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Emergency Rainwater Harvesting, Water Storage, and Distribution System for an Affordable Housing Development in Barbados

Abstract

Background: To sustain both permanent residents and an intense tourism industry, Barbados overpumps its sole source of natural freshwater—the aquifer. Climate change is projected to increase both storm intensity and drought, further hampering groundwater recharge. These intense rainfalls quickly saturate topsoil and result in extensive surface run-off that causes flooding, erosion, sedimentation, and eutrophication. By providing more water for households and reducing aquifer withdrawal, rainwater harvesting has the potential to both mitigate water scarcity and reduce the amount of harmful run-off. However, rainwater harvesting is not currently practiced in Barbados. This paper proposes a hurricane-resistant rainwater harvest, storage, and distribution system to be implemented in an affordable housing community in St. Thomas, Barbados.

Methods: In the creation of the distribution system design, social, economic and environmental concepts need to be considered. We first conducted a field survey within the neighbourhood to understand what the residents felt the local water supply lacked. Afterwards, we performed a detailed rainfall analysis to determine the amount of rainwater that can realistically be captured. Finally, we consulted with various academic experts, local industry members, and supply stores to determine an affordable design.

Results: Our findings suggest that an initial household investment of $2790.90 BBD appears adequate to provide a system for rainwater harvesting, dual plumbing, and communal distribution which can withstand and utilize 1/50 years storms.

Limitations: Given that rainwater harvesting is not currently practiced in Barbados, government initiatives are needed to encourage its development.

Conclusion: Affordable rainwater harvesting, dual plumbing, and community distribution systems can be implemented to possibly reshape life in countries facing water scarcity.

Introduction

As a tropical Island, Barbados is exposed to climate change-powered natural disasters, droughts, and extreme rainfalls. Since 1960, temperatures on the island have risen by 0.6 °C; rainfall during the wet season has increased by 6.2% per decade, and rainfall during the dry season has decreased by 2.9%. (1) Combining this with rising sea levels and aging infrastructure makes Barbados vulnerable to floods, storms, and hurricanes, and it is uncertain whether the country is prepared for a potential disaster. (2-3)

In Barbados, 90% of potable water is pumped from the aquifer; the remaining is produced by a desalination plant. (4) Whereas desalination is extremely expensive, the aquifer provides cheap, high-quality water treated through limestone percolation and disinfected through chlorination. Rainfall is the sole source of water that contributes to recharging the aquifer. As population, urbanization, and droughts increase, this indispensable source of water is progressively being depleted. Overpumping leads to a lowering of the water table which puts the reservoirs at risk of salt-water intrusion. As a result of a proposal by the Barbados Water Authority (BWA) to impose water rationing in some neighbourhoods, Barbados residents are left with less than 281.5 m^3 of renewable water per capita per year, making it the 15th most water scarce country in the world. (5-6) In parishes like St. Thomas, residents claim to experience water shutoffs from 9 a.m. to 4 p.m. twice a week to provide for water-demanding agricultural areas to the north of the island. Meanwhile, countries Bermuda, Nigeria, and Guyana have developed sustainable programs to move towards rainwater harvesting methods for greywater, irrigation, and potable purposes. (7-9) Chennai, India has made it mandatory to include rainwater systems in all residences. (10) Furthermore, the city created a sustainable design that directs the overflow of water harvested into wells that recharge aquifers. As a result, Chennai has seen a replenishment in the top aquifer and retarded their water scarcity issues. (11) Efficiently harnessing an abundantly available resource like rainwater can provide a viable route to mitigating water scarcity. Unfortunately, widescale rainwater harvesting efforts have not been implemented in Barbados.

As the frequency, intensity, and duration of hurricanes is expected to increase, the ability for communities to maintain themselves can be compromised. Hurricane Dorian recently devastated areas in the Bahamas and left some residents without water and power, resulting in more than 56 deaths, 600 missing peoples, and over $7 billion USD in damages. (12-13) Barbados has not endured this kind of disaster since Hurricane Janet in 1955 and is both overdue and unprepared for a disaster. Tropical storms regularly cause flooding and erosion in Barbados. Storm run-off also leaches through fertilized agricultural land where it picks up nutrients. These sediment-rich and nutrient-rich waters eventually reach the coral reef causing eutrophication and bleaching. Systems that have the capability to harness tropical storm and hurricane waters and energy could exacerbate the destructiveness of these events. (14)

In Barbados, owners of houses with a surface area greater than or equal to 1500 ft^2 are legally bound to purchase water tanks that are supplied by water from the mains. (15) Residents with smaller houses also invest in water storage tanks to better deal with water shut offs. Some of them rely on an electric pump to provide the house with the previously stored water in times of shut-off. Others choose to elevate their tank on a tall foundation to use gravity head to supply their house with water. However, these structures are usually built without consultation with engineers and can potentially be dangerous, especially during a hurricane with high wind speeds. Safe circulation of water during power outages has not been extensively researched and may be essential to developing a water resilient country.

