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Probabilistic assessment of the rainwater harvesting potential of schools in South Africa

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Abstract In comparison to other sources of water supply, rainwater harvesting (RWH) has the typical advantages of being cheaper and easier to operate and maintain. This study aimed at assessing the hydrologic rainwater harvesting potential of rural schools in South Africa by obtaining RWH storage capacity (level of supply) reliability relationships of representative schools. Thirty-two schools located in three rural areas that have varied rainfall characteristics were selected for the analysis. For each school, a daily time-step behaviour analysis of the rainwater harvesting system with a specified storage was carried out for a period of 101 years (over which rainfall data was available) and the number of days that the school's daily water demand was met in each year obtained. Using the Weibull plotting position formula, the expected number of days that the demand can be met per year was then obtained for 85, 90 and 95% reliability. For the two summer rainfall regions where a large proportion of rain falls during school holidays, the expected number of days of supply per year improved up to a storage capacity of 25 m^3. For the winter rainfall region where the rainfall periods and school learning times have more co-incidence, a tank volume of 5 m^3 obtained similar supply levels as larger capacities. At 90% reliability, the supply levels for different schools in the summer rainfall area with a mean annual precipitation (MAP) of 800–1000 mm/year ranged from 60 to 120 days per year, while the summer rainfall region with a lower MAP (500–600 mm) gave supply levels ranging from 40 to 70 days per year. The winter rainfall area had a MAP of 500–600 mm and obtained supply levels ranging from 60 to 80 days at 90% reliability.

Key words rainwater harvesting, storage, reliability, days of supply, schools

INTRODUCTION

Rainfall is a directly accessible water source which can be used for many purposes, including augmenting other sources of water supply in urban areas. Rainwater harvesting (RWH) is typically easy to access, has relatively low implementation and maintenance costs, and its operation does not require specialised training. South Africa is a water-scarce country and only 4% of the available water is allocated to rural water use (Department of Water Affairs (DWA), 2009). Consequently, in many rural parts of South Africa, a large proportion of people have no access to adequate water supply and RWH may therefore hold great promise. The need to comprehensively assess the RWH potential in rural South Africa is therefore hardly an option (United Nations Environmental Program (UNEP), 1997). As schools have large roof areas, they are naturally suitable candidates for investigating RWH potential and the Department of Water Affairs considers RWH as one of the practical water sources for Schools (DWA 2008). Furthermore, the South African National Planning Commission (NPC) reveals that 1727 schools in South Africa do not have safe drinking water (NPC 2012). The objective of this investigation was to assess the RWH potential of rural schools in South Africa using probabilistic storage-yield analysis.

METHODOLOGY

Various methods are available for storage-yield analysis amongst which the Mass Curve method stands out as a popular graphical approach. This method uses a mass balance of the worst drought recorded, thereby assuming that a more severe drought will not occur in the future. The Mass Curve method therefore does not provide an estimate of the expected reliability of the storage capacity. More recently, the Behaviour Analysis method has been adopted as the preferred storage-yield analysis approach (McMahon and Adeloye 2005) and has been applied for RWH analysis (Su *et al.* 2009, Ward *et al.* 2010, Ndiritu *et al.* 2011a, Santos *et al.* 2012). The Behaviour Analysis method carries out a continuous simulation of the system of a specified storage capacity assuming a specified starting storage state. As the simulation carries on, a time series of the levels of water supply is obtained and used to determine the system performance. By carrying out the analysis for 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).

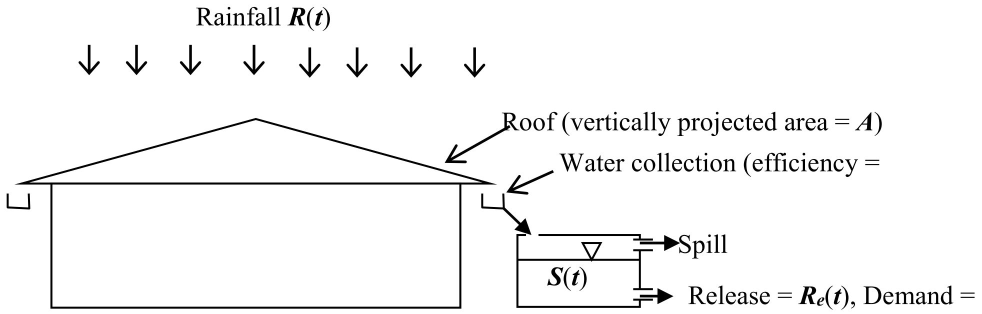


Fig. 1 Illustration of RWH system simulation.

