Incorporating hydrological reliability in rural rainwater harvesting and run-of-river supply

JOHN NDIRITU[1], JOHN ODIYO[2], RACHEL MAKUNGO[2], CELIWE NTULI[3] & BEASON MWAKA[3]

1 *University of the Witwatersrand, School of Civil and Environmental Engineering, P/Bag X3, Wits 2050, South Africa* john.ndiritu@wits.ac.za

2 *University of Venda, Department of Hydrology and Water Resources, P/Bag X5050, Thohoyandou 0950, South Africa*

3 *Department of Water Affairs, P/Bag X313, Pretoria 0001, South Africa*

Abstract Many households in rural areas obtain water from rainwater harvesting (RWH) and/or run-of-river (ROR) flow, but many of the methods used to assess the yield of RWH and/or ROR supply unrealistically aggregate data into monthly or annual time steps, and do not incorporate measures of reliability. Most approaches do not assess the improvement in supply that would be obtained from integrated utilization of the two sources. This paper demonstrates: (i) the incorporation of reliability for the widely applied mass curve method, and (ii) realistic incorporation of reliability and integration in RWH and ROR hydrologic analysis via behaviour analysis of household supply and frequency analysis of the annual levels (number of days) of supply. The behaviour analysis approach has the ability to simulate complex operating rules and configurations while including measures of performance comprehensively. It is therefore considered the method of choice for RWH and ROR supplies.

Key words yield-reliability analysis; rainwater harvesting; run-of-river; rural water supply; mass curve; behaviour analysis

INTRODUCTION

Rainwater harvesting and run-of-river supply are some of the main or supplementary sources of water in many regions of the world. The use of rainwater harvesting (RWH) is prevalent in many rural areas where centralized water supply is unavailable (e.g. Duncker, 2000; De-Lange, 2006; Mwenge Kahinda *et al.*, 2007; DWA, 2009; Zhou *et al.*, 2010). RWH is also widely used for non-potable water use (mainly toilet flushing) in many regions of the world (e.g. Fewkes, 1999; Kwan *et al.*, 2000; Liaw & Yao-Lung, 2004; Su *et al.*, 2009; Ward *et al.*, 2010). Run-of-river (ROR) supply from weirs and directly from the river is widespread in many rural areas of Africa and other resource-constrained regions (e.g. Kusiluka *et al.*, 2004; Mazvimavi & Mmopelwa, 2006; Manyatsi & Mwendera, 2007).

Although the value of these alternatives to reticulated water supply systems has long been recognized, not much effort seems to be put in the hydrologic design of these systems, particularly in rural areas where these sources are often the major supply sources. In South Africa, many rural schemes supplied by run-of-river, boreholes, RWH and small dams frequently fail to supply the required amount of water (Makungo, 2009), indicating likely absence or inadequacy of inclusion of reliability in hydrologic design. Mwenge Kahinda *et al.* (2007) question why the pilot domestic RWH scheme in South Africa (De Lange, 2006) use a constant tank size of 30 m^3 across four provinces of the country that receive substantially different rainfalls. Some approaches (e.g. Abdulla & Al-Shareef, 2009) ignore tank water balance and determine required storage size on the basis of amount of water available from the rain (for a given roof area) during the rainy season, or the demand during the dry season. Although many methods that account for the variability of rainfall are in use, the use of average monthly rainfalls applying mass balance (e.g. the mass curve method) is still a fairly common practice (Gould & Nissen-Peterson, 1999; Handia *et al.*, 2003; Olanike & Omotayo, 2010). However, some of these studies (Gould & Nissen-Peterson, 1999) also recommend the use of approaches that incorporate rainfall variability.

