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Research paper

The prospects for rainwater harvesting at the University of Cape Town

Tšepiso Lepota[1] and Neil Armitage[1]

[1]*Department of Civil Engineering, University of Cape Town, Private Bag X3, Rondebosch 7701, South Africa*

The viability of rainwater harvesting (RWH) as a fit-for-purpose water source for supply at the University of Cape Town (UCT) was investigated to reduce dependence on municipal water treated to unnecessarily high standards for purposes like toilet-flushing. Representative buildings on the UCT Upper and Middle Campuses, a parking area, and the tennis court on Upper Campus were identified as potential catchment areas. The 'Yield after spillage' (YAS) algorithm was used to identify the relationship between water demand and supply for various flush frequencies and storage sizes. The cost savings from harvested rainwater were estimated using the City of Cape Town (CoCT) 2021/2022 tariffs for Level 1 and Emergency Response water restrictions. A 20-year discount period and a 4% interest rate were used to determine the capital recovery amounts of the cost of ownership of the RWH systems. A multi-criteria analysis (MCA) tool that considered 3 weighting scenarios of the harvestable rainfall and economic viability was used to identify the most viable RWH systems. It was found that student residences could potentially reap the greatest benefits from installing RWH systems. Approximately 4 900 kL·yr^{-1} and 4 000 kL·yr^{-1} of rainwater can be harvested from Woolsack and Fuller Hall, respectively, if 100 kL tanks are provided, depending on the toilet flush frequency. The tennis court was identified as the most viable catchment for RWH. Approximately 7 500 kL·yr^{-1} of rainwater could be harvested if 1 000 kL tanks are provided when the rainwater from the tennis court catchment is supplied to all Upper Campus buildings. It was also concluded that UCT is in a relatively good location for RWH due to its rainfall pattern as compared with those enjoyed by other universities across South Africa.

CORRESPONDENCE
Neil Armitage

EMAIL
Neil.Armitage@uct.ac.za

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INTRODUCTION

Water shortages have detrimental effects on the well-being of people and the ecosystem. This was evident when the lives of the people of Cape Town almost came to a standstill because of a 3-year drought between 2015 and 2018. When dam levels dropped below 20% in 2018, the City of Cape Town (CoCT) started preparations for 'Day Zero' – the day when taps would run dry. Climate models have predicted a decrease in mean rainfall together with an increase in temperatures in the future, thereby increasing the risk of water shortages (Stafford et al., 2018). South Africa (SA), as a water-scarce country, needs local authorities to start investigating measures that will provide resiliency against drought, for example, by developing adaptive water infrastructure and water services, and promoting water sensitivity among all users.

Large developments like universities have significant water demands. Water is used for heating and cooling systems, toilet-flushing, drinking, irrigation, cooking in cafeterias or kitchens, in laboratories, and for recreational activities such as swimming. This suggests the need for water demand management (WDM) practices such as the implementation of alternative or fit-for-purpose water supply technologies (EL-Nwsany et al., 2019; Almeida et al., 2021).

On 12 February 2020, the University of Cape Town (UCT) made a call for projects that address environmental, social, and financial sustainability across its campuses as part of its mission to contribute to sustainability, resilience, and water sensitivity. EL-Nwsany et al. (2019) promote exploration of the use of alternative fit-for-purpose natural water sources such as rainwater as part of sustainable water management (SWM) in academic institutions. This research thus investigated the viability of rainwater harvesting (RWH) as a fit-for-purpose water source for supply at the university scale to reduce UCT's dependence on municipal water treated to unnecessarily high standards for purposes like toilet-flushing.

LITERATURE REVIEW

RWH is the collection of rainwater directly from the roof or surface collection systems and stored in rainwater tanks or other storage facilities for later use or groundwater recharge (Hamdan, 2009; Despins et al., 2009; Chanan et al., 2010; Sung et al., 2010; Armitage et al., 2013; Ayog et al., 2016). The rainwater collected from roofs is generally of better quality than the rainwater collected from ground surfaces since roofs are generally cleaner (Amin et al., 2013).

Potable water is frequently used for both domestic and commercial activities that could otherwise be fulfilled using non-potable water, while industries and institutions still rely heavily on conventional centralised water supplies (Kloss, 2008). Doyle (2008), Lade and Oloke (2015), Fisher-Jeffes (2015), and Amos et al. (2016) all note that most studies on RWH systems focus on domestic use; however, there have also been studies on the use of RWH for commercial or institutional uses (e.g., Ndiritu et al., 2014; Lani et al., 2018; Andavar et al. 2020; Ariyani et al. 2021; and Almeida et al. 2021). It allows for potentially substantial savings in the use of potable water for non-potable uses such as irrigation and toilet-flushing – which in turn reduces water bills and promotes sustainability (Chiang et al., 2013; Ndiritu et al., 2014).

RWH systems can be cheaper and easier to operate and maintain than other alternative water supply sources (Chiang et al., 2013).

Success with the implementation of RWH is dependent on: rainfall; the size, age, location, and layout of buildings (for roof catchments); and the capital and running costs (Hamdan, 2009; Mohammed, 2018). RWH is not generally viable in areas that have hot and dry climates due to the low volumes of harvestable rainfall (Almeida et al., 2021). RWH also requires water quality monitoring, especially if the rainwater is harvested for potable uses.

The most important factor in the design of the RWH system is the storage capacity because this determines key elements of system performance such as the yield and thus the volume of potable municipal water conserved, and the average detention time of the rainwater, which impacts its quality. The storage capacity is also generally the largest factor in the total installation cost of a RWH system (Fewkes and Butler, 2000; Campisano and Modica, 2012; Matos et al., 2014).

Several RWH models can accommodate seasonal changes, a fluctuating demand, and the use of a range of time intervals (e.g., hourly, daily, etc.) that are necessary to estimate the storage requirement and resulting performance of RWH systems (Fewkes, 1999; Fewkes and Butler, 2000; Mitchell, 2007; Campisano and Modica, 2012). These include: the Rippl method; the Yield Before Spillage (YBS) method; and the Yield After Spillage (YAS) – all typically using a daily mass balance (Fewkes and Butler, 2000; Matos et al., 2014). Of interest to this research were the YBS and YAS approaches developed by Jenkins et al. (1978).

Mitchell (2007) preferred the YAS algorithm for the analysis of the storage–yield relationship as it provides a more conservative estimate of yield regardless of the time step used. This is because YBS models assume that all rainwater passing through the tanks is available for use during the time step without any allowance for spillage which is calculated at the end after deducting for demand. Hajani and Rahman (2014), who used the YBS algorithm in their study to investigate the water savings and financial viability of RWH systems, found that the algorithm typically results in a 10–15% percent higher estimate than YAS. Fewkes and Butler (2000) determined that YAS calculations using monthly time steps result in uneconomically large storage sizes compared with those determined using daily time steps. When the use of hourly time steps was compared to the use of daily intervals, it was found that the differences in results were small, suggesting that a daily time step is satisfactory for use and that the use of hourly data is both unnecessary and labour-intensive, as the smaller time steps require much more rainfall data and highly detailed information on demand use patterns (Fewkes, 1999; Campisano and Modica, 2012).

The viability or suitability of a RWH system in terms of its performance can be assessed from several criteria, depending on the requirements of the design or analysis (Fisher-Jeffes, 2015). For example, the RWH system could be used to primarily reduce the runoff volume (and reduce flooding); alternatively, it could be focused on ensuring continuous water supply using rainwater. As a result, different indicators have been developed to assess the performance of RWH systems:

- Volumetric reliability (also known as water-saving efficiency, WSE) is the percentage of potable water conserved (yield) compared to the overall demand (Fewkes and Butler, 2000; Campisano and Modica, 2012; Hajani and Rahman, 2014; Almeida et al., 2021).
- Time-based reliability considers the length of time when the demand is met. Alternatively, the dry cistern frequency is the percentage of days when the demand is not met with rainwater (Fisher-Jeffes, 2015).
- The runoff reduction is the percentage of total precipitation captured by the system.

In all cases, the reliability of a RWH system is highly dependent on the rainfall variability, the catchment characteristics (particularly the area), the tank size, and the water demand pattern (Preeti and Rahman, 2021).

The total costs of a RWH system project are usually compared to the total benefits achievable to help decide whether the project is worth pursuing. To be considered economically viable, the economic benefits of a project need to exceed the economic costs (Dandy et al., 2013).

METHOD

Figure 1 presents the research method followed. First, the most appropriate uses of the harvested rainwater on the UCT campus

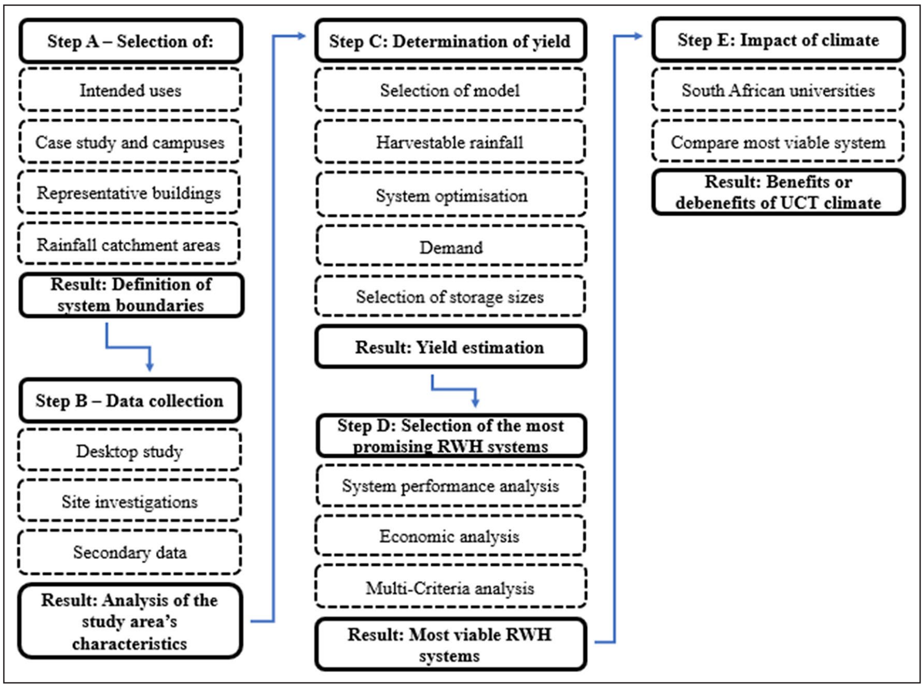

Figure 1. The research framework (adapted from Dandy et al. (2019))

were identified. Then, representative buildings and other rainfall catchment areas for the analysis were selected. Relevant details of the catchments and water users were collected through desktop studies and site investigations. The yields from the prospective RWH systems were then calculated using the YAS algorithm, considering the harvestable rainfall, various demands and storage. The most promising RWH systems were then identified based on the volume of harvestable rainfall and the economic performance in a multi-criteria analysis (MCA). Finally, the potential for RWH at other universities across SA within different climatic regions was compared with UCT.

