POSSIBILITIES FOR ROOFTOP RAINWATER HARVESTING FOR OFF-GRID HOUSEHOLDS

CASE STUDY: SERANG, INDONESIA

POSSIBILITIES FOR ROOFTOP RAINWATER HARVESTING FOR OFF-GRID HOUSEHOLDS

SERANG, INDONESIA

by

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Master of Science
in Civil Engineering, Water Management

at the Delft University of Technology, to be defended publicly on Thursday 24 November, 2016

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Preface

During my work on my master thesis I have been excited, proud, happy, surprised and grateful but also uncertain, confused and bored.
I was very excited to make small contributions to the improvement of the water supply in an area where this is still very important. In these areas improvements in water supply can cause significant health gains and possibly save lives. I have been proud when people asked my advice. However when giving advice I also felt uncertain resulting from this increasing responsibility.
I am happy with the opportunity to travel to Indonesia which was a valuable experience both for my research and my personal development. I was very surprised by the huge groups of people who were present during the meetings I had in Indonesia. Sometimes I was confused by the language barrier, or the statements that were made by people from different cultural backgrounds. However I am convinced that a lot can be learned from these welcome and friendly people.
I am very grateful to my friends who took the time to help me when needed. In case I was confused about any of my results I could always count on them. I was very happy with the positive energy and support in the graduation room. During the finishing of my report I have been bored by improving language mistakes or layout. However when looking back, this seems unimportant.

I enjoyed working on my master thesis and actually I am quite disappointed to stop working on this topic. Especially since I discovered that more knowledge always leads to more questions. Resulting in an endless cycle, which will never stop. I expect that I will always remain interested in rainwater harvesting.

This thesis would not have been possible without the help of my friends, family, graduation committee and colleagues at World Waternet.
I especially would like to thank Professor Jan Peter van der Hoek for all his patience, in case I had a new idea or issue which I wanted to discuss. Beside this, I really appreciated the time he took to critically look at my work. I would like to thank Dr. Frans van der Ven for making good points, which made me rethink about my work. I am really grateful for the enthusiastic attitude and positive feedback from Dr. Markus Hrachowitz. They gave me energy to continue and further improve my work.
From World Waternet I would like to thank all my colleagues. Special thanks go to Ir. Paul Bonné for valuable discussions and feedback. During my time at World Waternet I learned to look at issues from a more practical view, something which I expect to be very valuable in my future carrier.

Beside this I would like to thank everybody who took time for an interview both in the Netherlands and Indonesia. The knowledge I gained during these interviews proved very valuable.
I was very surprised by people who were helping me with practical tips for my trip to Indonesia. Even though I did not know many of them in advance, many people were happy to help me with transport or accommodation. I enjoyed dinner together, and made great trips during the weekend with them.

I hope you will enjoy reading of the report as much I enjoyed working on it!

Executive summary

Introduction

Approximately eighty countries, containing forty percent of the world population, are facing water scarcity. This causes serious threats to human health, and thereby the sustainable development of the domestic, agricultural and industrial sector, limiting economic growth and perpetuating poverty. In addition to water scarcity, approximately eight percent of the world population has to deal with unimproved water sources, which are often contaminated with either microbial or chemical contamination or both.

A potential solution which can increase and improve the water availability and quality is rainwater harvesting. Rainwater harvesting is defined by Pacey & Cullis (1986) as *"the gathering and storage of water running off surfaces on which rain has directly fallen"*. This thesis looks at the potential of domestic rooftop rainwater harvesting in an area without piped water supply in a developing country, Indonesia, with as case study kabupaten Serang, Java. The focus of this thesis is on water quantity, economic, social, cultural and legal aspects of rainwater harvesting. The goal of this research is the development of rainwater as a valuable resource and to develop design guidelines for best practices. New and existing scientific knowledge is combined with local knowledge from the population and from governmental and non-governmental organizations.

Methodology

In order to identify the potential of rainwater harvesting, a modified version of the method of Studer (2013) was used, in which rainwater harvesting is evaluated from a multidisciplinary perspective. Thereby there is attention not only for technical but also for economic, social-cultural and legal aspects. Existing rainwater harvesting projects by individual households in Serang and by external parties within Indonesia were evaluated. Semi-structured interviews were done with several stakeholders at national, regional and local level, including the users of rainwater harvesting systems. During these interviews attention was paid to the different aspects of rainwater harvesting including acceptance, quality and costs. Moreover, rainwater quality measurements were performed on site: direct rainfall, roof runoff and water inside existing tanks was sampled and analysed. A conceptual model was built to identify the amount of water that can be extracted from rainwater harvesting systems, for different operating scenarios. Investment costs were calculated based on material requirements and local material prices. Operation and maintenance costs were approximated and also included. Based on this, a calculation was done to determine the a payback period and water costs per cubic meter.

Case study area

Kabupaten Serang is located on the west side of the Indonesian island Java. Annual rainfall is 1722 mm, yearly average (open pan) evaporation is around 3.5 mm/day and yearly average temperature is 27.1 °C. Average population density is 1232 inhabitants/km^2 and lifetime expectancy is 63 years. In general, the Indonesian population uses around 130 liter per person per day, mainly at the toilet or during praying. It is very common to treat water before potable use, by boiling. Moreover, a large part of the population uses a combination of water sources. Current water supply in some sub-districts in Serang was found to be insufficient. In the coastal areas, like Tirtayasa, groundwater is brackish and surface water is heavily polluted. In areas more inland, like Baros and Pabuaran, groundwater levels are deep. In these areas easy groundwater extraction requires electricity and comes with additional costs. Well digging by hand is difficult. Although spring water can be used, springs are often located in remote places. In general the piped network just reaches a limited part of the population. Bottled water, or refilled gallons can be bought, but are relatively expensive.

Results - Existing systems currently on site

The rainwater harvesting systems installed by the households in Serang, were placed inside the houses and not always closed. Tank volume ranged between approximately 50 to 8000 liters. Often only a part of the roof area was connected, and rainwater was only used in the wet season. Water use is based on availability. Local materials were used, combined with local knowledge, creativity, preference and the ability and willingness to pay for the system. As treatment, a cloth filter is often installed to prevent large organic material from entering the tank. In some tanks small fishes eat mosquito larvae. Water is boiled in case it is used for potable purposes.

