Comprehensive Assessment Methodology for Urban Residential Rainwater Tank Implementation

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Abstract: Rainwater tanks are increasingly being implemented as part of the integrated urban water management paradigm where all sources of water, including potable, stormwater and recycled, are considered eligible to contribute to the urban water supply. Over the last decade or so, there has been a rapid uptake of rainwater tank systems in urban areas, especially in Australian cities, encouraged through financial incentives, but more importantly, from change in residential building codes effectively mandating the installation of rainwater tanks. Homes with rainwater tanks in Australian cities have increased from 15% to 28% over six years to 2013. These building codes specify certain rainwater tank specifications to achieve a stated rainwater use, and hence potable water savings. These specifications include minimum rainwater tank size, minimum connected roof area, plumbing for internal supply for toilets and washing machines, and external supply for garden watering. These expected potable water savings from households are often factored into regional strategic water planning objectives. Hence if rainwater tanks do not deliver the expected saving due to sub-standard installation and/or poor maintenance, it will have an adverse impact on the regional water plan in the longer term. In this paper, a methodology to assess the effectiveness of a government rainwater tank policy in achieving predicted potable water savings is described and illustrated with a case study from South East Queensland, Australia. It is anticipated that water professionals across the globe should be able to use the same methodology to assess the effectiveness of similar rainwater policies, or indeed any other distributed water saving policy, in their local planning communities.

Keywords: rainwater tanks; water supply; water quality; community consultation; economics

1. Introduction

Integrated Urban Water Management (IUWM) and Water Sensitive Urban Design (WSUD) approaches are increasingly being implemented to help address the water challenges of urbanization, population growth and climate change impacts. Many cities across the world are facing a shortage of freshwater resources due to population growth and long term trends in rainfall reduction. Conversely, there are increases in wastewater and stormwater flows due to urban growth and increased housing density. These responses are further complicated by climate change, resulting in reduced rainfall and increasing evaporative demand.

Under IUWM approaches, alternative local water resources are promoted as *fit for purpose* end uses to replace traditional potable water resources through decentralised systems [1]. These resources are rainwater, stormwater, recycled water and greywater. Rainwater is defined as water collected directly from roofs before it reaches the ground, whilst stormwater is the runoff generated from rainfall once it impacts the ground. Various researchers have investigated the impact of rainwater harvesting on stormwater flows [2–5] and receiving water quality [3,6]. This paper covers the use of rainwater collected from household roofs into rainwater tanks for internal and external end uses, based on fit for purpose concepts. Rainwater tanks are generally highly valued in the community for both the personal benefit and as well as community water supply regardless of the reasons for owning a tank [7].

Australian states faced acute water shortage during the millennium drought (2001–2009) [8] and rainwater tank installations in urban areas were promoted through financial incentives and legislation. The Building Sustainability Index (BASIX) [9] in New South Wales (NSW), minimum regulatory requirements for achieving a 6-star water and energy standard in Victoria [10], and Queensland Development Code MP4.2 [11] in Queensland are some of the examples for enforcing rainwater tank installations through regulatory means. Chubaka et al. [12] have discussed in detail the regulations and specifications for rainwater tank installation in Australian states. However, to fully understand the effectiveness of such legislation, a comprehensive assessment protocol covering biophysical, economic, environmental and social aspects is required.

This paper describes a comprehensive methodology developed for the assessment of the effectiveness of a major rainwater tank policy implemented in South East Queensland, Australia [11]. The application of the methodology has been demonstrated in a case study example in the same region. It is anticipated that the methodology described here can be used by water professionals/water supply regulatory agencies on any part of the globe to assess the likely effectiveness of initiating a major rainwater policy or, indeed, any other potable water saving/substitution policy based on distributed technologies.

2. Growth of Rainwater Tank Uptake in Australia

Campisano et al. [13] have described the implementation and uptake of rainwater harvesting systems in Africa, Asia, Australia, Europe and America. Rebate programs, education and development regulations have effectively promoted the installation of rainwater tanks in Australia [14]. The millennium drought and sustainability legislation such as the BASIX program in New South Wales [9], Queensland Development Code MP4.2 [11] and 6-star standards for all new class 1 buildings [10] have seen a rapid growth of rainwater tanks over the last decade in Australia [15]. The capital expenditure (CAPEX) for rainwater supply was of the order of Aus $2 billion. The uptake of rainwater tanks in Australian cities is shown in Figure 1 [16]:

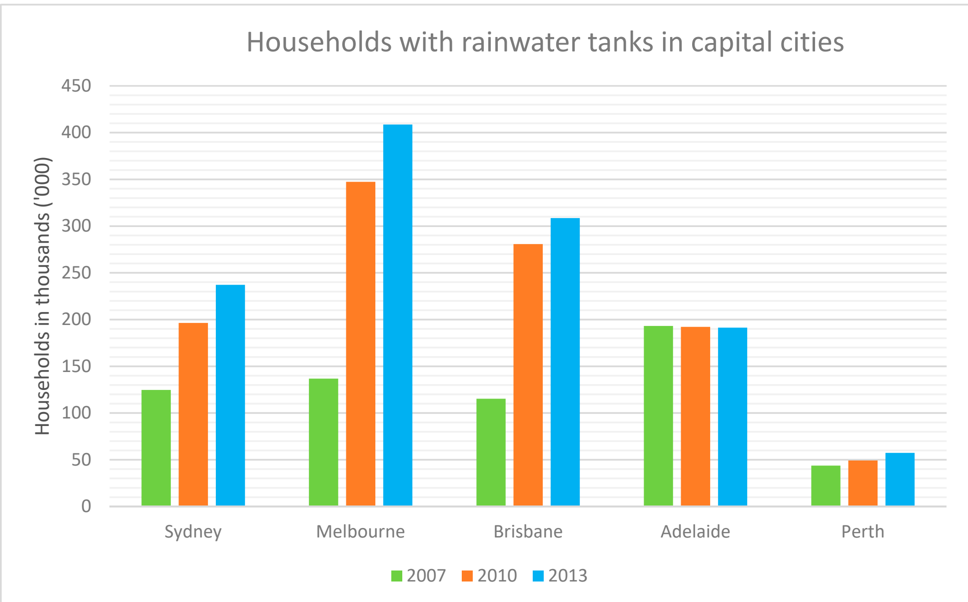

Figure 1. Rainwater tanks in capital cities in Australia [16].

