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School Water and Rainwater Use Modeller

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ABSTRACT

With climate change, schools in hot and dry areas are increasingly experiencing water shortages. This can affect the health of students and teachers, disrupt education and in the worst case, lead to school closures. Rainwater harvesting can help address water shortages by providing a safe alternative source of water. However, there is limited research and guidance on how rainwater harvesting systems can be applied to schools. A lack of guidance and knowledge has meant that schools are not aware of the potential of rainwater harvesting systems and do not adopt these systems. There is a need, therefore, for a simple tool that can be used by schools to understand the potential of rainwater harvesting systems at schools. This study aims to address this gap by developing the School Water and Rainwater Use Modeller (SWARUM). The modeller is presented and applied to a case study school in a drought-stricken area of Southern Africa. The findings of the application and the modeller are critically evaluated. The study finds that the modeller can be used to show the potential of a rainwater harvesting system at schools and enables different scenarios to be modelled and understood. The study makes recommendations for the improvement of the modeller and its application.

Keywords: Schools, rainwater harvesting, School Water and Rainwater Use Modeller

1. INTRODUCTION

Climate change is resulting in increased temperatures, long dry spells and the occurrence of droughts and water scarcity in many areas (Diedhiou et al., 2018; Makki, 2015; IPCC, 2022). Rapid urbanization exacerbates this problem by placing additional demands on existing water supplies that are already struggling to meet demands (UN-Habitat and IHS-Erasmus University Rotterdam, 2018). Limited capacity and resources in water utilities and municipalities mean that water infrastructure may not be maintained resulting in increased leakage and unreliable supplies (Wensley and Mackintosh, 2015). This combination is leading to increasingly unreliable water supplies and shortages in many areas.

A lack of water at schools has severe consequences and can lead to closure as they cannot function without drinking water, water for cleaning and water for flushing toilets (Jasper and Bartram, 2012). The closure of schools, even for a short time, has negative impacts on teaching and learning and the ability to achieve required education outcomes. If closures are prolonged, this in turn can negatively affect students' access to employment opportunities.

Large-scale interventions can be carried out to improve the resilience of municipal water supplies, such as increasing locally stored water (Gibberd, 2017). However, these interventions require significant resources and capacity and may take a considerable time to implement. It is therefore important that schools investigate what they can do themselves to improve the reliability and resilience of their water supplies. One of the most effective ways to do this is to have onsite water storage and to use rainwater harvesting. This reduces the reliance of the

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school on external water supplies and enables the schools to run for a part, or all, of the school year, on their supply.

However, as there is limited guidance on rainwater harvesting at schools, it is difficult for schools to ascertain whether this solution would work in their circumstances. This study presents a simple modeller that has been designed to enable a school to model key characteristics of water consumption and rainwater harvesting at a school. The modeller presents water use and rainwater harvesting capture patterns and allows the implications of different interventions to be determined. The modeller is applied to a case study school to show how it can be used to inform decision-making. The results of this application are critically reviewed to evaluate the value of the modeller and to make recommendations for its improvement. The study aims to address the following key questions:

- How can a school rainwater harvesting modeller be developed?
- What can a school rainwater harvesting modeller be used for?
- Is a school rainwater harvesting modeller useful in supporting decision-making in schools?

2. METHODOLOGY

To develop the school rainwater harvesting modeller an integrative literature review is undertaken. Literature reviews are used to analyze empirical findings from previous research to develop new models (Tranfield, Denyer, & Smart, 2003). Reviews can be systemic and based on highly defined rules for the selection of literature or, they can be integrative, where literature and data are sought from a range of sources to develop new models and knowledge (Snyder, 2019). An integrative approach is used to develop a specification for a school rainwater harvesting modeller and to develop a tool that responds to this. The modeller is developed in Excel as this software is readily available to schools and supports rapid development and testing.

To test the modeller and ascertain how it can be used to support decision-making, it is applied to a case study school. The case study school is selected because it is typical of many schools in drought-stricken areas. The modeller is used to investigate the impacts of installing a rainwater harvesting system at the school and to explore the implications of making changes to the water and rainwater harvesting systems. The case school is in the Eastern Cape of South Africa and data on the school and local climate are sourced from site visits, school databases and online resources such as Google Maps

Finally, results are critically reviewed and discussed to ascertain the value of the modeller as a tool to support decision-making about rainwater harvesting systems at schools. Conclusions are drawn and recommendations made for further research and development of the modeller.