Systems installed by external organizations were placed outside. Tanks were well closed and have a relatively large tank volume (around 9000 liters). Large roof areas were connected, and water is used the entire year. To make sure that water can be used in the dry season, water extraction should be limited, especially at the end of the wet season and in the dry season. Local materials are used, but knowledge comes from national organizations. It is important to involve the community in the project. System installation should be assisted by professionals. In general, the population should be aware of the technique, accept it and understand all important features to ensure successful implementation.

Results - Water quality

In the sampled rainwater harvesting tanks in Serang (Tirtayasa) the WHO and Indonesian water quality guidelines are met with the exception of microbial parameters. However, samples collected from the direct rainfall show values of aluminium and iron concentrations above the guideline values. These concentrations decrease after contact with the roof, most likely due to the formation of complexes on the roof surface. The same hypothesis counts for manganese, although guidelines are not exceeded for this parameter. Different from expected, the pH of the rainwater is found to be around seven. A clear first flush effect is observed in the roof runoff with respect to microbial concentrations. For the other parameters this effect was not observed.

Several stakeholders, especially at local level, are concerned about the mineral content of rainwater and the effect of air pollution. Calcium and magnesium concentrations in rainwater are found to be low and the main intake of these minerals occurs via food. Even when groundwater is used as a water source, the current mineral intake of the population is expected to be limited. Because of this, this research recommends the population to should shift their diet to products containing high amounts of calcium and/or magnesium. Examples include dairy products, dark leafy vegetables, nuts, seeds and avocado.

Heavy metals in rainwater, like lead and zinc are indeed related to air pollution. Other pollution, like aluminium, can be related to mineral dusts. However the measured concentrations of these metals inside the tanks did not exceed the drinking water guidelines from the WHO. However more research regarding the effect of air pollution on rainwater quality is required and especially polycyclic aromatic hydrocarbon, phthalate esters, pesticides and polychlorinated biphenyls need to be investigated further.

Results - Treatment

Appropriate handling of rainwater and suitable treatment can further improve the quality of the water. Pollution should be prevented by using appropriate materials and a closed tank with overflow pipe and tap. All system parts should be regularly cleaned (at least once a year) and first flush should be applied. The harvested water can be treated before consumption, dependent on the type of use. For potable purposes treatment is required with respect to microbial contamination. Solar water disinfection (SODIS), chlorine, copper and silver disinfection, biosand filter, ceramic pot filter, ultrafiltration, fiber and cloth filtration, fish in the tank and boiling were evaluated against technical, social and economic aspects. Based on this analysis it is found that cloth filtration, fish and boiling are currently a suitable treatment combination, tackling the microbial contamination present in rainwater, preventing turbidity and dealing with mosquitos. An important consideration that is taken into account in the selection of this treatment combination is the fact that boiling is currently widely practiced and socially accepted. In other locations another type of treatment would be preferred. If possible a closed tank is preferred above the use of fish, provided the tank is well closed to prevent mosquitos to enter. Algae growth should be minimized by limiting nutrient availability and light penetration in the tank.

Based on the treatment suggested above, a certain health risk will remain, both for the boiled water which is used for potable purposes (via ingestion), and the unboiled water which is used for non-potable purposes (via ingestion, aerosols and wounds). Pathogens of concern are spores of *Clostridium botulinum* which can cause infant botulism in case water is ingested. Other relevant micro-organisms which are spread by aerosols or wounds include *Legionella pneumophila* and *Aeromonas hydrophila, Pseudomonas aeruginosa* and *Staphylococcus aureus.* In general the infection risk, and/or the consequences of infection are largest for vulnerable groups which include very young children, elderly, individuals with weakened immune systems and people with skin injuries. These vulnerable groups should prevent the use of unboiled rainwater for non-potable purposes. Children below one year should not drink boiled rainwater to prevent infant botulism.

Results - Water quantity

Rainwater harvesting systems at a household scale were found most suitable in Indonesia, mainly due to system maintenance. This is confirmed by all interviewed stakeholders.

To get an indication regarding the possible water quantity a rainwater harvesting system can provide a conceptual water balance model is build (see Figure 23). It takes into account precipitation, evaporation, losses in the roof and gutter and first flush. Overflow occurs in case the storage tank is full. Different operating scenarios are developed, which describe the timing and volume of the water extracted from the rainwater harvesting system. In this summary just three of these scenarios are shortly described. These include the scenario in which the maximum amount of water is extracted from the rainwater harvesting system, the scenario in which 12.5% (or 1/8) of the tank is used as a maximum and the scenario in which a fixed amount is extracted each day, which differs per month. The conceptual model shows that rainwater harvesting at a household scale cannot provide sufficient water for an average family, which was also stated by the interviewed stakeholders. This implies that rainwater has to be combined with other available sources like groundwater or bottled water.

The volume of water that can be extracted from the system is dependent on the tank and roof sizes and the way of operation (the operating scenario). It is found that the operating scenario largely influences the water harvest. To optimize the average volume of water harvest, users should use

water directly. So in the case one wants to reach a maximum tap flow, saving does not help. This can be explained by the fact that storage of water increases the chance that your tank will overflow.
In the situation in which water is not saved an average tap flow of 190 liter/day is found for a tank of 2 m^3 and a roof of 100 m^2. The latter is divided in a tap flow of 90 liters a day on average in the dry season and 250 liters a day in the wet season. A lower average tap flow of 125 liter a day is found in case maximum 12.5% of the tank volume is used, thereby losing more water but also saving more water for the dry season when rainfall is more scare. By fixing the expected water volume (or demand) per month an average tap flow of 131 liters/day can be reached.

Results – Total costs and payback period
The local population currently views rainwater harvesting as a cheap water source which can be easily harvested in buckets or in locally made infrastructure. However, experts and case study experts think of more advanced rainwater harvesting systems which come with higher costs. A more advanced system is expected to have installation costs of around 450 to 500 euro for a tank of 2 m^3. For this tank size ferrocement tanks were found to be cheaper than plastic tanks. Moreover, this the lifetime of ferrocement tanks is expected to be longer. When considering the total costs and total lifetime of the rainwater harvesting system, water costs are similar compared to prices for the piped water supply. It is found that connecting the entire roof will result in lower water costs per m^3. However investments in bigger storage tanks do not necessary lead to lower water costs. For example for a ferrocement tank, water costs show a minimum for a tank of 2 m^3 (roof=50-150 m^2) for the scenario in which half of the tank volume is used. Although the water costs are lowest in the scenario in which the maximum volume is harvested, payback times are found to be lowest, in case more water is saved, to replace the expansive bottled water. The expected payback period is 2.5 year, in case the maximum amount of water is used from the tank directly, and 1.5 year in case 12.5% of the tank is used, if the assumption is made that one family currently buys 80 liter of big water bottles each day. In case it is assumed that a family buys currently 20 liter payback periods are 14½ year and 6 years for the no saving and 12.5% of the tank scenario respectively.

