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RAIN WATER HARVESTING IN BERMUDA[1]

Mark P. Rowe[2]

ABSTRACT: Roof-top rain water harvesting is mandated by law for all buildings in Bermuda and is the primary source of water for domestic supply. The average rate at which rain water is harvested at the typical house with four occupants is, however, insufficient to meet average demand. While just over one-third of households have access to supplementary water either from mains pipelines or private wells, the majority rely on deliveries from water "truckers" (tankers) to augment their rain water supply. Assuming a reasonably constant daily demand, there is a linear relationship between the "maximum optimum capacity" of a water storage tank and the size of the rain water catchment area, which depends on the characteristics of the rainfall at a given geographic location. A simple spreadsheet model was developed to simulate tank storage levels for various combinations of catchment area, tank capacity, and demand, with an input of actual daily rainfall data for a study period of nearly three years. It was found that for typical cycles of rainfall surpluses and deficits in Bermuda, the tank capacity which there is no benefit in exceeding — the "optimum maximum capacity" — is 0.37 m^3 of storage capacity per 1 m^2 of catchment area. Furthermore, it was concluded that many domestic water storage tanks in Bermuda are larger than necessary, especially so where there is a significant imbalance between rain water supply and demand.

(KEY TERMS: rain water harvesting; Bermuda; water supply; water storage; sustainability; simulation.)

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INTRODUCTION

This article summarizes some of the findings presented in a 2010 Bermuda Government report entitled "Bermuda's Water Supply." A major objective of the report was to evaluate the balance of supply *vs.* demand and assess the adequacy of a system where the principal supply, namely harvested rain water, is not directly measurable. This required an analysis of the erratic nature of rain water supply and an evaluation of the present capacity to supply supplementary water, taking into account the various combinations of sources and methods of delivery that exist.

GEOGRAPHY

Bermuda is a British Overseas Territory located in the North Atlantic, 1,015 km west of North Carolina in the United States (U.S.). It comprises a group of closely spaced limestone islands perched on the southern rim of a submerged volcanic seamount. The six largest islands are joined by short bridges and combine to form a connected island-chain with a maximum width of 2.5 km and a length of 25 km. The hilly topography of lithified limestone sand dunes attains elevations exceeding 50 m above sea level at many locations. In certain areas of Bermuda,

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[2] Hydrogeologist, Department of Environmental Protection, Bermuda Government, Botanical Gardens, 169 South Road, Devonshire DV04, Bermuda (E-Mail/Rowe: markprowe@gmail.com).

determined by the geology, infiltrating rain water has accumulated in the form of fresh groundwater lenses, which represent a significant source of supplementary water for public supply.

With a total population of approximately 64,000, Bermuda has one the highest population densities in the world at 11.4 persons per hectare. It enjoys a very high per capita GDP at US$76,000, attributable for the most part to the presence of international companies, which have incorporated in Bermuda to take advantage of a favorable tax regime. The tourism industry, once the mainstay of the economy, has been in steady decline for more than two decades.

CLIMATE

Bermuda's climate is subtropical and frost-free. Average daytime temperatures range from approximately 19°C in February to 29°C in August. Rainfall is evenly distributed throughout the year with an annual average of 1,458 mm (Figure 1). Rain tends to be delivered by frontal systems in the winter and by tropical disturbances and local thunderstorms in the summer. Extended wet periods are usually caused by slow-moving fronts.

DOMESTIC WATER SUPPLY

Every building in Bermuda has a roof catchment to collect rain water and an associated water storage tank. This is mandated under The Public Health (Water Storage) Regulations, 1951. For many households, this system of rain water harvesting meets all of their water supply needs. For the majority, however, supplementary water is required, either on a regular basis, due to a small catchment area (relative to demand) or, occasionally, due to episodes of lower than normal rainfall. Sources of supplementary water are: raw groundwater from private wells, treated groundwater from Government and commercial wells, and treated sea water.

