

several storage capacities, the relationship between storage capacity and performance is obtained to help make decisions on the appropriate storage capacity. For RWH systems, rainfall events typically have a large impact on the storage state and a daily time-step is therefore needed to obtain the required temporal precision (Ndiritu et al. 2011a). The analysis here therefore applied a daily time step behaviour analysis as illustrated in Fig. 1 and described by equations (1) and (2).

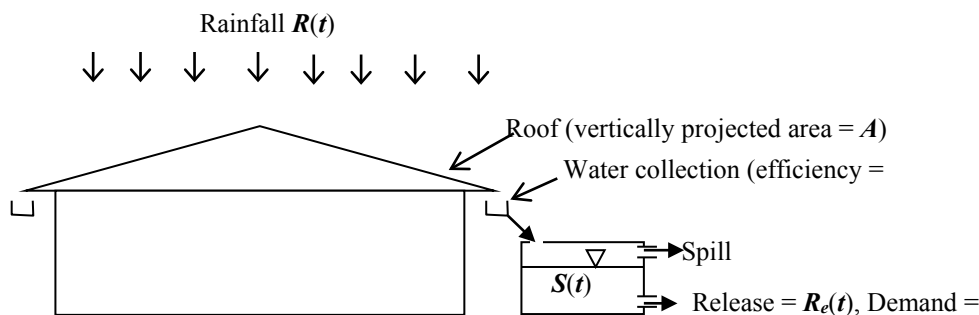


Fig. 1 Illustration of RWH system simulation.

$$S(t+1) = \begin{cases} S(t) + \eta R(t)A - R_e(t) & \text{if } 0 < S(t) + \eta R(t)A - R_e(t) \leq C \\ C & \text{if } S(t) + \eta R(t)A - R_e(t) > C \\ 0 & \text{if } S(t) + \eta R(t)A - R_e(t) \leq 0 \end{cases} \quad (1)$$

$$R_e(t) = \begin{cases} D_t & \text{if } \eta AR(t) + S(t) \geq D_t \\ \eta AR(t) + S(t) & \text{if } \eta AR(t) + S(t) < D_t \end{cases} \quad (2)$$

where $S(t)$ is the storage at the start of period (day) t , C is the live storage capacity of the tank, $R(t)$ is the rainfall intensity in period t , A is the vertical projection of the roof area, $R_e(t)$ is the volume of water released in period t and $D(t)$ is the volume of water demanded in period t .

Experience gained on RWH analysis in South Africa (Ndiritu et al. 2011a,b) reveals that household RWH is a within-year storage problem in which the storage typically fills up and becomes empty every single year. Trial simulations of RWH based on equations (1) and (2) for schools also revealed this, as illustrated in Fig. 2 for an 11 year-long storage trajectory of a 30 m³ tank and a demand of 5 m³/day of a hypothetical RWH storage-yield problem. The trajectory is a graph of $S(t)$ versus t and the year is taken to start at the beginning of August. Figure 2 shows the periods within each year that the storage mostly contains and therefore supplies water and the periods between years that the storage is mostly empty. For schools, a practical performance measure is the expected number of days within the year that the RWH system would be able to provide the water demand. For the same 11-year period the number of days in each year that the demand ($D(t)$) was met is indicated below the storage trajectory in Fig. 2. Since the number of days of supply in each year varies substantially, a statistical estimation of the expected number of days of supply per year at specified reliabilities would be an appropriate measure of system performance. The Weibull plotting position formula is commonly used for hydrologic frequency analysis (Chow et al. 1988) and was adopted for this. The number of days of supply for each year were ranked from the highest to the lowest and the probability p that the RWH system will supply the number of days ranked m was obtained as $p = m/(n+1)$ where n is total number of years of simulation. For the 11 years in Fig. 2, the reliability for 225 supply days per year (the highest ranked with $m = 1$) would be 1/12 (8%) and the reliability for 172 days per year (for which $m = 11$) would be 11/12 (92%). Interpolation can be used to obtain the number of supply days for a specific reliability.

