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Sizing Criteria for Domestic Rainwater Cisterns in The Grenadines

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Rainwater-harvesting systems is one of the oldest in and dates back to some 4,000 years. In the Grenadines, the population depends almost exclusively on rainwater-harvesting for its domestic use. Rainwater storage in barrels during the 1920s to 1940s has been replaced with concrete cisterns which have become standard features of new homes. This paper presents monograph that could be used by engineers and contractors in sizing cisterns for The Grenadines under conditions that average per capita consumption is 50 litres per day and allowing the cistern to rum empty once in 25 years. If rainwater continues to be the main source of domestic water supply in The Grenadines, the costs of higher water consumption patterns would result in cost-prohibitive cistern construction costs. Nonetheless, there is room for strategic improvement in the availability of domestic water (a) designing the roof to obtain maximum contributing area, and (b) optimising the household water use by targeting the areas of high water use in the home namely the bathroom and kitchen facilities by using low volume fixtures.

Keywords: The Grenadines, Cistern, Rainwater-harvesting, Storage.

1. Introduction

The Grenadines stretch from Ronde Island in the north of Grenada to Bequia to the south of St. Vincent. (See **Figure 1**). Carriacou is the largest with an area of 34 square kilometers while others are just big enough to accommodate a single resort. The economy of the islands is supported by tourism, shipping, fishing, trading, livestock-rearing with remittances from Europe and North America being the largest contributor. Generally, Grenadinians enjoy a higher standard of living on average than larger island mainlanders (**Poverty Study 2000** and **CDB Report on SVG**).

In the dry climate of The Grenadines, an adequate water supply is highly dependent on the timely arrival of the rainy season. The steep hills and small surface area of the islands result in the absence of any perennial streams. With an average annual rainfall of about 1,000mm, the islands depend almost exclusively on private and public Rooftop Rainwater Catchment Systems (RRCS) and concrete Communal Rainwater Catchment Systems (CRCS) as the primary

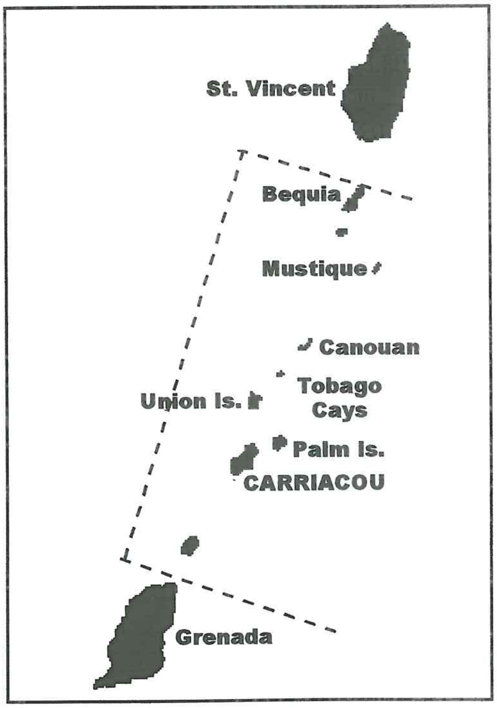

FIGURE 1: *A Sketch Map of The Grenadines*

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source of domestic water. Small public and private earthen dams used to store rainwater harvested from runoff are primarily for livestock use. There are also several dug wells and bore holes that provide limited ground water supply.

Growing demands for water in The Grenadines and the increasing costs of water supply with the use of desalination, result in a need for these islands to maximise the use of the traditional and existing water supply techniques. There has been a great deal of interest in the development of guidelines for construction of primary supply and standby cisterns in small islands, for example, US Virgin Islands, Hawaii and Micronesia (**Heitz *et al*, 1997** and **Smith *et al*, 1999**). The storage facilities are sized according to the rainfall in the area, the roof construction material and size, the expected water demand in the house that the cistern serves, the cost of constructing the cistern and the degree of reliability the owner desires. Although some research on rainwater-harvesting has been carried out in the region (**Hadwen, 1987**), no criteria for sizing is available for The Grenadines. There is some concern expressed as to whether the sizing requirements provide for too much storage. While a large storage system might be pleasant to boast about, the security it might seem to provide could be elusive. Further, if the system is oversized, it might never become filled and/or it might never be emptied. In both instances, there is excessive wasted capacity and investment of resources that might have been better used elsewhere (**Smith *et al*, 1999**).