The continuous simulation of storage behaviour (behaviour analysis method) has been applied widely for RWH tank storage–yield-reliability analysis (Fewkes, 1999; Coombes & Barry, 2007; Mitchell, 2007; Roebuck, 2007; Su *et al.*, 2009; Ward & Memon, 2010; Zhou *et al.*, 2010). Behaviour analysis has the advantage of simulating the storage behaviour realistically and can easily incorporate complicated operating rules and system configurations (McMahon & Adeyole, 2005). Using simulation approaches such as behaviour analysis also enables system performance to be assessed in a variety of ways. However, most of the behaviour analysis method applications to RWH tank sizing use long-term volumetric reliability as the measure of system performance and it is only recently that more comprehensive measures are being applied (Su *et al.*, 2009; Zhou *et al.*, 2010). Long-term volumetric reliability provides an idea of the expected average system performance, which will be also the expected average annual system performance. The chance of obtaining a higher or a lower performance in any given year will therefore be the same (and equal to 0.5) and the computed volumetric reliability can be considered to occur at a return period of 1 in 2 years. While this information may be adequate where RWH is only supplementing the main supply (Mitchell, 2007; Ward & Barry, 2010), it is unlikely to be adequate for situations where RWH is the sole or one of the main water sources as much higher levels of reliability are recommended for most uses (e.g. DWAF, 2009).

In ROR assessment, the flow duration curve from the complete streamflow time series is the conventional method applied (McMahon & Adeyole, 2005). Unlike the long-term volumetric reliability, the flow-duration curve informs about the expected range of system performance on an annual basis and is therefore a more adequate measure of system performance. However, ROR users may be more interested in the expected number of days of supply per year and not a flow value.

For situations where both RWH and ROR are potential water sources, hydrological analysis that integrates the two realistically would be needed in order to maximize utilization. This paper therefore addresses two problems: the incorporation of reliability and the integration of RWH and ROR for typical rural water supply. Specifically, the paper demonstrates: (i) the incorporation of annual reliability into the popular mass curve method for RWH storage–yield analysis, and (ii) integration of RWH and ROR supply while comprehensively incorporating annual reliability using a simulation (behaviour analysis) approach. Data from a semi-arid rural community in South Africa are used.

STUDY AREA

Siloam Village in the Nzhelele River catchment of Limpopo Province of South Africa was selected as a case study as it is a typical rural village where ROR and RWH supply is in use. The study area is located between 22°53′15.8″S and 22°54′5″S latitudes and 30°11′10.2″E and 30°11′23.5″E longitudes. Daily rainfall from gauging station 0766324 located at Siloam Hospital was used as input for the RWH analysis, while Nzhelele River daily flow at the village was obtained by simulation using the MIKE 11 NAM catchment model (Makungo *et al.*, 2009). The 49 complete hydrological years (October 1950–September 1999) of flow and rainfall data were used in the analysis. A household consisting of six members each requiring 25 L/d, giving a household water demand of 150 L/d (DWLS, 2008), was considered as representative. A roof area of 100 m^2 was selected as reasonably representative and a collection efficiency of 0.8 was adopted following an earlier study in the area (Mashau, 2006). The projected population of 2102 for Siloam Village in 2010 (DWLS, 2008) gave a total of 351 households.

INCORPORATING ANNUAL RELIABILITY INTO MASS CURVE ANALYSIS

Method – mass curve analysis

The following steps describe the procedure followed to incorporate reliability into mass curve analysis. The provided storage was considered to be for within-year supply and not for supply across years (multi-annual droughts):

– Rank the annual rainfalls in order of magnitude and obtain the probability of exceedence of associated with each year using the Weibull plotting position formula. The Weibull plotting position formula has the form $p = m/(n+ 1)$ where p is the probability that the magnitude ranked m is exceeded for a ranked series that is n years long. The reliability associated with the magnitude ranked m can therefore be obtained as reliability = $100p$%.

