical water scarcity and that most of the rest of the country will face this soon.

Climate change is exacerbating this situation. Projections by Engelbrecht (2016) indicate that temperatures will increase by 1 to 3°C in South Africa in the period 2021 to 2050, relative to temperatures in the period 1961 – 1990. They also show reductions in rainfall many areas of South Africa over the period 2021-2050, relative to 1971 – 2000.

METHODOLOGY

The study evaluates an alternative method for designing rainwater harvesting systems in buildings. This is carried out in the following way. Firstly, the case study building and climate are described. Secondly, two different methods of designing rainwater harvesting systems are described and applied to the case study house. Thirdly, the results from the two approaches are presented. Finally, results are discussed and conclusions and recommendations developed.

Case study

The case study is a house in Pretoria South Africa (25.7479° S, 28.2293° E). The average annual rainfall for Pretoria based on records between 1981 and 2010 is 692 mm (South African Weather Service, 2019). Recent records indicate that annual rainfall for 2019 was 773mm (South African Weather Service, 2019). Most rain falls in the summer months and winters are dry as shown in Figure 2.

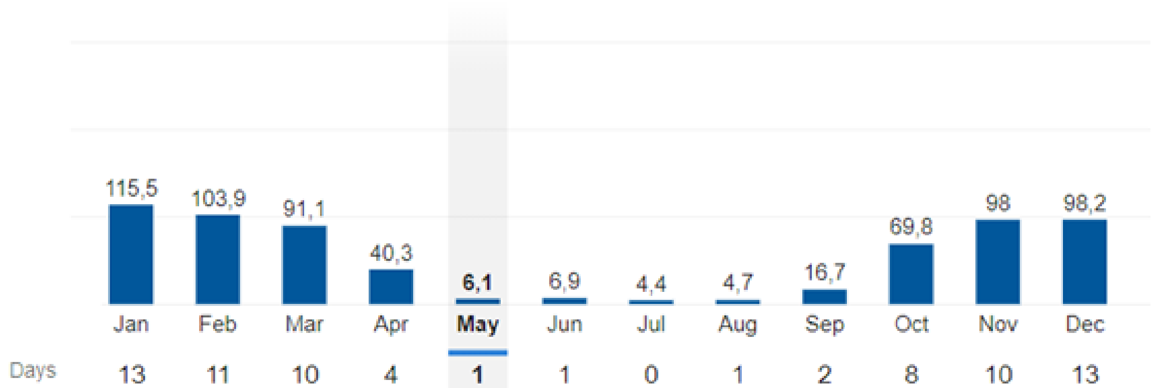

Figure 2: *Pretoria rainfall (National Centers for Environmental Information, 2020)*

An analysis of rainfall in Pretoria shows that there is considerable variation between years, as illustrated in Figure 3. To reflect this variation, two scenarios are used in the study; a drier year with about 500 mm annual rainfall and a wetter year with about 700 mm rainfall.

