Minimum design requirements for domestic rainwater-harvesting systems on small volcanic islands in the Eastern Caribbean to prevent related water quality and quantity issues

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Abstract:

Rainwater harvesting is the primary source of fresh water on the majority of isolated and volcanic islands in the Eastern Caribbean island chain that lack reliable sources fresh water. There are generally two types of rainwater systems on most Caribbean islands: traditional rainwater systems with an external brickwork cistern and modern rainwater systems with cisterns integrated in the foundation of the houses.
Recent research studies have determined that the microbiological quality of rainwater in cistern systems is generally unstable and can lead to serious health implications when used for human consumption. Another related issue is that rainwater shortages occur more frequently due to fluctuating rainfall patterns and increasing rainwater consumption rates.
In this paper minimum design requirements are determined, using data from the islands of Saba and St Eustatius, for the construction of new domestic rainwater systems on small volcanic islands in the Eastern Caribbean. These minimum design requirements can be used to prevent potential water quality and quantity issues. One of the conclusions of this research study is that mainly the collection and storage elements of rainwater systems need to be constructed using non-toxic and non-corrosive materials to mitigate potential health risks. Also, first-flush devices need to be installed in the collection system to divert the mostly contaminated first load of rainwater after a dry period. The storage tanks need to be watertight and protected from sunlight, preferably located at least 30 meters away from active bacterial sources (such as open street sewers or cesspits). The minimum rainwater catchment area for a standard rainwater system, based on a 4-person family with a modern water consumption pattern, is 113m^2; the minimum cistern storage capacity is 24m^3.

Keywords: rainwater harvesting, water quality, cisterns, water demand management, fecal contamination, design requirements

1 Introduction

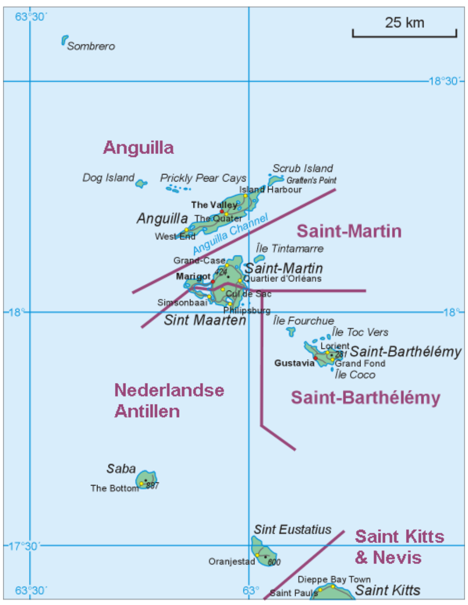

Figure 1 Northern Leeward islands

Rainwater harvesting refers to the small-scale concentration, collection, storage and use of rainwater runoff for both domestic and agricultural use (Nowbuth et al. 2007). Rainwater harvesting has been practiced more than forty thousand years ago, resulting in the existence of various methods of rainwater harvesting (Pacey et al. 1986). The roof water harvesting technique, also referred to as DRWH, is an important means of supplying water in many communities. Roof water harvesting employs simple and cheap technology and is often found in developing countries, small islands and in semi-arid regions where surface and groundwater resources are limited (UNEP, 1997). On the majority of isolated and volcanic islands in the Eastern Caribbean island chain (e.g. Turks and Caicos islands, the Cayman

islands, US and British Virgin Islands), rainwater harvesting serves as a major source of fresh water next to seawater desalination and bottled water (Lye, 1992).
Two examples of small isolated islands where DRWH still serves as the main source of fresh water are the islands of Saba and St Eustatius. The islands are currently overseas territories of The Netherlands and are part of the Leeward island chain, located northeast in the Caribbean Sea (Figure 1). The region in which Saba and St Eustatius (Statia) are located has a sub-tropical climate with approximately 80% of the annual rainfall concentrated between May and December (MDNA, 2010). The islands of Saba and Statia represent typical Eastern Caribbean islands and serve as general reference locations for this research study in order to develop minimum design requirements for new domestic rainwater systems on small volcanic islands in the Eastern Caribbean.