Results – Legal and institutional aspects
Legally it is found that no relevant restrictions apply to domestic rainwater harvesting systems. The national government has (theoretical) knowledge and guidelines regarding rainwater harvesting. Local governmental organizations like the ‘Dinas Health’, ‘Bappeda’ and ‘Puskesmas’ have practical knowledge regarding the operation of rainwater harvesting systems. Knowledge institutes have ongoing research and pilots regarding rainwater harvesting, and non-governmental organizations have been doing large scale projects. In general knowledge exchange between these stakeholders is limited.

Conclusion
This research showed that rainwater harvesting seems to be a suitable technique for the improvement of both the quality and quality of the water supply in Serang. Other potential sources (groundwater, surface water or the piped network) have limitations due to either availability or quality. Although unrealistic system sizes are required for households to solely rely on rainwater, it can provide significant volumes of water of sufficient quality, for reasonable costs. Legally rainwater harvesting systems are allowed without particular restrictions. Main social attention point remains the knowledge and acceptance of the technique by the population. Besides, a financing construction

will be required to cover large investment costs. Water quality control of these household systems will however remain difficult and the available water will remain partly uncertain due to uncertainty in rainfall.

Recommendation
For the rainwater harvesting systems visited in Serang it is recommended that tanks should be better closed and that overflow pipes, taps and first flush should be installed when absent. Fine wire mesh can prevent mosquitos entering, and alternatively small fishes can be used within the tank. As additional treatment cloth filtration will remove large organic material and boiling removes microbial contamination in case water is used for potable purposes. For the local systems, more attention has to be paid to the connection of the entire roof, and the type of operation. Depending on the preference of the population, a different way of operation is advised. For high average water withdrawals the population should use as much as water as needed directly, to limit the system overflow. This will come together with the lowest water costs per cubic meter. However to reach a short payback period, water should be saved, to replace the expensive gallons (19 liter bottles) which have to be bought in case no rainwater is available.

Governmental institutions should focus on increasing and sharing knowledge regarding rainwater harvesting. They should support and inform the community regarding improvements of their current rainwater harvesting systems. In case the water supply remains limited and further measurements confirm that the quality of rainwater harvesting systems is sufficient, governmental institutions can promote rainwater harvesting.

A broad range of scientific research still has to be done regarding rainwater harvesting. Regarding water quality more measurements should be done spatially and temporally and with respect to relevant parameters like polycyclic aromatic hydrocarbon, phthalate esters, pesticides and polychlorinated biphenyls and spores of *Clostridium botulinum, Legionella pneumophila*, *Aeromonas hydrophila, Pseudomonas aeruginosa* and *Staphylococcus aureus.* A better understanding is required regarding the immunity of the population towards microbial contamination. Moreover, more research is needed regarding both the positive and negative effects of the use of fishes in the tank and cloth filters. Finally, the risk related to water consumption should always be placed in the context of other environmental and human-induced risks facing the population.

Regarding water quantity, the conceptual rainwater harvesting model used should be calibrated, validated and the model structure uncertainty should be investigated. External factors, like climate change or changing demands should be included, together with other water use scenarios. Regarding economic aspects, more detailed and location specific information has to be found regarding material costs and requirements. Other tank designs should be considered and alternatives to reduce the high investment costs of rainwater harvesting systems should be further investigated. Looking from a global perspective it would be very valuable to create a map, visualizing the opportunities of rainwater harvesting worldwide. This map should not only include technical parameters, but also social, economic and legal parameters. Hereby it can highlight areas in which rainwater harvesting can be applied in the future.

Content

Abbreviations

cdf	Cumulative distribution function.
DRWH	Domestic rainwater harvesting.
HWT	Household water treatment.
MSE	Mean square error.
NPV	Net present value.
PDAM	Indonesian (drinking)water supply company, distributing clean water to the local population.
pdf	Probability density function.
PDNM	Percentage of days demand not met. Refers to the percentage of days the expected amount of water cannot be extracted from the system.
RWH	Rainwater harvesting.
SODIS	Solar disinfection.
UV	Ultraviolet.
WHO	World Health Organization.
WH	Water Harvesting.
YAS	Yield after spill.

Symbols

D	Demand [L^3/T].
E	Evaporation [L^3/T].
FF	First flush [L].
O	Overflow [L^3/T].
P	Precipitation [L^3/T].
Rmax	Maximal storage on the roof [L].
RS	Roof size [L^2].
SPL	Splash loss [L^3/T].
TF	Tap flow [L^3/T].
Tmax	Volume of the tank [L^3]

Glossary

Bappeda	The Regional Planning and Development Agency.
Bappenas	Ministry of national development and planning (Indonesia).
Domestic water	All water used at a household level, including drinking water. Synonym of household water.
Case study expert	(Ex)-employee of the local government (in this research the kabupaten or puskesmas) working in the field of water resources, health or planning.
Clean water	Term commonly used in Indonesia to describe water that can be used for non-potable purposes. Guidelines can be found in paragraph 5.2.3.3.
Demand	See expectation.
Dinas Health	Public health department of the local government (kabupaten).
Expectation	Amount of water that is requested (or asked) from the system within a certain time frame of a month or season. In the calculation performed in this research the expectation has to be met in 80% of the days.
Expert	(Ex)-employee of the national governmental, a non-governmental organization or a knowledge institute. Working in the field of water resources or rainwater harvesting.
Gallons	Big water bottle of approximately 19 liter.
Household water	All water used at a household level, including drinking water. Synonym of domestic water.
Individual system	A rainwater harvesting system on a household level.
Kabupaten	Regency in Indonesia.
Kecamatan	Sub-district in Indonesia.
Puskesmas	Local health center or small hospital in Indonesia.
Tap flow	Refers to the daily volume of water that can be extracted from the rainwater harvesting system (at the tap).

