Optimizing storage tank size in rainwater harvesting (RWH) systems based on daily demand and supply matching

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ABSTRACT

Optimizing storage tank size in rainwater harvesting (RWH) systems based on daily demand and supply matching

Fangwei Pu

Under current published guidelines for Rainwater Harvesting (RWH) systems, sizing procedure for rainwater tanks is based on annual climate data, which might underestimate the performance of RWH system and lead to oversized tanks. The aim of this study is to promote compact sizing of RWH systems such that RWH systems could be deployable for more situations.

To effectively evaluate the optimal size of rainwater storage tanks, this study proposes to consider the matching of demand and supply on a daily basis. A performance evaluation method, based on daily climate conditions, is developed. The approach and its effectiveness are demonstrated by various water demand scenarios for residential buildings.

The comparison between fulfillment rates for RWH systems with rainwater tanks sized using the annual method and those sized using the daily method showed that the annual method may oversize rainwater storage tanks of RWH systems. The performance analysis with consideration of extreme climates illustrates the daily method can be adopted to size the tanks for extremely wet areas.

The scope of this study is limited residential buildings with a wide variety of water consumption patterns. The uncertainty of the sizing approach reduces for office buildings, where the water consumption is more predictable.

By adopting this method, oversized rainwater tanks and biased performance evaluation of RWH systems can be largely avoided, and more practical recommendations on RWH systems at initial design stage can be offered.

Acknowledgement

After several months of snow season, summer, which is my favorite time in Montreal, is finally on its way. I can still remember the summer three years ago, at which I first came to Montreal. It was a time filled with anticipation as well as some anxiety, and my supervisor Dr. Bruno Lee really gave me lots of confidence to strive in this new environment and always encouraged me to face challenges. He always listens attentively to the difficulties I meet and gives me a direction on how to solve it. During these years, what he provided me with was not only the methods to solve problems on specific projects but also ways of thinking and perspectives of consideration, which bring a lot of benefits to my research and will also guide me in my future career and life. Dr. Bruno Lee is the person who leads me to enjoy the beauties of research and joining his research group is one of my best decisions thus far. It's a united and supportive group, we are always willing to share ideas and opinions with each other, seeking common progress, and I learned a lot from my colleagues. It's my pleasure and fortune to work with such a great group of people.

It was a task for me to leave my family and live by myself. Fortunately, I am surrounded with great people, who help me a lot on my studies and life, and I am going to thank them in the order of our encounter. I must say 'thank you so much' to Tiantian Chen, she helped me even before I arrived, and we first met each other after a few days I came to Montreal. Since that, it seems that I have an elder sister who always stand with me. I would like to give my best wishes to her new born baby, growing up healthily and happily. Wen Ma really sets me a great example of attitudes

on life and research. I can still remember last time I moved apartments, Wen spent a lot of time to helping me and did so much, even though she was preparing her thesis and had much work that needed to be done at that time, she is really kind and helpful. Wen, I wish you all the best in U.S. I spent most of the free time with Li Ma (Mary) during the past few years, sharing happiness and sorrow with each other. I cannot image how can I spend those difficult time without the companionship of Mary. Thank you, Mary, for being my friend and being around. Angel Lam helps me a lot on my research and gave me many suggestions when I felt confused in studies. Every time I seek help from Angel, she is always patient and listens to every specific problem and helps me to solve these troubles. She is a great researcher and colleague. I would like to say thank you to Danlin Hou. She is an optimistic and loving life person, every second I spent with her let me feel energetic and cheered me up.

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Chapter 1 Introduction

1.1 Background

Water is essential for all living things, including humans, plants and even the Earth is majorly comprised of water. Due to its fundamental role and significant importance, new incremental supply projects are under construction every year to capture water for human use and consumption, which lead to irreversible ecological disruptions. With the development of technology, humans can obtain water from nature by many ways now. However, due to predatory exploitation and population growth, one out of every four large cities are facing water stress, which occurs when the quantity or quality of water demand cannot be satisfied (ARUP, 2015; EEA), and approximately 1/5 of the world's populations are living in areas of water scarcity (Calder, Hofer, Vermont, & Warren, 2008; Connor, 2015). Growing populations, changing climates, depleting groundwater and wasting water are part of factors driving the increase of water demand (Schleifer, 2017). Serious water issues occur not only in developing countries with rapid population growth or in areas with dry climates and limited water resources, but also in water-rich regions (Luo & Young, 2015). Although water-rich countries have sufficient water resources, it should be recognized that some usage habits are unreasonable. For example, using potable water from utilities for non-potable purposes such as irrigation, toilet flushing, laundry, etc. Imprudent use of resources should be avoided not only in water-scare areas but also in water-rich areas. The base problem being the availability of potable water and the solution for most water issues is finding how to protect potable water. In other words, finding ways to reduce unnecessary consumption of potable water, utilizing water from other sources instead of water utilities (Rodriguez et al., 2009) or reusing wastewater (Al-Jayyousi, 2003; Tarrass, Benjelloun, & Benjelloun, 2008) for non-potable purposes, such as washing machines, toilets and irrigation, are solutions which may alleviate current strain caused by water demand. Among the available alternatives, the application of Rainwater Harvesting (RWH) systems has attracted many researchers' attention in recent years. Ghisi, Montibeller and Schmidt (2006) investigated the potentiality of potable water savings by rainwater usage in southern Brazil; Aladenola and Adeboye (2010) assessed the potential for rainwater harvesting in Nigeria; Matos and team members (2013) defined the configuration for an RWH system of a commercial building located in the north of Portugal. Ndomba's group and Taffere's group did reliability analysis on RWH systems in Tanzania and Ethiopia separately, both these two countries are located in East Africa (Ndomba & Wambura, 2010; Taffere, Beyene, Vuai, Gasana, & Seleshi, 2016); Notaro, Liuzzo and Freni (2016) studied the performance of RWH system on water saving efficiency in Southern Italy;

The major benefits of rainwater harvesting are listed as follow:

- High potential on water saving of RWH systems is a major drive for the widely research on the utilization, storage, distribution of rainwater, not only in developing countries, which account for most of the water-scarce regions, but also in developed countries which may suffer effects of climate change on water availability (Coombes & Kuczera, 2003; Eroksuz, Rahman, & Recycling, 2010;

Fengtai & Xiaochao, 2012; Ghisi et al., 2006) .

- Due to the decrease of the quantity of potable water from water utilities, less water pipes and sewage systems are constructed, which lessen stress on infrastructure and further contribute to low environment impacts as well as the decrease of financial burden. Although water-rich countries do not need to worry about water deficit, the advantage of releasing stress on infrastructure is attractive.
- Recycled rainwater is mainly used for non-potable purpose, the quantity of these recycled rainwater can be lower than potable water, which means that less chemicals are needed for water treatment and can resolve sanitation problems in some extent. RWH systems can capture surface runoff and release runoff pollution such as high heavy metal concentrations (Förster & technology, 1996; Gromaire-Mertz, Garnaud, Gonzalez, Chebbo, & Technology, 1999; Sample & Liu, 2014; Zhang & Hu, 2014).
- Rainwater harvesting can also decrease energy consumption of buildings due to its cooling effects, and further mitigate heat island effects as well as global warming by reducing surface temperature(An, Lam, Hao, Morakinyo, & Furumai, 2015; Schmidt, 2009).

1.2 Problem statement and motivation

For RWH systems, the rainwater storage tank volume is designed mainly based on the amount of water demand, rainwater catchment area and local rainfall. Precipitation depth is a useful indicator to determine the rainfall rate and patterns. As a common practice, precipitation depth in most of the published guidelines is according to annual precipitation data. The concept for sizing a rainwater tank under annual precipitation data is that the RWH system stores rainwater for a whole year without considering consumption. The stored rainwater is then used to meet the above-mentioned needs; however, the remaining water is not accounted for in the following year and the cycle repeats. Using annual precipitation data is a conservative way to decide rainwater storage tank volume, because it assumes that there is no input of precipitation data in a whole year, which may result in oversizing the storage tank in RWH systems.

Although, in some extent, larger rainwater volume helps to increase efficiency of RWH systems (CMHC, 2012), oversized rainwater tanks may lead to high investment and maintenance costs, large occupied areas, sanitary problems and more. Matos's group (2013) also showed that, before reaching the maximum efficiency of the RWH system, larger storage volumes after a certain point the efficiency improves in a much-reduced rate.

1.3 Objectives and scopes

The objectives of this study are:

- To identify the potential issues in existing sizing approaches for RWH systems in published guidelines.
- To investigate the matching of daily water demand with rainwater supply of RWH

systems.

- To get the optimal size of rainwater tank by assessing the performance of RWH systems in terms of demand and supply matching.
- To offer practical design recommendations for sizing of RWH systems in terms of building-related factors.
- To demonstrate the effectiveness of the recommended sizing approaches with consideration of extreme rainfall situations.

The scope of this study:

- The amount of water demand in this case refers only to that used for toilet flushing and washing machines in the residential buildings (BREEAM, 2018). If rainwater is intended to be used for other equipment, higher water quality by rainwater cleaning techniques may be necessary.
- Extreme rainfall situations include a) frequent rainfall with higher precipitation depth and b) highly uneven rainfall distribution with lower precipitation depth.

Chapter 2 Literature review

2.1 Application of rainwater harvesting systems

Main components of a rainwater harvesting (RWH) system are collection surface, guttering system and storage part (Thomas, 1998). Rainwater can be collected from rooftops, road surface, rock catchments or other impervious surfaces, and stored for later use, or utilizing check dams, which is a more complex technology to retain water flow for districts (Appan, 1999; Ibrahim, 2009; Pelak & Porporato, 2016). After being collected by the collection surface, rainwater goes through the gutter system. Because the pollutants in the surroundings and the type of roofs can also affect the quality of the run-off from it, the gutter system includes not only gutters but flush and filtration devices as well (Silva, Sousa, Carvalho, & Recycling, 2015; Thomas, 1998). When the treatment process is finished, rainwater will be delivered to the storage system, such as storage tanks or cisterns, which are connected to the water end uses. Pumps are optional depending on the available water pressure.

The application range of rainwater harvesting is wide, it may be applied from large scales, such as rural applications, (Campisano et al., 2017; Ibrahim, 2009; Kisakye, Akurut, & Van der Bruggen, 2018; Zhang, Hu, Chen, & Xu, 2012) to commercial buildings (Chilton, Maidment, Marriott, Francis, & Tobias, 2000; Matos et al., 2013), to smaller scales such as a residential building, also known as domestic rainwater harvesting (DRWH) (Kahinda, Taigbenu, & Boroto, 2007). Among such a wide application, collected rainwater is mainly used for non-potable purposes, such as irrigation, pavement washing, cloth washing and toilet flushing. High water quality by water treatment technologies, such as solar collector disinfection, are needed to minimize health risks if recycled rainwater is supplied for potable purposes due to contamination (M. Amin & M. Han, 2009; M. T. Amin & M. Han, 2009; Gwenzi et al., 2015; Nawaz, Han, Kim, Manzoor, & Amin, 2012).

2.2 Different aspects in evaluating the harvesting performance of RWH systems

The assessment on the performance of rainwater harvesting focuses mostly on the water saving potential of these systems, from single construction, to large-scale projects, such as cities (Ghisi et al., 2006) and countries (Nolde, 2007). Table 2-1 lists a review of some of previous studies on RWH for different scales. Domestic rainwater harvesting systems mainly adapt roofs as rainwater collection surfaces, while some researchers also investigated using roads or courtyards to collect rainwater (Fengtai & Xiaochao, 2012; Nolde, 2007) . In these selected studies, a majority of the research scopes focus on individual residential buildings, while Hashim et al. linked residential buildings into a community and studied rainwater harvesting under a neighborhood scale (Hashim, Hudzori, Yusop, & Ho, 2013). Besides residential buildings, other build types such as stadiums (Zaizen, Urakawa, Matsumoto, & Takai, 2000) and petrol stations (Ghisi, da Fonseca Tavares, & Rocha, 2009) were also considered to be served by RWH systems. In addition to the performance on potable water savings, cost effectiveness is another major consideration for rainwater harvesting. In most cases in table 2.1, there is a high potential for potable water savings while the investment is not always feasible, or considered only as “partly cost efficient”, which may depend on climate situations and regional practices, as is the case for the studied cases in Brazil (Ghisi et al., 2009). In Australia, Tam, Tam and Zeng (2010) found that reusing rainwater is an economic option for households located in Gold Coast, Brisbane, and Sydney due to greater rainfall patterns compared to other cities. In China, analysis results show that large size RWH systems are financially feasible when being applied to agricultural irrigation in the rural areas of Beijing (Liang & van Dijk, 2011).

Besides the environmental benefit and economic benefits from potable water saving, the ability of RWH systems on reducing surface runoff has arouse researchers’ interests in recent years. Zhang and Hu (2014) estimated the potential of collectable rainwater by using rainwater harvesting in an industrial park located in in southeastern China, and they found that 58% -100% (depending on the depth of daily rainfall) of runoff volume can be reduced by storing rainwater in the cisterns. Sample and Liu (2014) estimated and optimized RWH systems for various case buildings, including commercial buildings and residential buildings with different occupant densities, located in different areas within Virginia for improving the performance of water supply and runoff capture reliability. The optimization results in their study show that runoff capture reliability of the studied RWH systems came up to 85% and even the lowest runoff capture reliability also reached 38%. Campisano Liberto, Modica and Reitano (2014) evaluated the potential of RWH systems on reducing runoff flow peak for households in southern

Italy, and simulation results show that, by using tank-based RWH systems, there is a notable reduction of runoff peak, between 30% and 65%, depending on the size of rainwater tanks and water demand situations of the experimental households, for more than half of the rainfall events.

Table 2-1 Previous studies on rainwater harvesting evaluations (water saving)

Reference	Scope	Collection surfaces	Water end uses	Water saving potential	Energy consumption	Runoff capture ability	Cost effectiveness
(Zaizen et al., 2000)	Three dome stadiums in Japan	Roofs	Toilet flushing and irrigation	59%		78%	Yes
(Ghisi et al., 2006)	Residential sector in 62 cities in Santa Catarina, southern Brazil	Roofs	Data obtained from the water utility for the period 2000–2002	34% to 92%			
(Nolde, 2007)	Germany	Roofs, courtyards and a one-way street with low traffic density.	Toilet flushing	70%	0.88 kWh/m^3 for treatment and distribution		
(Ghisi et al., 2009)	Petrol stations located in Brasília, Brazil.	Roofs	Washing vehicles	Average water savings: 32.7%, and can be as high as about 70%			Partly yes
(Eroksuz et al., 2010)	Newcastle, Sydney and Wollongong in Australia	Roofs	Toilet flushing, laundry, hot water, irrigation	21% to 57% (can even achieve 100% if the catchment area is large enough)			

(continued)

(Fengtai & Xiaochao, 2012)	Handan, china	Road rainwater collection and utilization; Roof rainwater collection and utilization	Garden irrigating, the tap water of residents' flushing and cleaning	40%			Yes
(Mehrabadi, Saghafian, & Fashi, 2013)	Residential buildings in three climate areas in Iran	roofs	Non-potable purposes	23% -70% of time to supply at least 75% of non-potable water demand			Yes
(Hashim et al., 2013),	A community of 200 houses in Malaysia	Roofs	Cleaning, gardening and toilet flushing.	58%			Yes
(Palla, Gnecco, & La Barbera, 2017)	Residential buildings in Genoa, Italy	Roofs	Toilet flushing	76%-83%			

2.3 Sizing approaches for rainwater tanks

Published RWH system guidelines, such as (CMHC, 2012; Department of Environmental Health, 2011; Despins, 2010a, 2010b; EA, 2010; NWC, 2008; RDN, 2012) all provide recommended rainwater storage tank volume based on amount of water demand, catchment area and climate data. Canada design guide (CMHC, 2012) recommends two methods for rainwater tank sizing: rainwater harvesting design tool and rainwater tank sizing table which vary between provinces. UK Environment Agency (EA, 2010) provides an equation which includes annual rainfall depth, effective collection area, drainage coefficient and filter efficiency for determining the rainwater storage tank volume.