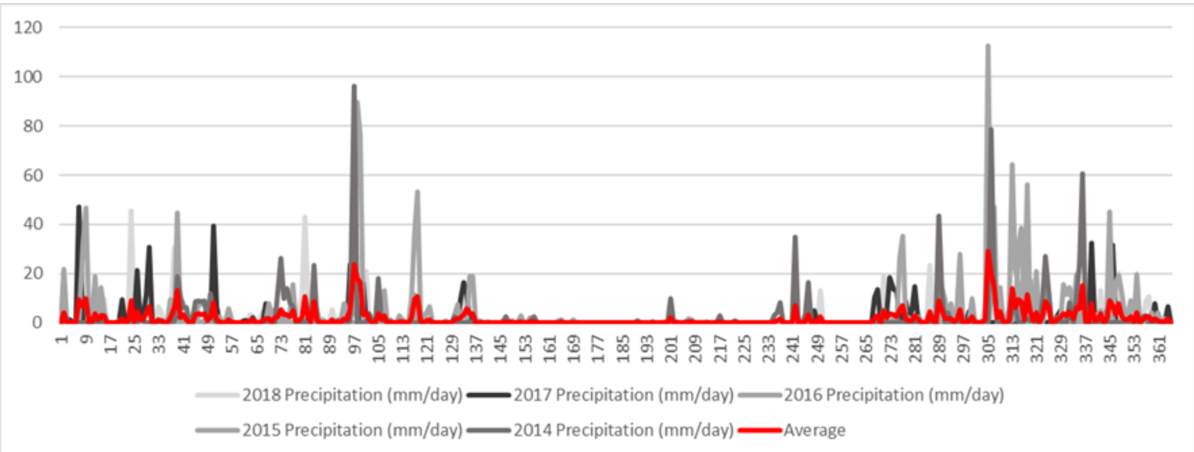

Figure 3: *Annual rainfall patterns in Pretoria, South Africa.*

The case study is a 200 m^2 house with 100 m^2 outbuildings. The house and outbuildings have corrugated iron roofs at a 30^0 pitch and gutters on all sides that catch runoff. Gutters from the buildings have downpipes that can easily be directed into rainwater tanks to capture rainwater.

The two sets of roofs provide the second set of scenarios. The first scenario is based on the rainwater harvesting system only using the roof of the house, so the catchment area is 200 m^2. The second scenario is based on both the house and the outbuilding roofs resulting in a catchment area of 300 m^2. The final set of scenarios explore the implications of two different sized rainwater tanks, a 40,000 L and a 50,000 L tank.

The house is occupied by four people and has water-efficient fittings resulting in average water consumption of 80 L per person per day for all their water needs. The house has an indigenous garden and there is no irrigation. The occupants wish to be water-neutral and meet all of their needs from rainwater harvesting. The figure of 80 L a day is the benchmark used for a water-efficient home (Department for Communities and Local Government, 2010). This figure was cross-checked by modelling the case study house using the Water Use Model (WUM) and a figure of 80 L per day was found to be realistic for a house occupied by 4 people with efficient water fittings (Gibberd, 2019).

Rainwater harvesting calculation methods

Centre for Affordable Water and Sanitation Technology (CAWST)

The most common rainwater harvesting calculations use the equation outlined below as an input for the design of rainwater harvesting systems (Centre for Affordable Water and Sanitation Technology, 2011). As these equations are included in guidance developed by the Centre for Affordable Water and Sanitation Technology (2011) this approach will be referred to as the CAWST methodology.

The CAWST methodology calculates the quantity of available rainwater supply based on the following information:

- Amount of rainfall
- Catchment area
- Runoff coefficient

The following equation is used to calculate the maximum amount of water that can be supplied by a particular catchment area:

Rainwater supply (m^3/year) = Rainfall (m/year) x Catchment Area (m^2) x Runoff Coefficient.

Rainwater tank sizes are based on the meeting the water requirements of the longest dry period of the year and are calculated using the following equation.

Size of rainwater tank required (L) = Longest dry period (days) x daily water consumption (L)

Rainwater Use Model (RUM)

The Rainwater Use Model (RUM) has been developed by the author. It provides graphs of water consumption, rainfall, and water in rainwater tanks over a year to help to understand the dynamics of a rainwater harvesting system. The model enables different water consumption rates, rainfall years, catchment areas and tank size scenarios to be applied and the impacts ascertained. This process provides valuable guidance that can be used to help size rainwater tanks and catchment surfaces. The following data is required for the RUM.

- Daily rainfall patterns over a year
- Daily water requirements over a year
- Catchment area
- Runoff coefficient

The RUM uses this information to calculate the water used and drawn from rainwater harvesting tanks as well as the water volumes harvested from rain and directed to tanks each day. This provides the daily water level in rainwater tanks which can be tracked over a year. Stored water is restricted to the volume of the tanks. Examples of the type of graph generated by the RUM are shown in Figures 5, 6, and 7.