2. Literature Review

2.1 Rainwater Harvesting Technology

Rainwater-harvesting has been practiced for more than 4,000 years and, in many developing countries, is becoming essential owing to the temporal and spatial variability of rainfall. For many small islands in the Caribbean, rooftop catchments and cistern storage have been the basis of domestic water supply. During World War II, several airfields were also turned into catchments (**UNEP, 1997**). Although the use of rooftop rainwater catchment systems has declined in some countries, it is estimated that more than half a million people in the Caribbean islands depend at least in part on such supplies. Further, large areas of some countries in Central and South America, such as Honduras, Brazil and Paraguay, use rainwater-harvesting as an important source of water supply for domestic purposes, especially in rural areas.

Very frequently, most of the rain falls during a few months of the year, with litle or no precipitation during the remaining months. There are countries in which the annual and regional distribution of rainfall also differ significantly. Rainwater-harvesting is necessary in areas having significant rainfall but lacking any kind of conventional, centralised government supply system, and also in areas where good quality fresh surface water or groundwater is lacking. Serious supply problems occur when the components of the RRCS are not sized appropriately. Therefore, there is a need for a criteria for properly sizing the components of a new RRCS or upgrading existing systems. There is also a need for suggestions on how to manage these systems.

Regulations relating to domestic rainwater-harvesting are slowly being introduced in the Caribbean region. Since January 1, 1996, all new residences in Barbados are required to construct water storage facilities if the roof area or living area equals or exceeds 279m^2. It is also mandatory for all new commercial buildings with a roof area of 93m^2 or more (**UNEP, 1997**). Virgin Islands' law requires that buildings provide for harvesting of runoff derived from rooftops and storage of the harvested water on site. (Title 29, Section 308, V.I. Code). This law requires that typical one-storey family homes provide 10 gallons of storage capacity for each square foot of roof area (**Smith *et al*, 1999**). California offers a tax credit for rainwater-harvesting systems and financial incentives are offered in Germany and Japan.

In The Grenadines, although rainwater-harvesting is of a high priority, there are no regulations or incentives to promote improvement in quality and quantity of rainwater harvested. However, the increasing dependence on tourism of these islands would soon force at least public facilities to establish quantity and quality standards.

2.2 Storage Capacity

The literature contains discussion of several approaches that may be considered in sizing rainwater stores. These approaches evolve from methods developed for the design of reservoirs being filled from streamflow or groundwater pumping. **McMahon** and **Mein (1978)** identified three (3) general types of reservoir-sizing methods, namely, critical period, behavioural and probability matrix methods. Critical period methods identify and use a sequence of flows where demand exceeds supply to estimate storage capacity. Probability matrix methods are based on transitional probabilities. Behavioural methods simulate the operation of the reservoir with respect to time by routing simulated mass flows through and algorithm which describes the operation of the reservoir (**Jenkins *et al* 1978; Latham 1983** and **Fewkes** and **Butler, 1999**).

Almost all the different methods assume that water consumption is at a constant daily rate throughout the year and they require data inputs such as daily rate, details of roof plan areas, rainwater catchment efficiency and rainfall distribution (**Thomas *et al*, 1997**). The outputs of these methods are recommended store sizes for one or more probabilities of storage failure (i.e., tank runs dry). **Ntale (1996)** reviewed some of these methods under Ugandan conditions and showed that in a not untypical location in Uganda, the crudest method (*Mean Dry-Season Deficit*) gives a storage size very much less than that given by more elaborate and accurate methods. Other variations of the dry season deficit are also suggested providing a cistern size based on a rainfall pattern, a roof plan area and a household demand. Design criterion based on drought concepts are the oldest forms of designing reservoirs supplied from stream flow. Similar methodologies are applicable in RWCS systems. **Heitz *et al* (1999)** developed a rooftop rainwater catchment system design criteria for Micronesia using daily rainfall, family size, roof catchment and consumption rates in a programme called ROOFRAIN (**Heitz *et al*, 1998**). **Heitz *et al*** considered a minimum size that would provide reasonable level of protection against shortages of consumable water during droughts. Further, a Drought Duration Depth Frequency (DDDF) drought criteria proposed by **Heggen (1999)** requires only a record of historic rainfall and can be used to address system behaviour for duration and risks appropriate to RRCS need.