Rainfall rates in the Caribbean range from 1.500 mm to in excess 3.000 mm per year, depending on the island size and geography. Generally, rainfall rates are higher on the larger, more mountainous islands (UNEP, 2009). The geographical conditions of Saba and Statia are normal for Eastern Caribbean islands. The average yearly rainfall rate is approximately 1100 mm, slightly less than the average rainfall patterns in the Eastern Caribbean island chain (Dijkshoorn, 2009).
Steep hillsides, thin soil layers and fractured igneous rock prevent natural catchment of rainfall on most volcanic islands. Alternative fresh water resources in the form of groundwater aquifers are generally not available or not large enough to serve as a reliable source of fresh water (Smith, 2009).
Seawater desalination is an important source of fresh water for mainly public facilities and commercial businesses. The desalination process is energy-intensive; the rates of desalinated water are directly related to the global fossil fuel prices. Drinking water rates are therefore generally high, ranging from 2 to 9 Euros per cubic meter (Reijtenbagh, 2008). A large part of the dwellings in the Eastern Caribbean are not connected to communal drinking water distribution networks. Often the production capacity of these desalination systems is limited. The quality of desalinated water is sometimes unstable since the production and distribution of drinking water are not fully regulated on many islands. Because of the previous issues, many homeowners in the Eastern Caribbean islands depend on private rainwater collection instead. The harvested rainwater is stored in large freshwater reservoirs (cisterns). When highly necessary, these cisterns can also be replenished with desalinated water.
Rainwater harvesting is generally a simple and reliable source of fresh water while other sources are expensive, unavailable or unreliable. Rainwater cisterns generally provide *water-independence* to their users, this is particularly important during natural disasters such as hurricanes, when individual houses may become isolated (Smith, 1999).
In the past it was believed that rainwater was pure and could be consumed without treatment. While this may be true for some remote areas, rainwater collected in most populated areas contain impurities (UNEP, 2009). An estimated 50% of the rainwater users on Saba and Statia consume untreated rainwater (Koot, 2009). Recent quality evaluations of cistern water on Saba and Statia show unstable microbiological compositions, exceeding WHO threshold levels for total coliform, e-coliform, enterococci and total plate count indicator parameters (Reijtenbagh, 2008). The main reason for these high plate counts seem to be active sources of animal and


Figure 2 Traditional rainwater cistern on Saba

human fecal bacteria. Using untreated rainwater for human consumption can therefore lead to serious health implications. Inhabitants of Saba and Statia who frequently consume untreated rainwater sometimes suffer from gastric disorders (Koot, 2009).
Similar health effects are reported on the other Caribbean islands (Lye, 1992; Waller and Haebler, 1985)
Next to serious water quality issues, rainwater harvesting is also related to quantity issues. In the last 5 years, rainwater shortages seem to occur more often than in the past. One reason for these shortages can be linked to potential climate changes; more frequent and longer periods of limited precipitation. Another important reason is the increasing domestic consumption patterns due to the introduction of modern household equipment on the islands (Reijtenbagh, 2008).
Because public drinking water is either not available or very expensive, rainwater harvesting remains the primary source of potable water on small isolated islands in the Eastern Caribbean. In order to safeguard public health and prevent water shortages, it is necessary to adapt rainwater systems to the changing context in which they are used. Recent research indicated that specific building regulations regarding the construction of new rainwater systems could reduce the existing quality and quantity issues experienced on Saba and Statia (Reijtenbagh, 2010). This research study determines what kind of building regulations can be applied taking into account the existing types and dimensions of residential houses while at the same time considering the modern drinking water consumption patterns. The goal of this paper is to determine minimum design requirements for domestic rainwater systems on small volcanic islands in the Eastern Caribbean to prevent potential health risks and water shortages.
Chapter 2 gives and overview of typical harvesting systems on the islands of Saba and Statia. Chapter 3 determines quality issues that are related to the use of rainwater systems and determines design strategies to mitigate these issues. Chapter 4 determines if existing rainwater systems can meet increasing consumption patterns due to the introduction of modern household equipment. Next, minimum design requirement are determined for new rainwater systems in order to prevent rainwater shortages during the year. The conclusions are presented in chapter 5.

