LET'S TALK
WATER

Master thesis

LEVERAGING ROOFTOP RAINWATER HARVESTING IN CHENNAI, INDIA

By Camille Fong

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COLOPHON

Leveraging decentralized rooftop rainwater harvesting system to mitigate Chennai's water challenges using a multi-purpose approach

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"I lived in Chennai for more than five months and was able to integrate myself in the culture and living style of chennaiite. This experience has not only given me the opportunity to understand better the people and the system but also to understand what it actually means living in a city with water scarcity. Their struggle has become my struggle as there was time without water or brown water flowing out of my shower nozzle, even within my university campus. Being ‘on the ground’ has definitely helped me to dive into the complexities of the system which is not reflected on papers or online sources. It is also useful to get ground data and people’s stories when working in a data scarce environment. It is very interesting to see how the water system is not only shape by the infrastructure itself, but also the politics, the users, the informal agreement between parties and how, at the end of the day, the water system finds its way to provide water to all."

CAMILLE FONG

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Camille Fong
Chennai, India

Photo : Local workshop in Chennai organized by WaL on March 6-7, 2019. From left to right: Naveed Khan (Arcadis), Jarl Kind (Deltares), Rogier van den Berg (UN-Habitat), Hans Gehrels (Deltares), Aaron Vermeulen (WWF), Shantha Sheela (retired IAS officer) and Camille Fong (TU Delft student)

PREFACE

The flood of 2015 in Chennai hit the city significantly, causing thousands of people to be stranded and trapped without power for several days. An estimated 188 people died, and damages and losses were between US$3 billion to over US$14 billion, pressing Chennai city to implement alternative solutions to mitigate future climate disasters such as floods and droughts. This extreme event has triggered the Dutch government to launch in April 2018 the "Water as Leverage (WaL)", a global water innovation program that aims at identifying interventions to tackle urban water challenges and build resilient cities in Asia, including Chennai city. The program was a nine-month-long collaboration in which the teams had to identify the major water problems and propose a conceptual design to address them. The author went to Chennai for seven months from January to July 2019 to understand the ground realities regarding the current water challenges experiences by the communities. Using the lens of a researcher, the topic of this thesis on leveraging rooftop rainwater harvesting (RRWH) emerged from this journey in Chennai, India.

The project location for this research is the Mambalam sub-catchment, located in the historical center of Chennai. It was chosen based on the WaL project location, the scale of the urban water system, the economic value of the area, the data availability, the accessibility and proximity of the project site. During this period, the author collected data, had multiple site-visits and interviews with the communities and high-level stakeholders including the government, collaborate with the WaL teams, participated in the local WaL workshop, and experienced the water crisis and the beginning of the southwest monsoon in Chennai.

The research has led to the development of a prototype of an online RRWH tool called "Let's Talk Water". With the outcomes of the research on the Mambalam case study and the tool developed, the author visited Chennai for a second time for three weeks, between January and February 2020. The author presented the findings at the Indian Institute of Technology Madras and met with key stakeholders to get their inputs and feedback.

From the discussions with the stakeholders, during the second visit, the author found out that in the southern peri-urban areas of Chennai, many households rely solely on mobile water suppliers (i.e. water tankers) for their water supply, charging at a much higher rate than in urban area. This case was also relevant to investigate in this research because of the greater incentive to adopt RRWH for water supply. Sabari Terrace residential apartment complex in Sholinganallur, located in the southern part of Chennai, was used as the specific case study because it has already implemented a successful RRWH pilot demonstration and data could be gathered to validate the preliminary tool developed. This information was added later on in the report.

Water for
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Leverage Asia

Photo : Typical decentralized water storage system along the Mambalam drain, Chennai, India (2019)

ABSTRACT

Chennai, one of the largest cities in India, has been suffering from multiple water challenges such as water shortage, groundwater depletion, urban flooding and water pollution. As a response, in 2002, the local government made rainwater harvesting structure mandatory for every building. This simple system contributes to take advantage of the excess water during monsoon and palliating the situation during the dry season, while preventing it from being discharged into the polluted waterways. However, the widespread uptake of rooftop rainwater harvesting systems has been slow partly due to the lack of accurate and reliable information on its benefits to make more informed decision.

This research seeks to bring forward the potential of leveraging decentralized rooftop rainwater harvesting (RRWH) systems to mitigate Chennai's water challenges – water supply, groundwater recharge and flood risk reduction - by quantifying the hydrological effects of RRWH using a multi-purpose approach. To do so, a RRWH model was developed using daily continuous simulation method with 'Yield Before Spill" as the operational rule to determine the optimum design capacity required and to provide its associated hydrological benefits. In this research, a closed RRWH designed to maximize water supply from rainwater for domestic use is applied for the analysis (also referred as RRWH for water supply). The feasibility and cost-effectiveness were also addressed briefly to give an estimation on the potential to leverage RRWH at a larger scale. Two areas of Chennai were investigated: urban area and peri-urban area.

For the urban area, the Mambalam, located in the historical center of Chennai, was selected as the specific case study. Assuming 380,000 inhabitants are living in an estimated area of 11,690,000m2, approx. four million m3/yr of rainwater can be harvested from the existing building's roofs. From this, 50% of the buildings in the Mambalam is assumed to be residential which can provide 15% of the annual domestic water demand and saving ~$0.2-0.5/yr/p. When considering the adoption of open RRWH systems (also referred RRWH for direct groundwater recharge) for the remaining 50% of the non-residential buildings in the Mambalam, approx. two million m3/yr of rainwater can be recharged into the aquifer. This can also be considered as available water for domestic use because in urban area, wells have also been used as a source of water. Following this premise, the potential of RRWH can be increased up to 30% of the annual water demand (equivalent to 3.5 months of continuous water supply). Regarding the urban flood risk reduction, the combined systems of RRWH for water supply and RRWH for groundwater recharge can contribute to reduce a volume of approx. four million m3/yr going into the stormwater drainage network. During a heavy rain event, RRWH can reduce up to 60% of the stormwater runoff in the Mambalam sub-catchment, which would otherwise be drained into the Mambalam drain and thus increasing the risk of flooding of vulnerable communities living along this drain. The results showed that scaling up RRWH at the macro-level can have a significant impact in terms of drought and flood resilience for the Mambalam area. These numbers can serve as inputs for stakeholders' dialogues to make informed decisions and raise awareness on the benefits of multi-purpose RRWH to transition Chennai toward a water resilient city.

Photo : Residential buildings for low-income household along the Mambalam drain, Chennai, India (2019)

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In practice, retrofitting existing building with RRWH for water supply in urban areas may become challenging mainly due to political, legal, physical and socio-economic factors. The adoption of a closed RRWH system for RRWH is found to be more relevant for the peri-urban areas of Chennai, particularly in the southern part of Chennai. Due to the geohydrological conditions and the absence of water piped connection, many residential apartment complexes have to depend solely on water tankers which is around 10 times more expensive than the cost of water per kL in urban areas. The case of Sabari Terrace residential apartment complex in Sholinganallur showed that the adoption of RRWH for water supply with a ratio rooftop area per person of 7.1m2/p contributes to 15% of the annual water demand and it saves up to $6/yr/p. Thus, depending on the local context closed RRWH system may be preferred over open RRWH system.

From an urban water management perspective, it is recommended to lower the floor space index (FSI) for planned building to increase the potential of RRWH for water supply and meanwhile reducing the dependence on piped water supply and water tankers. In other words, developing new residential areas horizontally rather than vertically would contribute to lower significantly the pressure on resources. For existing buildings, many has already an existing underground sump for piped supply. Adapting the current building regulation by allowing RRWH to be connected to the existing sump may increase the adoption of RRWH structure. In addition to adopt a RRWH for water supply, reducing daily water consumption and adopting water recycling system are important aspects to achieve self-sufficiency in water.

The outcomes of the research have led to the development of a comprehensive online tool called "Let's Talk Water" which is available to the public (prototype phase as of March 2020). This user-friendly tool provides the optimum RRWH design for domestic water supply and its benefits on water supply, groundwater recharge, and urban flooding reduction based on the inputs of the user.

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ABBREVIATION

A/P	Ratio roof/area person [m2/p]
C/P	Sump capacity/person [m3/p]
CGWB	Central Ground Water Board
CMA	Chennai Metropolitan Area
CMWSSB	Chennai Metropolitan Water Supply & Sewage Board
CSCL	Chennai Smart City Limited
GCC	Greater Chennai Corporation
MAWSD	Municipal Administration Water Supply Department
RRWH	Rooftop Rainwater Harvesting
RWH	Rainwater Harvesting
SDG	Sustainable Development Goal
SWMM	Storm Water Management Model
TWAD	Tamil Nadu Water Supply And Drainage board
VCA	Vulnerability Capacity Assessment
WaL	Water as Leverage
YAS	Yield After Spilloage
YBS	Yield Before Spillage

CHAPTER 1

LET'S UNDERSTAND: CHENNAI'S WATER CHALLENGES

Chennai is the fourth largest metropolitan areas in India (Tajuddin, 2017) and it is located in the state of Tamil Nadu (see Figure 1). It has an estimated population of 10 million and is expecting to increase to 13 million in 2026 (CMDA, 2020).

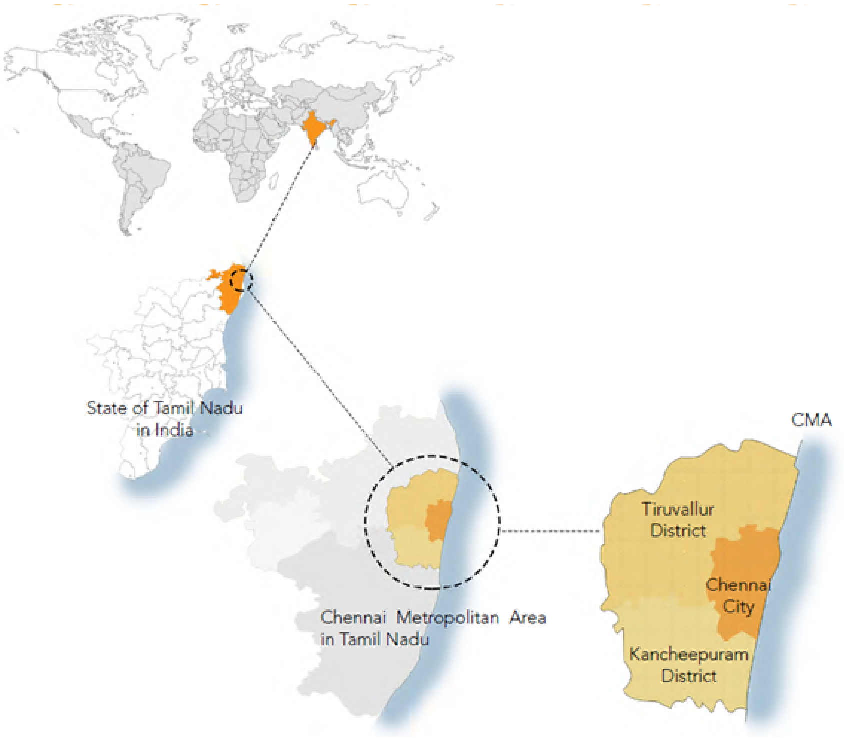

Figure 1. Location of Chennai City and Chennai Metropolitan Area (CMA), Tamil Nadu, India (© Tajuddin, 2017)

It is also the fourth-largest economy in India mainly driven by the automobile and IT industry (Tajuddin, 2017). Chennai has promised to its citizen to create the world-class IT Hub along the Old Mahabalipuram Road (OMR), attracting many real estate developers and renowned IT companies such as Tata Consulting Services (Tajuddin, 2017). It is known as "Chennai IT corridor", which is going from North to South, parallel to the Buckingham canal and few kilometers away from the Bay of Bengal (Tajuddin, 2017). Although Chennai bears an economic importance for India and hosting a large population, the city has failed to provide a robust, sustainable and resilient urban water management system to mitigate its water challenges (Resilient Chennai Strategy Report, 2019).

1.1 CHENNAI'S URBAN WATER SYSTEM

Chennai's urban water system is represented by the drinking water supply system and the urban drainage system. Both systems are link to the groundwater either to extract groundwater for water supply or to recharge the aquifer. This section will mainly address the 'man-made' systems to understand the complexity of the municipal services and network infrastructures.

1.1.1 DRINKING WATER SUPPLY SYSTEM

In Chennai, the primary source of water is supplied by municipal piped water which comes mainly from surface water, groundwater and desalination plants. Precisely, they are the desalination plants at Nemelli and Minjur (both supply water for a total of 200,000m3/d), aquifers in Neyveli, Minjur, and Panchetty, Cauvery water from Veeranam lake, Krishna River from Andhra Pradesh and Poondi, Red Hills, Chembarambakkam and Cholavaram reservoirs (CMWSSB, 2019). This centralized municipal water supply system is operated and managed by Chennai Metropolitan Water Supply and Sewage Board (CMWSSB). The four reservoirs have a storage capacity of 313,099,000m3 (CMWSSB, 2019). Figure 2 shows the main water sources locations and its distance to Chennai's city (highlighted yellow).

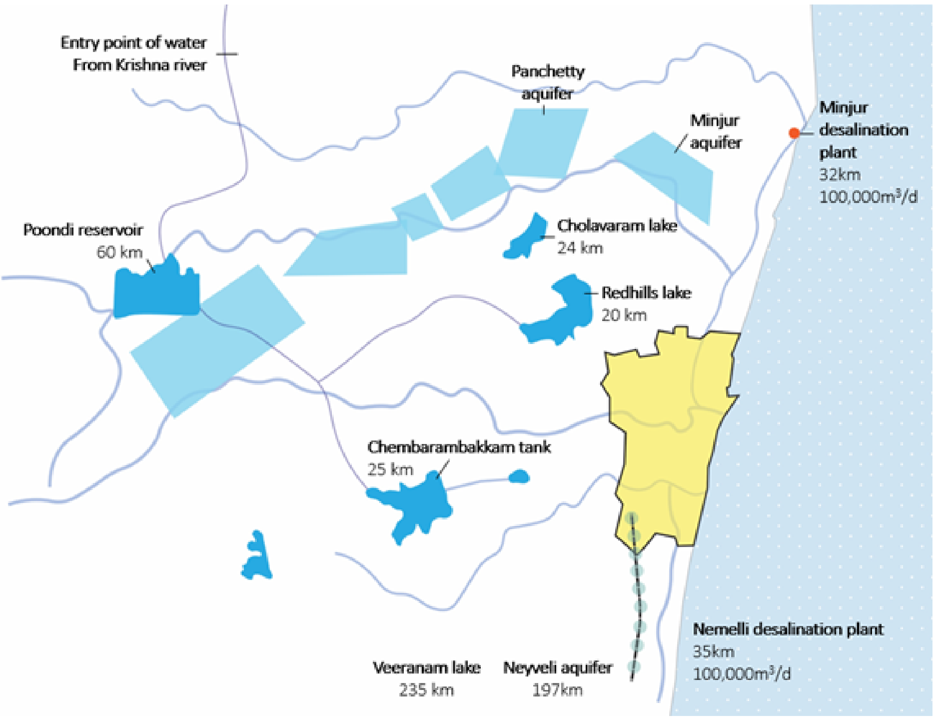

Figure 2. Chennai water supply system, highlighted yellow represented Chennai City and the line going towards the south is the IT Corridor. Adapted from CMWSSB, 2019 (©Janakiraman)

These water sources require a long-distance pipeline to be transported to Chennai, making the distribution network more complex to operate and manage and it is cost-inefficient. All these water sources combined are supposed to supply 830,000m3/d to Chennai's population living within the boundary of Chennai Metropolitan Area (CMA) (see Figure 1) (CMWSSB, 2019).

However, according to Chennai City Resilience Strategy report (2019), only 650,000 m3/d reaches the consumers, leaving 180,000m3/d loss (22% of loss per day) in the piped water network through leakages. In addition to poor water infrastructure, CMWSSB needs to deal with increasing drought events due to climate change. Chennai's drinking water supply system is intermittent and only available for few hours a day (Srinivasan, Gorelick & Goulder, 2010C). Most of the residential building has a storage sump underneath their building that allows consumers to convert intermittent piped water supply into continuous water supply (Srinivasan, Gorelick & Goulder, 2010C).

Chennai's centralized water supply is supplemented with a decentralized water supply, which can serve as a buffer during the summer period. Most of the people in Chennai use groundwater as a secondary water source from private borewell or community well (Srinivasan, Gorelick & Goulder, 2010A). With the increasing droughts, more and more people are extracting groundwater, further increasing stress to this common resource. It is mostly used for non-potable needs such as washing, sanitation, and bathing unless it is treated. When groundwater is no longer available, citizens turn into private tankers. The multiple sources of water supply in Chennai can be classified and ranked as follow: municipal piped (primary), borewell, or community well, including public standpipes (secondary) and water tanker (tertiary) (Srinivasan, Goerelick & Goulder, 2010A).

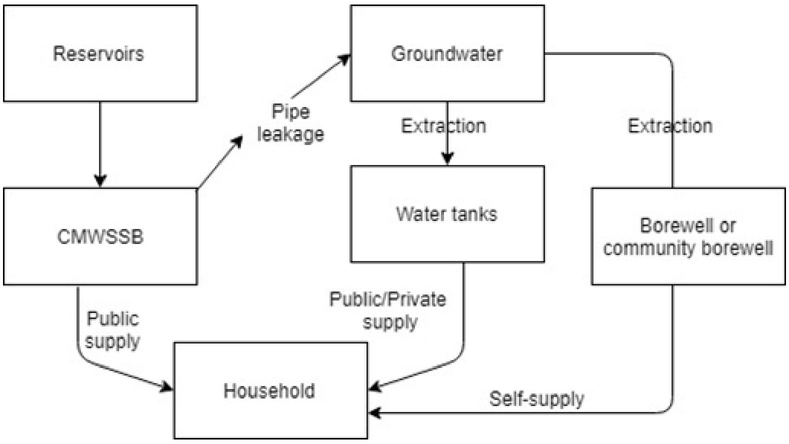

Figure 3. Integrated model of the simplified scheme of multiple drinking water sources at the micro-scale in Chennai, India (adapted from Srinivasan, Goerelick & Goulder, 2010A).

The current urban water supply system in Chennai is composed of a mix between a centralized water supply system with large scale infrastructures distributing water to the city from far away and decentralized small water supply systems. The poor water management and aging infrastructures resulted in unreliable piped water supply and significant loss of water through pipe leakage, and thus reducing water available down the pipe to the consumers. To meet their daily water demand, most of the people in urban areas tap into urban groundwater through borewell or community well.

1.1.2 URBAN DRAINAGE SYSTEM

The Storm Water Drain Department from the Greater Chennai Corporation (GCC) is the statutory body responsible to provide and maintain stormwater drainage system to prevent stagnation in the road and reduce flood risk during monsoon (GCC, 2008). The current drainage system has an insufficient coverage with storm water drains in the city and lack of proper connectivity, creating pockets of urban flooding in the city (Presentation, Balaji Narasimhan, IIT Madras, 2019). Moreover, excessive solid waste in the drainage channels and blocked inlets further increase the risk of urban flooding (Presentation, Balaji Narasimhan, IIT Madras, 2019). Through the ongoing Integrated Storm Water Drain Project, the GCC is planning to construct recharge wells and connect the storm water drain to temple tanks wherever possible to allow for groundwater recharge (Resilient Chennai Strategy Report, 2019).

1.2 CHENNAI'S URBAN WATER CHALLENGES

Due to rapid urbanization and climate change, urban areas in India are facing an unprecedented growing demand for resources, which increases severely pressure on municipal services and network infrastructures. Chennai has been facing several water challenges such as water shortage leading to over-extraction of groundwater, urban flooding and degradation of water quality. This section will describe the multiple water challenges to understand the extent of the problems and how multi-purpose system can allow for systemic approach to address water shortage, groundwater depletion, urban flood risk and water pollution simultaneously.

''TOO MUCH, TOO LITTLE, TOO POLLUTED''

Figure 4. Pictures of Chennai's water challenges, from left to right, 1. Water shortage, 2. Groundwater depletion, 3. Polluted waterways, 4. Urban flooding (Source: first three pictures from the left are taken by the author, March 2019; the last picture on the right is from Tajuddin, 2017)

1.2.1 WATER SHORTAGE

Erratic rainfall and increasing extreme events such as dry spells worsen the impacts on Chennai's water supply as the city is mainly dependent on rainfall to fill up their reservoirs. Although droughts have been a recurrent problem in Chennai, the 2019 drought was the worst water crisis over the last 140 years (NDTV, 2019). This 2019 drought may be due to the deficit of 55% of rainfall from the previous year compared to the average rainfall trend. As of August 15th, 2019, Cholavaram, Redhills, and Chembarambakkam reservoirs were completely dry (CMWSSB, 2019). In response to the water scarcity problem of 2019, Chennai brought 2500m3/d of water by train from a dam on the Cauvery River located in Tamil Nadu's Vellore district, approx. 225km away from Chennai from July 2019 until (The Hindu, 2019) the beginning of the monsoon season. As a long-term drought resilient strategy, the state government has planned to build two new desalination plants: in Nemmeli (150,000m3/d) and Perur (400,000m3/d) (Resilient Chennai Strategy Report, 2019). City's water shortage is also due to the mismanagement of the urban water system. As mentioned in section 1.1.1, Chennai loses around 22% of its water through pipe leakages.

1.2.2 GROUNDWATER DEPLETION

With the lack of regulations on groundwater extraction by end-users, groundwater depletion is becoming a severe problem (Resilient Chennai Strategy Report, 2019), especially during the summer when the piped supply is halted. It is estimated that the groundwater table is depleting between 10 to 20cm every year (Resilient Chennai Strategy Report, 2019). With a lower groundwater table, wells are being dug deeper and deeper, causing sea water intrusion and degrading the quality of groundwater (Kurian, 2019). In addition, lack of monitoring induced lack of data which further make it difficult to establish appropriate groundwater regulations with unknown information.

1.2.3 URBAN FLOODING

On one hand, Chennai suffers from droughts in the summer, and on the other hand, it suffers from floods during the monsoon seasons. The region, due to its deltaic nature, has historically been prone to floods (Tajuddin, 2017). Major urban flood in the past has caused substantial economic losses, such as the 100-year flood event in November 2015, which cost around $3 billion (Resilient Chennai, 2019). Low infiltration due to an increase in impervious land, low storage capacity and poor drainage infrastructure within the city have lead to an increase of high peak discharge and a loss of a large amount of stormwater runoff to the Bay of Bengal. Only an estimated 9% of rainwater in Chennai infiltrates to the aquifer (Srinivasan, Gorelick & Goulder, 2010A). It is a missed opportunity to collect rainwater and stormwater as a buffer for the dry and hot summer (Vivek, 2016).

1.2.4 WATER POLLUTION

Due to poor infrastructures and rapid urbanization, most of the water bodies and waterways in Chennai are severely polluted (Resilient Chennai, 2019). Untreated sewage and solid waste and runoff from the street end up in canals, rivers and the Bay of Bengal (Resilient Chennai, 2019). A report on Chennai Floods 2015 published by Narasimhan and al. (2016) stated that 84% of the micro-drains carried sewage while the rest carry stormwater. The quality of groundwater is also impacted due to groundwater over-extraction.

1.2.5 SUMMARY

It is clear that Chennai needs to rethink about the efficiency of its urban water management system to mitigate recurring and more extreme events of "too much and too little" water at different periods of the year. The management, operation and maintenance of large-scale infrastructures are difficult to manage. It is especially difficult to keep up the development of municipal services with the rapid growing population. Although both governmental bodies, CMWSSB and GCC, work under the Municipal Administration Water Supply Department (MAWSD), Chennai's governance is still siloed thinking and has failed to recognize that collaborative effort can lead to better water management system (Resilient Chennai Strategy Report, 2019). A systemic approach is needed to mitigate all these water challenges simultaneously.

1.3 RAINWATER HARVESTING IN CHENNAI

Rainwater harvesting has been part of the traditional water management of Chennai and can be traced back even before the British regime (Tajuddin, 2017). Water bodies such as lake, erys, wetlands and rivers were part of a larger cascading system of Chennai's hydrology. These water bodies were used to protect the city from flooding during monsoons and to store water and to replenish the groundwater during the dry season. With the rapid urbanization, water bodies became encroached and slowly disappeared from the urban landscape. This anthropological phenomenon has created a built-up land with low infiltration capacity and flushing laterally 'clean' water during rainy events into polluted waterways. To restore the urban hydrology, one of the measures taken in Chennai is to implement rainwater harvesting structures. Currently, there are many existing types of rainwater harvesting structure suggested in Chennai (see Annex B).

1.3.1 THE VALUE OF RAINWATER HARVESTING

Rainwater harvesting system can help achieving mainly two Sustainable Development Goals:

- SDG 6 – Clean water and sanitation
- SDG 11 – Sustainable cities and communities

6 CLEAN WATER AND SANITATION

11 SUSTAINABLE CITIES AND COMMUNITIES

Indeed, RWH system is a sustainable solution to improve water security, replenish the groundwater, and help to reduce the overall cost on future water supply infrastructures. It requires low energy and thus, producing low carbon footprint compared to desalination plants. It collects water at the source and reuses it on-site, avoiding complex pipe distribution network. Decentralized systems are easier in terms of maintenance and operation than centralized system. It helps to reduce the dependence on municipal intermittent piped water supply and water tank lorries during summer (Srinivasan, Gorelick & Goulder, 2010A; Viswanath, 2018; Rain Centre, 2019). It has enabled vulnerable community to access to relatively safe water for domestic purpose. Furthermore, small-scale RWH structure allows to give a sense of ownership of the system. It increases in citizen's power in managing its own water supply, especially in a political context in which access to water defines power (Anand, 2017).

1.3.2 LEGAL FRAMEWORK ON RWH

One of the major steps that Chennai undertook to cope with water scarcity is the 2002 amendment, which made mandatory for all buildings in Chennai to install RWH structures. The main objective of the 2002 amendment on RWH is for "augmenting groundwater resources" (Vivek, 2016; Jebamalar, Ravikumar & Meiyappan, 2012; Srinivasan, Gorelick, & Goulder, 2010A). Both CMWSSB and GCC promote the use of rainwater harvesting to recharge groundwater, but due to the lack of human resources and capacity, the implementation and enforcement of this regulation has been challenging to make it effective (Resilient Chennai Strategy Report, 2019).

Chennai City Municipal Corporation Act

"Every owner or occupier of a building shall provide rainwater harvesting structure in the building in such manner and within such period as may be prescribed." (CMWSSB, 2019)

Tamil Nadu Combined Development and Building Rules, 2019

" (1) Rainwater Harvesting – Effective measures shall be taken within each premises for conservation of rainwater, and rainwater-harvesting structures shall be provided as prescribed in Annexure – XXII of this Rule'' (see Annex A in this report)

> (c) High Rise buildings (Residential/Commercial) – ''In plots that are being developed/buildings with a source well [or without an open well], rooftop water to be diverted to a sump for immediate use (if that is relevant), through a first flush cum pebble-sand filter combination or an Special filter that is available in the market and the overflow to be diverted to the source well. '' (GCC, 2019)

(2) Additional regulation for all buildings

> (c) "A separate sump shall be constructed for storing potable where the water is supplied by the Local Body and the volume of such sump shall not exceed 1000 liters per dwelling unit. This sump shall be independent of other tanks, which may be constructed for storing water obtained from other sources. Rooftop water to be diverted to a sump for immediate use (if that is relevant), through a first flush cum pebble-sand filter combination or a Special filter that is available in the market and the overflow to be diverted to the source well." (GCC, 2019)

1.3.3 SUMMARY

Rainwater harvesting used to be part of the indian traditional water management. It is an ancient technology which has been forgotten over time and now brought back to the city as an alternative to mitigate groundwater depletion. Since 2002, in Chennai, building regulations mandate all buildings (old and new) to have a rainwater harvesting. Although it is widely accepted that rainwater harvesting has multiple benefits, many of them are just fulfilling the building requirement for the sake of ordinance, leaving the rainwater harvesting structure unused.

CHAPTER 2

LET'S ASK THE RIGHT QUESTION: RESEARCH FOCUS

2.1 KNOWLEDGE GAP IN RRWH IN THE CONTEXT OF CHENNAI

As presented in section 1.3, RRWH in Chennai is mainly perceived and used for groundwater recharge purpose. It not only contributes to replenish the aquifer, but it also serves to increase groundwater availability for water supply. RRWH for groundwater recharge can be defined as an open RRWH system. There are advantages of using an open RRWH system, but also disadvantages compared to a closed RRWH system with a long-term storage. The latter has not yet been investigated in depth, especially for the case of Chennai. This is discussed in the following section. The research also attempts to leverage RRWH from a single to a multi-function system into a comprehensive approach.

2.1.1 OPEN SYSTEM VS CLOSED SYSTEM FOR RRWH

As presented in section 1.3, RRWH in Chennai is mainly perceived and used for groundwater recharge purpose. It not only contributes to replenish the aquifer, but it also serves to increase groundwater availability for water supply. Since groundwater is a common resource, when adopting RRWH for groundwater recharge, the asset is usually in private ownership, but with a public good outcome (Sharma, Begbie & Gardner, 2015). Indeed, the amount of rainwater recharged by one maybe used by another. Similarly, if groundwater is contaminated at one-point source, it can affect everyone who is depending on it. It is difficult to control the quality of the water or to regulate the abstraction of groundwater in an open system like RRWH for groundwater recharge and manage it in a sustainable way. The latter can be related to the 'Tragedy of the Commons" by Garret Hardin which stated that shared-resources can lead inevitably to over-exploitation for the benefits of people's own self-interest (Coelho & Reddy, 2004).

Although there is a regulation which obligates all buildings to have a rainwater harvesting structures, monitoring and enforcement of this regulation is poor. For new buildings, owners can only obtain a construction permit when rainwater harvesting structure is part of the design construction. However, for existing buildings, the local government relies mainly on the collaboration and the cooperation of all to invest in RRWH for groundwater recharge which may not be adopted for the reasons mentioned above.

In this light, it becomes interesting to investigate the potential of a close system under this local context. A closed RRWH system is defined as rainwater collected from the rooftop and stored in a confined module and recirculated back to the households for domestic use. With a greater control of the quantity and quality of the rainwater collected, individuals or communities may have a greater sense of ownership, better understanding on the importance of rainwater collection and engaging in more maintenance of the system for their own benefits. In a closed system, the incentive to adopt a RRWH may be higher for individuals or communities because they can get a direct benefit on improving their water security, whereas in an open system, the incentive is lower due to the indirect benefits.

2.1.2 MULTI-PURPOSE RRWH APPROACH

Although rainwater harvesting (RWH) is not a newly introduced method in Chennai nor India, it has only been used and perceived as a method to secure freshwater supply during droughts and recharge groundwater. It is only until recently that CMWSSB and CGWB acknowledged RWH for flood mitigation by reducing the peak flow and the runoff volume. In the case of Chennai, it is known that RWH can help to mitigate water shortage, urban flooding, and groundwater depletion. Although it is known that RWH has multiple hydrological benefits, it has not yet been explicitly investigated into a comprehensive approach, particularly rooftop rainwater harvesting (RRWH). There is a limited number of technical studies done on dual-purpose RRWH for drought and flood management (Mugume, Melville-Shreeve, Gomez & Butler, 2015; Melville-Shreeve, 2017; Islam, Chou & Liaw, 2010; Kwak & Han, 2014) or even multi-purpose RRWH including groundwater recharge to quantify information about its direct effects (see Annex C). There is, therefore, an interest in understanding and quantifying the hydrological impacts of RRWH.

Photo : Residents taking water from water tankers in Chennai, India (2019)

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2.2 OBJECTIVES OF THIS RESEARCH

Drawing upon the author's experience in Chennai and the knowledge gap in the rooftop rainwater harvesting system, the goals of this research is to quantify the hydrological impacts of a closed RRWH system using a multi-purpose approach for the Mambalam area. This multi-purpose approach aims to provide quantitative information on water supply, groundwater recharge and flood risk reduction.

In other words, the objectives of this research are formulated as follows:

- Investigate the feasibility of a closed RRWH system;
- Investigate the potential of decentralized water supply system using RRWH;
- Investigate the direct hydrological effects of RRWH using a multi-purpose approach.

2.3 RESEARCH QUESTION

The main research question can be formulated as follow:

(1) (2) (3)
To what extent can decentralized and multi-purpose rooftop rainwater harvesting system mitigate the urban water challenges in the Mambalam area, Chennai, India?
(4)

The sub-questions are :

(1) How can decentralized and multi-purpose RRWH be investigated effectively and systematically?
(2) Can Mambalam become water-sufficient for domestic water supply from using only RRWH considering the existing local infrastructure?
(3) What are the hydrological effects of RRWH on water supply, groundwater recharge and stormwater runoff at the micro-scale (building level)?
(4) Does RRWH have a significant impact to mitigate the water challenges – water supply, groundwater recharge and flood risk reduction – at the macro-scale (neighborhood level)?

In sub-question 2, RRWH for water supply refers to a closed system which means it captures rainwater from the rooftop and stored it in a sump before recirculating to every household. It does not refer to water supply from groundwater recharge. The optimum sump capacity required to meet the water demand will also be investigated.

In this research, unless mentioned otherwise, the term "rooftop rainwater harvesting (RRWH)" is used interchangeably with "proposed RRWH design", "closed system" and "RRWH for water supply".

2.4 METHODOLOGY

To answer the main research question quantitatively,an urban water balance model was developed to simulate a RRWH system. The proposed RRWH model has a specific structure and objective to provide quantitative information. In this research, RRWH system designed to maximize water supply to meet the water demand is the objective of the model. The research is divided into two parts: the development of a model and the application of the model to the case study.

2.4.1 DEVELOPMENT OF A RRWH MODEL

The RRWH modeling part contributed to answer the first sub-question "How can decentralized and multi-purpose RRWH be investigated effectively and systematically?". An extensive literature review was first performed on existing RRWH models. Based on the findings, an improved model adapted to the context of Chennai was developed. The model has a single objective function, which is to maximize water supply based on several parameters given. The output provides the optimum RRWH design for water supply. Using this optimum RRWH design found, the model provides quantitative information on the hydrological effects on water supply, groundwater recharge and stormwater runoff. The optimization process and the multi-purpose approach of RRWH was developed in one comprehensive model, which can be applied to general use in an effectively and systematically way. The RRWH model was only a mean to answer the main research question, but it was not the objective of the research itself. However, it was important to develop a scientifically-based model as the model set-up may influence the outcomes which served to answer the main research question. Finally, a sensitivity analysis was performed to examine the effects of the parameters used in the model and to interpret the results appropriately.

2.4.2 CASE STUDY: MAMBALAM, CHENNAI

The RRWH model developed in part one was applied to the case study of the Mambalam area, Chennai to answer all the other sub-questions. The methodology used specifically for the case study is elaborated in details in section 4.2. Data collection used to perform the analysis is a combination of literature review, governmental documents, field data collection and personal communications from key local stakeholders in Chennai. The analysis was first performed at the micro-scale and then at the macro-scale to assess the hydrological performance of RRWH of the Mambalam sub-catchment. Conclusions was drawn from the outcomes on the potential of RRWH for water supply, groundwater recharge and stormwater runoff reduction and its relevance under the current local context. A cost-benefit analysis was performed to give an indication on the economic factor of RRWH.