3. Methodology

This research was carried out in two (2) parts. First, a survey of 200 homes in Carriacou and Petite Martinique was undertaken to establish the status of rainwater-harvesting in The Grenadines. The survey investigated issues like storage facilities, water quality, maintenance issues and consumption patterns. The survey/questionnaire contained 40 questions. Data from the certified property valuation list for Carriacou and Petite Martinique were used to develop the relationship between floor space, contributing roof area, residential construction costs roof area and current cistern size. Per capita consumption was estimated based on survey results and the limited unpublished data (**Procicaribe, undated**). The restriction on the design was that the cistern was allowed to empty once in 25 years and there was sufficient water to fill the tank from another source before commissioning a new cistern. Finally, a visual basic programme was developed to simulate cistern sizes from the available data including available rainfall data, different consumption patterns and residential occupancy.

3.1 Data

Monthly rainfall data for Carriacou, Union Island and Bequia for periods of 1927-1959 (GoG, 2000), 1923-1981 and 1930-1981 (GoSVG, 2002) respectively were used in the simulations. Mean monthly rainfall for the three (3) islands are in **Table 1**. Monthly variation in consumption pattern are shown in **Table 2(a)** and **2(b)**. Typical roof-contributing, roof area, floor space relationship for both single and multi-storey residents which were derived from a survey of existing houses in Carriacou and Petite Martinique (**Peters, 2003**) used in the study are summarised in Equations 1a and 1b.

$$TCRA_{SS} = 1.065TFS + 8.405 \qquad \text{.............(1a)}$$

$$TCRA_{DS} = 0.5523TFS + 5.7593 \qquad \text{.............(1b)}$$

where

$TCRA_{SS}$ = total contributing roof area for single-storey (ft^2)
$TCRA_{DS}$ = total contributing roof area for double-storey (ft^2)
TFS = Total floor space (ft^2)

4. Rainwater Systems in The Grenadines

Rainwater storage systems in The Grenadines include underground and above surface cisterns (average 30,000 litres), metal tanks with capacity of 760 - 1,900

TABLE 1: *Cistern Size of An Average-Sized Household for Different Water Use Patterns*

Per Capita Water Use	Cistern Capacity (m^3)
40	14.5
50	39.0
55	53.5
60	73.5
75	523.5
100	1,640.0

litres, plastic tanks (760 - 3,000 litres), drums (170 litres), wooden barrels (130-150 litres). (See **Figure 2**). There is a steady increase in the construction of household cisterns; 21% and 70% in 1981 and 1991 respectively. Communal cisterns can be found at public buildings, schools, hospital and medical clinics, churches, community centres and administrative offices. In Carriacou and Petite Martinique, there are 33 communal catchments and 78 public storages. Typical systems consist of a rooftop, water-harvesting surface, a conveyance system for the harvested water, a cistern for storage and a means of distributing the water either by gravity, drawing, using bucket and rope or a pumping and plumbing system. The harvesting surfaces are usually corrugated galvanised roofing material, concrete tiles, clay tiles, asphalt-type shingles or wooden shingles. The roof runoff is collected by means of PVC gutterings and directed straight into the storage system. In less than 2% of cases, there are some devices that are used to divert the first flush of water from the roof to waste or treatment devices to enhance water quality. The cisterns are usually sealed at the manhole and at the overflow with insect screens. Routine maintenance for gutterings and tanks can be carried out over periods of two to three years.

In most cases in The Grenadines, although the cistern can account for 5% - 30% of a property, sizing is done arbitrarily and is often of a lower concern than bedroom-sizing, roof design and the quality of interior finishing. This results in many cases where cisterns are oversized and unnecessary mortgage burdens, or undersized, creating inadequate water supply during the dry season. An evaluation of the homes in Carriacou

TABLE 2(a): *Mean Monthly Rainfall (mm) at Four Sites in The Grenadines*

Period	Bequia	Union Island	Carriacon At Limlair	Carriacon At Belair
January	89	66	89	84
February	59	46	59	53
March	55	36	55	40
April	60	40	60	56
May	88	63	88	79
June	150	105	150	137
July	182	130	182	167
August	177	148	177	123
September	171	122	171	143
October	200	154	200	182
November	199	165	199	169
December	141	104	141	139
Total	1,571	1,179	1,039	1,372

