BERMUDA’S WATER SUPPLY

PART I

Rain water harvesting in Bermuda

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APPENDIX I

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BERMUDA'S WATER SUPPLY

PART I. Rain water harvesting in Bermuda

1. Supplementary sources and methods of delivery

i. Introduction

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 some 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 ground water from private wells, treated ground water from Government and commercial wells, and treated sea water.

ii. Private wells

19% of households (dwelling units) are supplied with supplementary water from private wells. This water must not be used for potable purposes without treatment and a licence (the Public Health Act, 1949); so it is generally piped, via a separate plumbing system, directly to facilities such as toilets and clothes washers.

Where a residence has a well, demand on harvested rain water is greatly reduced. The 60% of private wells which are brackish (greater than 1200 mg/l total dissolved solids) tend to be used only for toilet flushing, which accounts for between 30% (low flush) and 50% of total household demand. Meanwhile, the 40% which are fresh may be used to supply clothes washers, dish washers and for ablutions as well for toilet flushing, which together account for more than 80% of total household demand. The majority of residences with private wells, whether brackish or fresh, are self sufficient with respect to water supply.

iii. Mains supply

19% of households (dwelling units) are connected to a mains (pipeline) supply [2% have both a private well and mains supply]. The sources of mains water in Bermuda are ground water abstracted from fresh and brackish wells, and sea water abstracted from shoreline wells or deep wells. Water from these sources is treated - usually by reverse osmosis - to remove salt and contaminants, and is then blended together in reservoirs prior to distribution. There is presently the licensed capacity between the Government and private water companies to produce approximately 1.43 million Ig/day (Imperial gallons per day) of treated ground water and 1.57million Ig/day of treated sea water (Part II, Figure 5).

iv. Trucked water

19,560 dwelling units, or 64% of the total, have neither a well nor a mains connection and, therefore, rely on harvested rainfall supplemented by "trucked" water if 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 900 Imperial gallons. Sources of the water which is supplied by truckers are the same as those for mains supply, but sometimes truckers also transfer rain water between tanks, for example, between a tank at a warehouse and a tank at a residence.

Quantities of supplementary water supplied to residences from the various sources are detailed in Part II, *Section* 2 *and are presented in Figure 1b.*

2. Residential rain water harvesting systems

i. Construction

All residences in Bermuda have a roof catchment to collect rain water and an associated storage tank, from which water is supplied to the household via a surface mounted pump and a pressure tank. 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 less than 100 Ig (Imperial gallons) of storage capacity for every ten square feet of guttered roof shall be provided. So, for example, a 1000 square foot roof shall have a guttered area of 800 square feet and an associated storage tank with a capacity of not less 8000 Ig.

Bermuda roofs are constructed of overlapping 1"x12"x18" 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.

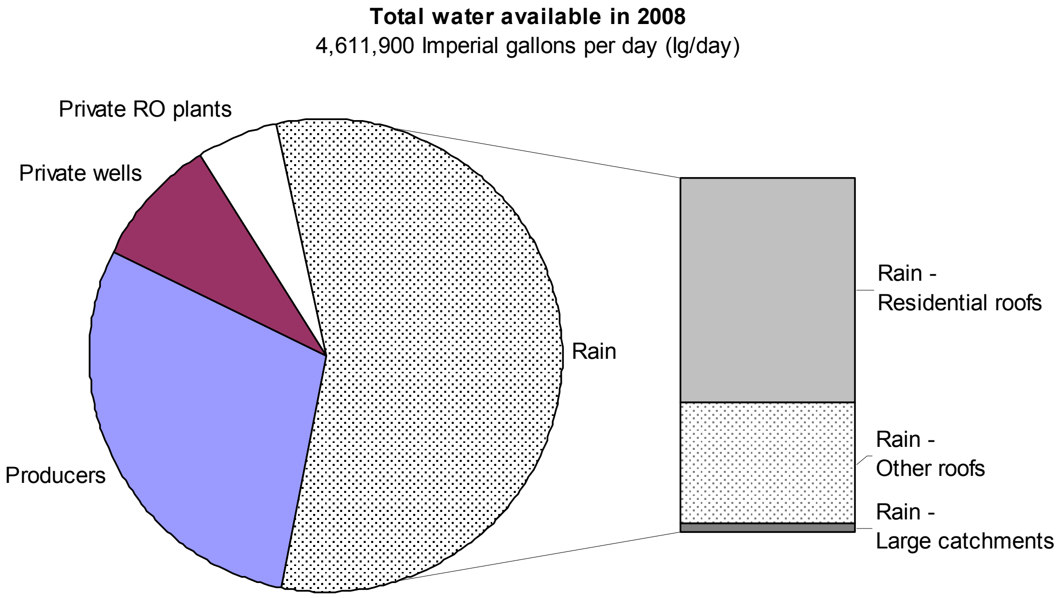
4" x 4" x 18" gutter stones, triangular in cross-section, are mortared end to end near the edge of the roof to create sloping channels or "glides". These divert rain water via a number of vertical "leader" pipes into a tank, which in all but the oldest homes, is located in an excavation below the house (Figure 3). Tank walls are 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 rock wall of the excavation is backfilled with concrete to provide lateral support against the weight of water.

ii. Catchment area

The regulations, which dictate that four fifths, or 80%, of a roof shall be guttered, are largely un-enforced. Bermudians understand the importance of maximising catchment area when building a new house. However, several factors conspire to force gutters inwards away from the edge of the roof. First of all, catchment area is often affected by the presence of obstacles, such as chimneys and elevation changes, which oblige gutters to detour around valuable roof area. The placement of "leader" pipes, which drain rain

Figure 1. Water supplied in 2008 - quantities and sources.

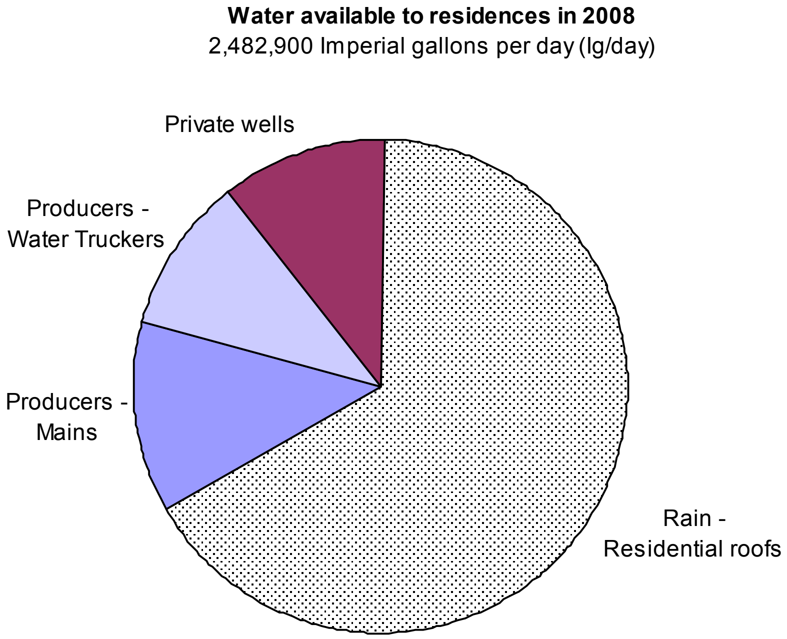
a.



Source	Rate of supply (Ig/day)	Percentage
Producers *	1,348,930	29%
Private wells	409,660	9%
Private RO plants	254,100	6%
Rain - Residential roofs	1,651,500	36%
Rain - Other roofs	887,030	19%
Rain – Large catchments	60,670	1%

Producers * - The Bermuda Government and private water companies which treat ground water and sea water for distribution by mains and water truckers.

b.



Source	Rate of supply (Ig/day)	Percentage
Producers - Mains	307,840	12%
Producers - Truckers	259,320	10%
Private wells	264,220	11%
Rain - Residential roofs	1,651,500	67%

Figure 2. Bermuda roof under construction. Shown are the timber frame and the limestone slates ready for positioning.

Figure 3. Rain water storage tank. 24 ft x 12ft x 8ft (deep), with a capacity of approximately 14,500 Imperial gallons, which is typical of a modern household tank.

Figure 4. Roof catchment. Gutters or "glides" slope down to leader pipes, which transfer rain water to the tank. Approximately 80% of this roof is guttered, which is the typical percentage.

water from the roof into the tank, is another key factor.

Catchment area is very much affected by the gradient of gutters (Figure 4). A gradient is required to move water at an adequate rate to prevent accumulation of leaves and other debris in the channel (some homeowners insert strainers in the top of their leader pipes to trap debris; others let it wash into the tank). Loss of catchment area, associated with the gradient, can be minimised by the provision of numerous leader pipes, so that gutters can be brought back to edge of the roof at multiple locations. It is not uncommon, however, to see the combination of excessive gutter gradients and a scarcity of leader pipes, which result in squandered catchment area. (An additional 6” strip of roof catchment along the outside edge of a 1700 square foot roof will provide approximately 2,000 Imperial gallons of rain water per year).

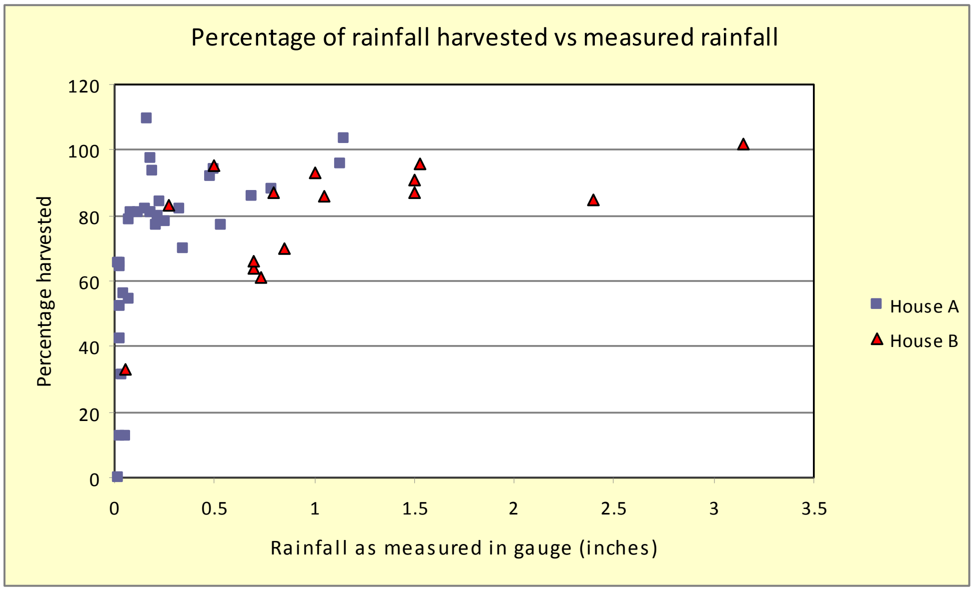
Guttered portions of three houses were measured accurately and found to enclose 80% , 86% and 86% of the total roof area (in plan), respectively. At the last two houses, it was evident that more effort than usual had been made to maximise catchment area at the time of house construction. Following further investigations, involving observations of many Bermuda roofs, including aerial photos, and by counting slates as a means of estimating distances, it was concluded that gutters, on average are placed two feet horizontally from the roof edge (Figure 4). On this basis, perfectly square houses with, for example, 1700 sq.ft (square feet) roof and 2200 sq.ft roof areas, respectively, would achieve 82% and 84% catchment coverage. Roofs which, more realistically, deviate from a perfect square (i.e. with a proportionally longer perimeters), achieve a significantly lower catchment coverage. With these findings in mind, it was concluded that 80% catchment coverage is a reasonable, representative value for Bermuda roofs. Usefully, this is also the minimum value that must be met under the regulations.

iii. Catchment efficiency

Not all rain which falls within the guttered area of a Bermuda roof is transferred to the storage tank. In fact 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 1 year, respectively. The results demonstrate that the catchment efficiency - the depth of rainfall caught as a percentage of that caught in a 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 run-off will occur. Evaporation is another loss which will reduce and delay the onset of run-off, particularly in the summer. Finally, there is wind, which at exposed locations has the potential to significantly diminish catchment efficiency.