3. RAINWATER HARVESTING IN SCHOOLS

To develop the school water rainwater harvesting modeller it is important to understand the different components and characteristics of a rainwater harvesting system. A typical rainwater harvesting system is shown in Fig 1 and consists of the following elements. A. This is the catchment surface, where rain is collected. As this surface can be dusty or have other debris it is usual to filter runoff, this is shown as B. Clean rainwater is then directed to rainwater harvesting tanks, shown as C. From the rainwater tanks, a distribution system then takes water to where it will be used. If the water will be used for drinking there may be further filtering, shown as D. Rainwater uses in and around buildings include irrigation, cleaning, and flushing toilets, shown as E.

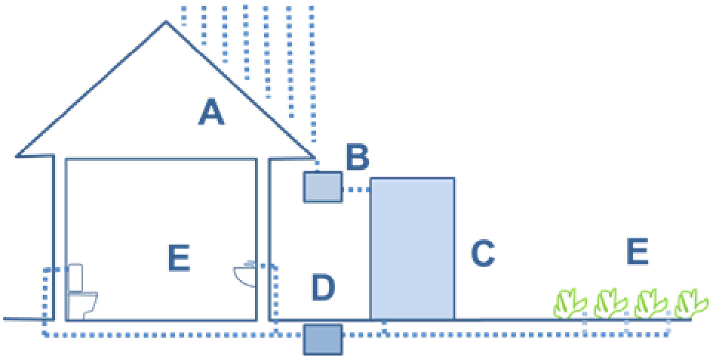


Fig. 1. A rainwater harvesting system

Calculating the amount of rainwater that can be captured off a hard surface requires data on rainfall patterns and an understanding of the physical characteristics of the hard surface. Simple rainwater harvesting calculators use readily available annual or monthly rainfall figures measured in mm/year or mm/month (Centre for Affordable Water and Sanitation Technology, 2011). More complex tools use daily rainfall throughout the year (Gibberd, 2020). However, daily rainfall data is more difficult to access.

The key attribute of collection surfaces that must be ascertained for a rainwater harvesting system is the runoff coefficient of the surfaces. The runoff coefficient is the percentage of precipitation that appears as runoff and is a result of the physiographic characteristics of the drainage area and is expressed as a constant between zero and one. Runoff coefficients for different roof types and surfaces are shown in Table 1.

Table 1. Runoff coefficients (Farreny *et al.*, 2020; Goel, 2011).

Roof type/surface	Runoff Coefficient
Sloping corrugated metal roof sheeting and tiled roofing	0.9
Flat concrete roofing with gravel topping	0.8
Level cement surfaces, such as driveways and tennis courts	0.8
Pavements and roads	0.70–0.95
Parks and pastures	0.05–0.30

Rainwater harvesting can be calculated for the collection surface using a simple calculation that multiplies the area of the collection surface, the volume of rain that falls on the surface and the runoff coefficient. This is shown in the example below for a 200m^2 corrugated iron roof in an area with an annual rainfall of 500mm.

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

Rainwater supply (m3/year) = Rainfall (m/year) x Catchment Area (m2) x Runoff Coefficient
Rainwater supply (m3/year) = 0.5 x 200 x 0.9
Rainwater supply = 90.00m3 or 90,000 liters

3.1 Water consumption in schools

Water consumption in schools can be calculated by metering the volume of water supplied by water systems, for instance, a municipal water supply to a school. Water consumption can also be modelled by identifying all possible water uses in a school and then calculating the projected water usage.

There are many different water uses in schools including drinking, cleaning facilities, flushing toilets and irrigation. To model these, it is important to understand the equipment used to deliver water, how this equipment is operated and how often and how much water is used each time the equipment is used. This can be illustrated through a simple example.

Research indicates that female students use the toilet 4 times a day. If the water used by the toilet after each use is 8 litres, water consumption by toilets for 1 female student would be 4*8 or 32 litres a day.

3.2 Water balance

Rainwater harvesting systems can be designed to supplement an existing water supply and therefore reduce the pressure on this supply. Alternatively, it may be designed to provide for all the water needs of a school. This means that the rainwater harvesting system would enable the school to be ‘’off-grid’’ for water. One of the most important aspects of designing a rainwater harvesting system is understanding which of these need to be achieved and then designing the system for this. The balance between the ‘’production’’ of water from rainwater harvesting and the ‘’consumption’ of water within the school over a school year is an important aspect of this.