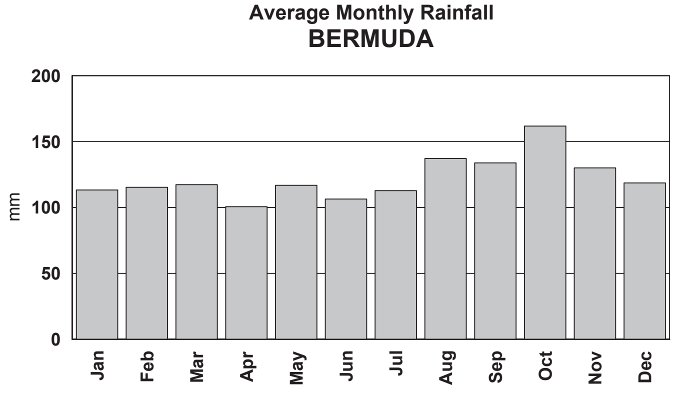

FIGURE 1. Bar Chart of Monthly Average Rainfall in Bermuda. The average annual rainfall of 1,458 mm is relatively evenly distributed throughout the year. There are no wet or dry seasons. This reduces the required capacity of water storage tanks and contributes to the efficacy of rain water harvesting in Bermuda.

There are currently approximately 30,500 "dwelling units" in Bermuda. A dwelling unit is a house or apartment for which a Government land tax is payable; the rate being based on the assessed rentable value. Since many houses in Bermuda are subdivided into self-contained apartments, there is nearly twice the number of dwelling units as there are residential buildings.

Nineteen percent of dwelling units supplement their supply of harvested rainfall with raw water from private wells. More than one-third of these wells produce "fresh" (low salinity) water because they are located within fresh groundwater lenses, the remainder are "brackish" (high salinity). Regardless of the quality, the use of raw well water for potable purposes is not permitted (Government of Bermuda, 1949, Public Health Act); so it is generally piped, via a dedicated plumbing system, directly to facilities such as toilets and washing machines, depending on the quality.

Another 19% of dwelling units are connected to water mains (pipelines) which are fed from reservoirs containing a blend of treated water from low salinity groundwater wells and from coastal sea-water wells. The method of treatment is almost exclusively reverse osmosis. (Note that 2% of dwelling units have both a well and mains supply.)

Sixty-four percent of dwelling units have neither a well nor a mains connection and, therefore, rely on harvested rainfall supplemented only by "trucked" water, as necessary. There are 41 water trucks (tankers) in Bermuda, many of which are individually owner-operated. The majority of the trucks have a capacity of 4,100 l. Water which is supplied to the truckers for distribution is generally from the same source as that supplied by mains.

Under the Public Health (Water Storage) Regulations, 1951 it is stipulated that four-fifths of the roof area of every building must be adequately guttered for catching rain water and that not <100 Imperial gallons (0.45 m^3) of storage capacity for every 10 square feet (0.93 m^2) of guttered roof shall be provided. So, for example, a 100-m^2 roof shall have a guttered area of 80 m^2 and an associated storage tank with a capacity of not <39 m^3.

Bermuda roofs are constructed of overlapping 1 × 12 × 18 inches (25 × 305 × 457 mm) locally quarried limestone "slates," bedded in cement mortar and supported on a heavy timber frame (Figure 2). The porous, limestone roof surface is sealed with two coats of cement-wash and painted with an approved white coating (usually cement-based). Roofs require cleaning and re-coating every two to four years.

Gutter stones measuring 4 × 4 × 18 inches (101 × 101 × 457 mm), triangular in cross-section, are mortared end to end near the edge of the roof to create sloping channels or "glides" (Figure 3). These divert rain water via a number of vertical "leader" pipes into a storage tank, which in all but the oldest homes, is located in an excavation below the house (Figure 4). Tank walls are today built of solid-filled concrete block, founded on a poured concrete slab, and are water-proofed with a cement-and-sand plaster. The gap between the tank walls and the vertical bedrock faces of the excavation is backfilled with concrete to provide lateral support against the weight of water.

FIGURE 2. Photograph Showing the Construction of a Bermuda Roof. A heavy wooden framework of rafters is constructed to support "slates" of Bermuda limestone which are shown stacked up ready for positioning. They will be overlapped with an intervening bed of cement-and-sand mortar.