2.5 SCOPE, CHALLENGES AND LIMITATIONS

There are multiple existing types of rainwater harvesting structures including soft and hard measures and they all contribute to a certain extent to mitigate water challenges. This research primarily focuses on the RRWH system (hard measure) for residential building with a design structure that maximizes water-saving for domestic use. The closed RRWH system in this research did not aim to compare the efficiency or performance of RRWH with other alternative RRWH designs, but rather to understand its impacts with such structure in the context of Chennai. It is acknowledged that small-scale decentralized RRWH for water supply may require a higher operation and maintenance from the users, but this aspect goes beyond the scope of this research.

The case study investigated is mainly based on the available data and fieldwork data. Quantitative data are especially scarce when assessing at the micro-scale in urban areas. The research primarily investigated water quantity rather than water quality due to the lack of site-specific qualitative data. The comparison of water quality of stored rainwater with municipal piped water supply or water from groundwater extraction can play a critical factor in the adoption of RRWH. Currently, most of the people use groundwater as a resource. However, there is a lack of high-quality data that support its suitability for daily domestic use. Regarding the artificial groundwater recharge from RRWH, the hydrogeological conditions are a critical factor in estimating the infiltration rate and storage capacity in the aquifer. However, data like the soil profile or the groundwater level is highly site-specific and no high-resolution data were found in the area of interest.

Finally, the political, economic and socio-cultural factors which play an important role in the adoption of RRWH systems was not addressed in depth but only discussed briefly in this research. As an example, it is known that the water tanker's mafia controls an important part of Chennai's urban water supply system and that the implementation of RRWH may reduce their economic activities. Thus, this example would fall under the 'grey' area of Chennai's urban water management (Anand, 2017). Performing research in such context cannot only rely on scientific literature or statistics from governmental documents, community or citizen-data are also valid sources which can help to cross-check information.

CHAPTER 3

LET'S DEVELOP: URBAN WATER BALANCE MODEL

In this chapter, the development of an urban water balance model for RRWH for domestic water supply using a multi-purpose approach is explained and elaborated based on existing models taken from the scientific literature. This model is mainly designed for the context of Chennai and it serves to provide technically-sound information on optimal RRWH design and quantify the hydrological effects of RRWH on water supply, groundwater recharge and stormwater runoff at the micro-and macro- scales.

3.1 LITERATURE REVIEW

Literature review was performed to understand the existing RRWH model. This section first presents the general concept of RRWH modeling, addressing the main components of a RRWH system. For a closed system of RRWH for water supply, a storage unit is required. To properly size the storage unit, optimization processes are investigated. Finally, many articles are reviewed to understand the current methodologies used to assess the performance of RRWH using a multi-purpose approach.

3.1.1 GENERAL CONCEPT OF RRWH MODELING

There are many methods used for RRWH modeling from simple models using a spreadsheet to complex models using computer programming simulation (Sharma, Begbie & Gardner, 2015). The most common approach for modeling RRWH performance is to use continuous water balance simulation (Sharma, Begbie & Gardner, 2015) with a daily time-step for accurate evaluation (Campisano & Modica, 2014).

In RRWH modeling, there are two main important modules: the rooftop and the rainwater tank (Sharma, Begbie & Gardner, 2015). A simple scheme of an RRWH model is presentred in Figure 5. Depending on the utilization of the collected rainwater (i.e. toilet flushing, irrigation, washing, drinking, cooking, serving air-conditioner), water demand can be pre-determined. All other parameters are dependent on meteorological data and the structural design of the system (i.e. rooftop catchment area and storage capacity), which will provide the performance of the system based on the output(s).

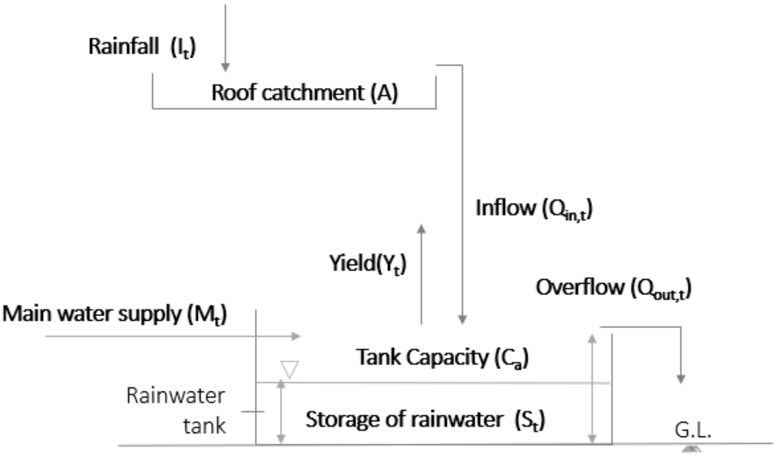


Figure 5. Simple scheme of an RRWH model

Rooftop runoff modeling

When small time-steps of rainfall data are available, the rational method for runoff modeling is the most suitable for a building's rooftop (Han and Nguyen, 2018; Melville-Shreeve, 2017; Mahmoud, Elagib, Gaese & Heinrich, 2014). The Rational method's equation is as follows:

$$Q_{in,t} = C * \ i_t * \ A$$

where *Qin,t* is the flow [m3/d], *C* is the runoff coefficient [-], it is the rainfall intensity [m/d], t is time-step and *A* is the catchment area [m2]. Most urban building rooftops have a reinforced concrete structure and are designed to drain stormwater rapidly and completely (Han and Nguyen, 2018). Therefore, it can be assumed that no infiltration occurs. The evaporation factor can also be omitted as it does not have a significant impact during heavy rainfall (Han and Nguyen, 2018).

Rainwater tank modeling

The operation between inflow and outflow in the rainwater tank is based on the concept of the simple mass balance equation over time:

$$\Delta S/\Delta t = (\text{Inflow} - \text{Outflow})/\ \Delta t$$

In this case, the inflow (*Qint,t*) is the runoff from the rooftop at time *t* and the outflow are the yield (*Yt*) withdrawn from the storage at time *t* and the overflow (*Qout,t*) at time *t*, both are in the unit of m3/d. These parameters can occur in any order or can occur simultaneously during any time-step. Therefore, to simulate the change in storage in the rainwater tank, many studies have used the method of yield after spill (YAS) or yield before spill (YBS) for RRWH modeling, also known as behavioral models (Han and Nguyen, 2018; Melville-Shreeve, 2017; Mugume, Melville-Shreeve, Gomez & Butler,2016; Steffen, Jensen, Pomeroy & Burian, 2013; Islam, Chou and Liaw, 2010; Fewkes and Butler, 2000).

YAS assumes that *Qin,t* in the tank occurs prior to yield. The exceeding volume of water which cannot be stored overflows (*Qout,t*). Unlike YAS, YBS assumes a virtual storage (Steffen, Jensen, Pomeroy & Burian, 2013). If there is any excess, when the inflow of rainwater occurs, it is stored temporarily in a virtual storage. Then, the yield is susbtracted from the sum of the inflow of rainwater and the stored water from the previous day (*Qin,t* + *St*-1). At the end of any time-step, the water volume inthe tank is constrained by the tank volume. Both YAS and YBS differ in the order of calculation (Sharma, Begbie & Gardner, 2015; Jensen, Pomeroy & Burian, 2013). The operation rules of YAS and YBS are summarized in Table 1 and graphically illustrated in Figure 6.

Table 1. Summary of YAS and YBS (Adapted from Sharma, Begbie & Gardner, 2015; Fewkes and Butler, 2000)

Method	Operating rules	Comments
YAS	$Y_t = \min[D_t, S_{t-1}]$ $S_t = \min[S_{t-1} + Q_{in,t} - Y_t, C_a - Y_t]$ $Q_{out,t} = \max[(S_{t-1} + Q_{in,t} - Y_t) - (C_a - Y_t), 0]$	Using YAS method, C_a will never be at full capacity at the end of the time interval t. It is the most conservative method.
YBS	$Y_t = \min[D_t, S_{t-1} + Q_{in,t}]$ $S_t = \min[S_{t-1} + Q_{in,t} - Y_t, C_a]$ $Q_{out,t} = \max[S_{t-1} + Q_{in,t} - Y_t - C_a, 0]$	Although $S_t = C_a$, YBS considers the inflow of water as part of yield and can take more volume of water in a 'virtual storage' at time-step t. YBS can be at full capacity at the end of the time interval t.

Where *Dt* is the water demand at time *t* [m3/d], St is the storage at time *t* [m3/d] and *Ca* is the storage capacity [m3]. In this case, *Yt* is determined from the available stored water. If *St-1* (for YAS) or *St-1 +Qin,t* (for YBS) ≠ *Dt*, then the main water supply (*Mt*) or external water supply [m3/d] will complement the stored rainwater to meet the daily total water demand (*Mt* = *Dt* - *Yt*) (Fewkes & Butler, 2000).

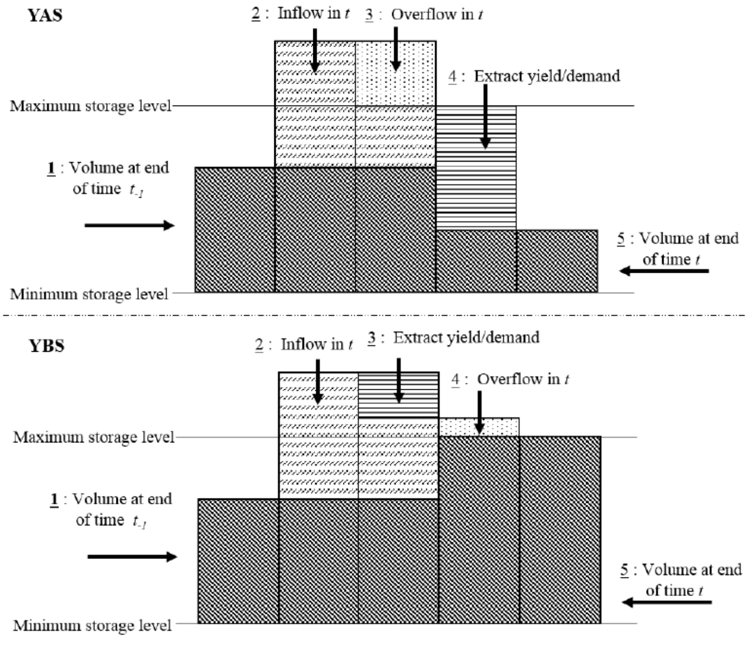


Figure 6. The difference between YAS and YBS operating rules (Fisher-Jeffes, 2015)

3.1.2 OPTIMIZATION MODEL FOR SIZING RAINWATER TANK FOR WATER SUPPLY

Many studies have used specific tank sizes to model the behavior of rainwater based on the rooftop catchment and water supply required (Han & Nguyen, 2018; Melville-Shreeve, 2017; Mugume, Melville-Shreeve, Gomez & Butler, 2016; Steffen, Jensen, Pomeroy & Burian, 2013). However, in this research, optimum tank size is used using an optimization process. This process is defined as the optimal storage capacity required to meet the water demand which depends on a number of parameters such as the rainfall pattern, the water demand, the roof area and the roof runoff coefficient. Several studies in the literature have already addressed the use of computer modeling of the optimization of tank capacity in a systematic way using continuous simulation based on the historical daily rainfall, the rooftop catchment and daily water demand (Sharma, Begbie & Gardner, 2015; Ghisi, Bressan & Martini, 2007). To evaluate the performance of RRWH, reliance of RRWH for water supply (also referred as water-saving efficiency) is used. More precisely, the reliability for water supply is calculated using the yield performance over the demand (Melville-Shreeve, 2017; Mugume, Melville-Shreeve, Gomez & Butler, 2016; Steffen, Jensen, Pomeroy & Burian, 2013; Islam, Chou & Liaw, 2010). It is usually expressed in percentage. A long period of historical daily rainfall is necessary for accurate estimation of the system reliability. Basinger, Montalto & Lall (2010) mentioned that the simulation period (T) should be at least longer than the useful life of the RWH system to represent reality.More details of the reliability are presented in section 3.2.6.

3.1.3 DUAL- AND MULTI-PURPOSE RRWH APPROACH AND MODELING

> Dual-purpose RRWH systems have been studied mostly for water supply and stormwater runoff control. A summary of the literature review on modeling dual- or multi-purpose rooftop rainwater harvesting in urban areas is given in Appendix D. It compares each study based on the location, the scale investigated, the urban water problem tackled, the method and time-step used and its limitations. Only one study water found addressing water supply, stormwater runoff control and groundwater recharge (Nguyen, 2017).

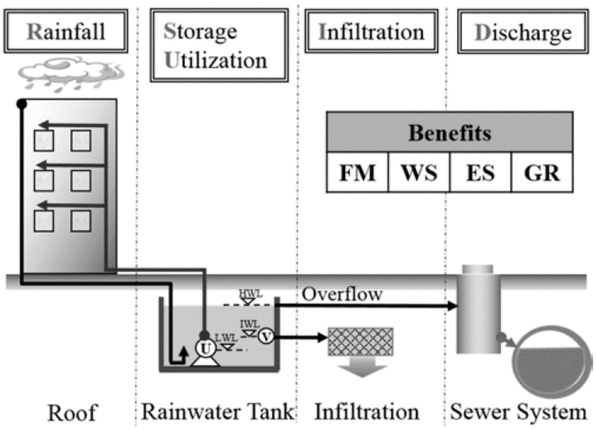


Figure 7. Rainfall-Storage-Utilization-Infiltration-Discharge (R-S-U-I-D) system. FM (Flood mitigation), WS (Water-Saving), ES (Emergency storage) and GR (Groundwater recharge) (Han & Nguyen, 2018)

The multi-purpose RRWH model proposed by Nguyen is called R-S-U-I-D (Rainfall-Storage-Utilization-Infiltration-Discharge). Figure 7 shows a schematic of the R-S-U-I-D system. Nguyen (2017) demonstrated the benefits of multi-purpose RRWH by comparing it with different RRWH systems (1. R-S-D (Rainfall-Storage-Discharge), 2. R-S-P-D (Rainfall-Storage-Pump-Discharge), 3. R-S-I-D (Rainfall-Storage-Infiltration-Discharge), 4. R-S-U-D (Rainfall-Storage, Utilization-Discharge) and 5. R-S-U-I-D (Rainfall-Storage-Utilization-Infiltration-Discharge) (see Figure 8). The R-S-U-I-D showed that both the effects on water saving and runoff reduction are larger than on groundwater recharge. Since the infiltration module is modeled as an infiltration box with a certain infiltration rate, groundwater recharge has a lower hydrological effect than the others. When the tank volume has reached its maximum capacity, rainwater overflows to the sewer system or the stormwater drainage system. For more detailed information about the R-S-U-I-D simulation model, the flow chart can be found in Annex D. The model is based on a continuous water balance simulation using the YBS method. It uses the rational method as presented to compute the inflow in the tank. The author used the Huff method, which has not been mentioned or used in other studies related to rainwater tank sizing to determine the rainwater tank volume required. Finally, the R-S-U-I-D model considers not only water saving but also stormwater control as an objective function for sizing the rainwater tank. Further details on this method can be found elsewhere (Han & Nguyen, 2018; Nguyen, 2017) and will not be discussed in this chapter.

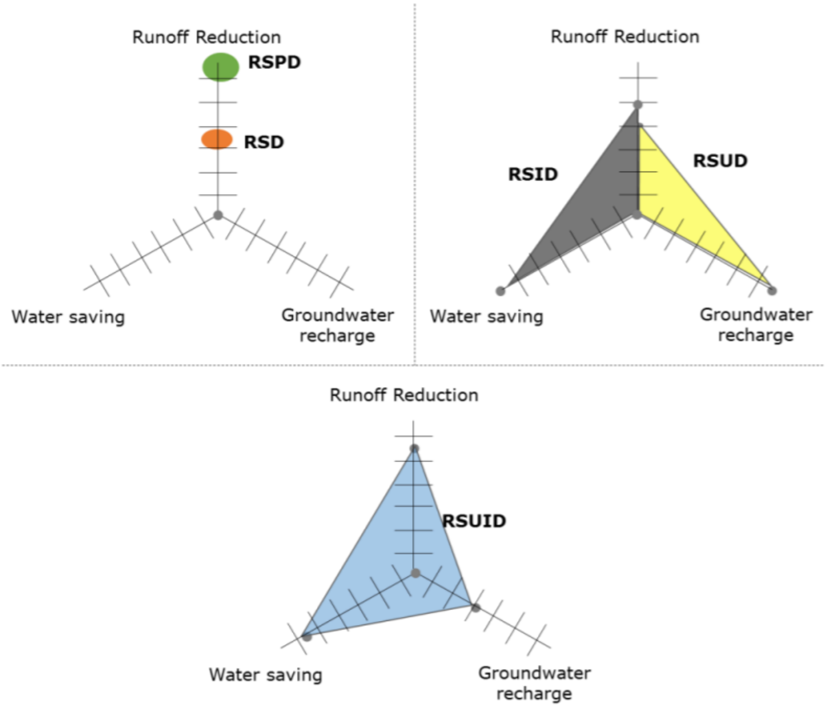


Figure 8. Multi-purpose effect of different Rainwater Management System. 1. R-S-D (Rainfall-Storage-Discharge), 2. R-S-P-D (Rainfall-Storage-Pump-Discharge), 3. R-S-I-D (Rainfall-Storage-Infiltration-Discharge), 4. R-S-U-D (Rainfall-Storage, Utilization-Discharge) and 5. R-S-U-I-D (Rainfall-Storage-Utilization-Infiltration-Discharge) (Nguyen, 2017)

3.1.4 SUMMARY AND CONCLUSION

Most of the RRWH models set-up use the rational method and the operation rules of YAS and YBS for the tank water balance configuration. These can then be integrated into a computer model to simulate the performance of the RRWH system based on a high-resolution historical rainfall data, total daily water demand, roof runoff coefficient and rooftop catchment area. The most common modeling approach is the use of continuous simulations of the rainwater tank system over a significant period to minimize errors due to initial conditions and to ensure a representation of the relevant rainfall patterns. Since the objective function of the RRWH developed for the case of Chennai is to maximize reliance on RRWH for water supply, optimization modeling based on a continuous water balance can be used to provide a preliminary estimate of the optimal rainwater tank. This method also allows considering the statistics of extreme values. Only one study done by Nguyen (2017) was found to address the performance of RRWH from a multi-purpose approach. In this study, the multi-purpose RRWH system includes emergency storage, water supply, stormwater runoff and groundwater recharge. None of the reviewed studies found explicitly combine the optimization process of sizing rainwater tank for water supply using continuous water balance simulation and the evaluation of the performance of the RRWH system from a multi-purpose approach into one comprehensive RRWH model.

3.2 PROPOSED RRWH MODEL SET-UP

Based on the limitations drawn from the extensive literature review in section 3.1, this section will elaborate on the development of an improved and adapted multi-purpose RRWH model for Chennai.

3.2.1 SPECIFIC OBJECTIVES OF THE PROPOSED MODEL

The aims of developing an RRWH model is to answer to the first sub-question: *How can decentralized and multi-purpose RRWH be investigated effectively and systematically?* As a reminder, the optimal RRWH design is designed for water supply purpose. The multi-purpose approach is then applied to quantify the hydrological effects of RRWH. A RRWH model was developed based on the same model setup:

Table 2. The proposed RRWH model with two sub-models for an existing building and a planned building

	Optimum RRWH design				Design performance
RRWH model	Building	No. of users	Rooftop area	Sump capacity	Hydrological effects of RRWH
Model 1	Existing	Known	Known	Unknown	Unknown
Model 2	Planned	Known	Unknown	Unknown	Unknown

The proposed RRWH model has two sub-models, defined as Model 1 and Model 2. The difference between both sub-models is that Model 1 is based on a known roof catchment area (*A*) and known daily water consumption (*Dt*) to determine the optimal sump capacity (*Ca*) whereas Model 2 computes with only known *Dt* to determine the optimal *A* and *Ca*. In other words, Model 1 is used for retrofitting an existing building and Model 2 is used for a new building. The later allows computing for an ideal scenario of a completely decentralized water supply system. It helps to answer the second sub-question which is "*Can Mambalam area become water-sufficient for domestic water supply from using RRWH only considering the existing local infrastructure?*". Both sub-models have similar model set-up; the output of *A* in model 2 can be the input of *A* in model 1 and give the same output for *Ca.*

Once the optimal RRWH design (optimal *A* and *Ca*) is known, the multi-benefits of RRWH system can be quantified by developing algorithms that provide the required outputs. The outputs of both sub-models provide the quantitative information described in Table 3. The detailed description of the outputs and units are presented later in section 3.3.2.

Table 3. Quantitative outputs of the proposed RRWH model

HYDROLOGICAL BENEFITS	QUANTITATIVE OUTPUTS
Water supply	Optimal rooftop area (For proposed building only)
	Optimal sump capacity
	Reliance on RRWH for water supply (Reliability)
	Number of days supplied by RRWH only
	Annual volume saved from external water supply
Groundwater recharge	Annual volume of groundwater recharge
Stormwater runoff	Annual stormwater runoff reduction of a building
	Max. stormwater peak reduction of a building

3.2.2 RRWH SYSTEM CONFIGURATION

The current RRWH design structure in Chennai is to recharge groundwater mainly and can be summarized in the scheme shown in Figure 9. The proposed RRWH model is based on the core structure of the R-S-U-I-D model (see section 3.1.3). The model uses a continuous daily historical rainfall simulation with the YBS method and evaluates the performance of RRWH on water saving, stormwater runoff, and groundwater recharge. The following components are added or modified for the proposed RRWH model for Chennai:

- An optimization process based on the continuous water balance simulation to determine the optimal tank capacity only to maximize reliability on RRWH for domestic water supply

- A recharge well is used for groundwater recharge instead of an infiltration box. A recharge well is a dug well which for the time being is unable to yield water for use because the water table in the soil has gone below its bottom. Thus, it is used only for receiving rainwater.

- All overflow will be discharged into the recharge well

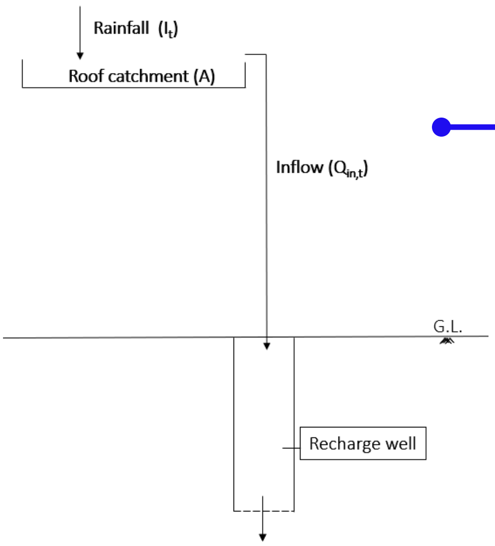


Figure 9. Scheme of RRWH in Chennai for groundwater recharge (open system)

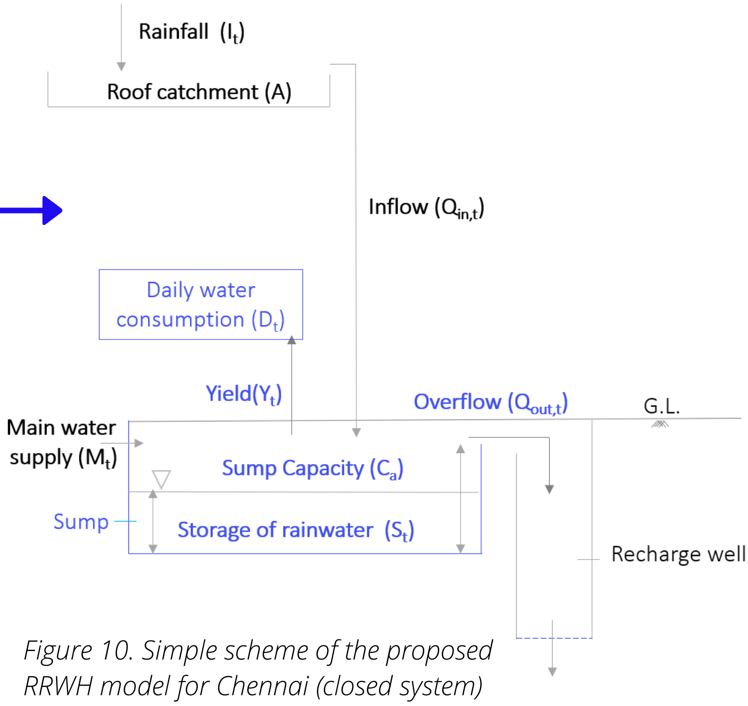
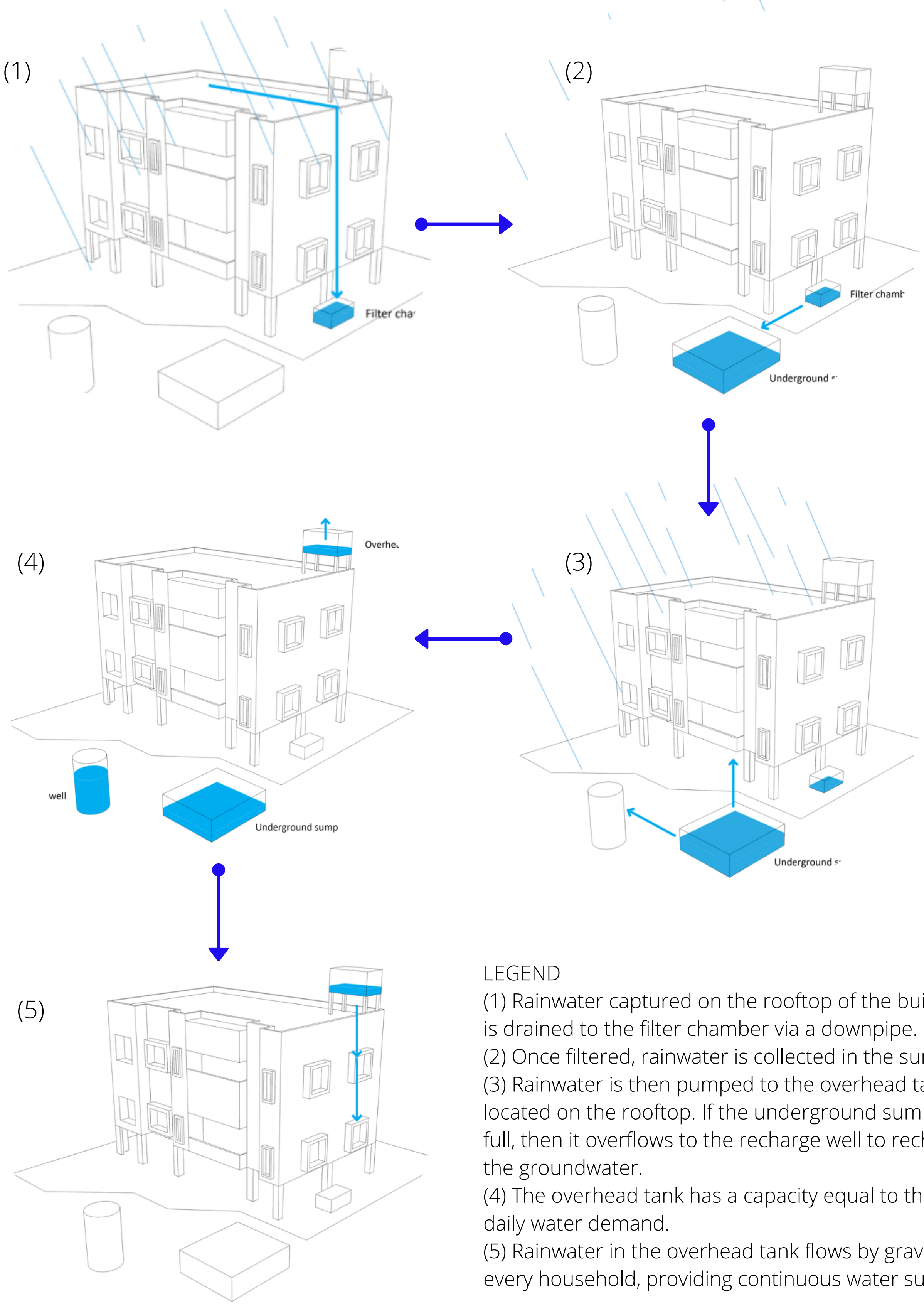


Figure 10. Simple scheme of the proposed RRWH model for Chennai (closed system)

The proposed RRWH model was first developed on Excel spreadsheet (see Annex e) before developed on MATLAB, a programming software (see Annex F). The model on MATLAB was tested using the same data by comparing the results from the model on Excel as both have similar assumptions and operating rules.

The scheme presented in Figure 11 shows step-by-step the flow of rainwater from the rooftop to the consumer.



LEGEND
(1) Rainwater captured on the rooftop of the building is drained to the filter chamber via a downpipe.
(2) Once filtered, rainwater is collected in the sump.
(3) Rainwater is then pumped to the overhead tank located on the rooftop. If the underground sump is full, then it overflows to the recharge well to recharge the groundwater.
(4) The overhead tank has a capacity equal to the total daily water demand.
(5) Rainwater in the overhead tank flows by gravity to every household, providing continuous water supply.

*Figure 11. Flow of the rainwater from rooftop to*the consumer

3.2.3 ASSUMPTIONS

In the RRWH model, the rooftop is assumed to be flat and the infiltration rate of the filter chamber is not taken into account. They are different types of existing recharge wells such as borewell, tubewell, borewell, deep dug well (see Annex B). The type of recharge well required depends mostly on the soil profile of the location and the average groundwater level. Since it is location-specific, the general term "recharge well" is used in this research. The recharge well is assumed to have an infinite capacity of storage which means that all rainwater captured from the rooftop will not be discharged to the stormwater drainage or the street. It is assumed that stored rainwater in the sump is pumped once a day to the overhead tank. The overhead tank is assumed to have a capacity of the total daily water demand of the residential building.

3.2.4 DETERMINISTIC AND PROBABILISTIC APPROACHES

The optimization process for sizing the optimal sump for water supply is based on a deterministic method, while the evaluation of the performance of the RRWH system on water savings for water supply, groundwater recharge and stormwater runoff is based on a probabilistic method. Using a deterministic approach allows evaluating the optimal objective based on the entire simulation period. The probabilistic approach can provide information yearly which has more understandable and tangible outputs, such as having the results in units of d/yr or m3/yr. However, the probabilistic approach requires a certain length of historical rainfall data to be representative (Sharma, Begbie & Gardner, 2015).

3.2.5 OPERATIONAL RULES

Using the YBS method, with a varying *Yt* depending on *St* could become complex if these operating rules are applied in the real world. The volume of water required from *Mt* to meet *Dt* would vary considerably and it would require a monitoring system to evaluate the inflow and outflow continuously to control the valve of the inflow of *Mt*. It may not be effectively and systematically manageable compared to a daily fix volume of water, such as having *Mt* switching between *Dt* and 0. Thus, in this research, the operational rules follow a binary method.

Table 4. Operating rules for the proposed RRWH model

Method	Operating rules (adapted from Fewkes and Butler, 2000)
YBS	$Y_t = \min[D_t, 0]$ If $Q_{in,t} + S_{t-1} - Y_t > C_a$. Then, $Q_{out,t} = Q_{in,t} + S_{t-1} - Y_t - C_a$ $S_t = \min(S_{t-1} + Q_{in,t} - Y_t, C_a)$

Moreover, the overhead tank in the RRWH system allows reducing the energy of pumping water every time it is needed.

3.2.6 OPTIMIZATION PROCESS FOR THE SUMP SIZING

The optimization process for sump sizing is to maximize the reliability (*ET*) on RRWH for water supply over the simulation period (*T*). The performance of RRWH system by its water-saving can be evaluated using the following equation (adapted from Islam, Chou & Liaw, 2010):

$$E_T = \frac{\sum_{t=1}^{T} Y_t}{D_t\ (T-365*n)} * 100$$

Where 365*n is added in the denominator and discuss later in section 3.4. The boundary conditions using *ET* to determine the optimal *A* and *Ca* are described in Table 5.

Table 5. Boundary conditions in the proposed RRWH model

BOUNDARY CONDITIONS	DESCRIPTION
$E_T \leq E_{T,\ max}$	$E_{T,\ max}$ can be either 100% or lower, depending on the feasibility and set target. Moreover, 100% reliance on RRWH for water supply may be difficult to achieve as it would require a large rooftop area, which involves higher cost (Santos & Taveira-Pinto, 2013).
$E_{T,i-1}=E_{T,I}$	E_T may become constant even before reaching E_T = 100% due to a high-density population. Therefore, the second boundary condition is necessary to stop the simulation. Ghisi, Bressan & Martini (2007) used this method to define the optimum tank capacity for residential applications.

3.3 RESULTS OF THE PROPOSED RRWH MODEL

In this section, the proposed RRWH model is addressed based on the literature review on RRWH modeling. Firstly, the main design parameters is presented, then the potential outputs parameters that the model can give. The RRWH model was developed in MATLAB and presented in a flow chart formats for better understanding.

3.3.1 MAIN DESIGN PARAMETERS (INPUTS)

Table 6. Inputs parameters of the RRWH model

INPUTS PARAMETERS	UNITS	SYMBOL	DESCRIPTION
Daily rainfall	mm/d	I_t	Daily rainfall fell on the specific area of interest
Simulation period	d	T	Total number of daily rainfall data (T = length (I_t)) in the period of simulation.
Number of people	-	P	No. of people living in the same residential building
Daily water consumption per person	$m^3/d/p$	W_t	Average daily water consumption per person (including toilet flushing, washing, drinking water, cooking)
Total daily water consumption per person	m^3/d	D_t	Total daily water consumption W_t x P. It assumes that the total daily water consumption is constant.
Daily yield withdrawn from the sump	m^3/d	Y_t	Yield withdrawn from the sump. $Y_t = D_t$ or 0
Time-step	d	t	Daily time-step
Roof catchment area	m^2	A	Rooftop area of existing residential building
Roof runoff coefficient	-	C	Coefficient in the rational method used to calculate the actual rainfall captured
No. of years	yr	n	No. of years it takes until the initial storage of the first year has no more effect on the reliability. See section 3.4

OTHER VARIABLES	UNITS	SYMBOL	DESCRIPTION
Rainwater runoff from the rooftop	m^3/d	$Q_{in,t}$	I_t x C x A (Rational method)
Stored volume of rainwater	m^3/d	S_t	$Q_{in,t} + S_{t-1} - Y_t$
Overflow	m^3/d	$Q_{out,t}$	When the underground sump capacity ($S_t = C_a$) is full, overflow occurs. This water is then discharged to the groundwater via the recharge well.
Design factor	-	X	It is only used in Model 2. It converges the roof area and the sump capacity to realistic values.