CASE STUDY AREAS AND DATA

The selection of the case study areas needed to consider the rainfall variability that exists in South Africa and to specifically include a high summer rainfall, a low summer rainfall and a winter

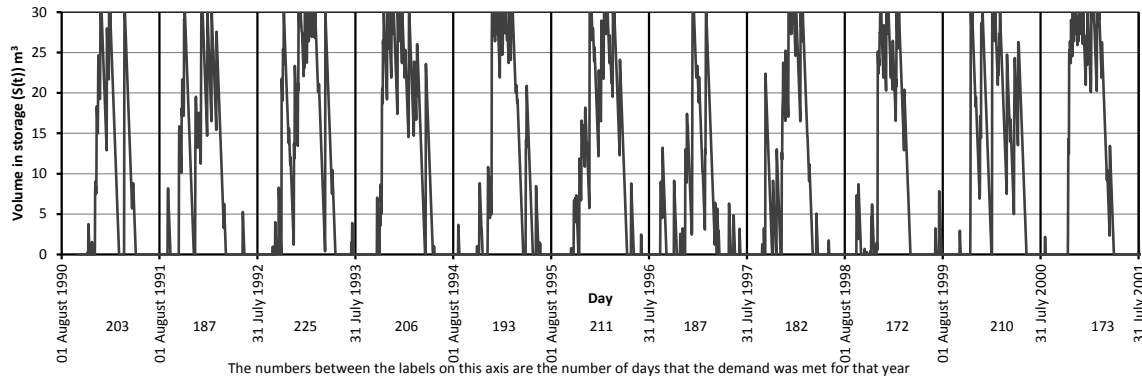


Fig. 2 School RWH storage behaviour and number of days supplied for an 11-year long period.

Table 1 Number of students attending the schools (obtained from South African Schools.net 2010) and the vertically projected roof areas (A) obtained from Google-Earth

| Name | No. S | Area (m ²) | Name | No. S | Area (m ²) | Name | No. S | Area (m ²) |
|--------------------------------|-------|------------------------|------------------|-------|------------------------|----------------------------|-------|------------------------|
| Sisonke (Kwa Zulu Natal (KZN)) | | | Mopani (Limpopo) | | | Khayelitsha (Western Cape) | | |
| Zamokuhle | 203 | 548 | Bolebedu | 500 | 1860 | Bulumko | 1379 | 2337 |
| Dumisa | 784 | 877 | Mashao | 466 | 1144 | Chumisa | 1149 | 2600 |
| Mbumbulwana | 322 | 806 | Modumane | 250 | 771 | Eluxolweni | 791 | 1550 |
| Kukhanyeni | 343 | 589 | Mohokone | 233 | 660 | Homba | 950 | 2500 |
| Mahwaqa | 73 | 302 | Morwatshehla | 342 | 1265 | Ikhusi | 1029 | 1940 |
| Delamuzyi | 463 | 817 | Motsipa | 309 | 1166 | Injongo | 1051 | 2845 |
| Zakhele | 264 | 1158 | Pembelani | 606 | 1622 | Intshayelelo | 1300 | 2640 |
| Qondokuhle | 303 | 410 | Ramabolela | 347 | 946 | Isiphiwo | 1255 | 4075 |
| Ezimpungeni | 311 | 751 | Sekgware | 501 | 1265 | Masiphumelele | 1500 | 4159 |
| Bombasi | 336 | 1495 | Seripe | 406 | 1056 | Nkazimulo | 1220 | 2904 |
| | | | | | | Nomsa | 1720 | 3460 |
| | | | | | | Sivuyiseni | 880 | 2904 |

No. S: number of students.

rainfall area. On this basis, 10 schools located in the high summer rainfall Sisonke District of Kwa Zulu natal (KZN) province, 10 in the low summer rainfall Mopani District of Limpopo province, and 12 in Khayelitsha located in the winter rainfall Western Cape were selected. Table 1 shows the number of students attending the schools (obtained from South African Schools.net 2010) and the vertically projected roof areas (A) obtained from Google-Earth.