Although the regulations, which dictate that four-fifths of a roof shall be guttered are not enforced, Bermudians recognize the importance of maximizing catchment area, and so typically 80% of roof areas are guttered (Figure 3). Factors which thwart maximum catchment coverage include: the requirement for sloping gutters to provide a sufficient rate of water flow to clear debris, a limited number of vertical "leader" pipes for transferring water to the tank, and elevation changes and obstacles, such as chimneys.

Not all rain which falls within the guttered area of a Bermuda roof is transferred to the storage tank. Indeed, the term "tank rain" was coined by locals to distinguish rain which greatly benefits water storage levels from that which does not. To investigate this phenomenon, records of water tank storage levels and measurements of rainfall were collected at two houses for periods spanning several months to more than one year, respectively. The results demonstrate that the catchment efficiency — the depth of rainfall caught as a percentage of that caught in a 4-inch (101 mm)-diameter rain gauge — increases with the quantity of rain that falls during a given event (Figure 5). The ineffectiveness of short showers is in part attributable to roof surface roughness and porosity, which must be saturated before runoff will occur.

FIGURE 3. Photograph of a Bermuda Roof. Bermuda roofs are coated in an approved white paint which is usually cement-based. Gutters or "glides" are positioned close to the roof edge, achieving 80% coverage (as catchment) of the total roof area.

FIGURE 4. Photograph Showing Construction of a Bermuda Water Tank. This rain water storage tank constructed of concrete block is located in an excavation which will be covered with the floor slab of a future house. The size is typical for Bermuda, measuring 7.3 m × 3.7 m × 2.4 m (deep) with a capacity of 65 m^3.

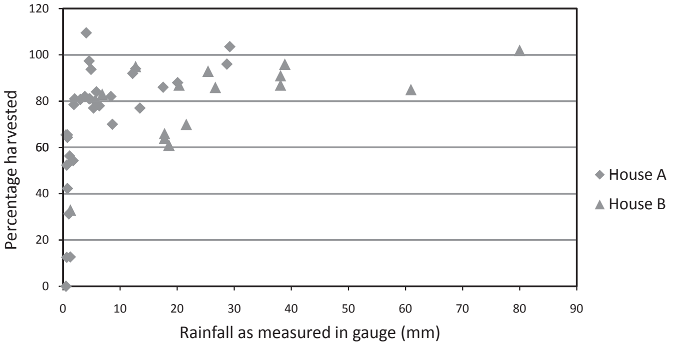

FIGURE 5. Graph of Catchment Efficiency *vs.* Rainfall for Two Bermuda Roofs. The percentage of harvested rainfall (the "efficiency") was determined by measuring changes of depths in the water tanks relative to the "recorded" rainfall caught in 4-inch (102 mm) gauges placed close to each of the houses, respectively. The chart demonstrates substantial variations in efficiency but a general increase in efficiency with increasing rainfall in a given event.

Evaporation is another loss which will reduce and delay the onset of runoff, particularly in the summer. Finally, there is wind, which at exposed locations has the potential to significantly diminish catchment efficiency.

The considerable variation in catchment efficiency between rainfall events of approximately equal magnitude is a function of rainfall intensity, climatic conditions, time of day, and antecedent roof moisture content.

Cumulatively over the entire study period, the depth of rainfall caught on the roof catchments at each of the two houses in the study, amounted to 87% of that collected in the rain gauges, which were situated at 2 m elevation close to, but away from the influence of, each roof. A conservative figure for the catchment efficiency of a Bermuda roof is, therefore, taken to be 85%.

Water Quality

Roof-top rain water harvesting has been practiced in Bermuda for over 350 years, and for most of that period it was thought to provide a perfectly adequate quality of water for potable purposes. Indeed, for a couple of centuries or more, it probably was of superior quality relative to the water available for human consumption elsewhere in the world. Today, despite the fact that use of raw rain water for potable purposes is not deemed an acceptable option in many countries, in Bermuda it is still lawful to build a house with a plumbing system which supplies rain water directly to the kitchen sink, without any intermediate treatment.