Location of case study

UCT is spread over several campuses around Cape Town, Western Cape (WC) Province, and is the oldest university in SA. Only the Upper and Middle Campuses (Fig. 2) were assessed for RWH at UCT, based on their topography (a steeply sloping site makes gravity supply from a roof catchment to a down-slope building possible), availability of suitable storage areas, variability of building types and the size of potential demand compared to the other campuses.

The Upper Campus has an approximate area of 0.41 km^2 and is mainly occupied by mixed-use buildings with only a few solely devoted to offices or lecture theatres. It is located on the western side of the M3 Rhodes Drive Road – an arterial that connects the upper part of the City Bowl and the Southern Suburbs of Cape Town – and extends up a portion of the eastern slopes of Table Mountain. The Middle Campus, which houses many of UCT's administrative activities, has an approximate area of 0.21 km^2. It is located on the eastern side of the M3 Rhodes Drive Road and extends down the mountain slope almost as far as the M4 (Main Road) in Rondebosch. The M4, which is parallel to the M3, connects the central business district (CBD) with the Cape Peninsula. The campuses also accommodate parking areas and sports grounds. The parking areas are variously covered by impermeable asphalt, brick paving or permeable interlocking pavements (PICP). Figure 3 indicates the location of the selected representative buildings used for the analysis. The characteristics of the representative buildings (Fig. 4) are listed in Table 1.

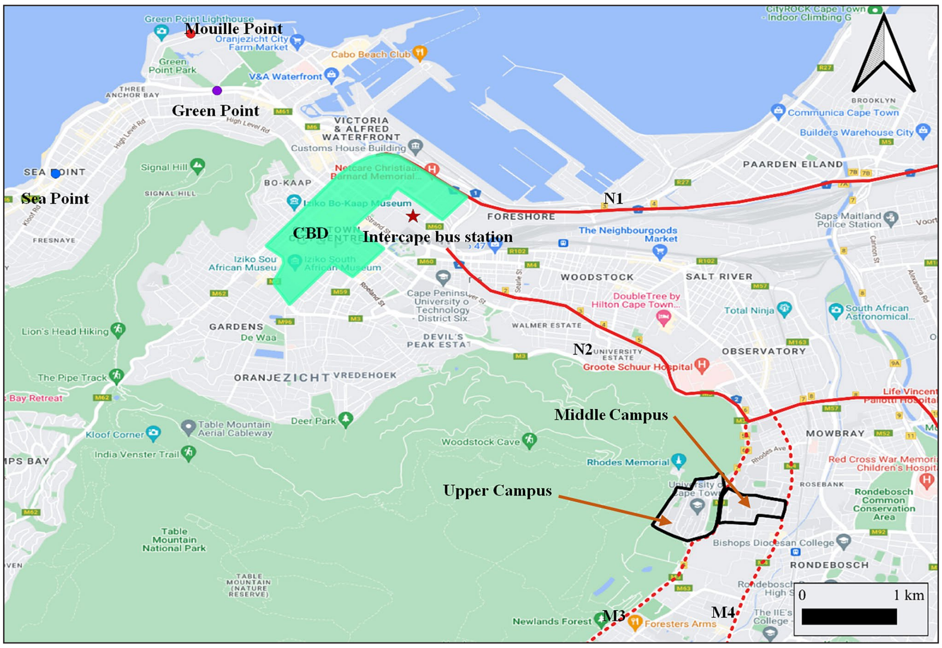

Figure 2. Location of Upper and Middle Campuses of UCT within Cape Town

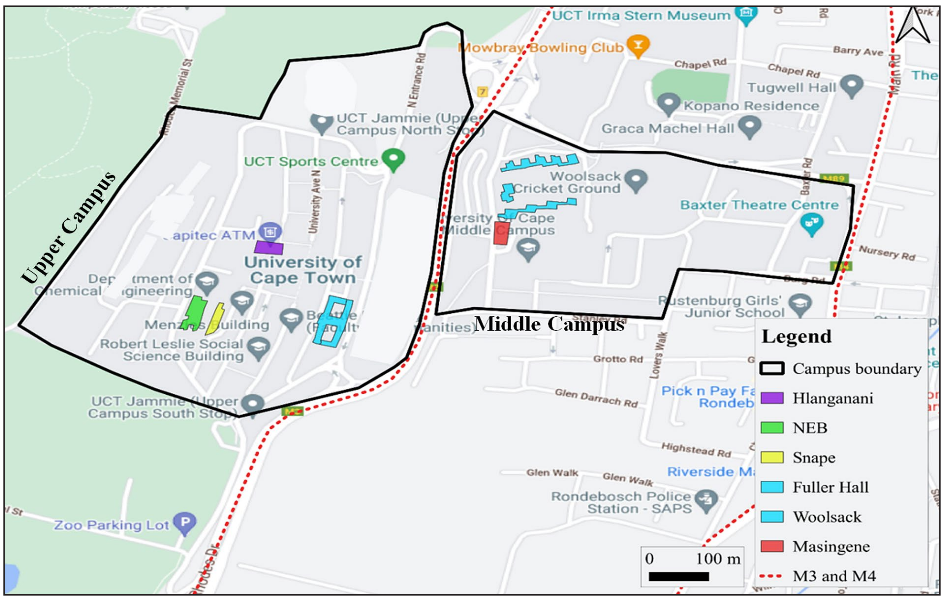

Figure 3. Location of the selected representative buildings

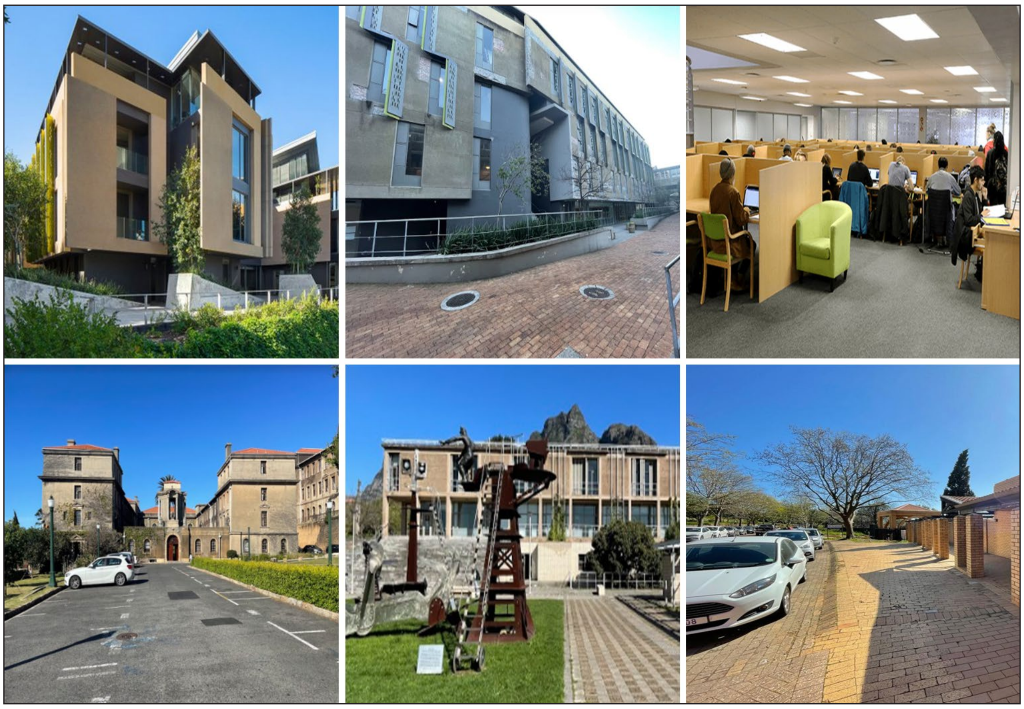

Figure 4. NEB, Snape, Hlanganani, Fuller Hall, Masingene, Woolsack (SAOTA, 2017)

Table 1. Summary of representative buildings on Upper and Middle Campuses

Campus	Building	Classification	Roof area (m^2)	Roof type	Availability of smart water meters	Availability of access control
Upper Campus	NEB	Mixed-use	1 890	Flat	✗	✓
	Snape	Lecture theatre	980	Pitched	✓	✓
	Hlanganani	Library	1 210	Flat	✗	✓
	Fuller Hall	Residence	3 480	Pitched	✓	✓
Middle Campus	Masingene	Office	1 230	Flat	✗	✓
	Woolsack	Residence	4 280	Pitched	✗	✓

Well-placed large surfaces that could be used as potential catchments for RWH were also identified (Figs 5 and 6). The tennis court complex and parking area P18 on Upper Campus are both located near the highest point of the campus with large areas of open ground below them that could be used for a reservoir that could potentially supply substantial volumes of rainwater to the buildings below that. The Sports Centre on Upper Campus was also identified as a potential catchment area due to its large roof area. Because of its location, the harvested rainwater from the Sports Centre would best be gravitated under the M3 to the Woolsack residence on Middle Campus.

Determination of harvestable rainfall

The volume of harvestable rainfall was calculated using Eq. 1, with accommodation of both the catchment and collection system losses.

$$V_t = A \times (P - \mathrm{IL} - \mathrm{FF}) \tag{1}$$

where: V_t = volume of harvestable rainfall at time t (L); A = roof area (m^2); P = rainfall (mm); IL = initial losses (mm); FF = first flush (mm).

The plan area of the roofs of representative buildings was measured from Google Earth Pro (v7.3.6.10201). A differentiation was made between pitched and flat roofs as well as the roof material, as each roof type has a different runoff coefficient/initial interception loss that affects the volume of harvestable rainfall. Typical initial loss values for various roof types are presented in Table 2 (Mitchell, 2007; Farreny et al., 2011; Fisher-Jeffes, 2015). An initial loss of 3.8 mm proposed by Farreny et al. (2011) for flat gravel was used for the tennis courts and P18.

To account for the collection system losses, a first flush of 2 mm suggested by Fisher-Jeffes (2015) and Freitas and Ghisi (2020) was used for the representative buildings. A first flush of 2 mm suggested by Doyle (2008) for catchment areas with high pollution was also used for both the tennis courts and P18, even though the tennis courts are much cleaner than P18. Rainfall data were available from the UCT Weather Station located on Upper Campus.

Optimisation of RWH system simulation

Daily time steps were used for the model since the water demand patterns of academic buildings such as those at UCT vary enormously, due to the impact of weekends and vacations, and can only be readily accommodated when relatively small-time steps are used. On the other hand, it was impossible to determine water demand fluctuations at a higher resolution e.g., hourly.