The rainfall database developed by Lynch (2003) was used to obtain the rainfall data to apply for each school and it was found reasonable to apply 101 years of daily rainfall data for the period 1901–2001 for all the schools. The nearest rainfall station to each school with a long rainfall record was located and the daily time series data was used as the rainfall input $R(t)$. For Mapani area, four rainfall stations with Mean Annual Precipitation (MAP) ranging from 554 to 580 mm/year (averaging 559 mm/year) were used, while for Sisonke seven rainfall stations with MAP ranging from 712 to 1106 mm/year (and averaging 924 mm/year) were used. Only a single station with an MAP of 505 mm/year was used for Khayelitsha. The distances from the schools to the nearest raingauge ranged from 4.0 to 11.5 km for Mapani, 5.1 to 35.1 km for Sisonke and 2.4 to 4.8 km for Khayelitsha. All the schools have corrugated iron sheet roofs and a water collection efficiency (η) of 0.8 was applied for all of them based on information from the Council for Scientific and Industrial Research (CSIR) (2003) and Mashau (2006). A water demand of 20 L per-capita per day recommended by CSIR (2003) was used and this was assumed to apply on all days of the week when the schools were open. These periods were obtained from the Ministry of Basic Education National Education (1996). Communication with tank manufacturers revealed that tank sizes are mostly available as multiples of 5 m³. After some trial simulations, it was

therefore decided to confine the storage capacities in the analysis to multiples of 5 m³, starting with a minimum of five to a maximum of 40 m³. The realistic range of reliability (*p*) was considered as 85–95% and three reliabilities of 85, 90 and 95% were adopted for the analysis.

RESULTS

Figure 3 shows the relationships between the expected number of days that the demand would be met per year for reliabilities of 85, 90 and 95% and tank sizes varying from 5 to 40 m³. For Sisonke and Mapani, the number of days of supply increases as the tank size increases with an observed tendency for this number to level off as the tank size increases in some cases. A larger tank is able to store some of the water that would otherwise spill (if the tank was smaller) and retain it for supply. The number of days of supply therefore increases as tank size increases. There is however a limiting tank size beyond which negligible (if any) spillage occurs because the incoming water hardly ever fills the tank. When this size is reached, the number of days supplied levels off as tank size increases. This was mainly observed in Fig. 3 for winter rainfall zone Khayelitsha where the demand periods (when schools are open) coincides more closely with the rainfall season meaning that spillage is much less significant for Khayelitsha than for the two summer rainfall regions.