Bermudians have certainly become increasingly conscious of potential detrimental effects of airborne contaminants, bird droppings and of the storage of water in tanks which may not be routinely cleaned. Hence, the growing popularity of bottled and filtered water for drinking and cooking purposes. Despite the change in attitude, however, the practice of rain water harvesting is not under threat. It is recognized that the quality of harvested rain water continues to be perfectly adequate for activities which are responsible for the largest share of domestic water consumption, such as clothes washing and toilet flushing. A detailed account of the quality of harvested rain water in Bermuda can be found in Peters *et al.*, 2008.

The Typical House

The availability of water to supplement harvested rain water is a critical issue in Bermuda. The major water producers (including the Bermuda Government) are in the business to meet the demand for this supplementary water, which fluctuates as a function of the status of water storage levels at the typical house. When, for example, the tank at the typical house is more than half full, national demand is at a low, and supplementary water supplies, where needed, are generally dependable. As storage levels start to become depleted at the typical house, national demand for supplementary water accelerates and challenges to the public supply system arise. The status of Bermuda's water resources can, thus, only be understood through knowledge of the characteristics and performance of the water supply system at a typical Bermuda house. A "typical" house being defined here as one that is representative of the majority of homes; in other words, the mode as opposed to the average.

When applying to the Bermuda Government's Planning Department for permission to develop or even to redevelop a property, compliance with the water storage regulations must be demonstrated by submitting roof and water tank dimensions. A frequency distribution analysis of these data demonstrates a very wide spread of roof areas (very few Bermuda houses are alike) with the greatest frequency falling in the 150-167 m^2 range. Combining this information with data derived from aerial photographs, it was determined that a 158-m^2 roof can be considered representative of the "typical house." This translates to a guttered, catchment area of 126 m^2.

Residential rain water tank capacities range from as little as a 14 m^3 in older houses, up to and beyond 220 m^3. A frequency distribution analysis of the planning application data reveals that the majority of tanks are in the 40-110 m^3 range. The average of tank sizes in this range is 62 m^3, which is consistent with the results of a homeowner's water-use survey conducted by the Ministry of Public Works. The modal tank capacity, of those who responded, was 60.5 m^3. Thus, a realistic figure for tank capacity at a "typical house" is considered to be 61.5 m^3.

Water Demand at the Typical House

After evaluating all data available on residential water consumption in Bermuda, it was concluded that 137 l/day per capita is an appropriate conservative value applicable to the typical household. This is compared to a figure of 160 l/day per person used for planning purposes by the department of U.S. Housing and Urban Development; and compared to 140 l/day per person average consumption at 969 residences in the United Kingdom (Russac *et al.*, 1991).

The number of occupants per residential building in 2009 has been calculated at 3.6 persons (2.1 persons per dwelling unit and 1.7 dwelling units per house). Allowing for a correction for unoccupied units (estimated at 10%), conservative round-figure occupancy at the typical Bermuda house can be taken as four persons. Hence, we can assume a water consumption of 548 l/day at the typical house.

Adequacy of Rain Water Harvesting

Based on a long-term average annual rainfall of 1,458 mm, the supply of rain water harvested from the roof of the "typical" Bermuda house is calculated at 438 or 107 l/day per person (after correction for catchment efficiency). Whilst, prior to the 1970s this rate of supply was well matched to the estimated per capita demand at that time of 91 l/day (or 364 l/day per four-person household or 455 l/day per five-person household), it is evident that the typical house today, with a demand of 548 l/day, experiences a deficit in rain water supply of 118 l/day. This figure is consistent with the findings of a homeowner's survey of water-use habits conducted by the Ministry of Public Works. The average quantity of supplementary water purchased by those respondents who buy trucked water, was 8.6 truckloads per year (at 4,100 l per load). This equates to an average of just over 91 l/day of supplementary water per residence (house).