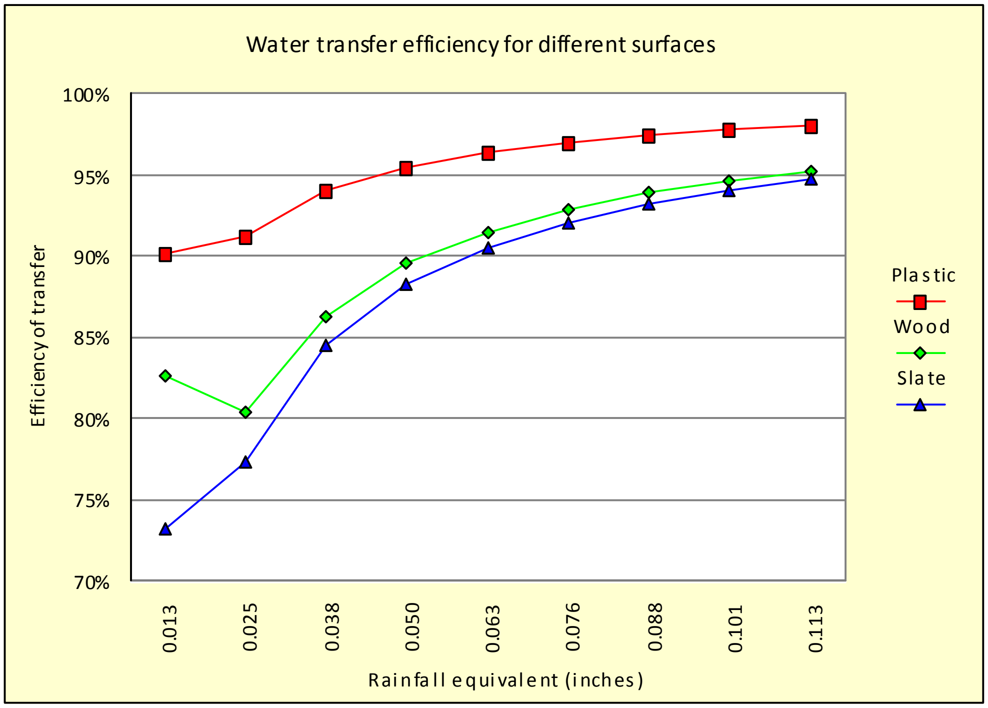
Studies of rain water catchments must consider, and document, the source of data against which efficiencies are being measured. The depth of rainfall collected in a traditional 4” diameter rain gauge, cannot necessarily be scaled up to represent the depth of rain falling on a roof. Apart from dimensional differences, there is the question of differences in elevation and exposure (4” gauges used for this study were elevated at approximately 6ft from the ground). Analysis of Bermuda rainfall data, by Macky (1957), revealed that placement of gauges at different elevations, at the same location, produced significant

Figure 5. Catchment efficiency of two Bermuda roofs.



The depth of rainfall (over the catchment area) which was transferred to each water tank expressed as a percentage of the depth of rainfall measured in a 4” rain gauge. Efficiency of the catchments, based on the total depth of rainfall caught on the roof, relative to the total depth caught in the gauge, over the respective study periods, was 87% at each house.

Figure 6. The effect of materials on catchment efficiency.



The efficiency of transfer of water sprayed onto sloping surfaces constructed of plastic, wood and slate (Bermuda limestone). Collected water was directed from each surface via a tube into a container below. Quantities of water applied to the surfaces and those collected were measured by weight (grams) and converted to depth.

disparities in the measured rainfall. Nonetheless, we still need to know the efficiency of the Bermuda roof relative to the traditional rain gauge, since the latter is the ongoing source of official rainfall data in Bermuda.

In this study, it was found that the relationship between rainfall caught in a 4" gauge and rainfall caught on a roof (and delivered into the tank) was generally consistent with anticipated efficiency of a roof catchment. At both of the houses studied, the results showed that the cumulative depth of rainfall caught on the roof catchments amounted to 87% of that collected by the rain gauge. There were considerable variations in efficiency between rainfall events, even between those of equal magnitude (Figure 5). Influential factors included the character of the rainfall (such as its intensity), antecedent roof moisture conditions, temperature and wind. Given this complexity, it was concluded that making efficiency corrections for each rainfall event, particularly short ones, is not feasible. For the purpose of long-term studies (6 months or more), it is justifiable to apply a slightly conservative value of 85% efficiency to correct daily rainfall totals.

iv. Roof configuration and materials

Physical factors, which have a bearing on roof catch efficiency, are roof configuration and materials. Roofs can be "hip" or "gable end" in configuration. Hip roofs slope down on all sides of the house to a guttered edge (Figure 4); whereas a roof with a gable end terminates at a vertical wall. Sometimes there is a decorative lip, which retains rain water on the gable end, but often there is nothing to prevent wind from driving rain over the edge.

The effect of materials is principally a function of porosity and roughness. An investigation into the efficiency of three different test surfaces was undertaken as part of this study. The results show that Bermuda slate, with the same coatings as is traditionally applied to a Bermuda roof, is marginally less efficient than painted plywood but significantly less efficient than plastic (Figure 6). As the addition of water (from a spray bottle) increased, up to the rainfall equivalent of 0.1 of an inch, so did the efficiency of the slate, which ranged from 73% up to 95%, with an average of 88%. Beyond 0.1 inches (rainfall equivalent) any increases in efficiency were minimal. These efficiencies, measured under controlled conditions, are high compared with data from actual roofs, which for rainfalls up to 0.1 of an inch, exhibited extremely scattered results in the range of 0% to 80%, with an average of only 49% efficiency. Thus, although a contribution to catchment inefficiency by surface materials was demonstrated by these tests, other factors attributable to the interaction of meteorological conditions with the roof, are apparently of greater consequence.

v. 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. In fact, for a couple of centuries, or more, it probably was of superior quality relative to water available for human consumption elsewhere in the world. Today, despite the fact that in most western countries use of raw rain water for potable purposes is not deemed an acceptable option, houses in Bermuda continue to be built with plumbing systems which supply rain water directly to kitchen sinks without 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 are not routinely cleaned. Hence, the growing usage 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 lion's 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 contribution of harvested rain water in the context of Bermuda's total water requirements is discussed and quantified in Part II.

3. The typical house

i. Introduction

The success of rain water harvesting with roof catchments, in Bermuda, has been as much by chance, as by good planning. Up until the middle of the last century, a typical house comprised a modest one storey building with a roof area that happened to be sufficient to provide an adequate supply of water, relative to domestic demand, in an average rainfall year. Towards the end of the twentieth century, land prices drove an accelerating rate of two storey condominium and apartment block construction, in addition to the subdivision of traditional houses into apartments. Average roof catchment area per dwelling unit decreased, while, at the same time, per capita demand for water rose – from 20 Ig/day (Imperial gallons per day) per person in the 1950s (Macky 1957) up to approximately 30 Ig/day per person today (see later). Over one generation or so, there was a transition from water self-sufficiency to water deficiency at many residences.

As "new builds" have increasingly outpaced population growth over the last few decades the trend of declining roof areas per dwelling unit has been counteracted by decreasing average occupancy levels per unit. The typical house certainly remains in a state of deficit with respect to harvested rain water, but the net balance between supply and demand across all residences, in Bermuda, is probably no longer worsening and may be improving. This is discussed in more detail in Part II, Section.5.ii.

The availability of water to supplement harvested rain is a critical issue in Bermuda. The major water producers (including the Bermuda Government) are in 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 water supplies are generally reliable. 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 – the mode as opposed to the average. This is discussed in more depth below.

Figure 7. Housing statistics and rain water harvesting data – 2008

Population	64,000
All buildings	19,000
Residential buildings	17,356
Houses	17,250
Condos	106
Dwelling units (valuation numbers)	30,535
Average dwelling units per house	1.7
Average occupancy per dwelling unit	2.1

Note that average per capita water consumption at home is estimated at 30 Ig/day which in a year of normal rainfall, such as 2008, can be met by 450 sq.ft of catchment area (per capita).

The average house has 3.6 occupants who consume an average 108 Ig/day. This can be met in a year of normal rainfall by 1620 sq.ft of catchment, area which is more than the "typical" and average residential roof areas.

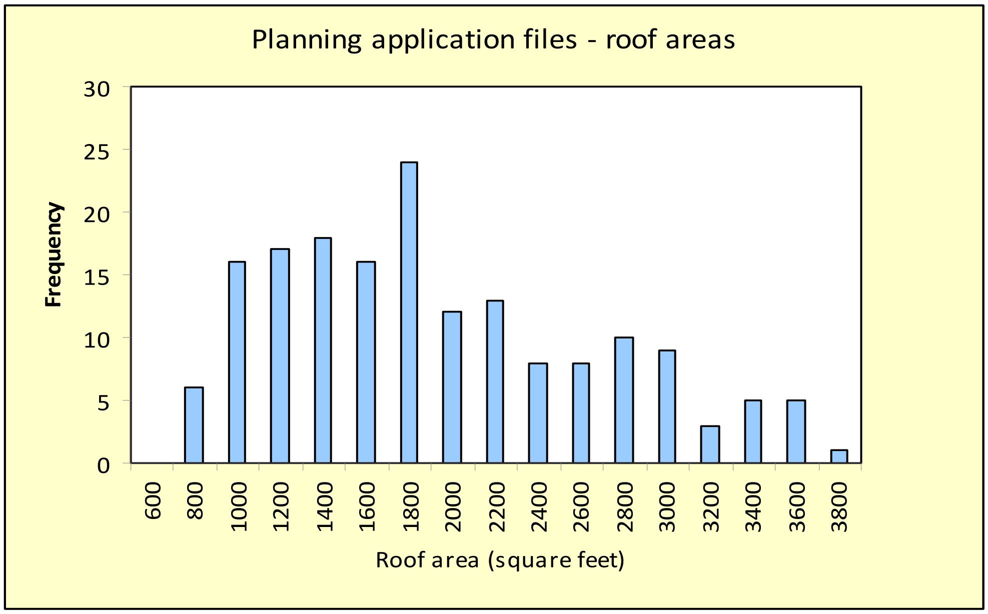
	Catchment area sq.ft	Catchment area sq.ft/person	Harvested rain Ig/day	Harvested rain Ig/day/person
All buildings (roofs)	37,630,000		2,538,500	
Active ground level catchments	899,000		60,600	
TOTAL	38,528,000	602	2,599,000	41
Residential buildings only (roofs)	24,480,000	382	1,660,440	26

	Occupancy	Catchment area sq.ft	Catchment area sq.ft/person	Harvested rain Ig/day	Harvested rain Ig/day/person	Balance* Ig/day
Pembroke sample area	4.1	1085	262	74	18	-49
Warwick sample area	4.8	1501	316	102	21	-41
Tuckers' Town sample area	1.6	3117	2009	211	136	+163
"Typical house"	4	1360	340	92	23	-28
Study "House 1"	3	1645	548	111	37	+21
Study "House 2"	4.5	1860	413	126	28	-14
Study "House 3"	8	3000	375	203	25	-37
Condominium (sample)	23	6270	273	425	18	-265

* Balance = harvested rainfall less water consumption per residential building.

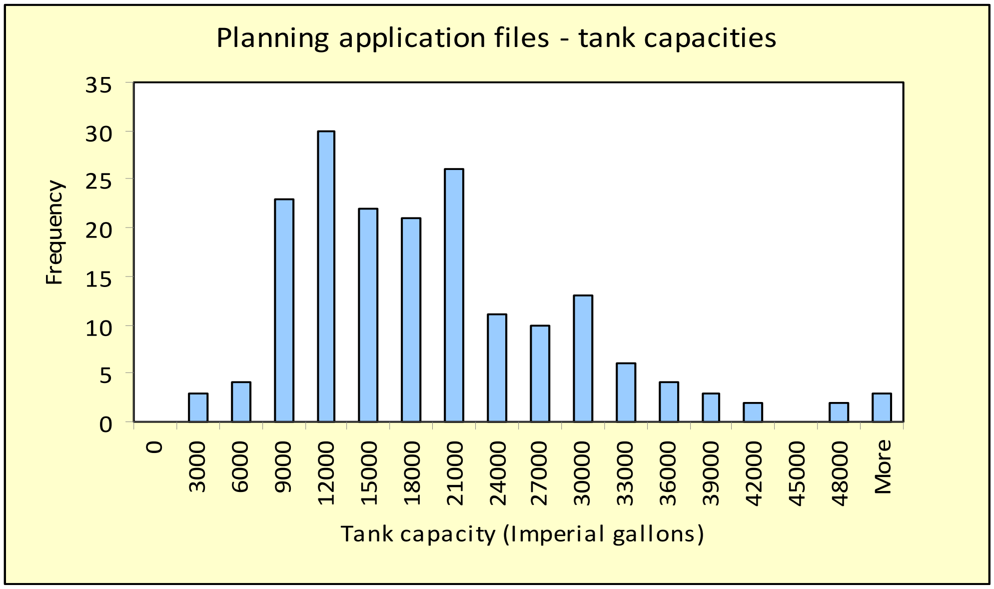
Information on roof areas was provided by the Lands, Building and Surveys department of the Ministry of Works & Engineering, from the Bermuda Topographic Map Database

Figure 8. Roof areas from Planning Department application files.



Roof area data from 182 residential applications for development. It was determined from this information and other data (see Figure 10) that the roof area of the typical Bermuda house is 1700 square feet. This equates to a catchment area of 1360 square feet.

Figure 9. Tank capacities from Planning Department application files.



Tank capacity data from 182 residential applications for development. The majority of these tanks are in the 9000 to 24000 Imperial gallon range. It was determined from this information and from a survey of homeowners conducted by the Ministry of Works & Engineering that the typical Bermuda house has a tank capacity of 13,500 Imperial gallons.

ii. Roof area

Raw roof area data was provided from the Bermuda Topographic Map Database by the Lands, Building and Surveys Department of the Ministry of Works & Engineering.