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

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

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

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 m^3 tank and a demand of 5 m^3/day of a hypothetical RWH storage-yield problem. The trajectory is a graph of $\boldsymbol{S(t)}$ *versus* $\boldsymbol{t}$ 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 ($\boldsymbol{D(t)}$) 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 $\boldsymbol{p}$ that the RWH system will supply the number of days ranked $\boldsymbol{m}$ was obtained as $\boldsymbol{p = m/(n+1)}$ where $\boldsymbol{n}$ 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 $\boldsymbol{m} = 1$) would be 1/12 (8%) and the reliability for 172 days per year (for which $\boldsymbol{m} = 11$) 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

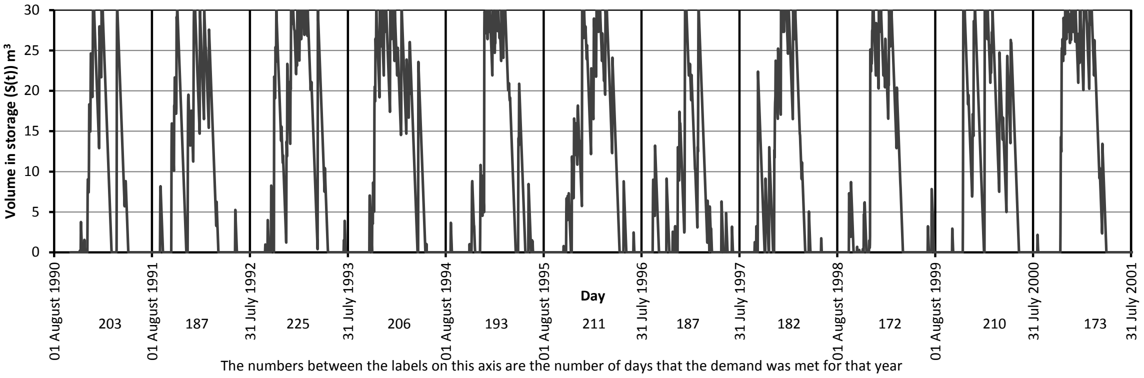


Fig. 2 School RWH storage behaviour and number of days supplied for an 11-year long period.

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
Delamuzi	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

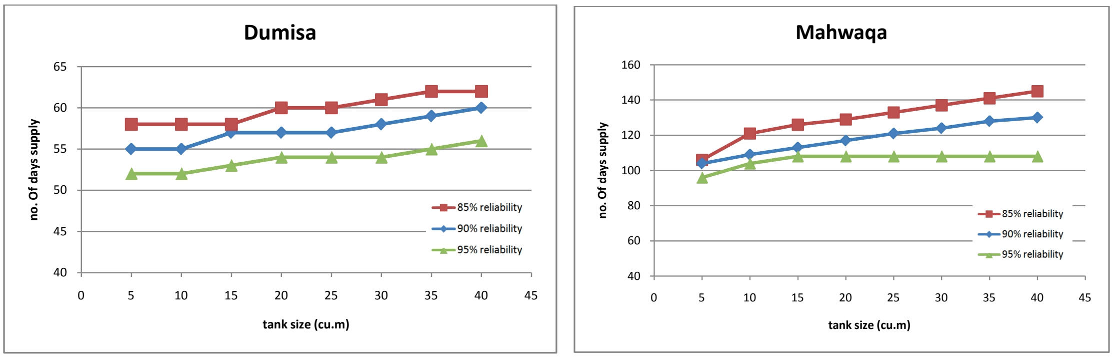
No. S: number of students.

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.