Based on stormwater's potential for reuse, this paper proposes a water storage and distribution system centered around an assessment survey conducted in the affordable housing neighbourhood of Content, St. Thomas. The design's intended purpose is to provide relief to residents by having a reliable source of water when main water is unavailable. It is categorized by three major components. Firstly, a rainwater harvesting system gathers the abundance of fresh water into individual water storage tanks that are already common throughout Barbados. Secondly, a dual plumbing system assures that rainwater and main water are being separated and allocated to specific utilities within the house. Lastly, a community distribution system allows the excess water harvested to be shared between neighbours instead of being released as run-off.

Survey and Needs Assessment

On September 28, 2019, we surveyed 25 households scattered randomly around the existing development in Content using a questionnaire relating to water use and quality, frequency of shutoffs, willingness to invest in a tank, and disaster preparedness. We observed a mix of gender, age, and backgrounds, but all households were within the same financial conditions as they cohabited the same neighbourhood. Although the community needs are coherent within Content, it might not necessarily be the case elsewhere on the island, which forms our main limitation. Based on this survey, we found that rainwater harvesting is not usually practiced due to a lack of awareness.

Residents were asked, amongst other things, about their experience with water management and their willingness to invest in a tank. The questions gauged the resident's value of the following eight parameters: maintainability, workability, affordability, security, practicability, water quality, durability, and aesthetics. The most important decision parameter for Barbadians seemed to be affordability, while aesthetics did not matter as much. Accordingly, a Tuff Tank will be used for the design, aligning more with the social needs of Barbadians, instead of fiberglass underground tanks. Tuff Tanks are readily available and affordable, black coloured, aboveground water storage tanks.

Rainwater Harvesting System

Rainfall Analysis

The study site was localized on qGIS along with 24 rain gauges across the Barbadian territory for which monthly volume recordings from 2000 to 2015 were provided by Tara Mackey, a University of the West Indies Ph.D. candidate. Thiessen polygons were subsequently drawn to attribute an area to each gauge and the proposed site fell on two different polygons (Fig. 1). To accurately represent the neighbourhood, data were averaged over these two gauges and compared with rainfall data (1887-1986) from monthly rainfall volume maps as shown in Fig. 1. (15)

When designing for extreme events, high-intensity-short-duration and long return period data are expected. Due to the lack of public short-duration rainfall data for Barbados, local IDF curves for 1/50 years floods were not readily available. (16) The longest return period available for Barbados is currently 1/25 years. Hence, it was decided to use the Bahamas' IDF curve for 1/50 years storms. (17) This decision will result in a conservative design since, from a comparison of the 1/25 years storm curves for the two countries, it is clear that the rainfall intensity of the Bahamas is much larger than that of Barbados. (17) Indeed, in a 10-minute duration, the 1/25 years rainfall intensity was 250 mm/hour in the Bahamas while it was only 150 mm/hour in Barbados. Furthermore, the shortest duration represented in the Bahamas' IDF curve for a 1/50 years rainfall was 10 minutes. To account for the most extreme event, the rainfall intensity for a 5-minute duration was extrapolated and found to be approximately equal to 350 mm/hour or 13.8 inch/hour.

