

Optimization of Rainwater Catchment Systems Design Parameters in the Arid and Semi-arid Lands of Kenya

Stephen N. Ngigi

Department of Agricultural Engineering

University of Nairobi

P.O. Box 29053, Nairobi, Kenya

e-mail: sngigi@swiftkenya.com

Abstract

It is evident from experiences in Kenya that rainwater could be the long awaited answer to water scarcity in the next millennium. However, some technical and policy hindrances need to be addressed. Lack of appropriate technical designs, among other factors, has led to low adoption of rainwater harvesting technology, especially in Arid and Semi-arid Lands (ASAL), where rainwater is one of the most viable water supply. This calls for optimisation of Rain Water Catchment Systems (RWCS) design parameters and formulation of comprehensive water policy. Therefore, to address this problem, the paper focus on the hydrological criteria for determining RWCS design parameters, especially storage capacity and catchment area, using historical rainfall records of Kibwezi rainfall station. Specifically, a design procedure for determining optimal design parameters and developing design curves is outlined. The mass curve analysis was adopted for the determination and optimisation of the design parameters due to outlined inadequacies of most empirical formulae. The strength of the design procedure is the determination of optimal design parameters at various reliability levels of rainfall amount and distribution. The analysis of design parameters revealed that the catchment area and the storage capacity are affected by variations in rainfall amount and distribution respectively.

In addition, the paper proposes a procedure for incorporating rainfall distribution, which has been consistently ignored in the designs of RWCS. The proposed procedure involves adjustment of monthly rainfall by using rainfall distribution indices such that the monthly rainfall totals correspond to annual rainfall at a given rainfall reliability level. The adjusted monthly rainfall is subjected to mass curve analysis to determine the design parameters at various reliability levels. The selection of optimal design parameters is simplified by the development of design tables and curves from which the catchment area and storage capacity for a specific water demand can be easily obtained at various reliability levels. The paper concludes by proposing some recommendations to promote utilisation of rainwater, and adoption of RWCS technology in Kenya. Therefore, the developed procedure could enormously contribute to the adoption and implementation of optimal RWCS designs, and hence supplement government efforts towards meeting ever increasing water demand. The procedure could also be used to evaluate the reliability of existing RWCS.

Introduction

Population pressure has led to substantial settlements in the ASAL, which covers over 80% of Kenya's land surface. These areas were predominantly used for livestock production. The ASAL currently carries more than 35% and 50% of human and livestock population respectively. The ASAL normally experiences low, erratic and unreliable rainfall, with frequent droughts even within the rainy seasons. Hence unreliable and poorly distributed rainfall patterns is the most limiting factor to settlement and agricultural production. In addition, drought occurrence in Kenya has preceded wet seasons or years when so much water is lost as runoff. This is a clear manifestation of the need to promote RWCS technologies both for domestic use and agriculture. There is need to improvise sustainable ways of dealing with the twin problem of lack of adequate water and food supply. The issue of food security is

currently in the development agenda of the ASAL. Therefore, sustainable technologies and supporting policies are necessary to augment water supply.

Thus the development of the ASAL poses a major challenge in the provision of water for economic activities. Provision of adequate domestic water supply and food security are a prerequisite for decent settlement in the ASAL which is compromised by water scarcity. The natural water scarcity is aggravated by alarming population growth rates, environmental degradation, competition over use of limited natural resources, and increasing water demand due to improving living standards, industrialisation and irrigation. In the ASAL, surface water is scarce and exploitation of groundwater is not economically feasible, especially for the rural poor. Therefore, sustainable RWCS remain predominantly one of the most attractive solution to water scarcity. It is unfortunate that such an important technology has not been fully developed despite its world-wide success. For example, in the Negev Desert of Israel, domestic and agricultural water supply is obtained from the meagre rainfall of less than 100mm per year. Ironically, most of the famine stricken ASAL of Kenya receive far much more rainfall.