It can be seen from Figure 1 that the rainwater tank uptake has increased significantly in Sydney, Melbourne and Brisbane cities between the years 2007 to 2013, while the growth of rainwater tanks in

Adelaide and Perth was more or less constant over these years. Regulatory approaches adopted in NSW, Victoria and Queensland states can be considered as the primary driving force in the increased uptake of rainwater tanks in Sydney, Melbourne and Brisbane.

3. Rainwater Tank Policy in Various States of Australia

Most of the Australian states (South Australia, Victoria, New South Wales, Queensland, Northern Territory and Australia Capital Territory), with the exception of Western Australia and Tasmania, have regulations/specifications for rainwater tank installation [12].

NSW Government introduced BASIX during 2004 [9]. It was a key planning policy requiring all new houses and units to be designed to use less potable water and generate less greenhouse gas emissions. It set a target of 40% less water use and 40% fewer greenhouse gas emissions than the average business-as-usual NSW dwelling. BASIX requires, inter alia, installing a toilet of minimum water efficiency (water star rating), installing a rainwater tank of a certain size, and connecting it to certain end uses (e.g., toilets and washing machines).

In Victoria, installing a rainwater tank can help in achieving the minimum regulatory requirements of the 6-star standard. To meet the 6-star standard with a rainwater tank, it must have a minimum catchment area of 50 square meters, have a minimum capacity of 2000 L, and be connected to all the toilets in the building [10].

Description of Queensland Development Code MP 4.2

Queensland Development Code MP4.2 [11] describes the state rainwater tank policy, an extract of which is listed below.

An installed rainwater tank system:

(a) has a minimum storage capacity.

- (1) of at least 5000 L for a detached Class 1 building
- (2) at least 3000 L for a Class 1 building other than a detached Class 1 building (described in next para);

(b) is installed to receive rainfall from.

- (1) a minimum roof catchment area that is at least one half of the total roof area or 100 m^2, whichever is the lesser;

(c) is connected to.

- (1) toilet cisterns and washing machine cold water taps and
- (2) an external use;

A Class 1 building is a single dwelling being a detached house, or one or more attached dwellings, each being a building, separated by a fire-resisting wall, including a row house, terrace house, town house or villa unit [17].

QDC MP4.2 [11] provisions are described in detail in the above section for the benefit of readers' ease to follow the paper.

QDC MP4.2 water-saving targets were formulated in 2008 based on a rainwater tank model that predicted that tanks in South East Queensland could supply 70 kilolitres per household per year (kL/hh/yr) [18]. Thus, on average, 70 kL/hh/yr of potable water resources should be saved by the implementation of rainwater tanks (one kL is one cubic meter (m^3)).

However, since 1 February 2013, rainwater tanks are now only required on new houses and/or commercial buildings where the local government has been approved to opt-in to the QDC. It is no longer a Queensland government requirement. Our comprehensive research was conducted during the mandatory QDC period (2008 to 2012), but we expect our findings will benefit the wider water community in assessing the effectiveness of similar policies, as well as local councils who wish to opt-in to the QDC.

4. Rainwater Tanks in Australia

Various studies were conducted in Australia to quantify the effectiveness of mains water saving from rainwater tanks. Sydney Water [19] conducted a 12-month study of rainwater tank water savings and their energy use in 52 real-world installations. On average, 38 kL/yr of rainwater was used, which substituted for about 20% of household potable water consumption. The actual demand for rainwater was 59 kL/yr, but only 38 kL/yr could be supplied. This shortfall was made good by potable water backup. Energy use by tank pumps was on average 78 kWh/hh/yr with an average energy intensity of 2.1 kilowatt hour (kWh) per kL. Ghisi et al. [20] reported on an average 41% potable water saving in southeastern Brazil. Smart Water Fund Victoria sponsored a survey of water savings and the physical condition of rainwater tanks in Melbourne metropolitan region [21]. Based on the results from 20 monitored households, rainwater usage was 31 kL/yr for indoor connection only households, 11 kL/yr for outdoor connection only households, and 42 kL/yr for homes where rainwater was used for both indoor and outdoor purposes. The average energy intensity used to supply rainwater was 1.7 kWh/kL. This study also conducted a visual inspection of 417 household tanks to understand the physical condition of rainwater tank systems. They found faulty automatic switches for backup flow (i.e., defaulted to potable supply), uneven foundations, the leaning of tanks against walls or fences, and a risk of mosquitos entering the tank. Twenty households with mandated rainwater tanks were also monitored in South East Queensland for measuring rainwater usage and thus freshwater savings. The study outcomes will be described in detail later in this paper.

Much of the evidence to support tank supply efficacy is generally limited to simple modelling, and/or monitoring water use from a limited number of household rain tanks. The Urban Water Security Alliance (UWSRA), Queensland, Australia, (http://www.urbanwateralliance.org.au) initiated an Aus $3 million research program to explore the yield, design, water quality, health, social, regulatory, management and economic aspects of rainwater tanks from a policy perspective. This study is described in detail in this paper as the case study example.

5. Comprehensive Methodology for Rainwater Tank Effectiveness Assessment

To achieve a sustainable and successful implementation of rainwater tank policy, we argue that tanks should be installed as specified in the associated code/guidelines, water quality management devices are installed, the community is willing to support the policy, management procedures for long term successful operation of rainwater are documented, and the economics of the rainwater supply is assessed. Finally, and perhaps most importantly, the average household should be able to save potable water volumes predicted by the rainwater tank model(s), which are documented in the associated codes/guidelines.

There has been a limited amount of research conducted on the comprehensive assessment of urban residential rainwater tanks policies. Consequently, an assessment methodology was developed under a Queensland UWSRA-funded project to understand the effectiveness of the rainwater tank policy. The methodology involved six steps and provides a generic framework for water professionals to assess the likely effectiveness of similar policies. The framework is shown in Figure 2 and briefly described in this section. The application of this methodology is then described in detail, with a case study example and analysis of results. Comprehensive assessment included investigating rainwater usage by households, auditing of rain tank systems if installed as per local code, water quality of rainwater in tanks, level of community acceptance, need for management models to ensure on-going operation of tanks and economics of rainwater systems.