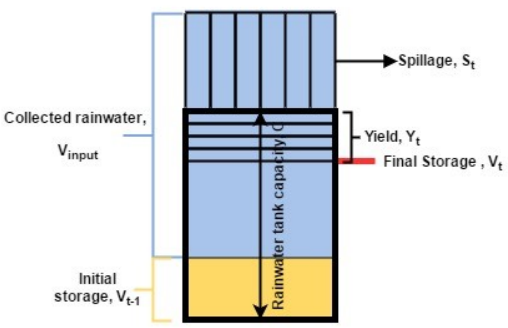
2.4 Optimization approaches applied to the sizing of RWH systems

Many methods and models have been proposed for the initial design stage of RWH systems. Okoye, Solyalı and Akıntuğ (2015) adopted a linear programming approach for a single residential housing unit to determine the optimal rainwater storage tank volume for rainwater harvesting and storage while Sample and Liu (2014) used a lifecycle cost-benefit model and a nonlinear metaheuristic algorithm to optimize RWH systems considering water supply reliability as well as runoff capture. Bocanegra-Martínez (2014) presented an optimization-based model, which aims for cost-efficiency and water saving, for the utilization, storage as well as distribution of rainwater, and implemented it into a residential development in Morelia, Mexico. In 2015, an analyses model called Plugrisost was developed, and this model can analyses the optimal design variables, cost and environmental performance of RWH systems, and made comparisons between Plugrisost model and other models, including Aquacycle and RainCycle (Morales-Pinzón, Rieradevall, Gasol, & Gabarrell, 2015). Santos and Taveira-Pinto (2013) analyzed six different methods for sizing rainwater tanks, including two simplified procedures which were presented in German technical specifications(ANQIP, 2009) and DIN standard on RWH systems (DIN, 1989), 100% Efficiency method, 80% Efficiency method, Maximum Rainwater Used method and Rippl method, and concluded that, compared to other methods in the study, the 80% Efficiency method is the optimal way to size rainwater tanks due to the best ratio between economic savings and installation cost.

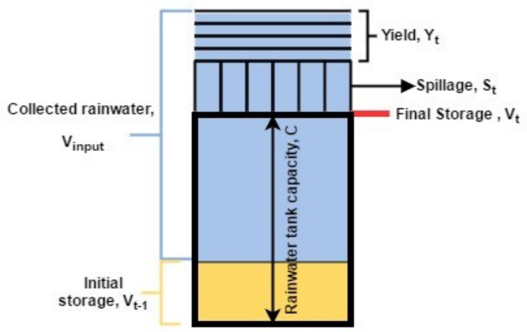
The development of water balance situations, especially those based on daily water situations, is notable in the past ten years. Imteaz and team members (2011) adopted a water balance model, which is based on daily rainfall data in three different climatic regimes in Melbourne, Australia, to evaluate the effevtiveness of RWH system during wet years, dry years and average years. Next year, Imteaz's team (2012) used the climate date of a typical dry year (1998) in southwest Nigeria as a background to analyze the performance of RWH systems on water saving under two water demand scearios and design water tank according to a spreadsheet-based daily water balance model. By comparing the analysis results from this model with the results from another model using monthly average rainfall data. They found that rainwater storage tank volume based on monthly average rainfall data is larger than the required rainwater storage tank volume. Karim, Rimi and Billah (2015) analyzed the reliability of RWH systems for different scenarios under three climate conditions (dry, average and wet years) based on the water balance model to discover the optimal rainwater storage tank volume of the RWH systems serving for a typical six members family. Some research teams utilized the daily water balance model to evaluate the performance of RWH systems under climate change (Haque, Rahman and Samali, 2016; Musayev, Burgess, & Mellor, 2018; Youn, Chung, Kang, & Sung, 2012).

2.5 Accounting methods for RWH systems

There are two approaches to describe the accounting methods of rainwater harvesting systems, namely YAS (yield after spillage) and YBS (yield before spillage), and the difference between these two accounting methods is the order of the consideration on using rainwater to meeting water demand and the consideration on rainwater outflow. Figure 2.1 shows the sequence of YAS and YBS accounting methods.



(a)



(b)

Figure 2.1 (a) Sequence of yield-after-spillage (YAS) accounting method; (b) Sequence of yield-before-spillage (YBS) accounting method. (1)

A number of researchers have investigated the influence of the algorithms in the accounting methods on the performance of RWH systems. Jenkins and Pearson (1978) laid the foundation of analysis of RWH systems and they used the YAS algorithm on monthly-based interval to investigate the feasibility of rainwater harvesting systems in California and found that this application is feasible for domestic use and recommended for rural areas. Based on the YAS accounting method, Fewkes (1999) described the results from field testing for a rainwater collector installed in a U.K. house. Sensitivity analysis was conducted and the results reflected that daily data can be used to accurately predict system performance, while hourly data is not necessary. Fewkes and Butler (1999) sized rainwater tanks and investigated the relative accuracy of accounting methods for different demand fractions and storage fractions through hourly, daily, and monthly time steps under YAS as well as YBS.

(1) The graphs are inspired by the studies of Mitchell (2007) and Schiller and Latham (1987)

They found that YAS accounting method is more conservative and under evaluates the amount of water provided by the rainwater harvesting system, while YBS accounting method over estimates the amount of rainwater yield. As a result, they recommended the use of the YAS algorithm in preference to YBS algorithm. Mitchell (2017) investigated the impact of time step, accounting method, initial storage level, and the length of simulation period on the accuracy of the storage–yield–reliability relationship. In terms of accounting method, their studies demonstrated that, compared to YBS accounting method, evaluations by YAS accounting method are less sensitive to variations in storage as well as demand fraction, and can provide a more conservative performance evaluation for RWH systems.

Although YAS accounting method is widely used due to its conservativity, YBS algorithm is preferred under some specific situations. Liaw and Tsai (2004) investigated the optimal combination of roof area and rainwater storage capacity in Taiwan and conducted sensitive analysis on a rainwater tank within five-time intervals, including one, three, five, seven and 10 days. They found that RWH systems with small rainwater storage tank volume should better be analyzed under a short time interval and YBS accounting method is recommended when the RWH system's rainwater storage tank volume is small and the storage capacity is usually smaller than the water demand.

Chapter 3 Investigation workflow

In this thesis, an investigation workflow has been developed to support the sizing of rainwater collection tank. The key is to optimally size the tank based on a demand supply matching approach. Demand profile includes the amount of daily water demand, which is determined by the situations of case buildings, such as occupant behaviors on daily individual water demand, occupant density, building floor area, etc. Supply profile mainly includes the amount of roof-collected rainwater in a day, which is determined by precipitation depth, catchment area and runoff coefficient of the collection surface. The demand profile, supply profile as well as the rainwater tank capacity are inputs of the Python-based daily water balance model. With this model, daily water balance situations of a scenario can be developed and exported to an excel file for the calculation of fulfillment rate. After analyzing on the relationship between the fulfillment rate and rainwater storage tank volume, optimal rainwater tank size of the RWH system can be obtained.

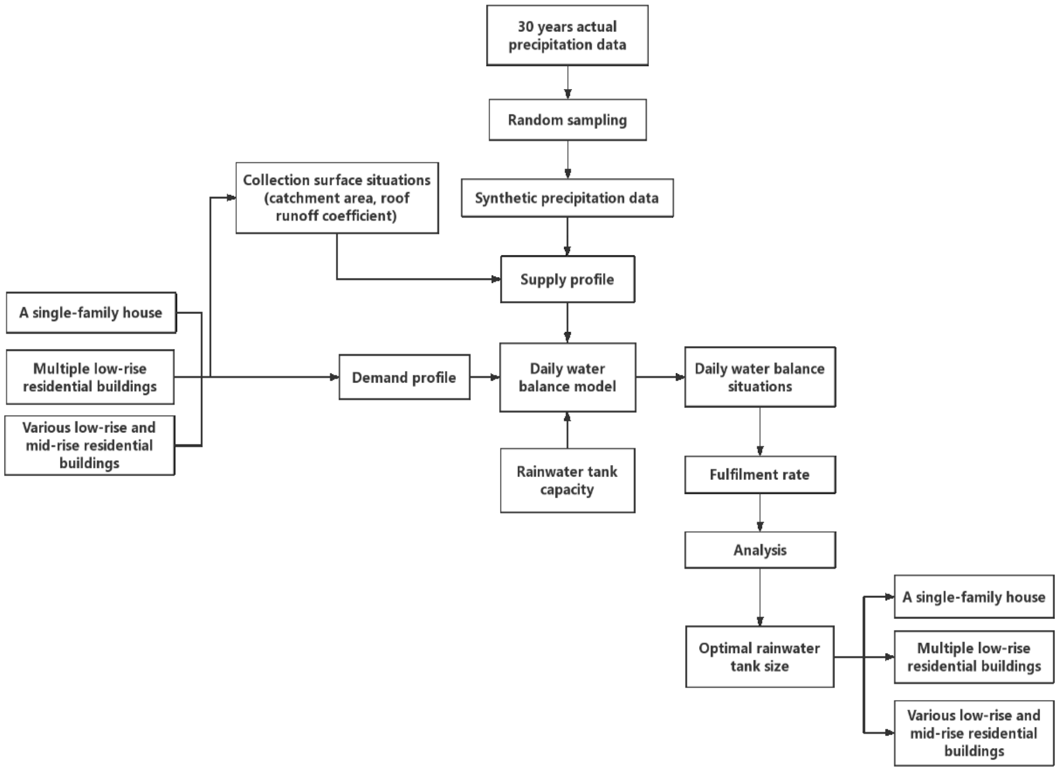


Figure 3.1 The breakdown of the study

3.1 Collection surface situations on catchment area and runoff coefficient

When using whole roof to collect rainwater, the size of the catchment area is based on the "footprint" of the roof (TAMA, 2018). Figure 3.2 shows as a demonstration on roof footprint.

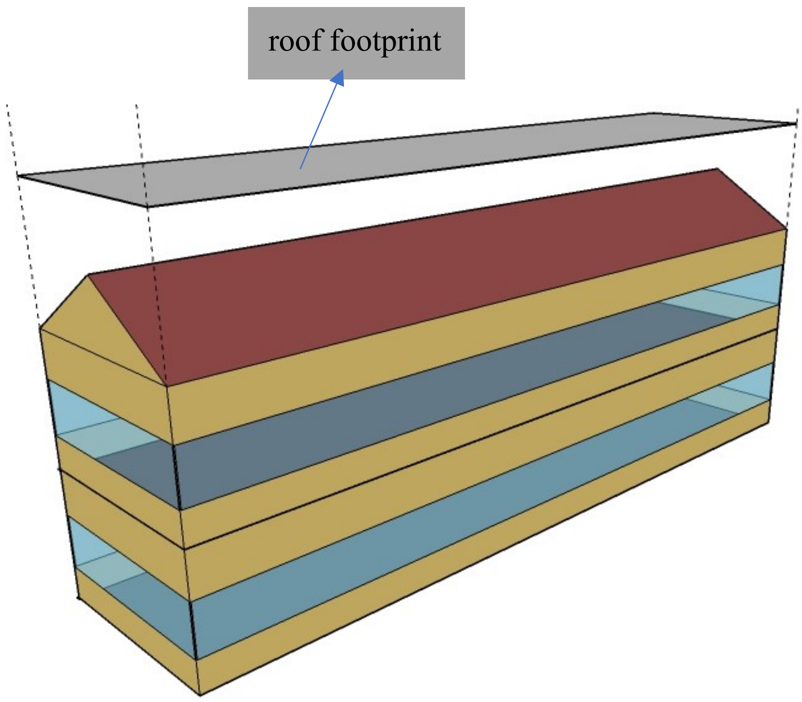


Figure 3.2 A demonstration on roof footprint

Roof materials and slope should not be ignored due to their significant effects on the roof runoff coefficient (non-dimensional) (Farreny et al., 2011; Lancaster, 2006). In this thesis, unless explicitly noted, material of building roof was assumed as asphalt to follow the common practice in Canada, and runoff coefficient was assumed as 0.8 (Farreny et al., 2011; Lancaster, 2006; Leggett, 2001)

3.2 Procurement of precipitation data by random sampling

Daily precipitation data of an area can be acquired from official websites or documents, and generally, data for more than 10 years instead of only one year are preferable, which let each single day in year has more than one precipitation depth. Based on this situation, Python is introduced to pick a value randomly from multiple values of precipitation.

3.3 Calculation of the amount of rainwater collected by roof

Ghisi et al. (2016) presented the formula, as shown in Equation 3-1, for calculating the volume of rainwater that can be collected by roof surface during a given period, which was determined by rainfall conditions, catchment area and roof runoff coefficient.

$$V_{input} = \frac{A_{catchment} \times P_{daily} \times c_{roof}}{1000} \qquad 3\text{-}1$$

Where V_{input} (m^3) is the amount of rainwater that can be collected by roof during the, $A_{catchment}$ (m^2) is the size of RWH system's catchment area, P_{daily} (mm) is the daily precipitation depth, which is determined by the historical daily precipitation data of the studied location, and c_{roof} is the roof runoff coefficient which was explained above.

3.4 Daily water balance model

YAS (yield-after-spillage) accounting method, which is a more conservative algorithm compared to YBS (yield-before-spillage), was chosen as the accounting method for RWH systems and used to discover daily water balance situations of studied scenarios. Concrete explanations on YAS and YBS accounting methods and comparisons between fulfillment rate under YAS and YBS and are presented in Appendix A. A python-based daily water balance model was developed under the consideration of daily precipitation depth, catchment area, runoff coefficient, rainwater storage tank volume as well as water demand situations.