Both methods use runoff coefficients to ensure that losses associated with evaporation and partial infiltration of the collecting surfaces are taken into account. Runoff coefficients depend on physiographic characteristics of the collection area and are expressed as a constant between zero and one. Table 1 shows the runoff coefficient of common roof types.

Table 1: Runoff coefficients of common roofs (Farreny** et al.**, 2020).

Roof type	Runoff coefficient
Sloping corrugated metal roof sheeting and tiled roofing	0.9
Flat concrete roofing with gravel topping	0.8

RESULTS

CAWST

Applying the Centre for Affordable Water and Sanitation Technology (CAWST) equation to the case study house generates the following results.

- Amount of rainfall: 500 mm
- Catchment area: 200 m^2
- Runoff coefficient: 0.9 (for a corrugated iron roof)

Rainwater supply (m^3/year) = Rainfall (m/year) x Catchment Area (m^2) x Runoff Coefficient
Rainwater supply (m^3/year) = 0.5 x 200 x 0.9
Rainwater supply = 90 m^3 or 90,000 L

This rainwater supply can be compared to water requirements by calculating the water requirements for the house as follows.

- Number of occupants: 4
- Consumption per occupant: 80 L
- Number of days: 365

Annual water requirements (L) = number of occupants x consumption per occupant x number of days

Annual water requirements (L) = 4 x 80 x 365
Annual water requirements (L) = 116,800 L

In this example, as the annual requirements (116,800 L) are higher than the rainwater harvesting supply (90,000 L) the CAWST calculations indicate that the rainwater harvesting system would not be able to meet the water requirements of the house.

The CAWST calculations for the size of the rainwater tanks are outlined below.

Size of rainwater tank required (L) = Longest dry period (days) x daily water consumption (L)

A review of Figure 1 indicates that the longest dry period is approximately 120 days.

Size of rainwater tank required (L) = 120 x 320
Size of rainwater tank required (L) = 38,400 L (This can be rounded up to 40,000 L)

These CAWST equations are applied to the different scenarios described in the methodology to produce the results shown in Table 2.

RUM
The same data and scenarios used in the CAWST are applied to the RUM to provide the results outlined below. The RUM provides a picture of rainfall patterns over the year and this is shown in Figure 4.

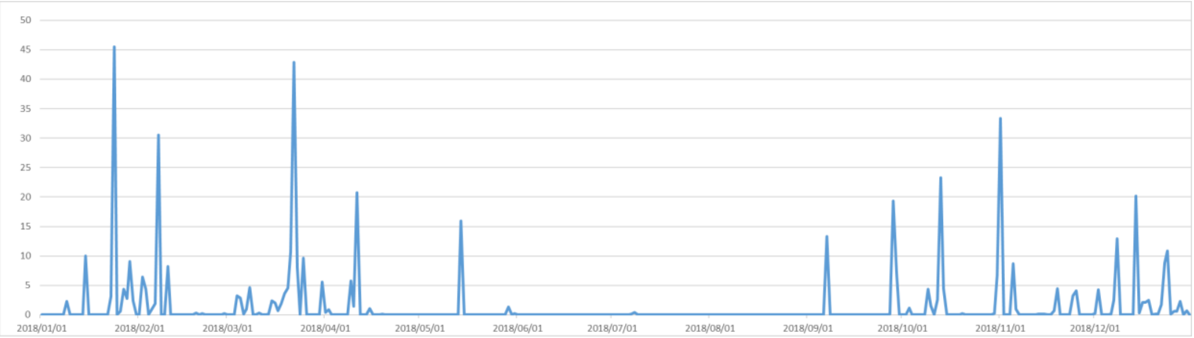

Figure 4: *Rainfall patterns over a year using the RUM.*

Figures 5 – 7 show RUM reports on rainwater capture, storage and use over a year for the case study house for the different scenarios. On these reports, the blue line show rainwater captured in litres over the year. This aligns with the rainfall pattern shown in Figure 4 and is calculated by multiplying daily rainfall by the catchment area by the runoff coefficient.