RWCS technology is cheap, technically simple and environmentally friendly as a water supply system, especially in the ASAL. This notwithstanding, RWCS technology has, in the past, been overshadowed by conventional water supply systems. However, currently it is receiving substantial recognition as a viable and important water supply option (Wafua, 1995; MoWD, 1992, GoK, 1994). This could partly be attributed to failure of conventional water supply systems such as community water projects and multi-million irrigation projects compounded by lack of funding which has led to shift in water resources development and management policies. A number of examples in the ASAL (Ngigi, 1996 and Kiggundu, 1998) clearly indicate that the potential for RWCS as an excellent option to improve food security and water supply. The challenge now is to improve these existing systems to optimise water supply and crop production.

Notwithstanding this recognition, the current approaches have been daunting due to lack of design procedures and guidelines to assist the farmers in realising optimal benefits. Unfortunately, despite increasing adoption of RWCS technologies, according to Ngigi (1996) and Kiggundu (1998), its promotion has been hampered by lack of inadequate designs and water management systems. A field survey conducted by Ngigi (1996) in Machakos and Makueni districts revealed that most of the existing RWCS were inadequate in terms of storage capacity with 40-70% cases of overflow and, despite the long dry seasons of more than 6 months, storage period lasted only 1-2 months. Further, apart from NGOs assisted projects which, unfortunately seemed to have standardised storage tanks, the others did not show any signs of prior designing, and most of the existing roof catchments were not adequately guttered. Generally, there is a mismatch between catchment area and storage capacities (Ngigi, 1996 and Kiggundu, 1998).

Therefore, promotion and adoption of RWCS requires optimisation of the design parameters to reliably meet the anticipated water demand at least cost. Unless this is done, RWCS technologies will remain a partial solution, and not the ultimate answer to water scarcity in the next millennium. The problems of inadequate designs can be addressed through technical, economic and policy options. The most appropriate solution should be self-sustaining, socially acceptable and adaptable to the environment and local technology. In this paper, a technical option is addressed through promotion of a hydrological design criteria which determine the adequacy and reliability of RWCS to meet the anticipated water demand. However, although hydrological criteria supersede economic considerations, the design of RWCS is a compromise between these two design criteria. The compromise is normally reflected in the reliability level of RWCS.

Optimisation of Design Parameters

Optimisation of design parameters entails analysis of rainfall, water demand, catchment area and storage capacity. The following section briefly outlines the necessary analysis of the design parameters using Kibwezi rainfall data as an example.

Rainfall analysis

Rainfall is the main input parameter in the design of RWCS. Therefore, appropriate rainfall analysis is a prerequisite in the determination of design parameters, mainly storage capacity and catchment area. Rainfall analysis entails integration and determination of rainfall parameters—amount, occurrence/reliability and distribution—which form the pillar for the selection of optimal design parameters. All the rainfall parameters are interrelated and equally important in the design of RWCS (Ngigi, 1995). More often than not, existing design procedures do not consider all the rainfall parameters and hence lead to inadequate RWCS.

The reliability of RWCS can be determined from the expected reliability of the rainfall amount obtained from frequency analysis of monthly and annual rainfall. Note that although shorter recording intervals are more predictive in the performance of RWCS, their application is not very practical because rainfall occurrence probabilities are normally very low, especially in the ASAL (Ngigi, 1997). Then the reliability is given by using the Weibull plotting positions formulae which compute the expected rainfall amount at various exceedance or non-exceedance probability levels. The higher the reliability the higher the cost of the RWCS, and therefore, the choice of reliability level should consider, not only hydrological criteria, but also the cost of alternative sources of water, and more importantly, the economic capability of beneficiaries. Therefore, the choice of the design rainfall is thus a compromise between hydrological and economic requirements. This entails optimisation of the RWCS to supply water at an economically feasible reliability level which takes into account the risk of failure. For RWCS, failure is taken as the period with rainfall lower than the design amount leading to exhaustion of the storage capacity. Hence, the reliability is taken as the probability of non-exceedance of the certain amount of rainfall.

The frequency distribution of monthly rainfall totals does not correspond to annual totals at the same probability of rainfall occurrence due to variation in rainfall distribution among the years. Therefore, application of monthly rainfall to determine the design rainfall amount need to be adjusted to tally with the expected annual rainfall amounts (Ngigi, 1997). However, rainfall distribution has not been adequately considered in the design of RWCS. In particular, it has not been well incorporated thus adversely affecting the storage capacity.