TABLE 2(b): *Monthly Non-Permanent Residents and Water Consumption Per Capita*

	No. of Non-Permanent Residents	Percentage of Mean Per Capita Use
January	1.0	0.90
February	1.0	0.80
March	0.2	0.75
April	0	0.60
May	0	0.60
June	0	0.80
July	0	1.00
August	2.5	1.00
September	0	1.20
October	0	1.25
November	0	1.20
December	1.5	1.00

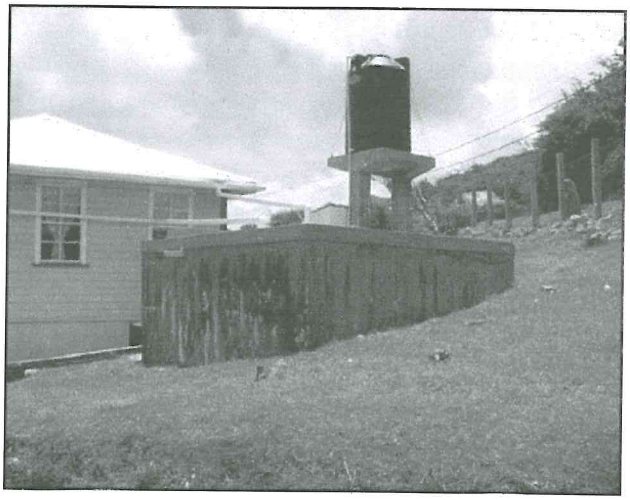


FIGURE 2: *A Typical Cistern found in Carriacou, Partly Above and Below Ground*

shows that the average-sized house has a floor space of 87m^2 and a construction cost of approximately US$27,700 (**Peters, 2003**). For homes valued over US$135,000, water consumption tended to be closer to that of the developed world, while for houses valued US$19,000 and less, per capita consumption was closer to that of water-stressed, developing countries.

Residential water needs vary depending on the type of dwelling; number of residence and type of plumbing fixtures, all of which are influenced by the economic status of the users. People in developed countries on average consume about six to ten times more water daily than those in developing countries (**UNESCO, 2000**). In 1995, per capita domestic water demand was estimated at 131 litres per day for developed countries and 70 litres per day for developing countries (**IFPRI, 2003**). A range of 27-200 litres per person per day is generally considered to be a necessary minimum to meet needs for drinking and sanitation, bathing and cooking (**Gleick, 1996**). **Gleick** proposes that international organisations and water providers adopt "*an overall basic water requirement of 50 litres per person per day*" as a minimum standard to meet four (4) basic needs; drinking, sanitation, bathing and cooking.

In the United States, by far the largest percentage of indoor water use occurs in the bathroom with 28% used for toilet-flushing, 23% for bathing, 14% for laundry and 3% for drinking and cooking (**USEPA, 1992**). In practice, most households in The Grenadines will use the water copiously during the rainy periods, especially if the tank is overflowing, while rationing during the dry periods. Many strategies are applied to conserve water, including the use of pit latrines and recycling laundry water for flushing. Consequently, there are three (3) consumption rates observed in Carriacou in a household of average-sized house and cistern:

(1) The Dry Season Consumption Rate of about *60% of mean per capita* during the period January to the beginning of the rainy season, when conservation and rationing are widely implemented,

(2) The Wet Season Consumption Rate of about *125% of mean per capita* during the period after the tank is filled when there is more liberal use of water, and

(3) The Mean Consumption Rate during the period when the rainy season begins and the tank is first filled.

The initiation of the Dry Season Consumption Rate is influenced by the level of the water in the tank and is based purely on the experience of the household. The increase in mean per capita is expected to increase in the future, particularly with the increase in internal plumbing and the use of flush toilets and washing machines in average Grenadinian homes. The use of internal plumbing with flush toilets increased from 9% and 22% in 1981 and 1991 respectively and estimated at about 37% in 2002.