3.3.2 OUTPUTS

Table 7. Outputs parameters of the RRWH model

OUTPUTS	UNITS	SYMBOL	DESCRIPTION
Deterministic approach (analysis over the simulation period T)			
Optimal roof catchment area	m^2	A	Rooftop area of the proposed residential building (for Model 2 only)
Optimal sump capacity	m^3	C_a	Based on $Q_{in,t,}$ and $Y_{t,}$ and D_t
Reliance on RRWH for water supply	%	E_T	It is the total amount of days which can be supplied by RRWH only divided by the total amount of the simulation period (See Eq. 1)
Probabilistic approach (year-by-year analysis) *The outputs are in the format of graph representation using the inverse cumulative probability function with the probability of exceedance. For the analysis, the value used is the value at 50% of probability of exceedance.* *The simulation period is yearly and the last storage volume of the year is the initial storage volume of the next year.*			
Total no. of days relying on RRWH for water supply per year	d/yr	N	$\frac{\sum Y_t}{Y_t}$
Volume saved from external water supply	m^3/yr	V	$\sum Y_t$
Annual volume of groundwater recharge	m^3/yr	Gw	$\sum Q_{out,t}$
Annual stormwater runoff reduction	m^3/yr	$Q_{out,\ max}$	Same as annual volume of potential groundwater recharge without water supply $\sum Q_{in,t}$
Linear equation for daily outputs			
Max daily stormwater runoff volume reduction	m^3/d	$Q_{daily,\ max}$	Max. daily rainfall over T x roof area x C (Rational method)

3.3.3 FLOW CHARTS OF THE RRWH MODEL

The RRWH models developed are presented in a flow chart format. The first flow chart represents the RRWH model for an existing building (see Figure 12) and the second and third ones are for a planned building (see Figure 13 and Figure 14). Both sub-models have the same model set-up, except model 2 has another component prior to the optimization process to determine the unknown rooftop area required. Therefore, Model 2 is represented by two flow charts (see Figure 13 and Figure 14) with the first one representing the simulation with unknown rooftop area and the second one with unknown sump capacity. Once the optimum RRWH design is determined, the RRWH design performance is analyzed. The RRWH design performance on the hydrological effects is not shown in the flow charts, but the algorithms used can be found in Annex F and Annex G in MATLAB code format. The parameters in blue shown in the flow charts represent the key parameters which may vary according to the local context. A sensitivity analysis is performed using these parameters.

RRWH model for existing building (Model 1)

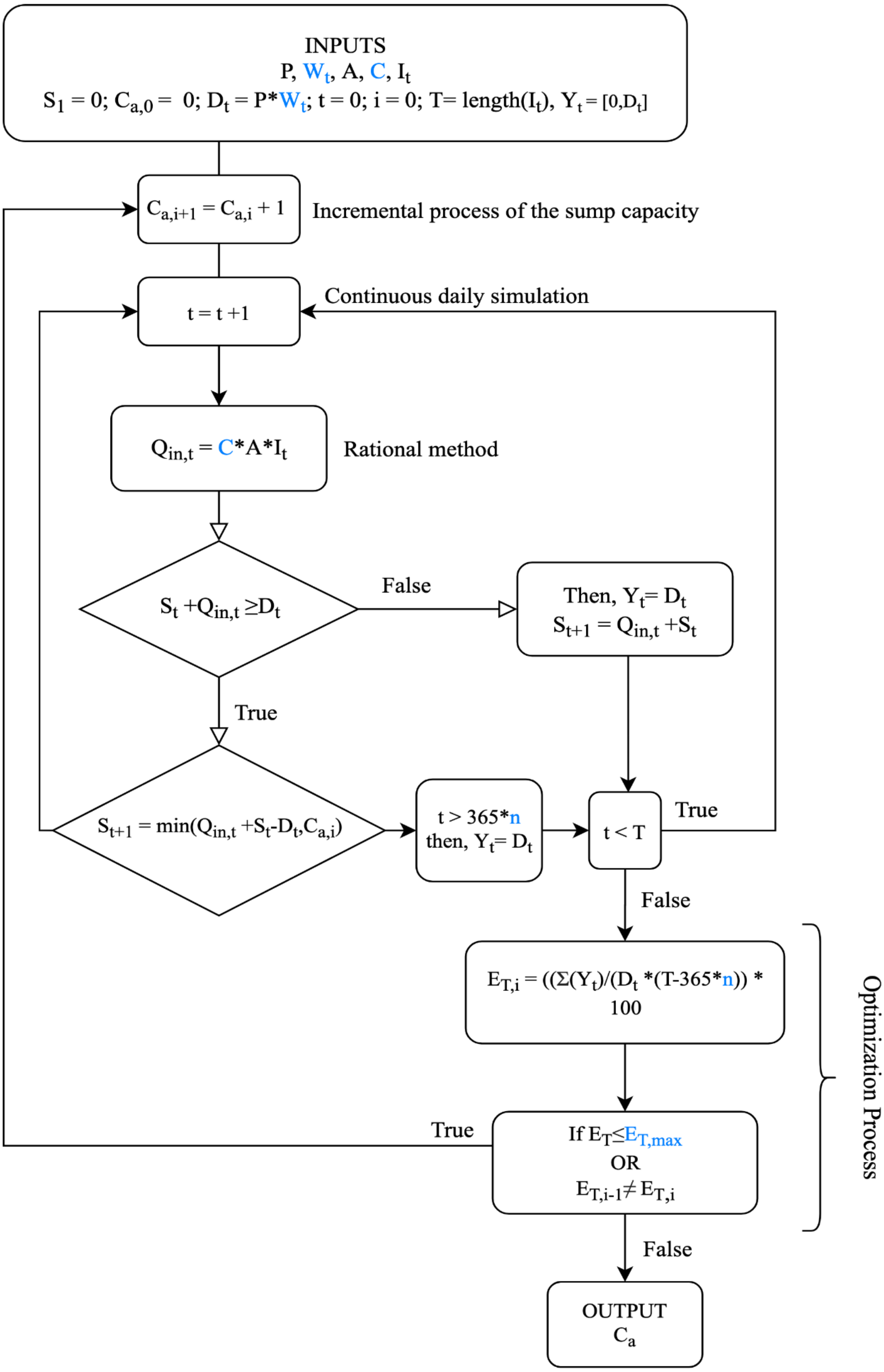


Figure 12. Flow chart of the RRWH optimization model for sizing sump for existing building using a deterministic approach

RRWH model for planned building (Model 2 – Part 1)

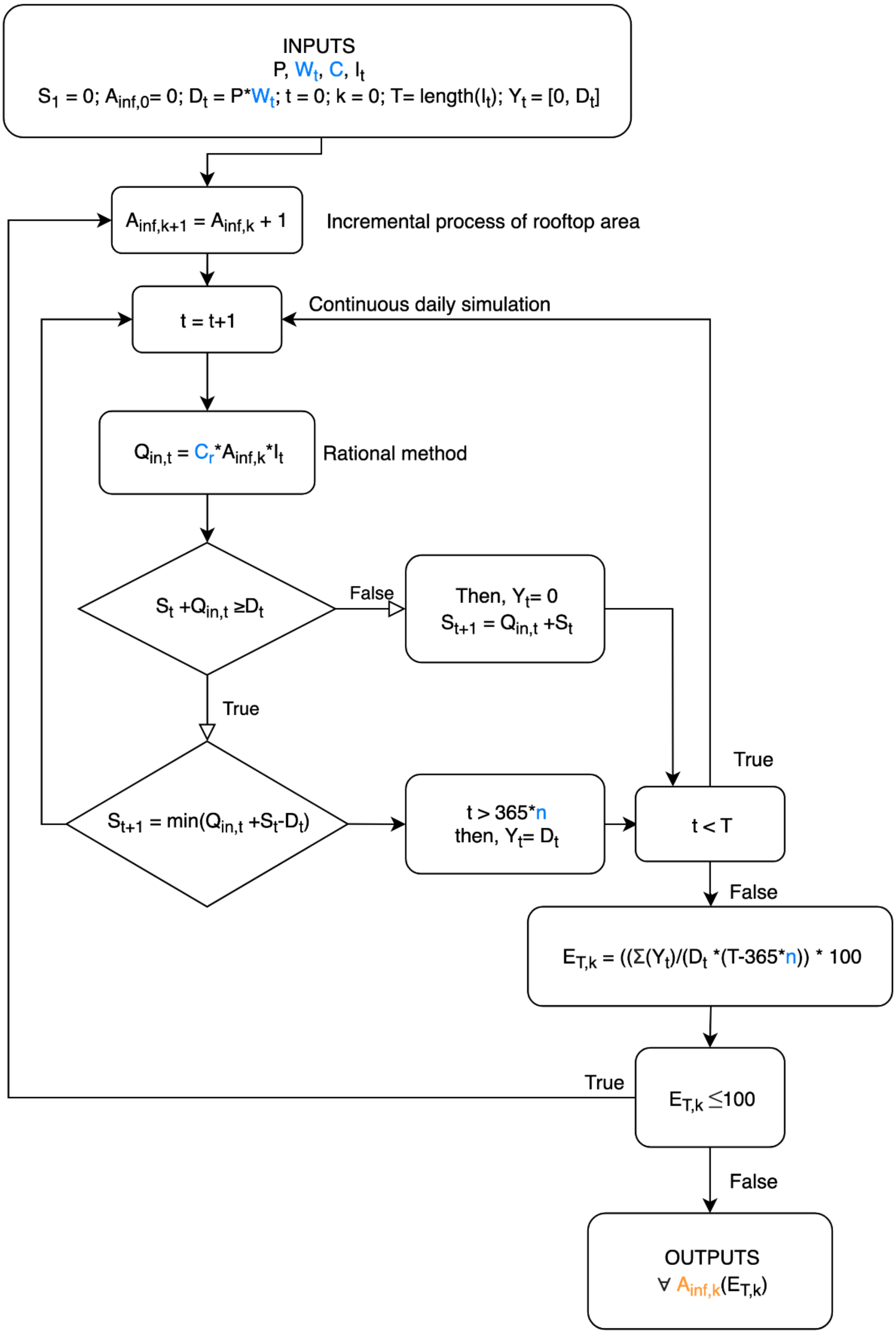


Figure 13. Flow chart of the first part of the RRWH model for planned building with infinite storage capacity using a deterministic approach

RRWH model for planned building (Model 2 – Part 2)

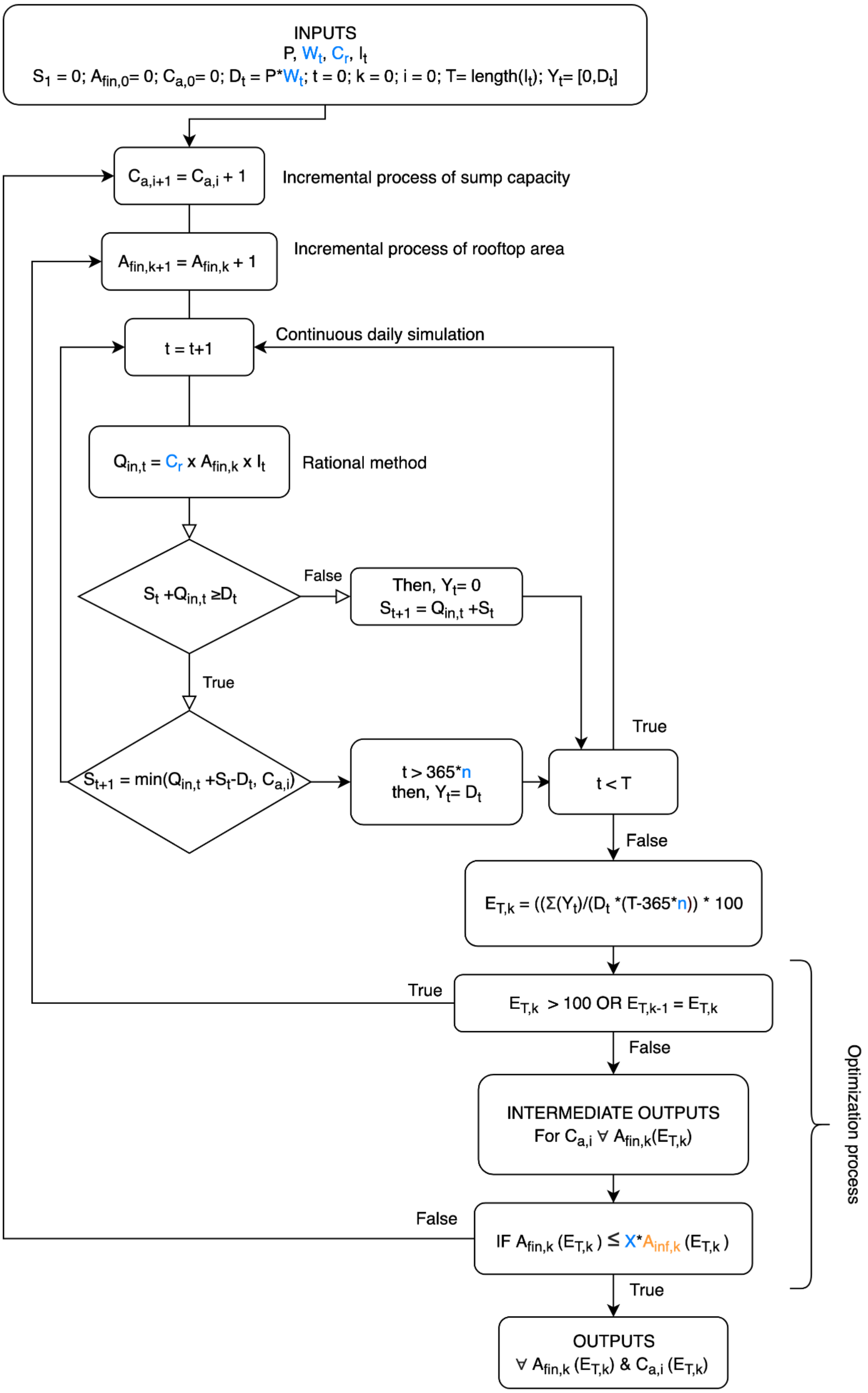


Figure 14. Flow chart of the second part of the RRWH model for planned building with infinite storage capacity using a deterministic approach

3.4 SENSITIVITY ANALYSIS

It is essential to understand the effect of the main parameters and methods chosen by performing a sensitivity analysis. The sensitivity analysis allows to interpret accurately the results obtained from the RRWH models developed. The data used to carry out the sensitivity analysis are the historical daily rainfall data from Nungambakkam weather station, Chennai, India (IMD, 2019) and input in the RRWH models. The data collection is explained in section 4.3. The results of this sensitivity analysis are discussed in section 5.1.1.

The main design parameters used for the sensitivity analysis are the runoff coefficient (*C*), the design factor (*X*), the number of years skipped (*n),* the daily water demand (*Wt*). The design factor is only used in Model 2 and all the other parameters are used in both RRWH models. These parameters are shown in blue in the flow chart of the RRWH models in section 3.3.3 and 3.3.4. Various values were simulated for each of these design parameters to evaluate the changes. The YAS and YBS methods are also compared.

C and *Wt* are both external parameters which means that the values are input by the user, whereas *X*, *n* and YBS method are internal parameters which means they are already integrated in the simulations of the RRWH model. External parameters can be controlled by the type of rooftop used or the water consumption patterns and internal parameters can be adjusted by changing the values and algorithms using in the model.

3.4.1 ROOF RUNOFF COEFFICIENT

For the roof runoff coefficient (*C*), the values from common types of roof (0.7 for concrete, 0.75 for tiled, 0.8 for asbestos and 0.9 for GI sheet) were simulated (CGWB, 2007). From 95% onwards, all C show a linear relationship. From 0-95%, *A* increases steeply up. At 95%, the difference in the rooftop area between the lowest and the highest runoff coefficient is up to almost 10m2.

Table 8. Pre-determined parameters used in the RRWH model to analyze the influence of C

Parameters	P [-]	X	C [-]	W_t [m^3/d/p]
Value	1	1.1	0.85	0.1
Method	YBS			

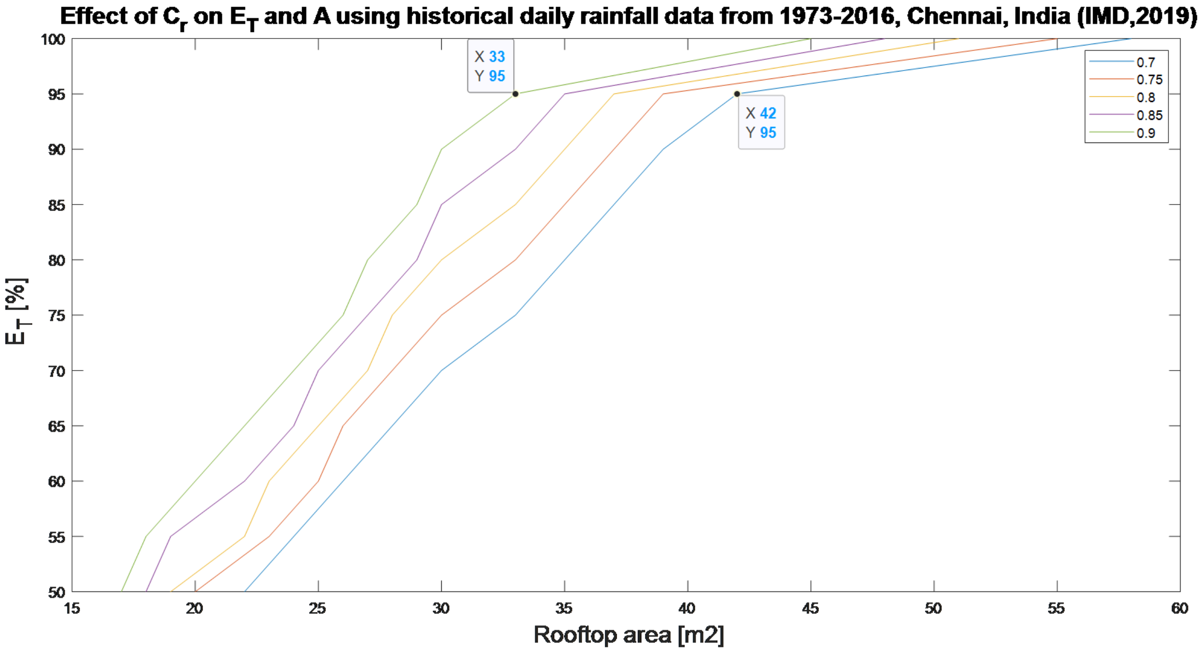


Figure 15. Effect of the roof runoff coefficient on reliance and roof area

3.4.2 DESIGN FACTOR

The optimization process for the RRWH for planned building (Model 2) uses a design factor (*X*) to converge the rooftop area and the sump capacity to realistic values. In model 2, *Ainf* is the minimum rooftop area required with an infinite storage capacity (and with the largest storage capacity). Increasing *Afin* (see Figure 16) would reduce *Ca* (see Figure 17) because increasing the rainfall catchment area will increase the potential volume captured and therefore less storage capacity is required. Therefore, there is a range of possible combinations for the same *ET*. The design factor selects the optimum design combination required. Without the design factor, the RRWH model for proposed building would give the minimum *A* with the maximum *Ca*. In terms of feasibility, having the largest sump capacity possible may not be the ideal design because it will come with higher costs and require more available land. At *X*=1 and *X* = 1.05, there is a significant difference in the *Ca*, especially at 95% (see Figure 17). Therefore, choosing *X*=1.1 or above would reduce the effect of an unreasonable volume of *Ca*.

Table 9. Pre-determined parameters used in the RRWH model to analyze the influence of X

Parameters	P [-]	C [-]	W_t [m^3/d/p]
Value	1	0.85	0.1
Method	YBS		

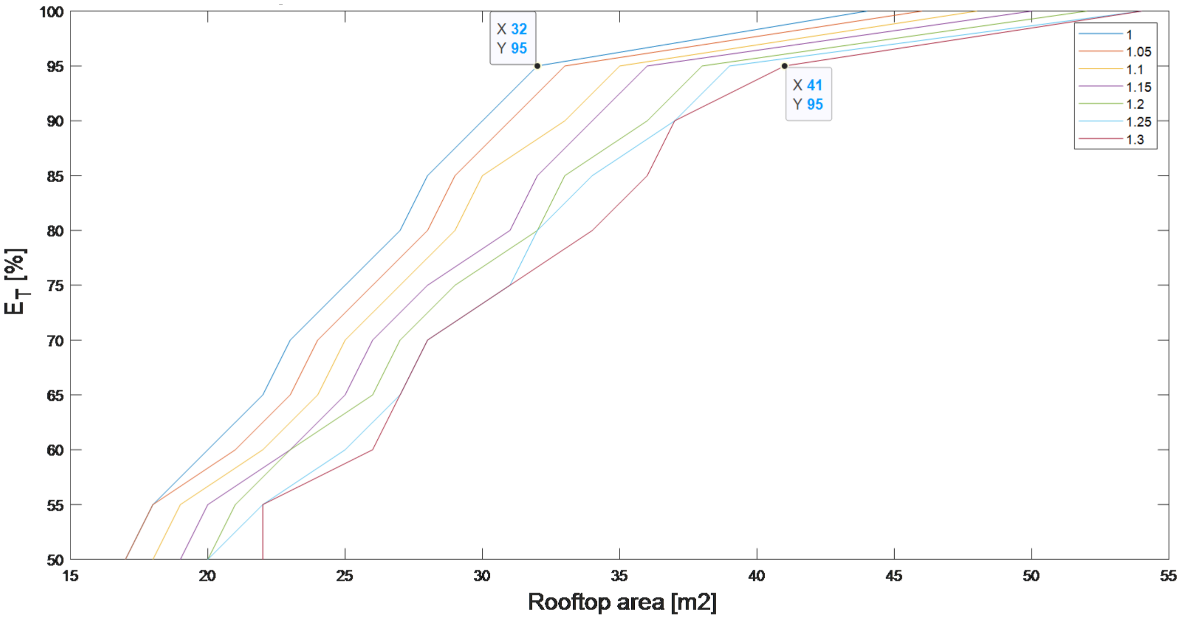


Figure 16. Effect of the design factor on reliance and roof area

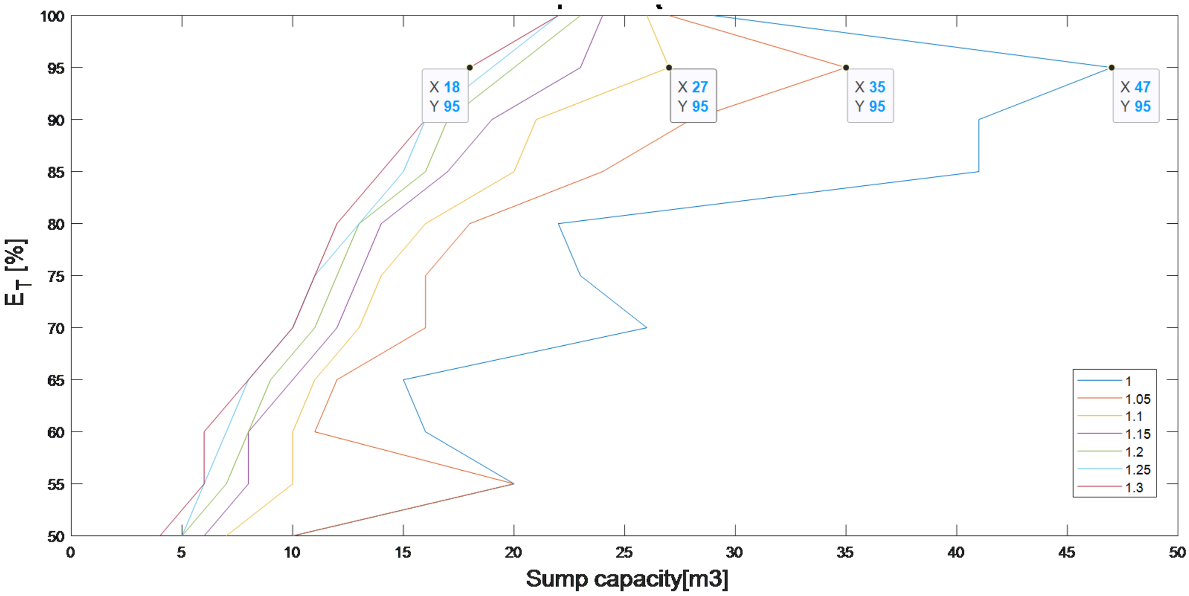


Figure 17. Effect of the design factor on reliance and sump capacity

With *X*=1, if the depth of the sump is 1m, the surface area of the sump (47m2) would be higher than the optimal rooftop (32m2). Considering the underground space used for the pile foundation of the building, it is assumed that a realistic RRWH design is a surface area of a sump which is smaller than the roof area. With *X*=1.1 and a depth of the sump of 1m, the surface area of the sump (27m2) would be around 3/4 of the roof area (35m2) (see Figure 18). Therefore, 1.1 is chosen as the design factor to be used in the Model 2.

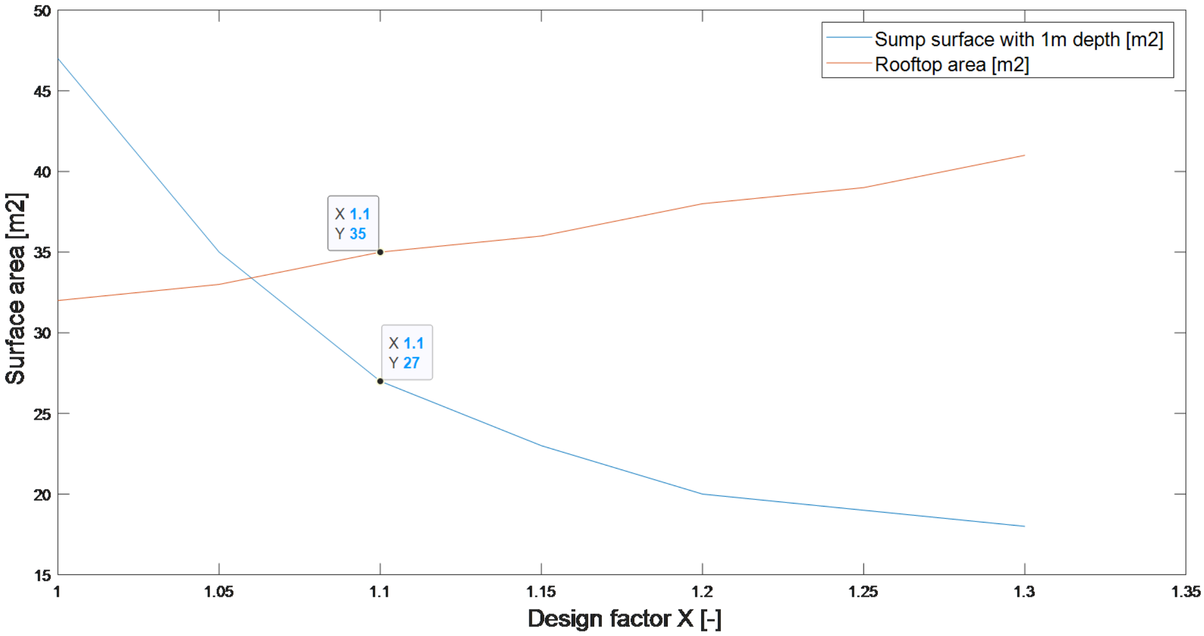


Figure 18. Surface area of the rooftop vs sump over the design factor

3.4.3 YEAR SKIPPED

Most of the rainwater is harvested during the monsoon seasons. Therefore, the number of days that can be supplied by RRWH in the first year may be biased because there is no previous storage at the beginning of the first year. To obtain accurate results, these initial years (*n*) are not considered when calculating the percentage of reliance on RRWH for water supply.

Table 10. Pre-determined parameters used in the RRWH model to analyze the influence of n with P=1

Parameters	P [-]	X	C [-]	W_t [m^3/d/p]	A [m^2]	Ca [m^3]
Value	1	1.1	0.85	0.1	33	21
Method	YBS					

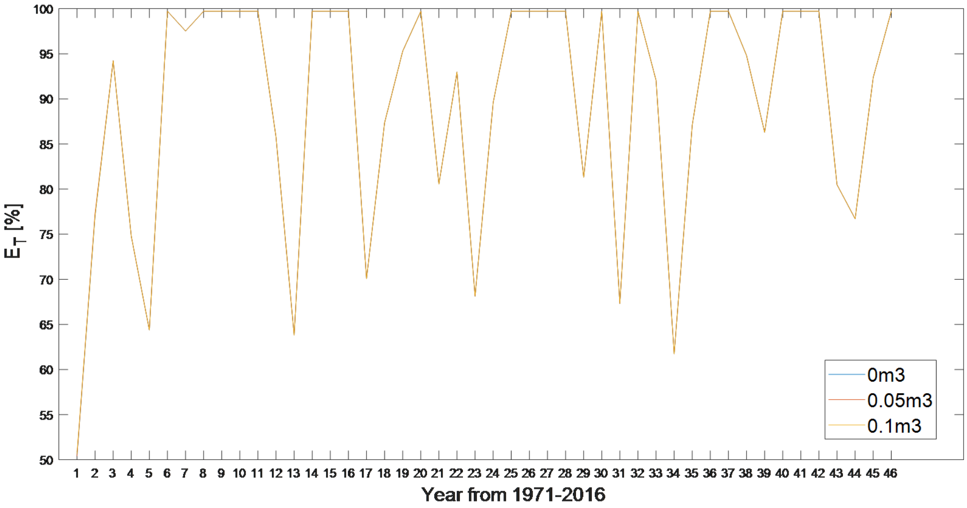


Figure 19. Effect of initial storage of year 1 on reliance for P=1 and A= 33m2

When simulating for 1 user with the 'ideal' area and sump capacity (see explanation in section 4.5.1 of an ideal scenario), the initial storage on year 1 does not affect the yield performance. However, using a different case with values which area lower than the 'ideal' scenario, the impact can be perceived. Figure 20 shows that only after a few years, *ET* converges and the initial storage has no more effect on the reliability. It can be concluded that the effect of *n* is not significant in the evaluation of the performance of RRWH, especially if the simulation period is long.

Table 11. Pre-determined parameters used in the RRWH model to analyze the influence of n with P=144

Parameters	P [-]	X	C [-]	W_t [m^3/d/p]	A [m^2]	Ca [m^3]
Value	144	1.1	0.85	0.1	250	25
Method	YBS					

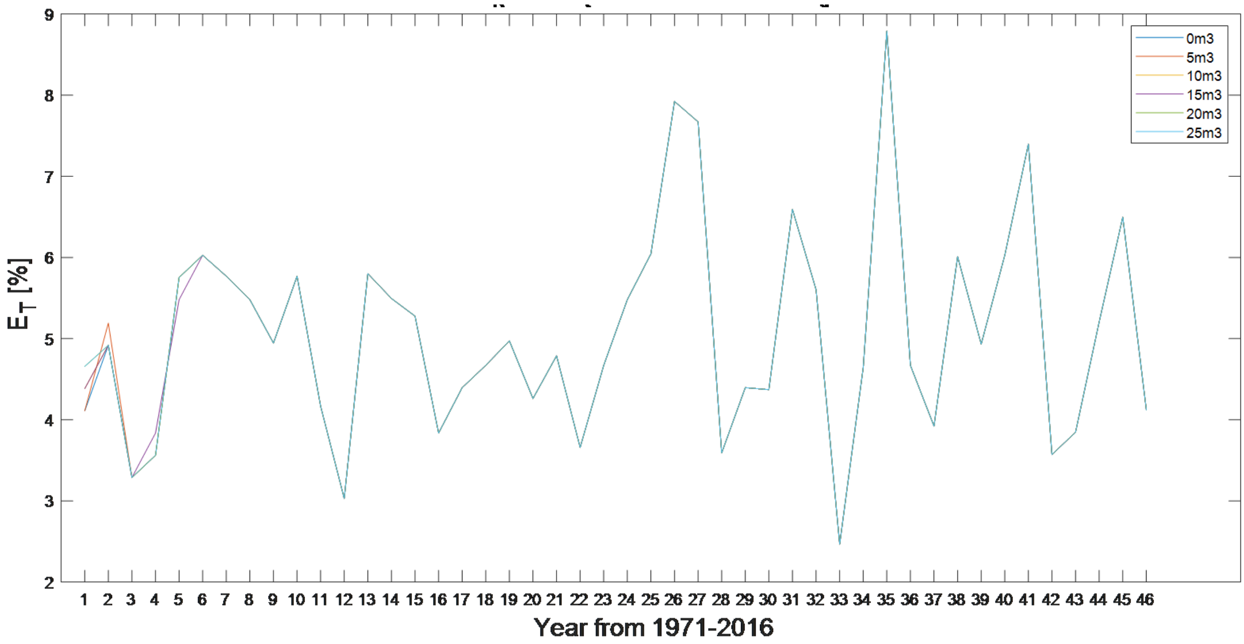


Figure 20. Effect of initial storage of year 1 on reliance for P=144 and A= 250m2

3.4.4 DAILY WATER DEMAND PER PERSON

Depending on the water consumption behavior, the income level and other factors, the water demand may differ from household to household. The difference in the rooftop area for Wt = 0.12m3/d and Wt = 0.06m3/d for the same reliability is double. This parameter should, therefore, be selected carefully.

Table 12. Pre-determined parameters used in the RRWH model to analyze the influence of Wt

Parameters	P [-]	X	C [-]
Value	1	1.1	0.85
Method	YBS		

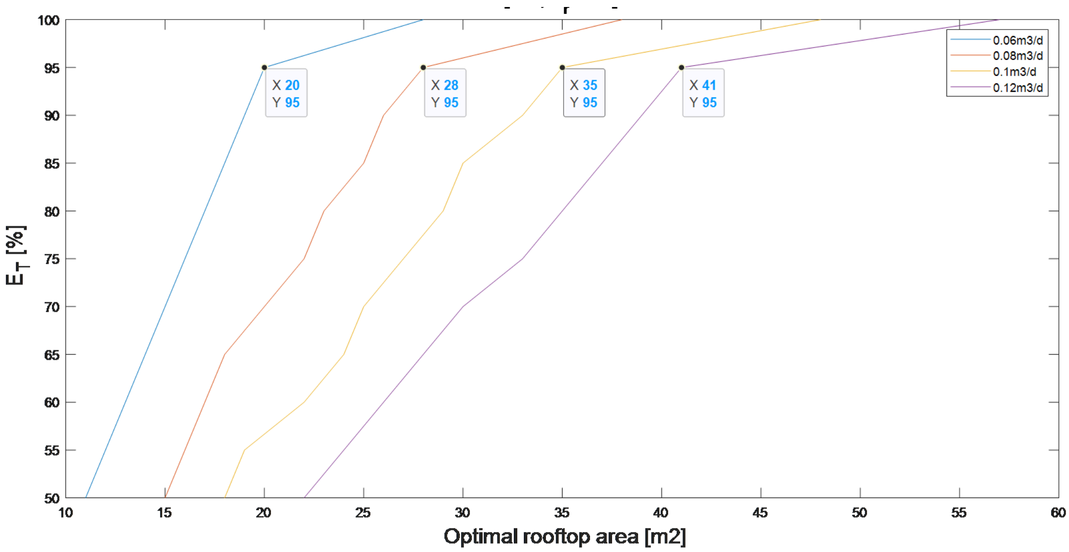


Figure 21. Effect of daily water demand on optimal rooftop area and reliance

3.4.5 YAS VS. YBS METHODS

YAS and YBS methods differ only in the order of calculation as explained in section 3.1.1. In this research, the yield has a binary function (see Table 13).