3.3 Specifications for a School Water and Rainwater Use Modeler

Based on an understanding of rainwater harvesting systems, a specification for a School Water and Rainwater Use Modeler (SWARUM) was developed. This is outlined below.

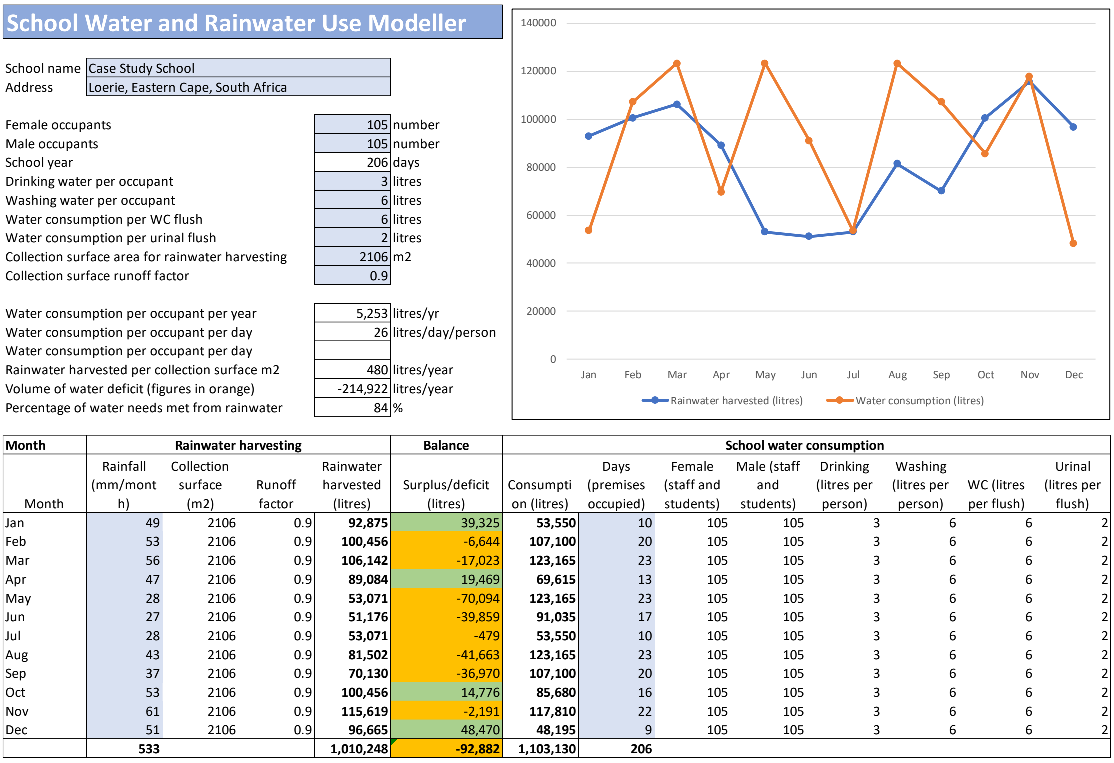
The modeller must achieve the following objectives:

1. It must be very simple to use and be readily understandable by teachers, students and school governing bodies
2. Data required in the modeller must be easily accessible and easy to input.
3. The modeller should enable users to model:
   a) A simple rainwater harvesting system at a school and understanding the patterns of rainwater production over a year.
   b) How different factors within the water and rainwater harvesting system can be manipulated to improve performance.

Based on this specification, a School Water Use Rainwater Modeler (SWARUM) was developed and is presented next.

4. SCHOOL WATER AND RAINWATER USE MODELER

The School Water Use Rainwater Modeler (SWARUM) has three parts: the input section, the table report and the graphic report, and is shown in Fig 2. To use the modeller, inputs are required in the light blue areas, as explained below.