The simulation period was guided by the availability of daily rainfall data from the UCT Weather Station which was for 2007 to 2019.

In SA, the hydrological year usually runs from October to September and thus the same hydrological year was selected for the analysis.

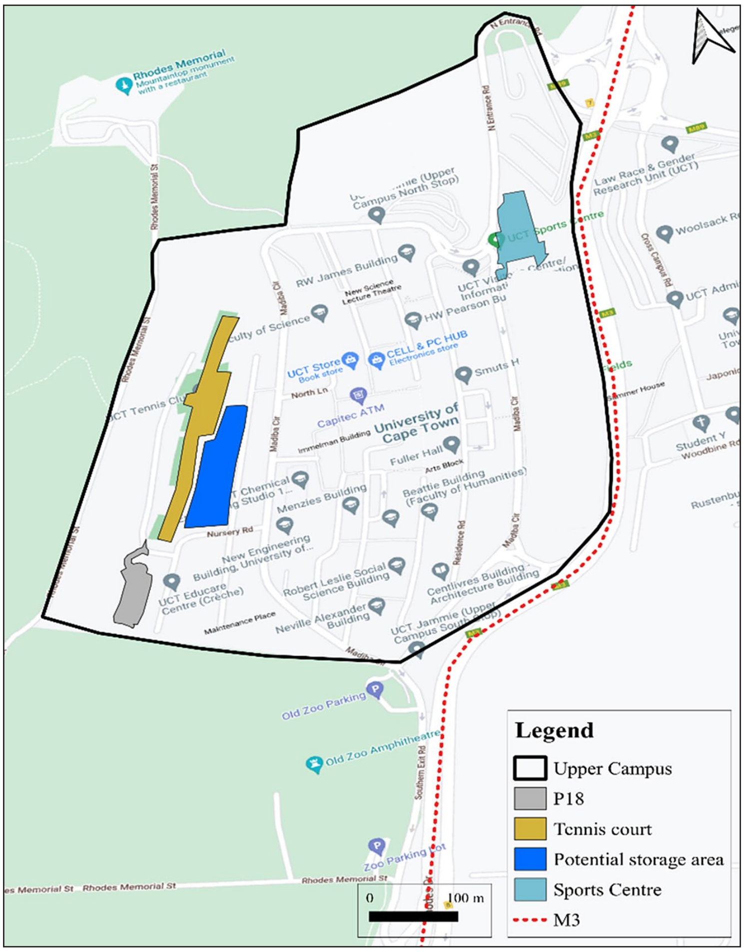

Figure 5. Location of other potential rainfall catchments

Figure 6. P18, tennis courts, Sports Centre (UCT, 2023)

Table 2. Typical initial losses for different types of roofs

Campus	Building	Classification	Roof type	Initial loss (mm)
Upper Campus	NEB	Mixed-use	Flat gravel	3
	Snape	Lecture theatre	Pitched clay tiles	1
	Hlanganani	Library	Flat gravel	3
	Fuller Hall	Residence	Pitched clay tiles	1
	Sports Centre	Recreational	Plastic	0
Middle Campus	Masingene	Office	Flat gravel	3
	Woolsack	Residence	Pitched clay tiles	1

Potential yield

The YAS algorithm (Eq. 2) was selected to calculate the potential yield because it would provide more conservative estimates of the yield compared with YBS. The decision to use YAS over YBS was recommended by Mitchell (2007), who found that the YAS algorithm yields more realistic results than YBS. YAS assumes the yield as the minimum value between the volume of rainwater in storage from the preceding time interval and the demand in the current time interval (Fewkes and Butler, 2000).

$$Y_t = \min \begin{cases} D_t \\ V_{t-1} \end{cases} \qquad V_t = \min \begin{cases} V_{t-1} + Q_t - Y_t \\ S - Y_t \end{cases} \tag{2}$$

where: Y_t = yield in the current time interval (L); D_t = demand in the current time interval (L) (daily); V_{t-1} = volume of rainwater in storage from the preceding time interval (L); and Q_t = rainwater runoff in the current time interval (L); S = tank size (L).

Rainwater can be used without significant treatment for several non-potable uses such as washing cars, irrigation, toilet-flushing, and building construction. Many potential non-potable uses, however, are unimportant for large institutions like universities. The intended use that was selected for the study was toilet-flushing as very little treatment – if any – would be required before use and it is a major component of water use on university campuses. The daily water demand for toilet-flushing was estimated using Eq. 3.

$$D_T = C \times U_T \times C_T \tag{3}$$

where: D_T = toilet flushing water demand (L·day^{-1}); C = number of occupants per building per day; U_T = number of toilet flushes per person per day; C_T = toilet flush volume (L).

Occupancy data for a typical week for both semesters of the 2019 academic year were provided by UCT for the representative buildings. The holidays and vacation demands were assumed to be the same as for the weekends.

It was assumed that each flush used 6 L of water, and that each person would generally flush 3 times per day (Hajani and Rahman, 2014, Preeti and Rahman, 2021). Flushing frequencies of 2 and 6 were also used to investigate the impacts of different flushing frequencies from the assumed value of 3 for Hlanganani, Fuller Hall, Woolsack and Snape. This also acted as a proxy for variations in the flush volume.

Three demand scenarios were considered for RWH from the tennis courts and P18 catchments as follows:

- Scenario 1 (S1) – The combined demand for Fuller Hall, NEB, and Snape on Upper Campus
- Scenario 2 (S2) – Hlanganani Library demand only
- Scenario 3 (S3) – The supply of all the buildings on Upper Campus with a population of approximately 23 000 people. Due to a lack of more detailed information, it was assumed that 75% of 23 000 (17 250) people come to the campus on weekends and holidays based on the assumptions made for the representative buildings.

Since there was limited harvestable rainfall and storage space next to some of the representative buildings, only storage tank sizes ranging between 10 kL and 100 kL were considered for the analysis of the potential RWH from the roofs of the representative buildings and Sports Centre. For the tennis courts and P18 analysis, tank sizes between 200 kL and 1 000 kL were considered given there is space available for much larger storage elements. Initial analyses indicated that tank sizes greater than 1 000 kL did not significantly increase the yield from the tennis courts and P18.

Hydrologic and economic performance of RWH systems

After estimating the potential yield of each RWH system, it was important to identify the best performing RWH systems that might be implemented to promote sustainability and resilience at UCT. The following measures were used:

- WSE
- The time-based reliability
- The overflow percentage
- Benefit cost analysis (BCA)

The BCA compared the potential monetary savings derived from replacing the potable municipal water with the harvested rainwater to the cost of installation of the systems. A combination of the two levels of water restrictions (Level 1 and Emergency Response) was used for the evaluation of the extent of cost savings. CoCT's 2021/2022 Level 1 water tariffs were applied during the normal years (the CoCT uses the Level 1 as the baseline) while Emergency Response water tariffs were applied during the dry years.

The indicative costs of installation were estimated from that of the storage containers as the largest component of the installation costs of a RWH is normally the tank or reservoir costs. The factory tank prices interpolated from information supplied by 5 suppliers were multiplied by arbitrary factors of 3, 4, and 5 to accommodate for other costs such as pipework, transportation, installation, and professional fees for all sites. This somewhat unusual approach was dictated by the extreme difficulty of estimating these additional costs without resorting to detailed design and subsequent costing for the multiple potential layouts in existing buildings whose plumbing had not been designed for RWH.

The capital recovery formula (Eq. 4) was used to determine the annualised cost of installation. A discount period of 20-years for educational institutions was used as a reasonable assessment of the relative lifespan of individual building systems given the need to accommodate a fluctuating student population and the changing nature of educational programmes (Mearig et al., 1999). Roebuck et al. (2011) state that local authorities and private sector companies usually use lower discount rates that vary between 3.5% and 5%. A 4% interest rate was thus selected for the calculations. The ratio of the mean annual cost savings and the capital recovery amount for the various tank sizes was then used to determine the benefit-cost ratio (BCR) values of the RWH systems.

$$A = \frac{\mathrm{i}\,(1+i)^n\,P}{(1+i)^n - 1} \tag{4}$$

where: A = capital recovery amount (ZAR); i = interest rate (%); n = discount years; P = cost of installation (ZAR).

Multi-criteria analysis

Multi-criteria decision making (MCDM) analysis, also referred to as multi-criteria analysis (MCA), is a tool used to compare alternatives based on a range of criteria, despite their units (Pengelly et al., 2018). The tool was used to identify the most promising RWH systems to supplement the potable water supply for toilet-flushing. The criteria were based on two key research questions:

- Which catchment – with respect to the potential supply – offers the most promising potential for RWH?
- Which RWH systems could offer the most economic benefits compared to costs?

The volume of harvestable rainfall from the catchment of each system and the BCRs from the economic analysis of each system were used to rank the RWH systems. A system with the highest volume of harvestable rainfall was scored 16 since 16 alternatives were evaluated, while the system with the lowest volume of harvestable rainfall was scored 1. Similarly, the system with the highest BCR was scored 16 and the system with the lowest BCR scored 1. In cases where the harvestable rainfall was the same (either from P18, the tennis court, or the integrated catchment of both P18 and the tennis court), the

RWH systems were allocated the same score. For example, the volume of harvestable rainfall was the same for S1 (Representative buildings without Hlanganani), S2 (Hlanganani), and S3 (all Upper Campus buildings) since the catchment is the same.

The scores were multiplied by the various weightings to determine the score of each system. The first weighting scenario assumed that the two criteria were equally important, hence the weightings of 0.5/0.5 each. The second scenario assumed BCRs were more important than the volume of harvestable rainfall, so a weighting of 0.6/0.4 was used, respectively. The third scenario assumed that the BCRs were less important than the volume of harvestable rainfall, thus weightings of 04/0.6 were used.

The total scores of the three weighting scenarios were used to allocate the final ratings of the RWH systems, whereby the RWH system with the highest score was rated 1 (top 1) and the system with the lowest score was rated 16.

Viability of RWH in other universities across SA

The research also aimed to investigate whether UCT's unique climatic situation advantages or disadvantages it compared with those enjoyed by other universities in SA. At least one university in each SA province was selected for this investigation. The viability of RWH in other universities was not assessed using their respective building and water use data but rather indirectly by assuming that their building types were like those at UCT. Using the same building dimensions and usage patterns with 3 flushes·person^{-1}·day^{-1} for the Woolsack residence helped to demonstrate the impact of climate and rainfall patterns on RWH while everything remained constant. The selected universities were Nelson Mandela University (NMU), University of the Free State (UFS), University of the Witwatersrand (Wits), University of KwaZulu-Natal (UKZN), University of Limpopo (UL), University of Mpumalanga (UMP), North-West University (NWU) and the Sol Plaatje University (SPU) (Fig. 7 and Table 3).