The average roof area of all approximately 19000 buildings in Bermuda is 2470 sq.ft (square feet) This includes many large institutional and commercial buildings, but excludes buildings which do not have an address point and which are very small (e.g sheds and detached garages). So it is certain that, even though many houses now have roof areas greater than 2470 sq.ft, the typical house roof area must be substantially smaller than that figure. (There are no attributes in the Bermuda topographic map database that can be used to distinguish residential from commercial buildings).

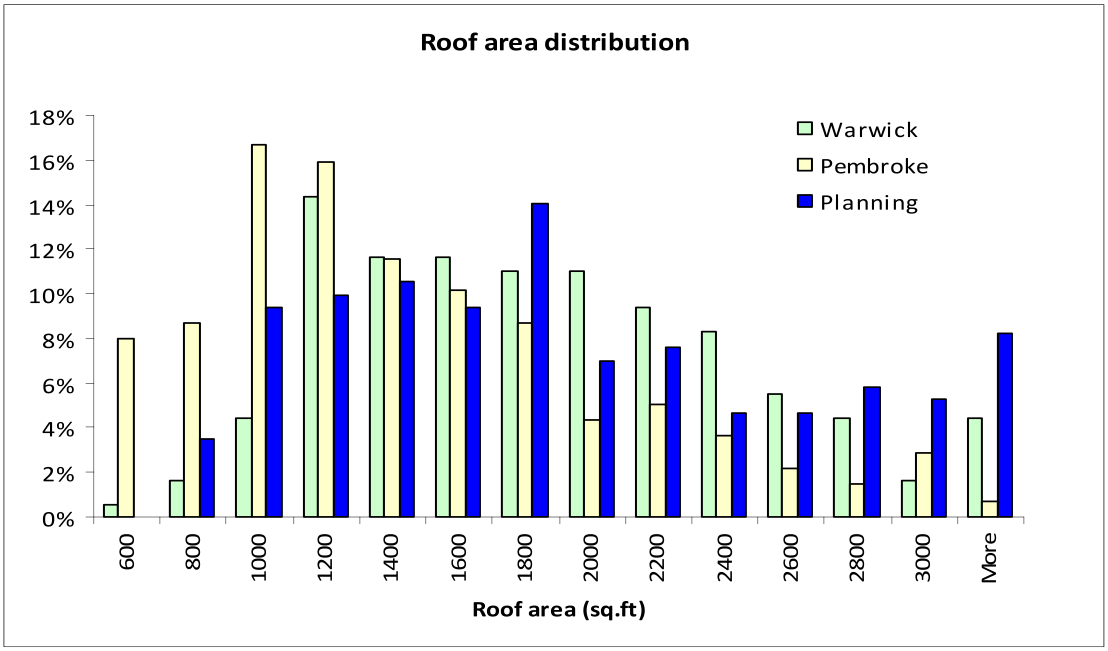
Certain parts of Bermuda are known to be almost entirely residential and can be isolated for analysis. Three such areas of Bermuda, representing high density, medium density and low density housing were identified* in Pembroke, Warwick and St George's (Tucker's Town) for the purposes of this study (* by John Arthur, Lands, Building and Surveys Department of the Ministry of Works & Engineering). Average roof sizes in these three sample areas were 1356, 1884 and 3897 sq.ft (square feet), respectively. The very large size and low number of houses in the lowest density sample area, lead to its exclusion from the process of identifying typical house parameters. Consequently, it was concluded that the typical roof area lies between 1356 and 1884 sq.ft, but probably at the higher end of this range, because medium density, middle income housing is dominant in Bermuda.

Another useful source of data on roof areas, and tank capacities, is the Ministry of the Environment's (Planning Department) development application files. When applying for permission to develop, or even to re-develop, a property, compliance with the water storage regulations must be demonstrated by the submission of roof and water tank dimensions. Such applications represent a cross section of new houses to be built and old houses to be renovated. A frequency distribution analysis of data from 182 residential applications, reveals a very wide spread of roof areas (very few Bermuda houses are alike) with the greatest frequency falling in the 1600 to 1800 sq.ft range (Figure 8). Combining this information with that from the topographic map database (Figure 10), it was determined that a 1700 sq.ft roof area is representative of the "typical house". This equates to a catchment area of 1360 sq.ft.

iii. Tank capacity

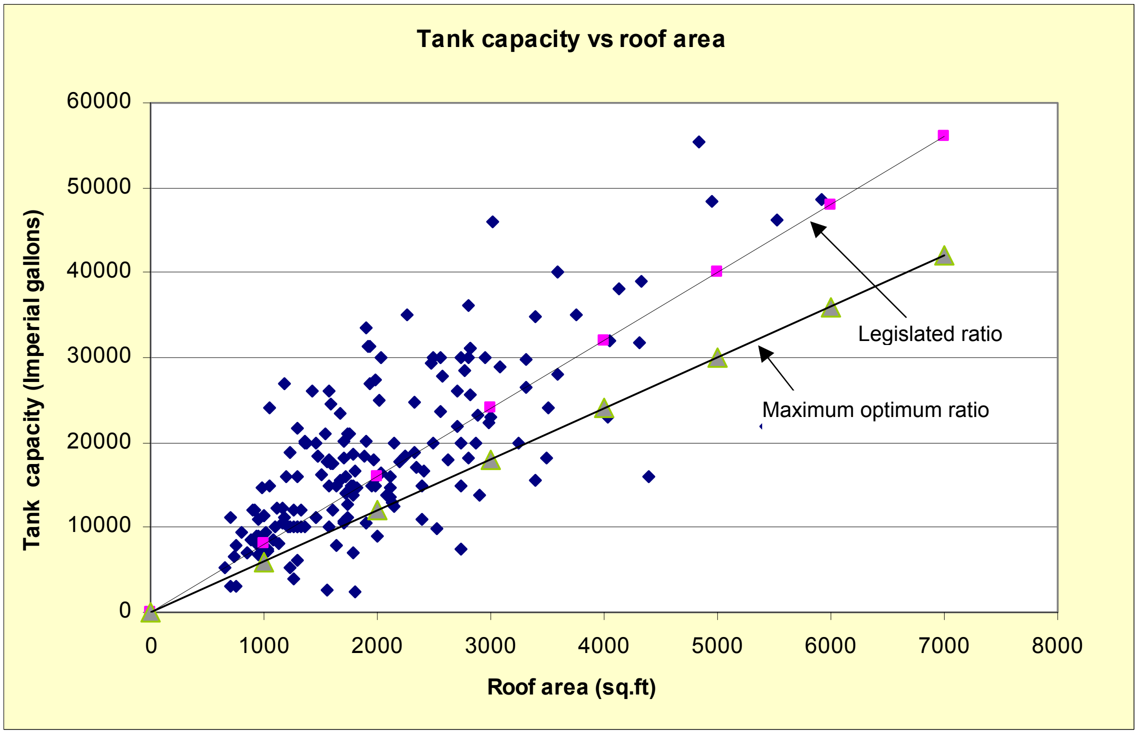
Residential rain water tank capacities range from as little as a few thousand Ig (Imperial gallons) up to and beyond 50,000 Ig. A frequency distribution analysis of the planning application data reveals that the majority of tanks are in the 9,000 to 24,000 Ig range (Figure 9). The average of tank sizes in this range is 13,600 Ig., which is consistent with the results of a homeowners water-use survey conducted by the Ministry of Works & Engineering. The average tank capacity, of those who responded, was 13,300 Ig. Thus, it was determined, for the purposes of this study, that a realistic figure for tank capacity at a "typical house" is 13,500 Ig.

Figure 10. Roof area data from sample areas and from Planning Department files.



Data from the Planning files and from sample areas in Warwick and Pembroke, identified and analysed by the Ministry of Works & Engineering, Land Survey Section using the Bermuda Topographic Map Database.

Figure 11. Tank capacity versus roof area from Planning Department files.



Data from the Planning files for residential and non-residential development applications. The majority of tank capacities exceed an optimum maximum capacity relative to roof area as determined by this study but also exceed that required by the Water Storage regulations. It is contended that such tanks have large volumes of unexploited capacity – being, persistently, either full to overflowing or depleted.

The ratio of the tank capacity of 13,500 Ig to the catchment area of 1360 sq.ft at the typical Bermuda house is close to 10 Imperial gallons per square foot, which corresponds to the legislated ratio, but as will be discussed later, it is rarely an optimum ratio.

iv. Water demand (at home)

All water delivered to residences in Bermuda is supplementary to harvested rain water, the consumption of which is not readily measurable. Nonetheless, data are available from some condominiums where water is drawn from communal rain water tanks and the supply to each unit is metered. Also, very early in this study, meters were installed in a traditional Bermuda house to determine consumption averaged over many years. Finally, spreadsheet models of domestic water supply systems were successfully verified on the basis of assumptions made about per capita consumption (see later).

The product of evaluating all of the information available, was a conservative modal value for water consumption of 30 Ig/day per occupant at the typical house where there is no well or mains connection. This is compared to a figure of 42 U.S.g/day (35 Ig/day) per person used for planning purposes by the department of U.S. Housing and Urban Development (HUD); and compared to 31 Ig/day per person average consumption at 969 residences in the UK (Russac et al, 1991)

The number of occupants per residential building, calculated from the 2000 census and GIS data in the three sample areas (described in Section 3.ii), are 4.1, 4.8 and 1.6. On the other hand, data from the Land Valuation Department for 2009 combined with estimates of the current total population, suggest an average national occupancy of 3.5 persons per house (2.1 persons per dwelling unit and 1.7 dwelling units per house). Taking all of this into consideration, and allowing for a correction for unoccupied units (estimated at 10%), a conservative modal value for a round-figure occupancy at the typical Bermuda house is considered to be 4 persons.

Total average water consumption at the typical house is, thus, estimated to be 120 Ig/day (4 persons x 30 Ig/day per person).

v. Adequacy of rain water harvesting

Based on a long-term average annual rainfall of 57.7”, the supply of rainwater harvested from the roof of the typical Bermuda house is 94 Ig/day or 23.5 Ig/day per person (after correction for catchment efficiency). Whilst, prior to the 1970s this rate of supply was well matched to a per capita demand of 20 Ig/day (*80 Ig/day* per 4 person household or 100 Ig/day per 5 person household), it is concluded that the typical house today, with a demand of 120 Ig/day, experiences a deficit in rain water supply of 26 Ig/day. This figure is consistent with the findings of a homeowner’s survey of water use habits conducted by the Ministry of Works & Engineering. The average quantity of supplementary water purchased by those respondents, who buy trucked water, was 8.6 truck loads per year (at 900 Ig per load). This equates to an average of just over 20 Ig/day of supplementary water per residence (house).

4. Spreadsheet modelling of rain water harvesting systems

i. Model input.

A spreadsheet model has been developed to simulate water storage levels in the rain water tanks of Bermuda houses. Input includes: daily rainfall, catchment area (size), catchment efficiency, tank capacity, and water demand. The model incorporates options to cause the model to automatically respond to pre-determined storage levels with the introduction of a water conservation factor and with the delivery of supplementary water, respectively. For the purposes of this study, a water conservation factor was not included, and the trigger for purchase of water was when storage fell to 10% of full capacity, at which point 1800 Ig (2 truck loads) was delivered to the tank.

The model generates daily water tank storage volumes for any chosen combination of roof area, tank capacity and water consumption. The output includes a chart of storage levels, the average daily rate of rainfall captured, the number of "truck loads" of water purchased and the average daily rate of overflow.

Data for model input, gathered from several houses, included: roof area, tank capacity, water consumption (or number of occupants), records of tank storage levels and of supplementary water purchases. Verification was achieved through comparison of actual purchases of supplementary water (usually measured in multiples of 900 Imp. gallons truck loads) with that calculated by the model. Verification was enhanced where periodic observations of tank storage levels were made by the home owners (House 1 owned by Ian Saunders). Other valuable information included precise measurements of water consumption obtained through the installation of meters by the owner, at one of the houses (House 2, owned by Clarkston Trott).

Models were run with an input of actual daily rainfall for the period from 1st January 2007 to 31st October 2009. 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 initial water tank level. It was found that this initial level can markedly influence the results over the first 6 months, but beyond that the model output is unaffected. For the purpose of this study, 50% of total tank capacity was chosen as the initial storage volume in all cases.