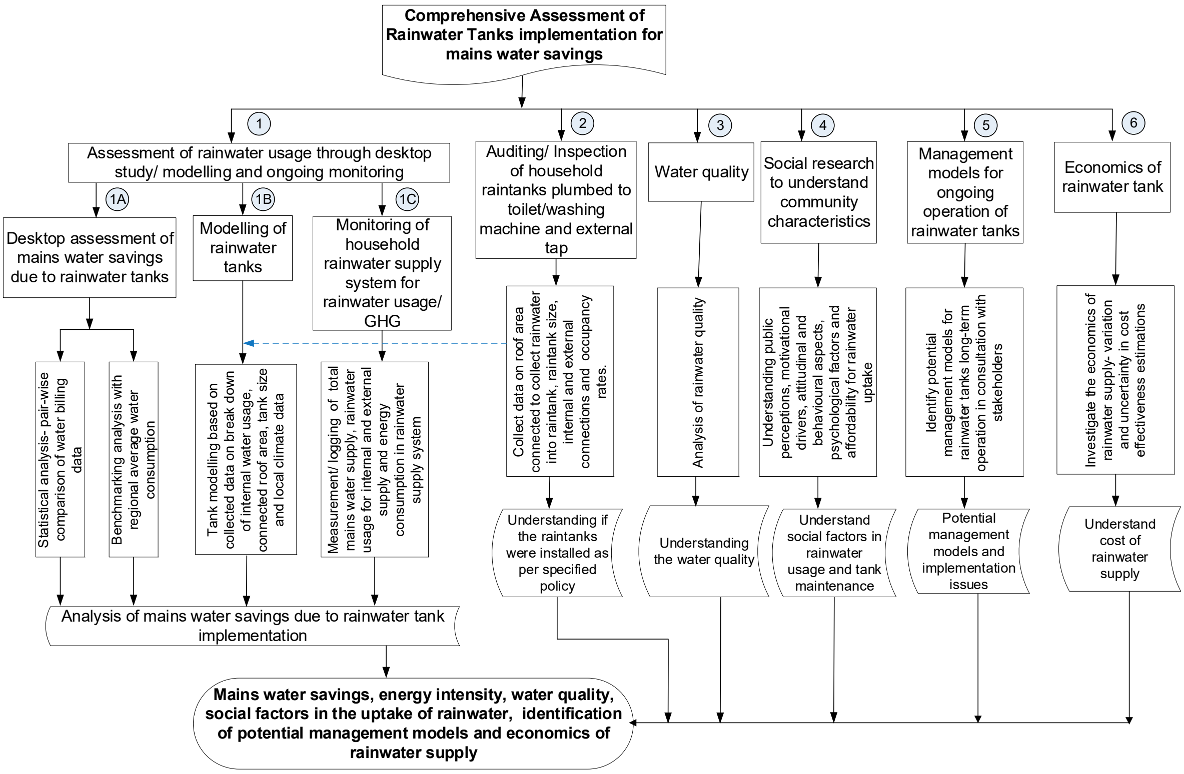

Figure 2. Methodology for a comprehensive assessment of household rainwater tanks for mains water savings.

The steps used for the comprehensive assessment of household rainwater tanks are briefly described below:

Step 1: Assess mains (potable) water savings through rainwater usage by conducting a desktop study, modelling and monitoring of rainwater tanks.

This step includes three activities:

(a) Desktop assessment of mains water savings due to rainwater tanks by comparing a large number of household water bills of similar homes (occupancy and size) with and without rainwater tanks over a period of a few years. The difference in potable water use between homes (+/− tanks) provides an estimate of rainwater usage by the household, and thus the amount of mains water saved.

(b) Rainwater tank modelling based on audited rain tank size, connected roof area, internal and external rainwater connections, water end use data based on recent studies and climate data. The modelling outcome provides a theoretical rainwater usage by the household, and is assumed to equal to the mains water saving.

(c) Physical monitoring of rainwater tank systems for rainwater usage by installing flow meters for actual rainwater use by a limited number of households. Energy meters to measure system electricity consumption are usually also fitted.

These three approaches provide both a statistically representative broad-scale estimate of savings as well as finer details to identify the validity of the various assumptions. The modelling predictions set the upper savings limit expected.

Step 2: Audit (physical verification) household rainwater tank systems for tank size (capacity), roof area connectivity as rainwater catchment and connections to toilets, washing machines and external taps, including any other requirements as per QLD MP4.2.

Step 3: Measure rainwater quality to assess its potential for other applications.

Step 4: Investigate the level of community acceptance of rainwater tank systems by conducting social research that addresses public perception, motivational drivers, attitudinal and behavior aspects.

Step 5: Investigate management protocols to ensure the long-term operation of rainwater tanks to achieve water savings as per strategic water planning for the region/area.

Step 6: Quantify the economics of rainwater tanks for rainwater supply and cost effectiveness of supply.

These steps are expected to provide a comprehensive assessment of the efficacy of rainwater tank implementation in order to understand if the desired policy outcomes are being achieved, as expected from QDC MP4.2.

6. Case Study for the Application of Comprehensive Assessment Methodology

Four local government authorities (LGA) (Caboolture, Pine Rivers, Redlands and Gold Coast) were selected as the case study areas in South East Queensland (SEQ), as shown in Figure 3. Caboolture and Pine Rivers were amalgamated into Moreton Bay Regional Council in 2012. These areas were selected due to their high annual growth rate (from 4.5% to 4.9%) and population numbers, resulting in growing water demands. The councils also had datasets with levels of reliable information that could be used (with permission) to extract consumption data for the required timeframes. The houses constructed post-2007 had rainwater that was plumbed to toilet(s), laundry cold water taps and external taps for garden supply [22,23].

Figure 3. Case study areas in South east Queensland: Map of the location of the 4 LGA that were used in the rainwater tank saving study from 2008 to 2012 (https://www.emerald.com/insight/content/doi/10.1108/02637470410570752/full/html).

7. Application of Comprehensive Assessment Methodology in a Case Study Area Application of comprehensive methodology is described in this section

7.1. Step 1: Assessment of Rainwater Usage to Understand Mains Water Savings from Rain tanks

The expected mains water savings from the implementation of rain tanks was investigated using three different approaches. It is assumed that the mains water saving equals the rainwater usage by the households. Based on QDC MP4.2 requirements, it was expected that each household had its rainwater supply plumbed to toilet cisterns, washing machine cold water taps, and external use, and was expected to save 70 kL/hh/yr of mains water [18].

The assessment of actual rainwater use can be estimated by desktop studies of household water bills, modelling using audited/measured input parameters, and monitoring of rainwater supply using flowmeters at household scale. The application of these approaches and associated outcomes for rainwater usage are described in the following sections.