1. Introduction

1.1. Problem statement

Water is one of the fundamental water requirements of human life. Without this resource, people can just survive for a few days, and lack of sufficient water supplies leads to the spread of diseases (Howard & Bartram, 2013). However water scarcity[1] is affecting many nations, and access to clean drinking water and sanitation stays poor (Cosgrove & Rijsberman, 2014).

Approximately 80 countries, with forty percent of the world population, are facing water shortages, causing a serious threat to health and thereby the sustainable development of the domestic, agricultural and industrial sector (Hamdy et al., 2003). With respect to economic and livelihood aspects, water related problems limit economic growth and perpetuate poverty (McGarvey et al., 2008).

Next to these issues regarding water shortages, the quality of the water available remains an issue. Worldwide four percent of the urban population and sixteen percent of the rural population has no safe drinking water (WHO & Unicef, 2015). These people rely on unprotected wells, springs, rivers or ponds, vendor-provided water, surface water, tanker truck water or bottled water. According to Sobsey (2002) the WHO underestimates the part of the population that has no access to safe water because of two reasons. First of all improved sources, like boreholes can still be contaminated by fecal material and secondly recontamination of improved water often occurs.

Figure 1 shows the stress on water supply systems. Especially in densely populated areas, this stress on water supply systems is increasing due to water quality degradation, increasing demand and source depletion. Additionally, droughts and floods, erosion, subsidence and seawater intrusion can cause stress on the water supply system, but can also be influenced by the water supply system.

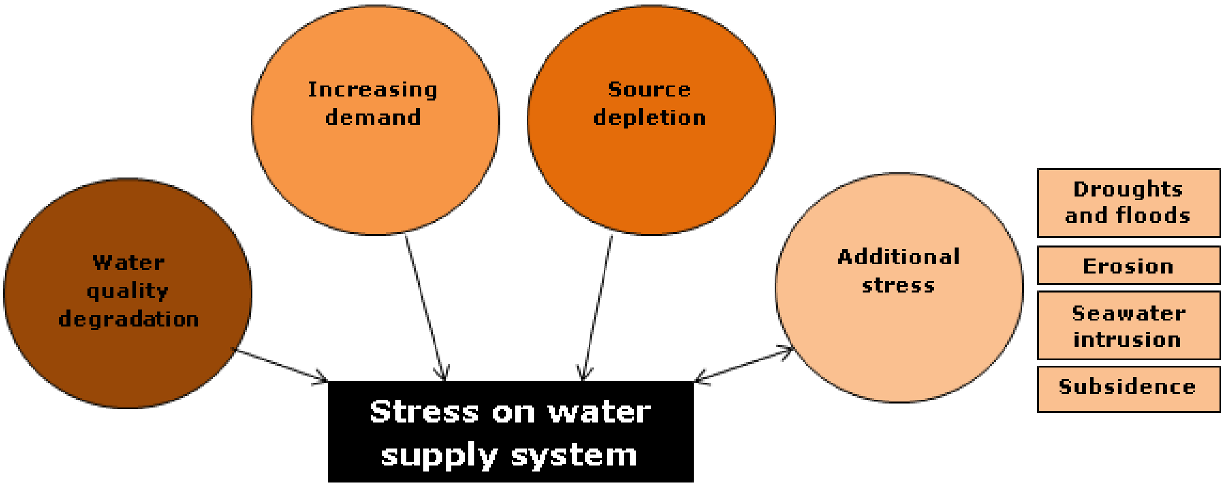


Figure 1: The stress on a water supply system.

[1] Different forms of water scarcity can be distinguished including aridity, which is caused by a dry climate, drought, which is an irregular phenomenon occurring exceptionally, desiccation, the drying up of landscape and soil due to for example deforestation and grazing and water stress due to population increase (Clarke, 2013).

The water quality degradation of natural water sources is often linked to urban, industrial or agricultural activities (Delpha et al., 2009) and can have huge consequences for the water supply. The lack of sanitation and wastewater treatment facilities is an important factor for the limitation of fresh water availability (Peters & Meybeck, 2000). Other sources of pollution include atmospheric pollution and deposition, pesticides, fertilizers and oil (Pandey et al., 2003; Peters & Meybeck, 2000). This water quality degradation causes a decline in the availability of clean water.
On the other side the demand for water is increasing due to of urbanization, population growth, the intensive development of agriculture, economic and industrial growth and requirements regarding the environment (Fulazzaky, 2014; Fulazzaky & Akil, 2009). Especially in developing countries people are migrating from the countryside to coastal cities in the last 50 years (Tibbetts, 2002). The dynamics of these rapidly changing urban environments implies a challenge for water infrastructure and services (Peter-Varbanets et al., 2009).

Droughts, wet periods and floods which can occur more often due to climate change (Jentsch and Beierkuhnlein, 2008), can cause additional stresses on the water supply system. Other issues related to water infrastructure include groundwater depletion, land subsidence, erosion and seawater intrusion, which are increasingly occurring all over the world. These natural but often human induced processes can largely influence the water supply by limiting the available amount of fresh and clean water and by increasing the chance of flooding (Pandey et al., 2003; Konikow & Kendy, 2005; Qin et al., 2013; Werner et al., 2013; Galloway et al., 2016).

A solution to increase access to water includes centralized water treatment and distribution, which can be economical feasible in densely populated urban areas due to the economics of scale, contrary to rural areas were centralized systems are seldom financially possible (Peter-Varbanets et al., 2009). Currently access to water is unequally distributed, where only the richer part of the population has access to the water supply system. Peri-urban and informal settlements for example are often excluded from the centralized supply due to socio-cultural, economic, political, technological and other reasons (Peter-Varbanets et al., 2009; Akbar et al., 2007). Moreover the quality of centralized water supply systems is often limited (Sorbey, 2002). Although centralized water supply may be successful in some situations, structural problems, not likely to be solved in the near future, cause malfunctioning of centralized water supply in other cases (Peter-Varbanets et al., 2009). In these cases decentralized solutions may be a good option.