School Water and Rainwater Use Modeller

School name: Case Study School
Address: Loerie, Eastern Cape, South Africa

Female occupants	105	number
Male occupants	105	number
School year	206	days
Drinking water per occupant	3	litres
Washing water per occupant	6	litres
Water consumption per WC flush	6	litres
Water consumption per urinal flush	2	litres
Collection surface area for rainwater harvesting	2106	m2
Collection surface runoff factor	0.9	
Water consumption per occupant per year	5,253	litres/yr
Water consumption per occupant per day	26	litres/day/person
Water consumption per occupant per day		
Rainwater harvested per collection surface m2	480	litres/year
Volume of water deficit (figures in orange)	-214,922	litres/year
Percentage of water needs met from rainwater	84	%

Month	**Rainwater harvesting**				**Balance**	**School water consumption**							
Month	Rainfall (mm/month)	Collection surface (m2)	Runoff factor	Rainwater harvested (litres)	Surplus/deficit (litres)	Consumption (litres)	Days (premises occupied)	Female (staff and students)	Male (staff and students)	Drinking (litres per person)	Washing (litres per person)	WC (litres per flush)	Urinal (litres per flush)
Jan	49	2106	0.9	**92,875**	39,325	**53,550**	10	105	105	3	6	6	2
Feb	53	2106	0.9	**100,456**	-6,644	**107,100**	20	105	105	3	6	6	2
Mar	56	2106	0.9	**106,142**	-17,023	**123,165**	23	105	105	3	6	6	2
Apr	47	2106	0.9	**89,084**	19,469	**69,615**	13	105	105	3	6	6	2
May	28	2106	0.9	**53,071**	-70,094	**123,165**	23	105	105	3	6	6	2
Jun	27	2106	0.9	**51,176**	-39,859	**91,035**	17	105	105	3	6	6	2
Jul	28	2106	0.9	**53,071**	-479	**53,550**	10	105	105	3	6	6	2
Aug	43	2106	0.9	**81,502**	-41,663	**123,165**	23	105	105	3	6	6	2
Sep	37	2106	0.9	**70,130**	-36,970	**107,100**	20	105	105	3	6	6	2
Oct	53	2106	0.9	**100,456**	14,776	**85,680**	16	105	105	3	6	6	2
Nov	61	2106	0.9	**115,619**	-2,191	**117,810**	22	105	105	3	6	6	2
Dec	51	2106	0.9	**96,665**	48,470	**48,195**	9	105	105	3	6	6	2
	533			**1,010,248**	**-92,882**	**1,103,130**	**206**						

Fig. 1. School rainwater harvesting modeller

In the input section of the modeller, in the top left-hand corner, data on the school is entered. Outputs from the modellers, such as the percentage of water needs met by rainwater harvesting, are also provided, as indicated below.

- **School name:** The name of the school is entered here.
- **School address:** The address of the school is entered here.
- **The number of female and male occupants:** The number of female and male occupants at the school is entered. This includes students, teachers and school staff, such as administrators.
- **School year:** This is the number of days the school is occupied by students and staff over a year. This is the sum of the days occupied each month which is shown in the table section (see below)**.**
- **Drinking water per occupant:** The amount of drinking water used per occupant is indicated here. This can be based on studies at the school or a norm, such as 2 litres per day per person (Meinders and Meinders, 2010).
- **Cleaning and washing water per occupant:** The amount of cleaning and washing water used per occupant is indicated here. This can be based on studies at the school and would include washing hands after using the toilet and meals, cleaning cooking and eating utensils, as well as building cleaning such as mopping floors. A guideline of 2-5 litres in water-restricted areas can be used.
- **Water consumption per WC flush: T**he amount of water each time the toilet at the school is flushed is indicated here. Flush rates can be obtained from the manufacturer or physically measured by measuring the amount of water required to fill a toilet cistern after a flush. Flush rates vary between 9 and 3 litres per flush, with most modern toilets having a flush rate of 6 litres per flush (Aurelien et al., 2013)
- **Water consumption per urinal flush:** This can be obtained from the manufacturer or measured by placing a container under the flushing mechanism and measuring the amount of water per flush. Urinal flushes vary between 1 and 2 litres per flush (Aurelien et al., 2013)

- **Rainwater collection surface**: The rainwater collection surface is the area used to collect rainwater. This may include roof surfaces and hard surfaces such as tennis and netball courts.
- **Runoff factor of rainwater collection surface:** The runoff factor relates to the type of material of the collection surface and can be read in Table 1.
- **Water consumption per occupant per year:** This provides the amount of water consumed at the school by each occupant over a year. It is calculated by dividing the total amount of water consumed by the school divided by the number of occupants.
- **Water consumption per occupant per day:** This provides the average amount of water consumed at the school by each occupant per school day. It is obtained by dividing water consumption at the school by the number of occupants and the number of school days.
- **Rainwater harvested per collection surface m^2 :** This provides the amount of rainwater captured by each square metre of the collection surface.
- **The volume of water deficit (figures in orange):** This provides water volume of the water deficit which is the volume of water consumed minus the volume of water captured and indicates the amount of water that will be needed to operate the school over the amount harvested from rain.
- **Percentage of water needs met from rainwater:** This indicates the percentage of water consumed at the school that has been harvested from rain.