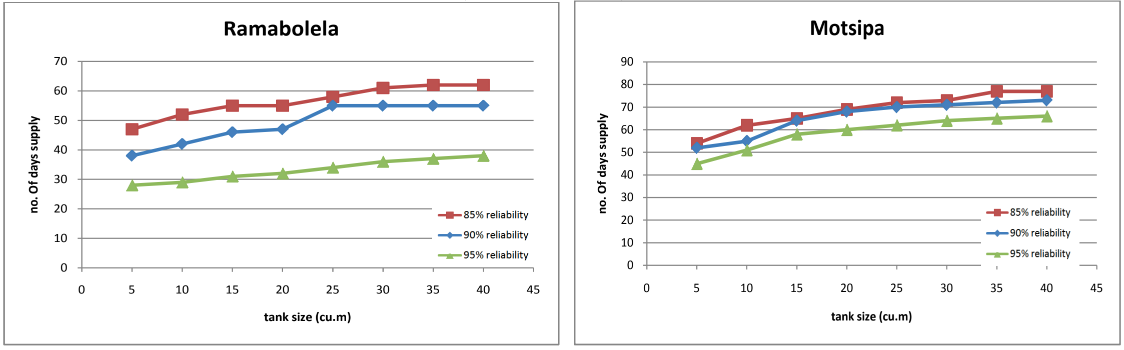
The rainfall database developed by Lynch (2003) was used to obtain the rainfall data to apply for each school and it was found reasonable to apply 101 years of daily rainfall data for the period 1901–2001 for all the schools. The nearest rainfall station to each school with a long rainfall record was located and the daily time series data was used as the rainfall input $\boldsymbol{R}(\boldsymbol{t})$. 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 ($\boldsymbol{\eta}$) 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 m^3. After some trial simulations, it was therefore decided to confine the storage capacities in the analysis to multiples of 5 m^3, starting with a minimum of five to a maximum of 40 m^3. 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

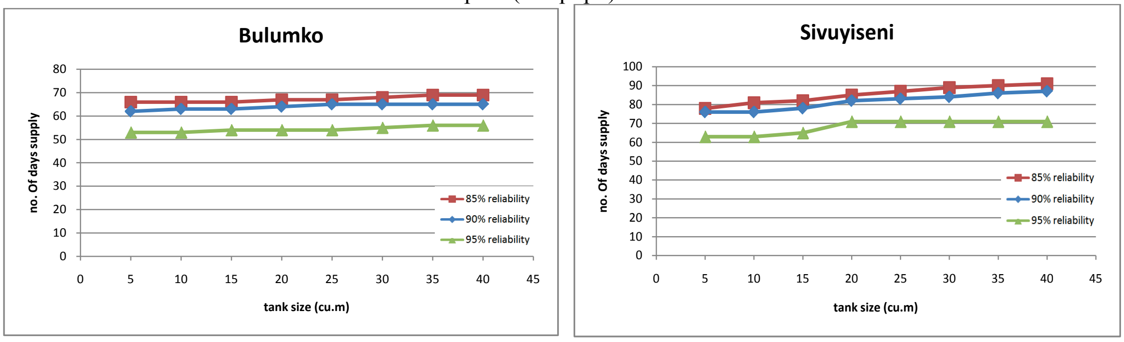
Figure 3 shows the relationships between the expected number of days that the demand would be met per year for reliabilities of 85, 90 and 95% and tank sizes varying from 5 to 40 m^3. For Sisonke and Mapani, the number of days of supply increases as the tank size increases with an observed tendency for 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 Khayelistsha 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.



Sisonke (Kwa Zulu Natal)



Mapani (Limpopo)



Khayelitsha (Western Cape)

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 $\boldsymbol{\alpha}$ 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.

$$\alpha = \frac{Average\ annual\ supply}{Annual\ demand} = \frac{MAP * A}{\frac{demand\ per\ year}{capita} * number\ of\ students} \tag{3}$$

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 m^3. 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.