– Plot mass curves for the daily roof catchment flows of the year for a range of reliabilities. The roof catchment flows are obtained as a product of the vertical roof area, the rainfall intensity and the harvesting efficiency.
– For the set demand, carry out mass curve analysis to obtain the required tank volumes. Make a plot of tank volume *versus* reliability to enable the selection of a tank size of given reliability. If the annual demand exceeds the annual inflow, mass curve analysis cannot be applied to obtain a reservoir size (Fig. 1(a)), and the easily obtainable information from the analysis is the maximum supply obtainable and the tank size that can achieve that (Fig. 1(b)). Plots of tank volume *versus* reliability and of maximum possible supply *versus* reliability can then be obtained. The proportion of the year for which there would be supply can then be estimated as the ratio of the maximum possible supply to the demand. This proportioning assumes a similar spillage pattern for the two demands, which may not always be the case as a smaller demand is expected to maintain higher tank storage levels and possibly higher spillage volumes.

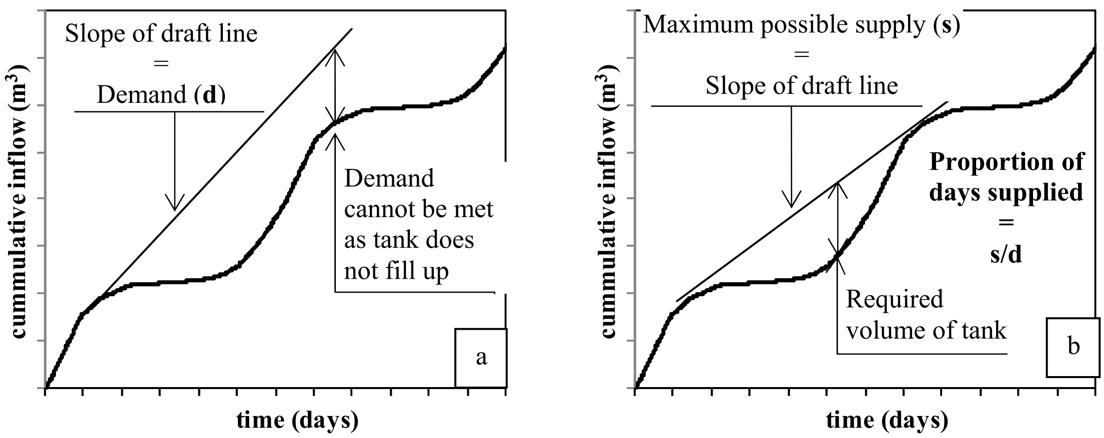

Fig. 1 Mass curve analysis where demand exceeds supply.

Results and discussion – mass curve analysis

For the range of reliabilities varying from 50% to 98%, it was found that the demand of 150 L per household per day of the representative household cannot be supplied throughout the year and the approach illustrated in Fig. 1 was therefore necessary. For the selected probabilities, Table 1 shows the maximum possible supply, the required tank size for this, and the estimated number of days this tank size would supply per year. Figure 2 shows a graphical representation of the variation of the number of days of supply and the required tank volume with reliability.

The expected reduction in the number of days of supply as reliability increases is observed on Fig. 2(a) while Fig. 2(b) informs that the required tank sizes reduce as the reliability increases. Thus if one intends to operate at a high level of reliability (say 90%), a tank volume larger than 9.4 m^3 (using the linear plot on Fig. 2(b)) would not achieve a higher reliability and the number of days of supply would be around 120 days (4 months). In order to operate at this reliability, another water source or sources would need to be available for 8 months of every year.

Table 1 Results of mass curve analysis for representative household.

Reliability (%)	50	60	70	80	90	98
Maximum supply (L/d)	97.6	89.2	90.2	64.7	50.7	43.2
No. of days of supply	238	217	220	158	124	105
Storage volume (m^3)	14.5	16.7	10.9	9.4	10.9	7.4