A possible decentralized solution that can tackle an unsatisfied demand with respect to water quality includes local household treatment in combination with groundwater, surface water or seawater. Examples of treatment techniques include the water pyramid (desalination of brackish groundwater), reverse osmosis, solar water disinfection (SODIS), or membranes (Klaversma, 2015). Important limitations of these solutions are that it only tackles the water quality issue, and that they are often expensive (in case for the water pyramid, reserve osmosis and membranes). Water treatment, as an end of pipe solution, is not tackling any other problem related to the water supply often occurring in urban deltas like (ground)water depletion, floods, drought, land subsidence, erosion and seawater intrusion.

A decentralized solution that both has potential to improve existing water quality and tackle other water related problems in urban deltas is rainwater harvesting.

Water harvesting is defined as *"the collection and management of floodwater or rainwater runoff to increase water availability for domestic and agricultural use as well as ecosystem sustenance"* (Studer, 2013). Despite the high amount of yearly rainfall in many areas, and the relatively high rainwater quality, rainwater harvesting is not frequently used. The reason for this is unclear. According to Worm (2006), rainwater harvesting is often overlooked by decision makers, planners, engineers and builders due to a lack of information on the feasibility of technical and other aspects.

Rainwater harvesting can limit urban flooding by increasing water retention locally. It can also tackle drought by increasing groundwater recharge, in case rainwater infiltration is done. Land subsidence and seawater intrusion can both be diminished by a decrease in groundwater extraction and erosion can be limited due to the fact that runoff is minimalized (Worm, 2006; Barron, 2009; Studer, 2013).

Rainwater is a relatively clean source, its exact quality however is determined by the concentration of atmospheric pollutants and the design, maintenance and cleaning of the rainwater harvesting system. Clear guidelines in the design of a rainwater harvesting system are missing, and information is scattered between different sources. There is a huge gap between science and practice within rainwater harvesting systems. It is unclear to which extent rainwater should be treated, and although local treatment systems are often used, their performance in reality is not always well documented. The same holds for the sizing of a rainwater harvesting tank or the possibility for rainwater infiltration.

1.2. Research Goals

The goal of this research is the development of rainwater as a valuable water resource. Furthermore, guidelines will be developed for best practices. To reach this goal, possibilities for domestic rooftop rainwater harvesting systems in Serang (Indonesia), an off-grid semi-urban setting in a tropical developing country will be investigated. Rooftop rainwater harvesting is one of the methods for the collection of rainwater whereby water is collected from a roof, private or public, and stored in a tank or bucket, open or closed. Domestic water includes all water that is used for all usual domestic purposes like consumption, bathing and food preparation (Howard & Bartram, 2003). It therefore also includes drinking water. Besides the technical possibilities of rainwater harvesting, this research will also evaluate the social-cultural, economic and legal aspects of rainwater harvesting.

The performed evaluation should help to design a rainwater harvesting system (when suitable) at low costs, which provides domestic water with a sufficient quality and quantity. Rainwater harvesting is currently not practiced frequently in all areas with sufficient rainfall. The reasons for this should be investigated before a successful system can be designed.

The additional goal of this research is to combine practical and scientific knowledge from a multidisciplinary perspective to make the future implementations of rainwater harvesting systems more successful. Both scientific literature and in field knowledge will be consulted. Current knowledge is not integrated and spread in a suitable way. Tests on existing systems are often limitedly done, or not shared. Because of this the same mistakes can be made over and over, which is a waste of valuable time and money. The goal of this research is to integrate knowledge, thereby preventing future mistakes or misconceptions in the design of rainwater harvesting systems.

The integration between current reality, local and scientific knowledge, and in specific the application of scientific knowledge to develop in field guidelines to improve and optimize microbial and chemical system performance, water availability and costs in an integrated way has not yet been done by the scientific community. Limited research is done in which rainwater harvesting systems are evaluated based on multiple criteria. Moreover, other research currently looks at the performance of one specific rainwater harvesting system, whereas this research will make an attempt to evaluate multiple different options in the design of a rainwater harvesting system.

1.3. Research Questions

To fill in the knowledge gap regarding why rainwater harvesting is not practiced frequently and to find more information regarding the quality of rainwater at different locations, the performance of existing rainwater harvesting systems, and the possibilities for cheap treatment of rainwater as discussed in the previous section, the following research question is set up:

How can a domestic rainwater harvesting system in an off-grid urban area in a developing country (with case study Serang, Indonesia) be designed to have an optimal or sufficient performance regarding technical (water quality and water quantity), economic, social and cultural and legal criteria?

In this research question optimal or sufficient performance has to be explained in further detail. For water quality the performance should ideally meet the worldwide and Indonesian water standards. However when for a very low cost large water quality improvements can be made, which still not meet the standard, this can also be considered. For water quantity the system should be sized in such a way that it meets the requirements of the local population regarding the supply. On the view of economic aspects, the local population should be able to afford the designed system, or when needed, with some loan. For the social and cultural criteria local preferences should be taken into account in the design, in case rainwater harvesting is accepted at all. At last legal criteria should be met, since the system should be legally excepted.

The sub-questions are as following:

1. What is the required outgoing water quality for the rainwater harvesting system?

2. What are possible treatment options that meet the requirements regarding water quality, economic, legal and social and cultural aspects?

3. What are the main remaining health risks of using rainwater at a household level in case the advised treatment is applied?

4. What is the optimal system size for a household rainwater harvesting system that is able to link supply and demand by considering the total demand?

5. What is the optimal system size for a rainwater harvesting system by minimizing water costs per volume?

These sub-questions are elaborated in more detail in the methodology section. To answer these research questions Serang (Indonesia) is taken as a case study. Although the research questions are answered for Serang, in the discussion there will be attention for the boundary conditions in which this research can be generalized to other areas.

Main attention of this research will be on the technical aspects of rooftop rainwater harvesting systems, including quantity, quality and treatment aspects and the economic aspects of the system. However for the implementation of rainwater harvesting, social-cultural and legal aspects have to be taken into account as well. Social cultural aspects that are considered include the acceptance of rainwater harvesting, but also the operation and maintenance of the system.

Due to time limitation, these aspects will get less attention in this research, which implies that the following sub questions will be answered in less detail.

6. What are dominating social and cultural preferences regarding water supply, use and the acceptance of rainwater harvesting in particular that need to be considered in the development of a rainwater harvesting system?

7. Is there legislation regarding other aspects than water quality, that should be taken into account in the design of a rainwater harvesting system?