2 Typical rainwater systems in the Eastern Caribbean

A rainwater harvesting system consists of three basic elements: a collection area, a conveyance system, and storage facilities. The collection area in most cases is the roof of a house or building. A conveyance system usually consists of gutters and pipes that deliver rainwater falling on the rooftop to cisterns or other storage vessels (OAS, 2010).
Generally there are two types of rainwater system in the Eastern Caribbean: traditional systems and 'modern' systems. When considering the reference islands of Saba and Statia, about 12,5% of the houses are built in the traditional way (before 1900 and collect rainwater in external brickwork structures (see Figure 2). These external cisterns are usually located in the garden and have an average storage capacity of 38 m^3. (Reijtenbagh, 2008). Rainwater is collected from the main roof of the house and from an additional catchment area on top of the external cistern; the total catchment area is approximately 100m^3.
Modern houses on Saba and Statia have cisterns integrated in the foundation of the house. Houses on volcanic islands are usually built on slopes, the

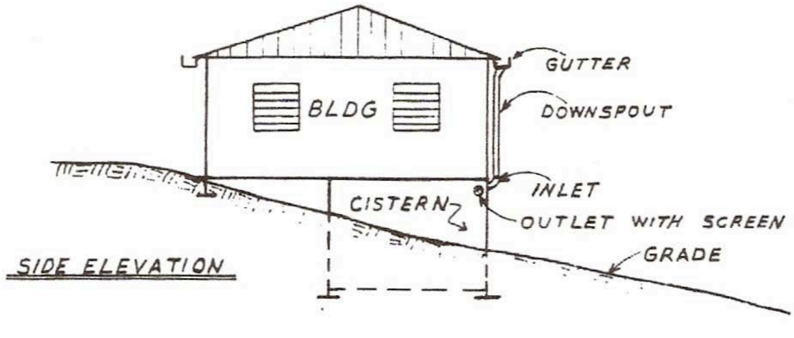

Figure 3 Integrated concrete cistern on the US Virgin Islands (Smith, 2009)

foundation of houses serves two purposes; providing a stable basis for the weight of the house and correcting for the angle of the slope. Cisterns located in the foundation of new houses often have triangular cross sections (see Figure 3). The capacity of integrated cistern depends on the surface area of the house and the angle of the slope on which the house has been built. Integrated cisterns have a capacity of approximately $60m^3$ and a rooftop catchment area of about $150m^3$ (modern houses are slightly larger than the traditional houses). The types of rainwater systems that are described in this section are typical for the islands of Saba and Statia, systems on other Caribbean islands may vary in the use of construction materials and the overall design. However, the general principles and dimensions of average rainwater system in the Eastern Caribbean are quite comparable (UNEP, 2009).

2 Quality and health aspects of rainwater systems

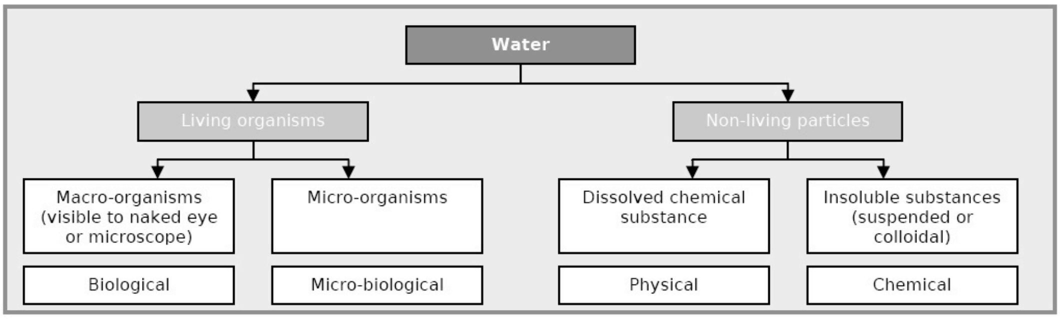

Figure 4 Factors determining rainwater quality (enHealth, 2004)