RESULTS AND DISCUSSION

Potential demand

According to Almeida et al. (2021), universities have distinctive water demand profiles, with varying consumption patterns and higher water demands. This holds true for UCT where there is considerable variation in toilet-flushing demand depending on the occupancy of each building.

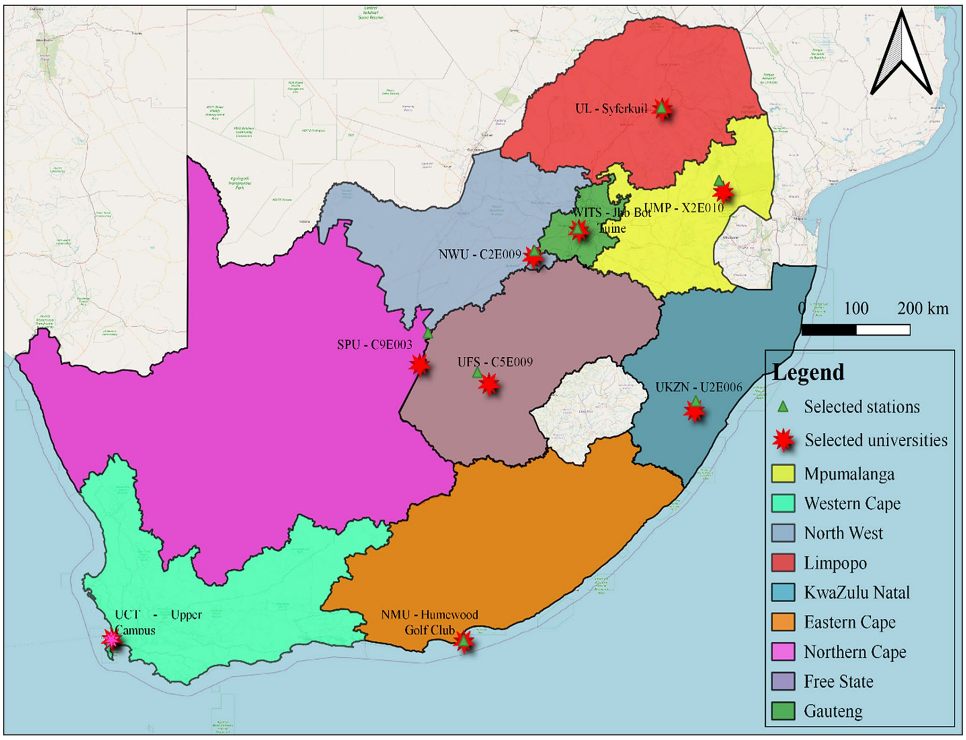

Figure 7. Location of SA universities and nearby rainfall stations

Table 3. A summary of universities and their respective weather stations

Province	Municipality	University	Campus	Rainfall station	Coordinates	Distance from university (km)
Western Cape	City of Cape Town	UCT	Upper Campus	Upper Campus station	33°57′18.10″S, 18°27′34.13″E	Within university
Eastern Cape	Nelson Mandela Bay	NMU	North Campus	Humewood - Golf Club	33°58′58.44″S, 25°40′1.20″E	2
Free State	Mangaung	UFS	Bloemfontein	C5E009	28°52′59.00″S, 25°56′60.00″E	34
Gauteng	City of Johannesburg	Wits	Braamfontein	Jhb Bot Tuine	26° 9′0.00″S, 28° 0′0.00″E	5.5
KZN	Msunduzi	UKZN	Pietermaritzburg	U2E006	29°25′46.28″S, 30°25′29.13″E	20
Limpopo	Mankweng	UL	Turfloop	Syferkuil	23°51′0.00″S, 29°43′12.00″E	4.5
Mpumalanga	City of Mbombela	UMP	Mbombela	X2E010	25°14′17.20″S, 30°53′59.21″E	26
North-West	JB Marks	NWU	Potchefstroom	C2E009	26°34′16.79″S, 27° 7′4.80″E	13
Northern Cape	Sol Plaatje	SPU	North Campus	C9E003	28° 7′59.36″S, 24°56′10.70″E	69

Unlike domestic water demands that remain almost constant throughout the year, the water demands in university buildings vary depending on the period of use (weekdays versus weekends and academic terms versus vacations) and the use of each building. Figures 8 to 11 present the variability of demand patterns in selected different types of buildings for 1 year (from October 2007 to September 2008) when a toilet flushing frequency of 3 flushes·person^{-1}·day^{-1} is assumed. They show that the residences, which accommodate students during the vacations (e.g., between 15 June and 15 July 2008), and office buildings have relatively constant weekly toilet-flushing water demand throughout the year, including during the summer and winter vacations. On the other hand, lecture blocks, mixed-use buildings, and libraries are impacted by the fewer people using the buildings during the vacation.

Overall, the Hlanganani Library had the highest mean annual water demand of the buildings assessed (Fig. 12) when 3 flushes·person^{-1}·day^{-1} is assumed, followed by Fuller Hall (a student residence). The office building (Masingene) had the lowest water demand for toilet-flushing. Figure 13 indicates the comparison of the mean annual demand of the three scenarios associated with P18 and tennis court catchments previously mentioned (S1 for representative buildings without Hlanganani, S2 for Hlanganani, and S3 for all Upper Campus buildings). Figure 14 indicates the variability of the demand for when the flushing frequency is varied between 2, 3 and 6 times per day to account for deviations from the base-line assumption of 3 flushes per day and a 6 L flush volume.

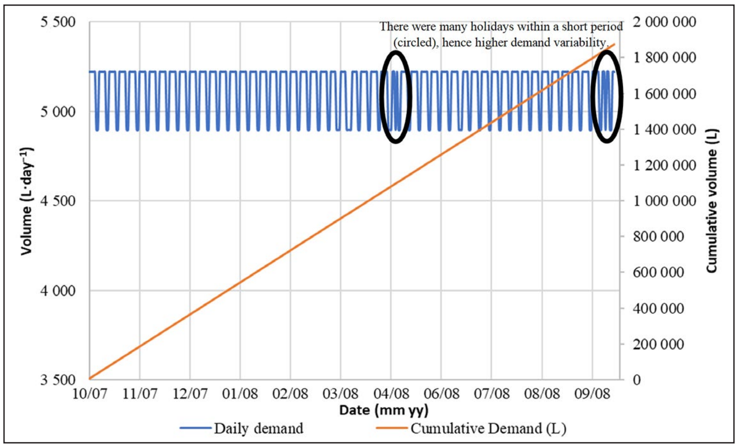

Figure 8. Weekly toilet-flushing demand pattern per year for Fuller Hall (residence)

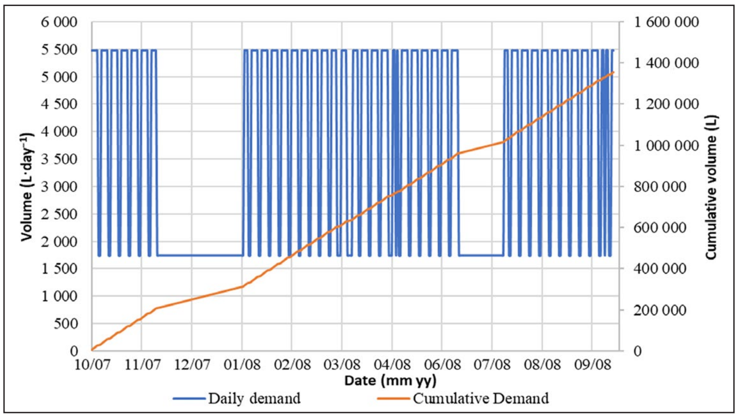

Figure 9. Weekly toilet-flushing demand pattern per year for the NEB (mixed use)

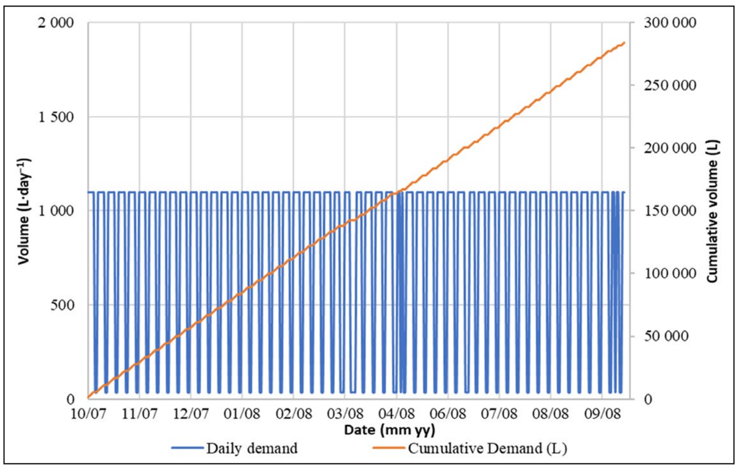

Figure 10. Weekly toilet-flushing demand pattern per year for Masingene (administration)

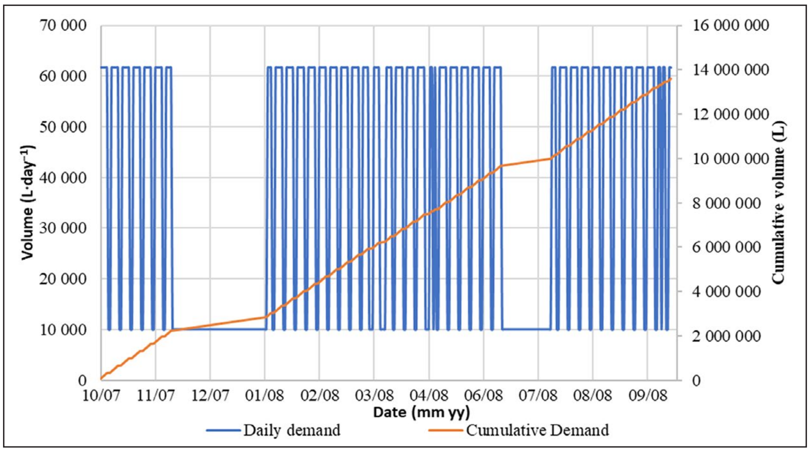

Figure 11. Weekly toilet-flushing demand pattern per year for Hlanganani (library)