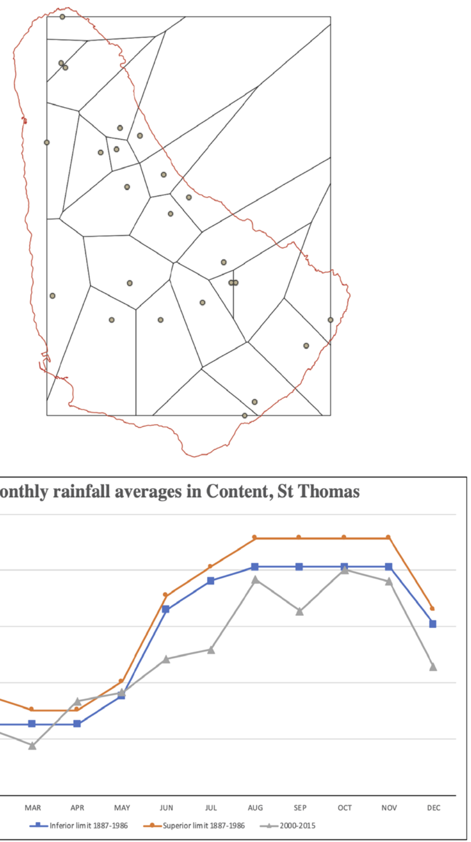

Figure 1. Thiessen polygon for rainfall gauges in Barbados (top) and plotted rainfall data for each month in millimetres (bottom)

Water Tank Sizing

With an average family of 5 using 823 L/week/person, a 1000 gallon Tuff Tank should supply six days of water to the family. (18) The tank must hold enough water in a hurricane situation both to provide head towards the house and not to tip over. Using the 1/50 years wind speed of 41.12 m/s for Barbados results in a 2.614 kN force acting on the centre of the water tank which has a 1.65 m diameter and 2.457 m height corresponding to the European Code. (19) Therefore, using moment summation $\Sigma M=0$ at the corner of the tank and force summation $\Sigma F=0$, the critical amount of water needed in the tank to prevent tip over was calculated at 162 gallons. In a power outage, the head required to transfer water from the tank to the least elevated appliances must be provided by a water level lower than 187 gallons (see *Rainwater Plumbing*). Thus, as long as the tank contains at least 187 gallons of water, it will both prevent tip-over and supply head.

Removing Particulate Matter

Not only do corrugated iron roofs reduce pathogens through the dry-heat effect, but their high run-off coefficient and smooth surface allow for optimal surface cleansing. (20-21) Additionally, gutter guards, or sheets of pierced metal placed on top of the gutter, will filter out solids larger than 1 mm. The first flush diverters, placed on each side of the roof, will then capture the initial volume of rainfall that swept sediment and small particles off the roof into separate storage. As the first flush compartment fills up, a spherical float will rise to close the storage and direct much cleaner water into the tank (Fig. 2).

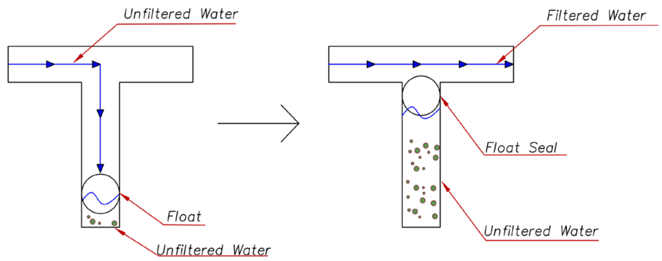

Figure 2. First flush diverters showing the flow of filtered and unfiltered water depending on the volume of water in the first flush compartment.

The first flush compartments were sized according to Blue Mountain Co rainwater harvesting regulations where for every square foot of roof, there should be a litre of first flush diverter volume. (22) To contain the calculated volumes, two diverters (10 gallons each) for each side of the roof will be 2361 mm long, 6 inch diameter pipes that will be connected to the 3 inch horizontal pipe above through a 3 inch corner tee and two consecutive expanders, a 3 to 4 inch and a 4 to 6 inch from Barbados Steel Works (Fig. 3). An end cap that can be manually unscrewed after a rainfall to empty the system will be placed at the bottom of the diverter.

Gutter Sizing and Pipe Sizing

The proposed development contains three different types of precast houses that have different surface areas (from smallest to largest: Evergreen, Flamboyant, and Tulip). The houses contain 2 to 3 bedrooms and 1 to 2 bathrooms.They are made of prestressed concrete designed for earthquake loads, and the roofs are made of corrugated steel, ensuring a large run-coefficient. (23) To withstand the massive influx of water during a hurricane, gutters and pipes were sized based on the largest roof catchment area (Tulip) and the Bahamas's 1/50 years rainfall intensity. Calculations followed Architectural Graphic Standards for Residential Construction and resulted in 6 by 6 inch gutters and 3 inch diameter downpipes on each side of the roof (Fig. 3). (24)

In order to maintain a consistent water velocity at a given flow rate, the pipes to the tank have the same cross-sectional area as the downpipe given that Q=AV, where Q is the volume flow rate, A is the cross-sectional area, and V is the mean velocity of the fluid. Hence, PVC pipes are 3 inches in diameter.