To adjust the monthly rainfall, the distribution indices of annual rainfall were obtained from the proportion of each month's rainfall contributing to the annual totals. These proportionality indices were computed by dividing the monthly rainfall by the annual rainfall for all the years in record (Ngigi, 1996). The indices were then subjected to frequency analysis and standardised to give the expected annual rainfall. The monthly rainfalls, and hence the rainfall distribution, were obtained by multiplying distribution indices by annual rainfall at various reliability levels. This process yielded adjusted monthly rainfall that closely agree with the annual rainfall at any given reliability level (see Table 1 below). This facilitated the determination of the expected annual rainfall distribution at various probability levels which can then be used as the design rainfall for RWCS, in that particular locality.

Table 1: Actual rainfall amounts, distribution indices and adjusted rainfall amounts at 30% and 70% reliability levels.

Month	Actual rainfall amount (mm)		Distribution indices		Adjusted rainfall amount (mm)	
	30%	70%	30%	70%	30%	70%
Jan.	43	8	0.058	0.022	34	25
Feb.	29	1	0.041	0.002	22	16
Mar.	119	22	0.149	0.078	69	52
Apr.	164	60	0.178	0.202	149	110
May	31	9	0.042	0.033	29	21
Jun.	2	0	0.003	0.000	0	0
Jul.	0	0	0.001	0.000	0	0
Aug.	2	0	0.002	0.000	0	0
Sep.	3	0	0.003	0.000	1	1
Oct.	38	1	0.054	0.003	14	10
Nov.	206	118	0.285	0.338	221	164
Dec.	157	99	0.219	0.284	184	138
Annual	727	547	--	--	723	537

Water demand

Water demand determines the amount of water to be harnessed, and consequently the catchment area and storage requirements. Water demand is computed from per capita water consumption, number of consumers, and the design period. The design period, or time span, used for design is normally one hydrological year which corresponds to the rainfall occurrence cycle. The per capita water consumption rate varies between 15-40 litres per person per day and it can go as high as 60 l/day depending on the climate. Water consumption is also influenced by the economic status of the users and also the composition of the family. The per capita water consumption is lower in disadvantaged than economically endowed areas. The amount of daily water consumption vary considerably depending on whether the users waste or ration water. In practice, most households will use the water copiously during the rainy periods, especially if the tank is overflowing, and will ration it or find other sources during the dry periods. Nevertheless, in order to estimate the total water requirements, an inventory of all water consumers is a prerequisite.

Catchment area and storage capacity

The type and size of the catchment determines the amount of rainwater that can be harvested and hence the storage capacity for a certain design rainfall amount. A reliable RWCS requires optimal combination of catchment and storage systems in order to maximise the overall reliability at the lowest cost. The design of a RWCS, requires the determination of the optimal size of the catchment which would yield adequate water to satisfy the anticipated demand. The water demand hence becomes an input parameter, equivalent to Q_y in equation (1) below. This would then dictate the capacity of the storage system, and subsequently the cost of the whole RWCS. The water yield of a RWCS depends on rainfall characteristics; amount (P), reliability and distribution, and the catchment characteristics; type, size (A) and runoff coefficient (C). The water yield, Q_y (l) is given by:

$$Q_y = CAP \dots\dots\dots (1)$$

Furthermore, determination of the optimal size of the storage capacity of RWCS is a prerequisite because the storage tank is the key and usually the most expensive component. The storage requirement is taken as the volume of water that would be stored to meet the water requirements throughout the critical dry spell. Storage capacity depends on the water demand, length of the dry period, water use strategies and the available tank sizes. Therefore, the anticipated water demand dictates the size of the required storage capacity, while the amount of expected rainfall, and the size and type of catchment will determine whether this demand can be satisfied.