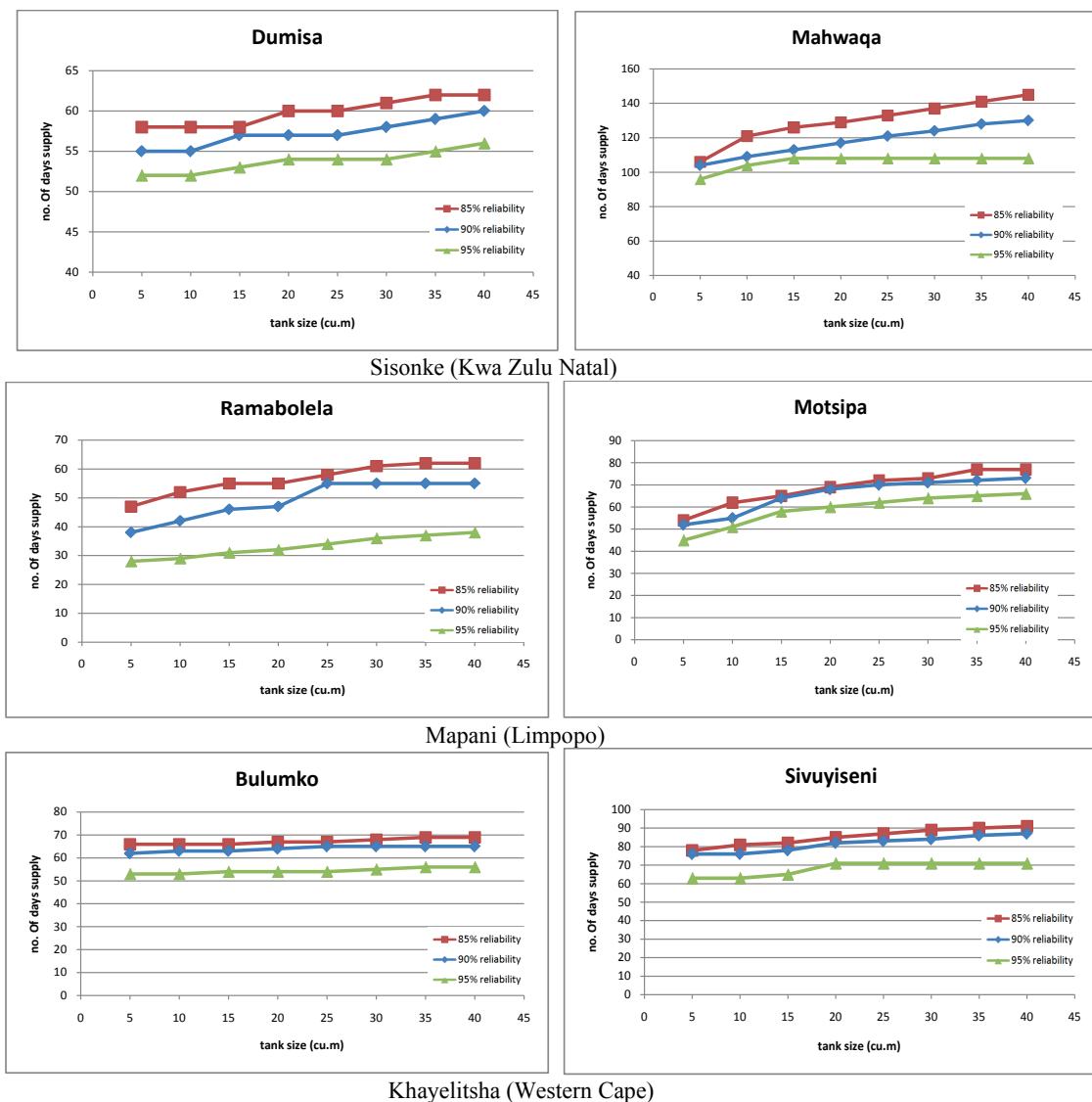


Fig. 3 Number of days supplied per year for various storage sizes and reliabilities.

The number of days of supply was found to vary considerably within and across the three regions (as expected) and it was considered appropriate to try and obtain a generalized relationship between supply, demand and number of days of supply that could be applied to assess RWH potential in other schools within the regions. Intuitively, the number of days of supply per year is expected to increase as the supply level increases and to decrease as the demand increases. It is therefore also expected that the number of days of supply would also depend on the ratio of the supply to the demand. Relating number of days of supply to this ratio (instead of both supply and demand as individual variables) is likely to obtain a simpler and more generalized relationship. The ratio of supply to demand was therefore obtained as a dimensionless parameter α defined as the ratio of the average volume of rainfall collected by the roof per year divided by the total annual water demand by the school.

$$\alpha = \frac{\text{Average annual supply}}{\text{Annual demand}} = \frac{\text{MAP} \times A}{\frac{\text{demand per year}}{\text{capita}} \times \text{number of students}} \quad (3)$$