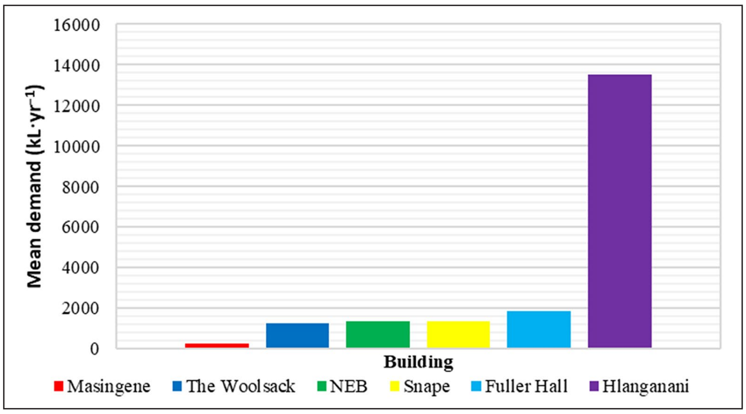

Figure 12. Mean annual demand of representative buildings in order of increasing demand (3 flushes·person^{-1}·day^{-1})

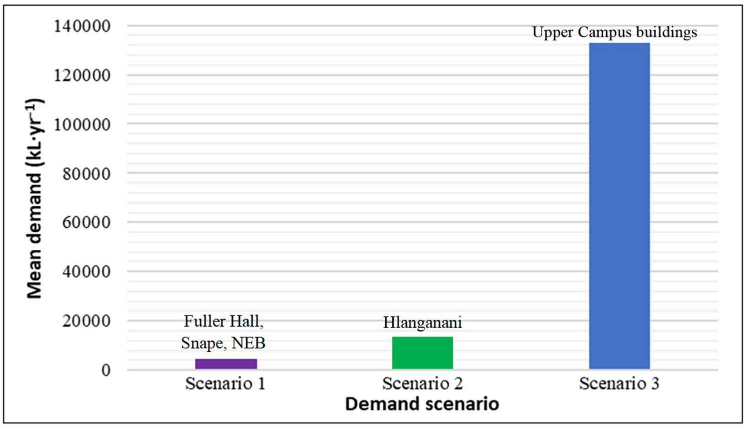

Figure 13. Mean annual demand of Scenarios 1, 2 and 3 in order of increasing demand (3 flushes·person^{-1}·day^{-1})

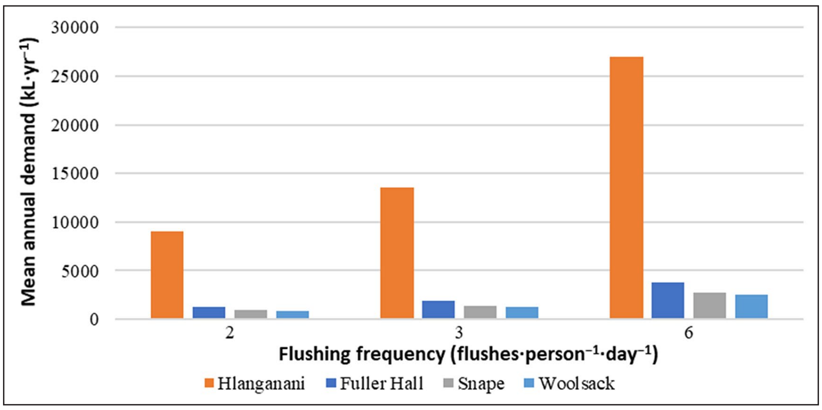

Figure 14. Comparison of the mean annual demand for various flushing frequencies

Potential harvestable rainfall

Figure 15 illustrates the variation in the harvestable rainfall between the representative buildings. The Snape building had the lowest potential for harvestable rainwater per year due to having the smallest available roof area. The Woolsack residence in Middle Campus had the largest roof area with the smallest losses – and thus the highest potential for harvestable rainfall per year. With regards to other catchment areas, the integrated catchment of P18 and the tennis courts had the largest contributing area and consequently had the highest potential for harvestable rainfall per year (Fig. 16).

Potential yield

The potential yield that could be supplied with the harvested rainwater increases as the tank sizes increase (Fig. 17). The demand, however, is not fully supplied in most of the buildings due to the limited rain volumes captured on the various surfaces and the linked storage. The provision of larger storage facilities

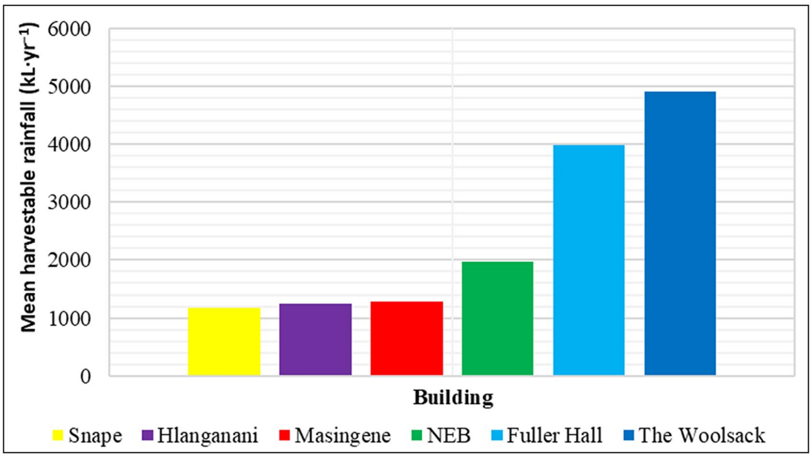

Figure 15. Mean annual harvestable rainfall from representative buildings in order of increasing harvestable rainfall

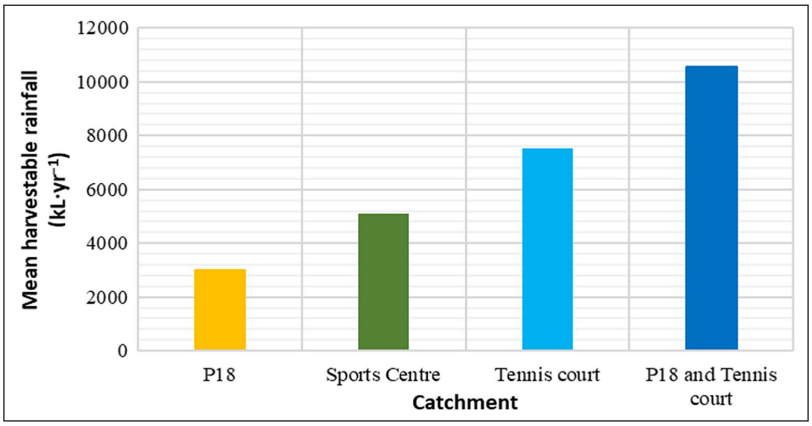

Figure 16. Mean annual harvestable rainfall from P18, tennis courts, and Sports Centre in order of increasing harvestable rainfall

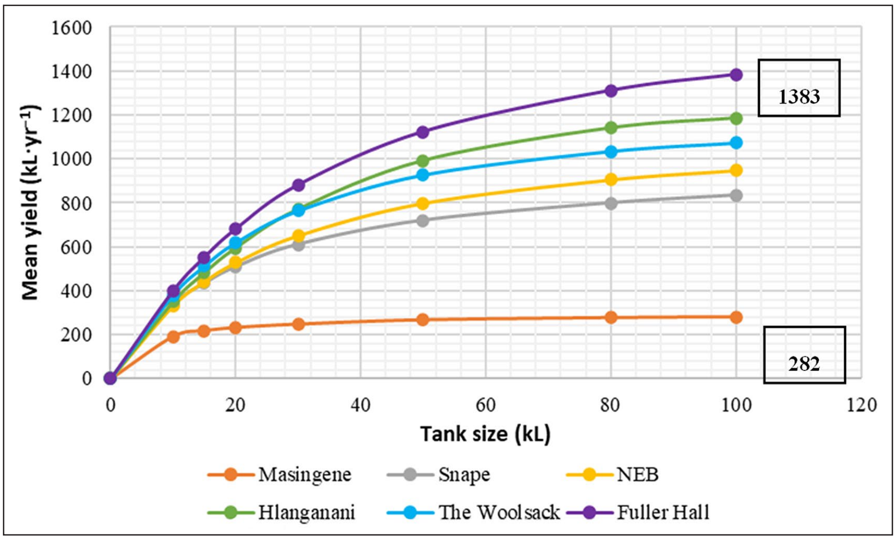

Figure 17. Mean annual potential yield curves for the representative buildings (3 flushes·person^{-1}·day^{-1})

increases the yield by diminishing amounts until the point when the limits of the supply or the demand have been met. Clearly, the additional yield comes at increasing marginal cost. For example, the yield curve for Masingene flattens beyond 80 kL storage when almost all the water demand for toilet-flushing three times per person per day is met while the Fuller Hall residence system requires tanks larger than 100 kL to meet the demand subject to the available rainwater. The analysis did not consider tanks larger than 100 kL due to the limited storage space available.

The curves indicate that it is possible to replace approximately 1 380 kL·yr^{-1} of potable water with harvested rainwater at Fuller Hall, while all the demand for Masingene of approximately 280 kL·yr^{-1} can be replaced by rainwater.

Figure 18 indicate the variability of the yield when different flushing frequencies are used for four selected buildings. It may be seen that flushing frequency has negligible impact on the yield for Hlanganani, but a significant impact for the remaining three buildings.

For 3 flushes per day, 100% of harvestable rainfall (3 039 kL·yr^{-1}) could potentially be achieved in Scenarios S2 for Hlanganani, and S3 for all Upper Campus buildings when the P18 is used as a catchment if an 800 kL tank (for S2) and a 400 kL tank (for S3) are provided (Fig. 19). This means that even if the demand was higher, the limited catchment area restricts the volume of rainwater that can be harvested making it impossible to meet the toilet-flushing water demand even if the storage tank sizes are increased. Overall, the harvested rainwater from P18 could replace approximately 3 030 kL of potable water each year. There was an enormous shortfall for S3 (129 990 kL) compared with S1 (combined demand) (1 710 kL) and S2 (10 440 kL). The larger demand met by a consequently larger supply obviously resulted in less loss of rainwater to overflow.

The harvested rainwater from the tennis courts could replace approximately 7 500 kL of potable water supplied to the entire Upper Campus each year, or 3 970 kL of the toilet-flushing water supplied to Snape, NEB and Fuller combined for 3 flushes·person^{-1}·day^{-1}. As with P18, there is an enormous shortfall with S3 (125 520 kL) compared to S1 (570 kL) and S2 (7 150 kL).

The integration of P18 and tennis courts into one bigger catchment was considered to maximise the volume of rainfall available. Approximately 10 380 kL of potable water supplied to all the buildings on Upper Campus each year could be replaced by harvested rainwater from the integrated catchment. For 3 flushes·person^{-1}·day^{-1}, a mean volume of 4 260 kL·yr^{-1} of water supplied to NEB, Snape and Fuller Hall combined could also be replaced with harvested rainwater if 1 000 kL of storage was provided.