7.1.1. Desktop Assessment of Rainwater Usage for Mains Water Saving

Household water bills can be used to estimate rainwater supply by comparing potable water use by demographically similar household cohorts with/without rainwater tanks. Two methods were used in this approach. In the first method (a), a pair-wise comparison of household water billing data, with and without internally plumbed rainwater tanks, was conducted to estimate the mains water savings and thus rainwater usage [22–24]. These paired households were selected on the basis of similar allotment sizes, roof areas and occupancy numbers. In the second method (b), water billing data from households with mandated rainwater tanks were compared with the suburb's average water usage, which was used as the baseline [24,25].

(a) The process for pair-wise comparison of household water utility water billing data is described in [23] and involves the following steps:

- Collect data for single-detached households (properties) on lot sizes, roof areas and occupancy rates from local councils and census data.
- Collect water billing data for selected properties.
- Separate No Tank properties from internally plumbed rainwater tank (IPRT) properties.
- Divide No Tank and IPRT properties data into groups based on lot sizes, roof areas and occupancy rates if required for each local council in the study area.
- Randomly pair each No Tank property with IPRT for each suburb (or postcode) with similar properties.
- Estimate the difference in annual water usage between No Tank and IPRT properties.
- The difference in water billing data of these two properties is rainwater usage.

One thousand one hundred eighty-two properties with rain tank and 68,828 properties with no tank were considered for developing similar pairs for analysis. Based on the pair-wise comparison of water billing data of households with (IPRT) and without rain tank (No Tank), an average mains water saving of 50 kL/hh/yr was estimated for the study year 2008. Council area specific mains water saving outcomes are shown in Table 1 [23]:

Table 1. Mains water saving in study area councils (LGA) for 2008.

Household Type	Average Water Consumption (kL/hh/yr)			
	Pine Rivers	**Gold Coast**	**Redland**	**Average**
No Tank	162	247	185	198
With tank (IPRT)	142	152	151	148
Savings	20	95	34	50

The households water billing data from the Caboolture local council was not analysed as this data was not sufficient to categorize whether a property was constructed pre- or post-2007 [22]. Only properties post-2007 would have rainwater tanks installed under QDC MP 4.2 [11].

The water savings shown in Table 1 are substantially different for three local councils and could have been caused by the level of water restrictions imposed by councils on the reticulated potable water supply. The most severe water restrictions in 2008 occurred in the Moreton Bay Regional Council area, which includes Pine Rivers. Outdoor watering using mains water was limited to only hand held buckets or watering cans until 1 August 2008, after which hand held hoses could be used. Gold Coast City Council had no restrictions between February and November 2008 due to high rainfall events overtopping their main water supply dam. Thus, there was no limitation to outdoor watering with mains water. Properties in Redland Shire Council were allowed outdoor watering only using mains water to occur with a hand-held hose both for established and new gardens [22].

(b) The second method of estimating water savings using population scale data involves comparing water use by IPRT households with suburban average water usage. It is briefly described here (but see [24,25] for a more detailed description):

- Identify single-detached households (properties) with IPRT from local councils.
- Collect water billing data and occupancy rate for IPRT properties.
- Collect average mains water use per person data for the respective water utility or local council for suburb under consideration.
- Based on water billing data for IPRT properties and respective occupancy rates, calculate per person water usage per day.
- Estimate the difference in IPRT properties per person water usage and average suburb water usage. The difference in mains water usage equals rainwater usage.

A total of 691 households across four LGA (Caboolture, Pine Rivers, Redland, and Gold Coast) were considered for benchmarking analysis. The benchmarking analysis provided mains water saving in different local council areas, as listed in Table 2 [25]:

Table 2. Average annual water savings in IPRT in four LGA during 2010 [25].

Local Council and Sample Size */ Description	Pine Rivers (197 *)	Caboolture (158 *)	Gold Coast (172 *)	Redland (164 *)
Average person per household	3.21	3.20	3.34	3.18
Average daily mains water consumption in local council area in liters/person/day (L/p/d)	143.3	143.3	192.0	183.10
Average daily mains water consumption per person in households with IPRT (L/p/d)	109.40	108.20	125.70	121.90
Average daily mains water saving per person in households with IPRT (L/p/d)	33.90	35.10	66.30	61.20
Average annual water saving in household with IPRT (kL/yr)	39.7	40.9	81.0	71.0
Average overall annual saving in mains water per IPRT household	58 kL/hh/yr			

* sample size of household billing data.

7.1.2. Modelling of Rainwater tanks for Water Usage Based on Actual Household Raintank Data

Here, rainwater tank usage per household is estimated from water balance modelling using measured data on household occupancy numbers, raintank capacity (kL), roof area connected to raintank, connected end uses, and daily rainfall. The data was collected by contacting households and physical inspection/auditing of IPRT properties. The audited rainwater supply connections for each inspected dwellings were used in conjunction with water demand published in end-use studies in SEQ for toilet cisterns and laundry purposes [22,26].

The estimated rainwater usage, and thus potable water savings, for 18 households using tank modelling and nearby climate data for 2009 is listed in Table 3 [27].

Table 3. Average modelled annual water savings in 18 households in four LGA in SEQ for 2009 [27].

Household Number	Annual Rainfall (Average) (mm/year)	Occupant (Average)	Active Tank Volume (Average)	Roof area Connected to Tank (Average)	Connected Cisterns + Washing Machine Cold Tap (Average)	Modelled Rainwater Usage (Average/Year)
18	1406 mm	3	4.79 kL	81 m^2	2 + 1	49 kL

The modelling was extended over a 40-year period using climate data from 1972 to 2011. The average rainwater usage was 53 kL/hh/yr [27]. Only a low number of households (18) were considered for raintank modelling due to available actual data on limited properties at the time of study. The modelling was conducted based on daily time step, as also suggested in [28].

Another rainwater tank modelling study used a stochastic simulation approach, which allowed an iterative evaluation of a deterministic raintank model using a set of random numbers drawn from probability distributions assigned to each input variables [29]. The input parameters for tank size and roof area connected as rainwater catchment were sourced from Biermann et al. [30], which are described in Section 7.2. Using climate data from 1961 to 2011, Maheepala et al. [29] estimated expected rainwater yields for Moreton Bay (which includes Pine Rivers and Caboolture) and Gold Coast of 43 and 44 kL/hh/yr, respectively. These raintank yield values represented median value from 10,000 stochastic simulation runs. Using a similar modelling approach considering 33,720 scenarios, Custodia and Ghisi [31] reported 41% of potable water saving when rainwater is used in toilets and washing machines.