Cost

Based on quotes from Akeem Nurse at Alan Armstrong and the BWA, the cost of installing a 1000 gallon water tank in Content was estimated to be $9024.3 BBD by adding the cost of gutters, pipes, connectors, and the first flush system (Table 1).

The monthly volume of water captured by the harvesting system was estimated by multiplying historical rainfall intensity recordings by the catchment area of the roof for each house type. The economic savings on the water bill was then estimated by subtracting the volume captured from household consumption for a family of five and calculating the BWA water bill that would be incurred by such a volume (Table 2). (25) Household consumption was based on per capita estimates for St. James, Barbados. (18)

The initial investment was then divided by the average monthly savings to calculate the time to break even. As shown in Table 2, when taking into account the total cost (tank installation with connection to the main, construction, and harvesting system), the time to break even based on savings from harvested water is high (about 20 years depending on the house type). However, people already do invest in water tanks and pay for installation to store main water and avoid experiencing frequent shutoffs. The only addition to current practices is the harvesting system which allows for main water savings. The initial investments for the harvesting system (gutters, meshes, etc.) should be recovered in less than three and a half years. The installation cost of a harvesting system is only about 2% of the average local yearly salary of $62,000 BBD. (26)

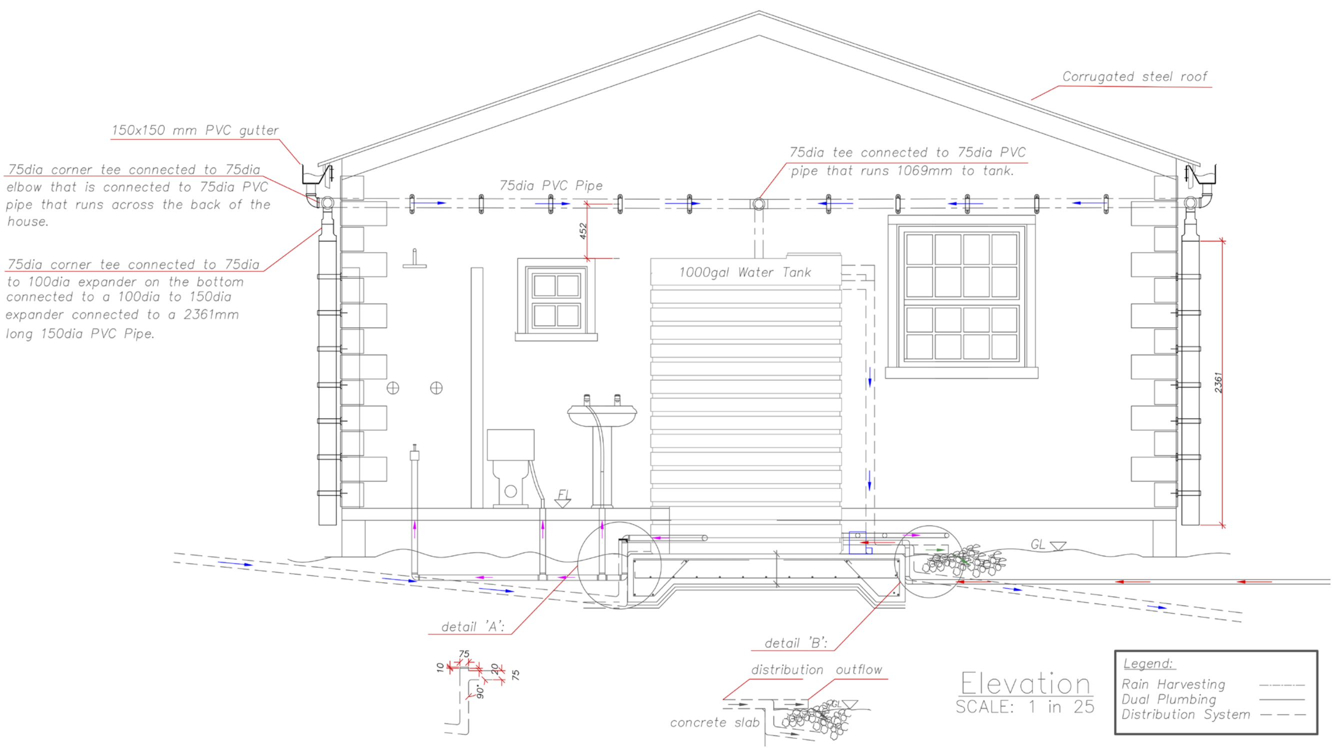

Figure 3. Elevation View of Rain Harvesting, Dual Plumbing, and Distribution System