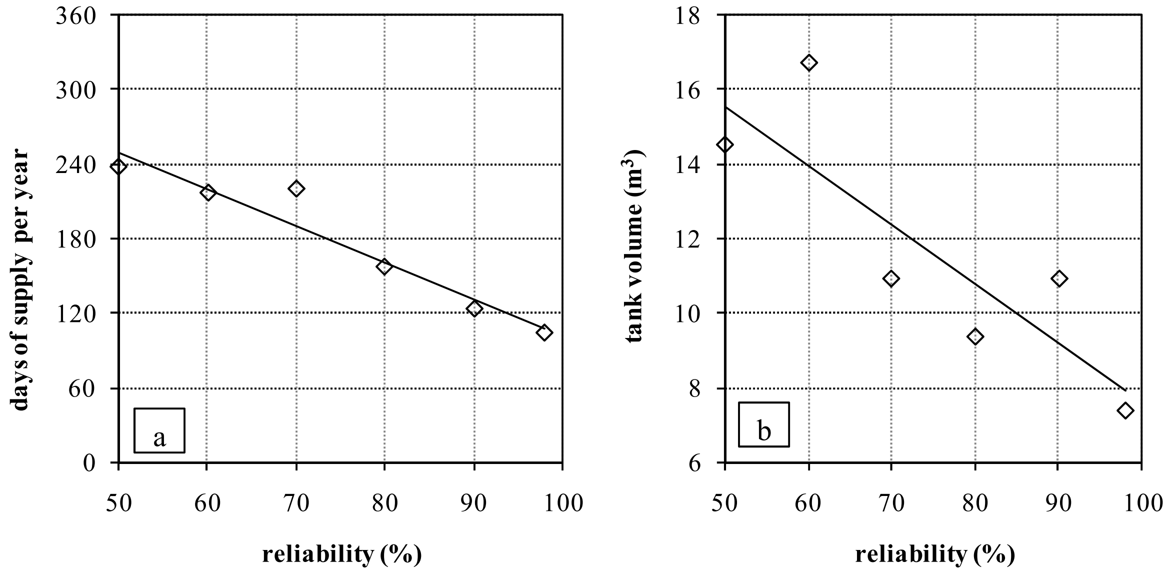

Fig. 2 Days of supply and tank volumes from mass curve analysis of representative household.

INCORPORATING ANNUAL RELIABILITY TO COMBINED RWH AND ROR YIELD ANALYSIS

Method – combined RWH and ROR analysis

The yield–reliability and operation analysis was based on historic behaviour analysis (simulation) of water supply followed by frequency analysis of the number of days of water availability in each year of the analysis period. As with the mass curve analysis, the Weibull plotting position formula was adopted in frequency analysis. This approach considered each year to represent one possibility of the level of supply that could be expected in any year during the life of the system and frequency analysis helped to obtain a relationship between reliability and the number of days that the household obtained water from ROR and RWH per year. It was assumed that the available river water after environmental flow allocation would be shared equally among all households. It was further assumed that the representative household would use ROR water whenever available (as the infrastructure for ROR typically stores water only temporarily) and use RWH water from the tank when ROR is unavailable (equation (1)). The ROR water was thus taken to be of sufficiently good quality and to be conveniently close to the household. If this is not the case other operating scenarios can be adopted. The analysis reported here is for tank sizes of 0, 5, 10, 15, 20, 30 and 40 m^3 and the representative roof area of 100 m^2.

$$\text{If}\begin{Bmatrix} R_t \geq D_t & \text{then} & F_t = D_t & \text{and} \quad Y_t = 0 \\ R_t < D_t & \text{then} & F_t = R_t & \begin{bmatrix} \text{if } S_t \geq D_t - F_t & \text{then} & Y_t = D_t - F_t \\ \text{if } S_t < D_t - F_t & \text{then} & Y_t = S_t \end{bmatrix} \end{Bmatrix} \quad (1)$$

where R_t is the supply available from ROR supply in period t; F_t is the actual supply from ROR in period t; Y_t is the supply from tank in period t; D_t is the household demand in period t; and S_t is the storage in tank at the beginning of period t.

Results and discussion – combined RWH and ROR analysis

Figure 3 shows the level of supply (number of days of supply per year) for reliabilities ranging from 80 to 98% for various tank sizes. Within bounds, the expected reduction in the number of days of supply with increasing reliability and reduced tank size is generally observed. Figure 3 also enables the determination of the minimum tank sizes for the highest supply level at the selected reliability (i.e. optimal size). These are obtained as 20 m^3 for 80% reliability; 30 m^3 for 82–94% reliability; 15 m^3 for 96% reliability and 5 m^3 for 98% reliability. While RWH provides substantial improvement to the supply level for most reliabilities, the benefit is negligible for the high reliability of 98%.