Table 13. The operating rules of YAS and YBS methods used in the sensitivity analysis

Method	Operating rules
YAS	$Y_t = [D_t, 0]$ $S_t = \min[S_{t-1} + Q_{in,t} - Y_t, C_a - Y_t]$
YBS	$Y_t = [D_t, 0]$ $S_t = \min[S_{t-1} + Q_{in,t} - Y_t, C_a]$

Table 14. Pre-determined parameters used in the RRWH model to analyze the influence of the YBS method compared to the YAS method

Parameters	P [-]	X [-]	C [-]	W_t [m^3/d/p]	A [m^2]	C_a [m^3] (YAS method)	C_a [m^3] (YBS method)
Value	1	1.1	0.85	0.1	33	21	21

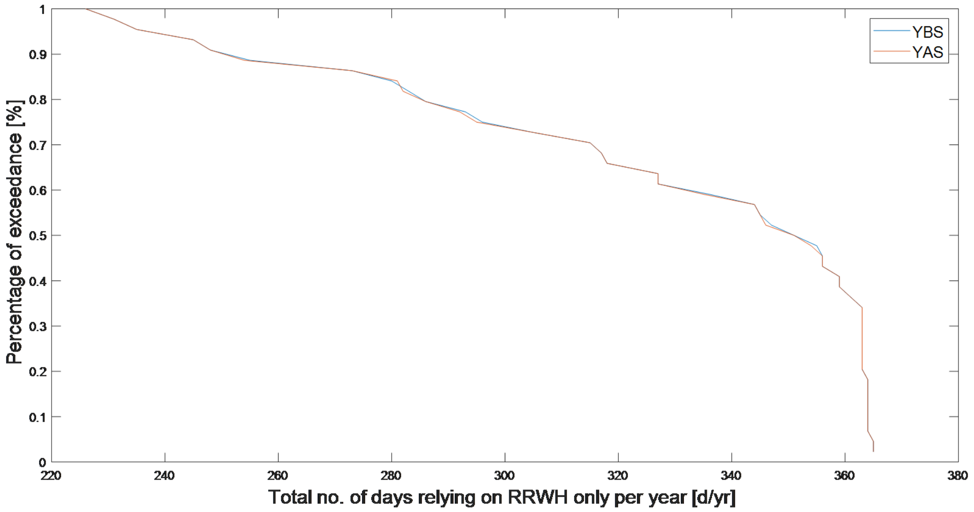


Figure 22. Difference between YAS and YBS method for P=1 and A=33m2

The difference between YAS and YBS methods on reliability is not very significant when using the 'ideal' values for RRWH design (see explanation in section 4.5.1 of an ideal scenario). The 'ideal' values are based on 90% of reliability of RRWH for water supply and given in ratio A/P. The resulted sump capacity of both methods is the same.

However, when using values of *P* and *A* which give a reliability lower than 90%, the results show a slightly larger difference than using the ideal values. Figure 23 shows a difference of one day of reliability for the same probability of exceedance between both methods.

Table 15. Pre-determined parameters used in the RRWH model to analyze the influence of the YBS method compared to the YAS method

Parameters	P [-]	X [-]	C [-]	W_t [$m^3/d/p$]	A [m^2]	C_a [m^3] (YAS method)	C_a [m^3] (YBS method)
Value	144	1.1	0.85	0.1	250	33	25

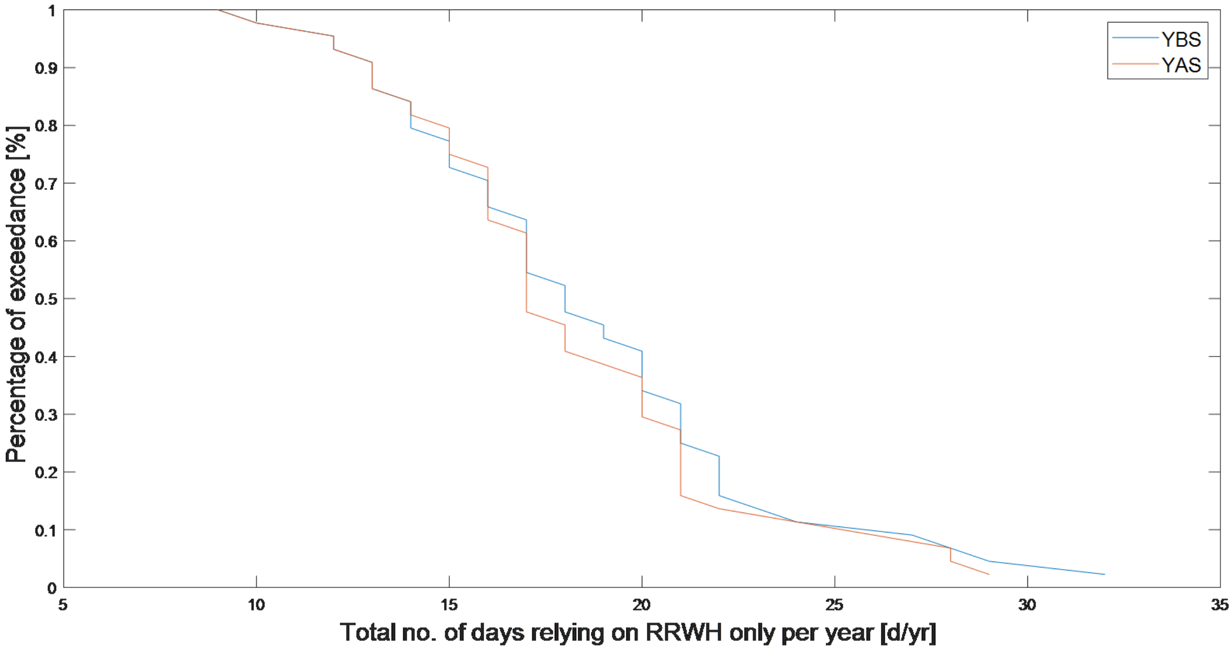


Figure 23. Difference between YAS and YBS method for P=144 and A=250m2

The “stair curves” can be explained by the binary function of *Yt* = [*Dt*, 0] which is 14.4m3 in this case. If the *St* is below 14.4m3, then no yielding occurs.

Like the parameter *n,* YAS and YBS methods are not affected when using the 'ideal scenario' which means that the ratio area and sump is close enough to the optimum reliability value. More information on the 'ideal scenario' is given in section 4.5.1.

3.5 SUMMARY AND CONCLUSION

Sensitivity analysis was performed to investigate the effect of changing *C, X, n* and *Wt* on the outputs of the RRWH model. YBS method was also compared with YAS method.

The results from the sensitivity analysis are summarized in Table 16. It shows that daily water demand (Wt) has a significant influence on the outputs of the RRWH model. Indeed, reducing by half the daily water demand can reduce by half the roof area required.

Table 16. Summary of the sensitivity analysis of different parameters in the RRWH model

Effects	Low	Moderate	High
Roof runoff coefficient (C)		x	
Design factor X		x	
Year skipped (n)	x		
Daily water demand (W_t)			x
YAS and YBS methods		x	

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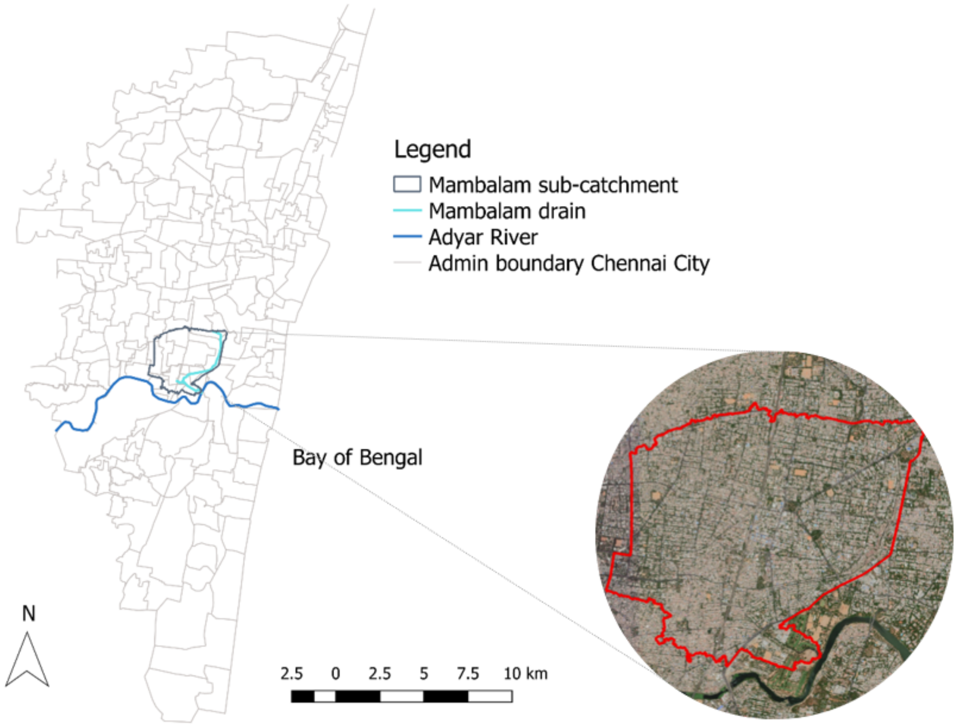
CHAPTER 4

LET'S APPLY: CHENNAI, INDIA

As mentioned in the preface, the Mambalam area was chosen as the study area because it was an area of interest for the WaL program, and therefore, more data was accessible for an in-depth investigation. Mambalam is located in the historical center of Chennai. There is an estimated population of 380,000 living in this area (Water As Leverage, 2019B). This area hosts Theagaraya Nagar which is a very affluent commercial and residential area in Chennai. It is, in fact, the largest shopping district in India. It is also an important area because Chennai Smart City Limited (CSCL) has been retrofitting this area into a digital water area, such as installing smart water meters (CSCL, 2019). Another objective of the CSCL is to provide a 27/7 water supply to households (CSCL, 2019). It is, therefore, an area of opportunities for change. An optimal rainwater harvesting system for residential buildings may help to satisfy the water demand, taking advantage of the excess water during monsoon and palliating the situation during the dry season.



Source: Dr. Balaji Narasimhan, IIT Madras (2019)

Figure 24. Location of the Mambalam sub-catchment in Chennai, India

4.1 MAMBALAM SUB-CATCHMENT AND THE MAMBALAM DRAIN

From a hydrological perspective, the Mambalam sub-catchment covers approximately 11,690,000m2 of area (calculated from QGIS, see Annex G). When it rains, stormwater runoff drains towards the Mambalam drain, located on the east side of the sub-catchment, see the light blue line in Figure 24 (Balaji, 2019). The drain is highly polluted by household's waste (see Figure 26). Then, it flows to the Adyar river, one of the major rivers in Chennai, before reaching the Bay of Bengal. RRWH can have a significant impact in avoiding 'clean' rainwater to reach polluted water in the drain by collecting, reusing and recharging it to the groundwater.

Figure 25. Photo of the Mambalam drain (taken by the author, March 2019)

4.2 METHODOLOGY

The methodology presented in this section describes how each case study was modelled and analyzed at different scales and different locations in Chennai (urban and peri-urban). Indeed, besides the case study of the Mambalam area, another interesting case study was identified after the second visit in Chennai. The case study is located in the southern part of Chennai, along the IT Corridor. This case was also investigated due to its relevance using a closed RRWH system for water supply. Although the second case study is not within the boundary of the area of interest in this research, it is nonetheless contributing to demonstrate the importance of the adoption of RRWH. More details are given for this specific case in section 4.7.

4.2.1 PLANNED BUILDING

First, the ideal scenario is determined and is used as a reference to compare with the current situation. The ideal scenario is referred to as the optimal ratio rooftop area/person (A/P) and sump capacity/person (C/P) using the RRWH model for the planned building (see Figure 12) to achieve high reliability on RRWH for water supply. The value of reliability for the 'ideal scenario' is location-specific and is given in section 4.5.1.

4.2.2 EXISTING BUILDING

For the existing building, the Tamil Nadu Slum Clearance Board (TNSCB) building in the Mambalam sub-catchment is selected as the case study and applied to the RRWH model for an existing building. This type of building is mostly used by low-income household with a lower ratio A/P.

A multi-story residential apartment complex for middle and high-income household (with higher ratio A/P) located outside the Mambalam area was also investigated. The specific case analyzed is Sabari Terrace residential apartment complex which is located in Sholinganallur area, southern part of Chennai. t is an interesting case to study because it was found that these type of residential apartment complexes located in the southern part of Chennai are solely dependent on water tankers for their water supply. For this reason, the adoption of RRWH for water supply is found to be more relevant in the southern part of Chennai than in the city itself. In addition, it has already implemented a RRWH for their domestic water provision. Data on the volume of rainwater collected from the rooftop has been recorded since November 2017 and can be used as a preliminary validation of the RRWH model. More details on the apartment complex and its specifications are given in section 4.7.1 and the results obtained for this case are given in section 4.8.1.

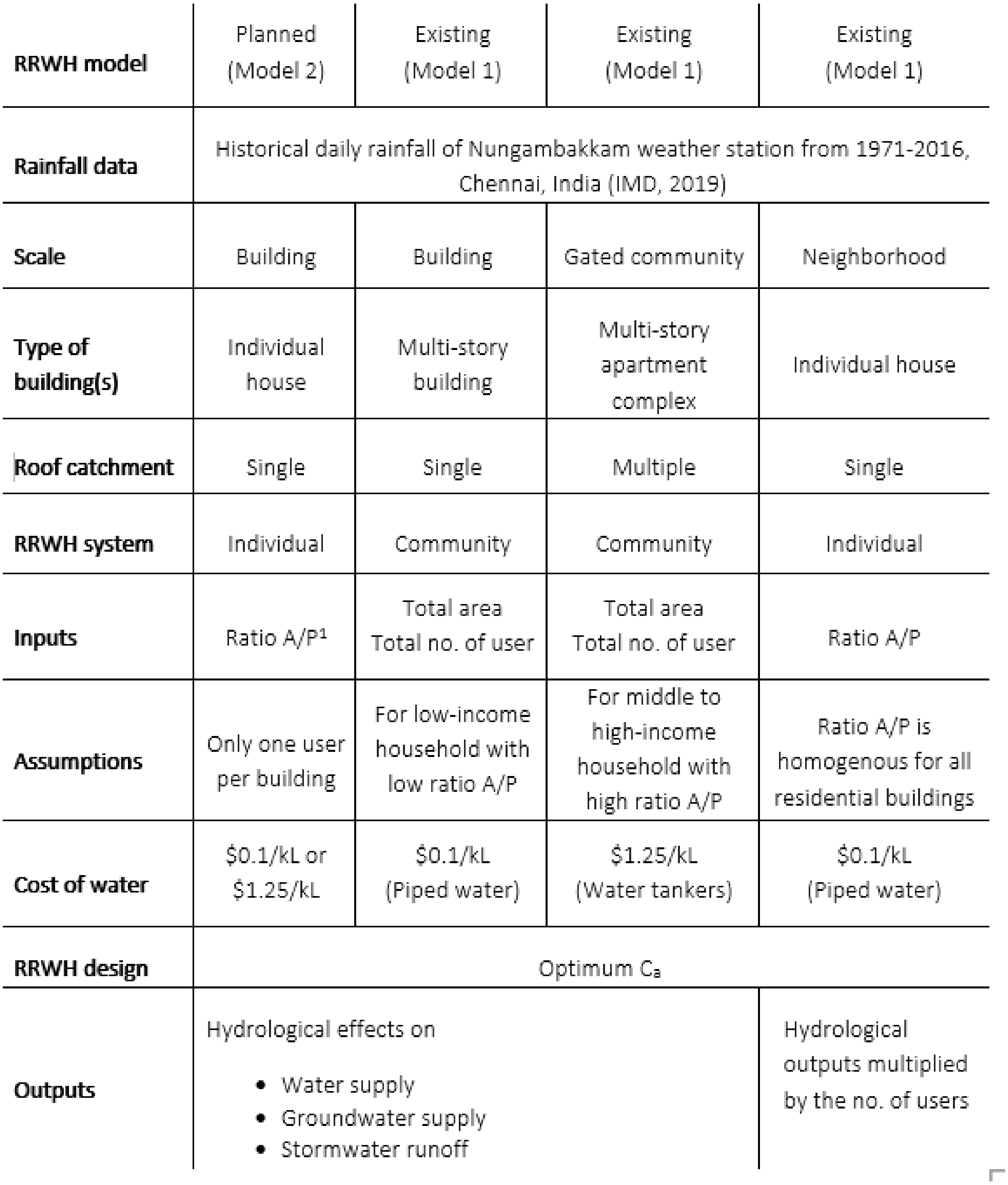
4.2.3 NEIGHBORHOOD

Since the RRWH model can only simulate per building, simulations are made based on the ratio A/P (total residential rooftop area/total estimated population for the entire Mambalam sub-catchment) and then multiplied the outputs by the estimated population in the Mambalam sub-catchment.

4.2.4 SUMMARY

A summary of the methodology used for each of the case studies are presented in Table 17. For each case study, a brief cost benefit analysis was performed based on section 4.3.5. In the city (incl. Mambalam area), residents rely on piped water supply and private wells whereas in the southern part of Chennai, in the IT Corridor area (incl. Sabari Terrace), residents rely completely on water tankers for their water supply (Kaveri, 2019).

Table 17. Summary of the methodology used for the case study



RRWH model	Planned (Model 2)	Existing (Model 1)	Existing (Model 1)	Existing (Model 1)
Rainfall data	Historical daily rainfall of Nungambakkam weather station from 1971-2016, Chennai, India (IMD, 2019)			
Scale	Building	Building	Gated community	Neighborhood
Type of building(s)	Individual house	Multi-story building	Multi-story apartment complex	Individual house
Roof catchment	Single	Single	Multiple	Single
RRWH system	Individual	Community	Community	Individual
Inputs	Ratio A/P[1]	Total area Total no. of user	Total area Total no. of user	Ratio A/P
Assumptions	Only one user per building	For low-income household with low ratio A/P	For middle to high-income household with high ratio A/P	Ratio A/P is homogenous for all residential buildings
Cost of water	\$0.1/kL or \$1.25/kL	\$0.1/kL (Piped water)	\$1.25/kL (Water tankers)	\$0.1/kL (Piped water)
RRWH design	Optimum C_a			
Outputs	Hydrological effects on • Water supply • Groundwater supply • Stormwater runoff			Hydrological outputs multiplied by the no. of users

(1) Roof area is unknown, but once roof area is found, the ratio A/P is applied to the calculation.
(2) Used as a comparison to analyze the trade-off between water supply and groundwater recharge. With smaller sump capacity, water supply will be reduced and groundwater recharge will increase.

4.3 DATA COLLECTION

The primary data required to simulate the proposed RRWH model are the historical rainfall data, the water consumption behavior (*Wt*) , the number of residents (*P*) and the rooftop area (*A*).

4.3.1 RAINFALL CHARACTERISTICS

Historical hourly rainfall data from 1971 to 2016 from Nungambakkam weather station (closest weather station available to the study area, located 3km away) were obtained from the Indian Meteorological Department (see Annex I). Some rainfall data were missing and were not considered in the simulation. It is important to understand the main characteristic of the rainfall pattern of the Mambalam area to be able to draw appropriate conclusions from the results obtained from the model. Annual rainfall varies considerably over 46 years of hourly rainfall data with two high extremes in 1996 and 2005 and one very low extreme in 2002 (see Figure 26). With climate change, the variation of extreme is expected to be higher. However, in this research, only historical rainfall data are considered in the proposed RRWH models.

Table 18. Rainfall statistic of Nungambakkam weather station (IMD, 2019)

Parameter	Value	Time
Max. hourly rainfall intensity	93.5mm/h	Sept 11th, 1996
Max. daily rainfall intensity	394.4mm/d	Oct 25th, 2005
Max. annual rainfall between 1971-2016	2499mm/y	2005
Min. annual rainfall between 1971-2016	623mm/y	2003
Average annual rainfall	1394mm/y	Average between 1971-2016
Annual rainfall (Median)	1274mm/y	Median between 1971-2016

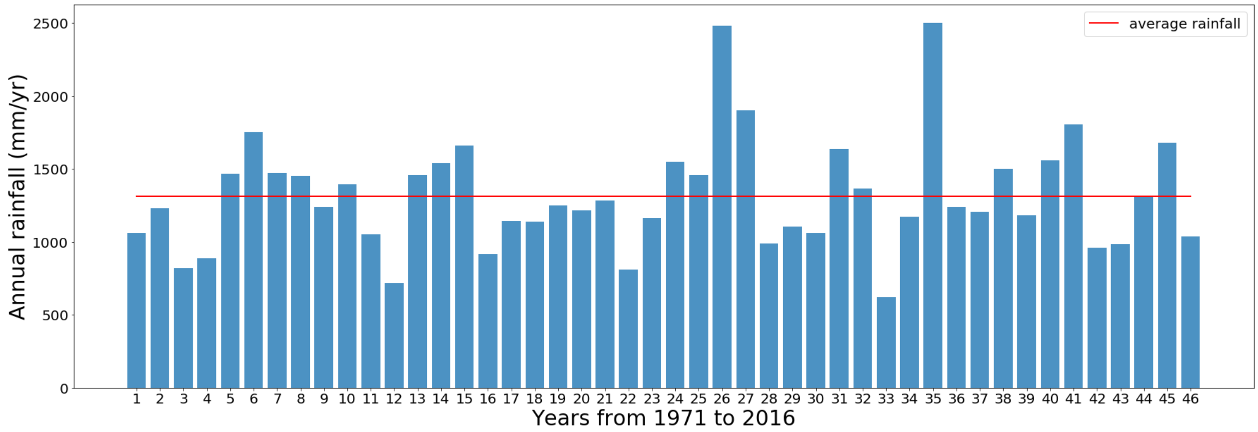


Figure 26. Variation of annual rainfall from 1971 to 2016 of Nungambakkam rainfall station (IMD, 2019)

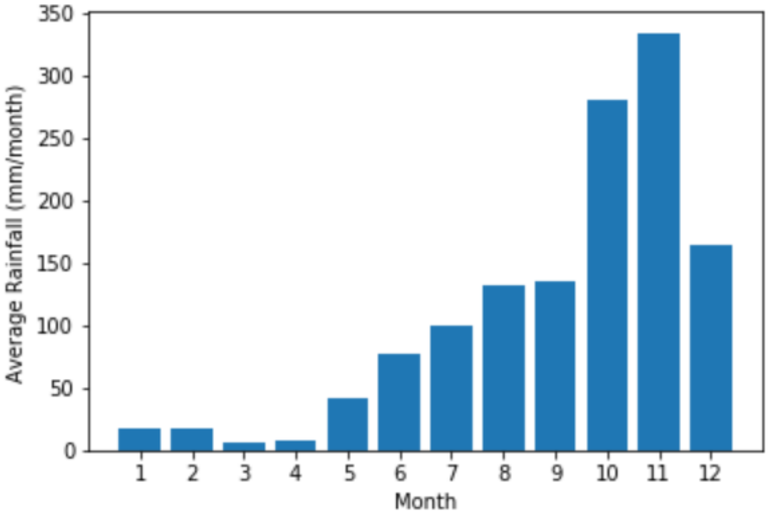


Figure 27. Average monthly rainfall from 1971-2016 of Nungambakkam weather station (IMD, 2019)

Chennai has a unique rainfall pattern with two monsoon seasons, occurring at the end of the year. The rest of the year, it is dry. Therefore, most of the rainwater can be collected at the end of the year and served for next year's water demand. If one year has deficient rainfall, then it will impact next year's water supply. Table 18 shows the difference between daily rainfall of two extreme years, 2003 and 2005.

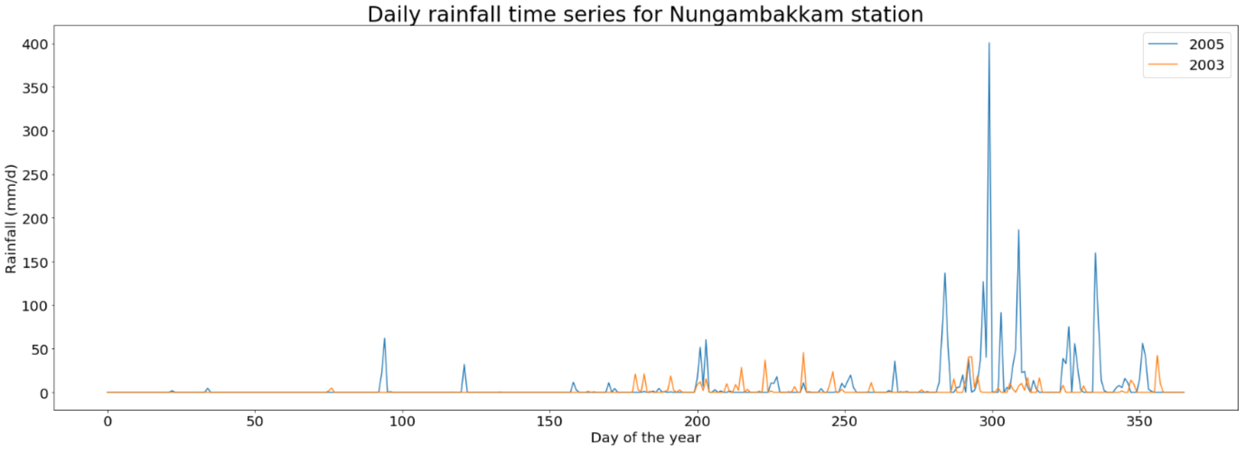


Figure 28. Variation of daily rainfall for the year 2003 and 2005 (Nungambakkam rainfall station, IMD, 2019)

When evaluating the temporal performance of RRWH over a year, the years 2004 and 2005 were used because it represented the two possible extremes of water shortage and urban flooding. The year 2003 was the driest year over the 46 years, thus it impacted severely Chennai’s water supply in 2004. Therefore, the year 2004 is used for the analysis of the performance of RRWH (see Figure 29).

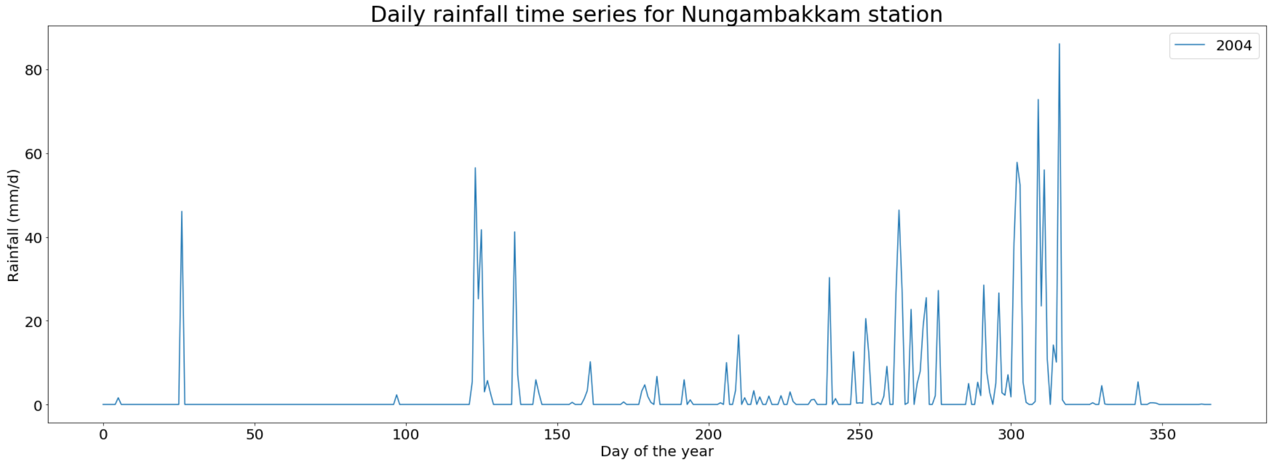


Figure 29. Daily rainfall time series of year 2004 of Nungambakkam station (IMD, 2019)

4.3.2 HOUSEHOLD SURVEY

According to Tamil Nadu Red Cross report (2019), around 80 households living along the Mambalam drain were surveyed on March 23-24th, 2019. It should be noted that the community survey is not statistically sound, and it represents the most vulnerable group. The results show that around 48% uses 0.1m3/d/p for domestic use, 73% are 4-5 people per household, 45% mentioned to have experience on average 15 days of water shortage and 98% of them get their water from water tanker or municipal water (see Annex J).

Photo : Fieldwork for the vulnerability capacity assessment with Tamil Nadu Red Cross (March, 2019)

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4.3.3 BUILDINGS' SPECIFICATIONS

For a rooftop rainwater harvesting system, specifications of the buildings such as rooftop area (A) and number of residents (P) are required for the inputs of the RRWH models. Firstly, an ideal building of one occupancy will be used for the RRWH model for planned building. Then, specific buildings are selected for the case study. Two existing residential buildings are analyzed in this research:

1. A typical residential building of Tamil Nadu Slum Clearance Board (TNSCB) located along the Mambalam drain (see Figure 30)

2. Sabari Terrace, a multi-story apartment complex located in Sholinganallur area, southern part of Chennai. The specific location of the apartment complex is shown in Annex H. For the later, more information is given in section4.7.1 to explain the selection of this particular building.

Figure 30. Existing building (Tamil Nadu Slum Clearance Board Housing) along the Mambalam canal (Pictures taken by the author, March 2019)

4.3.4 ROOF AREA

The Mambalam sub-catchment is taken as the boundary of the study area. Figure 31 suggests that the Mambalam area is densely built up with only a few green areas, depicted as large white space in the Figure 31. All rooftop areas used to compute the RRWH's performance in the Mambalam sub-catchment are taken from OpenStreetMap and calculated using QGIS.

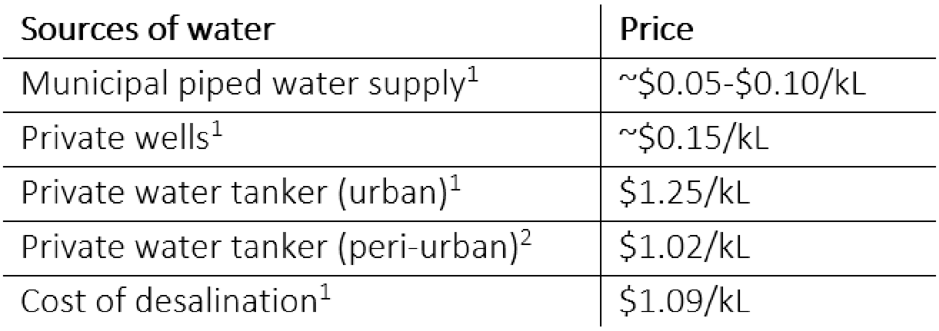
Source: Open Street Map, Buildings, 2018

Figure 31. The Mambalam sub-catchment boundary and total building footprint (Source: OSM, Buildings, 2018)

4.3.5 COST OF WATER

The economic is addressed briefly in this report as it is an important factor in the adoption of RRWH. However, it is not the main focus of this research. According to Table 19, the cost of water varies significantly depending on the sources (Srinivasan, Gorelick & Goulder, 2010B). In Chennai city, people rely mostly on intermittent piped water supply, supplemented with private wells. Private water tankers usually come as the last alternative of water as it is almost an order of magnitude more expensive compared to the other sources of water (Srinivasan, Gorelick & Goulder, 2010B). Table 19 is used to provide a first estimation for the cost-benefit analysis. It is important to note that the cost may vary depending on the location and the context.

Table 19. Cost of water from various sources for residential consumers



Sources of water	Price
Municipal piped water supply[1]	~\$0.05-\$0.10/kL
Private wells[1]	~\$0.15/kL
Private water tanker (urban)[1]	\$1.25/kL
Private water tanker (peri-urban)[2]	\$1.02/kL
Cost of desalination[1]	\$1.09/kL

(1) Srinivasan, GOrelick & Goulder, 2010B
(2) Personal communication, Harsha Koda, Secretary of Sabari Terrace, February 2020 (Rs. 900/12kL) (see section 4.7.1)

4.4 ASSUMPTIONS

Assumptions are made for the simulations for the case studies using the proposed RRWH model. The preliminary cost-benefit analysis is also based on assumptions which are elaborated in this section.

4.4.1 RRWH MODEL

To contextualize the proposed RRWH model to Chennai, the colored parameters in the flow charts presented in section 3.3.3 need to be pre-determined. All the results presented in section 4.5 used these values. Due to the lack of rainfall data available for Sholinganallur area, the case of Sabari Terrace also used the same historical daily rainfall data from Nungambakkam weather station.

Table 20. Parameters specific to Chennai, India

PARAMETERS	UNIT	VALUE	DESCRIPTION
C	-	0.85	See section 3.4.1
W_t	m^3/d	0.1	See section 4.2.2
X	-	1.1	See section 3.4.2
$E_{T,\ max}$	%	90	Discuss later in this report. See section 4.5.1

4.4.2 COST-BENEFIT ANALYSIS

The total annual water-saving from RRWH was converted into cost-saving to provide a rough estimation on the economic benefits of the adoption of RRWH for water supply. The calculations were based on the cost per kL given in Table 21. The calculations assumed that if the water collected from the RRWH does not meet the annual water demand, then residents would still have to buy water from water tankers during summer.

Table 21. Cost of water depending on the time of the year and the location

Area	Rest of the year	Water shortage period (15 days)
Urban (Mambalam)	$0.1/kL	$1.25/kL
Peri-Urban (Sabari Terrace)	$1.02/kL	$1.02/kL

4.5 RESULTS OF THE MAMBALAM CASE STUDY

At the building level, both RRWH sub-models were used. Firstly, the 'ideal design' for the RRWH system for a building with one individual was determined as a reference and secondly, the design of an RRWH system for an existing building in the Mambalam area was determined. Then, the RRWH model was applied for the entire Mambalam sub-catchment. It is important to note that all results using the probabilistic approach are presented at 50% of the probability of exceedance, equivalent to the median (see Figure 34) unless stated differently. Therefore, the final results of "annual volume saved from external water supply", "the annual volume of groundwater recharge" and the "annual stormwater runoff reduction" presented in each of the tables in this chapter may not necessarily balance out because the median value may not be from the same year for each of the hydrological components.

4.5.1 PLANNED BUILDING

Using the RRWH model for the planned building, the roof area shows a linear relationship with reliability until 94% (see Figure 32). This linearity is due to the first-order equation of the rational method $Q = C* A* It$. After 94%, the increment of *ET* reduces for the same increase in the roof area. To achieve a completely water-sufficient building from RRWH, 48m2 of the rooftop area (see Figure 32) is necessary with a sump capacity of 26m3 (see Figure 33) for one individual. As shown in Figure 32, a more substantial area is required to move from 95-100% of *ET*. Therefore, 94% of reliability or lower is suggested as the ideal scenario for the rooftop area because beyond 94% of reliability, more rooftop area is required to increase by 1% of reliability.