The orange line shows water consumption over the year and this is 320L per day. The yellow line shows water levels in the rainwater tanks over the year and is calculated in the following way. Rainwater harvested is directed into the tanks and therefore when there is rain, the daily volumes of water captured are reflected as an increased water level. These increases are apparent in Figure 5 around 2018/04/01 when there was heavy rain. As water is used, it is drawn from the tanks at a rate of

320 L per day. This shown as reductions in water level and this can be seen for the long dry period between 2018/04/01 to 2018/10/01 as shown in Figure 5.

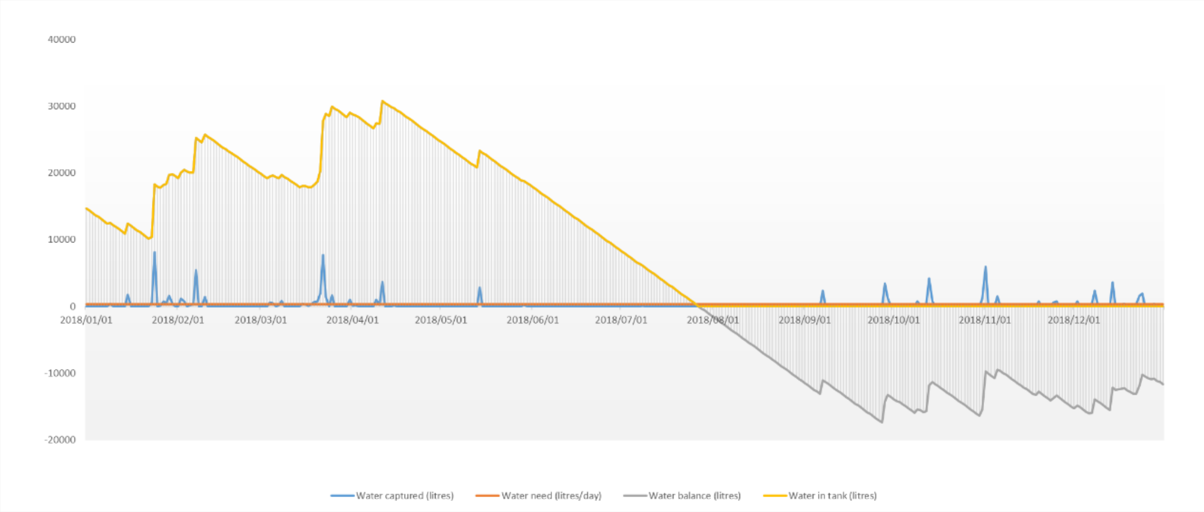

Figure 5: *Rainwater capture, storage and use over a year with a 500 mm annual rainfall, 40,000 L rain tank and 200 m^2 catchment surface.*

Figure 5, with 500 mm annual rainfall, a 40,000 L tank and a 200 m2 catchment area shows that the rainwater tanks are empty for part of the year (shown by the dark line that goes under zero). This suggests that a 40,000 L tank and a 200 m^2 catchment area would not be sufficient to meet the house's water requirements.