The quality of rainwater used for domestic supply is of vital importance because frequently it is used untreated for human consumption. It is not possible to find completely pure water in nature since water droplets dissolve a whole range of substances in the atmosphere, such as gases, airborne dust particles and salt from sea spray. Atmospheric pollution can have a major effect on the composition of rainwater. Water that reaches the earth as rain, acquires other substances from processes such as wastewater leaching, weathering, and dissolution. Depending on the source of the contamination, three types can be distinguished:

· (Micro)biological contamination:
The most common hazard in water sources obtained from roof or surface catchments is microbial (biological and microbiological) contamination, especially enteric pathogens. Enteric pathogens are micro-organisms (bacteria, viruses, and protozoa) that cause gastrointestinal illness. These organisms are introduced into drinking water supplies by contamination with fecal material (from human or animal origin) or by dead mammals and insects (enHealth, 2004). Inhabitants of Saba and Statia who frequently consume untreated rainwater sometimes suffer from gastric disorders; these disorders might be caused by the 'helicobacter pylori' bacterium. This bacterium is mainly responsible for stomach ulcers (Koot, 2008).
One explanation for the presence of these types of bacteria is because rainwater-harvesting systems are typically vulnerable to external sources of pollution. Animal (iguana's, goats, birds) excrements are an important source of rainwater contamination in the Eastern Caribbean. Another source of bacterial contamination are mosquitoes that make their way into the storage tank and lay their eggs (Haebler, et al., 1985). The link between rainwater storage and mosquitoes are extensively researched; a clear link exists between the presence of mosquito larvae and rainwater storage containers. Where containers are open or lack secure covers or screens, they are far more vulnerable to infestation. There is a particular concern with mosquitoes in tropical areas

where they are vectors of serious diseases as malaria, yellow fever, dengue fever and 'filariasis' (Kolsky, 1997).
Another important source of pollution is human fecal contamination; sources of fecal bacteria can be found everywhere on Caribbean islands in the form of open street sewers and domestic wastewater infiltration systems. The main problem is that there are often no collective sewer systems available; most villages have open street sewers, many households have private septic tanks or infiltration pits (leeching cesspits). The fecal contamination problem is mainly related to the location of wastewater systems relative to the location of rainwater cisterns. When wastewater infiltration tanks or open street sewers are located too close to rainwater systems, bacteria and viruses can percolate through the walls and plaster of the cisterns into the rainwater (Reijtenbagh, 2008).

· Chemical contamination:
Under certain circumstances, such as in areas with severe air pollution or where lead-based paints or other potentially toxic building materials have been used, chemical contamination of rainwater can pose a serious health theat. Under normal circumstances, serious contamination of rainwater is rare. Extra attention needs to be paid to very old roof catchment systems, that are constructed at times when building codes and regulations relating to the use of lead based paints, lead fittings and other hazardous materials were less stringent (Gould, et al., 1999). The latter situation is the case for the traditional houses in the Caribbean; sometimes their rainwater systems can contain collection and storage elements made from lead or asbestos (Reijtenbagh, 2008).

· Physical contamination:
Physical contamination includes inorganic and organic sediments like sand, silt, clay, or plant material. Physical contamination affects the color, odor or taste of the water, but it poses no direct health risk. Users can however object to water if its color, odor and taste are found less attractive (enHealth, 2004).

Minimum design requirements to reduce health risks
The most practical approach to improve and maintain the quality of rainwater for domestic supply is to insist on simple and adequate measures of sanitary protection that can significantly improve the quality of rainwater. This is especially important for locations where systematic quality monitoring and treatment of rainwater sources is not always performed (Gould et al., 1999). It has been demonstrated that if careful construction measures are taken, rainwater catchment systems can provide rainwater with a quality that is high enough to consume (Michaeledis, 1989)

The following design measures are recommended to prevent health implication related to the consumption of rainwater from cisterns. Requirements are proposed for the main elements of a rainwater system: collection area, conveyance system and storage tank.