7.1.3. Monitoring of Household Rainwater Tanks for Water Usage and Energy Consumed

Monitoring of rainwater tanks allows the quantification of actual rainwater usage. It is conducted by metering the rainwater used for internal and external end uses [32,33]. The installation of flow measuring instruments for the monitoring of rainwater tanks involves the following steps:

- Select a representative number of IPRT properties from local council area.
- Collect information on IPRT properties for lot size, roof area, garden area, rainwater tank supply for internal and external uses, and occupancy rate.
- Install instrument in selected homes for measuring hourly rainwater usage and electricity consumed.
- Collect local rainfall data for the monitoring period.
- Monitor for ≥12 months to cover seasonal variability.
- Calculate annual rainwater usage from the recorded data.
- Estimate energy required (kWh/kL) for supplying rainwater.

The main drawback of this approach is that the high cost of instrumentation (AUD 5000 per house) limits the number of households that can be recruited in any one year. Hence only 20 households were instrumented for rainwater use monitoring over a period of 12 months (April 2011 to March 2012). The selected sample houses were reasonably well distributed across the local government areas of Pine Rivers, Caboolture, Redlands and Gold Coast. The local rainfall at the 20 homes during this period was obtained from the nearest gauging station, and ranged from 1376 to 1952 mm [33]. The survey data showed the average rainwater tank capacities for the 20 households was 5.7 kL (range 2.5 to 7.6 kL) and the average roof rainwater catchment area was 81 m^2 (varied between 27 and 135 m^2).

The average total water usage for the 20 households was 136 kL/household over an 11 month period, with 36 kL/household supplied from rainwater. Due to remote data transfer and the distributed locations of monitoring sites across four local councils, only 11 months data could be collected for all the sites. It was due to time taken in fixing data collection/transfer/system-related issues at remote locations immediately. Scaled up to a 12 months period, rainwater supply was 40 kL/hh/yr from a total water use of 151 kL/hh/yr. The average energy consumption in supplying rainwater was 1.52 kWh/kL.

Taken overall, it could be concluded that annual mains water savings was in range of 40 to 58 kL/hh/yr with an average of 49 kL/hh/yr, which is significantly short of the expected annual savings of 70 kL/hh/yr. The pairwise comparison of household 2008 water billing data with and without rainwater tanks was based on 1182 data sets indicating a mains water saving of 50 kL/hh/yr. The comparison of 2009 and 2010 water billing data of 691 households having rainwater tanks concluded a potable water savings of 58 kL/hh/yr. Similarly, the modelling of 18 households rainwater tanks in 2009, and the monitoring of 20 households with rainwater tanks in 2011–2012 estimated 49 and 40 kL/hh/yr, respectively. Generally, these studies were conducted in different years with different sets of households data. Adoption of any of the described methods will depend upon the availability of data over a period of time, and financial resources. The metering of households can provide the most reliable outcome, but is expensive if a statistically significant number of households are monitored.

7.2. Step 2: Physical Verification of Household Rainwater Tanks

We argue it is essential to confirm if rainwater tanks installations are conducted as per specifications in the policy document. If the tank systems are not installed as per the policy, the projected potable water savings cannot be fully achieved and may have serious implications on regional water supply planning. The post installation auditing and inspection of IPRT households were conducted to assess if the tanks were installed of specified size, connected to the required roof area, and rainwater connected to the specified end uses. Under QDC MP4.2, a household must have a ≥5 kL tank connected to a catchment roof area of 100 m^2, and rainwater supplied to toilet cistern, washing machine cold tap and external use.

The physical verification of household rainwater tanks can be conducted using the following steps [21,30,34]:

- Select a local council(s) or a region for physical verification of households covered under the policy for rainwater tank installation.
- Identify the total households in the selected area where rainwater tanks were installed under the policy.
- Identify a representative number of households required for physical verification based on a statistical measure of the required accuracy.
- Collect information on characteristics of individual dwellings (e.g., dwelling type, total roof area, property dimensions) for required number of households.
- Collect information on the rainwater tank systems (e.g., tank volume, roof area connected, pump size).
- Record internal connections for rainwater supply (e.g., plumbing connections to/from the tank).
- Record other water related features on the property if required (e.g., swimming pool, spa).
- Analyse the collected data for rainwater tank size, roof area connected as catchment and internal and external application of rainwater for toilet cisterns, washing machine cold taps and external uses.

A phone survey was conducted among 1134 household participants to recruit households for auditing rainwater tank systems for installation as per provisions in QDC MP4.2 and collecting baseline information from households on their rainwater tank system [25]. Based on the collected information through the phone survey, it was concluded that 78% of the rainwater tanks were ≥5 kL; 87% of the houses had two or more downpipes connected to their rainwater tanks; 97% of householders used rainwater for toilet flushing, 94% clothes washing and 77% for garden irrigation. No information could be collected about the connected roof area with rainwater tanks, which was an important factor for rainwater collection. Two hundred and twenty-three households in four local councils consented for their rainwater tank system to be inspected, as per Table 4 [30]:

Table 4. Household sample and population sizes [30].

LGA	Number of Sites Inspected	Number of Dwellings with Tanks
Caboolture	59	4000
Gold Coast	45	3300
Pine Rivers	78	5000
Redland	41	3300
Total	223	15,600

There were a total og 15,600 properties with rainwater tanks in four local councils (LGA) of the case study area. The actual sample size was small (due to limited funding availability) given that around 1000 households were required for a margin of error of +/− 3%, increasing to around 6000 for a margin of error of +/− 1%.

7.2.1. Roof Area as Rainwater Catchment (Connected Roof Area to Supply Rainwater to Raintank)

The average roof area of 223 households was estimated based on the dimensions of the house. The calculated roof areas were 310, 326, 281 and 294 m^2 for Caboolture, Gold Coast, Pine Rivers and Redland, respectively, with an overall average of 300 m^2. QDC MP 4.2 required that rainwater tanks should be connected to either a minimum of 50% of total roof area or 100 m^2, whichever is the lesser. An indirect method was developed to estimate the roof area connected to the rainwater tank, as described in Biermann and Butler [30,34].

Based on the connected roof area and total roof area estimations, it was found that only 60% of homes met QDC MP4.2 requirements, as listed in Table 5.