	Unit Price/rate	Quantity	Total price
MATERIALS	2384.78	1	2384.78
3VM06		1	
19G Pressure Tank		1	
Pressure Switch		1	
Pressure Gauge		1	
Float Switch		1	
1000 GALLON TANK	1677.87	1	1677.87
Pipework including fill line, discharge, 2" supply with 1/2" Return		1	
ELECTRICAL INSTALLATION	1105	1	1105
EARTHWORKS			
excavation of foundations	120	1	120
Filling and compaction			
General filling		1	0
Excavated marl fill under water tank	120	1	120
Excavated marl fill to trench at connection	12	1	12
Excavated 20 mm single size stone	55.8	1	55.8
INSTITU CONCRETE			
Concrete slab X-section 0.01-0.02m2	874.5	1	874.5
binding to slab	142.5	1	142.5
CONCRETE ANCILLARIES			
Formwork with 25*25mm chamfer	211.2	1	211.2
mild steel bars 10mm diameter	32	1	32
High yield bar to BS 4449 12mm	340	1	340
steel trowel finish	34	1	34
OVERHEADS AND PROFITS	570.6	1	570.6
TOTAL before tax			7680.25
Tax @ 17.5%			1344.04
TOTAL after tax			9024.29

Table 1. Construction and water tank installation costs based on DM Simpson quotes sent by Akeem Nurse for a system in Trents, St. Lucy. Monetary values in BBD.

House	Evergreen	Flamboyant	Tulip
Tanks Installation BDS$	9024.29	9024.29	9024.29
Harvesting system BDS$	931.52	1057.60	1266.58
Total Cost BDS$	9955.82	10081.90	10290.87
Average monthly saving BDS$	24.28	29.45	31.59
Yearly savings on water bill %	48%	59%	63%
Months to break even	410.10	342.36	325.75
Years to break even	34.18	28.53	27.15
Years to Break Even for harvesting only	3.20	2.99	3.34

Table 2. Estimated costs, savings based on water not withdrawn from the mains, and time to break even on the initial investment. Monetary values in BBD.

Dual Plumbing System

Concept

The BWA provides potable water that is mainly sourced from aquifers and treated with chlorine. Main water from various locations has been collected and tested at the University of the West Indies laboratories. The results showed that the water quality requirements were met. Amenities like the toilet, sinks, faucets, and showers are already connected to the mains as part of the design for a residential development. Rainwater harvesting provides an additional source of water that can be installed during construction or added to an existing house. The storage tank contains primarily rainwater collected from the harvesting system but is also branched to the main for back up when rainwater is scarce and pressure head becomes too low to feed the house.

A dual plumbing system consists of a network of two separate pipes: the typical main-to-house for potable water and the tank-to-house for tank water. The treated main water is hence physically separated from the non-treated rainwater, preventing contamination. The main plumbing feeds the amenities that require potable water like the kitchen sink, or high-water heads such as the shower, while the secondary plumbing feeds amenities that require neither potable water nor a high-pressure head, such as the toilet. For such utilities, non-return valves and knobs allow users to switch between sources.

Main Water Plumbing

The main water pathway going to the kitchen faucets remains unaltered as potable water is indispensable not only for drinking, but also for cooking and washing food (Fig. 4).

2 inch polyblue pipes, which are flexible yet sturdy, will be used to account for unideal angles (30 degrees, 45 degrees, or 90 degrees). Although polyblue can be used above ground, it is strongly suggested to be run underground to limit risks of damage in hurricane circumstances. The elevation view in Fig. 3 illustrates how the main water pipe runs below ground until it reaches the concrete slab.