- Collection area

For domestic water supplies, the roof of the building is generally used as the catchment area. Some materials used to coat the roof such as bitumen, paint or sheeting containing lead, may pose risk to human health. RWH systems are best suited where the roofing material is smooth and coated with chemically neutral substances. Non-corrosive sheet metals such as galvanized sheets or aluminum are ideally suited for use with RWH systems. They are less prone to build-up and contamination from dust, leaves, animal droppings and other debris, compared to rougher roof surfaces such as tiles, shingles or thatch (UNEP, 2009). On the US Virgin Islands, specific regulations in the Safe Drinking Water Act define the materials that are required for the construction of rainwater harvesting systems. All materials need to comply with the National Safety Foundation P151 protocol. This protocol is required for all materials that are suitable for the distribution and treatment of potable water for human consumption (NSF, 2010).

- Conveyance system

The conveyance system like the other elements of the rainwater system needs to consist of non-toxic and non-corrosive materials. To prevent animals, organic matter and debris from entering the storage tank, screens and filters need to be placed at all inlets (Gould, et al., 1999). Next to that, a first flush filter needs to be installed to divert the first millimeters of rainfall (see Figure 5), containing the main load of pollution (UNEP, 2009). Pipes that are used to pump water from the cistern need to be located at least 5 cm above the tank floor to prevent debris from entering the pumping system (Gould et al., 1999).

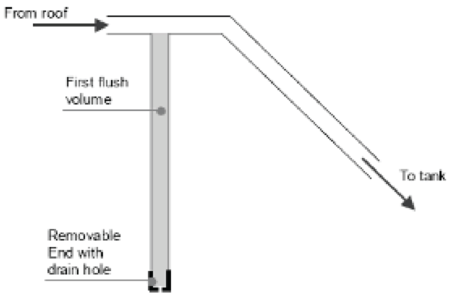

Figure 5 'First flush diverter' system

- Storage tank

Rainwater storage tanks need to consist of two separate chambers to allow maintenance while using the system (see Figure **6**). In order to enter the cistern for inspection or maintenance duties, a manhole cover is required. Cistern storages ideally need to be placed below ground and protected from light, to prevent the growth of algae and micro-organisms (Gould et al., 1999). Rainwater cistern tanks needs to be watertight; this can be done by applying non-toxic sealant coatings on the inside of the tank. These coatings do not only provide for extra strength and density but also prevent cross contamination from other bacterial sources (UNEP, 2009). Additionally it is advised to construct rainwater cisterns at least 30 meters from any type of pollution facility, e.g. latrines, open sewers, stables (Lye, 1992).

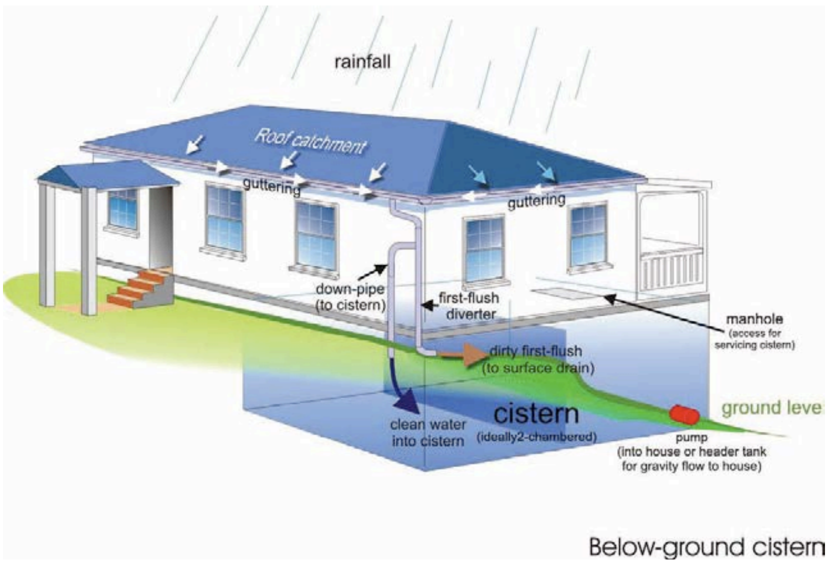

Figure 6 Overview of rainwater harvesting system

3 Quantitative aspects of rainwater systems

The average precipitation in the eastern Caribbean region is high, approximately 1100 millimeters per year (MDNA, 2010). In the past, these rainfall rates were sufficient to provide the population of Saba and Statia with enough drinking water during the year. During the last years, there seems to be less rainwater available for potable use. One reason for this might be changing weather patterns. The rainy season is getting shorter and is characterized by more intensive periods of precipitation. Another reason might be that the inhabitants consume more rainwater than before (Reijtenbagh, 2008). In the last decade modern household equipment (dishwashers, washing machines, flush-toilets) was introduced on the islands; these are typically large water consumers. The traditional cisterns and catchment areas are not dimensioned to keep up with the increasing consumption patterns.