The total amount of collected rainwater, which is determined by Equation 3-1, and initial storage of rainwater at the beginning of the day, which is represented by V_{t-1} (m^3) and determined by the remaining rainwater at the end of the previous day, contributes to the potential-available volume of rainwater $V_{potential}$ (m^3), as shown in Equation 3-2. Following the recommendation of (Mitchell, 2007), the initial storage at the first day is zero.

$$V_{potential} = V_{input} + V_{t-1} \qquad 3\text{-}2$$

Then, the amount of potential-available rainwater needs to be compared with rainwater tank capacity C (m^3) in order to determine the volume of rainwater that can actually be available $V_{available}$ (m^3), as shown in the following equation.

$$V_{available} = \begin{cases} C, & if\ V_{potential} > C \\ V_{potential}, & if V_{potential} \leq C \end{cases} \qquad 3\text{-}3$$

If the available rainwater $V_{available}$ (m^3) is more than the amount of rainwater demand V_{demand} (m^3), the RWH system can meet the needs. Otherwise, the deficit needs to be made up by other water resources. The comparison between available rainwater and water demand is the process to determine the rainwater yield Y_t (m^3) , the amount of final stored rainwater in the tank V_t (m^3) and the amount of make-up water from other water resources $V_{make-up}$ (m^3) (shown in Equation 3-4).

$$If\ V_{available} > V_{demand}, \begin{cases} Y_t = V_{demand} \\ V_t = V_{available} - V_{demand} \\ V_{make-up} = 0 \end{cases}$$

$$If\ V_{available} \leq V_{demand}, \begin{cases} Y_t = V_{available} \\ V_t = 0 \\ V_{make-up} = -(V_{available} - V_{demand}) \end{cases} \quad 3\text{-}4$$

Workflow of the daily water balance model is shown below and all the results will be eventually exported into an excel file.

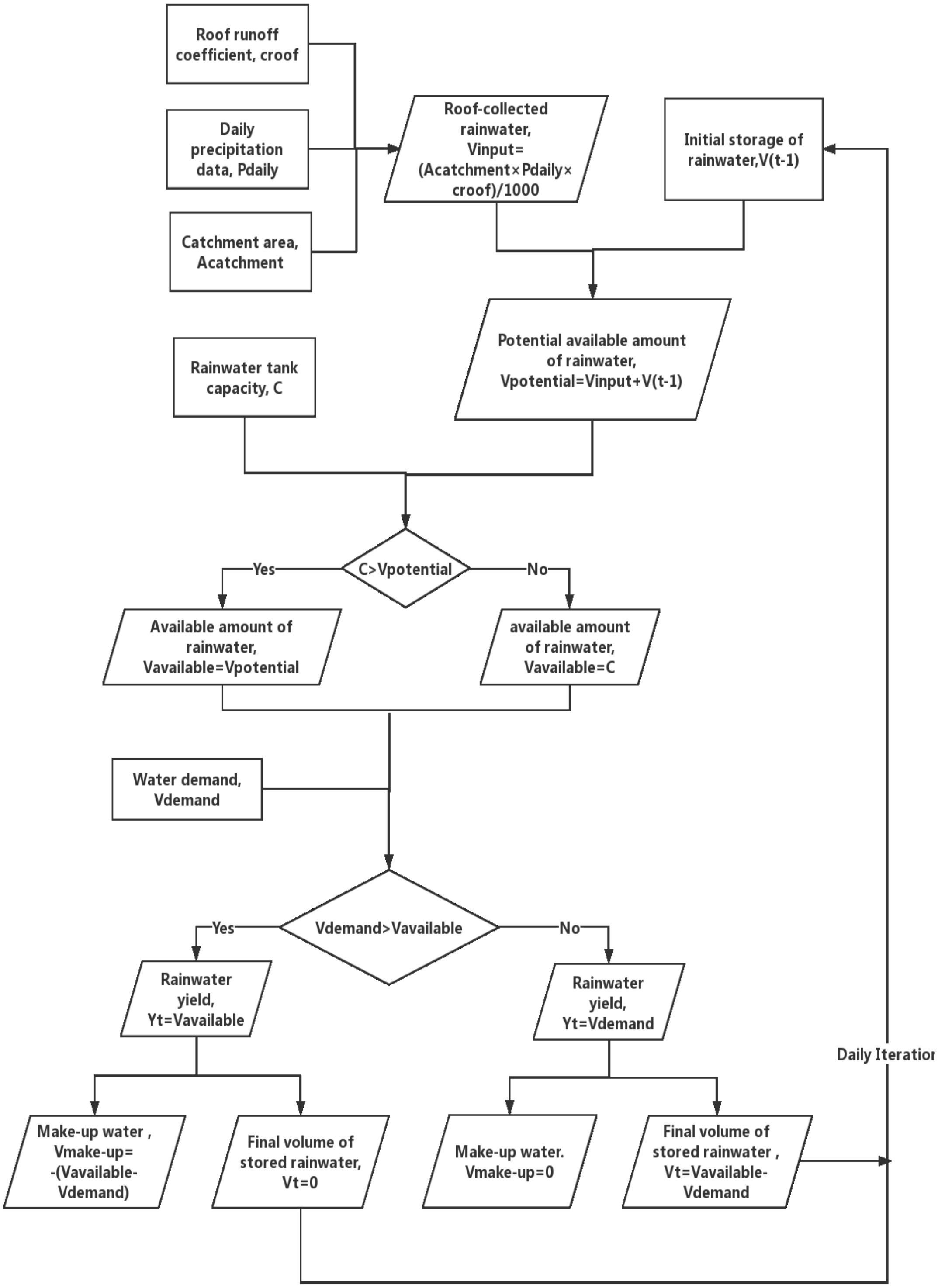


Figure 3.3 Workflow of the daily water balance model

3.5 Fulfillment rate of RWH systems

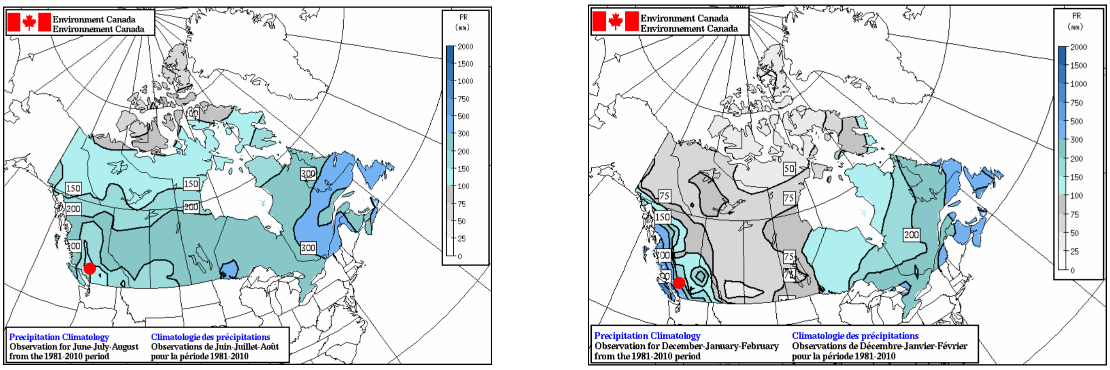
The performance of a rainwater harvesting system can be evaluated by the system's fulfillment rate, which was defined by the following equation:

$$FR = \frac{\sum Y_t}{\sum V_{demand}} \times 100\% = 1 - \frac{\sum_{i=1}^{T} V_{make-up}}{\sum_{i=1}^{T} V_{demand}} \times 100\% \qquad 3\text{-}5$$

Where FR is the RWH system's fulfillment rate (%), which can be adopted to any period, such as a day, a week or a year; Y_t (m^3) is the amount of rainwater yield by the RWH system to satisfy water demand of occupants, $V_{make-up}$ (m^3) is the amount of water resources; V_{demand} (m^3) is the amount of water demand of all the occupants; T represents the length of the period, and this study was on a daily basis.

Chapter 4 Case studies: a single-family house

Figure 4.1 show two precipitation climatology maps of Canada in summer (June-July-August) and winter (October- November- December), which were observed from 1981 to 2010 (Environment, 2010) .



(a) (b)

Figure 4.1 Precipitation climatology maps of Canada
(a) Summer
(b) Winter

Due to the relative high precipitation depth, which could be benefit to RWH systems, Vancouver, British Columbia, Canada, shown in red in Figure 4.1, was chosen as the location of the case study. The case building is a two-story residential house located in the Hyde Creek in the neighborhood of Burke Mountain, Vancouver (Figure 4.2), namely Case A. The total floor area is 220 m^2, including three bedrooms. The roof is used as rainwater collector for the RWH system of this house.

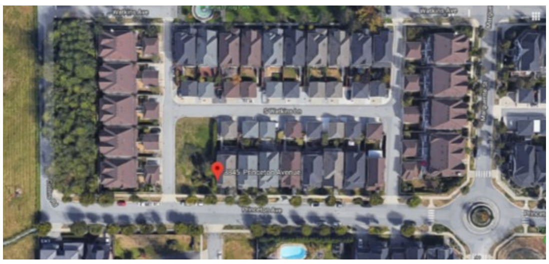


Figure 4.2 Case residential house
(source: https://www.polyhomes.com/)

4.1 Demand side considerations for RWH systems

The number of occupants can simply depend on the number of bedrooms. There are three bedrooms in this house, thereby the assumption on the number of occupants is four, a couple with two children and 90 L/day/person was used as their individual daily water demand for toilet flushing and washing machines (DeOreo, Mayer, Dziegielewski, Kiefer, & Foundation, 2016).

4.2 Supply side considerations for RWH systems

4.2.1 Procurement of precipitation data

As a basis of RWH system design, precipitation situations vary with regions. For Vancouver, real daily precipitation data in each day during 30 years were provided by Environment and Climate Change Canada (ECCC,2008). By random selection, the adopted values are shown in the following figure, which shows obvious seasonal differences of precipitation. 171mm and 500.7mm are the total precipitation depth of summer (June-July-August) and winter (October- November- December) separately, which evidently shows that winter is the rainiest season in Vancouver.

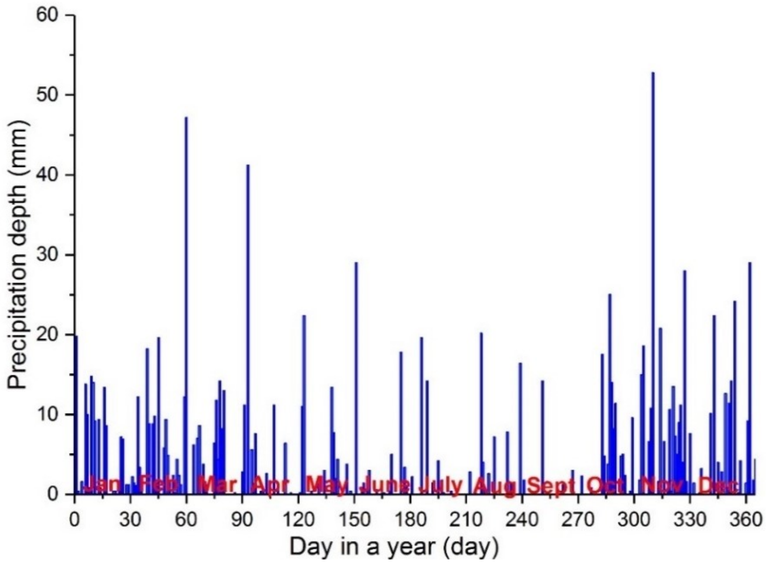


Figure 4.3 Daily precipitation depth of Vancouver

4.2.2 Catchment area and roof runoff coefficient

Utilized roof area in this case study is shown in the Figure 4.4, contributing to 120 m^2 catchment area of the RWH system. Runoff coefficient was assumed as 0.8 which has been explained in Chapter 3.

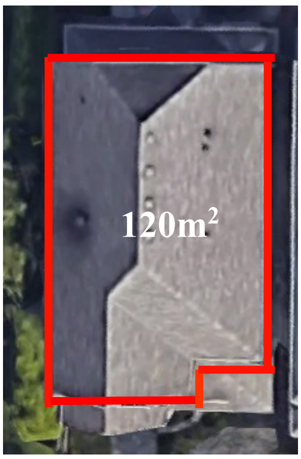


Figure 4.4 Catchment area of the RWH system for the case building

4.3 Daily water balance situations

Daily rainwater surplus or deficiency situations for the case building under different rainwater storage tank volumes can be acquired by the daily water balance model. As a demonstration, Table 4-1 shows several days' daily water balance situations when the case building is served by $0.5m^3$ rainwater storage tank volume. For the full table of 365 days' daily water balance situations, please refer to Appendix B.

Table 4-1 Daily water balance situations for the case building
(Rainwater storage tank volume = $0.5m^3$)

Day in a year	Initial storage (V_{t-1}) (m^3)	Roof-collected rainwater (V_{input}) (m^3)	Potential-available rainwater ($V_{potential}$) (m^3)	Actual-available rainwater after spillage ($V_{available}$) (m^3)	Rainwater yield (Y_t) (m^3)	Final stored rainwater (V_t) /Make-up water ($V_{make-up}$) (m^3)
1	0	0.52	0.52	0.5	0.36	0.14
2	0.14	0.5	0.64	0.5	0.36	0.14
……						
179	0	0.11	0.11	0.11	0.11	-0.25
180	0	0.07	0.07	0.07	0.07	-0.29
……						
364	0.14	0.54	0.68	0.5	0.36	0.14
365	0.14	0.36	0.5	0.5	0.36	0.14

4.4 Relationship between fulfillment rate and rainwater storage tank volume of the RWH system applying to the case building

The relationship of the fulfillment rate of the RWH system and rainwater storage tank volume is shown in Figure 4.5. The slowdown appears on the upward trend of fulfillment rate after using 0.8 m^3 rainwater tank. When the rainwater storage tank volume is 0.8 m^3, fulfillment rate of the RWH system is around 73%, after that, until utilizing a 12 m^3 rainwater storage tank volume, the RWH system's fulfillment rate is still lower than 80 % without significant rise.

Two sizing approaches were defined in this study: AP (Annual Precipitation) method and DP (Daily Precipitation) method. Canadian guidelines for RWH systems (CMHC, 2012) was referred as an example of sizing rainwater tanks by AP method. For a studied scenario, a DP-based fulfillment rate curve showing the relationships between fulfillment rate (DP-based fulfillment rate) and rainwater storage tank volume was developed. A guideline-recommended rainwater storage tank volume was recommended by the handbook under AP method, which is indicated on the DP-based fulfillment rate curve. Then, the corresponding fulfillment rate of this guideline-recommended rainwater storage tank volume was shown on the curve. This corresponding fulfillment was DP-based fulfillment rate of the system with guideline-recommended rainwater storage tank volume, rather than the guideline-expected fulfillment rate (AP-based fulfillment rate) for this guideline-recommended rainwater storage tank volume in the handbook.

Besides the optimal rainwater storage tank volume attributed using the DP method, a guideline-recommended rainwater storage tank volume, 6 m^3, was provided by Canadian guidelines (CMHC, 2012), which is represented by the black triangle in

Figure 4.5, and the corresponding fulfillment rate of the guideline-recommended rainwater storage tank volume is around 75%. Compared to fulfilment rate of the RWH system with the DP method-generated optimal rainwater storage tank volume (0.8 m^3), 2% increase at the expense of 7.5 times rainwater storage tank volume, which reflects that AP method used in the published handbook underestimates fulfillment rate and result to an oversized rainwater tank.