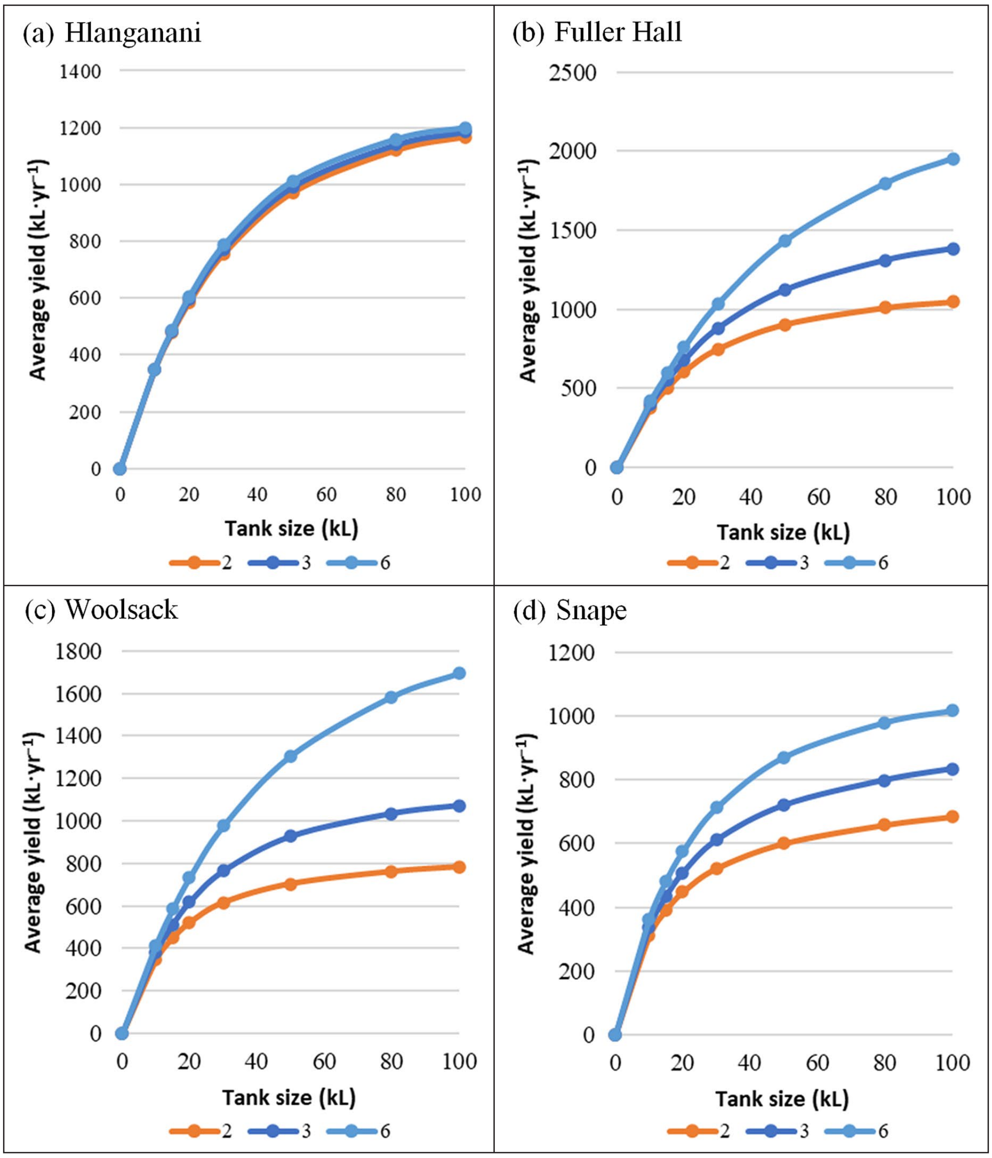

Figure 18. Mean annual potential yield curves for different buildings when different flushing frequencies are used

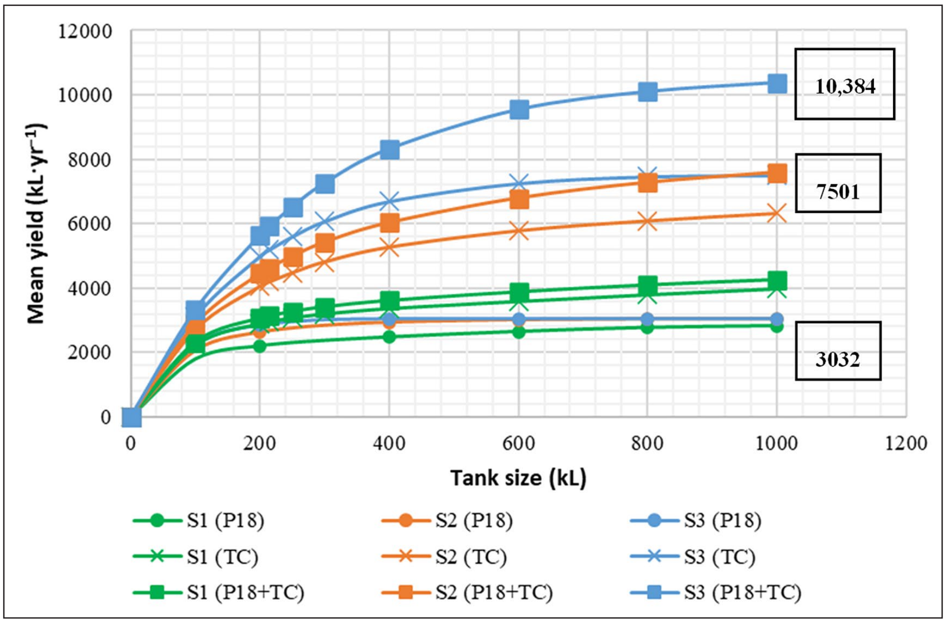

Figure 19. Mean annual potential yield curve for all P18, tennis court and integrated catchment scenarios for 3 flushes·person^{-1}·day^{-1}

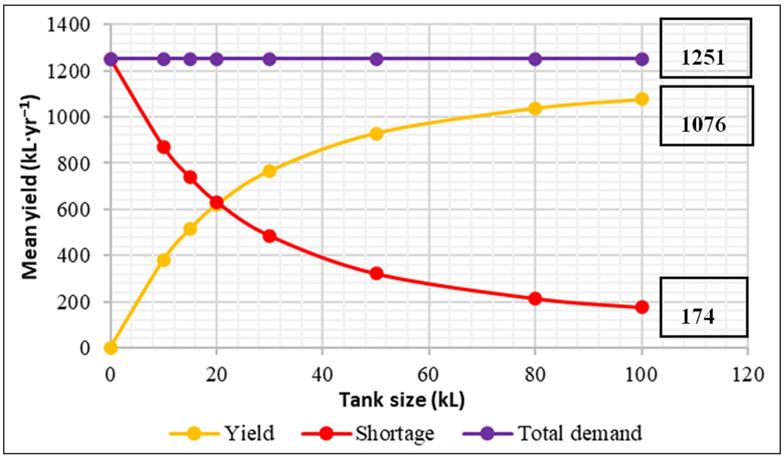

Figure 20. Storage-demand yield curve for Sports Centre and Woolsack system for 3 flushes·person^{-1}·day^{-1}

In addition to the P18 and tennis court systems, RWH from the Sports Centre to supply the Woolsack residence could replace approximately 1 080 kL of potable water required for toilet-flushing in the residence when 100 kL tanks are used for storage (Fig. 20). This is as large a volume as that which could be harvested directly from the roof of the Woolsack residence but does not require pumping.

System performance results

The WSE and reliability curves show a general trend of non-linear increase of performance with increasing storage capacities while the overflow percentage curves show a non-linear decrease as the storage capacities increase (e.g., Figs 21 and 22) for 3 flushes·person^{-1}·day^{-1}.

The curves become more flattened as the tank sizes increase, indicating the marginal benefits of increased performance with additional storage in the system gradually reduce e.g., the WSE curve when the rainwater is collected from P18 and supplied to the Hlanganani library (S2) presented in Fig. 23.

Ultimately, the system performance becomes practically constant when no additional volumes of water can be harvested or supplied regardless of the increasing tank sizes. This has been noted by other researchers such as Almeida et al. (2021). Overall, all RWH schemes are initially sensitive to storage capacity, but the sensitivity decreases as storage increases until sufficient storage has been provided such that negligible water is lost to overflow or the point is reached where the marginal benefit of increasing storage is not warranted by the cost of the additional storage provision.

The WSE is one of the most important factors used to assess the viability of a RWH as it considers the building type and use of the buildings. Buildings whose water demand can be supplied by the harvested rainwater are considered to have high WSEs. For example, the Masingene RWH system had a higher WSE than other RWH systems but the largest potential overflow as the system required the least volume of rainwater to satisfy the demand. As with the WSE, higher reliability is achieved for larger tanks and lower water demands (Almeida et al., 2021).

The WSE and reliability curves show that there is a need for optimal balance between the water demand, the harvestable rainwater, and storage to capture as much rainwater as possible without the need for excessive storage. The larger the first flush and initial loss, the lower the volume of harvestable rainfall. However, the larger the catchment area and storage capacity, the higher the volume of harvestable rainfall.

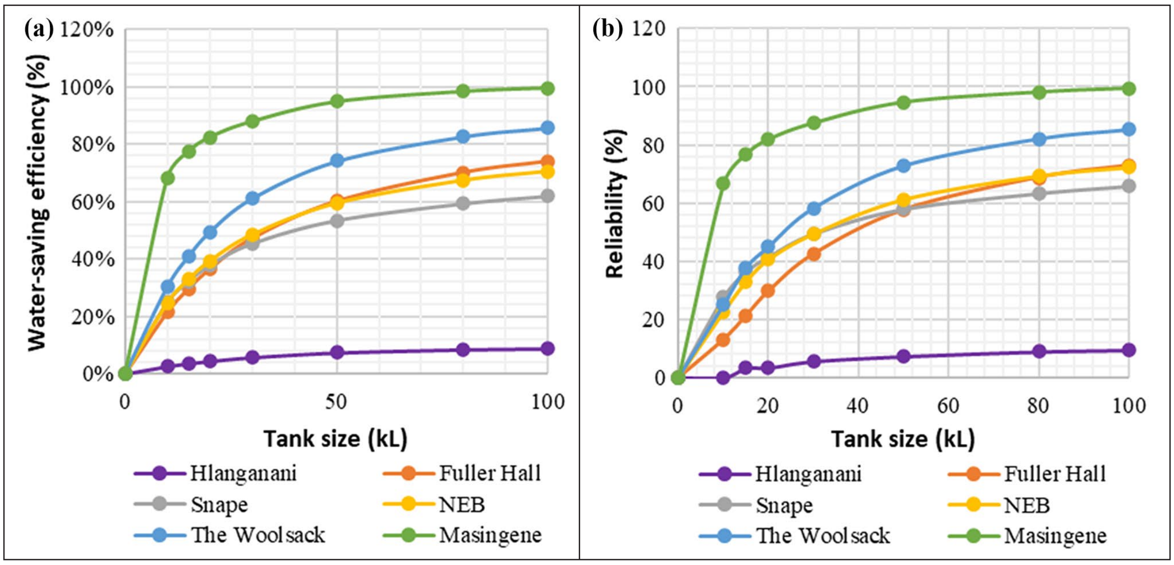

Figure 21. (a) Water-saving efficiency, and (b) reliability curves for the representative buildings for 3 flushes·person^{-1}·day^{-1}