The total (guttered) area of all catchments in Bermuda is 3,583,000 m^2, which can harvest an average of 11,825 m^3/day of rain water. The residential component, of 2,277,000 m^2, captures 7,555 m^3/day or an average of 118 l/day per person. This average value is larger than the 107 l/day per person calculated for the typical house, because of the existence of "mansions" with very large roofs which skew the data. In any case it is evident that, collectively, there is insufficient residential roof area to meet average domestic demand of 137 l/day per person.

To address the shortfall in harvested rain water, the Government of Bermuda and the largest private water company have, over the last four decades, fully developed the fresh groundwater resources and, additionally, have both built reverse osmosis plants to treat sea water. Meanwhile, the expansion of mains networks for distribution of this water has also continued. However, given the high capital and operational cost of sea water desalination, and the fact that the majority of domestic water consumption is for nonpotable purposes, it is considered prudent to balance this approach with the development of low cost sustainable nonpotable sources, as offered by private wells, for example. If a well was to be installed at the "typical" house and, assuming that the water quality was only adequate for toilet flushing, the use of that well water at an estimated rate of 180 l/day would convert a deficit in rain water supply of 118 l/day to a surplus of 62 l/day. This represents an opportunity for Bermuda to maintain a system of water supply based largely on traditional self-sufficiency and sustainability at the level of individual households.

Spreadsheet Modeling of Rain Water Harvesting Systems

A spreadsheet model has been developed to simulate water storage levels in the rain water tanks of Bermuda houses. Inputs include: daily rainfall, catchment area (size), catchment efficiency, tank capacity, and daily water demand. The model incorporates functions which can, respectively, cue the introduction of a conservation factor and the delivery of supplementary water at predetermined storage levels. For the purposes of this study, a water conservation factor was not included, and the trigger for the delivery of supplementary water was when the storage level fell to 10% of full capacity, at which point 8,200 l (two truckloads) were automatically added to the tank (typically two truckloads of water are purchased at a time).

The model calculates daily water tank storage volumes for any chosen combination of roof area, tank capacity, and water consumption. The output includes daily water storage levels, the daily volume of rainfall captured, the number of "truckloads" of water purchased and the daily volume of water lost through overflow.

The model was run with an input of actual daily rainfall for the period from January 1, 2007 to October 31, 2009. This included an extended period of accumulating rainfall deficit which was determined to be once in 20-year drought. A reasonably long time span was important, both to assess the performance of the model over a number of wet and dry climatic cycles, and to overcome the influence of arbitrarily selecting an initial water tank level.

Data from four actual houses were collected for model verification purposes. These included their catchment area, tank capacity, and average number of occupants (converted to water consumption). Also available were precise measurements of water consumption obtained from one house at which a meter had been installed. Verification of the model was accomplished largely through comparison of actual purchases of supplementary water at these houses (recorded in multiples of 4,100-l truckloads) with the number calculated, respectively, by the model. The process was, however, facilitated by the availability of periodic measurements of tank storage levels from one of the houses, which were successfully matched by the model. (A follow-up study should include the placement of water level data-loggers in several water tanks so as to provide continuous records of storage levels.)

The model was used to simulate a variety of scenarios, one of which was that of the "typical house," as described earlier. In this case the output, presented in Figure 6, very effectively demonstrated how a large number of Bermudian households suffer from a deficit of rain water supply relative to their needs. As illustrated, the tank at the typical house is "emptied" on a regular basis and numerous deliveries of supplementary water must be ordered, at an average rate of 118 l/day. Furthermore, it is apparent from the chart that a large proportion of the typical house's tank capacity is permanently unexploited. This is symptomatic of an undersized catchment area, which is out of balance with water consumption.