The study period experienced an annualised average rainfall of 57.1", compared to a long term average for Bermuda of 57.7". It included an extended period of rainfall deficit, which according to rainfall statistics (see later) and in terms of the number of households affected by water shortages at the time, qualified as a genuine serious "drought". This period began in late August 2008 and progressively intensified between February and May 2009.

ii. Verification and case studies

The three houses used as case studies for model verification, cover a range from being permanently self sufficient to being heavily dependent on supplementary trucked water deliveries. None of them had a private well nor a mains connection. Parameter values for the three houses are presented in Figure 12 as is the output of water storage levels at each house throughout the study period. The findings are summarised below:

House 1*:* The catchment area, in this case, exceeds the "balanced" size, the significance of which will be explained more fully later, but is that which just provides sufficient harvested rain water to meet household demand. Simulated water storage levels fluctuated within a narrow range at near-full to overflowing levels (Figure 12). There was never any risk of having to purchase supplementary water and the average rate of overflow was 28 Ig/day. Even during the relatively severe drought experienced within the study period, unexploited tank capacity is evident. Verification of the model output was achieved through the homeowner's record of occasional noteworthy maximum and minimum storage levels. In general, the model output matched the homeowners records very well (Figure 12).

House 2*:* The catchment area, in this case, is just below the balanced size, at which complete self sufficiency might be possible. There is a net long-term drain on tank storage levels, which is offset by the occasional purchase of supplementary water. However, the rate of depletion is slow, and therefore the tank capacity is almost fully utilized (Figure 12). Verification of the model at this house was based on the homeowners record of supplementary water purchased over 29 months within the study period. The model generated a demand of 10 loads over this period, as compared to 13 loads which were actually bought. A record of metered water consumption (meters were installed by the owner for this study) made it possible to input an accurate figure for household water consumption of 140 Ig/day (28 Ig/day per person).

House 3*:* This sizeable house has a tank with a very large capacity but, being divided into 3 dwelling units (apartments), the roof area per occupant is similar to House 2 . However, with more occupants than House 2, the total gallon per day deficit is larger. Simulated water storage levels showed a persistent downward trend with nearly one half of the tank capacity, not being utilized (Figure 12). Verification, as with House 2, was based on a record of purchases of supplementary water, in this case, over a 7 month period in 2009. The model generated a demand of 22 truck loads of water as compared to 26 loads which were actually bought.

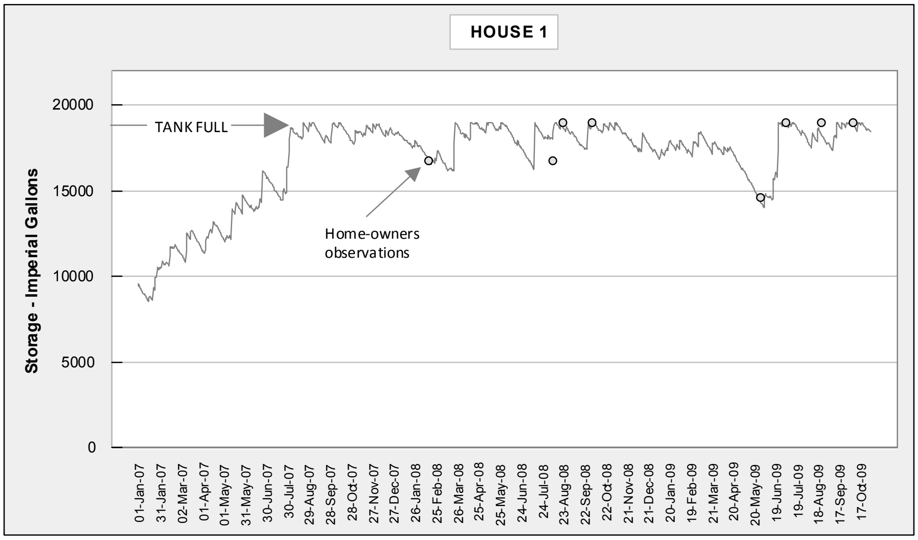
It should be noted that "tweaking" of model input parameters, such as catchment efficiency or the trigger point for water purchases, by just a few percent can readily produce perfect correspondence between the model output and actual records. However, the degree of correspondence achieved without "fine tuning", is believed to constitute adequate verification of the model.

iii. Other simulations

Since condominiums commonly have catchment sizes, relative to occupancy, which are below the range of traditional houses, as represented above, the model was run with input data from an actual condominium. It was also run with parameters from the hypothetical "typical house" as defined earlier.

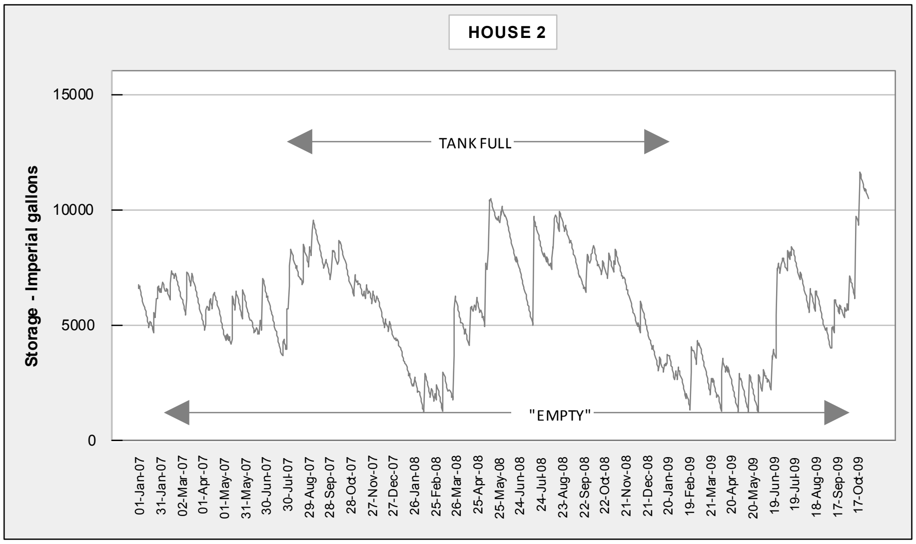
Condominium*:* This analysis was based on roof area, tank capacity and occupancy data for an actual condominium. The output presented in Figure 13.a illustrates the persistent state of depletion of water reserves and the related high demand for supplementary water

Figure 12. Simulation of tank storage levels at three houses using a spread sheet model.



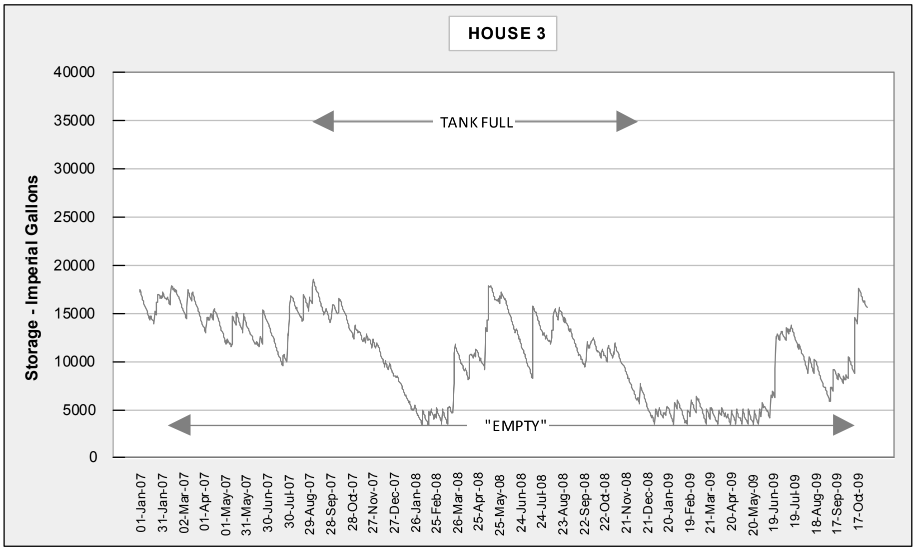
HOUSE 1

CA	1645	sq.ft
TC	19,000	Ig
DA	80	Ig/day
RS	109	Ig/day
TC/CA	12.3	
CApp	517	sq.ft
BCA	1200	sq.ft
MOTC	12,300	sq.ft
OTC	4800	Ig
OF	21	Ig/day
SS	0	Ig/day
$TC	59,000	$
$MOTC	44,000	$



HOUSE 2

CA	1860	sq.ft
TC	13,500	Ig
DA	140	Ig/day
RS	131	Ig/day
TC/CA	7.3	
CApp	372	sq.ft
BCA	2100	sq.ft
MOTC	13,950	sq.ft
OTC	11,500	Ig
OF	0	Ig/day
SS	12	Ig/day
$TC	47,000	$
$MOTC	48,000	$



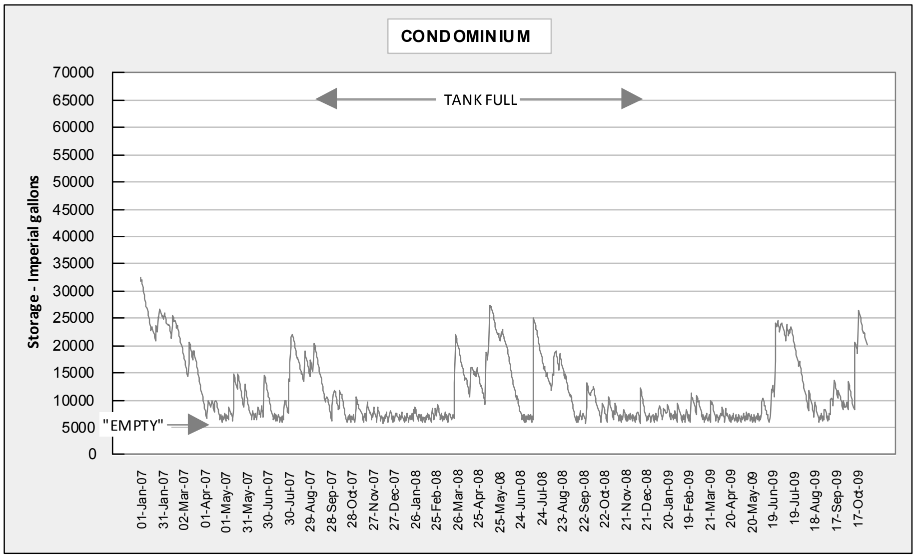
HOUSE 3

CA	3000	sq.ft
TC	35,000	Ig
DA	240	Ig/day
RS	212	Ig/day
TC/CA	11.7	
CApp	375	sq.ft
BCA	3600	sq.ft
MOTC	22,500	sq.ft
OTC	15,700	Ig
OF	0	Ig/day
SS	26	Ig/day
$TC	88,000	$
$MOTC	67,000	$

Parameter key: **CA** - Catchment area; **TC** - Tank capacity; **DA** - Water demand; **RS** - Rain water supplied; **Capp** - Catchment area per occupant; **BCA** - Balanced catchment area to meet demand; **MOTC** – Maximum optimum tank capacity; **OTC** - Optimum tank capacity; **OF** - average rate of overflow; **SS** - Supplementary water supplied; **$TC** - cost of existing tank; **$MOTC** - cost of max optimum tank. **"EMPTY"** – 10% of full capacity. It is assumed that supplementary water is bought at about this level.

Figure 13. Simulation of tank storage levels at a condominium and at the "typical house" using a spread sheet model.

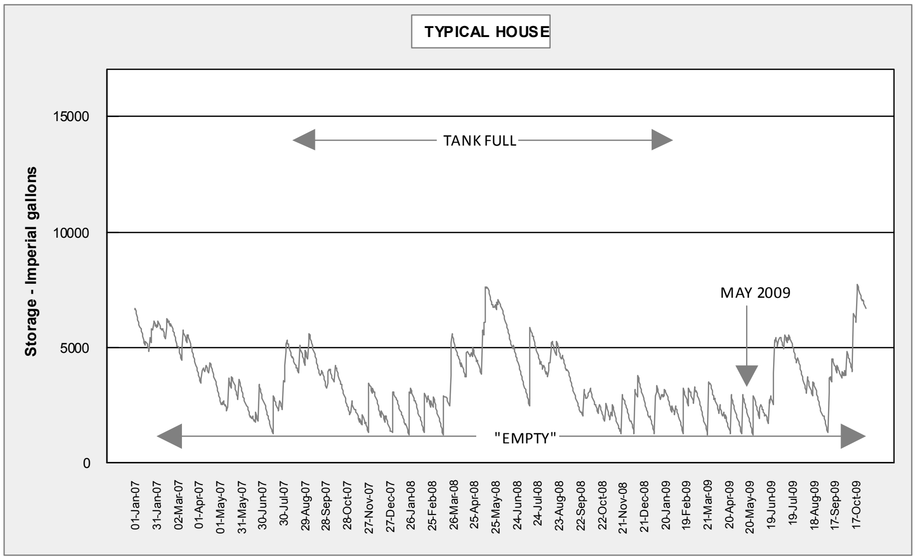
a.



CA	6271	sq.ft
TC	65,100	Ig
DA	700	Ig/day
RS	471	Ig/day
TC/CA	10.4	
CApp	272	sq.ft
BCA	10,500	sq.ft
MOTC	47,030	sq.ft
OTC	27,000	Ig
OF	0	Ig/day
SS	271	Ig/day
$TC	139,000	$
$MOTC	109,900	$

Simulated tank storage levels at this condominium indicate that the tank, which is of regulation size relative to the roof area, is persistently depleted. The small roof area per occupant of 272 square feet provides insufficient water to anywhere near meet demand. Total water consumption is 700 Ig/day compares to an average supply of harvested rain water of 471 Ig/day. More than 50% of the tank capacity is permanently unexploited over the study period which experienced average annualised rainfall.

b.