In The Grenadines, current per capita consumption is about 46 litres per person per day and would reach 136 litres per person per day (**Procicaribe, undated**). The number of residents in a typical Grenadinian home is stable for most of the year except for the periods of Christmas, Carnival, Easter and regular Regattas. During these periods, each household could have between two to six additional overseas-based family members with water per capita consumption higher than the permanent resident. On average, a typical home would have to accommodate annually three persons for three weeks at Christmas and Regatta and two persons for one week at Easter and Carnival seasons.

5. Results

Simulation results of the performance of cisterns for conditions that represent existing patterns of water use in The Grenadines are represented in **Figures 3, 4, 5,** and **6** and **Table 1**. An average consumption per capita of 50 litres per day, with seasonal variation in the number of permanent residents and per capita consumption (**Table 2(a)**). The cistern is allowed to empty once in 25 years. In **Figure 3**, it can be seen that there are two (2) distinct regions for the size of a cistern. In Region 1, the required size of the cistern for a given number of permanent residents, increases rapidly as the available contributing roof area decreases. In Region 2, the impact of increasing contributing roof area on decreasing cistern size is significantly lesser than in Region 1.. The line **AB** in **Figure 3** represents a threshold relationship between cistern size and contributing roof area. The line **AB** is obtained by locating the intersection O for the distinct lines OR and OS in the two (2) regions for the **4P** curve in **Figure 3**. Then, the point on an individual curve, for example, the location on the **5P** is obtained by joining the intersections for **4P** and **6P** in **Figure 3**. **Figure 4** demonstrates this threshold relationship between cistern size and contributing roof area.

Simulations for typical current conditions for an average-sized house (floor space of $94m^2$, valued about US$76,500 and occupied by six permanent residents) were carried out for per capita consumptions of 40, 50, 55, 60, 75 and 100 litres per day. The results are shown in **Figure 5** and **Table 1**. As the per capita consumption increases, the size of the cisterns increases non-linearly. At 50 litres per person per day, the required cistern capacity is about $39m^3$ which would cost about 8% of the total value of an average-sized house. Decreasing the consumption per capita to 40 l/d would result in a cistern capacity requirement of approximately $14.5m^3$. This would reduce the relative costs of the cistern to 7% of the total residential value. If the per capita was increased from 50 l/d to 60 l/d, the cost of the cistern would approximately be doubled.

Figure 6 is a monograph of the cistern design criteria based on current water consumption pattern. The use of gallons instead of m^3 is intended to make the monograph user-friendly for residents on The Grenadine islands. The use of the monograph is a simple procedure as follows:

(a) Identify the number of stories to be built, one or two;

(b) Decide on the total floor area of proposed residence;

(c) From Equation 1a and 1b, use (a) to obtain contributing roof area;

(d) Decide on the number of permanent residents in the household;

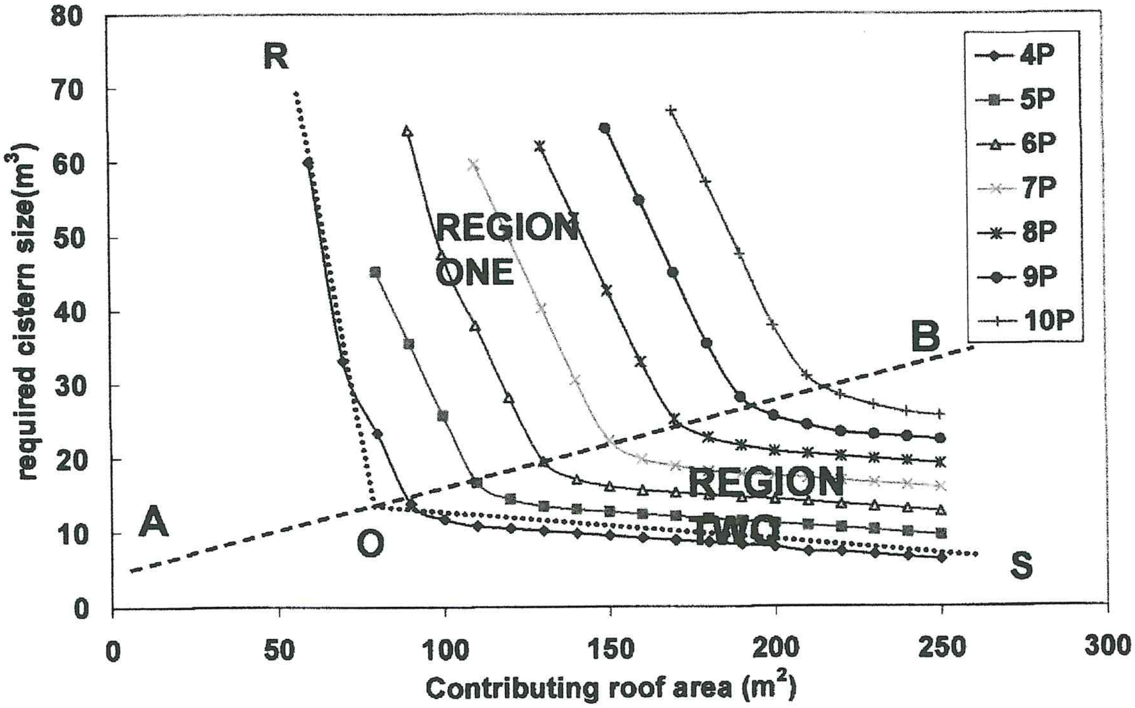
(e) From **Figure 6**, the required cistern size is obtained.