In most cases, empirical formulae have been developed to determine the design parameters (catchment area and storage capacity) for RWCS (Ndiritu, 1992). However, Ngigi (1996) found out that most of them are site specific, and hence inadequate without modifications to suit a certain locality. In addition, most of the empirical equations ignore one important input parameter rainfall distribution which is very critical in determining the design parameters. Another limitation of most of these empirical formulae is that they do not give the reliability levels in design. Ndiritu (1992) indicated that such formulae assume that the averages represent the rainfall series adequately, and thereby ignore the annual variability of rainfall. This variability is often high especially in ASAL and ignoring it could have a significant effect on the storage capacity and overall reliability. Therefore, application of these empirical formulae compromise their simplicity with reliability and the cost of the system. Repercussions can be far reaching and dangerous in terms of reliability of the RWCS. This revelations call for caution in applying empirical equations developed elsewhere. Unfortunately, empirical equations have been adopted and recommended by a number of authors (e.g. Kalders, 1986; Ndege, 1992; and Omwenga, 1984), for the Kenyan conditions without due consideration of their applicability and limitations. However, where applicable, modification of empirical formulae and consideration of reliability could give favourable results (Ngigi, 1996).

Nevertheless, the mass curve analysis is more appropriate in that it considers all the input parameters. It is also not site specific, and hence has a wide application. The mass curve analysis can also be used to monitor water management, by giving the tank volume at any time, provided that water inflows and outflows records are taken continuously. This is important, especially for regulating water utilisation, in case of unexpected drought. The mass curve analysis can be presented empirically by the following equation adopted from Ngigi (1996).

$$V_T = \sum_{t=1}^T (Q_t - V_{i,t} + L_t) \dots\dots\dots (2)$$

- Where; V_T = storage capacity at time, T,
- Q_t = water demand at time, t,
- $V_{i,t}$ = volume of inflow at time, t, and
- L_t = losses from the system during time, t.

The mass curve analysis, in which for an adequate design, the cumulative water demand equals cumulative supply over a given hydrological period, the storage required at time T was found to be the most ideal procedure for determining the design parameters for RWCS, and hence the design curves. However, the effectiveness of the mass curve analysis depends on the accuracy of determining the starting month of the hydrological year - the beginning of the rainy season and/or the end of the dry

seasonC-when the tank is almost empty. The starting month was determined by carrying out the mass curve analysis, starting in turn with the most probable initial months; September, October and November, which correspond to the end of the dry spell and the beginning of the rainy season. Besides giving the lowest tank volume, the initial month also corresponds to the optimal catchment area. In our case, November is the starting month. Thereafter, the optimal tank size is obtained from the largest cumulative 'surplus' that represents the residual water quantity in the tank, which will be large enough to store water during the dry months preceding the rainy season, a characteristic of rainfall in the ASAL. The size of the tank should also be adjusted to available sizes, especially for ready made GI or PVC tanks.

The mass curve analysis, unlike most empirical equations, can be carried out using various rainfall amount and distribution reliability levels to give the design parameters at various reliability levels, and hence a set of design values. However, a 100% reliability of water supply could hardly be achieved due to the stochastic nature of rainfall which determines the inflow during any given period. The choice of the optimal design values depend on *inter alia* availability and cost of alternative water sources, cost of raw materials and available market sizes, technology and skilled manpower, and socio-economic status of the household. In this regard, the determination of optimal storage capacity is not a straightforward exercise because both the rainwater supply and the demand patterns are non-deterministic, and follow time dependent, non-stationary stochastic processes. Hence, to ensure optimal storage capacity, an iterative process is used in which water demand is compared with water yield for a specified time interval within a hydrological year.

If the water yield does not meet the anticipated water demand, other alternative water sources are adopted. However, in ASAL, especially during the dry seasons, this option may not be feasible. In such a situation, one alternative to increase water supply is to, where applicable, expand the size of the catchment area. Therefore, quite often, the hydrological design criteria, only provide the basis for determining the optimal design parameters. Thus where the catchment area is predetermined, the only other technical option is to lower the design reliability level, and incorporate water management strategies, such as measures to reduce water consumption through water rationing.