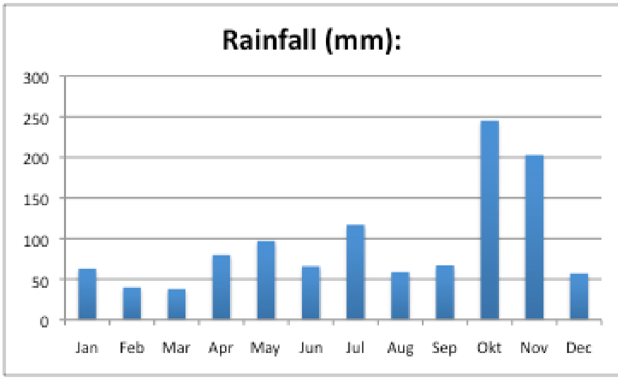

Figure 7 Average rainfall rates for Saba and Statia 2000-2008

Based on the average rainfall rates and the increased water consumption rates on Saba and Statia (as a reference for typical Eastern Caribbean islands), minimum design requirements are determined for rainwater collection and storage systems. First, the existing rainwater systems are analyzed to determine whether these systems can provide enough rainwater given the increased average consumption patterns and the average rainfall rates. The next step is to determine the optimal design requirements for new rainwater harvesting system, to prevent shortages of rainwater in the future.
Properties of the two main rainwater systems on Saba and Statia are presented in Table **1**.

Table 1 Rainwater system properties for Saba and Statia

Properties:	**Traditional system**	**Modern system**
Roof catchment area	100m^2 (roof surface and external catchment area)	150m^2 (only roof surface area)
Cistern capacity	38m^3	60m^3

The average rainwater consumption patterns of Saba and Statia are presented in Table **2**, a distinction has been made between normal and increased consumption rates. The difference between these rates is the application of water consuming household equipment such as dishwashers, washing machines and shower cabins.

Table 2 Average rainwater consumption patterns for Saba and Statia

Type of consumption pattern	Normal rainwater consumption [l/cap/day]	Increased rainwater consumption (including household applications) [l/cap/day]
Consumption rates[1]:	40	70

The next step is to determine whether the actual demand meets the amount of rainwater that is captured by the existing rainwater systems.

Potential rainwater supply

The potential rainwater supply is the theoretical volume of rainwater that can be collected with regard to the existing catchment area, runoff coefficient and rainfall rates. The following equation is can be used to determine the total rainwater supply:

Equation 1 Potential rainwater supply

$$S = R \cdot A \cdot C_r$$

[1] Based on average consumption rates provided by local inhabitants (Koot, 2009 and Dijkshoorn 2009)

S= Mean rainwater supply in cubic meters [m^3]
R= Mean annual rainfall in millimeters [m/a] = 1132 mm/a for Saba and Statia.
A= Catchment area in square meters [m^2]
C_f=Runoff coefficient = 0,8[2]

Based on the previous data sets, the following conclusions the total surplus can be calculated for each rainwater system based on the consumption pattern. The total demand of rainwater is based on a family composition of 4 persons and an average amount of 30 days per month.

Table 3 Total supply vs total demand

Rainwater harvesting system:	Total rainwater supply [m^3]	Total rainwater demand [m^3]	Surplus/deficit [m^3]
Traditional:			
Normal consumption	90,56	58,40	32,16
Increased consumption		102,20	-11,64
Modern system:			
Normal consumption	135,84	58,40	77,44
Increase consumption		102,20	33,64

From the results in Table **3** can be concluded that traditional rainwater systems in the Eastern Caribbean do not collect enough rainwater to meet the total water demand. Modern systems generally meet the increased water demand and even have an average rainwater surplus of 33,64 m^3.
In order to meet the increased consumption patterns, traditional cistern system would need to increase their catchment areas. The total catchment surface that is required (given a total demand on 102,20m^3) can be calculated using equation 1 and is 112,85m^2. Traditional rainwater systems therefore need to extend the rainwater catchment areas with a minimum surface area of 12,85m^2.