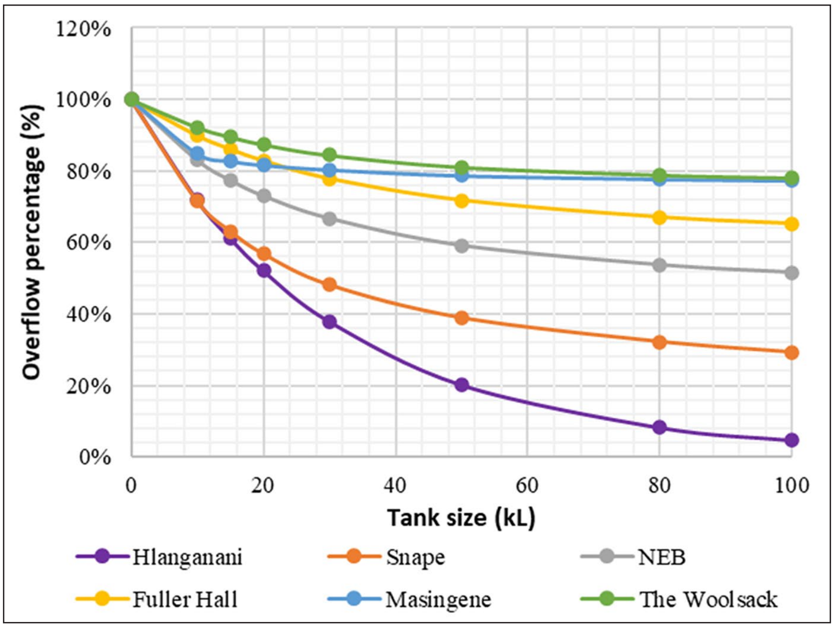

Figure 22. Normalised overflow from representative buildings for 3 flushes·person^{-1}·day^{-1}

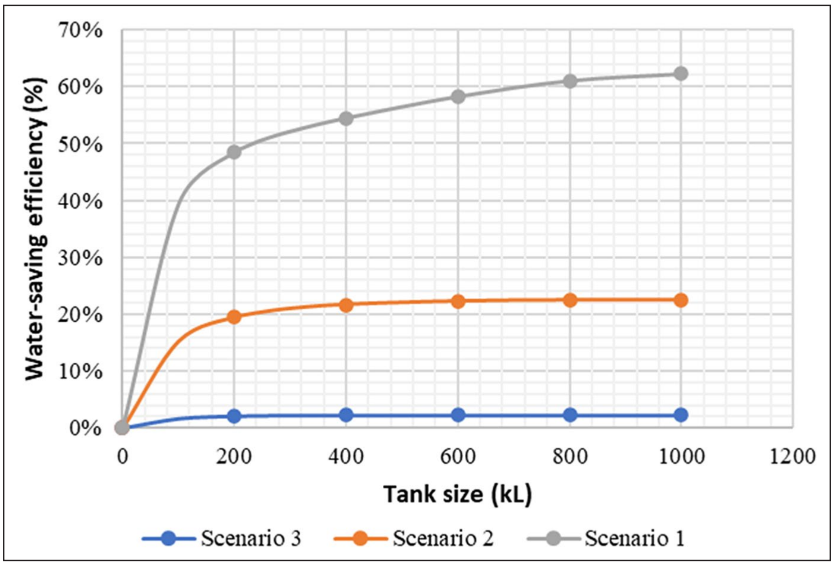

Figure 23. Water-saving efficiency curves for P18 scenarios for 3 flushes·person^{-1}·day^{-1}

Economic analysis

Figure 24 indicates that the cost savings from the reduced need to purchase potable water increase as the yield increases for 3 flushes·person⁻¹·day⁻¹. The RWH system at the Masingene office building had the lowest potential monetary savings for the replacement of potable water with harvested rainwater for toilet-flushing, while the Fuller Hall residence system had the highest potential cost savings amongst all the buildings studied. Fuller Hall also had the highest potential cost savings irrespective of the flushing frequency compared with the other buildings (Fig. 25).

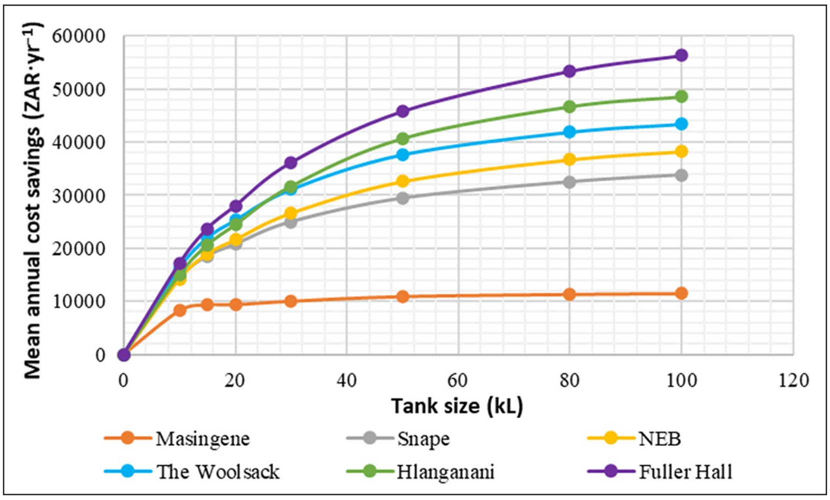

Figure 24. Potential mean annual cost savings from representative buildings for 3 flushes·person⁻¹·day⁻¹

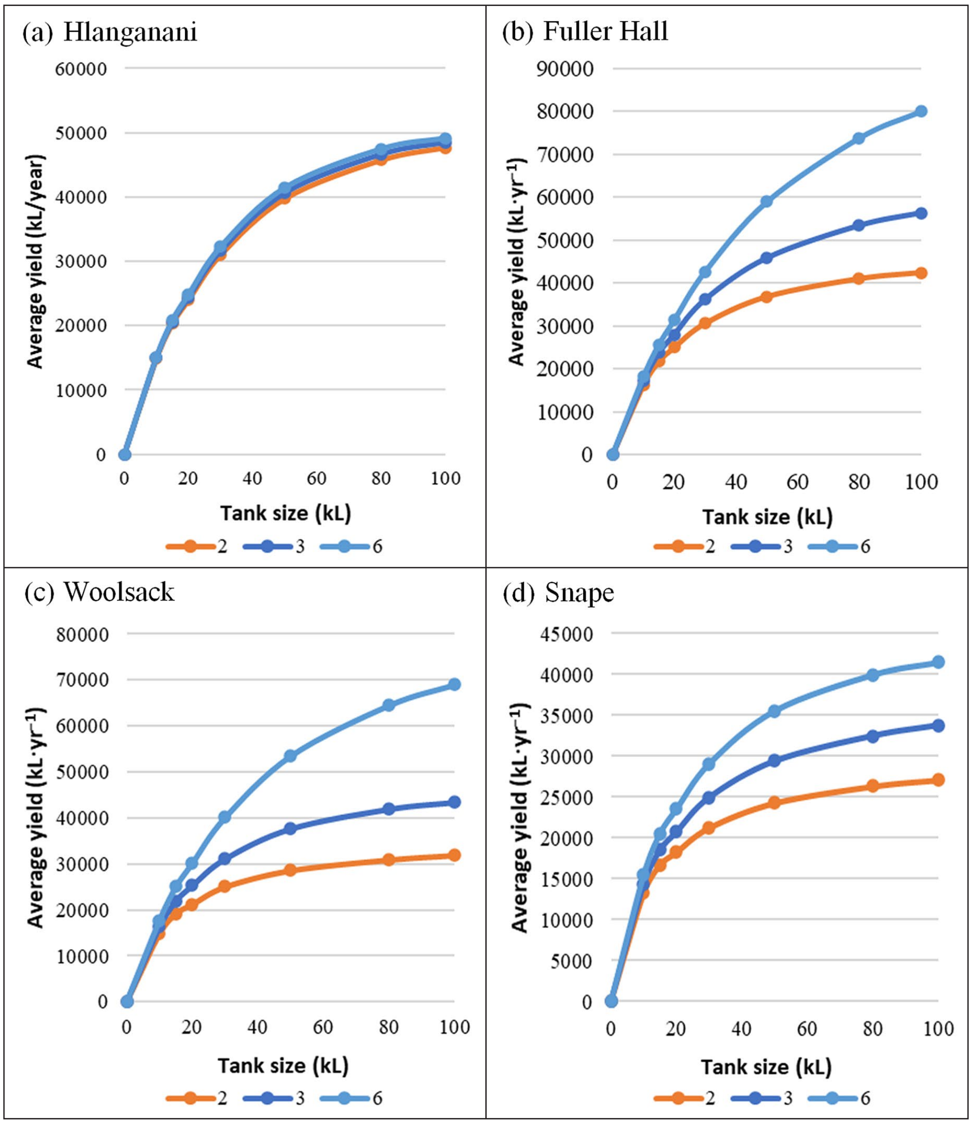

Figure 25. Potential mean annual cost savings from representative buildings when different flushing frequencies (2, 3 or 6) are used

The installation of a RWH system to collect water from the integrated P18 and tennis court catchment to supply the large demand of Upper Campus buildings (S3) had large cost savings because of the large volumes of water that could be harvested from these catchments (Fig. 26).

The cost of the installation needs to be lower than the total benefits of a RWH system for a system to be considered economically viable. The RWH systems in all the representative buildings can be considered economically viable for all flushing frequencies except for Masingene when a factor of 5 times the tank cost is considered (Table 4). As was expected, the BCRs became smaller as the cost of installation increases. Fuller Hall residence had the highest BCRs compared to all the RWH systems while the P18-tennis courts integrated catchment had higher BCRs for supply to the Upper Campus than for the individual P18 and tennis courts catchments (Table 5). However, the cost of a sand filter (identified in a separate project) to treat rainwater from P18 due to its dirtiness compared to other catchments made the P18 systems less economically viable compared to other systems when the treatment costs were considered (Table 6).