Development of the Design Curves

In view of addressing the technical design limitations, simple design curves were developed using the mass curve analysis. The mass curve analysis was carried out using the adjusted monthly rainfall at various rainfall amount and distribution reliability levels. The cumulative water inflows were computed by an iterative method for various catchment sizes until an optimal size which offset any given water demand was obtained. A range of design parameters were obtained by varying the water consumption rates between 60 and 600 l/day for various reliability levels. However, design values for higher water demands were computed by applying the law of proportionalityCwater demand is proportional to the storage capacity and hence the catchment area. The water yields were computed from equation (1) in which the runoff coefficient was, for convenience taken as 1. But for a particular RWCS, design parameters can be obtained by dividing the given values by specific catchment characteristics. Combinations of various water consumption rates, reliability of rainfall amount and distribution, produce a series of design parameters from which the optimal catchment area and storage capacity can be obtained for a given water demand.

The mass curve analysis may also be used to evaluate the adequacy for the design of the existing RWCS and their reliability. This could be accomplished by comparing the cumulative monthly catchment runoff and the cumulative monthly consumption throughout the year. If the difference is

positive for all months, the RWCS is adequate, otherwise a negative difference in any month indicates that the system is not sufficient. Precisely, an adequate design should give a cumulative difference between the water yield and demand close to zero at the end of the hydrological year, otherwise a large positive difference means that the system is over-designed whilst a large negative means that the system is inadequate, and hence the catchment area needs to be increased and/or water consumption reduced to make the system viable.

To ease the determination of RWCS design parameters, design curves presented in Figure 1 were developed for various water demand, reliability of rainfall amount and distribution. Such design curves simplify the process of design and/or evaluation of the RWCS. They also provide the designer with an option in terms of the reliability of water supply and thus facilitate the planning and operation of RWCS. However, the design curves are site specific and thus are not applicable to other areas, perhaps except with caution, to other localities with similar rainfall characteristics.

Conclusions and Recommendations

Rainwater harvesting is a potential source of adequate and reliable water supply, especially in rural areas, in particular, in less water endowed ASAL, where other water sources are not technically and/or economically feasible. Inadequately designed systems, in terms of storage capacity and catchment area, could only supply water for only a short period after the rainy season, and not the entire dry period. Further, incidence of tank overflow are also rampant during the rainy season. This clearly indicate a technical shortcoming in the existing RWCS designs for domestic water supply. Notwithstanding technical impendence, promotion of RWCS in Kenya, especially by NGOs and religious organisations through self-help groups, is recommendable. However, most of these organisations lack technical skills and design tools to promote sustainable and reliable RWCS. Therefore, there is an urgent need to develop simple design tools to enhance utilisation and adoption of technically optimal RWCS.

An attempt to address technical shortcoming in the design of RWCS has been made. This involve use of mass curve analysis to determine the optimal design parameters. This procedure take into accounts all the input parameters, especially rainfall distribution that is commonly ignored in the existing procedures. Otherwise, most of the simple empirical equations used for designing RWCS does not adequately consider all the input parameters related to rainfall characteristics. Notably, rainfall reliability and distribution are normally ignored. The rainfall time series analysis is not carefully integrated in the design procedures. In order to appropriately determine the design rainfall, the main input parameter, its reliability and distribution is important. As rainfall reliability and distribution varies from year to year, rainfall variability must be considered. Inadequate analysis of rainfall may lead to insufficient RWCS, especially storage capacity and catchment area. It is evident that variability in rainfall amounts only affects the catchment area while the variability in rainfall distribution affects the storage capacity.

The overall result of this paper is a simple design tool, in form of design curves for Kibwezi. Although emphasis has been put on domestic water supply, the same design curves can be used to determine design parameters for livestock and agricultural (runoff farming) water uses. Therefore, this paper goes a long way to initiate a process towards development of a design manual, by formulating a design procedure. It is envisaged that the proposed design procedure would be adopted to develop design curves for other regions, and subsequently a design manual for Kenya, and in general other parts of Africa, in the view of promoting rainwater as an answer to looming water crisis in the next millennium.