Based on its definition, a higher α value means that the supply is relatively higher than the demand and the number of days of supply would be expected to be higher. In addition, since α is dimensionless, it would allow comparison across regions and enable possible transfer of these relationships across regions with similar rainfall characteristics. Figure 4 shows a representative relationship between α and the expected number of days of supply at 90% reliability for storage sizes of 20 and 40 m³. The expected increase in number of days of supply with α is observed and the relationships for Western Cape (Khayelitsha) and Kwa Zulu Natal (Sisonke) are better correlated (have a smaller scatter) than those for Limpopo (Mapani). Figure 4 reveals that for a given α , the number of days supplied in Western Cape (Khayelitsha) is higher than for the other two regions, suggesting that RWH could be more effective there. This is considered to arise from the higher coincidence of rainfall with demand in Khayelitsha since it is located in the winter rainfall zone where a higher proportion of the rain falls during school term than in the summer rainfall regions. The temporal variation of rainfall distribution within the summer region itself could possibly explain the higher supply levels for KZN (Sisonke) than Limpopo (Mapani) for the same values of α . As Fig. 4 shows, the number of days supplied per year can vary highly within and across regions.

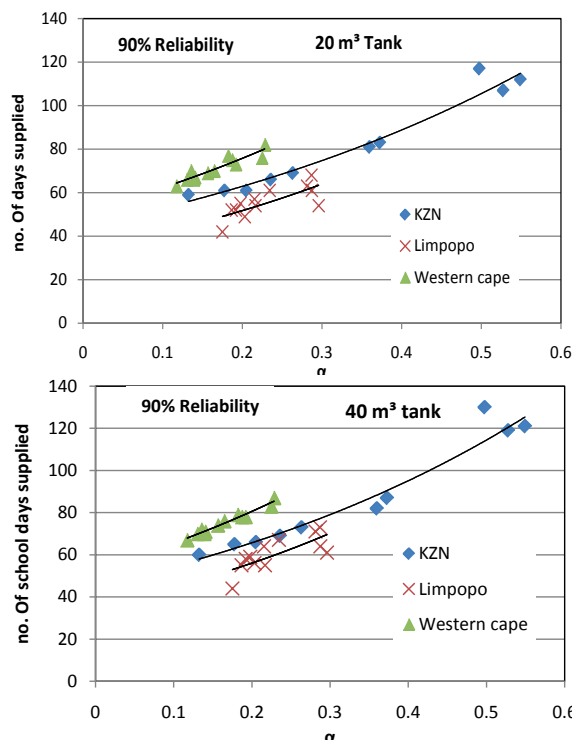


Fig. 4 Generalized relationships between supply to demand ratio (α) and number of days supplied.

All the supply levels obtained reveal that RWH cannot be used as the sole water source for schools in South Africa, but can be a significant water source for many schools. Since α is reasonably easy to estimate, the expected number of days of supply for a set reliability and storage for a school can be estimated in any region where the relationship of the form of Fig. 4 has been developed.

DISCUSSION AND CONCLUSIONS

The assessment of the rainwater harvesting (RWH) potential of schools in South Africa using 32 representative schools located in three regions of South Africa showed that supply levels ranging from 40 to 130 days per year can be achieved at 90% reliability (meaning this level of supply would be met in 9 out of 10 years on average). This high variability in the number of days of supply was expected due to: (i) the large differences in rainfall availability, (ii) the demand as determined by the number of students attending school and, (iii) the roof area available. Figure 3 revealed that tank volumes exceeding 5 m³ would not improve supply for the winter rainfall region of Khayelitsha, while a size exceeding 25 m³ would also not substantially improve supply in the two summer rainfall areas. The higher co-occurrence of rainfall with demand in the winter rainfall area is considered the likely reason why the tank storage required is much smaller for the winter rainfall region. This finding reveals the need for comprehensive hydrologic analysis of RWH systems and highlights why the use of constant tank sizes for RWH across large regions that has sometimes occurred (e.g. De Lange 2006) may not be justifiable. Generalized relationships between the supply, the demand and the level of supply were obtained (Fig. 4) and can be used to provide estimates of the number of days that a RWH system of a given size obtaining water from a specified roof area can provide if the MAP of the area the school is located can be reasonably obtained. A more comprehensive relationship than Fig. 4 can be obtained by analysing more schools in other regions of South Africa. However, the analysis here is considered adequately realistic for estimation of number of days of supply per year and the hydrologic viability of RWH for schools in South Africa.

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