CA	1360	sq.ft
TC	13,500	Ig
DA	120	Ig/day
RS	94	Ig/day
TC/CA	9.9	
CApp	340	sq.ft
BCA	1800	sq.ft
MOTC	10,200	sq.ft
OTC	7800	Ig
OF	0	Ig/day
SS	26	Ig/day
$TC	47,000	$
$MOTC	41,000	$

Simulated tank storage levels at the "typical house" indicate that a roof catchment area of 340 square feet per occupant does not meet demand. Storage levels are depleted to point where water has to be purchased over extended periods, particularly leading up to the drought of May 2009. Almost 50% of the tank capacity is unexploited (i.e. never occupied by water) despite normal episodes of above average rainfall during the study period.

Parameter key: **CA** - Catchment area; **TC** - Tank capacity; **DA** - Water demand; **RS** - Rain water supplied; **Capp** - Catchment area per occupant; **BCA** - Balanced catchment area to meet demand; **MOTC** – Maximum optimum tank capacity; **OTC** - Optimum tank capacity; **OF** - average rate of overflow; **SS** - Supplementary water supplied; **$TC** - cost of existing tank; **$MOTC** - cost of max optimum tank. **"EMPTY"** – 10% of full capacity. It is assumed that supplementary water is bought at about this level.

(supplied by pipeline in this case). According to the model, the average requirement for supplementary water during the study period was 217 Ig/day. Despite the tank being of regulation capacity, considerable under-exploitation of storage space is evident. This highlights the futility of a constructing a large tank in the absence of adequate catchment area.

Typical House: The results of simulating water storage levels at the "typical house", are presented in Figure 13.b. The inadequacy of rain water supply is evident from the quantity of supplementary water purchases calculated by the model, averaging 26 Ig/day. This substantial deficit of 9,450 Ig (9.5 truck loads) per year is approximately equivalent to the consumption by one person.

It is apparent that a large proportion of the typical house's tank capacity is permanently unexploited, which reflects the fact that the catchment area is small and out-of-balance with water consumption.

iv. Model verification against water trucking data

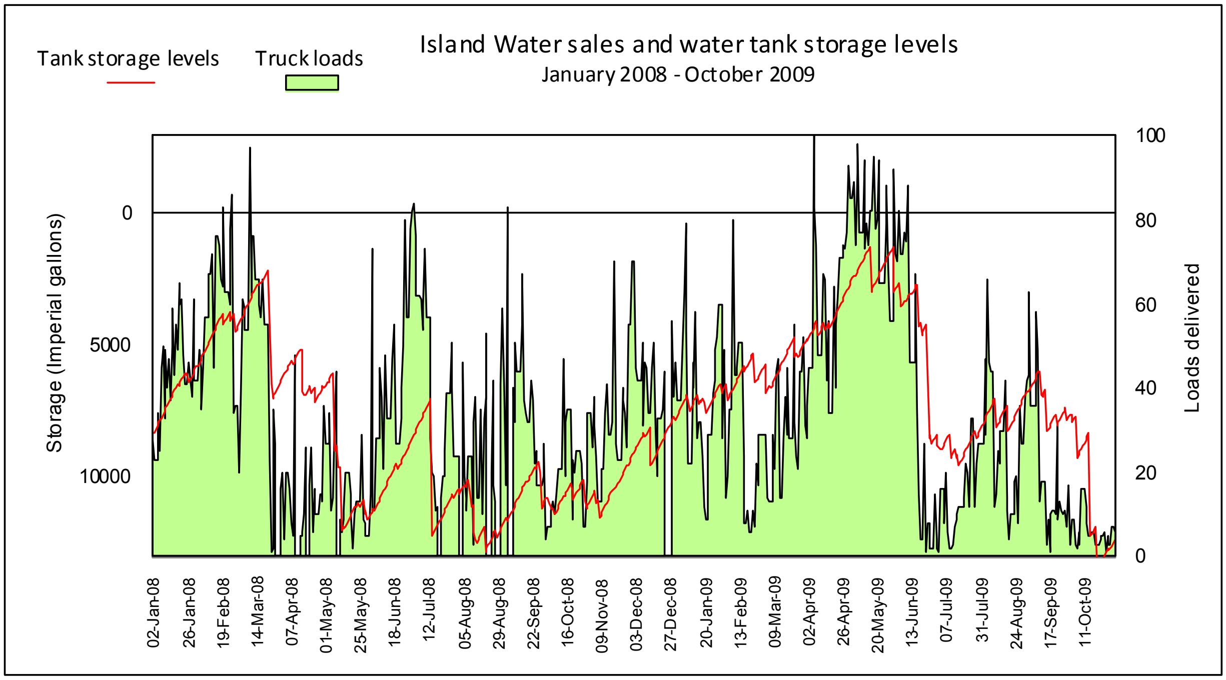
Daily deliveries of trucked water by Island Water trucks, and one independent trucker who is supplied by Island Water, are presented in Figure 14 (Data provided by Ron Smith, Island Water). Steady increases in the number of deliveries correspond to prolonged periods of rainfall deficit. On the other hand, precipitous declines in deliveries coincide with heavy rainfall events.

Many houses with roof areas, tank capacities and occupancies similar to the "typical house", defined above, will all face water shortages at about the same time. Fortunately, acceleration of demand is moderated by a large spread in the range of roof areas and tank capacities in Bermuda (Figure 11). Moreover, a significant number of households, similar to "House 1" (see above), remain self-sufficient throughout even the most severe drought due to large catchment areas relative to occupancy.

In periods of prolonged, intense rainfall deficit, an early rise in supplementary water demand is driven by "typical" houses with small catchment areas. Subsequent demand is driven by these same houses, which continue re-order water, plus houses with larger roof areas per occupant, which are beginning to experience water shortages for the first time.

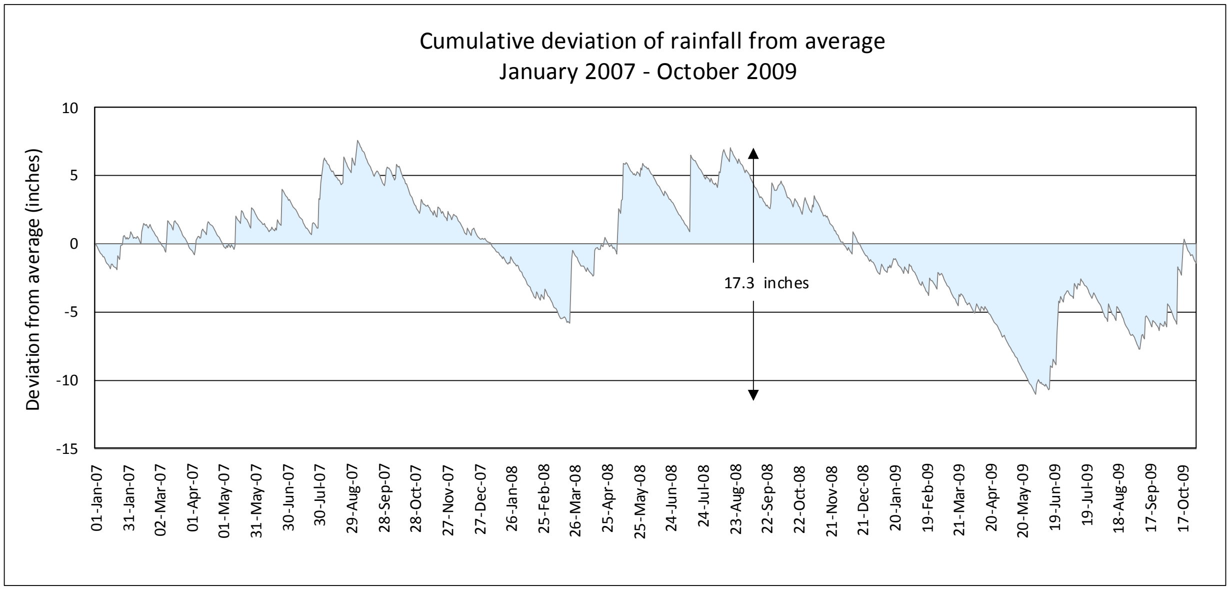
Figure 14 also includes a plot, generated by the spreadsheet model, of tank storage levels in a house with a large roof area and an adequate tank capacity. This is not the "typical house" but it better reflects an "across the board" pattern of increasing demand as a drought intensifies. The correlation with sales of trucked water is quite striking, and so contributes to model verification and supports its real world applicability. The potential of the model is demonstrated, as a tool to assess drought severity and continuously track the national status of household tank storage levels, warning of impending spikes in demand.

Figure 14. Daily deliveries of trucked water from Island Water.



Daily deliveries of trucked water correlate with simulated storage levels in a household water tank. By May 2009 deliveries peaked at a maximum capacity of over 80 loads per day. [Note that the time span is different from the chart below]

Figure 15. Cumulative deviation of rainfall from average over the study period.



Over the entire study period (for spreadsheet modelling) the cumulative deviation of rainfall from average was close to zero. However, the accumulation of a 17.3 inch deficit between August 2008 and the end of May 2009 - the “May 2009 drought” - was a once in 20 year event, which proved useful for the assessment of adequate and optimum household water tank capacity.

5. Application of the model

i. Validity of the model as a tool

There are no published guidelines for the sizing tank capacity relative to catchment area other than the Health Department regulations. The basis for the development of these regulations and the validity of assumptions which were made, are not known. Statistical analyses of rainfall data in the 1950s by W.A.Macky may have had some influence.

The recommendations in Macky's reports are not, however, consistent with the regulations or with the findings of this study. First of all, his catchment areas are not adjusted for efficiency and so are not directly comparable to those quoted in this study and will not catch the assumed quantity of rain water. More importantly, his reports seem to suggest that a small catchment area can be compensated for by increased tank capacity. He presents a chart (Technical Note 8. 1957, Figure 13.) from which for a given roof area, the tank capacity required to meet a chosen consumption can be determined. According to this chart, a 1000 sq.ft catchment coupled with a tank of approximately 13,500 Ig can meet a demand of 100 Ig/day, with "shortages" occurring less than once in every 10 years. However, a catchment of this size, in Bermuda, will only harvest an average of 81 Ig/day (not even accounting for efficiency losses) and no tank of any size will compensate for the deficit in supply of 19 Ig/day. Shortages will, in fact, occur several times within one year of normal rainfall.

Although Macky took into account the duration and intensity of rainfall deficits and the probability of their recurrence, he apparently did not consider the effect of the long term drain on storage tanks caused by a supply deficit associated with a small roof area. In other words, he calculated the effect of a drought of given severity only for the duration of the drought. He did not take into account antecedent trends in storage levels and he, seemingly, began his simulations with a full water tank, which is never achieved in a house with a small catchment area relative to occupancy. It was concluded in this study, that as much as the first 6 months of simulation output data must be discarded when an initial tank storage level is assumed (i.e. not based on a field measurement).

The approach taken here, using actual daily rainfall data over a period of nearly three years, which includes a prolonged deficit, largely eliminates the opportunity for erroneous assumptions and over simplification. The study period included a 288 day period from 21 August 2008 to 4 June 2009 in which rainfall amounted to only 61% of average, and a 17.3" deficit was accumulated (Figure 15). According to statistics presented by Macky (1957), this intensity and duration of rainfall deficit recurs approximately once in 20 years. It certainly proved to be a 'tank-emptying" event for the typical Bermuda house, culminating in May 2009, when Bermuda's 41 water truckers were operating at, or close to, maximum capacity.

Over the complete span of the study period, the net cumulative deviation from average rainfall was very small, which means that episodes of surplus rainfall were, also, well represented. Average rainfall for the period was 57.1" compared to a long term average at Bermuda of 57.7". In summary, large cumulative deviations from average, as necessary to stress rain water supply systems, were experienced within the study period, but as a whole the period was not abnormally wet or dry.

Geographical variations, which might affect the applicability of model to all parts of Bermuda, can be ruled out. Analyses by Macky (1957) revealed that, although individual rainfall events are often restricted to one or another part of Bermuda, over one year, or more, the average rainfall is comparable across the island. This was confirmed by the close correspondence, over the study period, between the rainfall total at Prospect (a central location) and that at the airport (eastern location). It should be noted that rainfall data from Prospect was used in the model.

Taking into account all of the above factors along with the simplicty of the model and an absence of any "leap of faith" assumptions, it is concluded the modelling undertaken as part of this study provides a legitimate basis for assessing the performance and viability of residential rain water harvesting systems in Bermuda.

ii. The concept of a "balanced" rain water harvesting system

The term "balanced condition" applies to a balance between the rate at which rainfall is harvested and water consumption. For a given catchment area, consumption can be described as low, high or balanced. While for a given consumption, catchment area can be described as small, large or balanced.