Optimum Tank Capacity

A key determinant of optimum water storage capacity is the character of rainfall deviations from the long-term average, which is unique to any given geographic location and associated climatic regime. With a relatively even distribution of average monthly rainfall throughout the year in Bermuda,

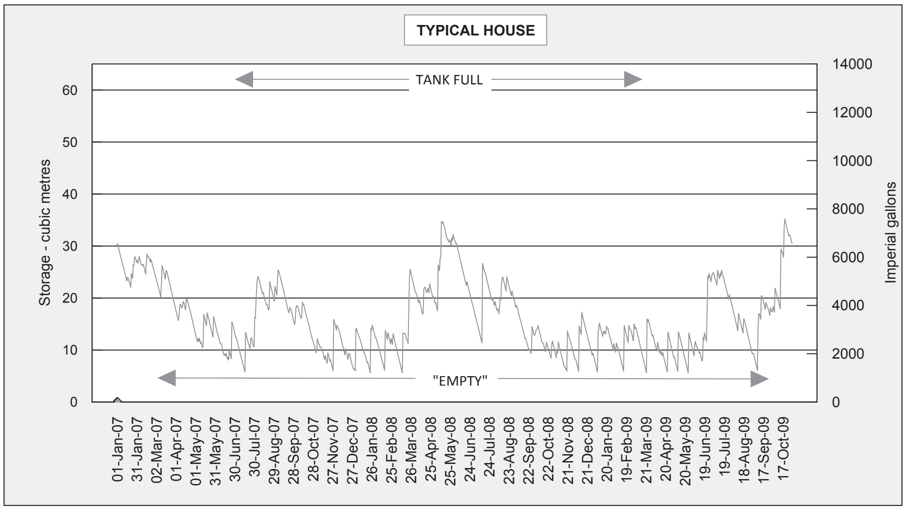

FIGURE 6. Graph of Simulated Water Storage Levels at a Typical Bermuda House. Note the inadequacy of rain water supply, which can be inferred from the multiple intermittent purchases of 8 m^3 of supplementary trucked water, indicated by the vertical lines. Also note that nearly 50% of the tank capacity remains permanently unexploited. A reduction in occupancy from four persons to three persons would result in closer balance between average supply and demand. Near full exploitation of tank capacity would then occur.

seasonal factors play a very minor role. It is the intensities and statistical frequency of random rainfall deficits and surpluses which have most bearing on tank capacity. Clearly, if rainfall data from a region with distinct wet and dry seasons were put into the model, much larger optimum tank sizes would be indicated than those determined, here, for Bermuda.

For the purposes of this study, a tank of optimum capacity was defined as that which never overflows in the case where average consumption exceeds the average supply of harvested rain water; and as that which is never emptied in the case where average supply of harvested rain water exceeds average consumption. In the former case, emptying is unavoidable while in the latter, overflows are unavoidable.

To determine optimum capacity, the spreadsheet model was run for multiple combinations of catchment areas and water consumption. The results for a house with a water consumption of 680 l/day are presented in Figure 7. It reveals that for small catchment areas the optimum tank capacity is small. As catchment areas increase, optimum tank capacity rises and peaks — at the "maximum optimum capacity" — when average supply and average demand are in balance. Beyond that point, optimum tank capacities decrease as catchment areas increase. The results demonstrate that as catchment areas diverge, in either direction, from the balanced size (that which exactly meets demand), they can be matched with increasingly smaller tanks. A deficiency of supply associated with a small roof creates an inexorable downward trend in storage levels and a moderate sized tank is never filled. Conversely, a large roof providing a surplus of water creates a persistent upward trend in storage levels and a moderate sized tank is never emptied. These under-filled and over-filled conditions represent unexploited capacity.

The relationships between tank capacity, catchment area, and water consumption established by modeling are illustrated in Figure 8. They indicate that for rainfall patterns represented over the study period, maximum optimum capacity in Imperial gallons is 7.5 times the catchment area in square feet (or 0.37 $m^3$of storage capacity for each 1 m^2 of catchment area).

Optimum tank capacity varies for a given house (with fixed catchment area) and is a function of occupancy, or demand. Maximum optimum capacity, on the other hand, is fixed for a given house (with fixed catchment area) and need not be exceeded regardless of occupancy, or demand. In other words for a given catchment area at a given geographic location, regardless of demand (as long as it is steady) there is a tank capacity — the "maximum optimum capacity" — which would be no benefit in exceeding.