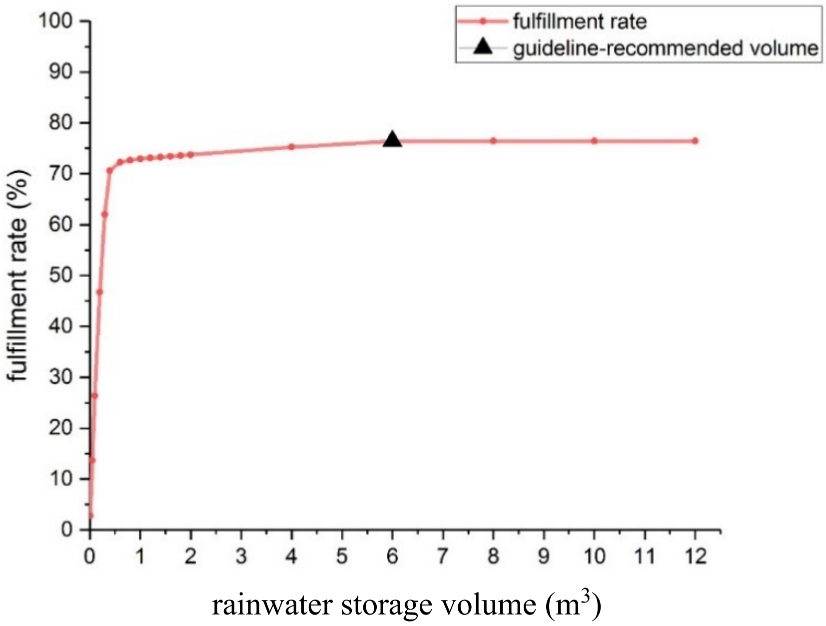


Figure 4.5 Relationship of the fulfillment rate and rainwater storage tank volume of the RWH system for the case building

Rainfall in Vancouver is predictable and even, while RWH systems might be used in some areas with extreme rainfall situations. Please refer to Appendix C for the comparisons of fulfillment rate of RWH systems for the areas with extreme rainfall situations and the area with predictable rainfall situations, and the study of the effectiveness of daily precipitation method (DP method) under extreme climates.

Chapter 5 Case studies: low-rise and mid-rise residential buildings

5.1 Low-rise residential building water demand scenarios

Based on Case A in the chapter above and under the same daily precipitation data of Vancouver, this section includes multiple low-rise residential buildings with different water demand scenarios. The characteristics of these case studies are presented in Table 5-1.

Table 5-1 Multiple low-rise residential buildings with different water demand scenarios

Scenario	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Number of building story	1		2						3					
Catchment area (m^2)	100	150	50	100	150	200	250	300	50	100	150	200	250	300
Daily water demand (L/day/person)	90													
Occupant density [a,b] (person/m^2)	0.03													

[a] Residential End Uses of Water, Version 2

[b] ANSI/ASHRAE Standard 62.2-2016. Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings.

The fulfillment rate curves for each selected scenario are shown in Figure 5.1. curves are divided into three groups and the scenarios in each group have the same ratio of daily water demand to catchment area. The ratio of daily water demand to catchment area of the scenarios is represented by yellow-serial curves, red-serial curves and blue-serial curves which represent 2 $L/day/m^2_{catchment}$, 4 $L/day/m^2_{catchment}$ and 6 $L/day/m^2_{catchment}$ respectively. With the same rainwater storage tank volume, water demand scenarios with lower ratio of daily water demand to catchment area have higher fulfillment rate.

In terms of a single curve, turning points appear on every fulfillment rate curve, and the values of fulfillment rate have no significant rise after the turning points, which reflects that enlarging rainwater tanks to pursue higher fulfillment rate is unavailing. Due to the slow rise rate of fulfillment rate after the turning points, a 100% fulfillment rate is difficult to be achieved or achieved by a large rainwater tank, which may not be suitable for residential buildings due to costs, maintenance, aesthetics, etc.

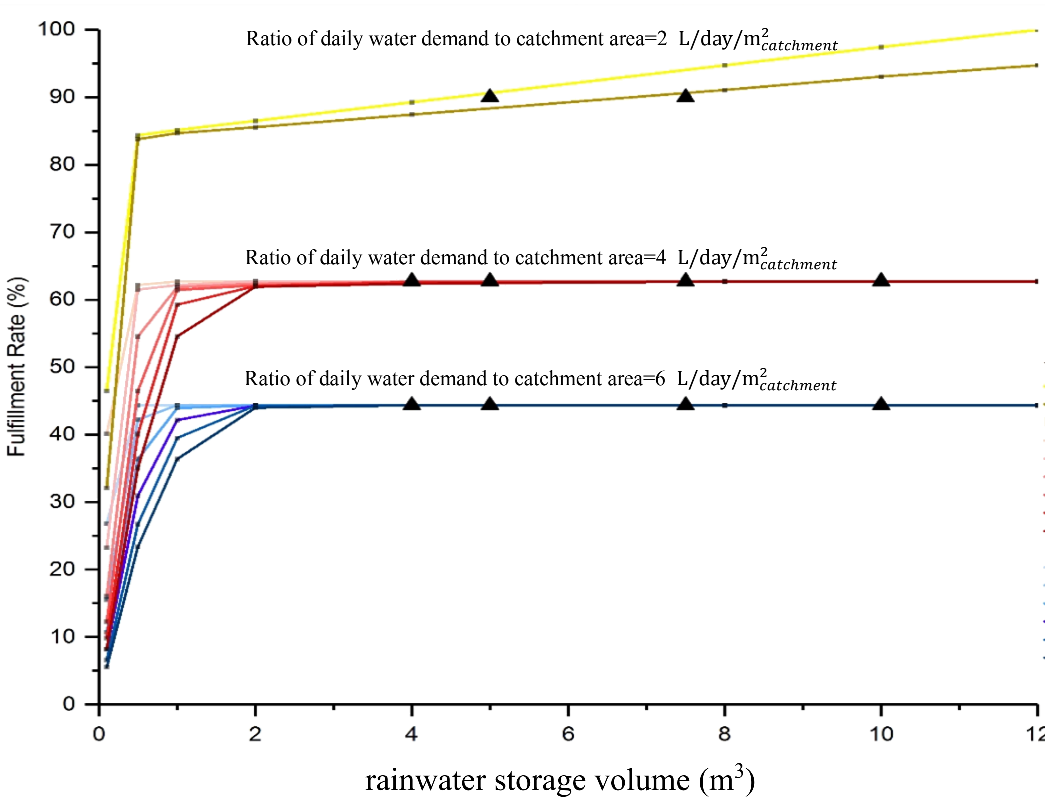


Figure 5.1 Relationship between fulfillment rate and rainwater storage tank volume for the scenarios of low-rise residential buildings.
Triangles represent guideline-recommended rainwater storage tank volume

Black triangles in Figure 5.1. show guideline-recommended rainwater storage tank volume for each water demand scenario, some triangles are overlapped. After positioning these guideline-recommended volumes on the curves, their corresponding DP-based fulfillment rate can be acquired. It can be noted that, when adopting fulfillment rate as a performance indicator, these guideline-recommended volumes are all oversized. Taking scenario of the lightest red curve as an example. The fulfillment rate of the RWH system with guideline-recommended rainwater storage tank volume (4 m^3) is about 63%; However, the DP-based fulfillment rate curve shows that 0.5 m^3 rainwater tank can already contribute to the same fulfillment rate (63%). In other words, RHW systems' fulfillment rate are underestimated when sizing its rainwater tank by AP method. Other scenarios show the same situation of unreasonable matching between rainwater storage tank volume and fulfillment rate.

5.2 General residential building water demand scenarios

The scope of this section is extended from low-rise to mid-rise residential buildings with more complex situations. the considered constraints included rainwater storage tank volume, catchment area, amount of daily water demand as well as the number of building stories.

5.2.1 Water demand calculation

According to the recommendation by Technical Specification ANQIP (ANQIP, 2009), the amount of individual daily rainwater demand for toilet flushing and washing machines can be calculated by the modified Equation 5-1.

$$V = T \times V_T \qquad 5\text{-}1$$

Where V (L/day) is the amount of water used for the water end use in a day, T is the daily use frequency of the water end use and its unit is decided by the type of use, V_T is the unitary amount of water used for end use and its unit is decided by the type of use. Table 5-2 was referred to determine the daily use frequency and the unitary amount of water use for toilet flushing and washing machines

Table 5-2 Daily water situations of toilet flushing and washing machines

Type of use	Units	Range of values
Frequency of toilet flushing [a, b, c]	Flushes/person/day	4-8
Flushing values [a, b]	L/flush	6-23
Washing machine use [a, b]	Loads/person/day	0.2-0.5
Volume of water [a, b]	L/cycle	170-190

[a] EPA Water Conservation Plan Guidelines. Appendix B Benchmark used in conservation planning.

[b] International Water consumption data table: Wastewater Gardens Information Sheet

[c] Toilets | Home Water Works. (2019). Retrieved from https://www.home-water-works.org/indoor-use/toilets

The calculated amount of individual daily rainwater demand for toilet flushing and washing machines was determined to be 58 and 279 L/day/person. According to the survey published by Water Research Foundation (DeOreo et al, 2016) based on 23,749 homes' billing data in North America, average daily indoor per person water uses on toilets and washing machines were approximately 54 L/person/day and 36 L/person/day separately, contributing to the individual daily water demand of 90L/day/person. Based on the calculated results and survey, the amount of individual daily rainwater demand was studied in the range of 50-120 L/day/person with an increment of 10 L/day/person.

As a summary, Table 5-3 presents the values and ranges of the considered constraints on the performance of RWH systems in water demand scenarios. Among these studied variables, rainwater storage tank volume is the only design parameter, while all other listed variables are building-related factors.

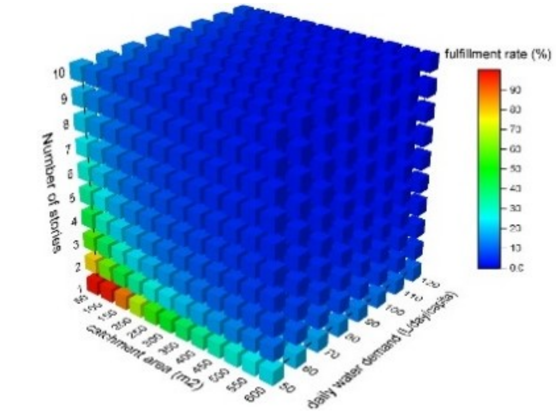
Table 5-3 Studied constraints on the performance of RWH systems

	Range /Value	Increment	Level of investigation
Catchment area (m^2)	50-600	50	12
Number of stories	1-10	1	10
Individual daily water demand (L/day/person)	50-120	10	8
Rainwater storage tank volume (m^3)	0.2-12	0.2	60
Climate background	Vancouver (Vancouver International Airport)		
Occupant density [a,b] (person/m^2)	0.03		
Roof runoff coefficient	0.8		

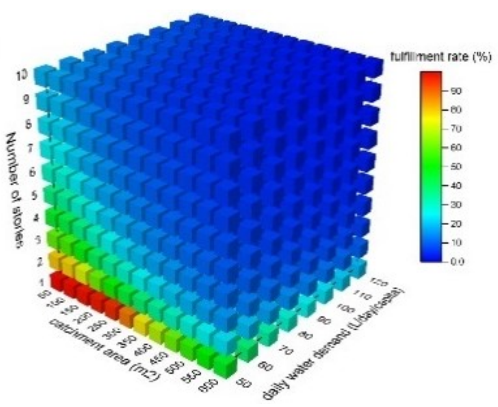
[a] Residential End Uses of Water, Version 2

[b] ANSI/ASHRAE Standard 62.2-2016. Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings.

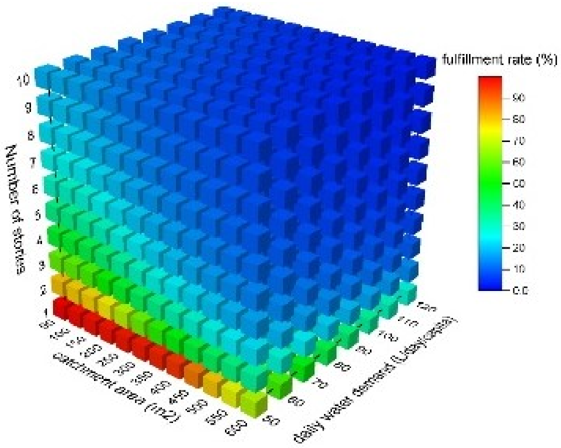
5.2.2 Performance of RWH system on fulfillment rate for studied water demand scenarios



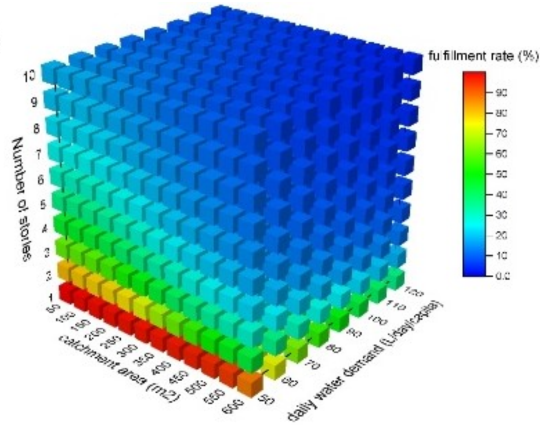
(a)



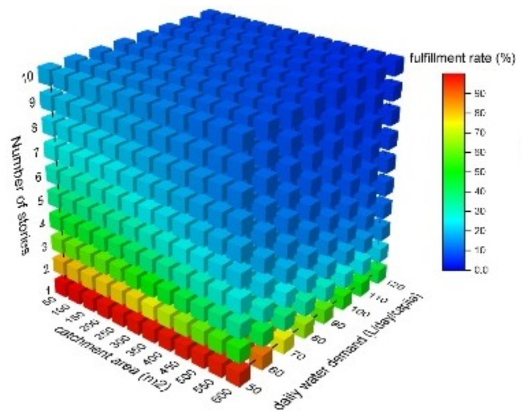
(b)



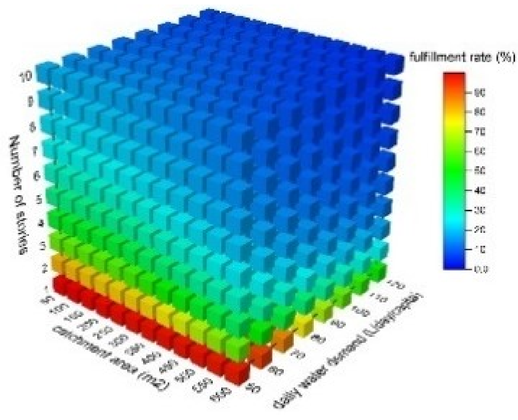
(c)



(d)



(e)



(f)