Rainwater Plumbing

Rainwater is distributed to the house using 2 inch pipes as shown on Fig. 4. A hole punctured in the concrete floor slab will allow the pipe to enter the house. This hole must be properly sealed to prevent faulty waterproofing and cracking in the floor slab.
A faucet located 0.525 m above floor level in the shower cabin (below the showerhead) can provide rainwater. Various fittings (T-fittings, Y-fittings, elbows, etc.) were used to direct the water flow (Fig. 3).
Bernoulli's equation of energy conservation and Darcy-Weisbach equation for minor losses

$$H_1 = H_2 + \sum S_{fi} L_i + \sum K_i \frac{V_i^2}{2g}$$

was used to determine the head needed to allow for gravity flow from the tank to the house. It states that the head at the free surface in the tank equals the head level of the utilities plus the friction losses along the pipe and minor losses due to parts (elbows and valves). The S_{fi} is given by the Hazen-Williams Equation for circular conduits

$$S_f = \left(\frac{Q}{0.278 * C * D^{2.63}}\right)^{1.65}$$

where C, the roughness coefficient, is 145 for a PVC pipe. (27) Knowing all the manufactured parts' head loss coefficients allows for the calculation of minor head losses in the pipes. (27) It was found that a 1000 gallon tank will supply water using only gravity flow until the water level in the tank reaches 187 gallons (0.399m) for the toilet, 426 gallons (0.912m) for the sink, and 246 gallons (0.526m) for the shower faucet. This is ideal because water will always stay above 187 gallons when there is no electricity (only gravity flow) meaning it will never reach the critical tipping point of 162 gallons (see *Water Tank Sizing*) in emergencies. A standard 1 horsepower pump, according to Alan Armstrong and Associates engineers, is placed to supply water into the house when electricity is running.

Maintenance and Repairs

If electricity is running and the water volume in the tank falls below 187 gallons, the pump and pressure tank activate to supply main water into the tank to provide enough head. The pressure tank acts as a sensor to detect water level and activate the pump only when required. All components of the dual plumbing system are protected from backflow by non-return valves (Fig. 4).

For cleaning or repairs, the tank must be disconnected from the plumbing network and emptied through an outflow valve. A 38 mm pipe (Fig. 4), bypasses the tank, pump, and pressure tank and redirects main water into the building.

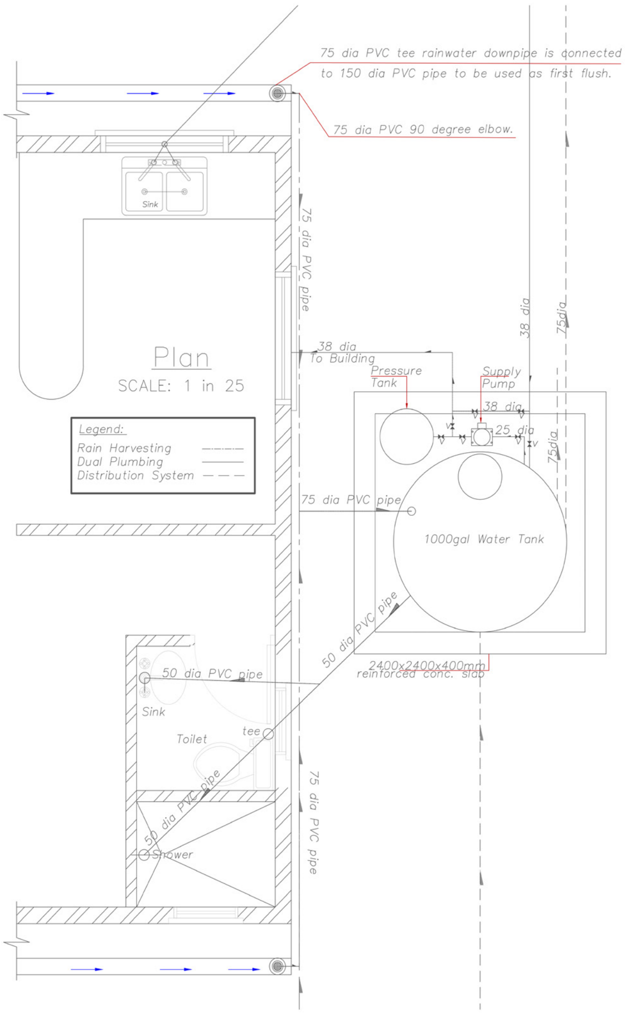

Figure 4. Plan View of Rain Harvesting, Dual Plumbing, and Distribution System. The solid lines represent potable water sourced from the main and the storage tank water distributed to the house. Non-return valves are represented as two triangles pointing at each other, and denoted by "v."