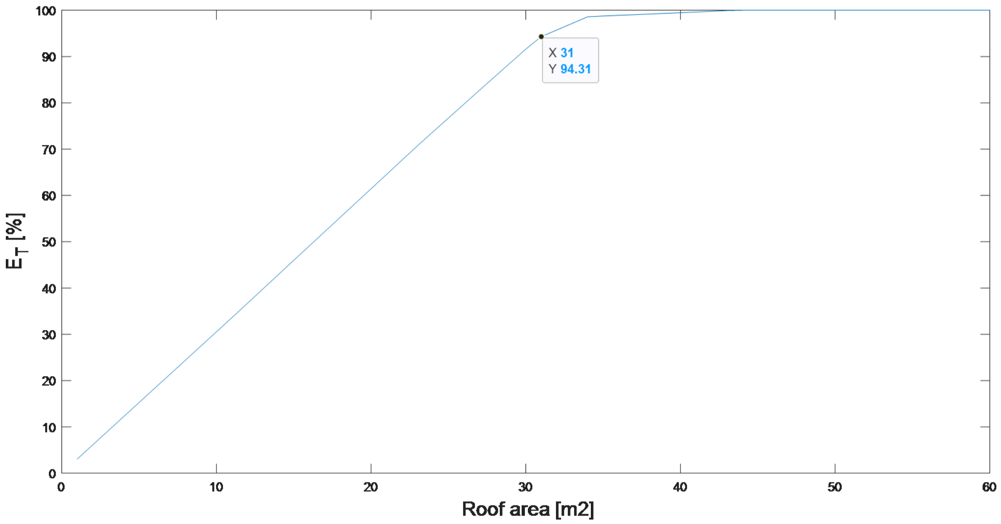


Figure 32. Graph showing the rooftop area and ET using RRWH model for planned building (IMD, 2019)

In Figure 33, the curve shows that from 20m3 to 21m3, it increases by 5% of reliability. After this point, to increase to another 5% of reliability, an additional 6m3 is required. Therefore, 90% of reliability with 21m3 of sump capacity shows the ideal scenario.

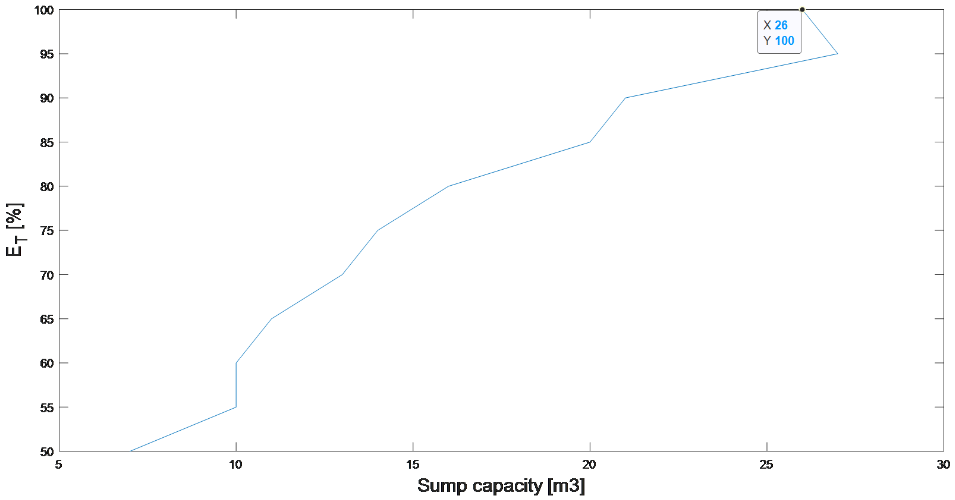


Figure 33. Graph showing the sump capacity and ET using RRWH model for planned building (IMD, 2019)

Table 22. Ideal RRWH design for Chennai (for planned building)

E_T [%]	50	60	70	80	90	100
A/P [m^2/p]	18	22	25	29	33	48
C_a/P [m^3/P]	9	10	13	16	21	26

The ideal scenario is the ideal ratio A/P and sump capacity/person to achieve the highest recommended reliability from a reasonable RRWH design point of view. In this case, 90% with a ratio A/P of 33m2 and ratio sump capacity/person of 21m3 is chosen as the ideal scenario.

Water supply

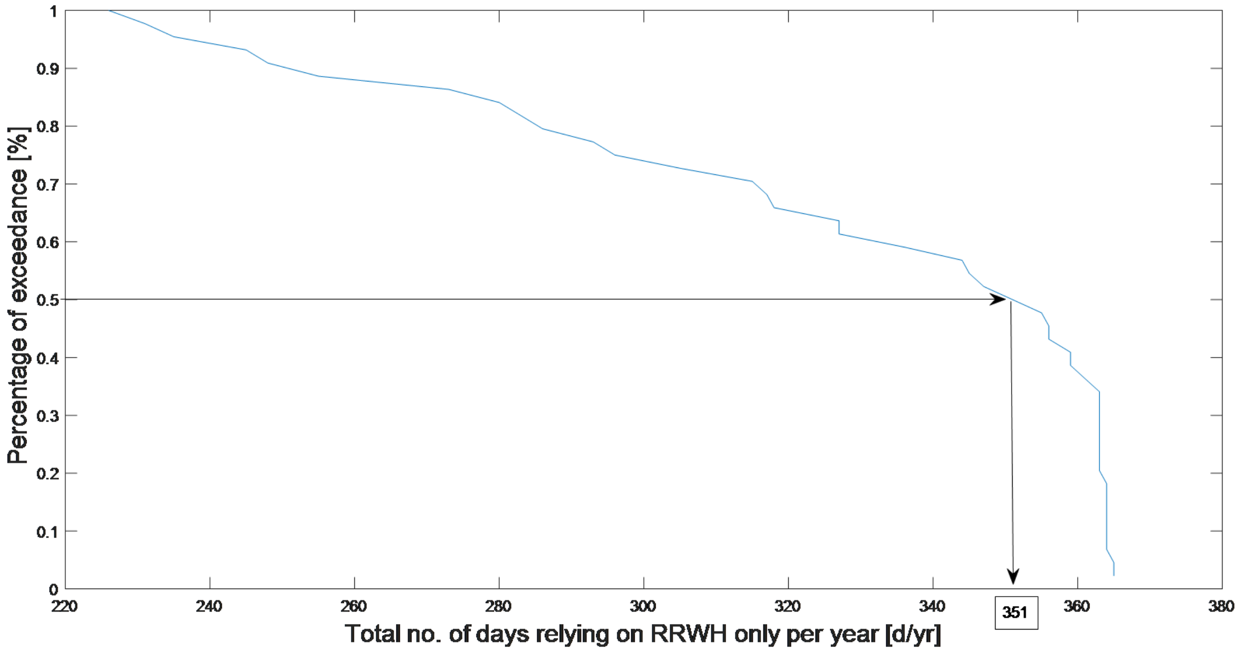


Figure 34. Inverse cumulative distribution function of the no. of days supplied only by RRWH per year (IMD, 2019)

There are multiple ways to interpret the probabilistic results from Figure 34. The results show that there is a 100% probability that for 226 days or more, one individual would have enough water supply from RRWH to meet his/her daily water demand. There is also approx. 35% of the probability that RRWH can be supplied all year long.

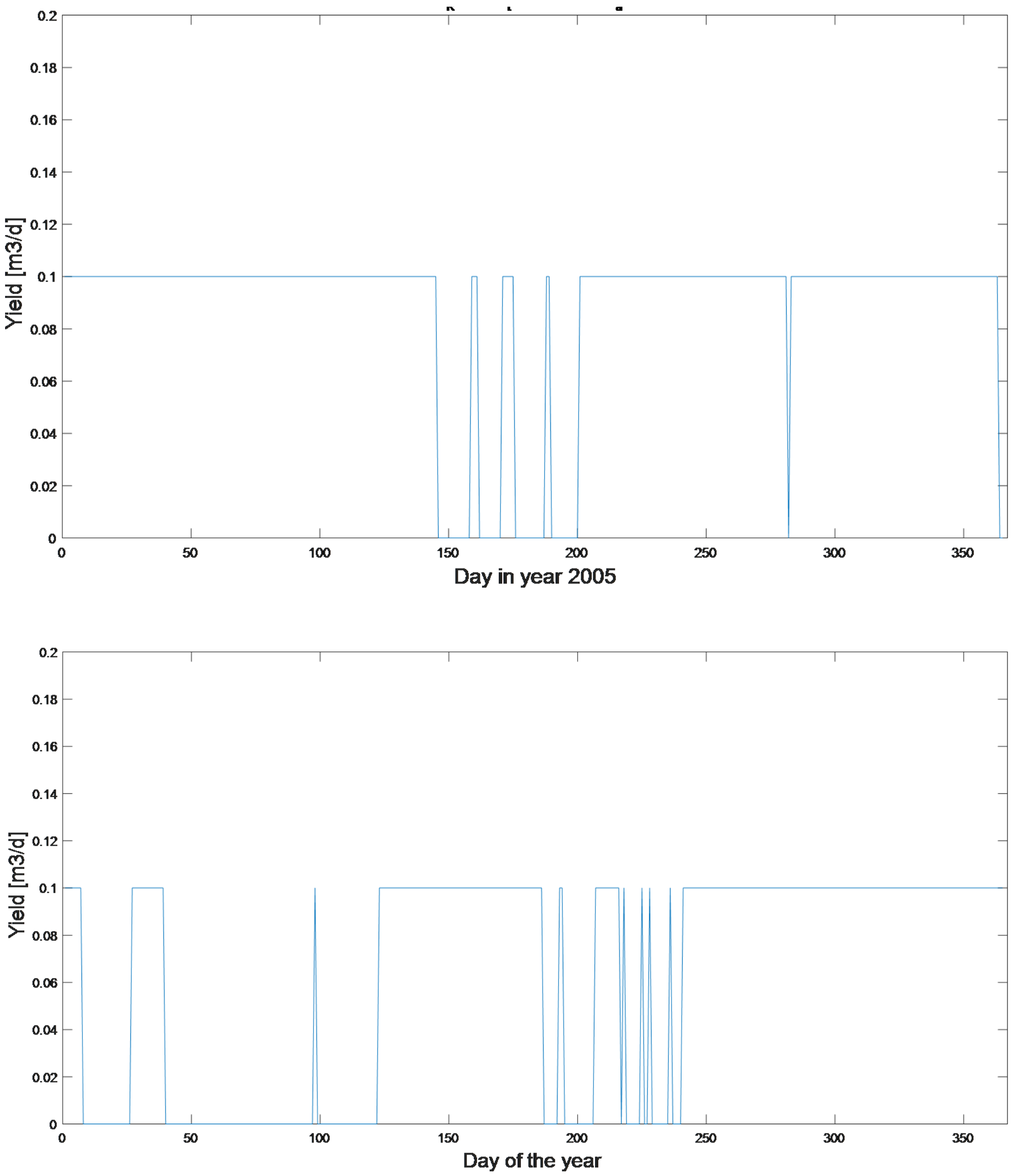


Figure 35. Temporal variation of yielding over a year using historical daily rainfall data, Chennai, India (Top=year 2005, bottom-year 2004) (IMD, 2019)

The temporal variation of yield over a year has also been investigated by selecting two years with extreme meteorological events which caused a severe water shortage (in 2004) and urban flooding (in 2005) . It can be concluded that yielding throughout a year differs significantly from year to year. Having no water for several days has much more impact than having water on alternate days. The temporal factor is thus an important factor to consider. This is further discussed in secion 5.2.1.

Groundwater recharge

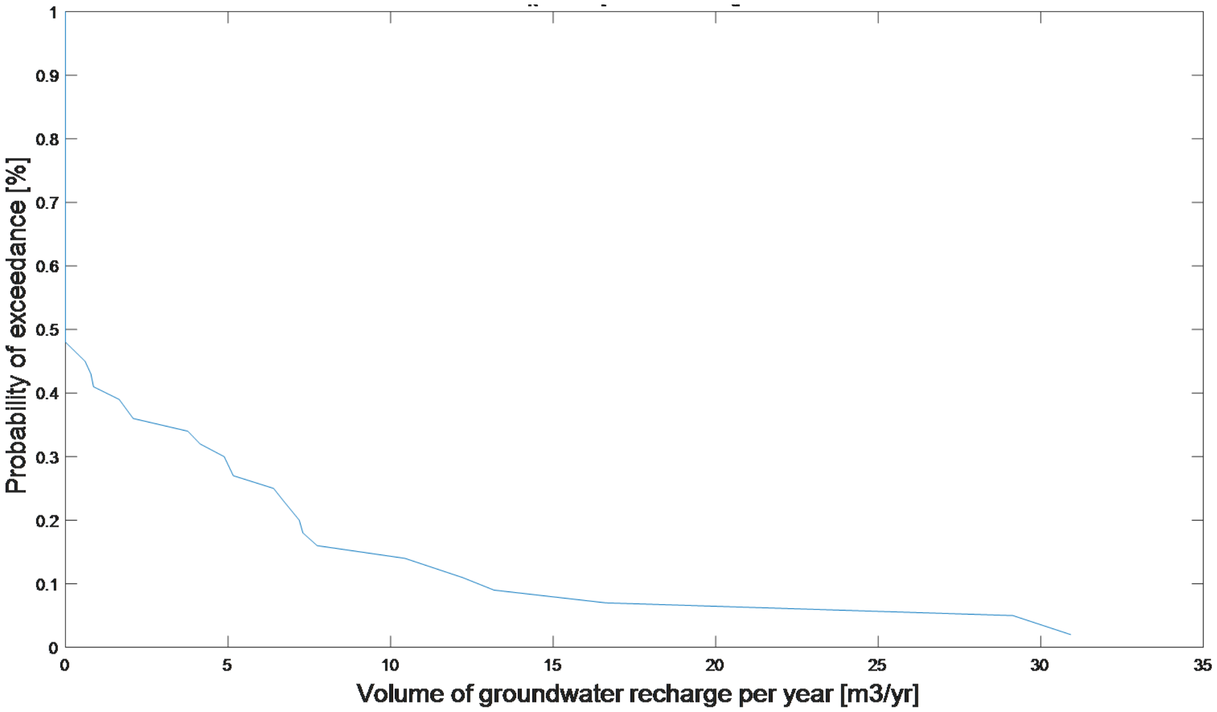


Figure 35. Temporal variation of yielding over a year using historical daily rainfall data, Chennai, India (Top=year 2005, bottom-year 2004) (IMD, 2019)

Stormwater runoff reduction

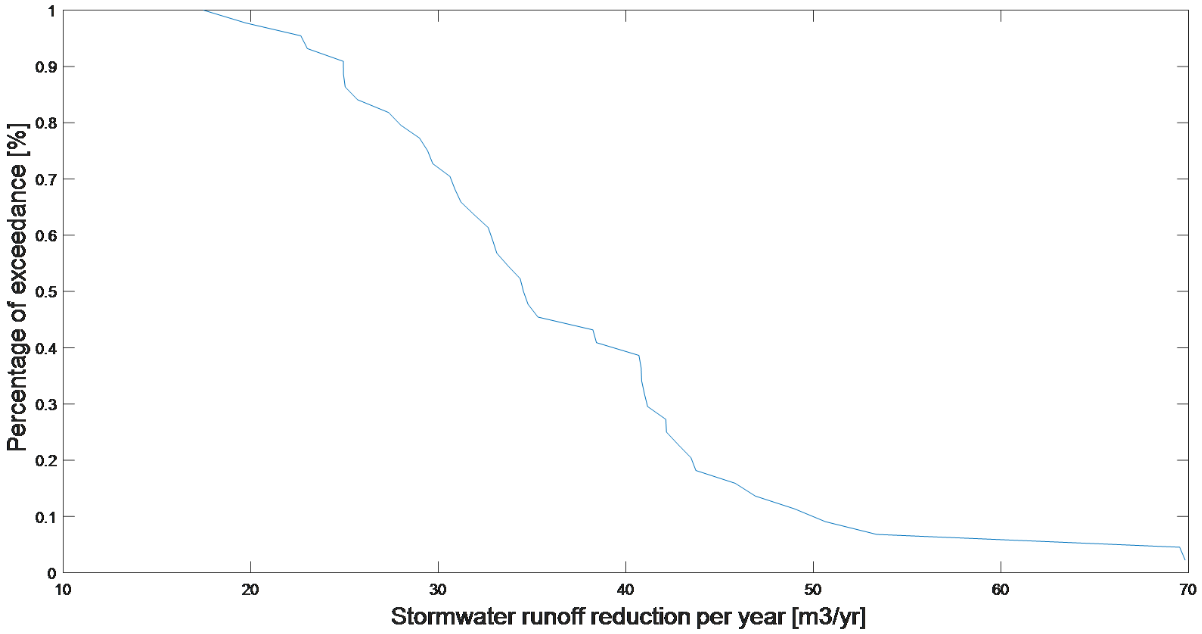


Figure 37. Inverse cumulative distribution function of the stormwater runoff reduction per year for proposed building (IMD, 2019)

Summary

Table 23. Results of the hydrological effects of RRWH for planned building (IMD, 2019) and the related cost-benefit analysis

PARAMETER	QUANTITATIVE OUTPUTS FOR P=1	Values	Units
Specifications of the RRWH design			
Specifications of the RRWH	Optimal rooftop area (For proposed building)	33	m^2
	Optimal sump capacity	21	m^3
Hydrological Benefits of RRWH			
Water supply	Reliance on RRWH for water supply	90	%
	Total no. of days relying on RRWH only per year	351	days
	Annual volume saved from external water supply	35	m^3/yr
Groundwater recharge	Annual volume of groundwater recharge	0	m^3/yr
Stormwater runoff	Annual stormwater runoff reduction	34	m^3/yr
	Max daily stormwater runoff volume reduction	11	m^3/d
Cost-Benefit Analysis			
Cost	Annual cost-saving in USD (from piped supply)	3.5	$/yr/p
	Annual cost-saving in USD (from water tanker)	43.7	$/yr/p

4.5.2 EXISTING BUILDING

The selected building in the Mambalam sub-catchment for the case study is a typical type of multi-story building with four floors found along the Mambalam drain where most of the low-income and vulnerable communities are living in. This building which is owned by Tamil Nadu Slum Clearance Board (TNSCB) is expected to be demolished and rebuilt with higher dwelling capacities (personal communication from the community leader, March 2019). Thus, there is an opportunity to suggest an optimum RRWH design for the building. Also, the community survey (see section 4.3.2) was performed with people living mostly in this type of building.

Estimations on the total number of people (144 residents) were based on the pictures and the information presented in section 4.3.2 and 4.3.3. With the calculated rooftop area of 250m2, the optimal ratio for roof A/P and sump capacity/person are 1.7m2/p and 18m3/p, respectively. With this ratio, it would supply only for 18 days per year of water supply from RRWH for 144 residents (see Figure 38, top). The "stair curve" of Figure 38 (top) is explained by the yield of 14.4m3/d (144 people x 0.1m3/d/p). There is no yield until the storage volume has at least 14.4m3 or more. Using the driest year (2003) to compute this ratio for existing building, RRWH would have been able to supply for 9d/yr and on the wettest year (2005), 32d/yr (equivalent to one month).

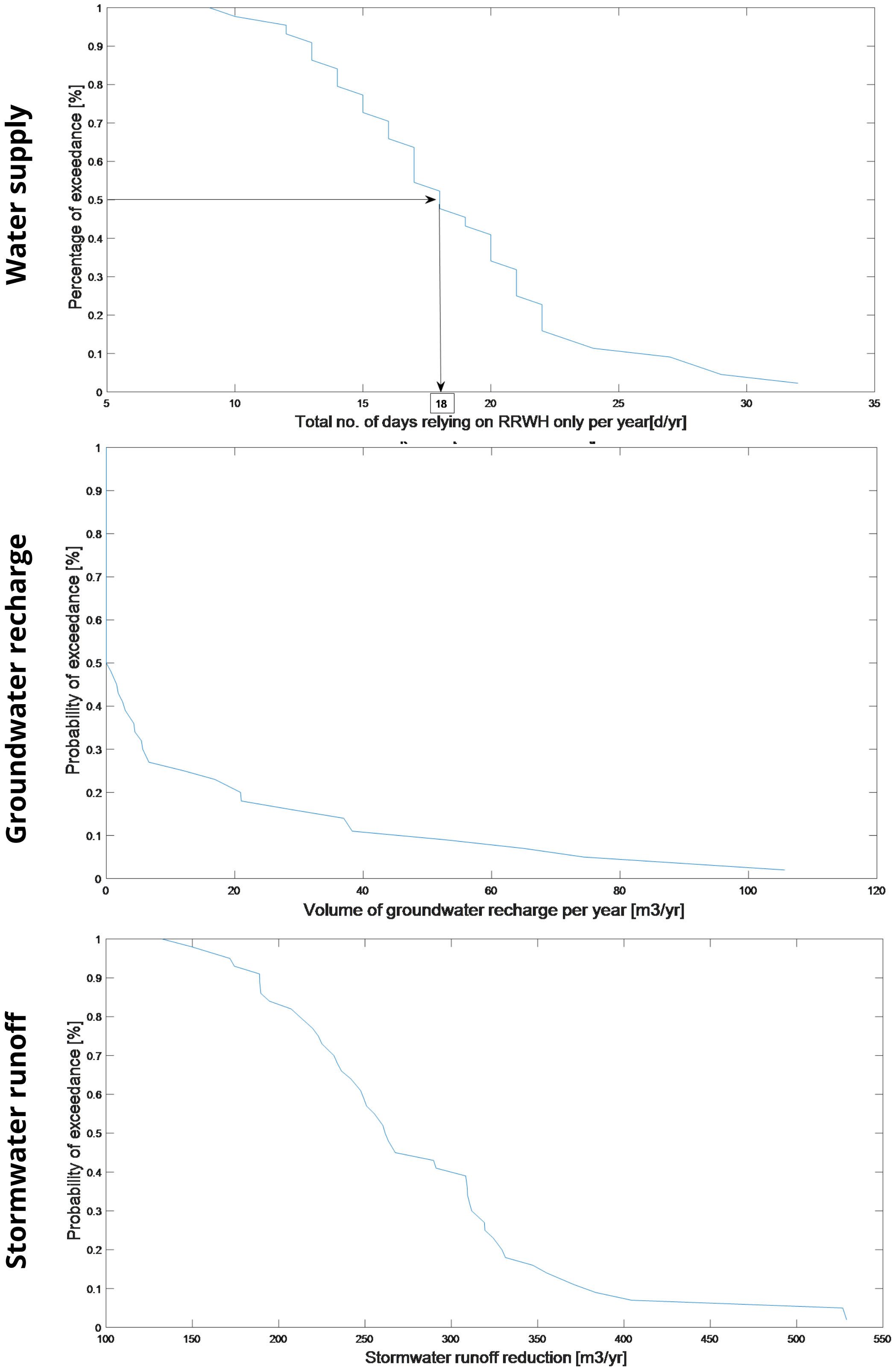


Figure 38. Inverse cumulative distribution function for water supply, groundwater recharge, stormwater runoff for existing building (IMD, 2019)

Summary

Table 26. Results of the hydrological effects of RRWH TNSCB building and the related cost-benefit analysis

PARAMETER	QUANTITATIVE OUTPUTS FOR P=144	Values	Units
Specifications of the RRWH design			
Design	Existing rooftop area	250	m^2
	Optimal sump capacity	25	m^3
Hydrological benefits of RRWH			
Water supply	Reliance on RRWH for water supply	5	%
	Total no. of days relying on RRWH only per year	18	days
	Annual volume saved from external water supply	259	m^3/yr
Groundwater recharge	Annual volume of groundwater recharge	0	m^3/yr
Stormwater runoff	Annual stormwater runoff reduction	262	m^3/yr
	Max stormwater runoff volume reduction	84	m^3/d
Cost-Benefit Analysis			
Cost	Current annual expenditure on water	5.7	$/yr/p
	Annual cost-saving in USD[*]	0.2	$/yr/p
	Total annual cost-saving in USD[*]	26	$/yr

The difference between the planned building (90% of reliability) and the existing building (5% of reliability) is very large. For this specific building and its specifications, it can only provide 18 days of water supply per year from RRWH. The result obtained may not be significant enough for the residents to invest in RRWH system.

However, it is important to note that this result is not representative of the entire Mambalam area because this type of building is mostly used by low-income households. These households usually have a large number of occupancies per dwelling, reducing the ratio A/P considerably and thus, the potential of RRWH. Another case of an apartment complex for middle to high-income households with a higher ratio A/P is presented in section 4.7.1 as a comparison.

4.5.3 NEIGHBORHOOD SCALE

To simulate the impacts of RRWH at the neighborhood scale, the characteristics of the Mambalam sub-catchment presented in Table 25 will be used. The ratio A/P is found using the following equation:

$$\frac{Total\ rooftop\ area\ [m2]\ in\ the\ Mambalam\ x\ estimated\ coverage\ of\ residential\ zone\ [\%]}{Estimated\ population\ living\ in\ the\ Mambalam\ area}$$

Table 25. Mambalam sub-catchment characteristics

Mambalam sub-catchment characteristics	**Value**	**Unit**
Total rooftop area	3,764,638	m^2
Estimated residential building	50[1]	%
Rooftop only of residential building	1,882,319	m^2
Mambalam sub-catchment area	11,690,000	m^2
Estimate population	380,000[2]	-
Ratio A/P	~5	m^2/p

[1] Source: CMDA, 2019 (Primary and mixed residential use zone for proposed land use 2026, p.297)
[2] Source: Water As Leverage, 2019B

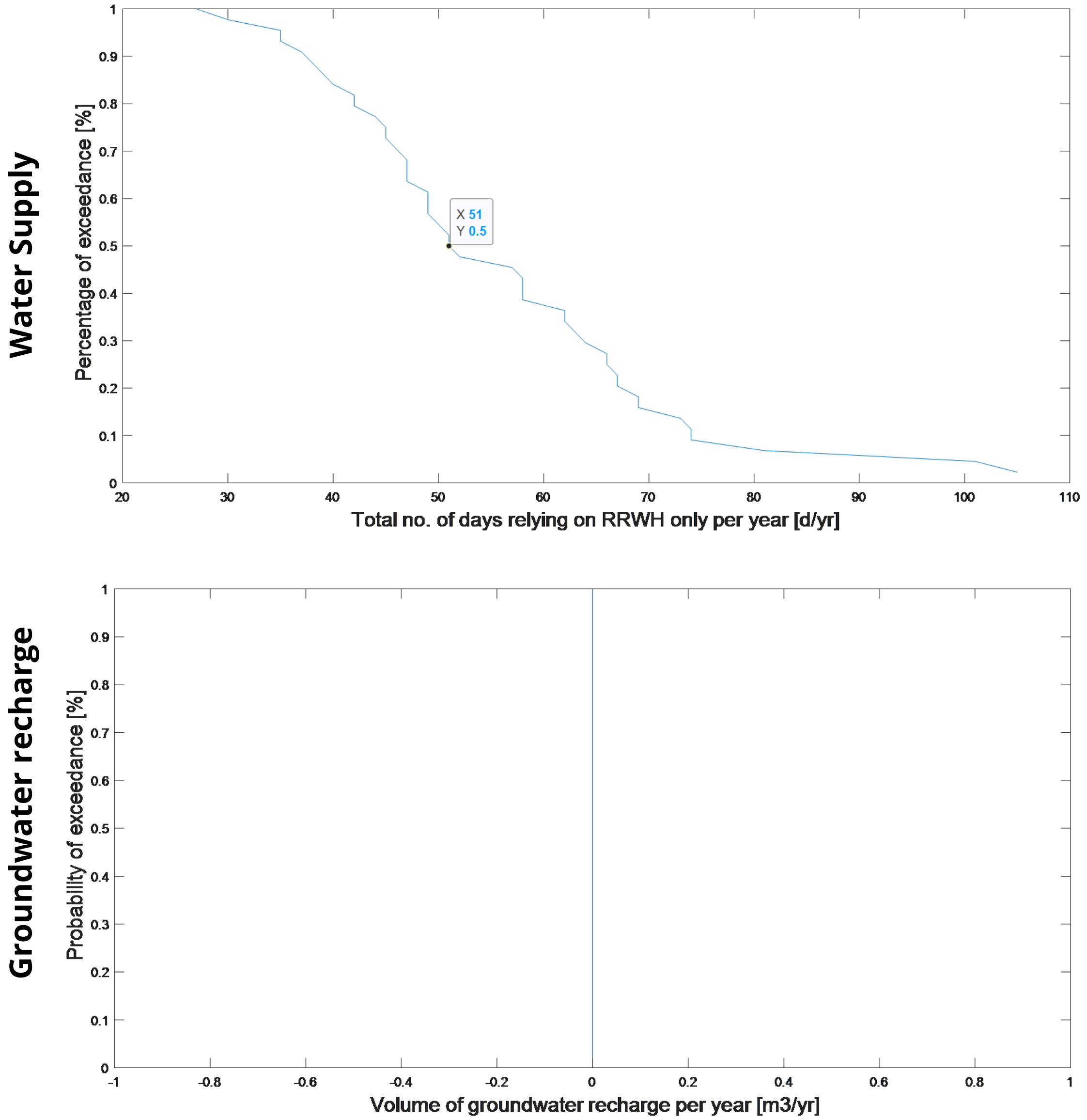


Figure 39. Inverse cumulative distribution function for water supply and groundwater recharge per year (IMD, 2019)

Figure 39 (top) shows that RRWH for water supply can achieve around 51d/yr of water-saving serving a population of 380,000. Figure 39 (bottom) shows a straight vertical line with 0m3/yr for any probability of exceedance. This could be explained due to the method of calculation used to estimate the potential of RRWH for the Mambalam which gives a ratio A/P of 5m2/p and a ratio C/P of 4m3/p. For the ratio A/P obtained for the Mambalam, it is almost 3 times more than the ratio found for TNSCB building (1.7m2/p). For the ratio C/P obtained for the Mambalam, it is almost 20 times more than the ratio found for an existing building. This is calculated using the sump capacity / number of user for an existing building, approx. 25m3/144 = 0.17m3/p. With a higher ratio C/P, larger sump capacity is used and therefore, lower potential of groundwater recharge.

Stormwater runoff

At a larger scale, the effect on the peak runoff can be calculated. The maximum daily stormwater peak runoff in 2005 was simulated with the RRWH model for an existing building and shown in Figure 40. The peak is reduced by approx. 30%.

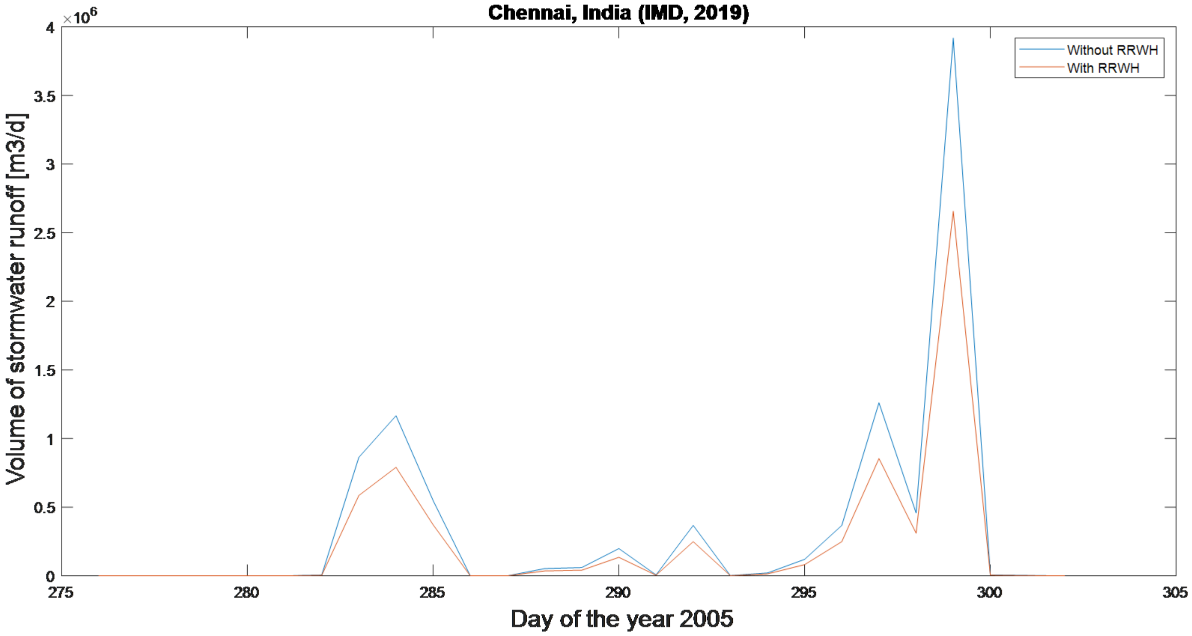


Figure 40. The effect of RRWH on stormwater peak runoff for the entire Mambalam sub-catchment for the year 2005, Chennai, India (IMD, 2019)

The results above represent the hydrological impacts of the proposed RRWH assuming 50% of the building footprint is residential building. Following this assumption, for the entire Mambalam sub-catchment, the remaining 50% of the building footprint is non-residential. For these non-residential buildings, it is assumed that RRWH can be applied but for direct groundwater recharge. Therefore, the potential annual groundwater recharge for non-residential buildings is equal to the potential annual stormwater runoff reduction for residential building. The sum of the hydrological impacts of RRWH for water supply and for groundwater recharge are presented in Table 24.

Summary

Table 24. Results of the hydrological effects of RRWH for the Mambalam subcatchment and the related cost-benefit analysis

	PARAMETERS	QUANTITATIVE OUTPUTS FOR P=380,000	Values	Units
	Specifications of the RRWH design			
	Design	Existing rooftop area per person (A/P)	5	m^2
		Optimal sump capacity per person	4	m^3
RESIDENTIAL BUILDING	**Hydrological benefits (using RRWH for water supply)**			
	Water supply	Reliance on RRWH for water supply	15	%
		Total no. of days relying on RRWH only per year	51	days
		Total annual volume saved from external water supply for the entire sub-catchment	1,938,000	m^3/yr
	Groundwater recharge	Annual volume of groundwater recharge	0	m^3/yr
	Stormwater runoff	Annual stormwater runoff reduction	1,979,800	m^3/yr
		Max daily stormwater runoff volume reduction	631,028	m^3/d
	Cost-Benefit Analysis			
	Cost	Current annual expenditure on water	5.7	\$/yr/p
		Annual cost-saving in USD	0.5	\$/yr/p
		Total annual cost-saving in USD	190,000	\$/yr
NON-RESIDENTIAL BUILDING	**Hydrological benefits (using RRWH for groundwater recharge)**			
	Groundwater recharge	Annual volume of groundwater recharge	1,979,800	m^3/yr
	Stormwater runoff	Annual stormwater runoff reduction	1,979,800	m^3/yr
		Max daily stormwater runoff volume reduction	631,028	m^3/d
ENTIRE MAMBALAM	**Hydrological benefits (using both RRWH for water supply and groundwater recharge)**			
	Water supply	Reliance on RRWH for water supply	15	%
		Total no. of days relying on RRWH only per year	51	days
		Total annual volume saved from external water supply for the entire sub-catchment	1,938,000	m^3/yr
	Groundwater recharge	Annual volume of groundwater recharge	1,979,800	m^3/yr
	Stormwater runoff	Annual stormwater runoff reduction	3,959,600	m^3/yr
		Max daily stormwater runoff volume reduction	1,262,056	m^3/d

4.6 CONCLUSION FOR THE MAMBALAM CASE STUDY

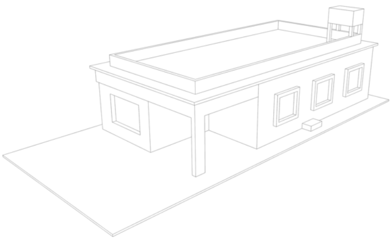
With the RRWH model developed in Chapter 3, Chapter 4 presented the hydrological effects of RRWH on water supply, groundwater recharge and stormwater runoff at the building and neighborhood scales for the Mambalam area.