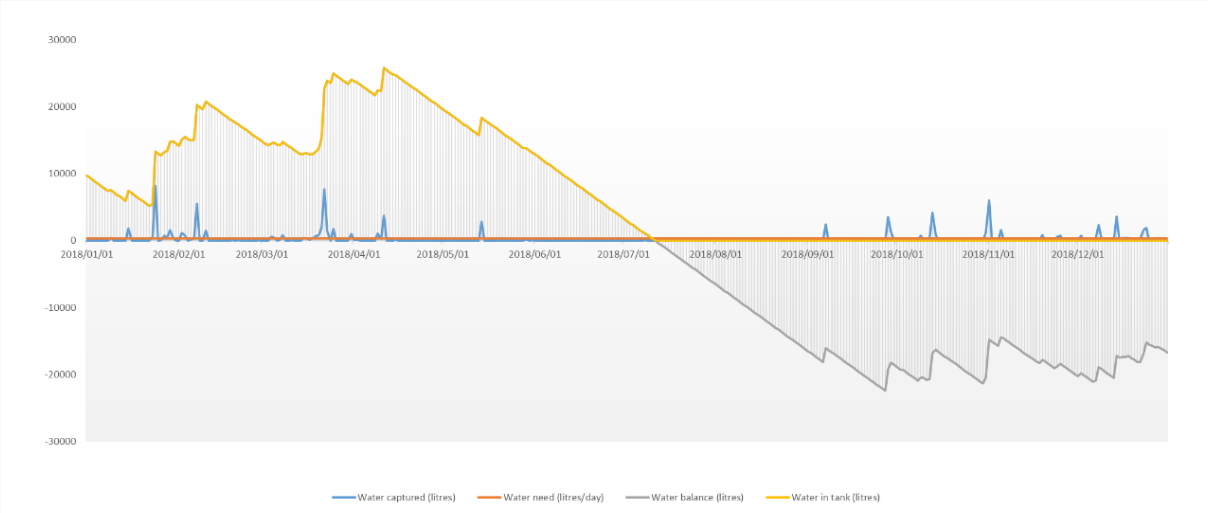

Figure 6: *Rainwater capture, storage and use over a year with 500 mm annual rainfall, 50,000 L rain tank and 200 m^2 catchment surface.*

Figure 6, with 500 mm annual rainfall, a 50,000 L tank and a 200 m^2 catchment area shows that the rainwater tanks are empty for the part of the year. This suggests that a 50,000 L tank and 200 m^2 catchment area would also not be sufficient to meet the house's water requirements.

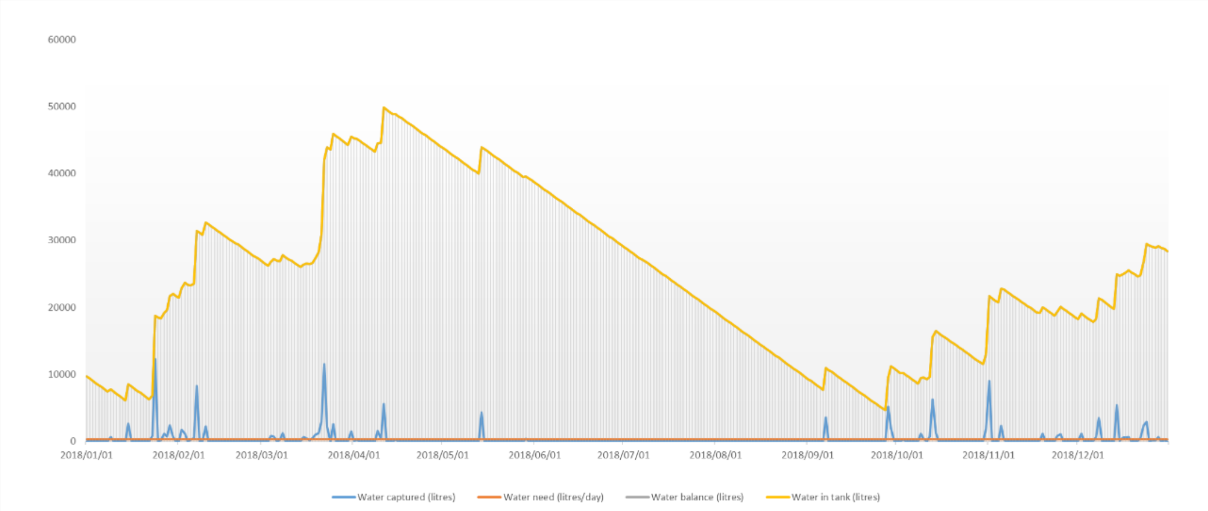

Figure 7: *Rainwater capture, storage and use over a year with 500 mm annual rainfall, 50,000 L rain tank and 300 m² catchment surface.*

Figure 7, with 500 mm annual rainfall, a 50,000 L tank and a 300 m^2 catchment area shows that the rainwater tanks have about 5,000 L left in them after the longest dry spell. This suggests that a 50,000 L tank with a 300 m^2 catchment area could meet the house's water requirements and provide a safety margin.