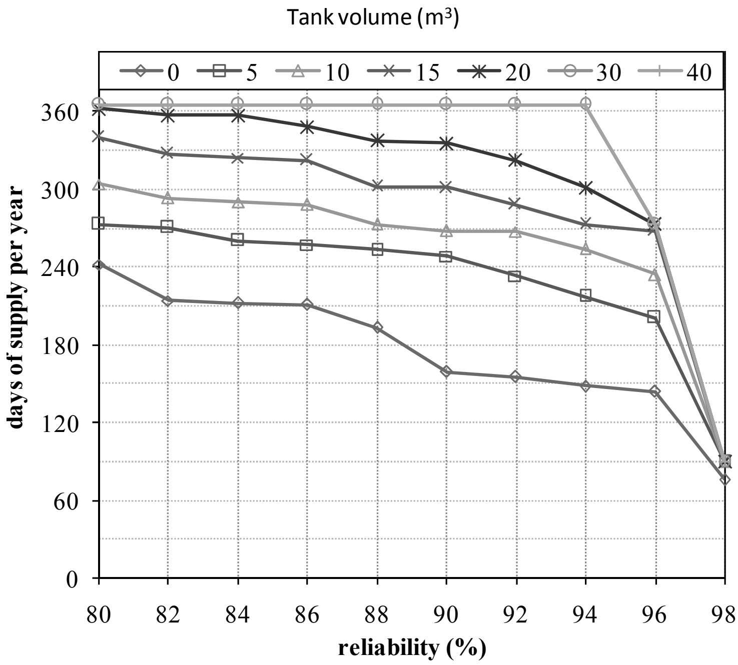

Fig. 3 Number of days of supply from combined RWH and ROR supply.

CONCLUSIONS AND RECOMMENDATIONS

A review of the literature revealed that reliability is mostly not incorporated or not sufficiently incorporated in the hydrologic design of rainwater harvesting (RWH) systems, particularly in rural areas where it is often a major source of supply. It was demonstrated how reliability can be comprehensively included in RWH using the widely applied mass curve and behaviour analysis methods using ranking and the Weibull plotting position formula. It was further demonstrated how the mass curve approach could be adopted to obtain the level of supply for situations where the demand exceeds supply that may be typical in low rainfall regions. The mass curve analysis enabled the determination of the number of days of supply that can be obtained for a given tank size and reliability. For the behaviour analysis method, the inclusion of run-of-river (ROR) supply to RWH was demonstrated. The behaviour analysis results enabled the estimation of the optimum tank size for a given number of days of supply per year for a selected level of reliability. The ability of behaviour analysis to (i) handle complex system operating rules and configurations (including several water sources) and (ii) to allow realistic and many approaches to evaluate expected system performance make this approach the method of choice for comprehensive hydrologic analysis of RWH and ROR supply that incorporates reliability adequately. However, storage-yield-reliability analysis can also be carried out for simple systems using the mass curve approach used here.

REFERENCES

Abdulla, F. A. & Al-Shareef, A. W. (2009) Roof rainwater harvesting systems for household water supply in Jordan. *Desalination* **243**, 195–207.

Coombes, P. & Barry, M. (2007) The effect of selection of time steps and average assumptions on the continuous simulation of rainwater harvesting strategies. *Water Sci. Technol.* **55**(4), 125–133.

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) (2009) Annual Report.

DLWS (2008) Bulk Infrastructure Feasibility Planning, Project LPR002 Nzhelele RWS, 2nd draft, Vhembe District Municipality, Limpopo Province, South Africa.

Duncker, L. C. (2000) Hygiene awareness for rural water supply and sanitation projects. Report no. 819/1/00. Water Research Commission, Pretoria, South Africa.