Multiplication of the area, in square feet, of a balanced catchment by the long term average daily rainfall in feet/day (after making a correction of 0.85 for catchment efficiency) will equal the average daily demand of the occupants in cubic feet per day, which can be converted to Ig/day. For a rainfall of 57.7" per year, a roof will collect 0.07 Ig/day per square foot of catchment area. At a per capita consumption of 30 Ig/day, a catchment area of close to 450 sq.ft per occupant is, therefore, considered balanced. A house with a catchment area smaller than the balanced size will require supplementary water sooner or later. The practical implications of out-of-balance systems are explored in Appendix I.

iii. Optimum tank capacity

With the spreadsheet model having been verified against data from three existing Bermuda houses, the next step was to apply the model to ascertain optimum water tank capacities relative to catchment area (input) and household demand (output). Optimum capacity being defined as the capacity, which there is no benefit in exceeding for a given water consumption.

In the architectural design process, the dimensions of a Bermuda roof are not based on water supply considerations. Roof areas are constrained by: plot size, building costs, floor plans, room sizes etc. Water tank capacities, on the other hand, are for the most part constrained only by cost and by the Public Health Act regulations. The lack of constraints and guidelines leaves the door open for irrational over-sizing.

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, 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. Were rainfall data from a region with wet and dry seasons to be input into the model, much larger optimum tank sizes would be indicated than those determined, here, for Bermuda.

The model was run for seven levels of water consumption ranging from 30 Ig/day up to 900 Ig/day. For each consumption level, incremental catchment areas were entered. Then, for each catchment area, the tank capacity was adjusted to the minimum value, such that, in the case of small catchment areas, it never overflowed and in the case of large catchment areas the tank was never emptied. "Small" and "large" being, respectively, those smaller and larger than the balanced size, at which harvested rainfall equals demand. Figure 16a displays the output from the model for the 150 Ig/day consumption level. 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 balanced condition where supply meets demand. 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 they can be matched with increasingly smaller tanks. A small roof, supplies insufficient water to ever fill a large tank; whereas a large roof provides a surplus of water, which causes a tank to be continuously full, regardless of its capacity.

iv. Maximum optimum capacity

For balanced conditions, the relationships between catchment area, optimum tank capacity and household demand determined by spreadsheet modelling, are represented in Figure 17 and can be expressed as follows:

Catchment area (sq.ft) = 15 x Demand (Ig/day)

Maximum optimum tank capacity (Ig) = 7.5 x Balanced Catchment Area

On this basis, an example of a balanced, self sufficient, rain water system would be: 150 Ig/day demand, 2200 sq.ft catchment area and 16,500 Ig tank capacity.

The term "maximum optimum tank capacity" is defined here as that which need not be exceeded regardless of household water consumption or occupancy; whereas "optimum capacity" takes consumption into account. Maximum optimum capacity is 7.5 times the catchment area. A tank of such capacity will be adequate for the "balanced condition" and will be over-sized for all other conditions (see Figure 16b).

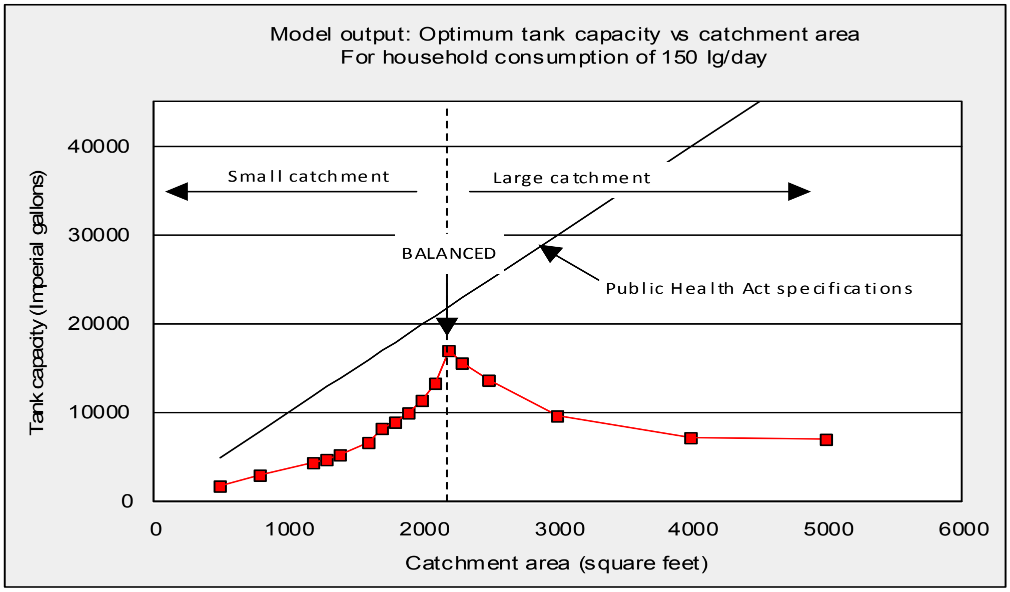
v. Summary

Optimum tank capacity varies for a given residence with a given roof area depending on occupancy, or demand. Maximum optimum capacity, on the other hand, is fixed for a given residence with a given roof area and need not be exceeded regardless of occupancy, or demand.

A roof catchment area is usually fixed on the architect's drawing board. The sustainable or balanced demand, in Imperial gallons, (able to be met by this catchment area) can be calculated by dividing the catchment area, in square feet, by 15. If the actual household

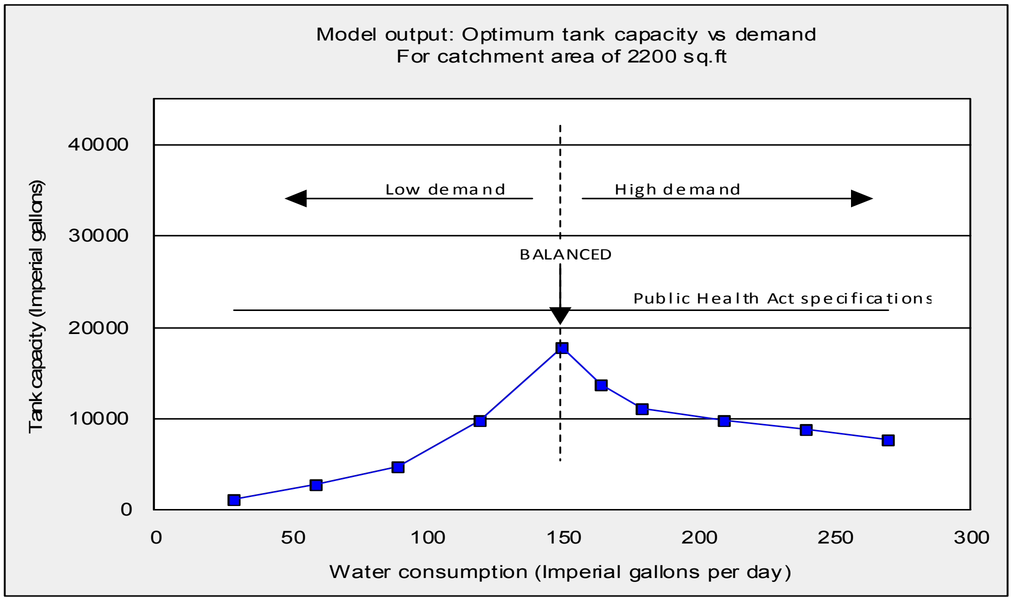
Figure 16. Examples of output from a spread sheet model used to investigate optimum household water tank capacities.

a.



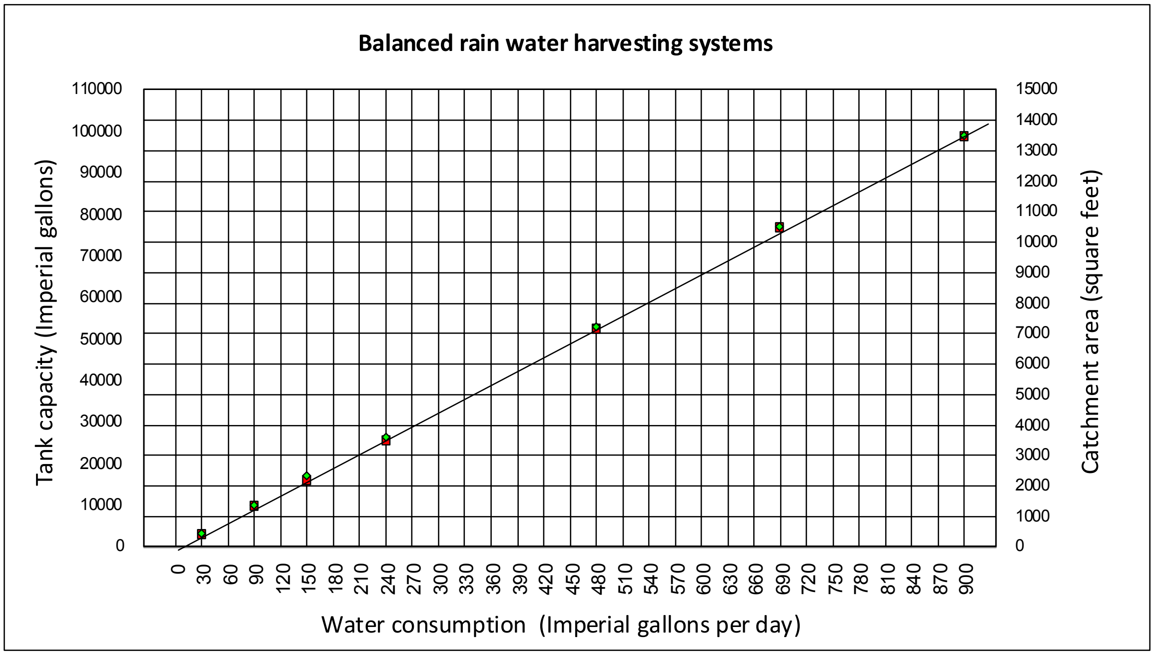
The optimum tank capacity is closest to that required by the regulations when the catchment area is just large enough (2200 sq.ft) to meet demand by the occupants (150 Ig/day). This is called the "balanced" state. For larger or smaller roof areas the optimum tank capacity is less.

b.



The optimum tank capacity is closest to that required by the regulations when consumption and supply of rain water are in a "balanced" state. When consumption exceeds or is exceeded by the supply of water, the optimum tank capacity becomes smaller. However, since the exact occupancy is not known in advance, traditional family homes should be provided with a tank capacity which is based on the assumption that a balanced state applies. Modelling indicates that this capacity in Imperial gallons is 7.5 times the catchment area in square feet.

Figure 17. The relationship between maximum optimum tank capacity, catchment area and water consumption for the "balanced" state, as derived from spreadsheet modelling.



When harvested rainfall matches consumption over the long-term, a "balanced" state exists and there is a simple relationship between the maximum optimum storage capacity, consumption and catchment area. It is unique to the rainfall patterns of a given geographic location and is best determined by an analysis which incorporates actual daily rainfall data over several years. This is how the relationships represented above were derived for Bermuda, with application of spreadsheet modelling to residential roof catchments and associated storage tanks. The relationships, derived, are that: catchment area (sq.ft) needs to be 15 times consumption (Ig/day) and tank capacity (Ig) needs to be 7.5 times catchment area (sq.ft) or 110 times consumption (Ig/day).

When the system is out-of-balance, the tank capacity relative to consumption never need be more than 110 times consumption. For example, if the catchment area is greater than that needed to meet consumption, nothing is achieved by increasing tank capacity above 110 times consumption. In fact as the system diverges more from the balanced state, smaller tank capacities are needed (Figure 16).

In the case of multi-unit residences such as condominiums, because rain water supply and consumption are so out of balance (Figure 13a) it is suggested that tank capacities need be 50% or less of the maximum optimum capacity indicated above.

demand is close to this value, then maximum optimum tank capacity is appropriate, and its volume in Imperial gallons can be calculated by multiplying the catchment area in square feet by 7.5. If the actual household demand is greater or less than that which is met by the catchment, then optimum tank capacity will be less than the maximum.

The relationships, illustrated in Figure 17, establish that, for rainfall patterns represented in the study period, all tanks with a capacity in Imperial gallons of more than 7.5 times the roof catchment area in square feet are over-sized; notwithstanding the regulations which require that tank capacity in Imperial gallons be equal to, or greater than, 10 times the roof catchment area in square feet.

vi. Rain water harvesting system scenarios

In Appendix I the practical implications of "balance" are explored. Roof areas and occupancy combine to control the balance between supply and demand which, in turn, affect optimum tank capacity. The extensive under-exploitation of tank capacity when systems are out-of-balance is demonstrated by modelling of various scenarios in Appendix I. Also investigated is the effect on balance and optimum tank capacity of a supplementary supply of water from a mains connection and a private well.