For example, a known contributing roof area selected on the x-axis for example, $220m^2$, with a permanent household population of six, the size of cistern should be 3,000 gallons in capacity. If the house contributing roof area was half the size of $110m^2$, the required tank volume would be about 9,000 gallons.

6. Discussions and Conclusion

A number of factors enter into the estimation of the cistern. In reality, the issue of cistern size is reduced to the rate of emptying versus the rate of filling and how much is required as a buffer. This depends primarily on the expected length of dry spells which could be probabilistic and how difficult it is to get water from another source if the cistern dries up. In this study, the estimates of cistern sizes assumed that the risk acceptable was for a cistern emptying completely once in 25 years. If the acceptable risk decreases, that is, cisterns are allowed to empty completely more often, then the desirable cistern size would decrease.

It is not clear that households will discipline themselves to keep to the water usage rates assumed in any storage-sizing exercise. Certainly household occupancy can fluctuate and unplanned activities consume unplanned quantities of water. In this study, it is observed that there is an optmum size of a cistern which can be obtained by simulating the cistern performance over a wide range of contributing roof area for a specified number of residents. However, in practice, the roof area is usually fixed since the size of the building and the corresponding roof area are constrained by the amount of money the proposed resident has available to spend. In addition, the number



Note: Cistern is filled after construction from another source and empties once in 25 years.