2. Literature review

In this literature review different aspects of rainwater harvesting are discussed. In the first paragraph a definition of rainwater harvesting is given and several advantages and disadvantages from rainwater harvesting are presented. Afterwards rainwater quality, drinking water guidelines and treatment options are discussed followed with water quantity aspects. Finally there is attention for the economic aspects of rainwater harvesting.

2.1. General aspects of rainwater harvesting

Alternative water sources, like rainwater harvesting (RWH), are of increasing importance when surface and groundwater sources face pollution or when these water sources reach their limits because of population growth and increased demand (Worm, 2006). Moreover, climate change is likely to cause additional stress on our water resources (Thomas & Martinson, 2007). Many communities throughout the world are or have been practicing rainwater harvesting, with traditions of thousands of years (Abdel Khaleq, 2007).

Rainwater harvesting is defined several times. Pacy & Cullis (1986) define it as "*the gathering and storage of water running off surfaces on which rain has directly fallen*". Studer (2013) as "t*he collection and management of floodwater or rainwater runoff to increase water availability for domestic and agricultural use as well as ecosystem sustenance*". And Helmreich & Horn (2008) describe rainwater harvesting as "*a technology where surface runoff is effectively collected during yielding rain periods*".

Main components of a rainwater harvesting system include the catchment area, the storage component and the target for which the is used (Oweis et al., 2012). Studer (2013) adds to this the conveyance system. However this is not required for all types of rainwater harvesting systems. Systems exist with different sizes and scales and systems can be designed for domestic, agricultural and industrial use. Additional benefits of rainwater harvesting systems include erosion control, flood control and aquifer replenishments. Depending on the purpose, different catchment areas and storage components are used.

Rainwater harvesting systems are mainly classified based on catchment type or on the size and the method of storage (Studer, 2013). Classification can also be done based on the type of usage. Helmreich & Horn (2008) distinguish three main types of RWH systems. The first is: in situ RWH were rainwater is collected on a surface on which it falls and is stored in the soil. The second is: external water harvesting were runoff is stored at a different location than where it is collected. The last is: domestic RWH, in which water is collected from roofs, streets and courtyards. Studer (2013) classifies rainwater harvesting based on catchment type and distinguishes flood harvesting, rainwater harvesting with a macro catchment, a micro catchment or with a rooftop or country yard. Classification based on type of usage is also possible, for example rainwater harvesting for domestic, agricultural or industrial use or for groundwater recharge.

Catchments sizes range from a few square meters to square kilometers and can be rooftops, paved roads, compacted surfaces, rocky areas or open rangelands, cultivated or uncultivated land and natural slopes (Studer, 2013). For domestic rainwater harvesting systems, roofs should be from a smooth and flat material like roofing tiles, slate, galvanized iron corrugated slabs or paper strengthened with sisal (Pieck, 1977).

Storage can occur in the soil profile as soil moisture, as groundwater in aquifers, above the ground in yards, ponds or reservoirs or underground in cisterns (Oweis et al., 2012). Storage for domestic rainwater harvesting can occur at different scales. It can be at very small scale (<1 m^3) in plastic bowls and buckets, jerry cans, clay or ceramic jards, old oil drums or empty food containers or at large scale in huge storage reservoirs up to around 100 m^3 which are installed at a community or school level (Worm, 2006). Pieck (1977) suggests storage tanks of wood, clay, cement plaster (with a mold), a framework and cement, metal sheets, brickwork or ferrocement. Other possibilities include water pillows, which are according the manufacture an economical and flexible option for rainwater storage (Rainwaterpillow, 2016).

For the implementation of a rainwater harvesting system the local situations should be taken into account. These local conditions include climate (rainfall intensity and distribution), technology, social-economic factors, the local livelihood, the political system and organizational management (Worm, 2006). For a rooftop rainwater harvesting system the distance between catchment and storage should be short to prevent long conveyance systems (Pieck, 1977). Moreover, one should prevent a location near any obstacles or damaging objects like high-tension lines, masts, trees, cattle etc. One should make sure that storage is located as high as possible, since water has to flow under gravity to the house (Pieck, 1977). Another attention point includes the stability of the soil. Furthermore, drainage may be required to prevent the washing away of the system during high groundwater levels (Pieck, 1977).

Rainwater harvesting has many advantages and disadvantages, related to economic, health, ecological and legal aspects and convenience as discussed by Worm (2006), Studer (2013) and Barron (2009) and summarized below. A distinction is made between rainwater harvesting (RWH) and domestic rainwater harvesting (DRWH). For RWH the harvested rainwater can be used for any purpose, were for DRWH it is only used for domestic purposes.

Advantages of RWH systems include water quantity aspects like increasing water availability, the buffering of rainfall variability and the coping with extreme events. However it is sometimes difficult to ensure sufficient water when required, especially when storage capacity is limited, for example by costs. Especially investment costs of a RWH system may be high. It can be difficult to find sufficient capital or labor for the implementation, operation and maintenance of RWH systems.
From a water quality point of view rainwater is of relatively good quality, although contamination is possible, since ponded water can be breeding ground for mosquitos, source of waterborne diseases, algal growth and lizards.
Environmentally, water harvesting can reduce erosion and limit desertification. However productive land may be used and water availability for downstream ecosystems may be reduced. In general RWH is seen as a flexible and adaptable technique, that can also limit work load and poverty. It can increase food production and security, offer changes to produce (higher value) crops or grow livestock. However acceptance of such systems can be low, and right issues can occur within a catchment.
Domestic rainwater harvesting (DRWH), has similar advantages and disadvantages compared to RWH. Agricultural advantages are limited for DRWH. In general a higher water quality is required and microbial or chemical guidelines are not always met. Mosquitos, rats and mice can damage or enter the storage tank. Moreover, the storage can be dangerous for children. Maintenance is found to be of low costs, and easy to control in case it is controlled by the tank owner. Environmental impact of DRWH systems is often low.

There is contradiction regarding advantages and disadvantages of rainwater harvesting between authors. This includes the maintenance aspect of harvesting systems. Maintenance by tank owners can be easier than in poor maintained and monitored centralized piped water supply, but it can also be a problem if it is badly done by individuals or in case the rainwater harvesting system is owed by multiple households. Another contradiction is present regarding the costs of rainwater harvesting systems. Worm (2006) mentions the high investment cost for DRWH systems, were Barron (2009) sees RWH as a low cost technology.