6. Implications of the findings.

i. Optimum tank capacities vs legislated tank capacities

A chart of tank capacity vs catchment area for an average house with a water consumption of 150 Ig/day is presented in Figure 16a. The ratio of 10 (Ig of tank capacity to sq.ft of catchment area) as mandated by law is represented by the inclined, straight line on the chart. Only for a balanced catchment area, which for a consumption of 150 Ig/day is 2200 sq.ft, does the plot of optimum tank capacities approach the mandated values (the apex of the curve represents the "maximum optimum capacity"). Thus, tank capacities which comply with the law always exceed the optimum capacity derived from modelling - often by a factor of two or three.

Ratios of roof area (not catchment area) to tank capacity for a random sample of houses drawn from the Planning Department files are presented in Figure 11. Also represented on the chart is the ratio as mandated by the law (upper inclined straight line) and the maximum optimum ratio based on the model (lower inclined straight line). Exceedence of the maximum optimum tank capacity by the majority of houses is evident, and is consistent with the findings of the case study investigations. It suggests widespread under-exploitation of existing tank capacities in Bermuda.

ii. Appropriate tank capacities

Most of the discussion above centers around residential rain water harvesting systems in existing Bermuda houses. There is no likelihood that they will be changed. Existing over-sized tanks will remain over-sized.

It is concluded, here, that a tank capacity (Ig) of 7.5 times the roof catchment area (sq.ft) which it serves, is a capacity which there is no benefit in exceeding, even in the event of a serious drought. However, it must be accepted that the difference between this ratio, of 7.5, and that of 10, prescribed by legislation, is too small to generate any great enthusiasm for a change in the law. It may be argued that a factor of 10 will provide more of a storage buffer in the event of an historic drought. However, it has been shown that houses with a ratio of 7.5 would have been just as well served, as those with a ratio of 10, during the May 2009 drought - a once in 20 year event. Furthermore, it has been demonstrated that houses with catchment areas which are out of balance with occupancy, or demand, will never exploit the full capacity of a tank which satisfies the 7.5 ratio. The majority of tanks are, thus, consistently overfilled or under-filled due to imbalance (See Appendix I). Certainly, under no circumstances need any tank exceed the legislated ratio of 10 times the catchment area for a traditional Bermudian residence, regardless of occupancy.

To be in balance, a house requires 450 sq.ft of catchment area per occupant. Thus, an increase or decrease in occupancy of 1 person makes a surprisingly large difference to the adequacy of the catchment area and to whether or not it is in balance. This is discussed, further, in Appendix I. Realistically, the average occupancy of each residence fluctuates, as families grow and shrink. 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 capacity designed to cater to balanced conditions i.e. not less than the maximum optimum capacity of 7.5 times the catchment area. More conservatively, a factor of 10 (as prescribed by law) could continue to be applied. The adequacy of water supply will then be a function of roof area alone.

Non-traditional houses, such as multi-storey and multi-unit developments have small catchment areas per occupant, typically less than 300 sq.ft. They can never approach self sufficiency by rain water harvesting and are often serviced by large tanks which are permanently depleted. In such cases, under-exploitation of capacity can be predicted with certainty at the design stage.

iii. Implications for multi-unit residential developments

The findings of this study could be used by architects in support of applications for tank capacity waivers (permission to provide less capacity than required by law) and by planners and regulators to assess the practicality of proposed tank capacities. A significant deficit in harvested rainfall, relative to demand, can often be predicted with certainty at the design stage - for example when the projected catchment area per occupant is less than 300 sq.ft. In such cases, reduced tank capacities (less than the maximum optimum) should be considered by the property developer and should be permitted by the authorities. It should, indeed, be a requirement to substitute excess tank capacity with provision of well water flushing or grey water re-cycling. Tens of thousands of dollars, which otherwise might have been spent on wasted tank capacity, would then be re-directed towards the cost of a dual plumbing system (potable and non-potable) thereby substantially reducing, or eliminating, the need for supplementary water purchases. A tank of 65,100 Ig capacity, as exists at the case-study condominium (Section 4.iii), would today cost $139,000 to construct compared to $59,600 to construct a 21,300 Ig tank of optimum capacity (costs calculated by Peter Holmes, QS Services).

iv. Non-residential systems

Offices, warehouses and institutions generally have large roof areas. However, water consumption tends to be at one extreme or the other. Large hotels and hospitals are multi-storey buildings with high occupancies. Water consumptions are so high relative to roof area that the contribution of harvested rain water is almost insignificant. Demand for supplementary water (usually supplied by mains supply or from a private treatment plant) is high and constant.

Offices, warehouses and schools can have high numbers of occupants during the day. Even so, relatively small amounts of water are consumed and this tends to be predominantly for toilet flushing. In these cases, harvested rainfall greatly exceeds consumption.

Thus non-residential buildings tend to have catchment areas that are out of balance with water consumption in one direction or the other. Tank capacities, therefore, need not be anywhere near as large as the maximum optimum capacity and waivers on tank capacity should always be considered where new non-residential buildings are planned.

7. Conclusions and Recommendations

i. Main Conclusions

Rain water harvested on residential roof catchments, in Bermuda, is insufficient to meet residential water demand. Currently, an average of 382 sq.ft (square feet) of residential roof catchment area is available per person compared to the required amount of 450 sq.ft, based on average annual rainfall. However, with the construction of housing outstripping population growth and declining levels of occupancy per dwelling, this deficit is, if anything, being reduced.

For a given residence, there is a water tank capacity - the “maximum optimum capacity” - which there is no benefit in exceeding regardless of water demand. This capacity depends on the catchment area and the characteristics of rainfall fluctuations associated with Bermuda’s climatic regime. Using a simple spreadsheet model with an input of daily rainfall totals for a period of nearly 3 years (including a 288 day period in which 17 inches of rainfall deficit accumulated) this capacity in Imperial gallons was determined to be 7.5 times the roof catchment area in square feet. This compares to a ratio of 10 prescribed in the Public Health (Water Storage) Regulations 1951.

Tank capacity does not substitute for a deficit in the supply of harvested rainfall caused by insufficient catchment area relative to occupancy/water demand. In fact, only under “balanced” conditions, when harvested rainfall is equal to demand, is maximum optimum tank capacity (7.5 x roof area) required. The majority of houses in Bermuda, especially those with tank capacities greater than is required by law, have under-exploited capacity and many tanks are consistently either near-full or in a state of depletion.

The spreadsheet model, developed for simulating storage levels in residential rain water storage tanks, has potential as a water management tool. It could be applied to tracking of the national status of stored rain water in residential tanks. Such information would provide forewarning of imminent spikes in demand which cannot be readily predicted by simply monitoring monthly rainfall totals. Furthermore, such a model could be applied to determine the impact of climate change (see Part II, Section 5.v) on water production capacity requirements.

ii. Recommendations

Housing developments for which it is certain that a roof area of 300 square feet per occupant will not be met should be required to install a well for toilet flushing or a grey water recycling system. The cost of this would be more than compensated for by a waiver for tank capacity (i.e. permission to provide less tank capacity than is required by law). This waiver will not compromise the contribution of the tank in any way, because the approved capacity would be such that the tank never overflows. Substitution of costly unexploited tank capacity* with a sustainable on-site source of non-potable water would contribute to a reduced demand for potable supplementary water, which is increasingly produced by energy hungry treatment technologies.

Construction of private wells, as a source of non-potable water, should generally be encouraged in the name of sustainability and self sufficiency. However, before embarking on a campaign to persuade the country of these benefits, a survey should be conducted to determine the level of satisfaction and self-sufficiency amongst the 19% of dwelling units which are served by wells.

* Built at a cost of approximately $2.50 per 1000 Imperial gallons.

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APPENDIX I. **Rain water harvesting system scenarios**

1. Balanced and out-of-balance catchment areas

a. Large catchment area and low demand

Tanks which are fed by large, out-of-balance, catchment areas will always be subject to a long-term trend of increasing storage to the point of inevitable, repetitive overflows. No amount of tank capacity can capture all the surplus water available from a large roof. The capacity of such tanks need only be sufficient to sustain a supply of water during periods of intense rainfall deficit. In sizing a tank for a new house with a large roof, storage capacity need be no greater than that which will provide a continuous supply of water during a severe drought.

House 1 (Section 4.ii) has a catchment area which is 129% of the balanced size. Storage levels through 2007 to 2009, as shown in Figure 12 indicate that the lower 10,000 Ig of storage, is permanently occupied by water i.e. not exploited (note that the first 6 months of 2007 were influenced by the conservative assumption of a half-full starting point). According to the model, the optimum tank capacity for a water consumption of 80 Ig/day at House 1, is only 4800 Ig (Imperial gallons) and the maximum optimum capacity (suitable for any consumption/occupancy) is 12,300 Ig, compared to the existing tank capacity of 19,000 Ig .

b. Small catchment area and high demand

Tanks which are associated with small, out-of-balance catchment areas will always be subject to a long-term trend of declining storage to the point of inevitable depletion. No amount of tank capacity will counteract a supply deficit created by a roof which is under-sized relative to demand. Supplementary water will be required, no matter what, and the capacity of these tanks need only be sufficient to store rain water during periods of surplus, without overflowing.

House 3 has a catchment area which is 83% of the balanced size. Storage levels through 2007 to 2009, as shown in Figure 12 indicate that the top 15,000 Ig of storage is permanently occupied by unexploited air space. According to the model, the optimum tank capacity for a water consumption of 240 Ig/day for House 3, is 15,700 Imp gallons and the maximum optimum capacity is 22,500 Ig, compared to the existing tank capacity of 35,000 Ig.

c. Balanced catchment area

Tanks which serve catchment areas which are balanced (with demand), or nearly so, will experience water levels which fluctuate more or less equally on either side of the half-full level. The capacity of such tanks is ordinarily sufficient to, both, capture rainfall surpluses without overflowing and to withstand rainfall deficits without being emptied. House 2 has a roof area which is 89% of the balanced size. Storage levels through 2007 to 2009, as shown in Figure 12, illustrate that that 85% of the 13,500 Ig capacity is exploited over the study period. According to the model, the optimum tank capacity for a water consumption of 140 Ig/day for House 2, is 11,500 Ig and the maximum optimum capacity is 13,950 Ig, compared to the existing tank capacity of 13,500 Ig .

d. Fixed catchment area and variable demand.

The degree of balance will obviously change with time where there is variable demand. For example at the "typical house" (see Section 3) with a catchment area which supplies 94 I g/day of harvested rain water, if the number of occupants were to increase from 2 to 3 to 4 , the water supply balance would change from a healthy surplus to a significant deficit. At 3 occupants (90 Ig/day) the system is virtually in balance and most of the tank storage capacity is exploited (maximum optimum capacity is required). With 2 occupants (60 Ig/day) almost two thirds of the tank capacity is permanently occupied by water (i.e. unexploited) and with 4 occupants (120 Ig/day) nearly half the capacity is permanently occupied by air. These scenarios are illustrated in Figure 18.

2. Over-sized tanks

Where a catchment area is small, it may be tempting to construct a large storage tank with the objective of building up a large stock of water. If, conversely, a catchment area is large, the same temptation may apply, but with the objective of capturing water which in a small tank would otherwise continuously overflow. As long as the catchment area is out of balance with demand, these objectives cannot, however, be realised. Super-sized tanks, in some cases, are in a continuous state of depletion to the disappointment of their owners. Others are always full to overflowing.

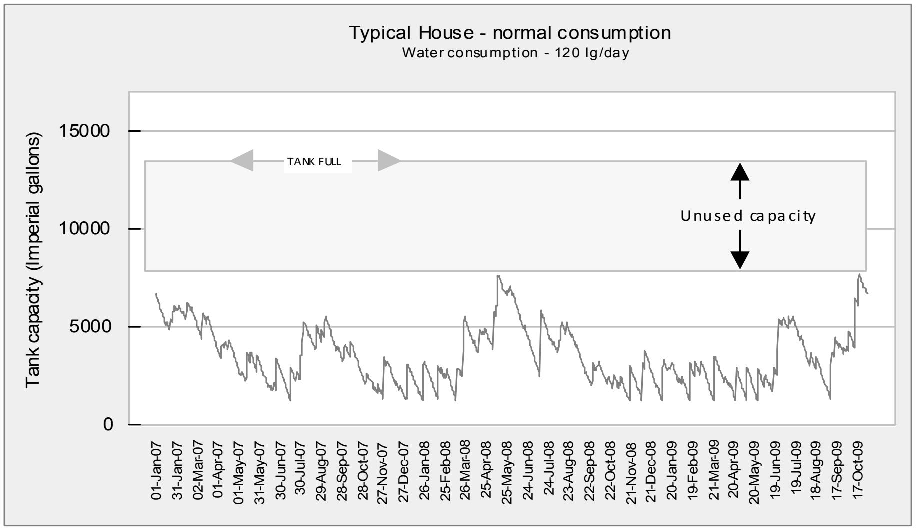
Spreadsheet modelling illustrates that a moderate sized tank of optimum capacity, will perform as well as a larger tank, even under drought conditions as experienced between August 2008 and June 2009. In the event that a more serious drought occurs, conservation of water will adequately compensate for the deficiency in capacity. (a water conservation mode can be "switched on" as an option in the model, but was left switched off in the interest of producing conservative results.)