FIGURE 3: *Cistern Size for Contributing Roof Area*

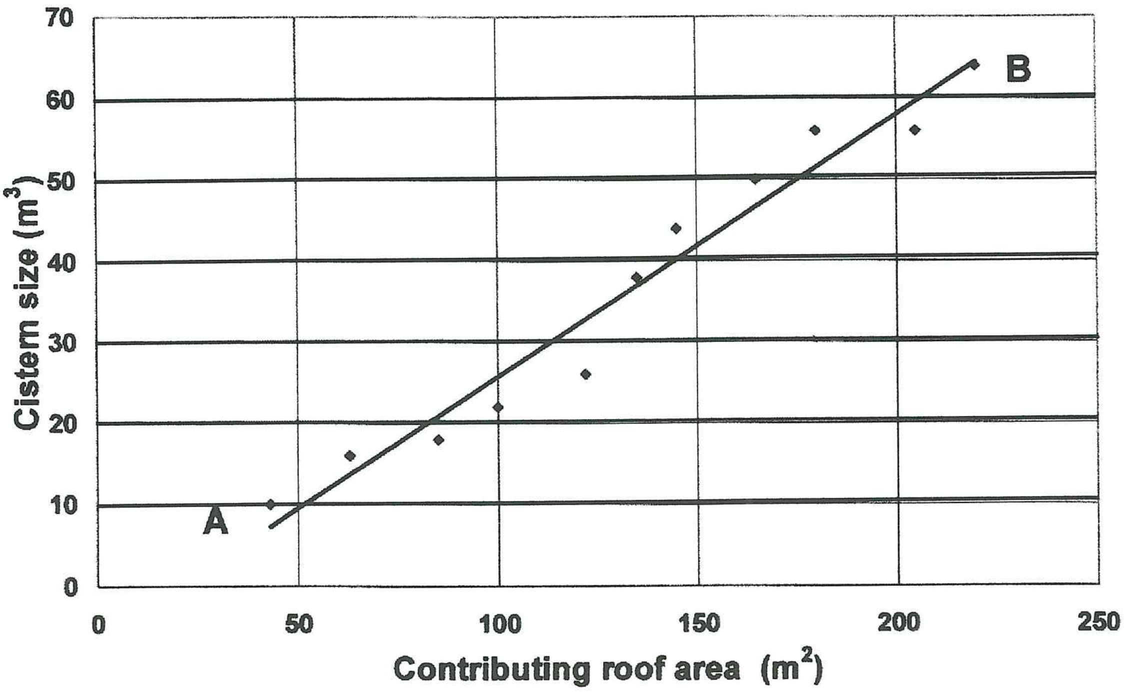


FIGURE 4: *Threshold Cistern Size for Specified Contributing Roof Area at 50 l/d/p Water Consumption*

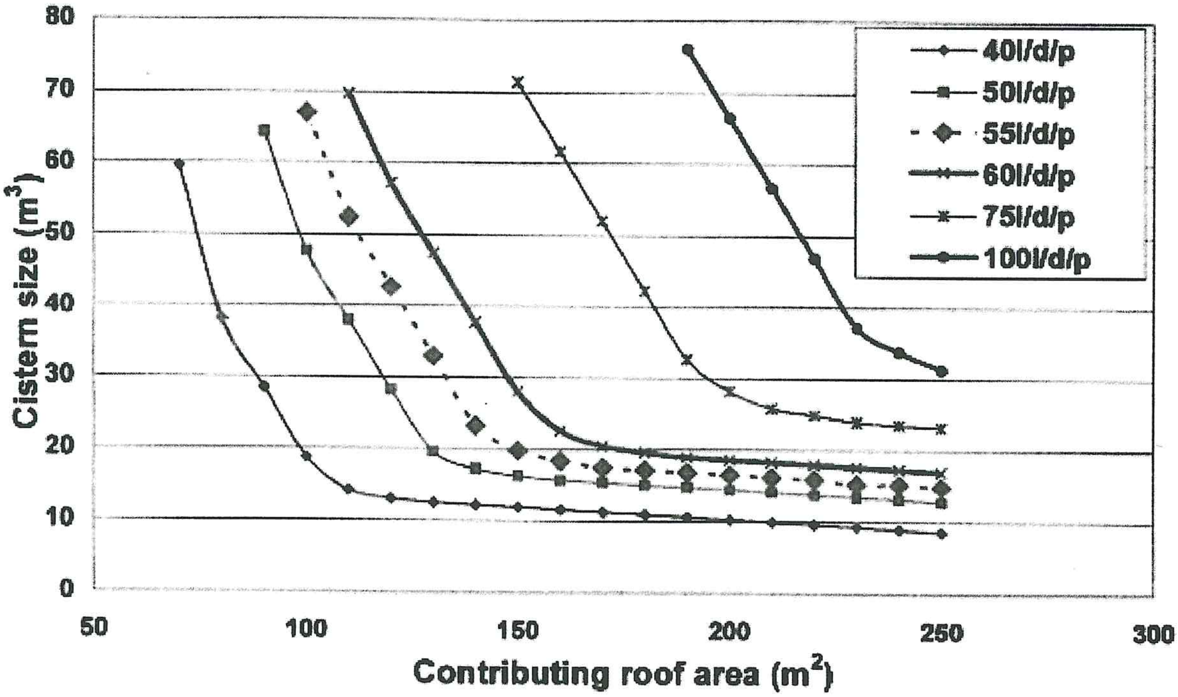


FIGURE 5: *Cistern Size Requirement for a Household of Six Permanent Residents for Varying Per Capita Consumption*