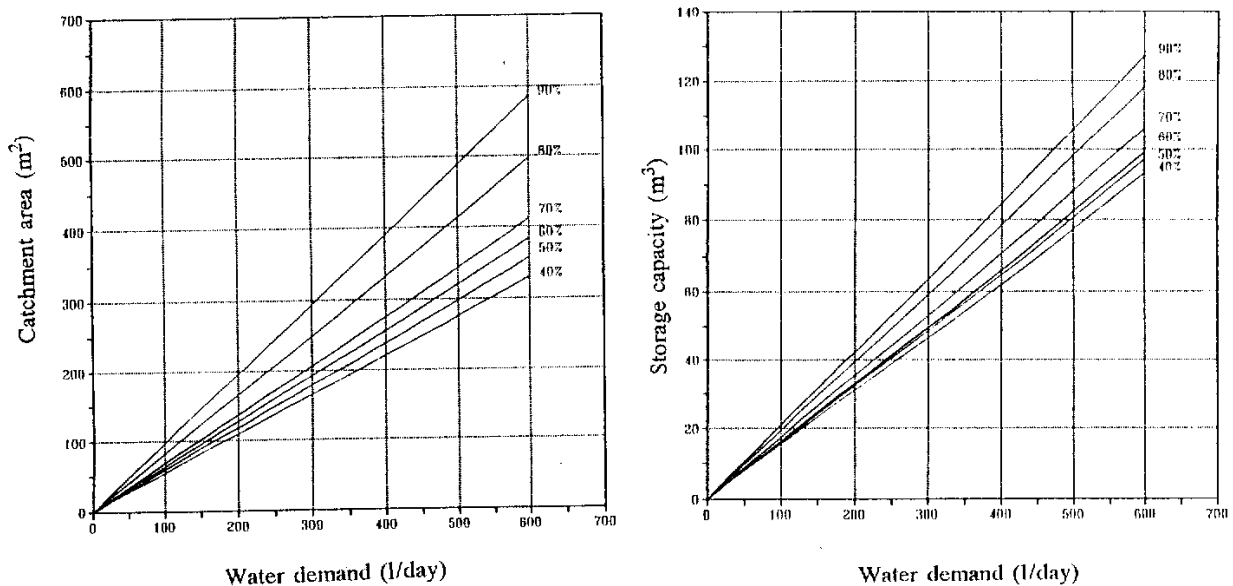


Figure 1: Rainwater catchment systems design curves for semi-arid Kibwezi region of Kenya.

References

- Government of Kenya (GoK). 1994. *National Development Plan, 1994-96*. Government Printers, Nairobi, Kenya.
- Kalders, J. 1986. *Design Manual for Water Supply in Kenya*. Ministry of Water Development, Nairobi, Kenya.
- Kiggundu, N. 1998. Evaluation of RWCS in Laikipia and Mijjwala Districts of Kenya and Uganda respectively. Uganda Country Report presented to the African Academy of Science.
- Ministry of Water Development (MoWD). 1992. *The Study of National Master Water Plan (Draft)*. Main Report Vol. 1. JICA, Tokyo, Japan.
- Ndege, M.M. 1992. *Rainwater Harvesting in Kenya: The State of the Art. Proceedings, 2nd National Conference on RWCS in Kenya*. Nairobi, Kenya.
- Ndiritu, J.G. 1992. *Rainwater Cistern Capacity: An Assessment of the Average Monthly Rainfall Rates. Proceedings of 2nd National Conference on RWCS in Kenya*. Nairobi, Kenya.
- Ngigi, S.N. 1997. *Development of Rainwater Catchment Systems Design Nomographs for Semi-Arid Kibwezi Region of Kenya*. Proceedings of KSAE, Nairobi, Kenya. August, 1997.
- Ngigi, S.N. 1996. *Design Parameters for RWCS in Arid and Semi-Arid Lands of Kenya*. Unpublished M.Sc. Thesis, University of Nairobi, Kenya.
- Ngigi, S.N. 1995. *Analysis of Rainfall as a Design Parameter for RWCS. Proceedings, 7th International Conference of IRCSA, Beijing, China*.
- Omwenga, J.M. 1984. *Rainwater Harvesting for Domestic Water Supply in Kisii, Kenya*. Unpublished M.Sc. Thesis, Tampere University of Technology, Finland.
- Wafua, A. 1995. *Regional Design for Rainwater Catchment Harvesting*. Kenya Engineer, Journal of the Institute of Engineers of Kenya, 16(1): 35-39.