Minimum required rainwater cistern capacity
The minimum rainwater catchment area has been defined (based on the average rainfall rates on Saba and Statia between 2000 and 2008) for the increased consumption pattern of 70 l/cap/day. The next step is to define the minimum cistern capacity. Rainwater cisterns need to contain a minimum amount of water as a buffer during the dry months within the year (Gould, 1999).
The rainfall rates on Saba and Statia vary per month; during the rainy season (May to December) rainfall rates are generally high, from February to April the rates are

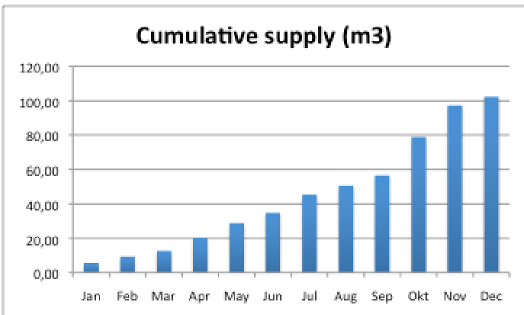

Figure 9 Cumulative supply of rainwater on Saba/Statia

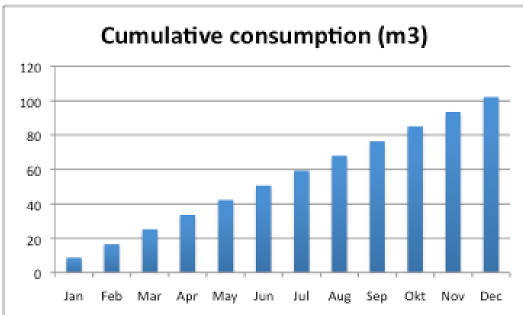

Figure 8 Cumulative consumption of rainwater on Saba/Statia (70l/cap/day)

generally low (see Figure 7). These patterns are typical for islands located in the

[2] The average runoff coefficient for well-constructed roof catchments (corrugated-iron sheet tiles) is generally 0.8 (Cuncliffe, 1998).

Caribbean hurricane belt. The capacity of rainwater cisterns needs to be large enough to provide enough rainwater throughout the year, especially during the dry period from February to April.

The minimum design capacity of the cisterns is based on the difference between the cumulative monthly rainfall supply and the cumulative monthly demand. The capacity is calculated as the absolute maximum between cumulative supply and demand minus the cumulative storage in the tank by the end of the year (UNEP, 2009). Figures of the cumulative supply and demand are presented in Figure 9 and Figure 8 and are based on the minimum catchment area of 113m². The values for monthly rainfall, supply, demand and storage are summarized in Figure 10.

The mathematical expression for the minimum design capacity of a rainwater cistern is described in the equation below.

Equation 2 Minimum design capacity (UNEP, 2009)

$$V = ([\min(S)] - \max(S)) - \sum S_c$$

V= Minimum design capacity [m³]
S= Monthly rainwater storage (cumulative supply-cumulative consumption) [m³]
S_c=Cumulative monthly storage [m³]

Month:	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Okt	Nov	Dec	Year	Unit
Rainfall	63	40	38	80	97	66	117	59	67	245	203	57	1132	mm
Supply	5,70	3,62	3,44	7,23	8,77	5,97	10,58	5,33	6,06	22,15	18,35	5,15	102,33	m3
Cumulative supply	5,70	9,31	12,75	19,98	28,75	34,71	45,29	50,62	56,68	78,83	97,18	102,33		m3
Consumption	8,68	7,84	8,68	8,4	8,68	8,4	8,68	8,68	8,4	8,68	8,4	8,68	102,20	m3
Cumulative cons.	8,68	16,52	25,2	33,6	42,28	50,68	59,36	68,04	76,44	85,12	93,52	102,2		m3
Stored (supply-demand)	-2,98	-7,21	-12,45	-13,62	-13,53	-15,97	-14,07	-17,42	-19,76	-6,29	3,66	0,13		m3
Cumulative storage	-2,98	-4,22	-5,24	-1,17	0,09	-2,43	1,90	-3,35	-2,34	13,47	9,95	-3,53	0,13	m3