Optimum Tank Capacities vs. Legislated Tank Capacities

It has been demonstrated that for houses with catchment areas which are out of balance with

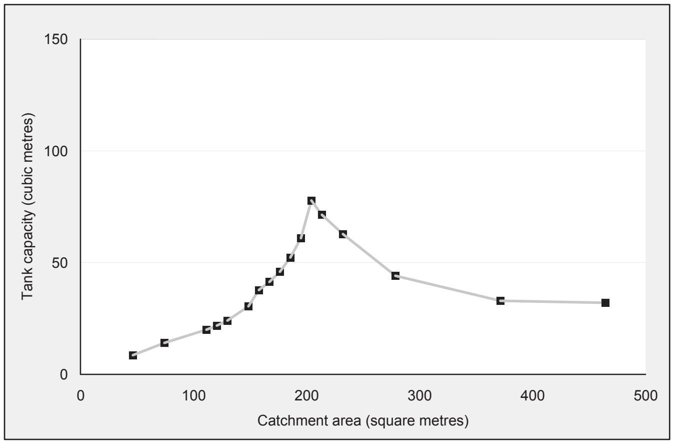

FIGURE 7. Graph of Optimum Tank Capacity *vs.* Catchment Area. Many rain water harvesting scenarios were investigated with a spreadsheet model. This chart illustrates the relationship between optimum tank capacity and catchment area for a consumption of 680 l/day. The peak optimum capacity or "maximum optimum capacity" occurs when rain water supply and consumption are in balance. Decreasing optimum capacities are associated with increasing imbalances (in both directions) between supply and demand.

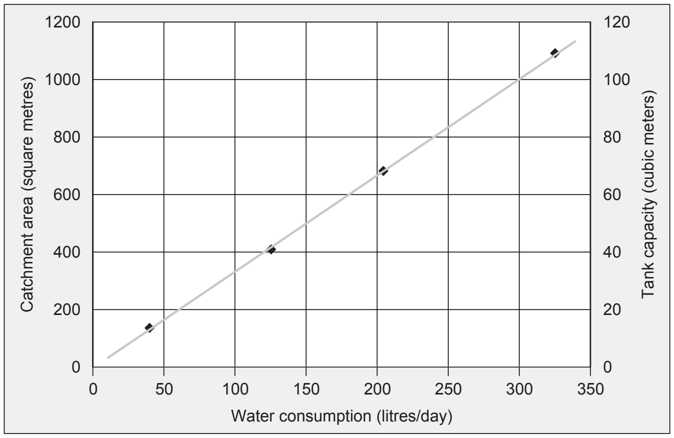

FIGURE 8. Graph of Maximum Optimum Tank Capacity, Catchment Area, and Water Consumption. The relationships, illustrated here, between adequate catchment area, optimum tank capacity, and water consumption were determined by spreadsheet modeling. For a given roof area, the maximum optimum tank capacity can be read from the graph. This is the capacity, which there is no benefit in exceeding regardless of water consumption (based on rainfall data over a three-year study period).

occupancy/demand, there is an optimum tank capacity which is less than the "maximum optimum" capacity. Arguably, the majority of tanks in Bermuda are oversized and are, thus, consistently overfilled or under filled due to imbalance, as is the case with the "typical" house (see Figure 6). A case for having an oversized tank can be made when there is erratic use of water, such as for occasional filling of a swimming pool. However, only under very unusual circumstances need any tank exceed the legislated ratio of 10 times the catchment area in Imperial units (0.49 in metric units) for a traditional Bermudian residence, regardless of occupancy.

To be in balance, a house requires 40 m^2 of catchment area per occupant. Thus, an increase or decrease in occupancy of one person makes a considerable difference to the adequacy of the catchment area and to whether or not it is in balance. In reality, the average occupancy at each house fluctuates. The exact average occupancy of a house can never be known in advance of its construction. For these reasons, it is reasonable to require traditional houses to have a tank of "maximum optimum capacity" which is designed to cater to balanced conditions, i.e., not <0.37 m^3 of storage capacity for each 1 m^2 of catchment area as derived for the study period. More conservatively, a factor of 0.49 (as prescribed by law) could continue to be applied. The adequacy of water supply will then be a function of catchment area alone.