Thomas & Martinson (2007) compared rainwater harvesting with competing technologies including protected shallow wells, boreholes, protected springs with a gravity pipeline to a standpipe, river and pond water and treated water pumped to a standpipe. The comparison was done based on costs, easiness of construction, convenience etc. In general it was found that rainwater harvesting is more convenient to use, has less chemical pollution and depends less on favorable geology or topology then competing technologies. However it does not give better access to poor households, and has no better drought security then the competing technologies.

2.2. Quality

In this section the guidelines for drinking water quality are discussed, and the water quality at different stages in a rainwater harvesting systems is investigated.

2.2.1. Guidelines for drinking water quality

The World Health Organization (2014) provides a three component framework for safe drinking water, in which health based targets should be set, water safety plans are made and system independent surveillance is done. Rainwater harvesting systems are considered as specific case by the WHO, for which the traditional framework is slightly modified. Below first the three components of the WHO framework are discussed, after that attention is paid to the specific case of rainwater harvesting systems.

In the first component of the framework for safe drinking water, health based targets are set. The WHO (2014) distinguishes four types of targets, which include health outcome targets, water quality targets, performance targets, and targets for specific technologies. These are discussed below.

1. Health outcome targets are based on a tolerable disease burden, which should be viewed in a broader public health policy. This implies that major contributors to disease should be dealt with first. In general health outcome targets are set at a national level. The tolerable infection risk for drinking water is set to 10^{-4} per person per year, and 10^{-6} disability adjusted life years (DALYs) per person per year. This can be translated into water quality targets for pathogens or toxic chemicals. For threshold chemicals the health outcome targets are based on no-observed-effect levels.
2. Water quality targets are generally formulated for chemicals and not for microbial or radiological contamination. The chemical drinking water guidelines, which are based on individual chemical risk assessments can be found in Appendix A1. Guidelines are not developed for parameters for which the currently available data does not indicate a health risk or aesthetic problem, or in case

the parameter summarizes multiple other parameters for which individual guidelines are needed (Moore, 1998).

3. Performance targets can be set for microbial contamination (as log reduction) and for chemical hazards (as reduction percentage). Specific targets can be set by a water supplier or generic targets can exist on a national level. Specific targets for microbial contamination are based on a quantitative microbial risk assessment and on health outcome targets for microbial contamination. For chemical contamination they are based on chemical guideline values. In general treatment processes are evaluated based on removal, and it can be checked whatever a certain treatment combination meets the performance target. The targets with respect to microbial performance of household water treatment technologies can be found in Table 1.

Table 1: Microbial performance classification for HWT systems (WHO, 2016).

Performance classification	Bacteria (log_{10} reduction required)	Viruses (log_{10} reduction required)	Protozoa (log_{10} reduction required)	Interpretation (assuming correct and consistent use)
★★★	≥ 4	≥ 5	≥ 4	Comprehensive protection (very high pathogen removal)
★★	≥ 2	≥ 3	≥ 2	Comprehensive protection (high pathogen removal)
★	Meets at least 2-star (★★) criteria for two classes of pathogens			Targeted protection
-	Fails to meet WHO performance criteria			Little or no protection

4. Specific technology targets are set to control microbial or chemical hazards. They contain recommendations for certain actions for small scale supply systems, and are based on source water quality. In targets specific permissible devices or processes are identified and with this they provide a recommendation whatever certain technologies are applicable in certain circumstances.

As second component of the framework for safe drinking water, water safety plans are advised for existing supply systems. Goal of the framework is to manage health risks that could threaten the water supply. One should identify hazards, hazardous events and risks, measure the water quality and improve the situation in a circular approach. Especially in small communities, many operators face lacking assistance from experts, seasonal variations in water quality and demand, limited management and technical support and limited access to financial resources. The water safety plan is an integral and ongoing way of operation, maintaining and managing the water supply. Six tasks are defined which are explained in detail in Appendix A2.

The third component of the safe drinking water framework is the system independent surveillance which is in most cases done by the public health ministry. It includes continuous and vigilant public health assessment and review of the safety and acceptability of the drinking water supply (on all scales). Information alone does not lead to improvement, it should be managed and used effectively. Follow up will be necessary to ensure that action is taken. Not only the quality of the water supply, but also the quantity, accessibility, affordability and continuity is assessed. Main goal of surveillance is to identify interventions that will result in water supply and health improvements, and to identify the communities for which improvements in the water supply will result in the greatest health improvements (Howard & Bartram, 2005).

In case independent surveillance not exists, self-surveillance can be done. Cheap self-surveillance methods under development include applications on a mobile phones, bio monitoring and test strips. The turbidity of the water can be checked visually. Furthermore, water can be assessed by smell. To get a better indication of the water quality testing kits could be used, or laboratory analysis could be done.

2.2.2. Rainwater and runoff quality

When discussing the water quality with respect to rainwater harvesting it is important is to make a distinction between rainwater quality, water quality after collection on the roof, water quality after transport towards the tank, water quality processes in the tank itself and at last the water quality at the point of extraction. In the text below the rainwater quality itself and the processes causing additional contamination or contaminant removal at these different steps are described. Main processes are illustrated in Figure 2.

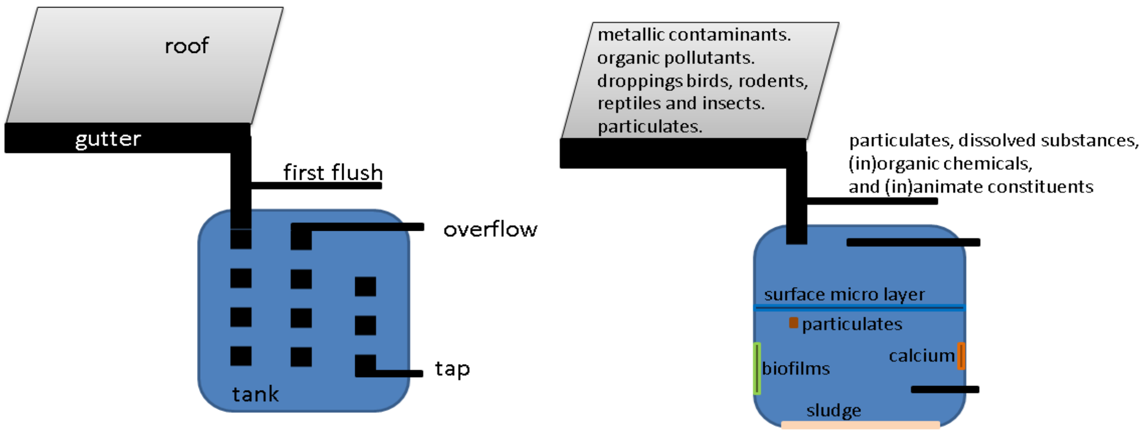


Figure 2: Schematization of a rwh system (left) and water quality processes (right) (Abbasi & Abbasi, 2011).