Table 5. Connected roof area (m^2) and % of total roof area connected to rainwater tanks across four LGAs [30].

LGA	Total Sites within Area	Connected Roof Area (m^2)					Number Comply	* % Comply
		<80	80–100	100–200	>200	Average Roof Area		
Caboolture	53	14	5	28	6	119	34	64%
Gold Coast	39	12	7	15	5	136	21	54%
Pine Rivers	76	23	10	37	6	110	44	58%
Redland	38	9	7	18	4	113	24	63%
Total	206	58	29	98	21	118	123	60%

* % overall compliance is based on the lesser of 50% of total roof area or 100 m^2 (as per QDC MP 4.2).

7.2.2. Rainwater Tanks Size

Out of 223 households, tank volumes for 180 sites could be calculated. For the remaining 43 sites, there were insufficient dimension data available due to tanks being underground, inaccessible for measurement, or irregular in shape. As shown in Table 6, 84% of household tanks met the QDC MP4.2 requirement [34].

Table 6. Calculated on-site rainwater tank storage volumes (vol.) [30].

LGA	Number of Sites with Tanks of Different Volumes								Compliance	Tank Volume (kL)
	* No vol.	<4 kL	>4 < 5 kL	>5 < 6 kL	>6 < 7 kL	>7 < 10 kL	>10 kL	Total	% Comply	Average/ Median
Caboolture	12	4	7	26	4	1	5	47	77%	6.8/5.6
Gold Coast	12	0	4	17	7	3	2	33	88%	7.5/5.7
Pine Rivers	10	4	3	43	11	3	4	68	90%	6.1/5.7
Redland	9	2	5	19	1	1	4	32	78%	6.5/5.4
Total	43	10	19	105	23	8	15	180	84%	6.6/5.7

* number of tanks volume could not be estimated.

7.2.3. Rainwater Supply Connections to Toilets, Washing Machines and External Uses

QDC MP4.2 required rainwater tanks to be connected to toilet cisterns, washing machine cold water taps and external uses. The majority of sites inspected were fully in compliance with the requirement.

The following outcomes were drawn on the compliance with QLD MP4.2 requirements, based on the physical verification of 223 households [30,34]:

- Installed tank capacity was mostly equal/above the required 5 kL. Sexteen percent of sites inspected had storage volumes of below 5 kL.
- Roof catchment area connected to rainwater tank did not meet requirements in 40% of cases, either in terms of having 100 m^2 or 50% of total roof area.

- Connection to toilets, washing machines and external taps met requirements in most cases.

Thus, the main issue with the rainwater installation was the connected roof area in 40% of the households, and the 16% of households with rain tanks smaller than the required 5 kL. Taken in combination, these two factors would reduce rainwater capture and availability and are most likely responsible for not achieving the 70 kL/hh/yr water savings target.

7.3. Step 3: Water Quality Assessment

Health agencies do not recommend the use of rainwater for potable applications in urban areas with a reticulated water supply system. However, rainwater is used for potable uses in rural and many peri-urban properties in the absence of mains water supply systems. Around 10% of Australian households are dependent on rainwater tanks as their main source of water [16]. Thus, investigation of local rainwater quality is essential to select appropriate end uses based on local drinking water guidelines and to assess if rainwater could be extended to potable applications in areas with piped water supply. Generally, the rain tank water quality is influenced by roof material, catchment parameters, precipitation events, local weather, chemical properties of the pollutants, and local environmental conditions [35,36].

Magyar and Ladson [37] indicated that lead has been found to exceed drinking water standards in many tanks, followed by excessive cadmium concentrations. They estimated that around 22% of tanks in Australian cities are expected to have high lead concentration, exceeding the drinking water guidelines of 10 mg/L [38]. Overall, they concluded that the chemical quality of rainwater in tanks is of concern if tank water were to be used for potable purposes. Due to the availability of significant information on the physical/chemical water quality of rainwater tanks in the public domain [37,39], the South East Queensland project focused on the microbiological quality of the rainwater in tanks.

A review paper published by Ahmed et al. [40] highlighted that there is no information on the prevalence of different pathogens in rain water tanks over time, and suggested a longitudinal sampling scheme for the occurrence and numbers of potential pathogens was required.

An investigation into the microbiological water quality of roof captured rainwater should focus on both faecal indicators and bacterial pathogens [41,42], given that faecal coliforms may not be suitable to indicate the risk of illness from untreated rainwater due to their poor correlation with actual pathogens [43].

Consequently, a qualitative detection of faecal indicator bacteria and pathogens in rainwater tank samples was conducted to investigate the microbial water quality in tanks. The following steps were adopted in this investigation [41]:

- Selection of households for rainwater sample collection and concentration of water samples.
- Possum and bird faecal sampling—to identify the source of faecal indicator bacteria and pathogens.
- Use of membrane filtration method to process the tank water samples for the enumeration of faecal indicator bacteria [44].
- Quantitative polymerase chain reaction (qPCR) analysis of samples.

Based on microbiological analysis of rainwater samples collected from 80 household rain tanks and faecal samples of birds (38 samples) and possums (40) samples, Ahmed et al. [41] reported the following:

- The number of *E. coli* in rainwater ranged from 0 to 4800 CFU per 100 mL of water, with an average of 180 CFU per 100 mL.
- Fifteen percent (12 samples), 1% (1 sample), and 7% (6 samples) were positive for the pathogenic *Campylobacter* spp. 16 S rRNA, *Salmonella invA* and *G. lamblia* β-giardin genes, respectively.
- The sources of these pathogens were most likely to be local bird and possum as their faecal samples were found to contain *Campylobacter* spp. 16 S rRNA, *Salmonella invA*, *C. parvum* COWP and *G. lamblia* β-giardin genes, with the actual percentage varying between samples.

Ahmed et al. [41] concluded that the presence of pathogens along with faecal indicator bacteria indicate poor water quality, which poses a potential health risk to end users, especially if rainwater is used for drinking and kitchen purposes. They concluded that any extension of rainwater for other potable substitution purposes, such as drinking and showering, would not be suitable unless an effective disinfection process is implemented.

However, Rodrigo et al. [45], after undertaking a rigorous epidemiological study into 300 households, concluded that consumption of untreated rainwater does not contribute significantly to community gastroenteritis, but they did give a caveat that their findings should not be generalized, as susceptible and immunocompromised persons were not part of the study.