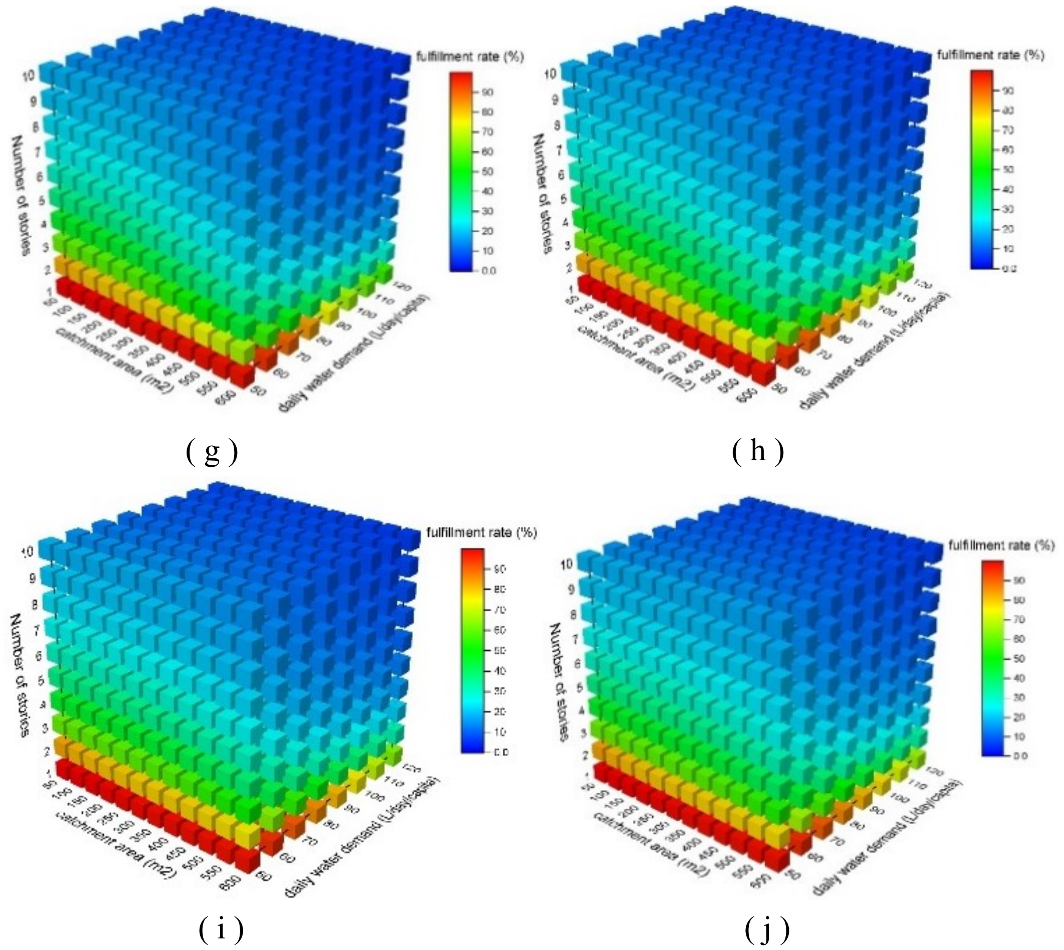


Figure 5.2 Voxel plot of fulfillment rate with respect to the constraints.
(Color bars show the level of fulfillment rate (%))
(a) Rainwater storage tank volume=0.2 m^3. (b) Rainwater storage tank volume=0.4 m^3.
(c) Rainwater storage tank volume=0.6 m^3. (d) Rainwater storage tank volume=0.8 m^3.
(e) Rainwater storage tank volume=1.0 m^3. (f) Rainwater storage tank volume=1.2 m^3.
(g) Rainwater storage tank volume=1.4 m^3. (h) Rainwater storage tank volume=1.6 m^3.
(i) Rainwater storage tank volume=1.8 m^3. (j) Rainwater storage tank volume=2.0 m^3.

Figure5.2 shows fulfillment rate with respect to catchment area, individual daily water demand and number of building stories under different rainwater storage tank volumes between 0.2 and 2 m^3 with an increment of 0.2 m^3.

In terms of the RWH systems with a given rainwater storage tank volume, sub-figures show notable effects of catchment area, number of building stories as well as daily water demand on fulfillment rate of RWH system. Difficulties for RWH systems to achieve a high fulfillment rate become obvious when increasing any of these three factors, especially under a small size of rainwater tank.

Taken together, it can be noticed that, with the increase of rainwater storage tank volume, more scenarios can achieve a relatively high value of fulfillment rate, while the colors of voxel plots have no obvious changes after 0.8 m^3 (e), which means under the background and assumptions in this study, the values of fulfillment rate for each scenario become stable when applying a 0.8 m^3 rainwater tank, and larger rainwater tanks are useless for improving the performance of RWH systems on fulfillment rate. This situation reflects that although increase rainwater storage tank volume can increase RWH fulfillment rate, simply using a larger rainwater tank is meaningless because of the limiting factors such as rainfall conditions. Because voxel plots become more and more similar, Figure 5.2 only presents the results for RWH systems with up to 2 m^3 rainwater tanks.

5.2.3 Ratio of daily water demand to catchment area

Although 0.8 m^3 has already been demonstrated as the optimal rainwater storage tank volume in this study, there are still some scenarios with fulfillment rate lower than the satisfying level (80%) (Figure 5.3), which reflects that besides rainwater storage tank volume, the joint action of other constraints, which are shown in Table 5-4, result to negative effects on fulfillment rate.

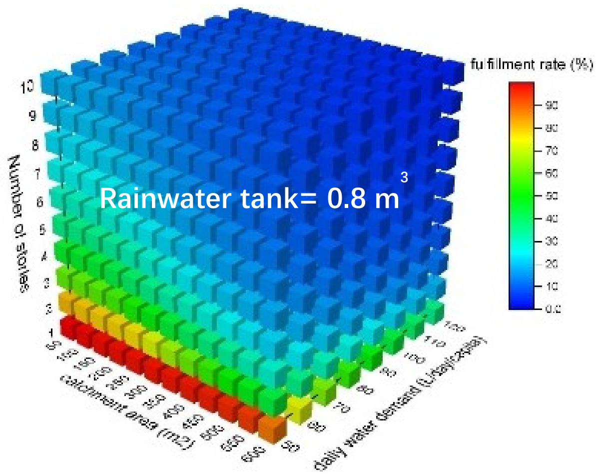


Figure 5.3 Voxel plot of fulfillment rate with respect to the constraints. (Rainwater storage tank volume=0.8 m^3) Color bars show the level of fulfillment rate (%)

Table 5-4 Constraints contributing to the fulfillment rate of 0.8 m^3 tank scenarios

Constrain	Range (Value)
Catchment area (m^2)	50-600
Number of building story	1-10
Individual daily water demand (L/day/person)	50-120
Occupant density (person/m^2)	0.03

In order to investigate the effects of these constraints on the fulfillment rate, daily water demand intensity and floor-catchment ratio was introduced, and the definition of these two terms are shown as Equation 5-2 and 5-3.

$$Daily\ water\ demand\ intensity\left(L/day/m^2_{floor}\right) = individual\ daily\ water\ demand\ (L/day/person) \times occupant\ density\left(person/m^2\right) \quad (5\text{-}2)$$

$$Floor - catchment\ ratio\left(m^2_{floor}/m^2_{catchment}\right) = \frac{area\ of\ each\ floor\ (m^2) \times number\ of\ building\ story}{catchment\ area\ (m^2)} \quad (5\text{-}3)$$

Individual daily water demand and occupant density in Equation 5-2 were based on survey and standard, so that daily water demand intensity can be considered as a certain value for a certain location. By contrast, area of each floor, number of building story and catchment area vary from building to building. The ratio between daily water demand intensity $(L/day/m^2_{floor})$ and floor-catchment ratio $(m^2_{floor}/m^2_{catchment})$ was used in order to better consider the effects of both of these parameters, the result is the ratio of daily water demand to catchment area $(L/day/m^2_{catchment})$.

Curves of the relationships between fulfillment rate and the ratio of daily water demand to catchment area for 0.8 m^3 rainwater tank are shown in Figure 5.4. For all studied catchment area, higher amount of daily water demand results to lower fulfillment rate, and $3L/day/m^2_{catchment}$ is the upper limit ratio of daily water demand to catchment area for the satisfying fulfillment rate.

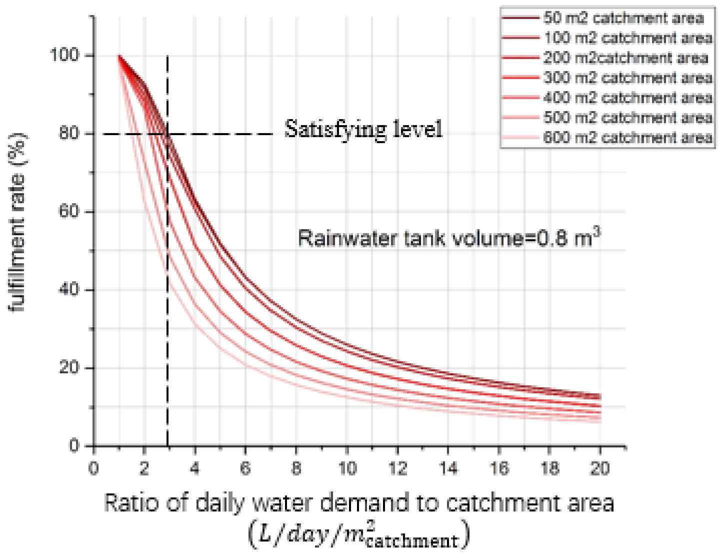


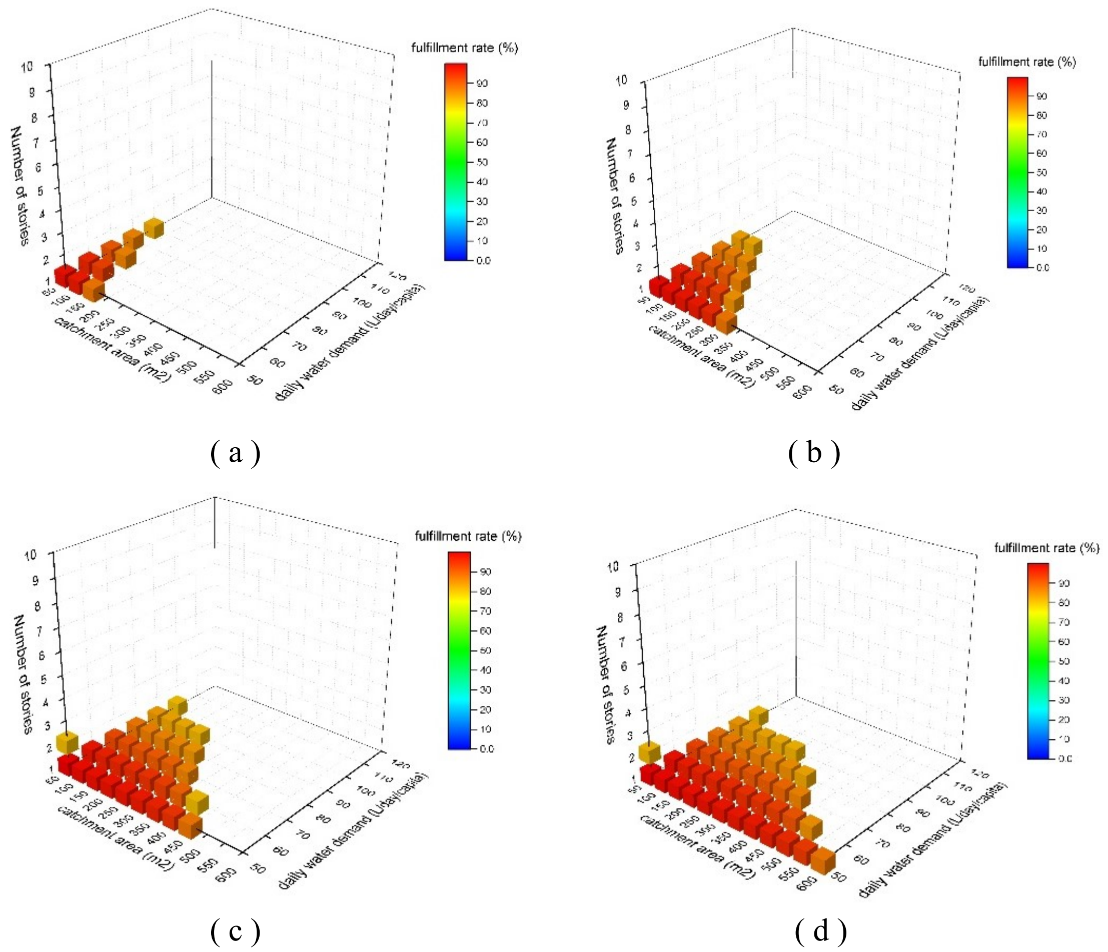
Figure 5.4 Relationship between fulfillment rate and the ratio of daily water demand to catchment area (Rainwater storage tank volume=0.8 m^3)

One of the assumptions for residential buildings, in this study, is that the area of each floor was taken to equal the roof's footprint, namely catchment area. While in reality, for residential buildings, the area of each floor is usually smaller than roof footprint due to roof overhangs. For this reason, real ratio of daily water demand to catchment area is usually lower than the theorical ratio, causing the fulfillment rate curves to be lower than the generated curves in the above figure, which strengthens the conclusion that the ratio of daily water demand to catchment area should be lower than 3 L/day/m^2 in order to satisfy the fulfillment rate.

5.2.4 Satisfying level of fulfillment rate

Following the conclusions and recommendations by (Santos & Taveira-Pinto, 2013), in this study, if a RWH system's fulfillment rate equals to or higher than 80%, this RWH system can be considered as having satisfied the fulfillment rate requirement, scenarios that reach this level are shown in Figure 5.5. As the rainwater storage tank volume increases, the number of overall scenarios deemed satisfactory increases as well but at a decreasing rate. Columns in Figure 5.6 show the number of satisfying scenarios under different rainwater storage tank volumes. If considering the increase of rainwater storage tank volume from 0.2 m^3 to 2 m^3 as a complete process, it can be noticed that during the earlier stage, the number of satisfying scenarios significantly increases if larger rainwater tanks are utilized. However, during the later phase, the number of satisfying scenarios tend to be stable. For example, when replacing the 1.0 m^3 rainwater tank with a 2.0 m^3 rainwater tank, 13 more satisfactory scenarios occur, at the expense of twice rainwater storage tank volume, which is negative for the economy and environment.

Another nonnegligible finding is that most of the scenarios with satisfying fulfillment rate occur in the low-rise building scenarios (number of building stories between 1 and 3). The total number of studied scenarios is 960, including 288 low-rise building scenarios, and Table 5-5 presents the number and the percentage of satisfying scenarios for all cases, resulting in two curves presented in Figure 5.6. The curve of the percentage in low-rise building scenarios is always higher, and the gap between these two curves become wider when applying larger rainwater tanks, which reflects the potential of utilizing RWH systems in low-rise buildings. A similarity between these two curves is that their upward trend is slowed with the increase of rainwater storage tank volume.