The eight scenarios reflecting variations in annual rainfall, catchment area and sizes of rainwater tanks are presented in Table 2 as Scenarios A – H. Results based on calculations using the CAWST and RUM methodologies are shown in the right-hand columns. The 'Sufficient to meet house needs' indicates whether the methodology calculates if the rainwater harvesting system proposed in the scenario will meet the water needs of the house.

Table 2: *CAWST and RUM results for different scenarios.*

Scenario	Annual rainfall (mm)	Catchment area (m^2)	Rainwater tanks sizes (L)	Sufficient to meet house needs? CAWST	RUM
A	500	200	40 000	No	No
B	500	300	40 000	Yes	No
C	700	200	40 000	Yes	No
D	700	300	40 000	Yes	Yes
E	500	200	50 000	No	No
F	500	300	50 000	Yes	Yes
G	700	200	50 000	Yes	No
H	700	300	50 000	Yes	Yes

DISCUSSION

CAWST results suggest that it is not possible to supply the case study house with its requirements for water from rainwater harvesting during a year when there is 500 mm rainfall using a rainwater harvesting system with a 200 m^2 catchment area and 40,000 L tanks. They, however, suggests that this is possible if the rainwater catchment surface is increased to 300 m^2. In years when there is 700 mm rainfall, they indicate that a system with 200 m^2 and with 300 m^2 catchment area and 40,000 L and 50,000 L tanks are sufficient to meet rainwater needs

RUM results suggest that it is not possible to supply the case study house with its requirements for water from rainwater harvesting during a year when there is 500 mm rainfall, using a rainwater harvesting system with 40,000 L tanks for both a 200 m^2 and a 300 m^2 catchment area. They, however, suggests that this is possible when a larger catchment surface of 300 m^2 and a larger tank of 50,000 L is used. In years when there is 700 mm rainfall, RUM results indicate that systems with 300 m^2 catchment area and both 40,000 L and 50,000 L tanks would be sufficient to meet water needs. The RUM results, however, indicate that systems with a smaller catchment area of 200 m^2 would not be sufficient to meet water needs.

These results are interesting for several reasons. Firstly they show that the CAWST methodology has more optimistic results. These results may be correct if there is heavy rainfall towards the end of the rainy season. This ensures that there is sufficient water in rainwater tanks (as these are full) for the dry season. However, if rainfall tapers off towards the end of the dry season, the tanks will not be full at the beginning of the dry season and there may be insufficient water to meet requirements. As the RUM methodology takes this ‘tapering-off’ into account it is likely to be more accurate and conservative in estimating system performance.

The RUM results are also interesting in that they highlight the importance of catchment surface area. In the case of the scenarios with 500 mm annual rainfall, they show that increasing tank sizes is not sufficient to ensure water requirements are met (Scenario E). Instead, they indicate that increasing catchment area (Scenario F) provides sufficient conditions for water needs to be met. This is an interesting result because it shows the importance of a large catchment area *as well as* large water tanks in areas with long dry periods. Thus, to have an optimal system, it is important to balance investment in rainwater tanks with investment in collection areas.

The relatively long dry season for Pretoria requires large volumes of water to be captured and stored. In this case, a minimum volume of 50,000 L is required. Standalone rainwater tanks are available in 5,000 and 10,000 L sizes enabling storage requirements to be visualized. Thus, ten 5,000 L round tanks (diameter 1,820 mm, height 2,255 mm) could be used. This has a footprint of about 40 m^2. Alternatively, five 10,000 L round tanks (diameter 2,200 mm, height 3,150 mm) which take up 32 m^2 could be used. The footprint areas required for rainwater tanks thus represents 16-20% of the floor of the house, which is substantial. Ratios for other aspects of the rainwater harvesting system in the case study have been calculated and are set out in Table 3.