Nontraditional residential buildings, such as multistorey and multiunit developments (e.g., condominiums) have small catchment areas per occupant, typically <28 m^2. They can never approach self-sufficiency by rain water harvesting and are often serviced by large tanks, which are permanently depleted. Modeling suggests that tank capacity need be no more than one-third of the regulation size in these situations and it is, therefore, recommended that substitution of costly excess tank capacity with a well-water flushing system should be permitted, if not required.

Findings in Other Parts of the World

Gould and Nissen-Petersen (1999) proposed four categories of rain water harvesting systems based on user regimes, namely: Occasional, Intermittent, Partial, and Full. In many parts of the world, rain water harvesting is adopted as a means of augmenting existing water supplies and can, therefore, be considered as "Partial." In Bermuda, however, where there is a high reliance on rain water for the majority of domestic applications, the regime can best be described as one of "Full" dependence.

In "Partial" regimes, the demand for rain water, on a supplementary basis, is often exceeded by the supply that is potentially available from roof-top harvesting. In such cases, unlike Bermuda where catchment areas are always maximized, an optimum combination of catchment area and tank capacity can be selected on the basis of cost and reliability (Liaw and Tsai, 2004). The concept described in this report of a tank of "maximum optimum" capacity which never overflows (for houses where demand exceeds rain water supply) or is never emptied (for houses where rain water supply exceeds demand) does, therefore, not have universal application.

CONCLUSIONS

The use of residential roof areas to create catchments is maximized in Bermuda, and yet the quantities of harvested rain water are insufficient to meet collective residential water demand. Currently, an average of 35.5 m^2 of residential roof catchment area is available per person compared to the required amount of 40 m^2, based on average annual rainfall.

Nearly two-thirds of houses in Bermuda do not have a piped supplementary supply or a private well. At the "typical" house with four occupants, the average supply of harvested rain water is 428 l/day which is barely enough rain water to meet the demand of a family of three (at 137 l/day per capita). The deficit has, for the most part, to be made up by deliveries of trucked water. It is recommended that this deficit be offset by supply of nonpotable raw well water for toilet flushing. This would foster self-sufficiency and reduce the demand for "produced" supplementary water which has been treated to a potable standard (at considerable expense by energy-hungry processes).

For a given ordinary residence, there is a water tank capacity — the "maximum optimum capacity" — which there is of no benefit in exceeding regardless of water demand. This capacity is a function of catchment area and the characteristics of temporal rainfall variations associated with Bermuda's climatic regime. Using a simple spreadsheet model with an input of daily rainfall data for a period of nearly three years (which included a prolonged drought), this capacity in m^3 was determined to be 0.37 times the roof catchment area in m^2.

Excessive tank capacity does not substitute for a deficit in the supply of harvested rainfall caused by insufficient catchment area relative to occupancy/water demand. It is recommended that for new high-rise/density housing, the regulations be modified such that construction of oversized tanks, which are destined to remain partially empty, can be replaced by installation of a well for flushing water.

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LITERATURE CITED

Gould, J. and E. Nissen-Petersen, 1999. Rainwater Catchment Systems for Domestic Supply: Design, Construction and Implementation. ITGD Publishing, London.

Government of Bermuda, 1949. Public Health Act, 1949. Laws of Bermuda, Hamilton, Bermuda.

Liaw, C.H. and Y.L. Tsai, 2004. Optimum Storage Volume of Rooftop Rain Water Harvesting Systems for Domestic Use. Journal of the American Water Resources Association 40(4):901–912.

Peters, A.J., K.L. Weidner, and C.L. Howley, 2008. The Chemical Water Quality in Roof-Harvested Water Cisterns in Bermuda. Journal of Water Supply: Research and Technology-AQUA 57:153–163.

Russac, D.A.V., K.R. Rushton, and R.J. Simpson, 1991. Insights Into Domestic Water Consumption From a Metering Trial. Journal of the Institute of Water and Environmental Managers 5:342–351.