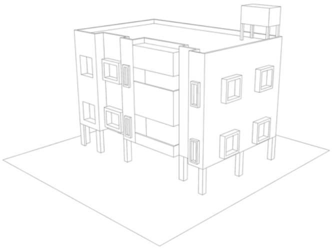
4.6.1 PLANNED BUILDING

According to the results from the RRWH model for the planned building, the ideal ratio of roof area per person is 48m2/ person to solely rely on RRWH all year long for domestic water supply. However, to achieve 100% of reliance on RRWH for water supply, a significant increase in rooftop area is required at a much higher cost. Therefore, it is suggested to achieve a maximum of 90% of reliance on RRWH for water supply with a ratio of 33m2/p and a sump capacity of 21m3.

4.6.2 EXISTING BUILDING

After the investigation on the field, it was found that RRWH designed for water supply for the case of TNSCB building is not a cost-effective alternative to cope with the water shortage in the summer. First, due to the high-density population living in this building leading to a low ratio A/P, only 18d/yr can be supplied by rainwater harvesting. Furthermore, the potential of reuse of rainwater for domestic use may occur mainly during the monsoon season and at the beginning of the year. Thus, stored rainwater would not be sufficient to supply during the summer when needed the most. Residents have been using multiple alternative sources of water, including piped water and borewell. This explained further the reason why a RRWH system with a sump may not be necessary in this area since they have already been using groundwater for domestic water supply purposes. Moreover, the current cost of the piped water is very low, ~$0.05-0.10/kL (Srinivasan, Gorelick & Goulder, 2010B). Thus, there is very little incentive to save water or adopt RRWH by the residents living in the Mambalam area. Retrofitting the TNSCB building with RRWH would only contribute to save up to $0.2/yr/p and due to a lack of space, it may not even be feasible to implement the optimum sump.





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4.6.3 NEIGHBORHOOD SCALE

The ideal ratio is approximately seven times more than the one estimated for the Mambalam area of 5m2/p assuming that 50% of the building footprint in the Mambalam area is residential building. At the neighborhood, approx. 2,000,000m3/yr of water can be saved from using RRWH which is equivalent to 51 days per year of water supply serving 380,000 residents. Thus, for the Mambalam area, RRWH cannot become water-sufficient if solely relying on RRWH for their domestic water supply. The main water supply must supply 85% of the water demand annually. From an economic perspective, the adaptation of RRWH for the Mambalam area would save in total approx. $200,000 annually, assuming the water supplied is from the municipal piped water supply. There is no groundwater recharge effect for the Mambalam area. The potential of max. daily runoff reduction is up to 630,388m3/d, this is particularly relevant to vulnerable communities living along the Mambalam drain who raised concerned about the frequency of urban flooding (once every two years, see Annex J). The hydrological impacts of the combination of RRWH for water supply and RRWH for groundwater recharge for the Mambalam area is discussed further in section 5.2.1

4.7 PERI-URBAN AREAS OF CHENNAI

> The water supply system situation in urban areas differs from the peri-urban areas, especially for the new development along Chennai IT Corridor. The pipeline laid to supply water to the IT corridor has not yet been connected to all its users (Kabirdoss, 2019; Kaveri, 2019). Moreover, in most of the area along the IT corridor, groundwater abstraction may not be possible due to the ingression of saline water or building regulations to conserve groundwater level (Kabirdoss, 2019). The IT corridor is developed on top of the Pallikaranai marsh with a high-water table level and saline water. Therefore, many of the IT companies and multi-story residential complexes have to rely on water tankers 365 days a year further inducing high annual water expense and high vulnerability on water supply (Kabirdoss, 2019).

Photo : Water tankers in Chennai, India (2019)

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4.7.1 SABARI TERRACE APARTMENT COMPLEX CASE STUDY

The case of Sabari Terrace residential apartment complex, located along the IT Corridor (see Annex K), was investigated due to its economic and environmental relevance for the adoption of RRWH for water supply. The residents have already implemented a rooftop rainwater harvesting system for water supply since 2017. To prove the benefits of RRWH, the manager of the buildings has been collecting data on
water-saving and cost-saving which are provided in Annex L. This information is used to give a preliminary validation of the RRWH model developed in this research.

According to the secretary of Sabari Terrace, Mr. Harsha Koda, there are 350 residents in this apartment complex and four blocks apartment with a total rooftop area of 2500m2. They invested 3610(Rs. 2.5 lakhs) to retrofit their buildings with a RRWH system. The sump with a capacity of 100m3 was already built since their water supply is completely decentralized. Every water tank costs around $13/water tank (Rs.900) and has a load of 12m3 (eq. to 12,000L/load). The price of private tanker is approx. the same as stated in a study by Srinivasan, Gorelick & Goulder (2010B) with $1.25/kL. With 350 residents, a total of 35m3/d of water is required to meet the demand, assuming a water demand of 0.1m3/person. This means that three water tanks are required per day for a total of $38/day (Rs.2,700/day). The current sump, when it is full, it can provide approx. 3 days of water supply for the community living in Sabari Terrace.

Figure 41. Pictures of Sabari Terrace multi-story apartment complex in Sholinganallur in the IT Corridor area, Chennai, India (Source : Proptiger, 2020 (left picture), taken by the author on February 4th, 2020 (right picture))

Their RRWH system has a cascading system. Rainwater is first collected in two rainwater tanks above ground with a capacity of 3m3 each. Once it is filled, water is diverted to the underground sump with a capacity of 50m3. Then, when the sump is full, the rainwater is diverted to a large open well. All the pipes' operations (i.e opening and closing the valves) are done manually. One of the four apartment blocks diverts rainwater from the rooftop top directly to a recharge pits. This water slowly infiltrates into the same open well. The data provided in Annex L are the daily measured volume of rainwater collected from the rooftop of Sabari Terrace residential apartment complex from November 6th, 2017 to December 31st, 2019. Sabari Terrace is also reusing greywater for toilet flushing and garden irrigation which is about 20m3/d of water reused (Personal communication, Secretary of Sabari Terrace, February 2020). All the water flow of Sabari Terrace is summarized in Annex M.

4.8 RESULTS OF SABARI TERRACE

> The results of Sabari Terrace residential apartment complex case study is presented in the same structure as section 4.5, presenting results on the hydrological impacts of RRWH on water supply, groundwater recharge and stormwater runoff reduction. In addition, the data collected from Sabari Terrace were used to provide a partial validation of the RRWH model

4.8.1 EXISTING BUILDING

A typical multi-story apartment complex (with three floors) for middle to high-income household located along the IT corridor may have a higher ratio A/P. Taking the example of Sabari Terrace multi-story apartment complex with around 350 residents and a total rooftop of 2500m2, the ratio A/P becomes approx. 7m2/p.

The difference in ratio A/P of an existing building of low-income household from TNSCB housing and a multi-story apartment complex located in the peri-urban of Chennai city is around 7 times.

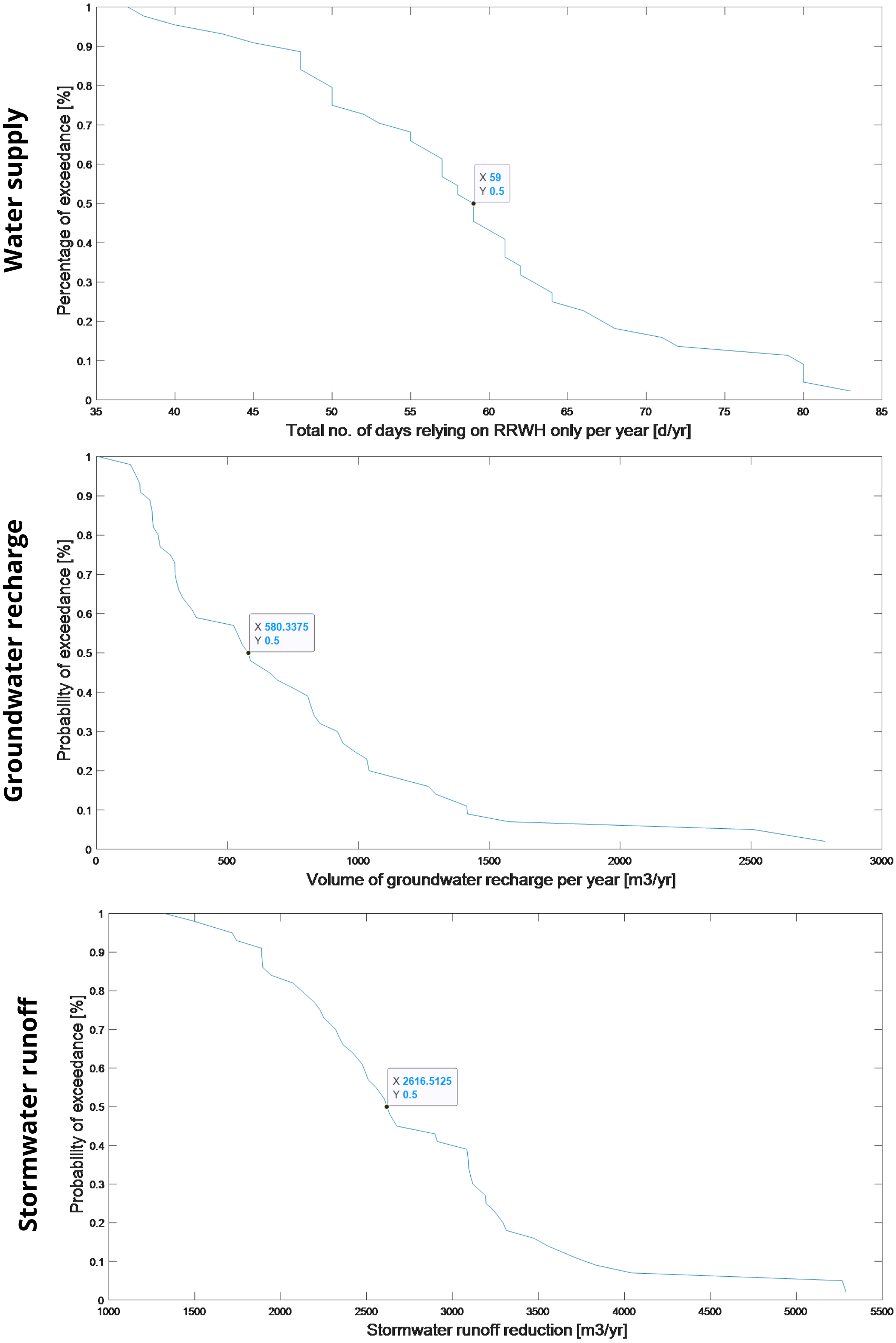

Figure 42. Inverse cumulative distribution function for water supply, groundwater recharge, stormwater runoff for Sabari Terrace Residential Apartment Compex (IMD, 2019)

Summary

Table 27. Results of the comparison of RRWH for TNSCB building and a multi-story building apartment complex located along the IT corridor in the southern part of Chennai

PARAMETERS	QUANTITATIVE OUTPUTS	Values with P=144	Values with P=350	Units
Specifications of the RRWH design				
Design	Existing rooftop area	250	2500	m^2
	Ratio A/P	**1.7**	**7.1**	m^2/p
	Optimal sump capacity	25	117	m^3
Hydrological benefits of RRWH				
Water supply	Reliance on RRWH for water supply	5	16	%
	Total no. of days relying on RRWH only per year	18	59	days
	Annual volume saved from external water supply	259	2065	m^3/yr
Groundwater recharge	Annual volume of groundwater recharge	0	580	m^3/yr
Stormwater runoff	Annual stormwater runoff reduction	262	2616	m^3/yr
	Max stormwater runoff volume reduction	84	838	m^3/d
Cost-Benefit Analysis				
Cost	Current annual expenditure on water	5.7	37.2	$/yr/p
	Annual cost-saving in USD	0.2	6	$/yr/p
	Total annual cost-saving in USD	26	2190	$/yr

The results show that the difference in the ratio A/P between residential buildings for low-income household (i.e. TNSCB building) compared to buildings for middle- to high-income household (Sabari Terrace building) is approx. fourfold. Residents from Sabari Terrace building could potentially obtain three times more water-saving (up to about 3.5 months of water supply) by implementing a RRWH system than residents from TNSCB building. Excluding high-rise residential buildings, it can be concluded that residential buildings for middle- to high-income households have usually more hydrological benefits to implement RRWH system than residential building for low-income households, due to a higher ratio A/P. The large difference in the results obtained from Sabari Terrace case study on groundwater recharge and stormwater runoff reduction is mainly due to a larger rooftop catchment area.

4.8.2 MODEL VALIDATION

The recorded daily harvested rainwater from the rooftop of Sabari Terrace residential apartment complex was used to validate the RRWH model. The sum of volume of rainwater collected per year was calculated from the data in the Annex L and divided by 350 users, which gave the annual no. of days relying on RRWH only for 2018 and 2019.

Table 28. Comparison between recorded data (2018 and 2019) and output from the RRWH model using historical daily rainfall data at Nungambakkam weather station from 1971-2016 (IMD, 2019)

Parameters	Year 2018	Year 2019	RRWH model
Total no. of days relying on RRWH only per year [d/yr]	20	55	59
Annual average rainfall [mm/yr]	607[1]	1183[1]	1274[2]

[1] Source: Annual average rainfall for Chennai city, India-WRIS, 2020

[2] See Table 18, median value

Since the year 2019 is closer to the median annual rainfall of 1274mm/yr than year 2018, year 2019 was used for the model validation analysis. Although the data collected are only over a period of two years which is not sufficient to validate the tool, it is enough to get a rough validation of the model which predicts similar value by comparing the modeled and the observed data. The observed data was only able to validate one output of the model which is the total no. of days relying on RRWH only per year.

4.9 CONCLUSION FOR SABARI TERRACE CASE STUDY

Section 4.7 presented the case of Sabari Terrace, a residential apartment complex, located in the South of Chennai. This area can be considered as the peri-urban area of Chennai city. The adoption of RRWH for water supply for this case was found to be significantly more relevant than the case of TNSCB for two main reasons:

1. From water-saving perspective, there is a high incentive to adopt a closed RRWH system. Indeed, both groundwater recharge or groundwater abstraction are not possible in this area because of high water table level and high salinity level. In addition, they are not yet connected to municipal piped water supply.
2. Following the first reason, the residents in this area are forced to buy water from water tankers which come at high cost. There is therefore a high financial incentive to adopt a RRWH for water supply.

The results from the RRWH model for Sabari Terrace showed that RRWH can achieve almost 2 months of the domestic water demand for 350 residents with 117m3 of underground storage capacity. This is equivalent to $2190 of cost-saving annually by reducing the need to buy water from water tankers. Since groundwater recharge is not possible in this area the result of 580m3 of volume of water for groundwater recharge is meant to be diverted to the open well (see Annex N) when the sump is full. Another particularity of Sabari Terrace is that they also implemented a system for greywater reuse for toilet flushing and garden irrigation, further reducing the need of water supply from rainwater or external water sources.

The potential of water-saving per person is similar to the case of the Mambalam area with 51day/yr of water supply. However, the cost-saving is almost 15 times more than the Mambalam area. It is clear that the adoption of RRWH would be more relevant in the peri-urban area than in the city (incl. Mambalam area) because of the economic benefits and the potential to reuse rainwater for domestic water supply and its feasibility in terms of retrofitting a building. It is important to take into consideration the temporal factor regarding the yield. The result of the potential of water-saving does not necessarily mean the stored water would be available during the summer.

4.10 SUMMARY OF THE CASE STUDIES

A summary of the results of both case studies on the hydrological effects of RRWH as well as the cost-benefit analysis is presented in Table 29. The unbalanced equation between the sum of the volume of water supply and groundwater recharged, and the stormwater runoff reduction can be explained by the fact that the results presented in Table 29 are the median value over 46 years. As an example, for the planned building, in some years, groundwater recharge occurred, but most of the time, the volume of groundwater recharge is nearly zero. Since the proposed RRWH system is a decentralized system, all rainwater captured from the rooftop is assumed to be avoided from going into the stormwater drainage system. Thus, the stormwater runoff reduction is highly dependent on the roof catchment area. The results of the model validation (in section 4.8.2) will be discussed in details in section 5.1.3. The highlighted value in Table 29 are the values for the combined results of RRWH for water supply and for groundwater recharge.

Table 29. Summary of the results on the hydrological effects of the proposed and existing buildings and for the Mambalam area using historical daily rainfall data from 1971-2016 of Nungambakkam weather station, Chennai, India (IMD, 2019) and its related costs (Legend: 1. Water supply, 2. Groundwater recharge and 3. Stormwater runoff)

	PARAMETERS	**UNITS**	**RESULTS**			
Specifications	Scale	-	Building (micro-scale)			Neighborhood (macro-scale)
	RRWH model		Planned	Existing	Existing	Existing
	Specific case study	-	Ideal	TNSCB (Mambalam)	Sabari Terrace (IT Corridor)	Mambalam
	No. of users	p	1	144	350	380,000
	Ratio A/P	m^2/p	33	1.7	7.1	5
Cost	Current annual expenditure on water	\$/yr/p	-	5.7	46	5.7
	Annual cost-saving in USD*	\$/yr/p	-	**0.2**	**6**	**0.5**
	Total annual cost-saving in USD*	\$/yr	37	26	2190	190,000
1	No. of days relying on RRWH only per year	d/yr	351	18	59	51
	Reliability	%	90	5	16	15
	Total volume of water saved per year	m^3/yr	35	260	2065	1,938,000
2	Total volume of groundwater recharge	m^3/yr	0	0	580	1,979,800
3	Annual stormwater runoff reduction	m^3/yr	34	276	2616	3,959,600
	Max daily stormwater runoff volume reduction	m^3/d	11	84	838	1,262,056

CHAPTER 5

LET'S DISCUSS: BENEFITS OF RRWH

To answer the main research question, a RRWH model was first developed and then applied to the case of the Mambalam area to assess quantitatively the hydrological benefits of a closed RRWH system. A cost-benefit analysis was also performed as the economic factor is a critical factor in the adoption of RRWH and thus, indirectly link to the potential of RRWH to mitigate urban water challenges at a larger scale. In this chapter, the RRWH model developed and the results obtained is disccused.

5.1 PROPOSED RRWH MODEL

A RRWH model was developed with two sub-models to determine quantitatively the hydrological effects of RRWH for the entire Mambalam area, Chennai, India. Model 1 was developed for an existing residential building and Model 2 was developed for a planned residential building. Firstly, this section discussed on the interpretation of the outputs of the model. Since the performance of RRWH system depends on a number of parameters such as number of residents, daily water demand, roof area, etc., the RRWH model was developed at the building level. Then, based on some assumptions, the outcomes of the RRWH model were used to scale up for the Mambalam area. Secondly, the single objective of the RRWH model and its limitations will be addressed. Finally, based on data collected from the existing RRWH of Sabari Terrace case study, the validation of the RRWH model developed will be discussed.

5.1.1 INTERPRETATION OF THE OUTPUTS OF THE RRWH MODEL

Sensitivity analysis

The sensitivity analysis performed in section 3.4 showed that some parameters of the model significantly influence the results obtained on the performance of the RRWH system. The parameters analyzed are the roof runoff coefficient (*C*), the design factor (*X*), the year skipped (*n*) and the daily water demand (*Wt*). The operational rules of YBS and YAS methods were also compared and analyzed. The results showed that daily water demand parameter is highly sensitive on the results of the RRWH design and in turn, on the performance of RRWH compared to the other parameters analyzed. For the Mambalam case study, the assumption made on consumer's water pattern of 0.1m3/d/p (or 100l/d/p) needs to be validated using a large sample size or cluster it based on people's socio-economic background in the area. Indeed, Chennai's water availability per capita varies between 40-100L per day (Srinivasan, Gorelick & Goulder, 2010C), while the Chennai's supply benchmark is 135 litres per capita per day (Resilient Chennai Strategy Report, 2019). Moreover, from the results of the case studies, it can be concluded that the ratio A/P is also a significant factor in the performance of RRWH. The ratio A/P includes the area and the number of users. Increasing the ratio A/P will increase the potential of water saving. If the RRWH model is used for other cases, the values of the main design parameters can be easily changed to values specific to the local context, if necessary.

Linear up-scaling of rainwater harvesting system for the entire Mambalam

The RRWH model developed in this research is designed for simulating a single RRWH system at a time. Thus, to estimate the impact at the Mambalam sub-catchment scale, the ratio A/P was multiplied by the total number of people living in this area. This approach uses a linear extrapolation based on the simulation of a single RWH system, implying a homogeneous spatial built landscape with the same average sump capacity and water demand characteristics. In other words, the calculations assume that every person lives alone in an individual house with a rooftop of 5m2 and has its own individual sump with a capacity of 4m3 (see Table 24). However, in reality, there are more multi-story buildings than individual house in the Mambalam sub-catchment. This means that more people are living under the same roof and would share the same sump for their water supply. Therefore, for more accurate results, it is not recommended to use simple scaling up of a single rainwater tank system because the results will have overestimation errors (Sharma, Begbie & Gardner, 2015). To consider the variability in the Mambalam sub-catchment, the cluster approach could be used. By grouping buildings with similar characteristics (i.e roof area, no. of users and water demand), the errors on the overall performance of the RRWH system can be reduced significantly (Sharma, Begbie & Gardner, 2015).

Model assumptions

It is important to understand the assumptions behind the model to interpret correctly the results. Three major assumptions addressed are the infinite storage capacity of the recharge well, the constant daily water demand and the historical rainfall data.

The RRWH model assumed that groundwater has an infinite storage capacity. However, depending on the geohydrology of the location, rainwater may overflow on the street if the soil is saturated. Assuming that groundwater has an infinite storage capacity, the results on the stormwater runoff reduction may lead to an overestimation. If the geohydrology of the location is known, using high-resolution rainfall data (min or hour), the results on the groundwater recharge could give an indication on the appropriate groundwater recharge system required (see Annex XX).

In addition, the current RRWH model assumed a constant daily water demand throughout the year. However, the daily water demand may vary seasonally. In summer, people may consume more water (i.e. washing or drinking) than in the winter. The seasonal pattern is an important factor that may affect the temporal pattern of yield and which can lead to an underestimation of the required sump size.

The model also assumed that the quality of the local rainfall data of Nungambakkam weather station obtained from the Indian Meteorological Department are reliable and accurate. It used historical hourly rainfall data from 1971 to 2016, which did not cover the recent variability of climate change in the recent years in Chennai.

5.1.2 OBJECTIVE FUNCTION OF THE PROPOSED RRWH MODEL AND ITS LIMITATIONS

The objective function of the proposed RRWH model was to design a RRWH system that meets the domestic water demand and from this design, the model assessed the associated hydrological benefits. As concluded for the case of the Mambalam, a combination of RRWH for water supply and RRWH for groundwater recharge can contribute to increase water availability for consumers, replenish groundwater and reduce stormwater runoff. The proposed RRWH model developed can also be applied for an open RRWH system like the RRWH for groundwater by removing the sump module in the model. Thus, this RRWH system would be simply described as a roof catchment area directly connected to a recharge well via a downpipe. Although the proposed RRWH model has only a single objective function, the model set-up could easily be modified depending on the purpose of the RRWH, either maximizing water supply, or maximizing groundwater recharge, or maximizing stormwater runoff reduction.

If the model was developed with a multi-objective function for water supply, groundwater recharge and stormwater runoff, the outcomes would have been different. Multi-objective function can become interesting for investigating cost minimization while optimizing of water-saving (Islam, Chou & Liaw, 2010). As cost is an important decisive factor for the uptake of RRWH, a preliminary cost-benefit analysis was performed to give an indication on the cost-saving based on the cost of water from external sources. The cost-benefit analysis was not integrated in the model yet, but it can further be added to provide a more complete RRWH model for design and decision-making. An in-depth cost-benefit analysis should also include the construction cost (more expensive underground sump than above-ground rainwater tank), the maintenance of the system and the additional water treatment required for drinking water purpose (Sharma, Begbie & Gardner, 2015; Islam, Chou & Liaw, 2010). These factors may or may not demonstrate that the adoption of RRWH system is a financially viable solution in the long-term.

5.1.3 MODEL VALIDATION

The RRWH model was first developed manually on a spreadsheet using similar calculations and used to compare with the results from the MATLAB code. This method helped to verify that the operations were accurate. However, an RRWH demonstration project is needed to validate the accuracy of the model representation using field data and on-going monitoring.

The RRWH model for existing building was partially validated using the data collected from the Sabari Terrace residential apartment complex (see Annex L). For this specific case, the results show the model’s ability to predict similar value for water-saving as the observed data (see Table 28). It is important to note that the historical daily data used in the RRWH model is from a weather station approx. 20km away from Sabari Terrace’s location which may impact the result obtained as rainfall can vary significantly within short distance inside a catchment. Nonetheless, a longer period of observed data with local rainfall data would be required to capture the long-term variability and to validate not only the water supply outputs but also, the groundwater recharge and stormwater runoff outputs. The validation of the optimization method used in the RRWH model is also critical in order to avoid overestimation or underestimation of the sump capacity. An overestimation of the sump capacity would induce more cost with no extra benefits while an underestimation would reduce the potential of water-saving.

5.2 MAMBALAM AREA CASE STUDY

The three last sub-questions are discussed in this section. First, the potential of the Mambalam area to become self-sufficient in water by solely harvesting rainwater in the locality is addressed. Then, the multi-benefits of scaling up RRWH at the neighborhood scale is discussed. Although understanding the hydrological impacts of RRWH was the main focus of this research, the feasibility to implement such system is also briefly addressed.

5.2.1 CAN THE MAMBALAM AREA IN CHENNAI BECOME WATER-SUFFICIENT FOR DOMESTIC WATER SUPPLY BY ADOPTING ONLY RRWH AND CONSIDERING THE EXISTING LOCAL INFRASTRUCTURE?

As a reminder, in this research, the proposed RRWH design is a RRWH for water supply. It is a closed RRWH system which is not in contact with other sources of water and rainwater is collected and stored in a sump for later usage (see Figure 10 and Figure 11).

Water-saving potential for water supply

For the case of TNSCB building, RRWH would only provide 18d/yr/p of water supply with a ratio A/P of 1.7m2/p. The potential of water-saving residential buildings for low-income household is very low. At the neighborhood scale, the average ratio A/P was estimated to be higher (5m2/p) and thus providing approx. 1.5 months of water supply from RRWH for a population of 380,000, equivalent to approx. 2 million of water per year. However, it is still far from achieving a complete decentralization on domestic water supply.

Cost-Benefit Analysis

From an economic perspective, the cost-saving for the residents of TNSCB building is estimated at $0.2/yr/p. This does not take into account the additional costs of retrofitting the building and operation and maintenance. For the Mambalam, when converting the volume of potential water that can be saved to an economic value, it gives approx. $200,000/yr of cost-saving. The volume is also equivalent to 20 days of operation of one desalination plant which is approx. $2 million per year of cost-saving if the water supply is from a desalination plant (see Table 30).

Table 30. Cost comparison for different sources of water for the case of the Mambalam, Chennai

Comparison of cost of water	Equivalent of cost-saving for the entire Mambalam area
Municipal piped water supply	$200,000/yr
Private borewell	$290,700/yr
Water tankers	$2,422,500/yr
Desalination plant	$2,112,420/yr

The cost comparison may not be applicable for Mambalam area, but when investigating the urban water balance at the city scale, the volume of water-saving from a neighborhood in Chennai becomes interesting. Indeed, it can be argued that this could be the volume of water which is not used from the main water supply. This means that this water retained in the upstream reservoirs can be used for underserved areas or unconnected to the piped water supply, saving potentially the investments shown in Table 30. At the individual level, there is less financial incentive to adopt RRWH compared to the community level. Further research needs to be done on the complete cost-benefit analysis of such intervention including the capital cost and the maintenance and operational costs. It is also important to note that RRWH is a one-time investment (capital cost) which benefits the current and future users of the residential building. In a megacity like Chennai, where workers move from place to place, there is little incentive to invest for the long-term benefits.

Existing local infrastructure

For an existing building, the sump would usually be installed on the side of the building, if there is no space to access underneath it. With limited land availability in urban areas, the possible sump capacity may be lower than the suggested optimal capacity, reducing further the reliance on RRWH for domestic water supply. Moreover, according to the building regulations (GCC, 2019), buildings are mandated to have a separate sump supplied only by the municipal piped water supply and which does not exceed 1000L per dwelling unit. Assuming that TNSCB building has 36 dwelling units with 4 residents per household for a total of 144 residents, this would give 36,000L (36m3) of sump capacity for the entire building. The results for sump capacity for TNSCB building case is 25m3 which is lower than the capacity required under this rule. Thus, the proposed sump capacity by the RRWH model can be achieved under the regulation only if the same sump can also be supplied by RRWH. Otherwise, having a second sump implemented for only RRWH may not be an efficient and effective solutions to manage two sumps separately for the water supply.

Temporal factor of stored rainwater

Temporal reliability from RRWH is another critical factor to consider as yield is strongly influenced by the local rainfall. Indeed, the availability of water supply from RRWH during the monsoon seasons has a different impact than during the summer, when needed the most. It varies annually as it is highly dependent on the meteorological conditions. However, in Chennai, it can be assumed that most of rainwater is harvested in the sump and used during the monsoon seasons. If there is rainwater left in the storage, it may be used at the beginning of the year after, but it might not last until the summer period. As an example, even during the highest annual rainfall year in 2005 and with the 'ideal RRWH design' (at 90% of reliability), water shortage occured mostly in the summer (see Figure 35) . The temporal factor was roughly addressed in this research but it gave an understanding on the influence of rainfall distribution over a year and the performance of RRWH during the summer. Further research could be done to investigate how RRWH could contribute to ensure water security during the summer period specifically.

© Cynthia van Elk I Water as Leverage

RRWH for drinking purpose

As rainwater remains the cleanest form of water, any options to save and reuse this water is worth to be investigated. If a sump to collect water is not a feasible option, then RRWH can be collected differently. When investigating the domestic water supply into drinking and non-drinking purposes, the volume of harvested rainwater could be used for drinking purpose only. The rainwater captured from the rooftop could be collected and stored directly on the roof and used by the households when needed. In this way, the sump can be replaced by a simple rainwater tank located on the building's rooftop. It is important to mention that RRWH for water supply may raise concerns regarding water quality. As most of the water is harvesting during the monsoon seasons for the following year, the stored water is not immediately used and becomes 'old'.

Alternatives to reduce dependence on the main water supply

There are multiple options to reduce the reliance on the main piped water supply. Water usage for cooking, cleaning and washing constitutes 50-60% of the total daily water demand (Ragade, 2005). If water used for these domestic purposes is recycled and reused for non-drinking purpose, the daily water demand required from external water source can be lowered considerably. A reuse of greywater system has already been used for the case of Sabari Terrace. Currently, it recycles approx. 20m3/d from 350 users for toilet flushing and irrigation purposes, representing almost 60% of their daily water demand. Another alternative to reduce the dependence on the main piped water supply is to multiply decentralized water supply sources such as community RWH, RWH ponds, etc. In the Mambalam area, due to the intermittent and unreliable piped water supply, people have been already using multiple water sources to meet their daily water demand. Borewell or open well are some examples of existing decentralized water infrastructures found in the Mambalam.

RRWH for water supply (closed system) and RRWH for groundwater recharge (open system)

As a reminder the difference between open and closed RRWH systems, (also referred in this research as RRWH for groundwater supply and RRWH for water supply, respectively) are well represented in Figure 9 and 10.

RRWH for groundwater recharge in the Mambalam area is not only used to replenish the groundwater, improve groundwater quality by diluting pollutant and reduce salt intrusion, it is also used as a resource for water supply. Thus, a combination of RRWH for water supply and RRWH for groundwater recharge can help to balance the urban water equation and manage water in a sustainable way. For the Mambalam, the results showed that approx. 2 million m3/yr could be achieved with RRWH for water supply, assuming 50% of the building footprint in the Mambalam is residential. In this case, the remaining 50% of the Mambalam's building footprint (which is non-residential) can adopt RRWH for groundwater recharge and has the potential to recharge approx. 2 million m3/yr. In total, approx. 4 million m3/yr (~104d/yr) can be saved for potential water-saving including approx. 2 million m3/yr of available groundwater for water supply. This is also not considering infiltration to the ground from soft areas (i.e parks, open green areas) or standalone artificial groundwater recharge infrastructures (i.e temple tanks, open wells, pits, driveway harvesting).

To put the concept of storage into perspective, the aquifer (natural open water storage) and the large underground sump (artificial closed water storage) are both water storage units which can be use for immediate and later use.

Summary and conclusion of RRWH for water supply in urban areas

In conclusion, with the current conditions, the results show clearly that the Mambalam area cannot depend solely on closed RRWH system to become self-sufficient in water. Due to the high-density population, especially in slum housing, the potential of water supply per person from RRWH is reduced significantly. Thus, it cannot secure water all year long from a single source of water.

However, when considering the combination of RRWH for water supply for residential building and RRWH for groundwater recharge for non-residential building, the potential of water-saving doubles, achieving almost 30% of the annual water demand. Greywater recycling system and other decentralized water systems for groundwater recharge can further reduce the reliance to the centralized water supply system by an additional 60% of the annual water demand.

But more importantly, reducing the daily water consumption can further contribute to achieve a decentralized water supply system for the Mambalam area. If Chennai Smart City Limited is planning to install water meter, it may influence slightly people's behavior on water-saving. From a hydrological modelling perspective, multiplying and diversifying decentralized RRWH and RWH systems can not only contribute to transition the Mambalam area closer to a water-sufficient neighborhood in Chennai, but also replenish the groundwater and reduce urban flood risk. However, this is very difficult to achieve in practice due to the low-cost of water supply in urban areas, demotivating dwellers for the adoption of RRWH. Highly urbanized area makes it technically difficult to retrofit the building with RRWH and legally challenging to implement an additional sump. The alternative of using RRWH for only drinking purpose may be interesting to investigate further as the implementation is much simpler and lower cost is involved.

Potential of closed RRWH system in the peri-urban areas

In this research, another case in the peri-urban area was also investigated and found to be more relevant to adopt the proposed RRWH design (or closed system) for water supply according to their local context. In the southern part of Chennai, due to its hydrogeological context, groundwater recharge and groundwater abstraction are not possible. According to the results, for the case of Sabari Terrace, RRWH for water supply can only achieve 16% of the annual total water demand. However, from an economic standpoint, it can save up to $2190/yr for the residential community. This amount could be reinvested in multiple other decentralized water systems and in improving the efficiency of the current water supply system and water reuse system. Diversifying water sources is a key to become resilient to water shortage and other water challenges and become water-sufficient.