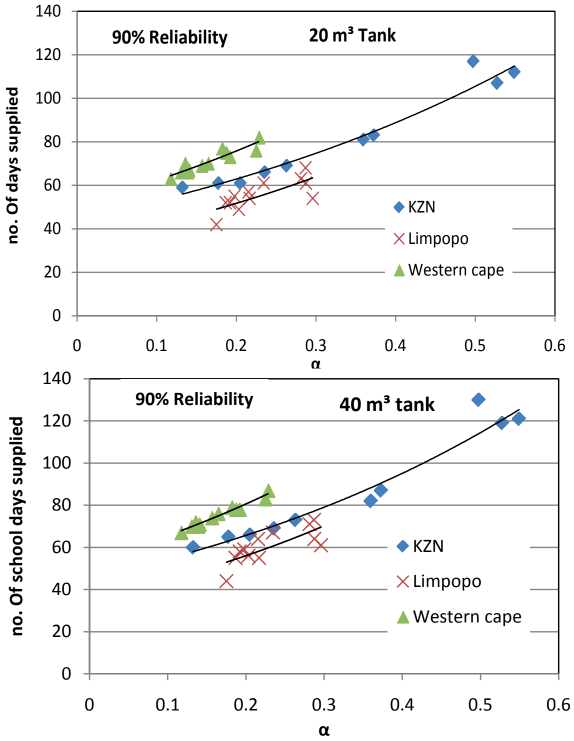


Fig. 4 Generalized relationships between supply to demand ratio (α) and number of days supplied.

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 m^3 would not improve supply for the winter rainfall region of Khayelitsha, while a size exceeding 25 m^3 would also not substantially improve supply in the two summer rainfall areas. The higher co-incidence 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.

REFERENCES

Chow, V. T., Maidment, D. R. and Mays, L. W. (1988) *Applied Hydrology*, McGraw-Hill, New York.

Council for Scientific and Industrial Research (CSIR) (2003) Building and Construction Technology, *Guidelines for Human Settlement Planning and Design Volume 2,* Pretoria, South Africa.

De Lange, M. (2006) War on hunger: some impacts of the DWAF Rainwater Harvesting Pilot Programme, Report to the Water Resources Finance and Pricing, DWAF directorate. Department of Water Affairs and Forestry, Pretoria, South Africa.

Department of Water Affairs (DWA) (2008) *Miminim Requirements For Ensuring Basic Water Supply and Sanitation in Schools and Clinics, Final version 7.*

Department of Water Affairs (DWA), (2009) *Water for Growth and Development.*

Lynch, S. (2003) *Development of a raster database of Annual, Monthly and Daily rainfall for Southern Africa.* Pretoria: Water Research Commission.

Mashau, F. (2006) *Rainwater harvesting for multiple uses in Siloam Village of Limpopo Province*, South Africa. Unpublished Honours research dissertation, University of Venda, South Africa.

McMahon, T. A. and Adeloye, A. J. (2005) *Water Resources Yield.* Highlands Ranch, CO: Water Resources Publications.

Ministry of Basic Education National Education Policy Act 27 of 1996, (1996): *2011 and 2012 School Calendars for Public Schools.*

Ndiritu, J. *et al.* (2011a) Yield-reliability analysis for rural domestic water supply from combined rainwater harvesting and run-of-river abstraction. *Hydrological Sciences Journal* 564(2), 238–248.

Ndiritu, J. *et al.* (2011b) Incorporating hydrological reliability in rural rainwater harvesting and run-of-river supply. In: *Risk in Water Resources management* (ed. by G. Bloschl *et al.*) IAHS Publ. 347, 247–252. IAHS Press, Wallingford, UK.

National Planning Commission (NPC) (2012) *Social Infrastructure*, viewed May 3, 2013, from NPC online: http://www.npconline.co.za/pebble.asp?relid=189.

Santos, C. and Taveira-Pinto, F. (2012) Analysis of different criteria to size rainwater storage tanks using detailed methods. *Resources, Conservation and Recycling* 71, 1–6.

South African Schools.net (2010) *Database of Schools*, viewed 10 June 2013, http://www.southafricanschools.net/.

Su, M.-D., *et al.* (2009) A probabilistic approach to rainwater harvesting systems design and evaluation. *Resour. Conserv. & Recycling* 53, 393–399.

United Nations Environment Programme (UNEP) (1997) *Source Book of Alternative Technologies for Freshwater Augmentation in Latin America and the Caribbean,* viewed 19 March 2013, http://www.oas.org/dsd/publications/Unit/oea59e/ch10.htm.

Ward, S., Memon, F. A. and Butler, D. (2010) Rainwater harvesting: model-based design evaluation. *Water Sci. Technol.* 61(1), 85–96.