The table at the bottom of the modeller presents input and output data. Areas in light blue require data to be entered, while other data is generated by the modeller. Monthly rainfall for the site should be entered in the light blue column on the left. This data is readily available for most sites (World Climate, 2022). The light blue column on the right requires the days the school is occupied by month to be entered.

Data in the columns on the left are used in the modeller to calculate the rainwater harvested per month using the following equation:

Rainfall*area of collection surface* runoff factor

Data in the columns to the right are used in the modeller to calculate water consumption at the school using the following equation:

Female occupants*toilet use per day*WC*flush rates + Male occupants* toilet use per day*WC flush rates + Male occupants* urinal use per day* urinal flush rate + Occupants*drinking water per occupant+ Occupants* Cleaning water per occupant.

The modeller is based on the assumption that users will use the toilets at school 4 times a day. Female users will use the toilet 4 times, while Male users will use the toilet once and the urinal 3 times.

In the coloured ‘Balance’ column in the middle, water consumption at the school is subtracted from the rainwater harvested to provide a negative or positive balance. This balance indicates whether the consumption of water is above or below the volume of water harvested that month. Positive balances are indicated in green and negative balances are indicated in orange.

The graph on the top right corner of the modeller indicates volumes of water harvested per month (in blue) and volumes of water consumed per month (in orange). This indicates whether water consumption is above or below the volumes of rainwater harvested each month.

5. CASE STUDY

The case study school is near Loerie in the Eastern Cape, in South Africa. The area has experienced severe droughts and water rationing over the last 5 years. Figure 2 shows photographs of the school indicating the large roof and hard surface areas available as collection surfaces.

Fig. 2. Photographs of the case study school.

Figure 3 shows a plan of the school with the main collection surfaces shown in dark grey (roofs). The roofs of the building are corrugated iron and can be used as collection surfaces. From Table 1 the collection surfaces have a runoff coefficient of 0.9. The collection surface area available for rainwater harvesting is 2,160 m^2 on a school site of 67,500m^2.

Fig. 3. A plan of the school indicating the site and the roof collection surface.

Fig. 4 shows rainfall patterns for the case study site over a year. This indicates that most rain falls in the summer months (November – March) when there is between 70 and 80mm per month. This decreases between April and October when rainfall is between 60 and 70mm. This indicates that rainfall is fairly regular throughout the year and there are no long dry periods.

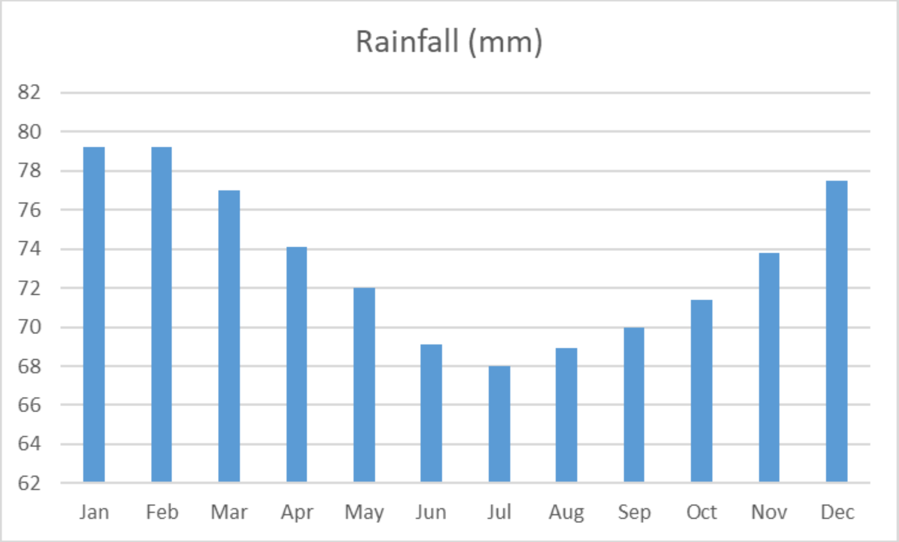


Fig. 4. Monthly rainfall in Loerie, Eastern Cape.