5.2.2 DOES RRWH HAVE A SIGNIFICANT IMPACT ON DROUGHT AND FLOOD RESILIENCE IN THE MAMBALAM AREA, CHENNAI?

This research mainly investigated the possibility of transforming RRWH in urban areas as the primary source of water supply and assessed its associated hydrological benefits for Chennai, India to draw conclusions on the impact of RRWH on drought and flood resilience. According to the results, RRWH has the potential to develop resilience to climate change and variability.

Drought resilience

It is important to distinguish between drought and water shortage. Drought is a meteorological event which experiences below-normal precipitation. It is directly link to water shortage in Chennai, since the city is mainly dependent on rainfall for its water supply. However, water shortage in Chennai may be due to drought or to the mismanagement of water supply or both at the same time (refer to Chapter 1). When water shortage occurs, most of the people extract groundwater to meet their demand, further exacerbating the consequences of the drought.

The combination of RRWH for groundwater recharge and RRWH for water supply can contribute to improve drought resilience. Indeed, RRWH for groundwater recharge is contributing to improve drought resilience as well as water security by providing more available groundwater for water supply, when needed. RRWH for water supply can help to regulate the over-extraction of groundwater because it has a finite volume capacity and allow a better management of water supply. Multiplying and diversifying water supplies sources (including rainwater harvesting and water recycling) by reducing reliance on the main water supply is necessary to increase resilience to drought.

Flood resilience

Similarly, adopting both RRWH for water supply and RRWH for groundwater recharge could reduce up to 60% of water on a heavy rainy day going into the stormwater drainage network (twice 30%, refer to section 4.5.3), and in turn in the Mambalam drain. Thus, reducing the risk of flooding in the nearby residential buildings along the Mambalam drain. Moreover, reducing the peak flow may reduce the need to increase the stormwater conveyance capacity and the associated costs (Sharma, Begbie & Gardner, 2015). It is especially relevant in a city in which the stormwater drain is most of the time not used. As discussed in section 5.1.1, the effect of RRWH on stormwater runoff may be overestimated because the RRWH model assumes that the recharge well has an infinite storage capacity. RRWH can mitigate urban flooding considerably and the frequency of small runoff event but field experiment and model calibration remain untested (Sharma, Begbie & Gardner, 2015).

CHAPTER 6

LET'S MOVE TOWARDS A WATER RESILIENT CITY: CONCLUSION

In Chennai, the current centralized water supply system is fragile and used to the limit of its capacity. With the growing population, it is difficult for the city to continuously adapt to the increase of demand. Thus, small-scale rainwater harvesting has been reintroduced recently as an alternative to mitigate Chennai's water challenges. This research examined the potential of leveraging simple decentralized rooftop rainwater harvesting (RRWH) system using a multi-purpose approach. RRWH, which has been mainly perceived and used for groundwater recharge, was investigated here as a closed system and from a multi-purpose approach while maximizing water supply from rainwater. The water challenges which are investigated are water shortage, groundwater depletion and urban flooding. The Mambalam sub-catchment, located in the historical center of Chennai, was used as a case study to assess quantitatively the hydrological impacts of implementing the proposed RRWH at the macro-scale (neighborhood level). The potential feasibility and cost-effectiveness were also addressed briefly to give an estimation on the potential to leverage RRWH at the scale of the city. As a reminder, the proposed RRWH design in this research refers to a closed system of rainwater as opposed to an open RRWH system like RRWH for direct groundwater recharge.

The results showed that only 15% of the total annual water demand in the Mambalam (~51d/yr/p) can be met by adopting the proposed RRWH design. In other words, Mambalam area is not able to rely solely on decentralized RRWH system to meet its water demand. However, adopting a multi-layered water resilient model can contribute to achieve a decentralized water supply system for the Mambalam area. Indeed, both RRWH for water supply (closed RRWH system) and for groundwater recharge (open RRWH system) can provide 30% of the annual water demand. This volume of rainwater is equivalent to 3.5 months of water supply serving a population of 380,000. This has the potential to save up to $400,000/yr in cost. Referring to the case of Sabari Terrace's greywater recycling system, water can be reused up to 60% of the water consumed. The remaining water required to meet the demand can be achieved through increasing other sources of decentralized groundwater recharge system including infiltration through soft areas and standalone artificial groundwater recharge infrastructures and reducing the daily water consumption. Therefore, from an urban hydrology perspective, the Mambalam area can achieve a decentralized water supply system to a large extent using a multi-layered water resilient model, attempting to achieve a closed-loop water system at the local level.

Regarding the associated hydrological benefits of RRWH for the Mambalam, approx. 2 million m3/yr can be recharged to the groundwater, if all non-residential buildings in the Mambalam adopt RRWH for groundwater recharge. Finally, regarding the impact on urban flooding, during a rainy day, RRWH can reduce up to 60% of volume of stormwater runoff going into the stormwater drainage system. This has significant impact on the frequency of urban flooding experienced by the vulnerable communities living along the Mambalam drain which receives all the rainwater from the Mambalam sub-catchment. The preliminary RRWH model developed in this research was able to provide scientifically-sound quantitative information on the potential of hydrological benefits of RRWH for this area.

In practice, the adoption of the proposed RRWH design in urban areas is difficult mainly due to many factors. Low potential of water-saving (< 50%), low financial incentive (cost-saving of \$0.2/yr/p), restricted building regulations (i.e existing sump can only be supplied by municipal piped supply), space limitation in urban areas and more importantly, the fact that people have been using wells as a source of water supply are the limiting factors in the adoption of a closed RRWH system for water supply.

Another area in the peri-urban area of Chennai was identified as more relevant for the adoption of the proposed closed RRWH system due to its local geohydrologic conditions where groundwater recharge and groundwater extraction. It is precisely the case in the southern part of Chennai, in IT Corridor area where lies directly on the Pallikaranai marsh, characterized by high water table and saline water. Most of the residential apartment complexes in this area are not yet connected to the municipal piped water supply system and they are not able to abstract water from the groundwater, thus, relying solely on water charging high rate. Thus, there is high financial incentive in harvesting rainwater from the rooftop and collecting it in a large community sump. For these reasons, the case of Sabari Terrace residential apartment complex in Sholinganallur, located in the southern part of Chennai city was also investigated. This apartment complex has already retrofitted their building with a RRWH for water supply in 2017. They have been able to save \$6/yr/p and meanwhile reducing their dependence on water tankers by 16% annually.

LET'S TALK WATER

Online public tool

LET'S TALK WATER, A SPIN-OFF FROM THE WATER AS LEVERAGE

By Camille Fong

As a relevant side product, this research has led to the development of a user-friendly RRWH tool called " Let's Talk Water" (prototyping phase as of March 2020).

Let's Talk Water is a rainwater harvesting Software as a Service (SaaS) tool that supports end-users to understand, decide, design and build an effective decentralized rainwater harvesting systems by providing credible, local scientific data and a network of experts. It also helps reducing the dependence on the centralized water supply and transforms the users to be more informed and responsible. The tool also has the potential to be scaled up to other cities experiencing similar water challenges.

The purpose of the tool is aligned to the WaL's vision which is designing smarter interventions to create sustainable impacts. Smart and responsible design means asking the right question in the first place instead of trying to solve multiple complex problems at the same time. Following the Dutch way of thinking, this research pushed the boundaries to act local and think global, starting at the local level by the adoption of RRWH and understanding the impacts of RRWH when scaling-up to an entire city.

This research contributed to leverage rooftop rainwater harvesting (RRWH) system in Chennai, India. The multi-purpose functionality of this traditional and simple technique was demonstrated into a comprehensive approach to tackle Chennai's water challenges. Although it is considered as a grey measure, it is nonetheless one of most effective solutions to obtain drastic impacts on the urban hydrology. Innovation is not only about creating something new, but also leveraging traditional wisdom of water management.

Water as Leverage for Resilient Cities Asia

CHAPTER 7

LET'S TALK: RECOMMENDATIONS AND FUTURE RESEARCH

RRWH model

- **Model calibration**

Long-term continuous monitoring of water quantity needs to be collected to calibrate the model for a better representation of the reality. Water supply and groundwater recharge can be monitored at the micro-level. Regarding the effect on urban flooding reduction, it would be more relevant at the macro-level and with a higher rainfall resolution (i.e. hourly time-step).

- **Improvement of the model accuracy**

An important aspect to investigate is the uncertainty factor which takes into account the variability of rainfall due to climate change. To develop sustainable solutions, climate predictions are important to consider when designing RRWH system.

- **Multi-objective function**

A critical factor in the adoption of RRWH is the cost factor. Multi-objective function may be required in the model to optimize water supply and cost and demonstrate the trade-off between different sources of water.

Decentralized water supply system

- **Water quality**·

Water quality - Contaminated water from RRWH may lead to serious concern regarding public health (Sharma, Begbie & Gardner, 2015). Therefore, water quality in the sump need to be frequently monitored and 'point source' supply should have the quality tuned to demand for a specific use. Household drinking water treatment systems available in the market and proven to be effective need to be further investigated, if RRWH is designed for drinking water purpose. When dividing domestic water supply into drinking water purpose ('clean water') and non-drinking water purpose ('less clean water'), only a small fraction of domestic water supply is used for drinking. It would be interesting to understand better the potential of RRWH designed for drinking water purpose only in terms of improving drinking water security and its feasibility, considering the local context of Chennai, India. Groundwater quality needs also to be investigated.

- **Cost-Benefit Analysis**

Capital and operational costs of RRWH need to be considered and compared to the cost required for external water source such as desalination plants, water tankers and municipal water supply per unit of volume of water. Moreover, with the implementation of water sensors under the Chennai Smart City Limited, there will be a financial incentive to harvest 'free' water from the roof. In some circumstance, RRWH might not be the most cost-effective (Sharma, Begbie & Gardner, 2015), therefore, further research needs to be done to support the implementation of RRWH from an economical point of view.

- **Decentralized water recycling system**

Reducing the water demand through decentralized greywater recycling is already suggested in Tamil Nadu Combined Development and Building Rules (2019). However, further research on the performance of a recycling systems in water-saving would be interesting to explore.

- **RRWH policy improvement**

The current building policy on rainwater harvesting structure uses a 'dwelling unit' for the limit of sump capacity (see section 1.3.2). Since there is no law regarding the maximum number of residents per dwelling, many people live in the same dwelling to save money. This is an important aspect to consider when designing building's service infrastructures, including water supply provision. Therefore, it is recommended to have more detailed standard design guideline, such as changing the unit to 'per person'. RRWH design guideline could use the ideal unit ratio of A/P presented in Table 22 to provide the design specifications. For existing building, buildings which has a ratio ≥ 18m2/p (equivalent to ET≥50%) could be mandated to install a RRWH for water supply. For planned building, regulations on low floor space index (FSI) for Chennai would be recommended to increase reliability on RRWH for water supply. This means that high-rise residential buildings are not recommended from a water management perspective. Moreover, most of the residential buildings have already a sump which stores municipal piped water supply. There would be a great potential to connect RRWH to this existing sump, if legally allowed. It is recommended to have a pilot demonstration to assess the water quality of both sources of water and understand the operational management required to operate this system effectively.

Multi-purpose RRWH

- **Water demand pattern**

The seasonally changing water demand pattern should be considered in the simulation. Indeed, in the summer, water demand may be higher due to high temperature, people may take more shower and drink more water to stay hydrated.

- **Geohydrology analysis**

Mapping out location-specific soil profile and daily groundwater level should be analyzed to understand the local urban hydrology, where recharge can have a maximum impact on storage and water quality.

- **Urban flood risk reduction analysis**

The proposed RRWH model need to be coupled with the existing stormwater drainage and the surface flow behavior (i.e using DEM) to understand better its impacts on the local flood hydrology. Such an undertaking is a topic of future research.

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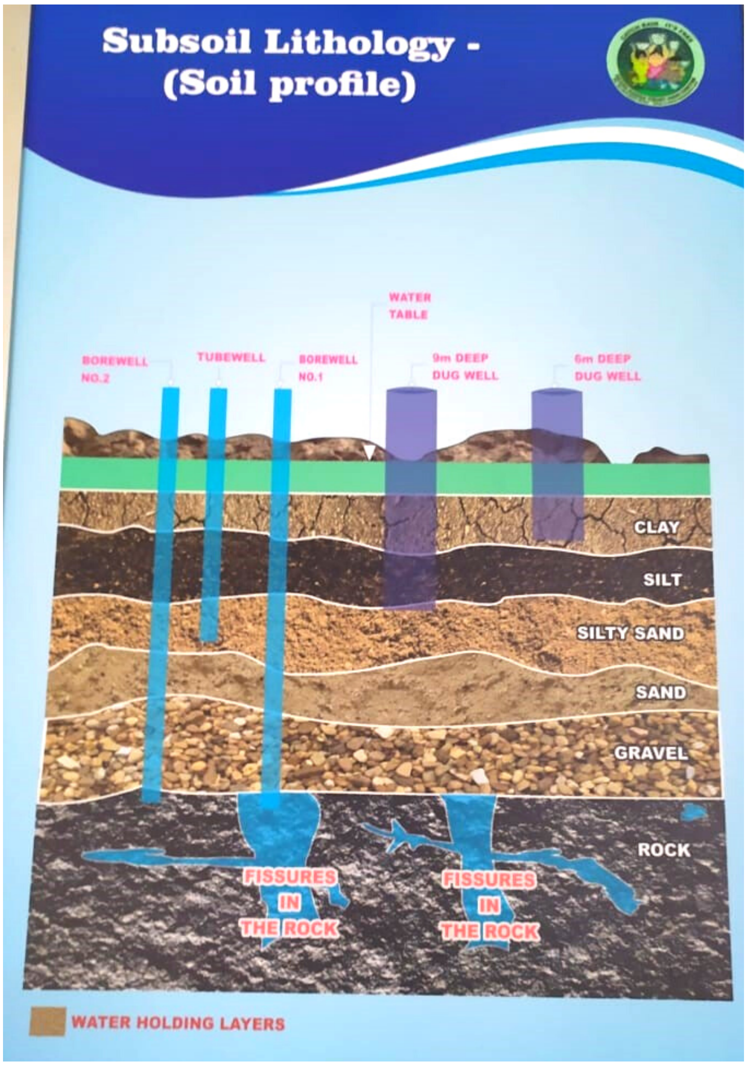
ANNEX A - Scheme of governmental RRWH

Source: Tamil Nadu Combined Development and Building Rules (2019)

ANNEX B - Different types of recharge well

Source: Poster, Rain Center, 2019



ANNEX C - Summary of the extensive literature review on dual- and multi-purpose RRWH in urban areas

Legend: 1. Water Supply, 2.Groundwater recharge and 3. Stormwater runoff reduction

Authors	Study location	Scale	1	2	3	Methods used for the simulation and evaluation	Time step	Limitations
Steffen et al., (2013)	USA	Neighbor-hood	X		X	• For water supply provision: YBS approach • For stormwater runoff reduction: SWMM	Daily	• Investigation for specific cistern sizes only. • No continuous daily simulation for the optimization of the sizing of the cistern
Mahmoud et al., (2014)	Khartoum, Sudan	Neighbor-hood	X		X	• For water supply provision: Rational method • For stormwater runoff reduction: United States Natural Resources Conservation Services method (US-NRCS, method, runoff-rainfall relationship)	Daily	• Investigate the potential of RWH with infinite storage capacity and without considering the water demand • No continuous simulation for the optimization of the sizing of the sump
Islam et al., (2010)	Taiwan	Building (school)	X		X	• For water supply provision: RRWH model developed on a spreadsheet-based on YAS and YBS • For stormwater runoff reduction: No quantitative method used	Daily	• For the tank optimization calculation, arbitrary tank volumes are used until it reaches the optimum size using a spreadsheet model • No continuous simulation for the optimization of the sizing of the sump • The author mentioned that air space between the overflow pipe and the top of the tank could be used as a stormwater detention. However, they did not quantify the potential of stormwater control from RRWH.

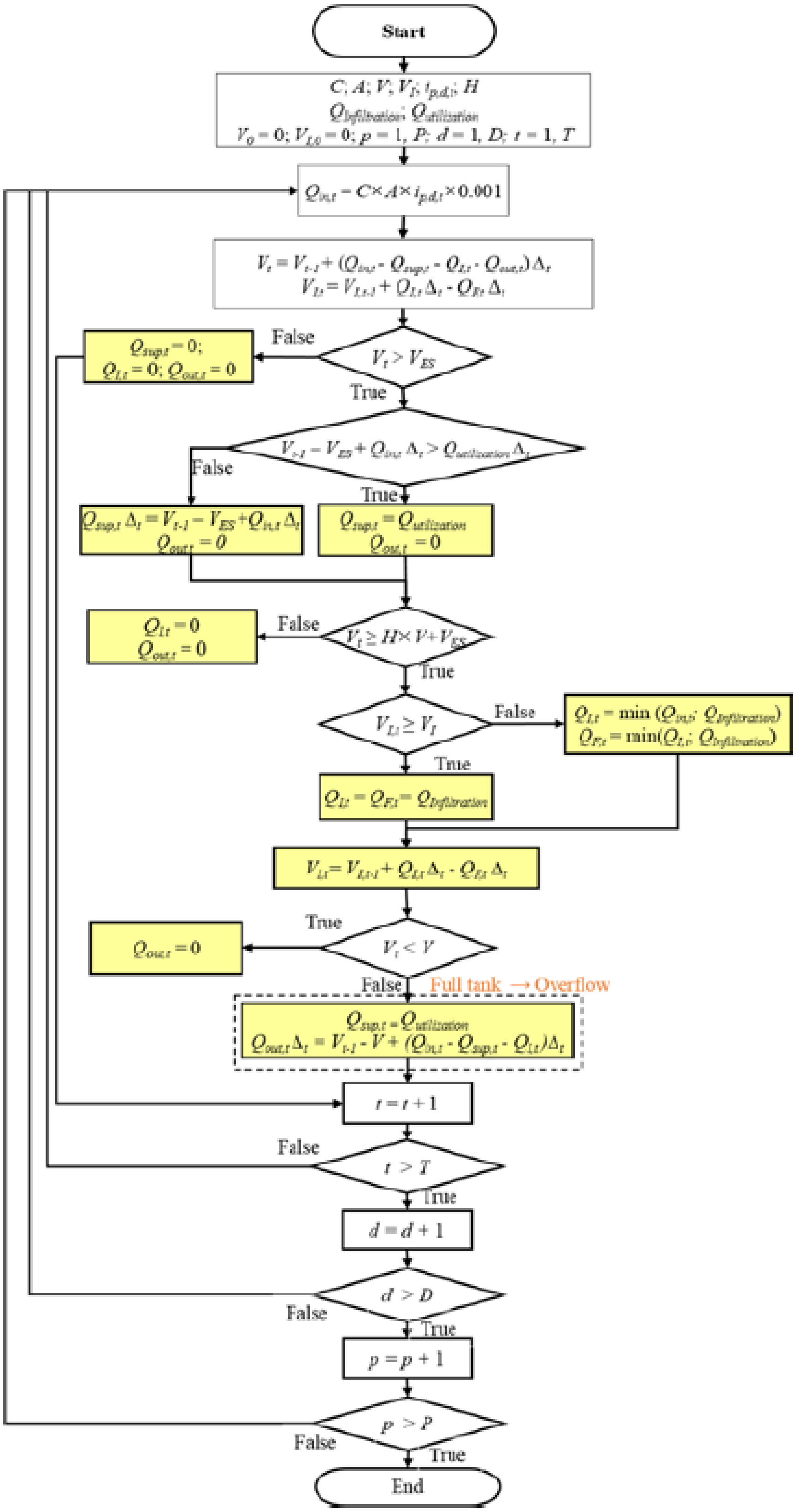
ANNEX C - Summary of the extensive literature review on dual- and multi-purpose RRWH in urban areas

Legend: 1. Water Supply, 2.Groundwater recharge and 3. Stormwater runoff reduction

Authors	Study location	Scale	1	2	3	Methods used for simulation and evaluation	Time step	Limitations
Mugume et al., (2016)	Kampala, Uganda	Neighbor-hood	X		X	• For water supply provision: YAS approach • For stormwater runoff reduction: SWMM	Daily	• Calculations based on the average daily rainfall from 1991-2009 • Investigation only for specific tank sizes • No continuous simulation for the optimization process of the sizing of the underground sump • Assume that RRWH tank is emptied before the onset of a rainfall event to investigate the effect of urban flooding reduction
Melville-Shreeve (2017)	UK	City	X		X	• For water supply provision: YAS approach • For stormwater runoff reduction: Identifying the largest discharge from the time series and calculating the reduction peak overflow	Daily	• Excel-based simulation tool "The Rainwater Harvesting Evaluation Tool (RainWET) • No continuous simulation for the optimization process of the sizing of the underground sump. The user defines its maximum tank capacity.
Han & Nguyen (2018)	South Korea	Building	X	X	X	• For water supply provision: Combination of YAS and YBS • For stormwater runoff reduction: Using a design rainfall hyetograph, the peak runoff curve can be generated from the tank volume and Peak runoff graph (Han & Nguyen,2018) • For groundwater recharge: Using an infiltration box with an infiltration rate of 1L/min	Daily	• No optimization process for the sizing of the volume of the tank. The volume of the tank is pre-defined as an input parameter. It is designed according to the design period required determined by the Huff method. • Outputs are the outflows presented by Tank volume - peak runoff curve and Tank volume - Design period curve

ANNEX D - Rainfall-Storage-Utilization-Infiltration-Discharge (R-S-U-I-D) system

Source: Han & Nguyen, 2018



ANNEX E - Excel RRWH model

A simple RRWH model was first developed on an Excel spreadsheet and it can be viewed at the following link:

https://drive.google.com/open?id=17_b_VXVJj3GV0Q_QzjWQYCSqaLAkP3xC_

ANNEX F - MATLAB RRWH MODEL - FOR EXISTING BUILDING

```
clear all
%%INPUT Indian Meteorological Data - Daily Rainfall data from 1971 to 2016 at
Nungambakkam rain station
data=xlsread('Nungambakkam-Hourly2.xlsx');%Read IMD hourly rainfall data
```

Inputs from user

```
n_people=1;
W=0.1; % Assuming 100l/d/c [0.1m3]
D=W*n_people;
A_roof=32;
c_roof=0.85; % between 0.7-0.9, Tiles:0.8-0.9 and Corrugated metal sheets: 0.7-0.9
n=2; %Years to skip in the simulation
S_0=0;% Initial storage on the first day of the first year
```

Historical daily rainfall data

```
data_daily(:,1:3)=data(:,1:3);%yyyy-mm-dd
hourly=data(:,4:27);%24 hours
daily=sum(hourly,2);% Convert hourly data into daily data
data_daily(:,4)=daily;
data_daily(:,1)=data_daily(:,1)-1970;% Convert years 1970-2016 to 1-46
data_daily(:,4)=data_daily(:,4)*c_roof;% Actual daily rooftop RWH catchment [mm]
data_daily=rmmissing(data_daily);% Remove missing data
M1(:,1)=data_daily(:,1);% Year
M1(:,2)=data_daily(:,4);% Daily rainfall [mm]
M1(:,3)=D; % Total daily water consumption [m3/d]
```

1. DETERMINING THE OPTIMUM SUMP CAPACITY [m3] USING A DETERMINISTIC APPROACH

```
Ca=1;% starting point at 1m3
kkc=1;
kkk=0;

while(kkc==1)
        Ca=Ca+1;
        kkk=kkk+1;

        %Creating matrix T1 for the loop
        T1=M1(:,2)*A_roof/1000;% rainfall runoff [m3/d]
        T1(:,2)=D;% Total daily water demand [m3/d]
        T1(:,3)=0;% Volume supplied only by RRWH (Y= D or 0) [m3]
```

ANNEX F - CON'T

```
        T1(:,4)=0; %Stored rainwater in sump [m3]
        T1(1,4)=min(T1(1,1)+S_0,Ca);%Value on 1-1-1971
        T=length(T1); % Simulation period

        for j=1:T-1 % Loop for every day from 1-1-1971 to 31-12-2016
            %Applying YBS method
            %When S(t) + Q_in(t) >= D
            if(T1(j,4)+T1(j,1)>=T1(j,2))
                T1(j+1,4)=min(T1(j,1)+T1(j,4)-T1(j,2),Ca);
               if(j>365*n)% Skipped the first few years in the simulation because
no initial storage
                   T1(j,3)=D;% Volume supplied by RRWH [m3] for each 'Ca'
               end

            %WHEN S(t) + Q_in(t) < D
            else
                T1(j+1,4)=T1(j,1)+T1(j,4); % Y= 0, then, stored rainwater is adding
up to the next day
            end
        end

        total=sum(T1,1);%Matrix with sum of each column [1x4]

        %Additional information on rainfall statistic
        max_vol=max(T1(:,1));%Max daily rainfall runoff over 46 years

        %Results from the deterministic approach
        T2(kkk,1)=Ca;%All possible sump capacity (Ca) given A_roof [m3]
        T2(kkk,2)=(total(3)*100)/(D*(T-365*n));% E_T = Percentage of RRWH reliance
for water supply over 46 years [%]
        T2(kkk,2)=floor(T2(kkk,2));

        %Conditions
        if(kkk>1)
            if(T2(kkk,2)>=90||(T2(kkk-1,2)-T2(kkk,2))==0) %Loop stops at 90% or
more of reliance on RRWH for water supply OR when E_T becomes a constant
              kkc=0;
            end
        end
end
```

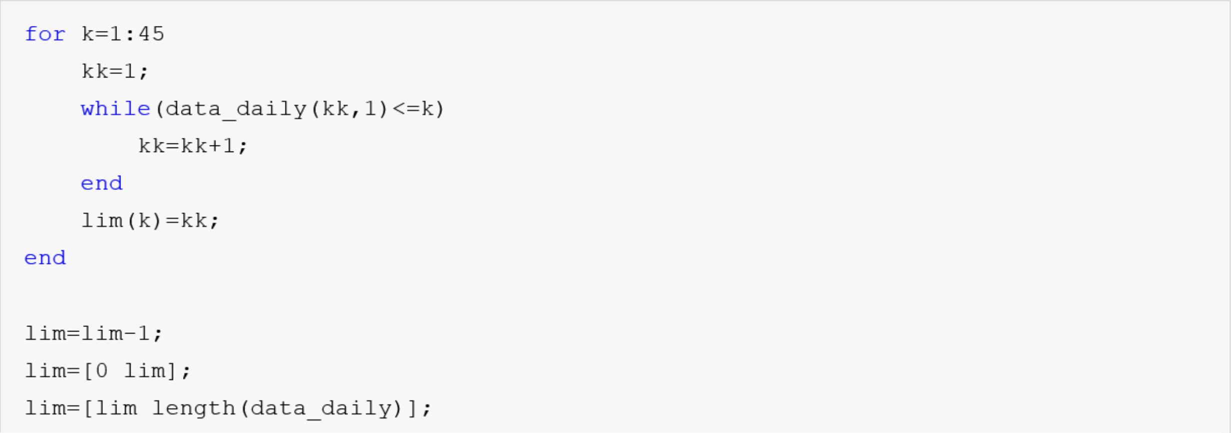
Optimal sump capacity for the given rooftop area

```
Opt_sump=T2(length(T2(:,1)),1); %A2
ET_Opt_sump=T2(length(T2(:,1)),2);%A3
```

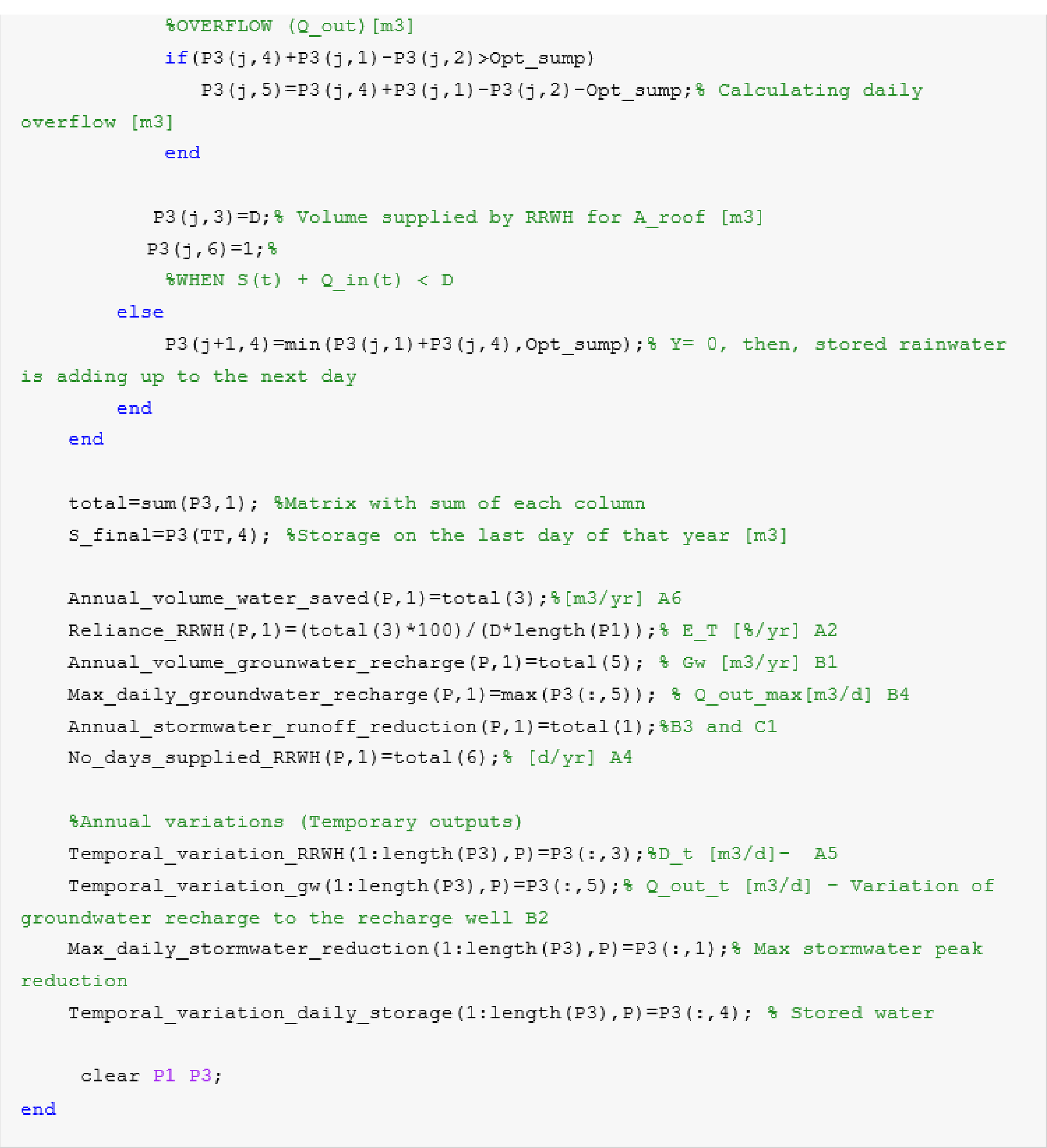
ANNEX F - CON'T

2. ANALYSIS YEAR-BY-YEAR USING A PROBABILISTIC APPROACH

Dividing historical rainfall data by year



```
for k=1:45
    kk=1;
    while(data_daily(kk,1)<=k)
        kk=kk+1;
    end
    lim(k)=kk;
end

lim=lim-1;
lim=[0 lim];
lim=[lim length(data_daily)];
```



```
            %OVERFLOW (Q_out)[m3]
            if(P3(j,4)+P3(j,1)-P3(j,2)>Opt_sump)
               P3(j,5)=P3(j,4)+P3(j,1)-P3(j,2)-Opt_sump;% Calculating daily
overflow [m3]
            end

           P3(j,3)=D;% Volume supplied by RRWH for A_roof [m3]
          P3(j,6)=1;%
            %WHEN S(t) + Q_in(t) < D
        else
            P3(j+1,4)=min(P3(j,1)+P3(j,4),Opt_sump);% Y= 0, then, stored rainwater
is adding up to the next day
        end
    end

    total=sum(P3,1); %Matrix with sum of each column
    S_final=P3(TT,4); %Storage on the last day of that year [m3]

    Annual_volume_water_saved(P,1)=total(3);%[m3/yr] A6
    Reliance_RRWH(P,1)=(total(3)*100)/(D*length(P1));% E_T [%/yr] A2
    Annual_volume_grounwater_recharge(P,1)=total(5); % Gw [m3/yr] B1
    Max_daily_groundwater_recharge(P,1)=max(P3(:,5)); % Q_out_max[m3/d] B4
    Annual_stormwater_runoff_reduction(P,1)=total(1);%B3 and C1
    No_days_supplied_RRWH(P,1)=total(6);% [d/yr] A4

    %Annual variations (Temporary outputs)
    Temporal_variation_RRWH(1:length(P3),P)=P3(:,3);%D_t [m3/d]-  A5
    Temporal_variation_gw(1:length(P3),P)=P3(:,5);% Q_out_t [m3/d] - Variation of
groundwater recharge to the recharge well B2
    Max_daily_stormwater_reduction(1:length(P3),P)=P3(:,1);% Max stormwater peak
reduction
    Temporal_variation_daily_storage(1:length(P3),P)=P3(:,4); % Stored water

     clear P1 P3;
end
```

ANNEX G - MATLAB RRWH MODEL - FOR PROPOSED BUILDING

```
clear all
%Input Indian Meteorological Data of Nungambakkam rain station - Daily rainfall
data from 1971 to 2016
data=xlsread('Nungambakkam-Hourly2.xlsx');%Read IMD hourly rainfall data
```

Inputs from user

```
n_people=1; % Nbr. of people living in the building
c_roof=0.85; % Runoff coef. between 0.6-0.9
W=0.1; % Assuming 100l/d/c [0.1m3]
D=W*n_people;% Total daily water demand
n=2;%Years to skip in the simulation
S_1=0;% Initial storage on the first day of the first year
```

Historical daily rainfall data

```
data_daily(:,1:3)=data(:,1:3);%yyyy-mm-dd
hourly=data(:,4:27);%24 hours
daily=sum(hourly,2);% Convert hourly data into daily data
data_daily(:,4)=daily;
data_daily(:,1)=data_daily(:,1)-1970;% Convert years 1971-2016 to 1-46
data_daily(:,4)=data_daily(:,4)*c_roof;% Actual rooftop RWH catchment
data_daily=rmmissing(data_daily);% Remove missing data
M1(:,1)=data_daily(:,1);% Year
M1(:,2)=data_daily(:,4);% Daily rainfall [mm]
```

1. DETERMINING THE OPTIMUM ROOFTOP AREA [m2] USING A DETERMINISTIC APPROACH WITH INFINITE UNDERGROUND STORAGE CAPACITY

```
%Boundary conditions for rooftop area to reduce the running time considering 50-
100% reliance on RRWH
 min_area=1*n_people; % Based on the ideal scenario for 1 user (for E_T=50%, 22m2
of rooftop area is required)
 max_area=70*n_people; % Based on the ideal scenario for 1 user (for E_T=100%, 58m2
of rooftop area is required)
 step=ceil((max_area-min_area)/1000);% step of 1

for A=min_area:step:max_area %Applying boundary conditions
    area=A;
    kk=(area-min_area)/step+1;

    %Create matrix M2
     M2=M1(:,2)*area/1000; % rainfall runoff [m3/d]
     M2(:,2)=D; % Total daily water demand [m3/d]
```