7.4. Step 4: Social Research to Understand Community Characteristic

Social research was conducted to understand community views on the adoption and acceptance of rainwater tanks implemented under QDC MP 4.2. Chong et al. [46] reported that most of the 1134 survey participants (households with mandated rainwater tanks) used rainwater for toilet flushing and laundry application, while 77% also used it for garden irrigation. The participants were happy to accept rainwater tanks and used rainwater around their houses.

Mankad et al. [47] reported outcomes from a mail out survey which recruited 754 households from an approach to 6100 homes with mandated tanks in four local council areas in SEQ. In urban areas, rainwater is not recommended for drinking and cooking by health authorities, and as expected, a low rate of rainwater for these applications was reported (<3%). In contrast, over 90% of households used the rainwater for toilet flushing and clothes washing, end uses encouraged by QDC MP 4.2. The survey also collected data on householder knowledge of their rainwater system. Almost 50% of participants were not aware of the automatic mains water switching device installed on their tanks, which was an essential component of mandated rainwater tanks [48]. This device provides seamless continuity of water supply if rainwater is not available in the tank. As the device "fails" in the open position, there is the potential to bypass the tank continuously, irrespective of tank water levels. Mankad et al. (2014) further highlighted that mandated tank owners were not maintaining their tank regularly, and even basic maintenance activities associated with checking mosquito-proof screens and first flush devices were performed poorly. It was suggested that education campaigns to enhance knowledge of rainwater tank systems and their maintenance among homeowners would help in securing a long-term rainwater source [48]. Encouragingly most participants reported they would be happy to maintain their rainwater tanks themselves or with assistance from the local council, provided they had appropriate information. An earlier study [49] found that participants with retrofitted rainwater tanks (an initiative of the householder) were more likely to engage with tank maintenance than mandated rainwater tank owners. It was also suggested that there is a need for state agencies to pay attention to households with mandated rain tanks to encourage greater engagement with their tanks and attain a greater knowledge of tank functioning [50].

In an earlier study, Gardiner et al. [14] investigated maintenance practices, reuse behaviors, and motivations of tank owners and reported that mandated tank owners have yet to learn to maintain or utilise their tank water effectively to reduce mains consumption. Personal engagement in households with mandated rainwater tanks was missing [7], and most of the households with mandated tanks treated them as part of the standard household plumbing [51]. These household were not learning about managing and maintaining their tanks and were more likely to stop if problems arose, rather than investing resources for their maintenance [7].

In a more recent study on rainwater tanks in Melbourne, Moglia et al. [21] investigated 417 householder attitudes to their rainwater tanks, which may impact on the ongoing operation and maintenance of rain tanks. Their survey indicated that 93% of the households were satisfied with their tanks.

7.5. Step 5: Management Models for Ongoing Operations of Rainwater Tanks

Rainwater tank management from a policy perspective involves ensuring that rainwater tanks perform as per design over a long period and minimize any public health risks. The inadequate management of urban rainwater tanks will result in failure to achieve the water-saving target as well as pose a public health risk due to water quality issues [52,53]. Due to the promotion of rain tank installation under rebates, education and regulations, a clear need for developing management strategies to address the effective use and maintenance of tanks was also highlighted by Gardiner et al. [14].

The maintenance of the rainwater tanks is the responsibility of homeowners, although tanks provide benefits to the wider community [54]. In order to provide problem definition and help develop management models for their long-term operation, a number of studies have been undertaken by various researchers [52–55].

Basically, to investigate possible management models, the following activities are recommended:

- Conduct survey and interviews with water professionals and other stakeholders to understand their perceptions and judgements relating to rainwater tanks' conditions and maintenance.
- Organise workshops with stakeholders to develop options for management of rainwater tanks in case study area context and evaluate their likely acceptability.
- Conduct focus group surveys to explore the views and attitudes of the community towards various policy options for rainwater tank management and the preferred options for ensuring the ongoing performance of household rainwater tanks.

Moglia et al. [54], investigating the need for governance protocol, interviewed key stakeholders and organised a web-based survey of over 250 professionals associated with rain tanks for their perception on rain tank issues, risks, management and governance needs. They reported that the professionals' perception of rain tank failure rates was high, and that rain tank inspections and regular maintenance were critical to ensure that the tanks were operating as intended. Based on the survey of professionals, four main failure modes of rainwater tanks were reported: (1) pump malfunction, (2) structural integrity of tank, (3) mosquitoes breeding in tank are potential for transmission of disease, and (4) poor water quality. The survey also reported that lack of and/or incorrect operation and maintenance were viewed as the major cause of rainwater tanks failure. In spite of this, the professionals argued that responsibility for regular inspections, operation and maintenance should still be retained by homeowners. Hence, homeowners should be encouraged/assisted to maintain their rain tanks.

Walton et al. [55] reported the outcome of a workshop aimed at exploring various management options for rainwater tanks. Thirty stakeholders participated from state government, regulatory entities, utility companies, local government, academia and industry. Thirty-five overlapping strategies were identified, which were grouped into five strategic themes for further discussion. The five themes were [55].

(i) Self-management strategy: Under this strategy, tank owners would independently undertake tank maintenance. However, the government would provide support to facilitate and enable tank maintenance.
(ii) Home-based service: This type of strategy was modelled on the current "Climate Smart" program, with the aim of providing an inspection service requiring a small co-payment from the tank owner.
(iii) Changes to regulations and codes to improve design and installation: This option was based on the belief that the prevention of problems could be influenced significantly by improving tank design and installation.
(iv) Create a register of tanks: A register of tanks would provide information on tank assets within the region and allow the evaluation of any policies related to maintenance.
(v) Regulate ongoing maintenance: New regulation to ensure the ongoing maintenance of the tank through regular inspections and associated penalties.

The workshop participants also observed that applying regulation to tank maintenance was likely to be difficult, expensive, de-motivating and interpreted by households as overregulation. Based on these political realities, self-management and improvements to the design and installation codes were the most-preferred strategies [55].

Walton et al. [55] also reported the outcome of focus group surveys, which explored the views and attitudes of community towards various policy options for rainwater tank management and the preferred options for ensuring ongoing maintenance and management. The five themes listed above provided the foundation for workshop discussions. Focus group participants were aware of the need for tank maintenance and that there was support for self-management approaches, improvements to standards that govern design and installation, and home-based services similar to the Climate Smart program. However, there was minimal support for periodic inspections aimed at ensuring ongoing maintenance. Nonetheless, tank inspections at the point of house sale was supported if it were integrated into the current pest and building inspection reports. Any strategy involving registration of tanks was viewed most negatively [55].