Emergency Scenario

During an emergency such as a storm, or hurricane, damages to the electrical grid and water mains will likely jeopardize power and potable water availability. As a result, the residents must rely on stored water for their daily necessities. A 1000 gallon tank at full capacity will require 187 gallons to pressurize the water distribution (section 4.3) to the toilet, leaving a remaining 813 gallons for usage. However, the collected rainwater is not potable since it did not go through disinfection. The addition of an emergency kit to render this rainwater potable is thus the most realistic and affordable solution. The proposed kit contains chlorine pills and a chart that gives chlorine to water ratios for optimal disinfection. Chlorine is chosen as it is readily available and cost-effective. Alternatively, boiling the water is another option as Barbados relies heavily on gas stoves which do not require electricity.

For other usages of water such as washing clothes, cleaning, and flushing the toilet, the rainwater can be used directly. Rainwater will go directly to the toilet bowl as long as the appropriate valve is turned on and the source is above 187 gallons. Similarly, the lower shower faucet can be used. The dual system supplies water directly from the tank to indoors preventing people from venturing outdoors during a storm, where they are putting their life at risk with heavy rainfall, slippery grounds, strong winds, and flying objects.

Distribution System

Rationale

The creation of a connected residential distribution system is based on the premise that in a situation of natural disaster, mutual help and fraternity can increase resilience of the whole community. In a hurricane situation, wind speeds and rainfall levels may display high local variations. Hence, houses that are located or oriented differently on the land's topography could be subjected to different levels of damage, disruption, and rainfall. The proposed distribution system would allow overflow from one tank to feed the adjacent tank. That way, if the gutters of any house break, and the rainwater harvesting system is disabled, the tank would be replenished from the neighbours' tank.

Design

Head differences were calculated both in hurricane and in normal circumstances according to Bernoulli's equation of Energy Conservation and Darcy-Weisbach equation for minor losses. The friction slope, S_{fi}, was calculated through the Hazen-Williams equation. In hurricane circumstances, when the tank is full to the distribution overflow level, head goes from 5.41 m in the highest tank to 0.92 m in the lowest; in normal circumstances, it goes from 5.41 m to 2.50 m. These differences in head assure a continued flow and the highest head difference in hurricane circumstances is due to a higher velocity.

The potential risk of local debris accumulation and pressure build up at the 135° elbow (Fig. 3) led to a design modification. Since debris would accumulate in the 135° angle elbow, a cap was simply added to the 90° angle elbow to allow physical access to the elbow for cleaning (Fig.3).

Cost

The cost of the distribution system, including the three pipes connecting the four houses, the second overflow pipe for the tanks, excavation, filling, and labour was estimated at $2939.3 BBD which is equal to $734.8 BBD per house. Such a cost represents only 1.1% of the average yearly salary (22). However, this investment is made for emergency situations only and does not yield any return.

Conclusion

Water storage and distribution is a prominent issue within water-scarce Barbados. With constant water rationing in communities, power shut offs, and aging infrastructure, Barbados needs immediate changes to their water policies and technologies. Furthermore, susceptibility to natural disasters and unpredictability of rainfall amplifies the dangers of water scarcity, causing malaise within residents. Indeed, climate change continues to exacerbate scarcity of a resource that is both indispensable and economically inelastic. Therefore, following this trajectory, the BWA will be forced to increase water prices. The design proposed above for Content, St. Thomas would potentially provide residents with a consistent viable source of water through rainwater harvesting, dual plumbing, and water distribution for $2790 BBD per household. This could be economically viable for residents who are interested in purchasing a water tank to palliate water rationing would save them money over time. Harnessing the abundance of rainfall for household use appears to be a sustainable approach to mitigate water scarcity. Furthermore, using this as a framework for further projects globally can revolutionize the lives of people living under similar circumstances. With these innovative solutions, not only would residents be equipped with a sustainable solution to provide water, but run-off would be reduced, slowing down coral eutrophication.

Future Work

In designing the distribution system, the issue of bringing water uphill for the houses located at the highest elevations arises. The only way to accomplish this task is to pump the water back up. In the case of a power outage, which is likely during category 3, 4, or 5 hurricanes, any electrical pump would be non-functional. Solutions to this constraint could possibly be found in investigating mechanical pumps and ram pumps. Moreover, since this distribution system is shared, the cost to build and maintain it needs to be fairly distributed among residents.
In order to implement rainwater harvesting systems, awareness of its potential to solve environmental issues need to be raised within the Barbadian community. Building and testing the proposed design is left for future work.

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