Table 3: *Rainwater harvesting system ratios for the case study*

Ratios	**Per person**	**Per m^2 of accommodation**
Water consumption	80 L/person/day	1.6 L/m^2/day
Rainwater harvesting catchment area required	75 m^2	1.5 m^2
Volume or rainwater harvesting tanks required	12,500 L	250 L
Footprint of rainwater tanks (using 5,000 or 10,000 L tanks)	10 m^2	0.2 m^2

The first line shows water consumption per person and per m^2 of the occupied house (not the outbuildings). The second line shows the catchment area required per occupant and per m^2 of the house. The third line shows the volume of rainwater harvesting tanks required per occupant and per m^2 of the house. The last line shows the footprint required to accommodate rainwater tanks if standard 5,000 L or 10,000 L round tanks are used. These ratios provide interesting results and it may be valuable to explore them further as a basis for rainwater design ‘rules-of-thumb’.

The ratios indicate the substantial requirements of a rainwater harvesting system that is designed to meet all of the water needs of occupants in an area like Pretoria with a 4-month dry season. Of particular interest is the extent of the catchment area required which is greater than the size of the occupied house. This indicates that unless water consumption can be reduced, catchment areas, in this case, need to be about 150% of the accommodation area in single-storey accommodation. This can be achieved in residential areas with free-standing houses but may require collaborative agreements in high-density areas where commercial buildings such as offices and retail with low water requirements share their harvested rainwater with neighbouring housing.

The costs of this type of self-sufficient system are also likely to be significant. Capital costs for the 5,000 L and 10,000 L standalone tanks (described above) as well as bases, pumps and reticulation are estimated to be about R70,000 in 2020. Applicable Pretoria water tariffs for 2019-2020 are R16.56/kL (City of Tshwane, 2019). This tariff can be multiplied by the water harvested by the system and used (117 kL) to calculate potential savings generated by the system which are about R2,000 per year.

A simple calculation that does not take into account future tariff increases and operating and maintenance costs indicate that the payback period of the rainwater harvesting system would be about 30 years. On this basis, the economic feasibility of rainwater harvesting system in the case study is not strong. However, it should be noted that factors such as water tariff escalation, tariff increases applicable during water restrictions, and the possibility of water outages considerably strengthen the case for rainwater harvesting as the location of the case study is in an area approaching physical water scarcity (see Figure 1) (UNEP, 2014; City of Tshwane, 2019). A review of Figure 1 indicates that large areas of Africa have economic water scarcity and have limited local water infrastructure. In these areas, self-sufficient rainwater harvesting systems such as the one presented in this case study may be considered as an alternative to conventional water infrastructure and are likely to have a stronger economic case.

CONCLUSIONS AND RECOMMENDATIONS

This chapter critically evaluates an alternative rainwater harvesting design methodology based on the Rainwater Use Model (RUM). The RUM and conventional methodologies are applied to a case study building to project rainwater harvesting system performance for different scenarios. These results indicate that the RUM methodology is likely to be more accurate than conventional methods.

It also provides useful insights into the nature of a rainwater harvesting system designed to meet all of the water needs of a case study house in Pretoria. These include the significant catchment area and water storage requirements needed to be water self-sufficient. The study suggests that the economic case for a self-sufficient rainwater harvesting system in the case study area is weak currently but that this may become stronger as water scarcity increases.

By enabling different aspects of rainwater harvesting systems to be tested rapidly, the RUM methodology provides useful guidance on the design of a rainwater harvesting system. The methodology also supports the development of outline 'rules-of-thumb' for rainwater harvesting design which will be explored in further research.

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