The school has 202 learners and 8 full-time staff equivalents and therefore has 210 occupants on site. As gender ratios vary over time, for this exercise the number of male and female occupants were made equal at 105 female and 105 male. The number of days the school is occupied is entered per month and is determined by the school calendar which remains broadly the same from one year to the next.

5.1 Application of the School Water Use and Rainwater Model to the Case Study

To test the modeller, it is used to model the following interventions at the school:

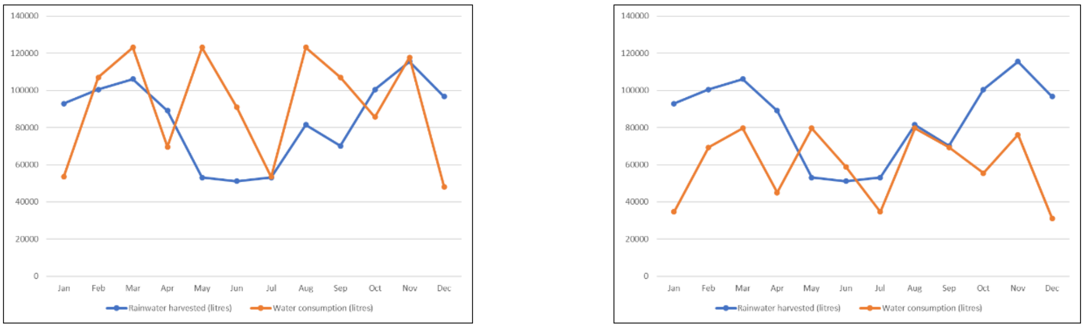
- Intervention 1: Use the school roofs for rainwater harvesting.
- Intervention 2: Use school roofs for rainwater harvesting, and reduce water consumption through increased efficiency including reducing washing water per occupant from 6 to 4 litres and reducing WC flush rates from 6 to 4 litres and urinal flush rates from 2 to 1 litre.
- Intervention 3: Use school roofs for rainwater harvesting, reduce water consumption through more efficient fittings, and increase collection area from 2,106 to 3,106m^2 by including yard hard surfaces.
- Intervention 4: Use school roofs and hard surfaces for rainwater harvesting, reduce water consumption through more efficient fittings, and install waterless sanitation. This means that all water associated with water-borne sanitation is reduced to zero.

The results of this application are shown in Fig 5. Results in Intervention 1 show that water consumption at the school generally exceeded the amount of rainwater harvested. This indicates that the rainwater harvesting system could meet about 84% of the school's water requirements.

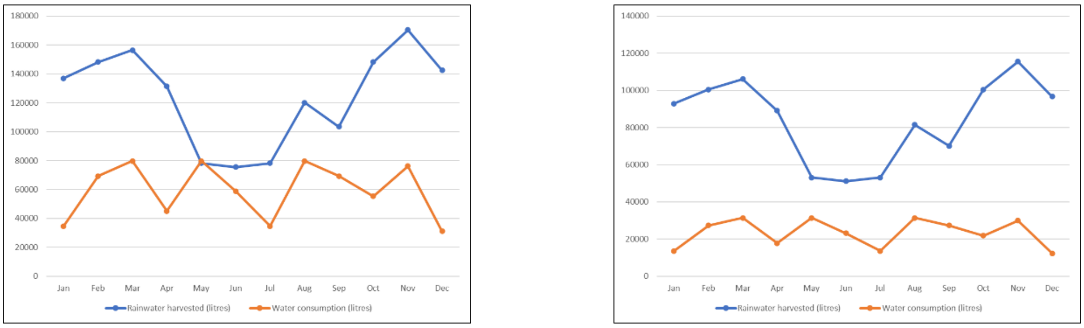
Results for Intervention 2, indicate that water consumption has dropped at the school resulting in more months where rainwater harvested water exceeds water consumed. This results in 95% of the school's water needs being met from rainwater harvesting.

Results for Intervention 3, indicate that rainwater harvesting exceeds the amount required at the school and that 100% of the school's needs are met. An exception is in May when consumption of water is equal to the amount of rainwater harvested.

Results for Intervention 4 indicate that rainwater harvesting far exceeds the amount of water required at the school and that the school could operate on 100% rainwater harvesting



Intervention 1 Intervention 2



Intervention 3 Intervention 4

Fig 5. Rainfall harvested, water used at the school under conventional conditions and the difference (author).