It could be concluded that management of rainwater tanks by homeowners would be the best option, however homeowners should be supported by providing them information on tank maintenance.

7.6. Step 6: Economics of Rainwater Tanks

The economics of rainwater supply was assessed using a cost effectiveness analysis method, which considers capital and operating costs of service provision. The unit cost of rainwater supplied over the life span of the rainwater tank system is one way of conducting such an economic analysis [56,57]. The analysis used the following steps [56,57]:

- Identify the objectives and limitations

Clearly define and justify the costs (capital, replacement required including operation and maintenance) over the life of services provided. Generally, the capital cost of installing rainwater tank and recurring cost of ongoing operation and maintenance are incurred by the households, although governments sometimes provide subsidies (financial incentives). In this analysis, these incentives were not considered.

- Identify the data variation and uncertainty

The cost effective analysis is based on different sets of data (e.g., rainwater yield per year and cost data), which may have high variability and uncertainty. The estimation of rainwater yield from an installed rainwater tank system using available models or monitoring techniques will have some uncertainty. There will also be uncertainty in future costs (tank, pumps and other accessories), interest rates, electricity charges for running a pump and potable water charges.

Cost Effectiveness Estimation

The cost effectiveness can be measured using different approaches. The unit cost estimation was adopted for this analysis, where the cost of rainwater supplied per kL is estimated. It is to be noted that positive externalities (e.g., reduced flooding, better stormwater quality, greening the area, reduced capital expenditure by water authority) and subsidies were not considered in this analysis.

The following steps were adopted for conducting economic assessment of rainwater tanks [56]:

- Select the geographical region (local councils) for the cost effectiveness assessment of rainwater tanks.
- Calculate average rainwater yield for each region/local council based on literature and current studies conducted for the region.

- Collect data for the capital cost of the rainwater tank, pumps, installation cost, pumping cost for end use and maintenance cost associated with the rainwater tank system.
- Select analysis period and discount rate.
- Select a suitable economic assessment method.

Based on the above steps, four regional councils (Moreton Bay, Sunshine Coast, Ipswich and Gold Coast) in the study area (SEQ) were selected for the economic analysis. The analysis period of 50 years and a discount rate of 3% was adopted. The most likely cost of rainwater tank ($1544), pump ($790), plumbing ($900) and tank installation ($250) were adopted, based on 2012 prices [57,58]. The annual operating cost was based on specific energy use of 1.48 kWh/kL, electricity cost of $0.23/kWh, energy price growth rate of 5%, and annual maintenance cost as AUD 20/year [56]. The life of the pump, rain tank and plumbing was adopted as 10, 25 and 50 years, respectively. The likely rainwater yields from tanks ranged from 34 to 48 kL/yr, reflecting variation in regional rainfall.

Levelised cost was calculated as

$$\text{Levelised cos t} = \frac{C + \sum_i^n \frac{A_i}{(1+r)^i}}{\sum_i^n \frac{Y_i}{(1+r)^i}} \tag{1}$$

where C = capital cost, A = annual costs, r = discount rate, Y = annual yield of rainwater, i = year and n = period of analysis.

The mean levelised cost of rainwater supply in Moreton Bay, Sunshine Coast, Ipswich and Gold Cost was estimated to AUD 8.97/kL, AUD 7.62/kL, AUD11.17/kL and AUD 8.90/kL. These values were considerably higher than the cost of mains water supply in the region during 2013/2014 (about AUD 4.70/kL based on [59]). When the analysis period was reduced from 50 years to 25 years, and the discount rate increased from 3% to 6%, the mean levelised cost changed from $9.22/kL to $14.11/kL [56].

Based on cost considerations alone, the average cost of rainwater supply of AUD 9.17/kL is significantly higher than that for reticulated mains water supply. Interestingly, the raison d'etre by the Queensland government to repeal MP4.2 in 2013 was largely based on a similar type of economic analysis. Thus, decisions to adopt/mandate rainwater systems should be based not only on economic considerations but also on the environmental/social benefits which could include avoided stormwater quality improvement infrastructure such as raingardens and encouraging a resource conservation ethic. Similar aspects in the economic assessment of rainwater systems are reported in [60].

8. Conclusions

A comprehensive assessment methodology has been presented for investigating the effectiveness of mandated rainwater tanks under state policy. This method can be adopted for the assessment of similar rainwater tank policies or any other distributed water-saving policy nationally and internationally by water professionals.

Based on the application of this methodology in South East Queensland, the following conclusions are made:

- The rainwater supply was around 49 kL/hh/yr against an expected 70 kL/hh/yr, as outlined in the policy document. This will have significant implications on the water planning for the region as rainwater use generally equals avoided potable water use.
- Post installation surveys have identified that about 40% of households rainwater tanks were connected to less than specified roof areas, whilst 16% of the households had rain tanks less than the specified 5 kL. The combination of these two factors would have contributed substantially to not achieving the 70 kL/hh/yr target.
- There is also a need to revisit the background rainwater tank modelling investigation adopted in developing the rainwater usage target of 70 kL/hh/yr [11,18]. The modelling outcomes provide results assuming ideal conditions. Sometimes the assumptions used in the modelling are over

optimistic, which can be significantly different from real-world system implementation and bio-physical factors. In this investigation, appreciable differences in the connected roof catchment area, tank size, and per household water use were observed, resulting in a rainwater usage of around 49 kL/hh/yr. It is concluded that practical considerations and potential variability in bio-physical parameters in developing any such policies should be factored in to allow the achievement of realistic outcomes.

- Microbiological quality of rainwater supply from tanks was not suitable for any potable application without first incorporating an effective disinfection process. Moreover, homeowners should be careful about the chemical quality of rainwater, especially lead.
- The community has a high acceptance of both installing rainwater tanks and for using rainwater inside the house. However, there seems lack of interest in maintaining rainwater tanks by the mandated tank householders. This will be detrimental in achieving the full water savings potential of tanks. There is a need for state agencies to encourage greater engagement of householders with their tanks and improved knowledge of tank functioning. Maintenance of rainwater tanks by homeowners appears the most practical option; however, homeowners need to be supported by providing information and training on tank maintenance.
- The cost of rainwater supply is significantly higher than mains water based on cost considerations only. There is a need to consider environmental benefits from rainwater tank implementation from a community perspective to justify rainwater usage.

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