ANNEX G - CON'T

```
     M2(:,3)=0; % Days supplied only by RRWH (Y= 1 or 0)
     M2(:,4)=0;% Stored rainwater in sump [m3]
     M2(1,1)=M2(1,1)+S_1; % Value on 1-1-1971
     M=length(M2);

        for j=1:M-1 % Loop for every day from 1-1-1971 to 31-12-2016
           %Applying YBS method
            %When S(t) + Q_in(t) >= D
            if(M2(j,1)+M2(j,4)>=M2(j,2))% If daily stored RWH >= Total daily water
demand
                M2(j+1,4)=M2(j,4)+M2(j,1)-M2(j,2);% Remaining RW stored in the
underground tank after water has been consumed
             else
                M2(j+1,4)=M2(j,4)+M2(j,1); %If stored RW < water demand, no
consumption, adding up to the next day rainfall
               if(j>365*n) % Skipped the first year because no initial storage
volume
                    M2(j,3)=1; %Days need main water supply
                end
            end
        end

        %Creation of matrix M3 for infinite underground storage
        total=sum(M2,1);%Matrix with sum of each column [1x4]
        M3(kk,1)=area; %All possible rooftop areas within the boundary conditions
        M3(kk,2)=((M-365*n)-total(3))*100/(M-365*n); % Percentage of RRWH reliance
for water supply
end
```

ROOFTOP AREA [M3] WITH ITS RELATED E_T

```
Out_A_Roof =floor(M3(:,2));
```

Output of A_roof with E_T between 50-100% with infinite underground capacity

```
    for E_T=50:5:100 % E_T = 50-100% (11 columns)
        kk=1;
        ind=1+(E_T-50)/5; % Creating an index from 1 to 11
        while(M3(kk,2)<E_T)% If E_T < 50%
            kk=kk+1;
        end
        Area_with_infinite_capacity(ind)=M3(kk,1); % [2x11] A_roof associated E_T
    End
```

ANNEX G - CON'T

2. DETERMINING THE OPTIMUM ROOFTOP AREA [m2] USING A DETERMINISTIC APPROACH WITH FINITE UNDERGROUND STORAGE CAPACITY

```
    Opt_sump=n_people;
    i=1;
    p(1:11)=0;
    Opt_sump=Opt_sump+1; % Incremental increase

while(i==1)
     Opt_sump=Opt_sump+1; % Incremental increase
    for A=min_area:step:max_area
        area=A;
        kk=(area-min_area)/step+1;
        M2=M1(:,2)*area/1000; % rainfall runoff [m3/d]
        M2(:,2)=D;% Total daily water demand [m3/d]
        M2(:,3)=0;% Days supplied only by RRWH (Y= 1 or 0)
        M2(:,4)=0;% Stored rainwater in sump [m3]
        M2(1,1)=min(M2(1,1)+S_1,Opt_sump);% Storage value on 1-1-1971
        M=length(M2); %Simulation period

        for j=1:M-1 % Loop for every day from 1-1-1971 to 31-12-2016
        %Applying YBS method
        %When S(t) + Q_in(t) >= D
            if(M2(j,1)+M2(j,4)>=M2(j,2))
                M2(j+1,4)=min(M2(j,4)+M2(j,1)-M2(j,2),Opt_sump);
            %WHEN S(t) + Q_in(t) < D
            else
                M2(j+1,4)=M2(j,4)+M2(j,1);
                if(j>365*n)
                    M2(j,3)=1; %Days need main water supply
                end
            end
        end
        total=sum(M2,1);
        M4(kk,1)=area;%All possible A_roof within the boundary conditions
        M4(kk,2)=((M-365*n)-total(3))*100/(M-365*n);% E_T
        storage2(1:M,kk)=M2(:,1);% Matrix of A_roof vs E_T
    end
        M4(:,2)=floor(M4(:,2)); % Round value of E_T
```

Output of A_roof with E_T between 50-100% with finite sump capacity

```
    for E_T=50:5:100 % Reliance on RRWH for water supply
        kj=1;
        ind=1+(E_T-50)/5;% Creating an index
      while(M4(kj,2)<E_T&&kj<kk)
           kj=kj+1;
```

ANNEX G - CON'T

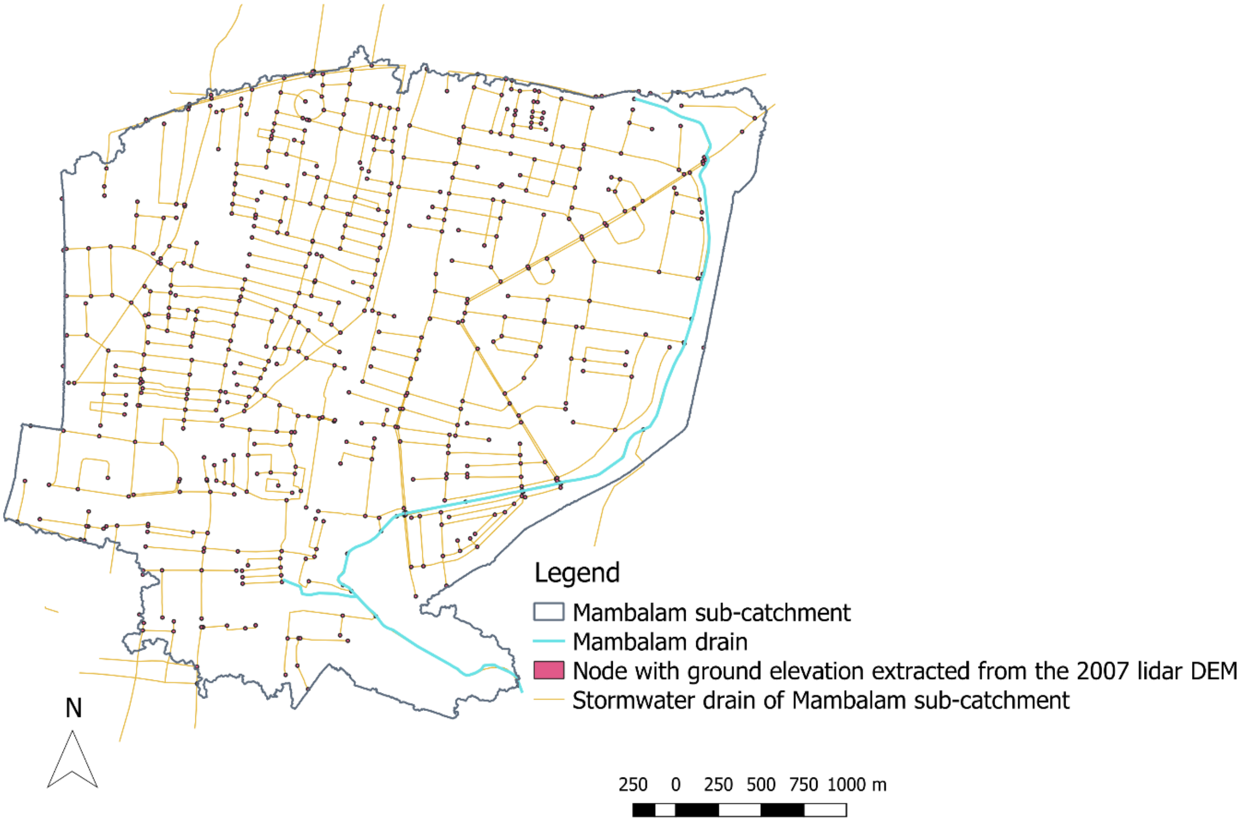
```
       end
      Area_with_finite_capacity(ind,1)=M4(kj,1);%All possible A_roof within the
boundary conditions
    end

    for E_T=1:11
        if(p(E_T)==0)
     %Convergence of A_fin and A_inf
 if(Area_with_finite_capacity(E_T,1)<=1.1*Area_with_infinite_capacity(E_T))
              p(E_T)=1;
              Opt_sump2(E_T)=Opt_sump;
              Opt_area2(E_T)=Area_with_finite_capacity(E_T,1);
           end
         end
    end
        temp=sum(p); % If all p = 1, then sum(p)=11
        if(temp>=11) % Stop loop when
         i=0;
        end
end
```

Output data for Ca and A_roof with its related E_T

```
init_mat=[0:10]*5+50;
Fina_Opt_Sump_size(1:length(Opt_sump2))=Opt_sump2;
Final_Opt_A_roof(1:length(Opt_sump2))=Opt_area2;
Fina_Opt_Sump_size=[init_mat; Fina_Opt_Sump_size];
Final_Opt_A_roof=[init_mat; Final_Opt_A_roof];
```

ANNEX H - STORMWATER DRAINAGE NETWORK FOR THE MAMBALAM SUBCATCHMENT

Source: Dr. Balaji Narasimhan, IIT Madras (2019)



Source: Dr. Balaji Narasimhan, IIT Madras (2019)

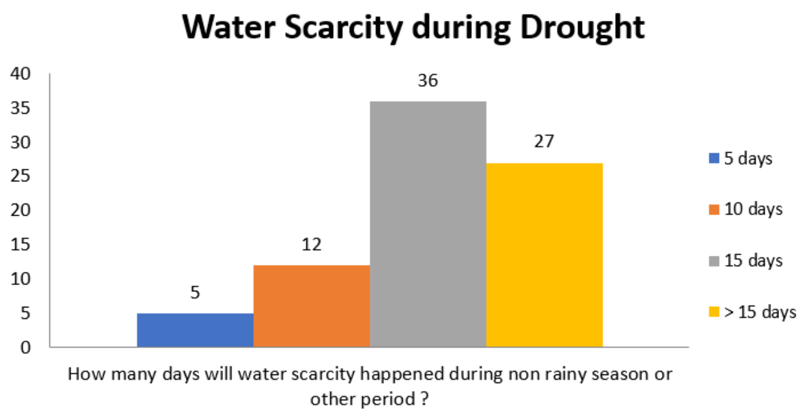
ANNEX I - HISTORICAL HOURLY RAINFALL DATA FROM 1971-2016 AT NUNGABAKKAM WEATHER STATION

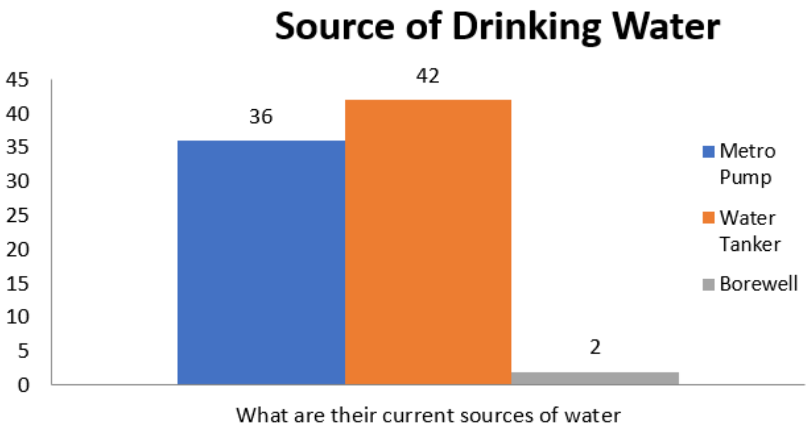
Source: IMD, 2019

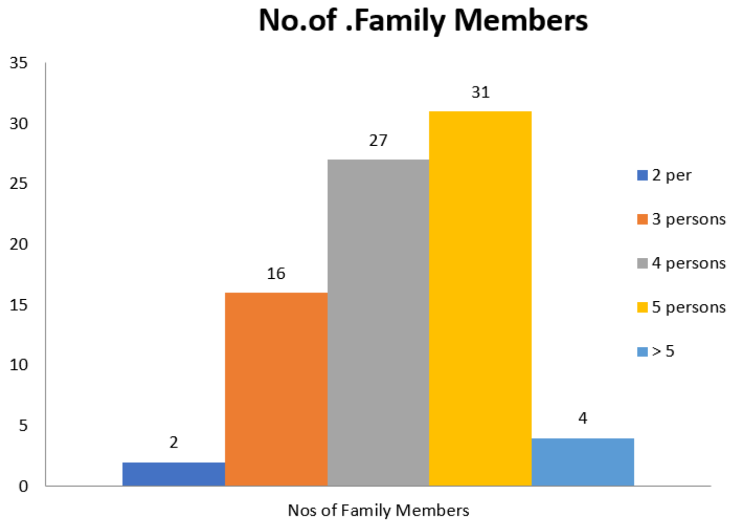
https://drive.google.com/file/d/15sWO6FgWMsPrdzuQHbGGdfU1dS-6NTZe/view?usp=sharing

ANNEX J - SURVEY WITH THE COMMUNITY

Source: Vulnerability Capacity Assessment Report, 2019

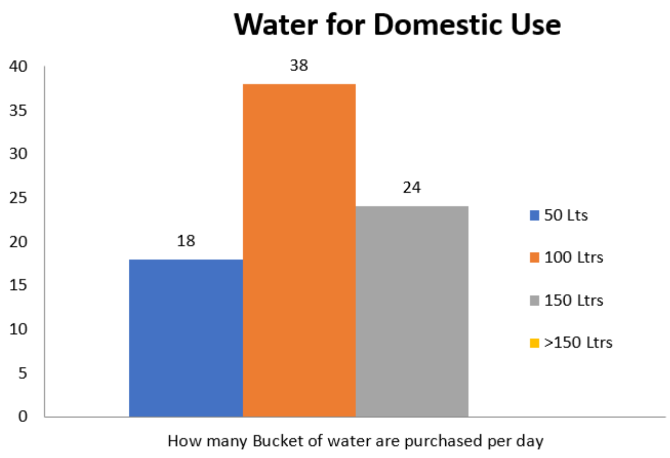


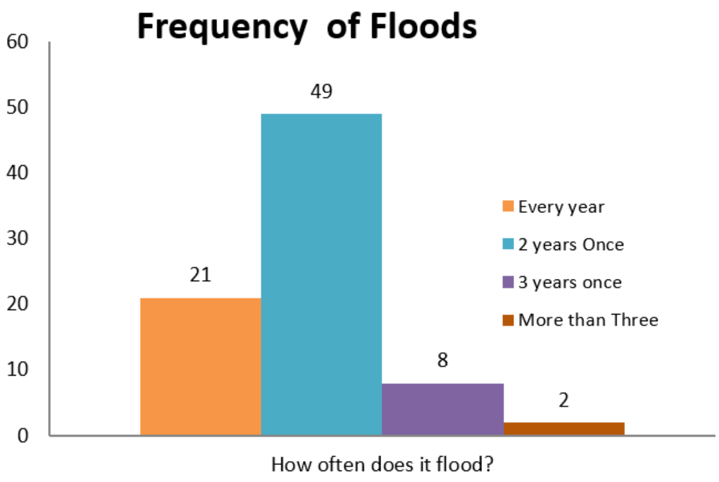




ANNEX J - CON'T

Source: Vulnerability Capacity Assessment Report, 2019

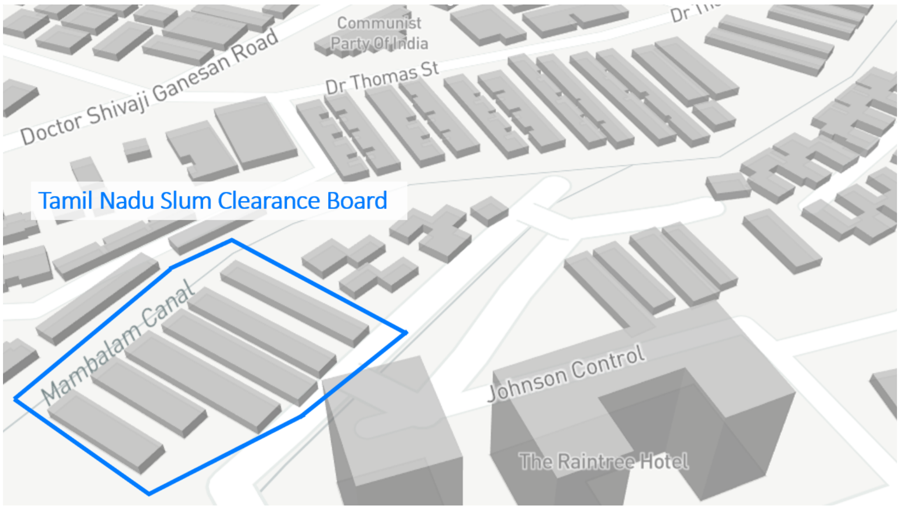


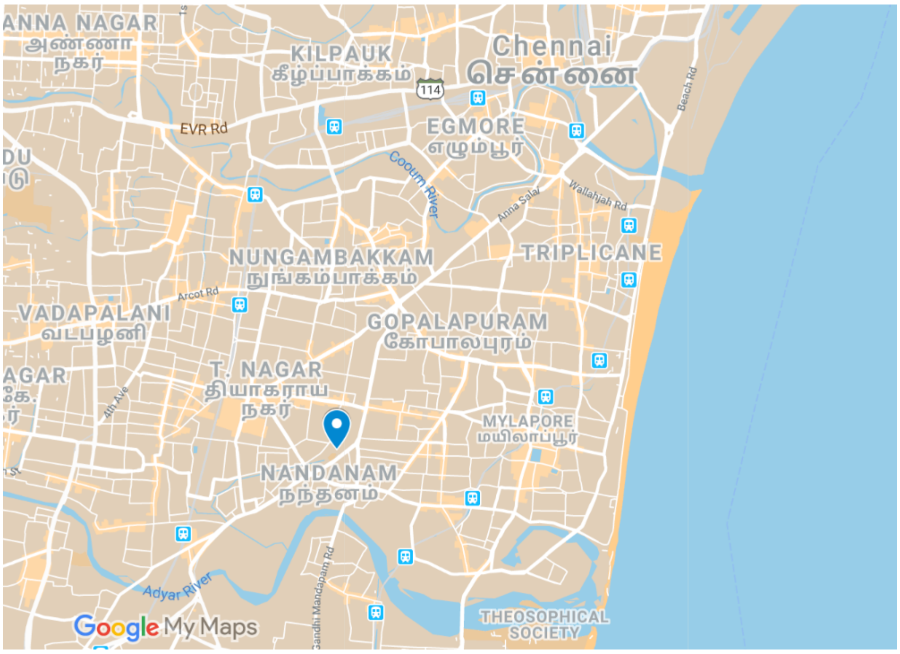


ANNEX K - LOCATION OF THE RESIDENTIAL BUILDINGS

Source: Google Maps, 2020

Tamil Nadu Slum Clearance Board residential building

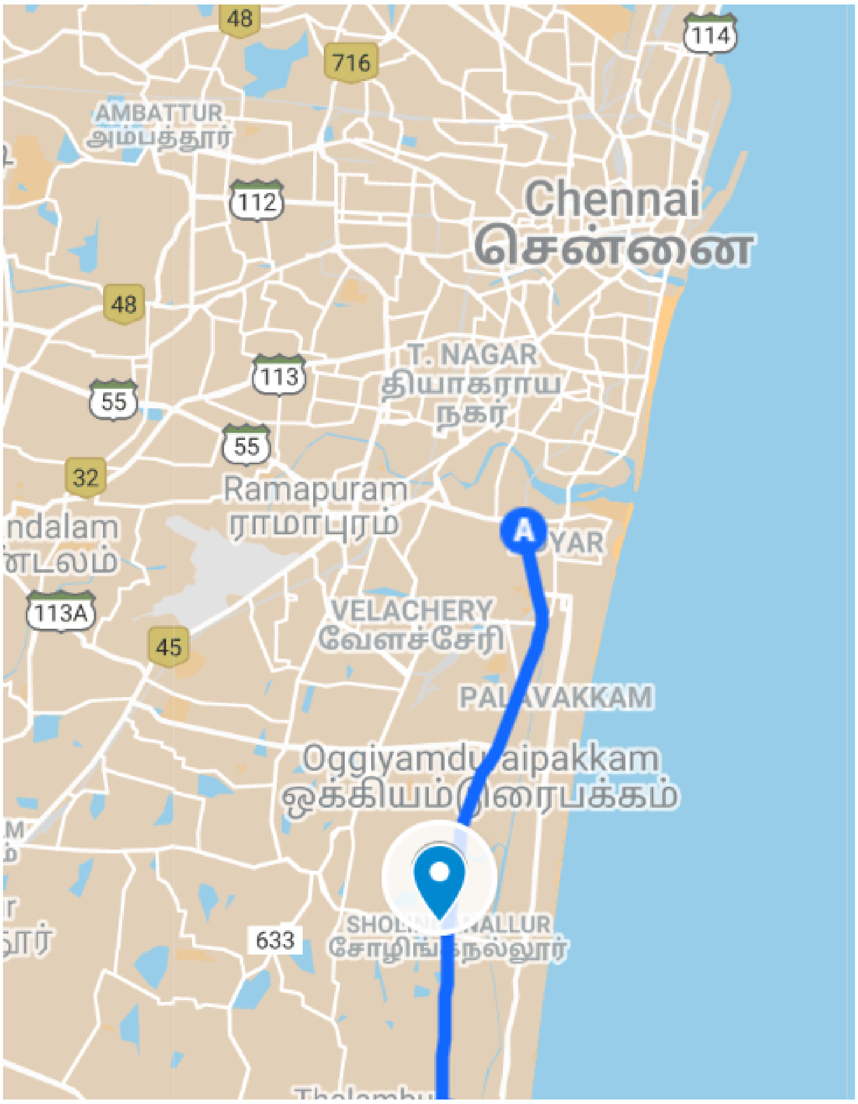




ANNEX K - CON'T

Source: Google Maps, 2020

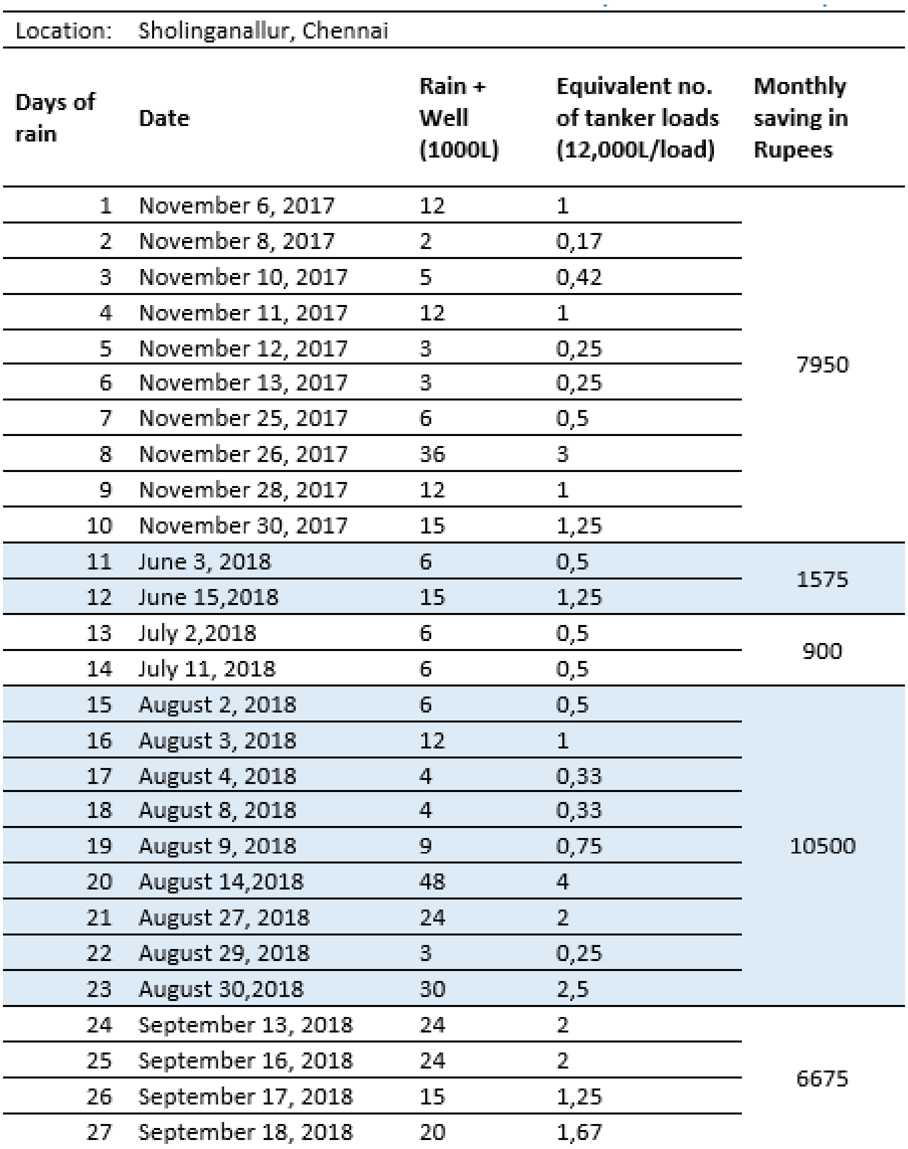
Sabari Terrace multi-story residential apartment complex, Shollinganallur, located along the Old Mahabalipuram Road, South of Chennai. The blue line is the OMR, or known as the IT Road, starting on Sardar Patel Road, south of Adyar River. The marker shows the location of Sabari Terrace.



ANNEX L - WATER DATA COLLECTED FROM SABARI TERRACE

Source: Data taken from the Secretary of Sabari Terrace residential apartment complex, February 2020

Only days with harvested rainwater from the rooftop are shown in the dataset below. The "rain + well" column is the total volume of water captured from 2500m2 of rooftop and stored into the two rainwater tanks, the sump, the open well and the recharge pit. The volume of daily rainwater collected was measured manually. With the known capacity of each storage and its dimensions, the depth of the rainwater was measured, then the volume of rainwater was calculated. Since the data are recorded manually, the volume of rainwater going to the recharge pit. The recorded data on days without rain represents the infiltration of rainwater water in the recharge pit into the open well.



Location: Sholinganallur, Chennai

Days of rain	Date	Rain + Well (1000L)	Equivalent no. of tanker loads (12,000L/load)	Monthly saving in Rupees
1	November 6, 2017	12	1	7950
2	November 8, 2017	2	0,17	
3	November 10, 2017	5	0,42	
4	November 11, 2017	12	1	
5	November 12, 2017	3	0,25	
6	November 13, 2017	3	0,25	
7	November 25, 2017	6	0,5	
8	November 26, 2017	36	3	
9	November 28, 2017	12	1	
10	November 30, 2017	15	1,25	
11	June 3, 2018	6	0,5	1575
12	June 15,2018	15	1,25	
13	July 2,2018	6	0,5	900
14	July 11, 2018	6	0,5	
15	August 2, 2018	6	0,5	10500
16	August 3, 2018	12	1	
17	August 4, 2018	4	0,33	
18	August 8, 2018	4	0,33	
19	August 9, 2018	9	0,75	
20	August 14,2018	48	4	
21	August 27, 2018	24	2	
22	August 29, 2018	3	0,25	
23	August 30,2018	30	2,5	
24	September 13, 2018	24	2	6675
25	September 16, 2018	24	2	
26	September 17, 2018	15	1,25	
27	September 18, 2018	20	1,67	

ANNEX L - CON'T

Source: Data taken from the Secretary of Sabari Terrace residential apartment complex, February 2020

28	September 29, 2018	6	0,5	
29	October 3, 2018	44	3,67	18150
30	October 4, 2018	44	3,67	
31	October 5, 2018	30	2,5	
32	October 18, 2018	30	2,5	
33	October 29, 2018	20	1,67	
34	October 30, 2018	24	2	
35	October 31, 2018	50	4,17	
36	November 15, 2018	20	1,67	10125
37	November 20, 2018	55	4,58	
38	November 21, 2018	36	3	
39	November 22, 2018	24	2	
40	December 3, 2018	48	4	3600
41	June 21, 2019	0,5	0,04	8385
42	June 22, 2019	30	2,5	
43	June 26, 2019	50	4,17	
44	July 10, 2019	12	1	24167
45	July 13, 2019	10	0,83	
46	July 15,2019	50	4,17	
47	July 21,2019	50	4,17	
48	July 23, 2019	12	1	
49	July 24, 2019	48	4	
50	July 25, 2019	50	4,17	
51	August 17,2019	24	24	17917
52	August 18,2019	24	24	
	August 19,2019	10	10	
53	August 20,2019	18	18	
	August 21,2019	12	12	
54	August 23, 2019	36	36	
	August 24, 2019	12	12	
	August 27, 2019	12	12	
55	August 28, 2019	25	25	
56	September 3, 2019	22	1,83	28438
	September 7, 2019	12	1	
	September 11, 2019	10	0,83	
57	September 13, 2019	38	3,17	
	September 17, 2019	12	1	
58	September 19, 2019	36	3	
	September 20, 2019	12	1	
59	September 22, 2019	42	3,5	
	September 23, 2019	12	1	
60	September 24, 2019	3	0,25	
61	September 25, 2019	24	2	
62	September 26, 2019	38	3,17	
	September 29, 2019	12	1	
	October 1, 2019	8	0,67	41875

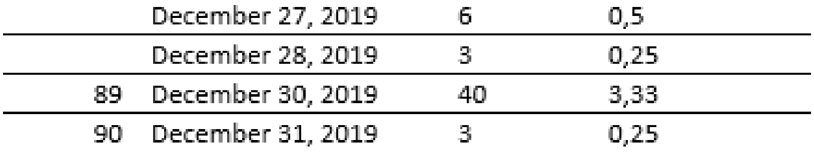
ANNEX L - CON'T

Source: Data taken from the Secretary of Sabari Terrace residential apartment complex, February 2020

	October 4, 2019	12	1	
	October 8, 2019	12	1	
	October 14, 2019	8	0,67	
63	October 17, 2019	56	4,67	
64	October 18, 2019	32	2,67	
65	October 19, 2019	18	1,5	
66	October 20, 2019	36	3	
67	October 21, 2019	56	4,67	
68	October 22, 2019	50	4,17	
	October 23, 2019	12	1	
	October 25, 2019	12	1	
69	October 28, 2019	30	2,5	
70	October 29, 2019	36	3	
71	October 30, 2019	24	2	
72	November 1, 2019	18	1,5	47604
	November 4, 2019	12	1	
	November 7, 2019	12	1	
	November 11, 2019	12	1	
73	November 15, 2019	41	3,42	
	November 18, 2019	12	1	
74	November 20, 2019	42	3,5	
75	November 21, 2019	24	2	
76	November 22, 2019	68	5,67	
77	November 23, 2019	38	3,17	
78	November 24, 2019	24	2	
	November 27, 2019	12	1	
79	November 28, 2019	68	5,67	
80	November 29, 2019	24	2	
81	November 30, 2019	50	4,17	
82	December 1, 2019	38	3,17	33646
83	December 2, 2019	36	3	
84	December 3, 2019	18	1,5	
	December 4, 2019	10	0,83	
	December 6, 2019	10	0,83	
85	December 7, 2019	20	1,67	
	December 8, 2019	12	1	
86	December 9, 2019	10	0,83	
	December 10, 2019	12	1	
	December 12, 2019	8	0,67	
87	December 13, 2019	30	2,5	
88	December 14, 2019	36	3	
	December 18, 2019	12	1	
	December 20, 2019	8	0,67	
	December 23, 2019	3	2,5	
	December 24, 2019	3	0,25	
	December 25, 2019	5	0,42	

ANNEX L - CON'T

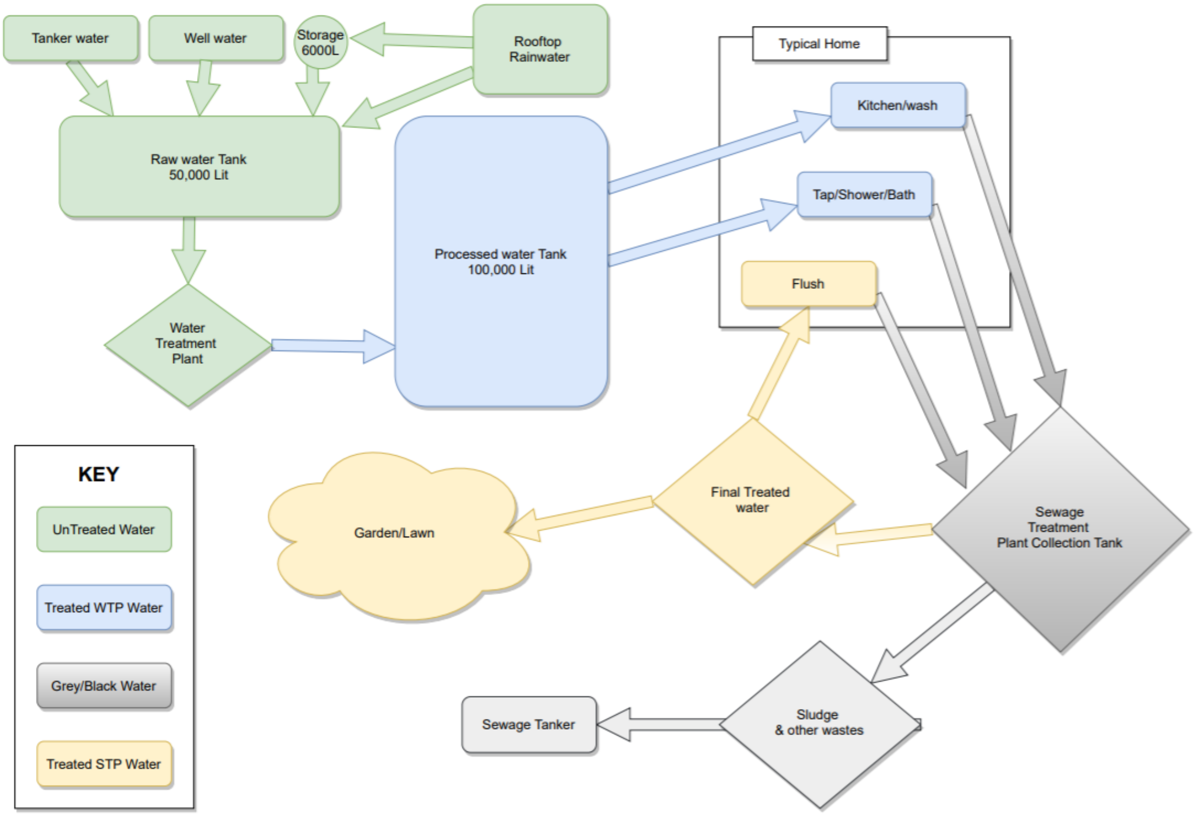
Source: Data taken from the Secretary of Sabari Terrace residential apartment complex, February 2020



	December 27, 2019	6	0,5
	December 28, 2019	3	0,25
89	December 30, 2019	40	3,33
90	December 31, 2019	3	0,25

ANNEX M - SCHEME OF THE WATER FLOW IN SABARI TERRACE

Source: Secretary of Sabari Terrace residential apartment complex, February 2020



ANNEX N - PHOTOS OF THE RRWH FOR WATER SUPPLY IN SABARI TERRACE APARTMENT COMPLEX

Source: Photos of the RRWH system in Sabari Terrace in Sholinganallur. The photos are: Community open well (top left), rainwater tank (top right), laying underground pipe (bottom left) and underground chambers of the pipe system (bottom right). Source: Photos taken by the author, February 2020, except for the bottom left photo taken by Harsha Koda

LET'S TALK
WATER