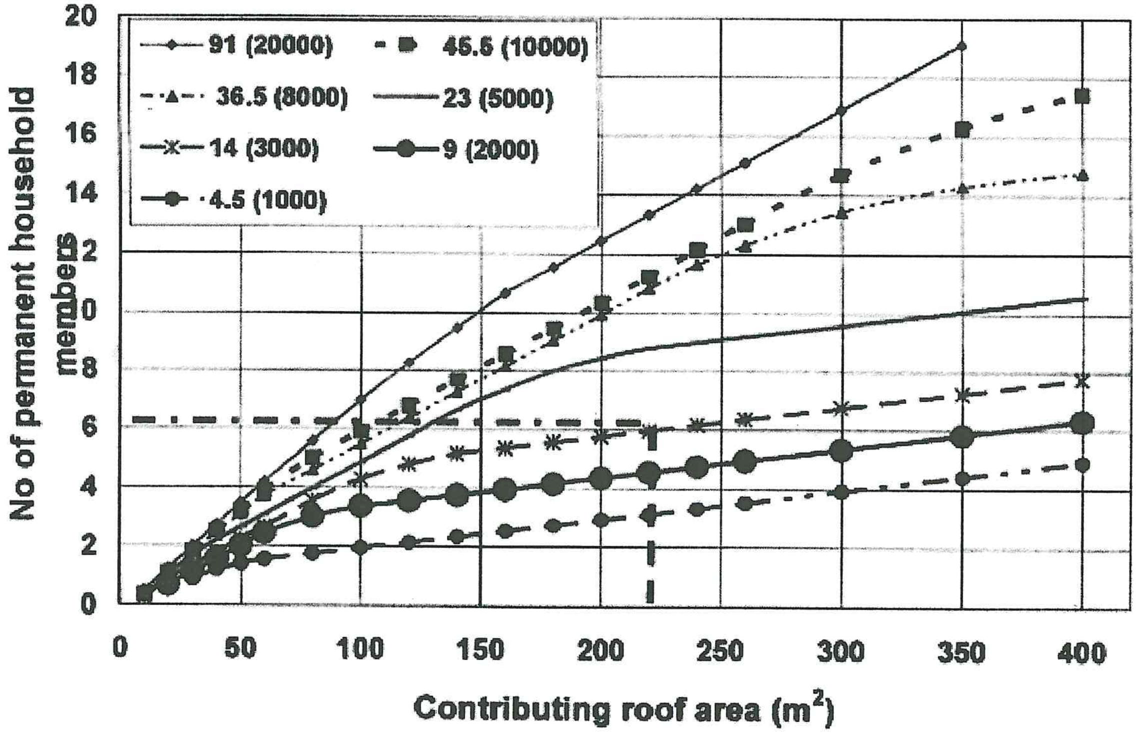


FIGURE 6: *Cistern Selection Criteria (Tank Size in m^3 (gallons)*

of residents does not vary greatly over time, hence the size of the cistern and adequacy are mostly dependent on the consumption patterns. At a consumption pattern of 50 l/d per person, averaged-sized families in middle-income-type homes can afford cisterns that have only 4% chance of emptying in any one year.

Unlimited sizing of cisterns to meet an increased usage of domestic water in The Grenadines is not a viable option. To satisfy higher consumption patterns that are typical in locations where other sources of water are available would require roof contributing areas and cistern sizes that are cost-prohibitive for average income families. Nonetheless, there is room for strategic improvement in the availability of domestic water:

(a) Designing the roof to obtain maximum contributing area, and

(b) Optimising the household water use by targeting the areas of high water use in the home, namely the bathroom and kitchen facilities by using low volume fixtures.

The reliability of RRCS can be determined from the expected reliability of the rainfall amount obtained from frequency analysis of monthly and annual rainfall. In this study, the historic monthly rainfall data was utilised. Although shorter recording intervals, for example, daily or hourly are more predictive in the performance of RRCS, their application is not very practical because rainfall occurrence probabilities are normally very low, especially in semi-arid regions (**Ngigi, 1997**). Nevertheless, research on rainwater-harvesting for domestic use in The Grenadines would be enhanced by the continuous collection of at least daily rainfall data in at least two (2) sites on the larger Grenadine islands. Such data would also permit a rigorous analysis of the reliability of RRCS.

In territories where rainwater is the primary water resource, building regulatory agencies mandated to implement compulsory cistern requirements for new residential buildings are often faced with the difficulty of objectively establishing what size of cistern to be associated with a given size of building. Typically, the number of residents that would occupy the building is not a requirement for the regulatory agency. The threshold curve in **Figure 4** provides a simple tool for objectively selecting a cistern size based on a typical consumption of 50 l/d/p.

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