3. Residences with on-site supplementary water sources

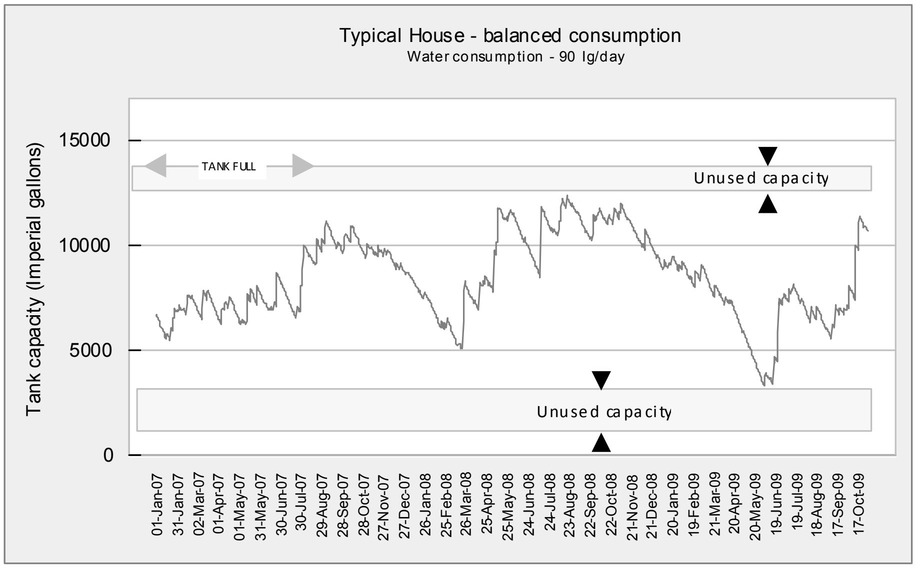
64% of dwelling units in Bermuda have no on-site source of water to supplement rain water; 19% have a mains connection; 19% have private wells; and an estimated 2% have both. Water tank storage levels cannot be satisfactorily modelled where the tank is topped up at the whim of the home owner, as is the case for houses with Government mains connections. However, for the customers of Bermuda Water Works, since 1000 Ig of "free" water is included in the monthly service fee, it can be justifiably assumed that 1000 Ig is drawn from the connection every month at some residences. This can be simulated in the model simply by reducing consumption of rain water by 1000 Ig/month or 33 Ig/day. This is equivalent to reducing occupancy by about 1 person and could bring the system into balance at a typical house, which would result in greater exploitation of tank capacity, as shown in the simulation in Figure 19 (bottom chart).

Supplementary water supplied from a private well is quite similar to the scenario of mains water purchases. Well water is connected directly to toilets and sometimes to

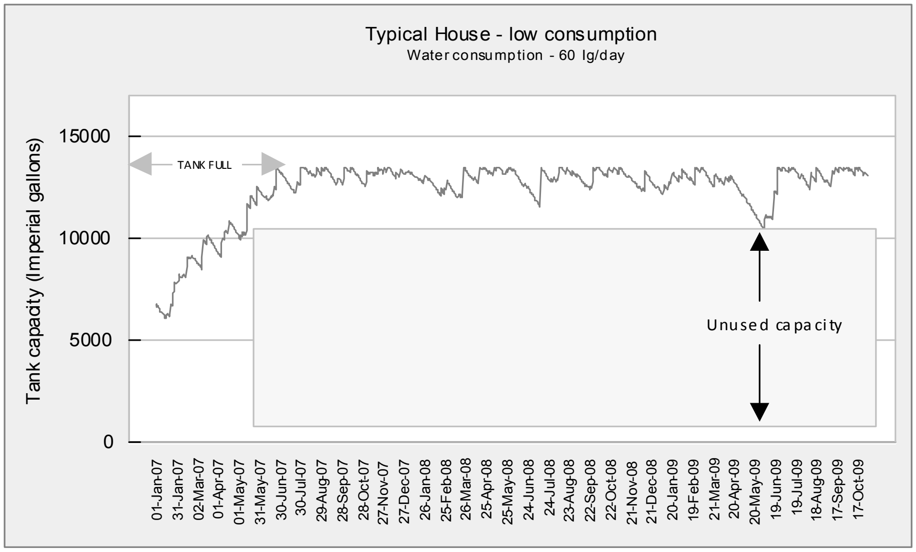
Figure 18. Simulation of the effect of varying water consumption at the “typical house”



CA	1360	sq.ft
TC	13,500	Ig
DA	120	Ig/day
RS	94	Ig/day
TC/CA	9.9	
CApp	340	sq.ft
BCA	1800	sq.ft
MOTC	10,200	Ig
OTC	6200	Ig
OF	0	Ig/day
SS	26	Ig/day



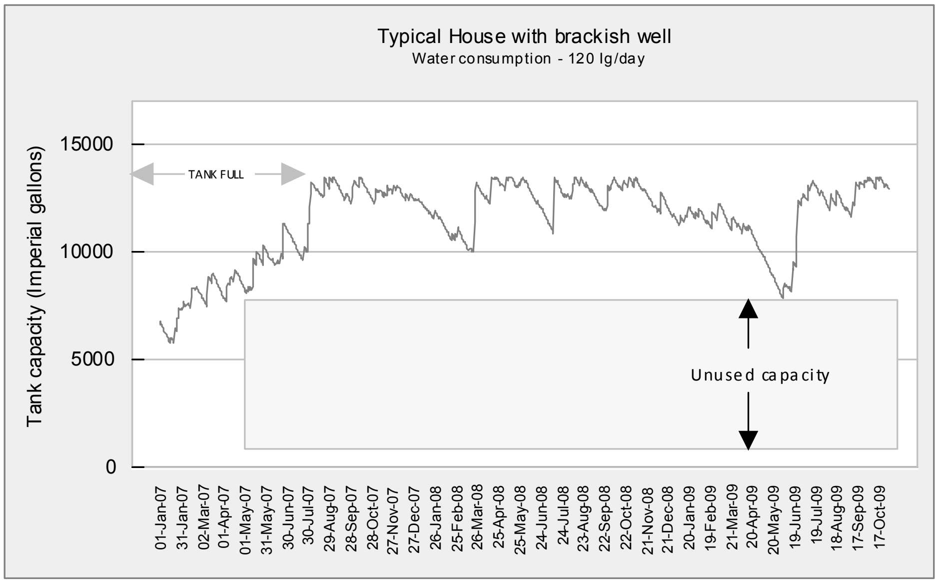
CA	1360	sq.ft
TC	13,500	Ig
DA	90	Ig/day
RS	94	Ig/day
TC/CA	9.9	
CApp	450	sq.ft
BCA	1350	sq.ft
MOTC	10,200	Ig
OTC	10.200	Ig
OF	0	Ig/day
SS	0	Ig/day



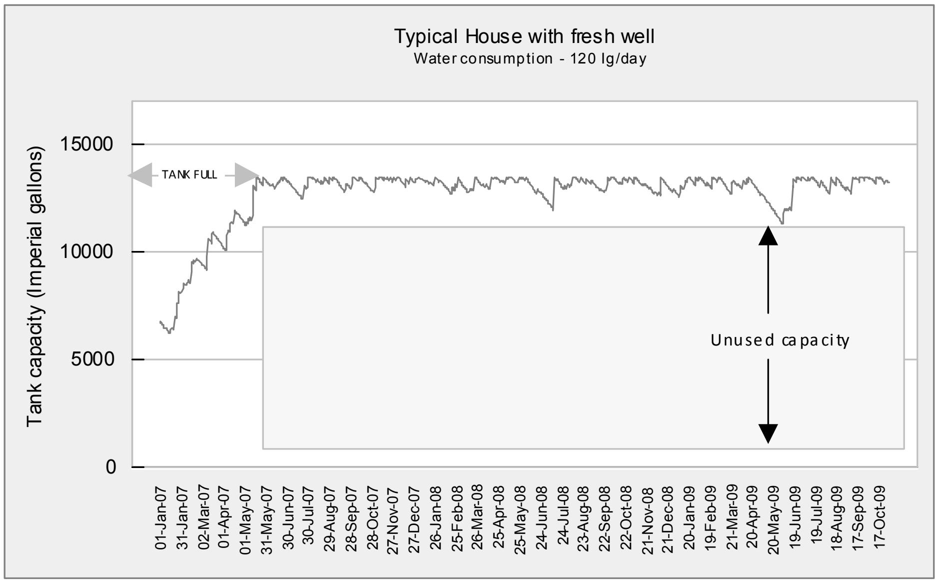
CA	1360	sq.ft
TC	13,500	Ig
DA	60	Ig/day
RS	94	Ig/day
TC/CA	9.9	
CApp	680	sq.ft
BCA	1200	sq.ft
MOTC	10,200	Ig
OTC	3400	Ig
OF	28	Ig/day
SS	0	Ig/day

Parameter key: **CA** - Catchment area; **TC** - Tank capacity; **DA** - Water demand; **RS** - Rain water supplied; **Capp** - Catchment area per occupant; **BCA** - Balanced catchment area to meet demand; **MOTC** – Maximum optimum tank capacity; **OTC** - Optimum tank capacity; **OF** - average rate of overflow; **SS** - Supplementary water supplied; $TC - cost of existing tank; $OTC – Cost of optimum tank.

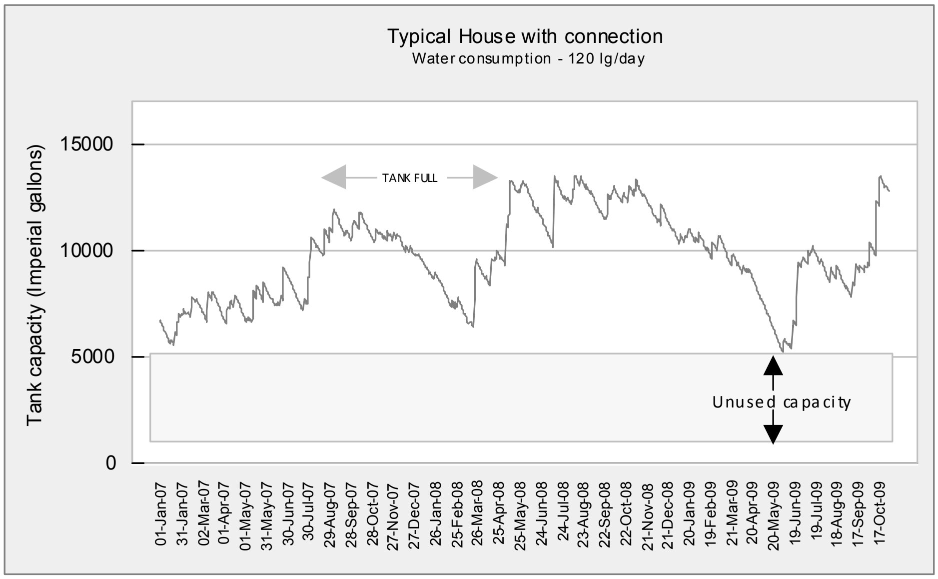
Figure 19. Simulated tank storage levels at residences with on-site supplementary water sources.



CA	1360	sq.ft
TC	13,500	Ig
DA	120	Ig/day
RS	94	Ig/day
TC/CA	9.9	
CApp	340	sq.ft
BCA	1200	sq.ft
MTC	10,200	Ig
OTC	6300	Ig
OF	13	Ig/day
SS	45	Ig/day



CA	1360	sq.ft
TC	13,500	Ig
DA	120	Ig/day
RS	94	Ig/day
TC/CA	9.9	
CApp	340	sq.ft
BCA	1200	sq.ft
MTC	10,200	Ig
OTC	2500	Ig
OF	38	Ig/day
SS	70	Ig/day



CA	1360	sq.ft
TC	13,500	Ig
DA	80	Ig/day
RS	94	Ig/day
TC/CA	9.9	
CApp	340	sq.ft
BCA	1200	sq.ft
MTC	10,200	Ig
OTC	9200	Ig
OF	1	Ig/day
SS	33	Ig/day
$TC	59,000	$
$OTC	28,000	$

Parameter key: **CA** - Catchment area; **TC** - Tank capacity; **DA** - Water demand; **RS** - Rain water supplied; **Capp** - Catchment area per occupant; **BCA** - Balanced catchment area to meet demand; **MTC** - Maximum optimum tank capacity; **OTC** - Optimum tank capacity; **OF** - average rate of overflow; **SS** - Supplementary water supplied. $TC - cost of existing tank; $OTC – Cost of optimum tank.

appliances and so its use tends to be non-discretionary and fairly constant. As such it can be modelled as negative consumption estimated at 45 Ig/day per residence for a brackish well and 90 Ig/day per residence for a fresh well. In most cases this amount of supplementary water brings the household water supply balance into surplus and thus tanks smaller than the maximum optimum capacity are adequate. Tank overflows may be frequent where there is a private well (Figure 19), but these are not considered as undesirable as at houses with mains connections where a portion of what overflows is high quality treated water.

Mark P. Rowe, May 2010.