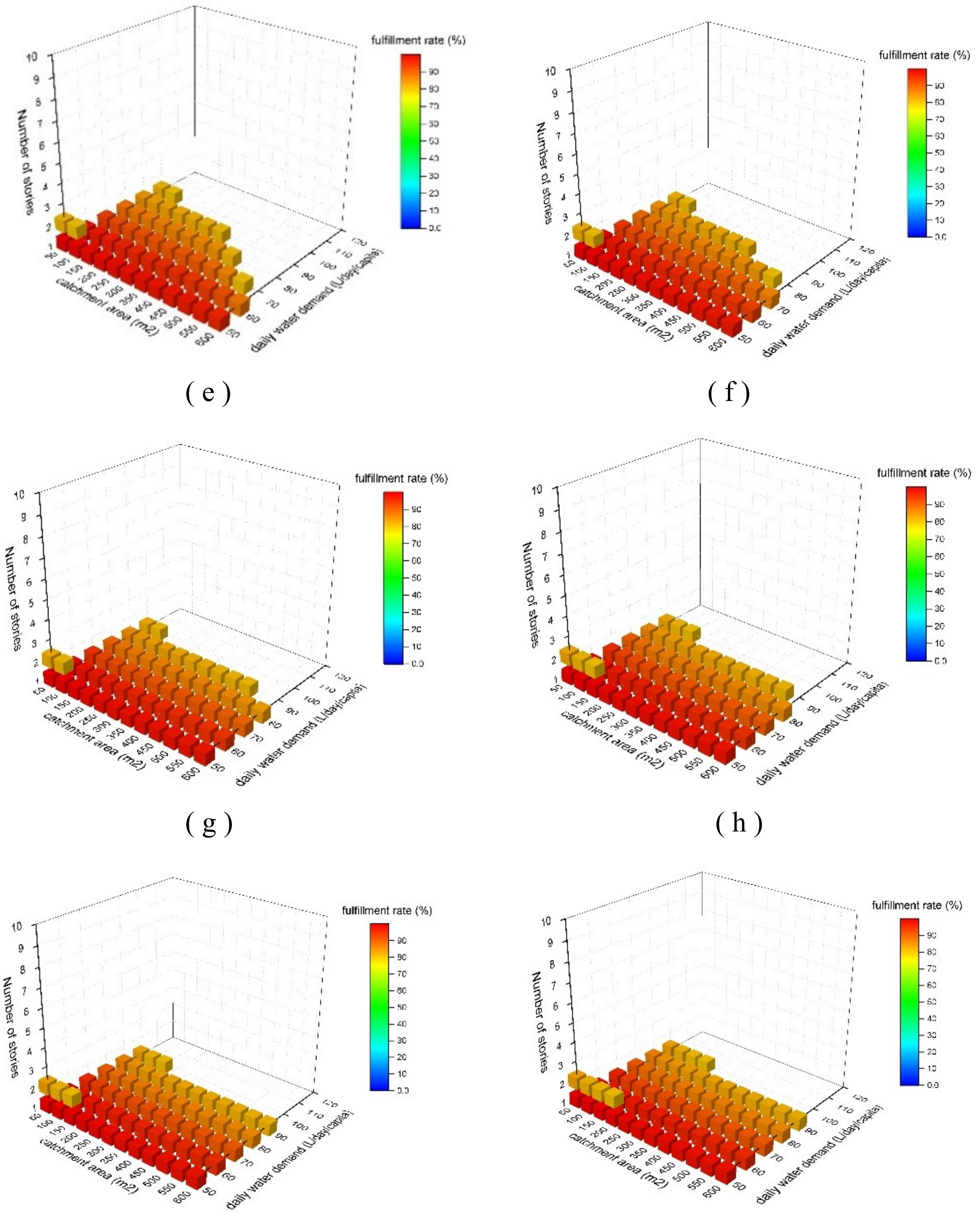


Figure 5.5 Voxel plot of fulfillment rate with respect to the constraints. Color bars show the RWH systems fulfillment rate (%)

(a) Rainwater storage tank volume=0.2 m^3. (b) Rainwater storage tank volume=0.4 m^3.
(c) Rainwater storage tank volume=0.6 m^3. (d) Rainwater storage tank volume=0.8 m^3.
(e) Rainwater storage tank volume=1.0 m^3. (f) Rainwater storage tank volume=1.2 m^3.
(g) Rainwater storage tank volume=1.4 m^3. (h) Rainwater storage tank volume=1.6 m^3.
(i) Rainwater storage tank volume=1.8 m^3. (j) Rainwater storage tank volume=2.0 m^3.

Table 5-5 Number and percentage of scenarios achieving satisfying level

	Rainwater storage tank volume (m^3)									
	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
Number of satisfying scenarios	9	20	34	44	55	59	62	65	66	68
Percentage in all scenarios (%)	0.94	2.08	3.54	4.58	5.73	6.15	6.46	6.77	6.88	7.08
Percentage in low-rise buildings (%)	3.13	6.94	11.81	15.28	19.10	20.49	21.53	22.57	22.92	23.61

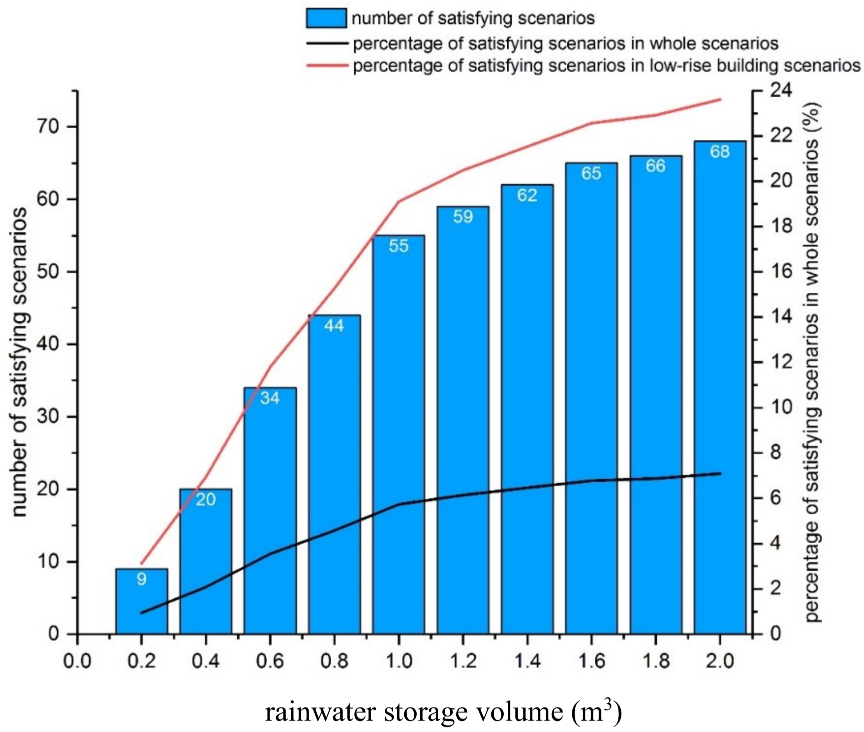


Figure 5.6 Number and percentage of the satisfying scenarios

Chapter 6 Conclusion

This study focuses on the relationships between fulfillment rate of RWH system and its constraints, especially rainwater storage tank volume. Python-based daily water balance model was developed to analyze water use situations on each day. Conclusions of this thesis are listed as following:

- 100% fulfillment rate is difficult to be achieved, or achieved by a large tank.

Fulfillment rate curves of case studies show slowdown after certain tank volumes, and for a given scenario, it has no significant effect on achieving higher fulfillment rate by using larger rainwater tanks after the certain volume. For all the studied scenarios, the corresponding fulfillment rate of the certain volumes are lower than 100%.

- Sizing approaches in published handbooks of RWH systems (AP method) lead to oversized rainwater tanks.

Through the comparisons between the optimal rainwater storage tank volume resulting from fulfillment rate curves, which were developed under daily precipitation data (DP method), and the guideline-recommended rainwater storage tank volume resulting from annual precipitation data (AP method) in the handbooks on RWH systems, it is obvious that AP method underestimate the fulfillment rate of RWH systems and lead to oversized tanks.

- A much-reduced rainwater tank size ($0.8m^3$) has been determined for RWH systems served to the studied residential buildings in Vancouver.

By discovering the joint effects of rainwater storage tank volume, catchment area and rainwater storage tank volume, daily water demand and number of building stories on fulfillment rate, voxel plot figures demonstrate that $0.8m^3$ is the optimal tank volume for the tank-based RWH systems served to the studied residential buildings.

- 3 $L/day/m^2_{catchment}$ is the upper limit ratio of water demand to catchment area to achieve 80% or higher fulfillment rate.

In addition to get the optimal rainwater storage tank size, this study also proposed the limit value of the ratio of daily water demand to catchment area, reflecting the importance of an integrative consideration during initial phase on daily water demand intensity and floor-catchment ratio of buildings.

- RWH systems work best in low-rise residential buildings.

By studying the building types of studied scenarios with 80% or higher fulfillment rate, it can be found that low-rise buildings in Vancouver, with moderate and precipitable rainfall situations, are easier to achieve high fulfillment rate.

- The maximum level of fulfillment rate is location-depended.

By comparing the fulfillment rate curves developed under the investigations on RWH systems in Las Vegas (with uneven and low-quantity rainfall), Hawaii (with frequent and high-quantity rainfall) and Vancouver (with predictable and moderate-quantity rainfall), it can be concluded that the maximum level of fulfillment rate is determined by the local rainfall situations. Also, fulfillment rate curves in these three areas with quite different rainfall situations prove that fulfillment rate of RWH systems cannot always increase with the increase of rainwater tank size.

Appendix A Accounting methods for RWH systems

The accounting method of YAS

The figure below shows the sequence of yield-after-spillage (YAS) accounting method for a given period.

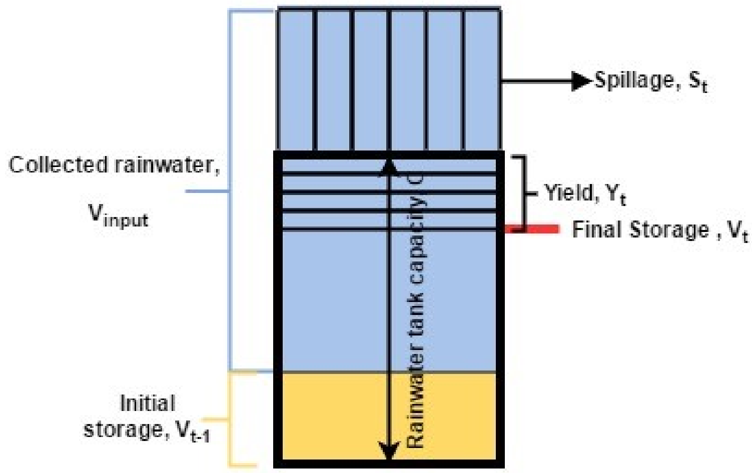


Figure A.1 Sequence of yield-after-spillage (YAS) accounting method (modified from (Mitchell, 2007; Schiller & Latham, 1987))

The rainwater yield and storage situations can be determined by using Equation A-1, A-2 and A-3.

$$V_{available} = \min\left(V_{t-1} + V_{input}, C\right) \quad \text{A-1}$$

$$Y_t = \min(V_{demand}, V_{available}) \quad \text{A-2}$$

$$V_t = V_{available} - V_{demand} \quad \text{A-3}$$

Where $V_{available}$ (m^3) is the volume of rainwater that is available for water demand under the consideration of tank capacity; V_{t-1} is the amount of rainwater in the tank at the end of the previous day, V_{input} (m^3) is the amount of collected rainwater during the time interval, Y_t (m^3) is the volume of rainwater yield supplied to meet water demand during the time interval, V_{demand} (m^3) is the rainwater demand during the time interval, V_t (m^3) is the final storage of rainwater during the time interval. If the calculated result of V_t is a negative value, this value represents the amount of make-up water required from other resources and the final amount of stored rainwater is zero. The time interval used in this study is one day.

The accounting method of YBS

The figure below shows the sequence of yield-before-spillage (YBS) accounting method for a given period.

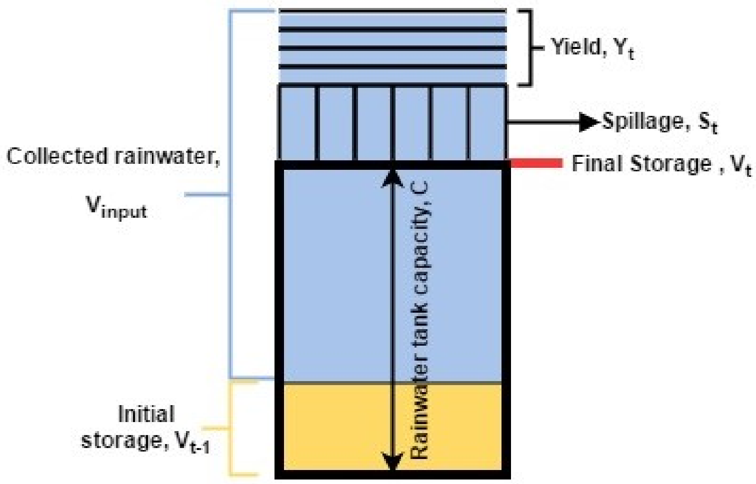


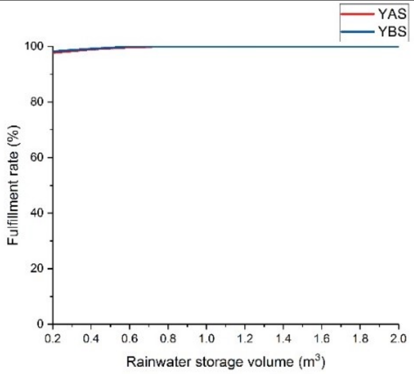
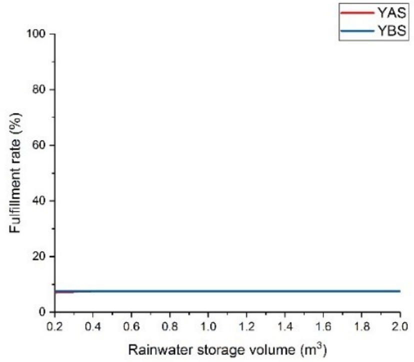
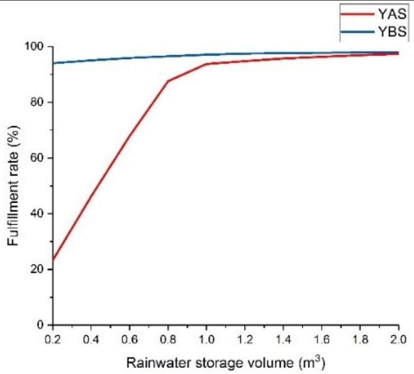
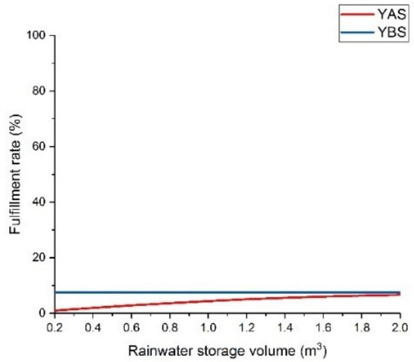
Figure A.2 Sequence of yield-before-spillage (YBS) accounting method (modified from (Mitchell, 2007; Schiller & Latham, 1987))