Figure 10 Rainwater properties for a design cistern with a catchment area of 113m³

Based on equation 2, the minimum storage capacity for a rainwater cistern, given a minimum roof catchment area of 113m² and a consumption rate of 70/l/cap/day (4 persons) is 23,29m³.

Figure 11 displays two curves that show the relation between the total roof catchment area and minimum storage capacities. The blue line represents a household of 4 persons, the red line a household of 5 persons. As can be seen in the figure, a 5 person household needs a minumum roof catchment area of 140m²

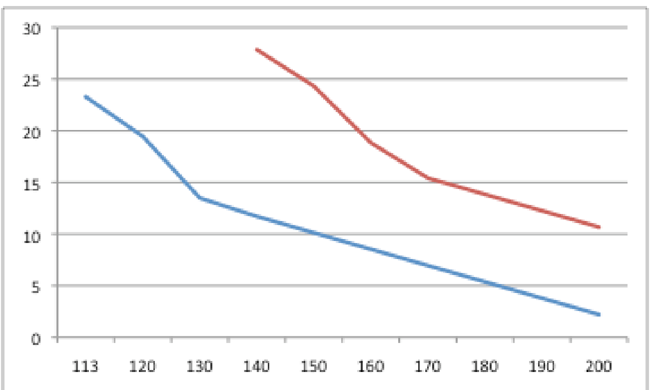

Figure 11 Storage capacity (m3) versus roof catchment area (m2) for 4-person household (blue) and a 5-person household (red)

4 Conclusion

Rainwater harvesting is the primary source of fresh water on many small volcanic islands in the Eastern Caribbean island chain. Steep hillsides and thin soil layers on top of impermeable volcanic rock prevents the existence of alternative fresh water resources. Public drinking water is either not available or expensive. Also, the quality of desalinated drinking water on the islands is sometimes unstable. Due to high yearly rainfall rates (over 1000mm/a) in the eastern part of the Caribbean, inhabitants of many isolated volcanic islands have always been able to collect and store enough rainwater for domestic use.
There are generally two types of rainwater systems: traditional system with an external brickwork cistern and modern rainwater system with cisterns integrated in the foundation of the houses.
Recent research studies have determined that the microbiological quality of rainwater in cistern systems is generally unstable and can lead to serious health implications when used for human consumption. Next to that, the introduction of additional water consuming household equipment and changing rainfall patterns lead to more frequent rainwater shortages on the islands.
To avoid the previous quality and quality issues related to the use of rainwater systems on the islands, minimum construction requirements for new rainwater systems have been defined. Through literature research various measures have been determined to prevent contamination of rainwater during the collection and storage processes.

Design requirements regarding rainwater quality:

- Use of non-toxic materials for the construction of rainwater systems; this implies that some traditional rainwater system need to be checked for asbestos and lead-based paints to prevent contaminations
- Application of proper screening and filtration of rainwater before it enters the storage tank
- Application of first-flush systems to divert the first load of rainwater containing high levels of debris and other pollutants
- Rainwater storage tanks need to be watertight and protected from light to prevent micro-biological contamination
- Rainwater storage tanks need to be located at least 30 meters from active fecal bacterial sources to prevent cross-contamination

Minimum design requirement regarding rainwater quantity:

- Considering a consumption rate of 70l/cap/day and an average yearly rainfall rate of 1131mm, a minimum roof catchment area of 113m^2 is necessary for a 4-person household to harvest enough rainwater throughout the year. For a 5-person household this minimum catchment area is 140m^2.

- Given a 4-person household, the minimum design capacity of a rainwater cistern is 23,29m^3 in order to supply sufficient rainwater through the year. For a 5-person household the minimum design capacity is 27,86m^3.

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