DWAF Limpopo Water Services (DLWS) (2008) Bulk Infrastructure Feasibility Planning, Project LPR002 Nzhelele RWS, 2nd draft, Vhembe District Municipality, Limpopo Province, 55pp.

Fewkes, A. (1999) Modelling the performance of rainwater collection systems: towards a generalized approach. *Urban Water* **1**, 323–333.

Gould, J. & Nissen-Peterson, E. (1999) *Rainwater Catchment Systems for Domestic Supply: Design, Construction and Implementation*. Intermediate Technology Publications, London, UK.

Handia, L., Tembo, J. M. & Mwiindwa, C. (2003) Potential of rainwater harvesting in urban Zambia. *Physics and Chemistry of the Earth* **28**, 893–896.

Kwan, T. L., Chin-Dee, L., Ming-Sang, Y. & Chih-Ching, Y. (2000) Probabilistic design of storage capacity for rainwater cistern systems. *J. Agric. Engng Res.* **77**(3), 343–348.

Kusiluka, L. J. M., Mlozi, M. R. S., Munishi, P. K. T., Karimuribo, E. D., Luoga, E. J., Mdegela, R. H. & Kambarage, D. M. (2004) Preliminary observations on accessibility and utilisation of water in selected Villages in Dodoma rural and Bagamoyo Districts, Tanzania. *Physics and Chemistry of the Earth* **29**, 1275–1280.

Liaw, C-H., & Yao-Lung, T. (2004) Optimum storage volume of rooftop rain water harvesting systems for domestic use. *J. Am. Water Resour. Assoc.* (JAWRA) **40**(4), 901–912.

Makungo, R. (2009) An operating strategy for run-of-river abstractions in typical rural water supply schemes using Siloam Village as a case study, MSc Thesis, University of Venda, South Africa.

Makungo, R., Odiyo, J. O., Ndiritu, J. G. & Mwaka, B. (2009) Rainfall runoff modelling approach for ungauged catchments. In: *10th WATERNET Symposium* (Entebbe, Uganda).

Manyatsi, A. M. & Mwendera, E. J. (2007) The contribution of informal water development in improving livelihood in Swaziland: a case study of Mdonjane community. *Physics and Chemistry of the Earth* **32**, 1148–1156.

Mashau, F. (2006) Rainwater harvesting for multiple uses in Siloam Village of Limpopo Province, South Africa. Honours Research Dissertation, University of Venda, South Africa (unpublished).

Mazvimavi, D. & Mmopelwa, G, (2006) Access to water in gazetted and ungazetted rural settlements in Ngamiland, Botswana, *Physics and Chemistry of the Earth* **31**, 713–722.

McMahon, T. A. & Adeloye, A. J. (2005) *Water Resources Yield.* Water Resources Publications, Canada.

Mitchell, V. G. (2007) How important is the selection of computational analysis method to the accuracy of rainwater tank behaviour modelling? *Hydrol. Processes* **21**, 2850–2861.

Mwenge Kahinda, J., Taigbenu, A. E. & Boroto, J. R. (2007) Domestic rainwater harvesting to improve water supply in rural South Africa. *Physics and Chemistry of the Earth* **32**, 1050–1057.

Olanike. O. A. & Omotayo, B. A. (2010) Assessing the potential for rainwater harvesting. *Water Resour. Manage*. **24**, 2129–2137.

Roebuck, R. M. (2007) A whole life costing approach for rainwater harvesting systems. PhD Thesis, School of Engineering, Design and Technology. University of Bradford, UK.

Su, M. D., Lin, C. H., Chang, L. F., Kang, J. L. & Lin, M. C. (2009) A probabilistic approach to rainwater harvesting systems design and evaluation. *Resources, Conservation and Recycling* **53**, 393–399.

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

Zhou, Y. C., Shao, W. Y. & Zhang, T. Q. (2010) Analysis of a rainwater harvesting system for domestic water supply in Zhoushan, China. *J. Zhejiang Univ.-Sci. A (Appl. Phys. Engng)* **11**(5), 342–348.