The rainwater yield and storage situations can be determined by using Equation A-4 and A-5.

$$Y_t = \min(V_{demand}, V_{t-1} + V_{input}) \quad \text{A-4}$$

$$V_t = \min(V_{t-1} + V_{input} - Y_t, C) \quad \text{A-5}$$

Table A-1 Comparison between fulfillment rate under YAS and YBS

<table>
<tr><td></td><td></td><td colspan="2">Water demand</td></tr>
<tr><td></td><td></td><td>Low (Individual water demand: 50L/day/person; Building story:1)</td><td>High (Individual water demand: 120L/day/person; Building story:10)</td></tr>
<tr><td rowspan="2">Water supply (Rainwater collection ability)</td><td>Low (catchment area=50m²)</td><td>
</td><td>
</td></tr>
<tr><td>High (catchment area=600m²)</td><td>
</td><td>
</td></tr>
</table>

Appendix B Daily water balance situations

Table B-1 Daily water balance situations for the case building (rainwater storage tank volume = 0.5 m^3)

Day in a year	Initial storage (V_{t-1}) (m^3)	Roof-collected rainwater (V_{input}) (m^3)	Potential-available rainwater ($V_{potential}$) (m^3)	Actual-available rainwater after spillage ($V_{available}$) (m^3)	Rainwater yield (Y_t) (m^3)	Final stored rainwater (V_t) /Make-up water ($V_{make-up}$) (m^3)
1	0	0.52	0.52	0.5	0.36	0.14
2	0.14	0.5	0.64	0.5	0.36	0.14
3	0.14	0.41	0.55	0.5	0.36	0.14
4	0.14	0.68	0.82	0.5	0.36	0.14
5	0.14	0.43	0.57	0.5	0.36	0.14
6	0.14	0.63	0.77	0.5	0.36	0.14
7	0.14	0.53	0.67	0.5	0.36	0.14
8	0.14	0.58	0.72	0.5	0.36	0.14
9	0.14	0.68	0.82	0.5	0.36	0.14
10	0.14	0.74	0.88	0.5	0.36	0.14
11	0.14	0.57	0.71	0.5	0.36	0.14
12	0.14	0.53	0.67	0.5	0.36	0.14
13	0.14	0.56	0.7	0.5	0.36	0.14
14	0.14	0.87	1.01	0.5	0.36	0.14
15	0.14	0.33	0.47	0.47	0.36	0.11
16	0.11	0.52	0.63	0.5	0.36	0.14
17	0.14	0.74	0.88	0.5	0.36	0.14
18	0.14	0.79	0.93	0.5	0.36	0.14
19	0.14	0.51	0.65	0.5	0.36	0.14
20	0.14	0.41	0.55	0.5	0.36	0.14
21	0.14	0.46	0.6	0.5	0.36	0.14
22	0.14	0.67	0.81	0.5	0.36	0.14
23	0.14	0.51	0.65	0.5	0.36	0.14
24	0.14	0.36	0.5	0.5	0.36	0.14
25	0.14	0.14	0.28	0.28	0.28	-0.08
26	0	0.16	0.16	0.16	0.16	-0.2
27	0	0.28	0.28	0.28	0.28	-0.08
28	0	0.42	0.42	0.42	0.36	0.06
29	0.06	0.89	0.95	0.5	0.36	0.14
30	0.14	0.49	0.63	0.5	0.36	0.14

(continued)

31	0.14	0.4	0.54	0.5	0.36	0.14
32	0.14	0.4	0.54	0.5	0.36	0.14
33	0.14	0.28	0.42	0.42	0.36	0.06
34	0.06	0.36	0.42	0.42	0.36	0.06
35	0.06	0.51	0.57	0.5	0.36	0.14
36	0.14	0.35	0.49	0.49	0.36	0.13
37	0.13	0.46	0.59	0.5	0.36	0.14
38	0.14	0.2	0.34	0.34	0.34	-0.02
39	0	0.33	0.33	0.33	0.33	-0.03
40	0	0.34	0.34	0.34	0.34	-0.02
41	0	0.21	0.21	0.21	0.21	-0.15
42	0	0.27	0.27	0.27	0.27	-0.09
43	0	0.46	0.46	0.46	0.36	0.1
44	0.1	0.23	0.33	0.33	0.33	-0.03
45	0	0.56	0.56	0.5	0.36	0.14
46	0.14	0.57	0.71	0.5	0.36	0.14
47	0.14	0.36	0.5	0.5	0.36	0.14
48	0.14	0.42	0.56	0.5	0.36	0.14
49	0.14	0.52	0.66	0.5	0.36	0.14
50	0.14	0.25	0.39	0.39	0.36	0.03
51	0.03	0.23	0.26	0.26	0.26	-0.1
52	0	0.24	0.24	0.24	0.24	-0.12
53	0	0.28	0.28	0.28	0.28	-0.08
54	0	0.27	0.27	0.27	0.27	-0.09
55	0	0.48	0.48	0.48	0.36	0.12
56	0.12	0.16	0.28	0.28	0.28	-0.08
57	0	0.19	0.19	0.19	0.19	-0.17
58	0	0.29	0.29	0.29	0.29	-0.07
59	0	0.17	0.17	0.17	0.17	-0.19
60	0	0.67	0.67	0.5	0.36	0.14
61	0.14	0.36	0.5	0.5	0.36	0.14
62	0.14	0.34	0.48	0.48	0.36	0.12
63	0.12	0.36	0.48	0.48	0.36	0.12
64	0.12	0.38	0.5	0.5	0.36	0.14
65	0.14	0.28	0.42	0.42	0.36	0.06
66	0.06	0.29	0.35	0.35	0.35	-0.01
67	0	0.5	0.5	0.5	0.36	0.14
68	0.14	0.54	0.68	0.5	0.36	0.14
69	0.14	0.46	0.6	0.5	0.36	0.14
70	0.14	0.58	0.72	0.5	0.36	0.14
71	0.14	0.32	0.46	0.46	0.36	0.1
72	0.1	0.34	0.44	0.44	0.36	0.08

(continued)

73	0.08	0.45	0.53	0.5	0.36	0.14
74	0.14	0.47	0.61	0.5	0.36	0.14
75	0.14	0.23	0.37	0.37	0.36	0.01
76	0.01	0.42	0.43	0.43	0.36	0.07
77	0.07	0.46	0.53	0.5	0.36	0.14
78	0.14	0.48	0.62	0.5	0.36	0.14
79	0.14	0.3	0.44	0.44	0.36	0.08
80	0.08	0.43	0.51	0.5	0.36	0.14
81	0.14	0.31	0.45	0.45	0.36	0.09
82	0.09	0.35	0.44	0.44	0.36	0.08
83	0.08	0.27	0.35	0.35	0.35	-0.01
84	0	0.27	0.27	0.27	0.27	-0.09
85	0	0.47	0.47	0.47	0.36	0.11
86	0.11	0.29	0.4	0.4	0.36	0.04
87	0.04	0.32	0.36	0.36	0.36	0
88	0	0.52	0.52	0.5	0.36	0.14
89	0.14	0.34	0.48	0.48	0.36	0.12
90	0.12	0.27	0.39	0.39	0.36	0.03
91	0.03	0.31	0.34	0.34	0.34	-0.02
92	0	0.24	0.24	0.24	0.24	-0.12
93	0	0.43	0.43	0.43	0.36	0.07
94	0.07	0.3	0.37	0.37	0.36	0.01
95	0.01	0.35	0.36	0.36	0.36	0
96	0	0.38	0.38	0.38	0.36	0.02
97	0.02	0.51	0.53	0.5	0.36	0.14
98	0.14	0.33	0.47	0.47	0.36	0.11
99	0.11	0.11	0.22	0.22	0.22	-0.14
100	0	0.24	0.24	0.24	0.24	-0.12
101	0	0.08	0.08	0.08	0.08	-0.28
102	0	0.28	0.28	0.28	0.28	-0.08
103	0	0.29	0.29	0.29	0.29	-0.07
104	0	0.13	0.13	0.13	0.13	-0.23
105	0	0.14	0.14	0.14	0.14	-0.22
106	0	0.25	0.25	0.25	0.25	-0.11
107	0	0.41	0.41	0.41	0.36	0.05
108	0.05	0.12	0.17	0.17	0.17	-0.19
109	0	0.25	0.25	0.25	0.25	-0.11
110	0	0.25	0.25	0.25	0.25	-0.11
111	0	0.07	0.07	0.07	0.07	-0.29
112	0	0.16	0.16	0.16	0.16	-0.2
113	0	0.46	0.46	0.46	0.36	0.1
114	0.1	0.4	0.5	0.5	0.36	0.14

(continued)

115	0.14	0.18	0.32	0.32	0.32	-0.04
116	0	0.24	0.24	0.24	0.24	-0.12
117	0	0.26	0.26	0.26	0.26	-0.1
118	0	0.17	0.17	0.17	0.17	-0.19
119	0	0.18	0.18	0.18	0.18	-0.18
120	0	0.22	0.22	0.22	0.22	-0.14
121	0	0.16	0.16	0.16	0.16	-0.2
122	0	0.27	0.27	0.27	0.27	-0.09
123	0	0.24	0.24	0.24	0.24	-0.12
124	0	0.26	0.26	0.26	0.26	-0.1
125	0	0.19	0.19	0.19	0.19	-0.17
126	0	0.19	0.19	0.19	0.19	-0.17
127	0	0.15	0.15	0.15	0.15	-0.21
128	0	0.13	0.13	0.13	0.13	-0.23
129	0	0.06	0.06	0.06	0.06	-0.3
130	0	0.08	0.08	0.08	0.08	-0.28
131	0	0.29	0.29	0.29	0.29	-0.07
132	0	0.11	0.11	0.11	0.11	-0.25
133	0	0.12	0.12	0.12	0.12	-0.24
134	0	0.33	0.33	0.33	0.33	-0.03
135	0	0.32	0.32	0.32	0.32	-0.04
136	0	0.11	0.11	0.11	0.11	-0.25
137	0	0.22	0.22	0.22	0.22	-0.14
138	0	0.18	0.18	0.18	0.18	-0.18
139	0	0.14	0.14	0.14	0.14	-0.22
140	0	0.13	0.13	0.13	0.13	-0.23
141	0	0.13	0.13	0.13	0.13	-0.23
142	0	0.27	0.27	0.27	0.27	-0.09
143	0	0.23	0.23	0.23	0.23	-0.13
144	0	0.1	0.1	0.1	0.1	-0.26
145	0	0.13	0.13	0.13	0.13	-0.23
146	0	0.27	0.27	0.27	0.27	-0.09
147	0	0.21	0.21	0.21	0.21	-0.15
148	0	0.33	0.33	0.33	0.33	-0.03
149	0	0.29	0.29	0.29	0.29	-0.07
150	0	0.16	0.16	0.16	0.16	-0.2
151	0	0.27	0.27	0.27	0.27	-0.09
152	0	0.18	0.18	0.18	0.18	-0.18
153	0	0.31	0.31	0.31	0.31	-0.05
154	0	0.18	0.18	0.18	0.18	-0.18
155	0	0.19	0.19	0.19	0.19	-0.17
156	0	0.07	0.07	0.07	0.07	-0.29

(continued)

157	0	0.24	0.24	0.24	0.24	-0.12
158	0	0.12	0.12	0.12	0.12	-0.24
159	0	0.3	0.3	0.3	0.3	-0.06
160	0	0.28	0.28	0.28	0.28	-0.08
161	0	0.26	0.26	0.26	0.26	-0.1
162	0	0.13	0.13	0.13	0.13	-0.23
163	0	0.16	0.16	0.16	0.16	-0.2
164	0	0.25	0.25	0.25	0.25	-0.11
165	0	0.19	0.19	0.19	0.19	-0.17
166	0	0.22	0.22	0.22	0.22	-0.14
167	0	0.17	0.17	0.17	0.17	-0.19
168	0	0.18	0.18	0.18	0.18	-0.18
169	0	0.19	0.19	0.19	0.19	-0.17
170	0	0.11	0.11	0.11	0.11	-0.25
171	0	0.1	0.1	0.1	0.1	-0.26
172	0	0.11	0.11	0.11	0.11	-0.25
173	0	0.06	0.06	0.06	0.06	-0.3
174	0	0.1	0.1	0.1	0.1	-0.26
175	0	0.3	0.3	0.3	0.3	-0.06
176	0	0.07	0.07	0.07	0.07	-0.29
177	0	0.04	0.04	0.04	0.04	-0.32
178	0	0.07	0.07	0.07	0.07	-0.29
179	0	0.11	0.11	0.11	0.11	-0.25
180	0	0.07	0.07	0.07	0.07	-0.29
181	0	0.24	0.24	0.24	0.24	-0.12
182	0	0.16	0.16	0.16	0.16	-0.2
183	0	0.18	0.18	0.18	0.18	-0.18
184	0	0.18	0.18	0.18	0.18	-0.18
185	0	0.08	0.08	0.08	0.08	-0.28
186	0	0.14	0.14	0.14	0.14	-0.22
187	0	0.17	0.17	0.17	0.17	-0.19
188	0	0.1	0.1	0.1	0.1	-0.26
189	0	0.22	0.22	0.22	0.22	-0.14
190	0	0.03	0.03	0.03	0.03	-0.33
191	0	0.16	0.16	0.16	0.16	-0.2
192	0	0.07	0.07	0.07	0.07	-0.29
193	0	0.13	0.13	0.13	0.13	-0.23
194	0	0.06	0.06	0.06	0.06	-0.3
195	0	0.1	0.1	0.1	0.1	-0.26
196	0	0.17	0.17	0.17	0.17	-0.19
197	0	0.11	0.11	0.11	0.11	-0.25
198	0	0.03	0.03	0.03	0.03	-0.33

(continued)