6. DISCUSSION

A review of the results in Fig. 5 indicates that the modeller provides useful insight into water use at the school. Patterns of water use per month relate directly to the number of days the school premises were occupied. The school premises are occupied for 23 days in May and August and as a result, water consumption is highest for these months and the rainwater harvesting system is not able to match consumption in Intervention 1. However, during months when the occupation is lower, such as April (13 days) and July (10 days), rainwater harvesting exceeds water consumption (see Intervention 1, Fig. 5).

This finding would be interesting for a school because it highlights the possibility of matching occupancy with rainwater harvesting patterns. Thus, there could be more days of school during months of high rainwater harvesting volume and reduced occupancy during drier months. This alignment of water consumption to rainwater harvesting production would reduce reliance on external water supplies and improve the school’s water resilience.

The results also show that a simple rainwater harvesting system based only on school building roofs (Intervention 1) and improved efficiency (Intervention 2) may not enable the school to be off-grid and wholly rely on rainwater harvesting for their needs. The results however do show that increasing the collection surface of the rainwater harvesting systems (Intervention 3) is likely to enable the system to meet all the school’s needs. The results also show that using a dry sanitation system makes a very significant reduction in water consumption at the school and that combined with a simple roof-based rainwater system there is sufficient water to meet the school’s needs throughout the year (Intervention 4).

These types of results enable schools to understand their water use and the potential of a rainwater harvesting system. The modeller demonstrates that using a simple rainwater system and improving efficiency could reduce their reliance on external water sources, such as municipal water, by up to 90%. It also indicates that should the school wish to be off-grid for water, more radical changes such as the use of external hard surfaces for rainwater collection and installing dry sanitation will be required.

The findings confirm that the modeller is easy to use and enables the implications of different interventions to be readily ascertained. However, it also shows that the modeller may not provide an accurate basis for the detailed design of a rainwater harvesting system. This is due to the following. Firstly, only one flush rate for toilets and urinals is provided. Schools with many toilets may have toilets and urinals with different flush rates and this diversity is not captured. Secondly, the modeller only allows for one collection surface runoff factor to be entered. Schools may have different collection surfaces with different runoff factors. Thirdly, schools may have other water uses, such as irrigation, that currently are not included in the modeller. Fourthly, the 'lag' effect of large rainwater tanks is not considered. Thus, water harvested, but not consumed entirely in a month, such as during January, is not reflected as a ''credit'' to the following month, as would happen in an actual rainwater harvesting system. Fifthly, the modeller assumes regular rainwater patterns with limited variation between years. Data from climate change projections indicate that rainwater patterns are likely to change and therefore this should be considered (Maúre et al., 2018).

A review of the original specification of the modeller indicates that the SWARUM appears to meet most of the defined requirements. The tool is easy to use and understand, the data used by the modeller is easy to access, and the modeller provides an indication of water use and rainwater harvesting over a year and enables the implications of interventions to the water and rainwater harvesting system to be understood.

The modeller can therefore be said to support increased knowledge and understanding and contribute to "responsible decision making" by the school governing body and staff (Williamson, 2010). Achieving a high degree of accuracy was not part of the specification and the complexity associated with achieving this is likely to have made the tool highly complex and difficult to use (Borgstein, et al., 2016). However, Williamson (2010), notes that while achieving a high degree of accuracy in modelling tools may not be necessary, tools should provide an indication of the levels of accuracy achieved, so this is understood. This recommendation should be incorporated into the SWARUM.

7. CONCLUSIONS AND RECOMMENDATIONS

The study develops a school water use and rainwater harvesting modeller and applies this to a case study school in a drought-stricken area of South Africa. The specification for the modeller indicates that school staff must be able to use this to understand the potential of rainwater harvesting and enables interventions to improve water resilience to be modelled. Applying the modeller to the case study school indicates that it can generate graphs of water consumption and rainwater harvesting over a year. It also shows that the modeller enables the implications of interventions such as more efficient use of water, increasing rainwater collection surfaces and the use of dry sanitation to be ascertained.

The modeller, therefore, shows some potential to support increased awareness and enable decision-making about water and rainwater harvesting systems by schools. This could make a valuable contribution to improving water resilience at schools. A recommendation, therefore, is to develop the modeller and test it with school decision makers, such as school management teams and governing bodies. The simple manual and notes on the modeller should indicate its role as means of supporting decision-making rather than as a design tool. These notes should also indicate the accuracy of the tool.

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