Multi-criteria analysis

The MCA results (Tables 7 and 8) indicate that the Sports Centre and Woolsack RWH system was the most promising system considering the volume of harvestable rainfall and economic viability, followed by the Fuller Hall system. This holds true even when the flushing frequency is varied. The tennis court systems (including when integrated with P18), especially for Upper Campus demand (S3), also had high scores. The P18 systems had the lowest BCRs of all, even when the cost of treatment was excluded. The MCA results, however, are subject to the valuation of the capital, operating and management costs, which could substantially change the analysis after a detailed design has been undertaken.

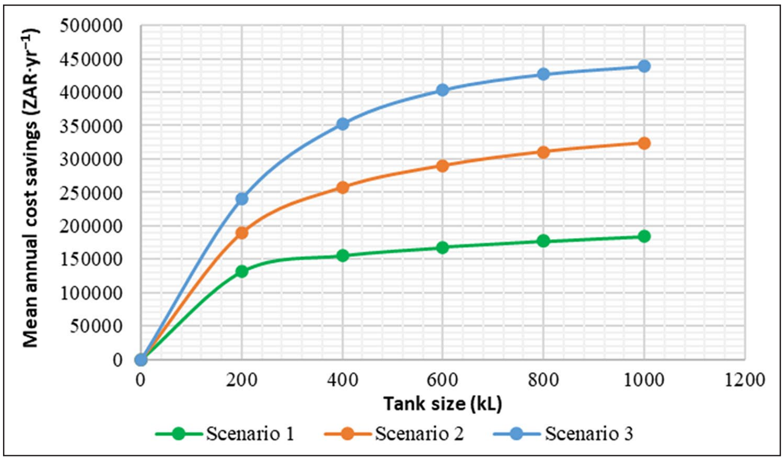

Figure 26. Potential mean annual cost savings for P18 and tennis court systems for 3 flushes·person^{-1}·day^{-1}

Table 4. BCRs for representative buildings (Factor 5) when a flush frequency of 3 flushes·person^{-1}·day^{-1} is used for all buildings

Tank size (kL)	Masingene	Snape	NEB	Hlanganani	Woolsack	Woolsack & Sports Centre	Fuller Hall
10	2.13	3.69	3.66	3.87	4.19	4.20	4.41
15	1.74	3.42	3.50	3.81	4.06	4.07	4.38
20	1.41	3.10	3.23	3.65	3.78	3.79	4.19
30	1.17	2.89	3.08	3.67	3.61	3.62	4.19
50	1.01	2.72	3.02	3.77	3.49	3.50	4.24
80	0.87	2.48	2.80	3.56	3.20	3.21	4.07
100	0.69	2.03	2.30	2.92	2.62	2.63	3.39

Table 5. BCRs for P18 and tennis court systems (Factor 5) without treatment for P18 when a flush frequency of 3 flushes·person^{-1}·day^{-1} is used

Tank size (kL)	P18+S1	P18+S2	P18+S3	TC+S1	TC+S2	TC+S3	P18+TC+S1	P18+TC+S2	P18+TC+S3
200	0.23	0.27	0.30	0.30	0.42	0.52	0.32	0.46	0.59
400	0.13	0.16	0.16	0.18	0.28	0.36	0.20	0.33	0.45
600	0.08	0.10	0.10	0.12	0.19	0.24	0.13	0.23	0.32
800	0.05	0.06	0.06	0.08	0.13	0.16	0.09	0.15	0.21
1000	0.04	0.04	0.04	0.05	0.08	0.10	0.06	0.10	0.14

Table 6. BCRs for P18 and tennis court systems (Factor 5) with treatment for P18 when a flush frequency of 3 flushes·person^{-1}·day^{-1} is used

Tank size (kL)	P18+S1	P18+S2	P18+S3	TC+S1	TC+S2	TC+S3	P18+TC+S1	P18+TC+S2	P18+TC+S3
200	0.02	0.02	0.02	0.30	0.42	0.52	0.02	0.04	0.04
400	0.02	0.02	0.02	0.18	0.28	0.36	0.03	0.04	0.06
600	0.02	0.02	0.02	0.12	0.19	0.24	0.03	0.05	0.06
800	0.02	0.02	0.02	0.08	0.13	0.16	0.03	0.04	0.06
1000	0.01	0.02	0.02	0.05	0.08	0.10	0.02	0.04	0.05

https://doi.org/10.17159/wsa/2025.v51.i2.4110

Table 7. Final scores and ratings of the RWH systems with treatment costs for P18 when a flush frequency of 3 flushes·person^{-1}·day^{-1} is used

Rating	RWH system	Weighting scenario						Total score
		0.5/0.5		0.6/0.4		0.4/0.6		
		BCR	Harvestable rainfall	BCR	Harvestable rainfall	BCR	Harvestable rainfall	
1	Sports Centre + Woolsack	7.5	7	9	5.6	6	8.4	43.5
2	Fuller Hall	8	6	9.6	4.8	6.4	7.2	42
3	Woolsack	7	6.5	8.4	5.2	5.6	7.8	40.5
4	TC + Upper Campus	4.5	7.5	5.4	6	3.6	9	36
5	TC + Hlanganani	4	7.5	4.8	6	3.2	9	34.5
6	TC + Rep buildings	3.5	7.5	4.2	6	2.8	9	33
7	P18 + TC + Upper Campus	3	8	3.6	6.4	2.4	9.6	33
7	NEB	5.5	5	6.6	4	4.4	6	31.5
9	Hlanganani	6.5	4	7.8	3.2	5.2	4.8	31.5
10	P18 + TC + Hlanganani	2.5	8	3	6.4	2	9.6	31.5
11	P18 + TC + Rep buildings	2	8	2.4	6.4	1.6	9.6	30
12	Masingene	5	4.5	6	3.6	4	5.4	28.5
13	Snape	6	3.5	6	3.6	4	5.4	28.5
14	P18 + Upper Campus	1.5	5.5	1.8	4.4	1.2	6.6	21
15	P18 + Hlanganani	1	5.5	1.2	4.4	0.8	6.6	19.5
16	P18 + Rep buildings	0.5	5.5	0.6	4.4	0.4	6.6	18

Table 8. Comparison of the total scores for the top three systems when various flushing frequencies are used for Woolsack, Fuller Hall, Snape and Hlanganani

Rating	RWH system	Total score		
		Flush frequency = 2	Flush frequency = 3	Flush frequency = 6
1	Sports Centre + Woolsack	45	43.5	42
2	Fuller Hall	40.5	42	42
3	Woolsack	39	40.5	42

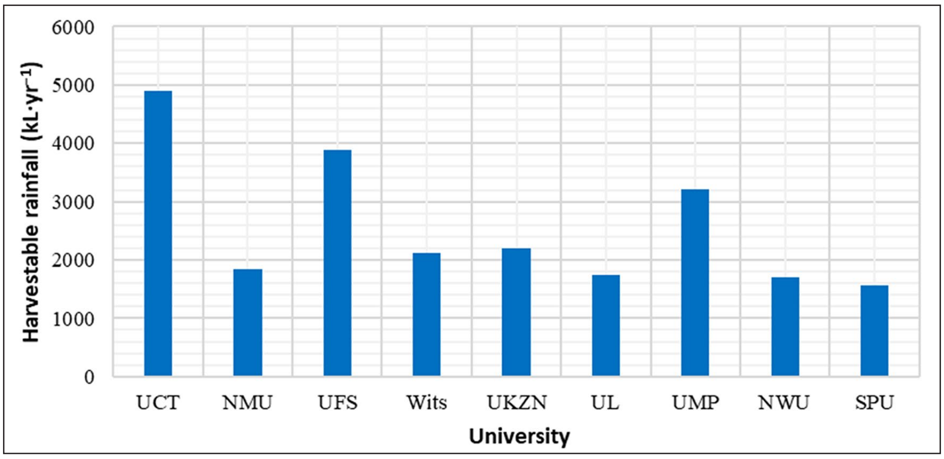

Figure 27. Comparison of mean harvestable rainfall assuming a residential building like Woolsack (UCT)

The impact of climate on the viability of RWH

The universities in SA with the highest rainfall are UCT and the UMP, with MAP of approximately 1 440 mm and 1 030 mm, respectively. These provinces are followed by Gauteng and North-West with MAP of approximately 610 mm and 580 mm, respectively.

The harvestable rainfall for the Woolsack residence at UCT was determined using rainfall data from the weather stations near the selected universities. The calculations (Fig. 27) indicate that the rainfall pattern at UCT affords greater opportunities to harvest rainfall compared to other provinces. In part this is because universities are usually closed between mid-November and January and sometimes February; hence more rainfall can be harvested to meet the demand at UCT with winter rainfall and shorter winter vacations than at other universities with summer rainfall and longer vacations.

CONCLUSIONS AND RECOMMENDATIONS

The research showed that RWH systems are likely to provide the highest benefit for student residences due to a better balance between the supply from their roofs and the water demand, compared to other buildings such as offices. Office buildings like Masingene have limited demand and, while the provision of RWH might be good for environmental sustainability, there will be very little economic savings since the volume of water replaced is very small.

Among all the RWH systems, the integration of the tennis courts and P18 into one catchment, especially when supplying Upper Campus with a large demand, offered the biggest water benefit due to the large quantity of rainwater collected that can replace potable water supplied by the municipality. However, P18 is very dirty compared to other catchments and will require an expensive sand filter to improve the quality of harvested rainwater. As a result, the cost of installation of any of the P18 systems will be very expensive (approximately 64% more expensive than roof systems) with BCRs close to 0. The tennis court catchment, on the other hand, is a lot cleaner and a 200 kL storage system to supply Upper Campus had a BCR of 0.52 which is much closer to 1, compared to the 0.04 of P18 which can be considered unviable if cleaning is considered. The tennis court catchment was therefore considered the most promising catchment in terms of both water and economic savings.

Regarding the uncertainty of the impact of the demand estimations, the analysis concluded that while the flushing frequency impacts the water demand and thus the potential yield, it has minimal impact on the ranking of systems in the MCA and hence a flush frequency of 3 flushes·person^{-1}·day^{-1} may be used for the purposes of assessing the viability of various options. It can be assumed that a similar outcome could be expected if the other variables making up the demand (e.g., occupancy) were varied while the others are kept constant (e.g., flush frequency and cistern volume).

The investigation also found that because of UCT's Mediterranean climate that results in full residences during the winter vacation combined with relatively high rainfall, it is favourably placed for RWH compared with other universities in SA.

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AUTHOR CONTRIBUTIONS

Tšepiso Lepota was responsible for the collection of the data, the construction and running of the various models, the analysis of the model outputs, and the writing of the draft paper. Neil Armitage was responsible for the conceptualisation of the project, critical intellectual input during the research, and the final editing of the paper.

ORCID

Neil Armitage
https://orcid.org/0000-0003-3704-3648

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