199	0	0.08	0.08	0.08	0.08	-0.28
200	0	0.03	0.03	0.03	0.03	-0.33
201	0	0.05	0.05	0.05	0.05	-0.31
202	0	0.09	0.09	0.09	0.09	-0.27
203	0	0.08	0.08	0.08	0.08	-0.28
204	0	0.08	0.08	0.08	0.08	-0.28
205	0	0.13	0.13	0.13	0.13	-0.23
206	0	0.1	0.1	0.1	0.1	-0.26
207	0	0.07	0.07	0.07	0.07	-0.29
208	0	0.05	0.05	0.05	0.05	-0.31
209	0	0.12	0.12	0.12	0.12	-0.24
210	0	0.09	0.09	0.09	0.09	-0.27
211	0	0.1	0.1	0.1	0.1	-0.26
212	0	0.02	0.02	0.02	0.02	-0.34
213	0	0.04	0.04	0.04	0.04	-0.32
214	0	0.06	0.06	0.06	0.06	-0.3
215	0	0.13	0.13	0.13	0.13	-0.23
216	0	0.05	0.05	0.05	0.05	-0.31
217	0	0.04	0.04	0.04	0.04	-0.32
218	0	0.12	0.12	0.12	0.12	-0.24
219	0	0.23	0.23	0.23	0.23	-0.13
220	0	0.1	0.1	0.1	0.1	-0.26
221	0	0.11	0.11	0.11	0.11	-0.25
222	0	0.11	0.11	0.11	0.11	-0.25
223	0	0.02	0.02	0.02	0.02	-0.34
224	0	0.01	0.01	0.01	0.01	-0.35
225	0	0.06	0.06	0.06	0.06	-0.3
226	0	0.1	0.1	0.1	0.1	-0.26
227	0	0.12	0.12	0.12	0.12	-0.24
228	0	0.09	0.09	0.09	0.09	-0.27
229	0	0.13	0.13	0.13	0.13	-0.23
230	0	0.04	0.04	0.04	0.04	-0.32
231	0	0.02	0.02	0.02	0.02	-0.34
232	0	0.13	0.13	0.13	0.13	-0.23
233	0	0.16	0.16	0.16	0.16	-0.2
234	0	0.25	0.25	0.25	0.25	-0.11
235	0	0.04	0.04	0.04	0.04	-0.32
236	0	0.01	0.01	0.01	0.01	-0.35
237	0	0.12	0.12	0.12	0.12	-0.24
238	0	0.2	0.2	0.2	0.2	-0.16
239	0	0.17	0.17	0.17	0.17	-0.19
240	0	0.13	0.13	0.13	0.13	-0.23

(continued)

241	0	0.29	0.29	0.29	0.29	-0.07
242	0	0.25	0.25	0.25	0.25	-0.11
243	0	0.35	0.35	0.35	0.35	-0.01
244	0	0.06	0.06	0.06	0.06	-0.3
245	0	0.11	0.11	0.11	0.11	-0.25
246	0	0.08	0.08	0.08	0.08	-0.28
247	0	0.07	0.07	0.07	0.07	-0.29
248	0	0.04	0.04	0.04	0.04	-0.32
249	0	0.11	0.11	0.11	0.11	-0.25
250	0	0.06	0.06	0.06	0.06	-0.3
251	0	0.2	0.2	0.2	0.2	-0.16
252	0	0.19	0.19	0.19	0.19	-0.17
253	0	0.13	0.13	0.13	0.13	-0.23
254	0	0.12	0.12	0.12	0.12	-0.24
255	0	0.11	0.11	0.11	0.11	-0.25
256	0	0.05	0.05	0.05	0.05	-0.31
257	0	0.14	0.14	0.14	0.14	-0.22
258	0	0.09	0.09	0.09	0.09	-0.27
259	0	0.3	0.3	0.3	0.3	-0.06
260	0	0.19	0.19	0.19	0.19	-0.17
261	0	0.28	0.28	0.28	0.28	-0.08
262	0	0.68	0.68	0.5	0.36	0.14
263	0.14	0.24	0.38	0.38	0.36	0.02
264	0.02	0.14	0.16	0.16	0.16	-0.2
265	0	0.11	0.11	0.11	0.11	-0.25
266	0	0.15	0.15	0.15	0.15	-0.21
267	0	0.24	0.24	0.24	0.24	-0.12
268	0	0.15	0.15	0.15	0.15	-0.21
269	0	0.44	0.44	0.44	0.36	0.08
270	0.08	0.13	0.21	0.21	0.21	-0.15
271	0	0.1	0.1	0.1	0.1	-0.26
272	0	0.28	0.28	0.28	0.28	-0.08
273	0	0.32	0.32	0.32	0.32	-0.04
274	0	0.16	0.16	0.16	0.16	-0.2
275	0	0.15	0.15	0.15	0.15	-0.21
276	0	0.21	0.21	0.21	0.21	-0.15
277	0	0.25	0.25	0.25	0.25	-0.11
278	0	0.17	0.17	0.17	0.17	-0.19
279	0	0.25	0.25	0.25	0.25	-0.11
280	0	0.23	0.23	0.23	0.23	-0.13
281	0	0.21	0.21	0.21	0.21	-0.15
282	0	0.37	0.37	0.37	0.36	0.01

(continued)

283	0.01	0.32	0.33	0.33	0.33	-0.03
284	0	0.21	0.21	0.21	0.21	-0.15
285	0	0.39	0.39	0.39	0.36	0.03
286	0.03	0.33	0.36	0.36	0.36	0
287	0	0.58	0.58	0.5	0.36	0.14
288	0.14	0.71	0.85	0.5	0.36	0.14
289	0.14	0.71	0.85	0.5	0.36	0.14
290	0.14	0.82	0.96	0.5	0.36	0.14
291	0.14	0.69	0.83	0.5	0.36	0.14
292	0.14	0.44	0.58	0.5	0.36	0.14
293	0.14	0.37	0.51	0.5	0.36	0.14
294	0.14	0.54	0.68	0.5	0.36	0.14
295	0.14	0.45	0.59	0.5	0.36	0.14
296	0.14	0.42	0.56	0.5	0.36	0.14
297	0.14	0.4	0.54	0.5	0.36	0.14
298	0.14	0.49	0.63	0.5	0.36	0.14
299	0.14	0.38	0.52	0.5	0.36	0.14
300	0.14	0.11	0.25	0.25	0.25	-0.11
301	0	0.46	0.46	0.46	0.36	0.1
302	0.1	0.64	0.74	0.5	0.36	0.14
303	0.14	0.65	0.79	0.5	0.36	0.14
304	0.14	0.44	0.58	0.5	0.36	0.14
305	0.14	0.56	0.7	0.5	0.36	0.14
306	0.14	0.47	0.61	0.5	0.36	0.14
307	0.14	1	1.14	0.5	0.36	0.14
308	0.14	0.6	0.74	0.5	0.36	0.14
309	0.14	0.39	0.53	0.5	0.36	0.14
310	0.14	0.87	1.01	0.5	0.36	0.14
311	0.14	0.86	1	0.5	0.36	0.14
312	0.14	0.5	0.64	0.5	0.36	0.14
313	0.14	0.52	0.66	0.5	0.36	0.14
314	0.14	0.56	0.7	0.5	0.36	0.14
315	0.14	0.41	0.55	0.5	0.36	0.14
316	0.14	0.81	0.95	0.5	0.36	0.14
317	0.14	0.62	0.76	0.5	0.36	0.14
318	0.14	0.47	0.61	0.5	0.36	0.14
319	0.14	0.55	0.69	0.5	0.36	0.14
320	0.14	0.69	0.83	0.5	0.36	0.14
321	0.14	0.51	0.65	0.5	0.36	0.14
322	0.14	0.38	0.52	0.5	0.36	0.14
323	0.14	0.86	1	0.5	0.36	0.14
324	0.14	0.59	0.73	0.5	0.36	0.14

(continued)

325	0.14	0.49	0.63	0.5	0.36	0.14
326	0.14	0.7	0.84	0.5	0.36	0.14
327	0.14	0.66	0.8	0.5	0.36	0.14
328	0.14	0.47	0.61	0.5	0.36	0.14
329	0.14	0.66	0.8	0.5	0.36	0.14
330	0.14	0.52	0.66	0.5	0.36	0.14
331	0.14	0.53	0.67	0.5	0.36	0.14
332	0.14	1.02	1.16	0.5	0.36	0.14
333	0.14	0.77	0.91	0.5	0.36	0.14
334	0.14	0.52	0.66	0.5	0.36	0.14
335	0.14	0.53	0.67	0.5	0.36	0.14
336	0.14	0.48	0.62	0.5	0.36	0.14
337	0.14	0.67	0.81	0.5	0.36	0.14
338	0.14	0.4	0.54	0.5	0.36	0.14
339	0.14	0.69	0.83	0.5	0.36	0.14
340	0.14	0.38	0.52	0.5	0.36	0.14
341	0.14	0.42	0.56	0.5	0.36	0.14
342	0.14	0.6	0.74	0.5	0.36	0.14
343	0.14	0.64	0.78	0.5	0.36	0.14
344	0.14	0.51	0.65	0.5	0.36	0.14
345	0.14	0.48	0.62	0.5	0.36	0.14
346	0.14	0.8	0.94	0.5	0.36	0.14
347	0.14	0.72	0.86	0.5	0.36	0.14
348	0.14	0.55	0.69	0.5	0.36	0.14
349	0.14	0.67	0.81	0.5	0.36	0.14
350	0.14	0.46	0.6	0.5	0.36	0.14
351	0.14	0.7	0.84	0.5	0.36	0.14
352	0.14	0.35	0.49	0.49	0.36	0.13
353	0.13	0.58	0.71	0.5	0.36	0.14
354	0.14	0.79	0.93	0.5	0.36	0.14
355	0.14	0.3	0.44	0.44	0.36	0.08
356	0.08	0.32	0.4	0.4	0.36	0.04
357	0.04	0.43	0.47	0.47	0.36	0.11
358	0.11	0.63	0.74	0.5	0.36	0.14
359	0.14	0.38	0.52	0.5	0.36	0.14
360	0.14	0.41	0.55	0.5	0.36	0.14
361	0.14	0.97	1.11	0.5	0.36	0.14
362	0.14	0.47	0.61	0.5	0.36	0.14
363	0.14	0.49	0.63	0.5	0.36	0.14
364	0.14	0.54	0.68	0.5	0.36	0.14
365	0.14	0.36	0.5	0.5	0.36	0.14

Appendix C RWH systems in areas with extreme precipitation situations

Fulfillment rate of RWH system for areas with extreme situations

Comparing to areas where rainfall is predictable and certain, areas with extreme rainfall situations and patterns, for example have dry periods throughout the whole year with small amounts of precipitation, or experience abundant rain for every month during a year, fulfillment rate curves of RWH systems might be different and unique. In addition to Vancouver, two new-added locations, Las Vegas and Hawaii, were analyzed.

Las Vegas, which is located in Nevada, U.S, has dry periods from January to December, and the amount of total precipitation in a whole year is only about 100 mm. In addition to low precipitation depth, the distribution of rainfall is highly uneven and irregular during a year. Figure C.1 shows the daily precipitation situations of Las Vegas in a year, including precipitation depth and rainfall distribution.

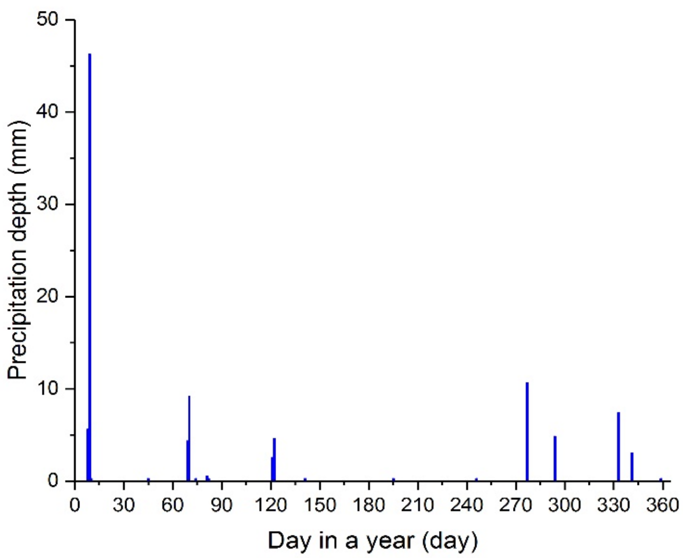


Figure C.1 Daily precipitation situations of Las Vegas in a year

Hawaii is an U.S. state which contains over hundred islands. It receives rain almost two-thirds of the days in a year, resulting to around 6000 mm annual precipitation depth. Figure C.2 gives a clear demonstration of how intensive and heavy the rainfall is in Hawaii.

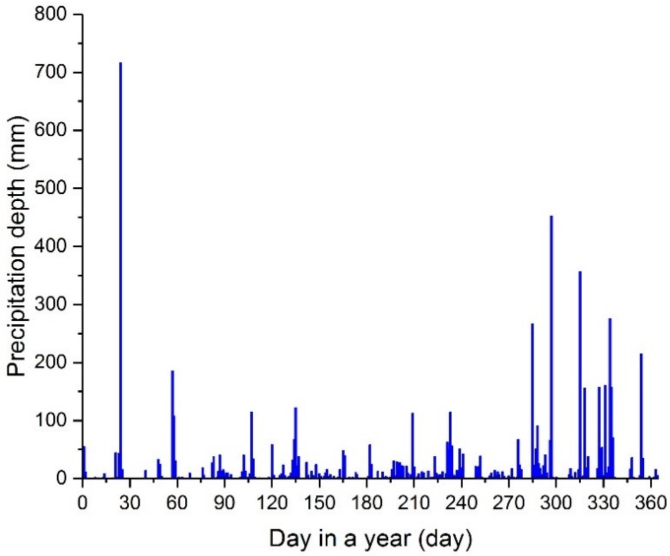


Figure C.2 Daily precipitation situations of Hawaii in a year

By applying the daily precipitation data of Las Vegas, Hawaii as well as Vancouver to the RWH system serving to the building of Case A, the relationship curves between fulfillment rate and rainwater storage tank volume can be developed, shown in Figure C.3.

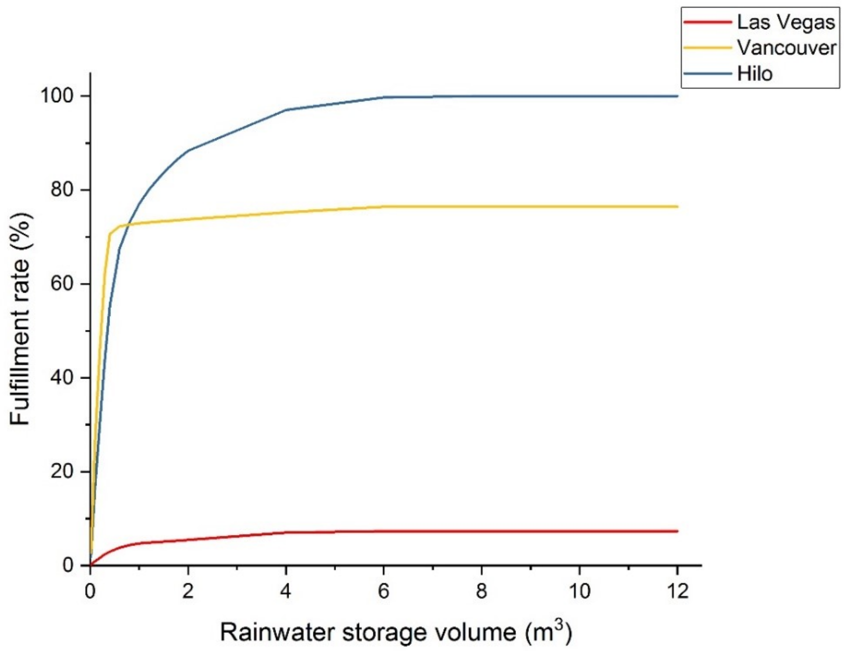


Figure C.3 Relationship between fulfillment rate and rainwater storage tank volume for three locations: Las Vegas, Hawaii and Vancouver (DP method)

It is obvious that no matter what kind of climate situations, fulfillment rate of RWH systems cannot always rise with the increase of rainwater storage tank volume, and the maximum level of fulfillment rate of RWH systems is location-depended.

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