Rainwater is initially a relatively clean water source, which is free of contaminants except those that are picked up in the atmosphere (WHO, 2013). An important characteristic of rain is that it is in general acid since it falls through air, which is saturated with oxygen and carbon dioxide. The pH can be around four to five in polluted urban areas and around six in rural areas (Thomas & Martinson, 2007). Also some heavy metals and urban pollutants can be present in the rainwater (Thomas & Martinson, 2007). In some areas air quality can be so bad that roof runoff is not suitable for drinking purposes (Abbasi & Abbasi, 2011). Especially for West-Java, attention should be payed to flying ash (Lufiandi, 2016), a hazardous material that comes into the air during the burning of coal.

On the roof, contamination can be added or removed from rainwater (De Kwaadstenied et al., 2013). This is dependent on the roof geometry and material, characteristics of the rainfall event and other methodological factors, concentration of several substances in the atmosphere, the location of the roof and the maintenance of the roof (Abbasi & Abbasi, 2011; Forster,1996). Water running from the roof, often still has pH values below the WHO guideline (Yaziz et al., 1989).
Roofs can be an important source of nonpoint water pollution (Chang et al., 2004). Metallic contaminants can be removed or added to the rainwater (copper, zinc, aluminium, manganese and lead) (Abbasi & Abbasi, 2011; Chang et al., 2004). Leaching of metals (and other substances) from the

roof can be facilitated by acidic rain especially in case lead based paints, fittings, bitumen based coatings or metals are used (Abbasi & Abbasi, 2011; WHO,2013). Roof runoff also can contain some organic pollutants. These pollutants are derived from the burning of fossil fuels, fuel leakage of vehicles, petrochemical and plastic-chemical industries and the application of pesticides (Abbasi & Abbasi, 2011). Polycyclic aromatic hydrocarbons (PAHS) are the largest class of carcinogens that are present in urban atmospheric deposition (Abbasi & Abbasi, 2011; Haberland et al., 2014). Other organic air pollutants include phthalate ester (Pes), pesticides, and polychlorinated biphenyls (PCBs) (Guidotti et al., 2000). Organic roofs may release chemicals that are used to preserve the roofing material, such as arsenic. Inorganic material like dirt can also be blown onto the roof (Intven, 2009). Dropping of birds, rodents, reptiles and insect cause microbial contamination entering the tank, of which some species of *Salmonella*, *Campylobacter*, *Giardia* and *Cryptosporidium* and various opportunistic bacteria are the most relevant in rainwater harvesting systems (Abbasi & Abbasi, 2011). Particulates carrying micro-organisms or organic matter can enter the tank via the roof. However the roof itself is for pathogens a less welcome environment, since they are evolved to live in a wet and warm environment with limited oxygen (Thomas & Martinson, 2007).The dry heat effectively kills pathogens, which is most effective on metal roofs (Thomas & Martinson, 2007).

Gutters can, especially when not cleaned regularly, be source of large amounts of organic material, which is an important source of nutrients for bacteria and insects. In gutters the die-off of pathogens is less than on the roofs (Thomas & Martinson, 2007).
First flush reduces the concentrations of various substances entering the tank, although not all contaminations have their highest concentration during the first flush. First flush is described in more detail in paragraph 2.3.1.

In the tank itself settlement takes place, creating a sludge layer. This process removes, together with the first flush, a large proportion of the heavy metals, urban pollutants and suspended sediment (Thomas & Martinson, 2007). Aerobic micro-organisms form a layer at the water surface (Abbasi & Abbasi, 2011). Leaching calcium (from the tank) may reduce acidity, causing dissolved metals to precipitate (Abbasi & Abbasi, 2011). Also biofilms can play an important role in the absorption of heavy metals (Abbasi & Abbasi, 2011). It is often the case that direct contamination routes, like drowning animals, swimming children and accidents with the spillage of raw sewage are the largest cause of reported illness (Thomas & Martinson, 2007). Mosquitoes can be a problem inside rainwater harvesting tanks and in gutters (Thomas & Martinson, 2007). Also in well-designed tanks larvae can be found, since a tight fitting is not always as tight as it should be. Mosquitos can cause malaria, heart worm, yellow fever, dengue fever and encephalitis (Kahinda, 2007). However in well-designed covered tanks, where no light can come in, and without nutrients larvae will not develop towards adult mosquitos (Thomas & Martinson, 2007). Next to mosquitos *Legionella* can be a serious risk (Ley, 2002), in systems in which temperatures exceed 20 degrees. Simmons et al. (2008) found *Legionella* in 10% of the rooftop rainwater harvesting systems in East Auckland (New Zealand).

At extraction harvested rainwater is according De Kwaadstenied et al. (2013) in many incidences not suitable for drinking purposes without treatment. This is confirmed by Gikas & Tsihrintzis (2013). Total bacteria and fecal indicators are tested and detected in several studies. An overview of the concentrations found is presented in Appendix A3. Lead, copper, zinc, aluminium, manganese were found to be above guideline values in harvested water (De Kwaadstenied et al., 2013; Yaziz et al., 1989; Abbasi & Abbasi, 2011). Organic pollutants, especially PAHs are in some cases found in

rainwater. Huston et al. (2009) found 4-methylphenol, anthracene, naphthalene, diuron, simazine and terbutryn above the detection limit, but below guideline values in rainwater tanks. Besides the pollution of rainwater, the lack of fluoride in harvested rainwater can require the use of fluor supplements (Sazakli et al., 2007).
However in the RAIN Water Quality guideline it can be found that treatment of harvesting water from rooftops is most of the time not needed (RAIN, 2008). Moreover, they state that in developing countries, water treatment is often impractical and expensive in most small and remote settlements. Important to mention is that the same guideline states that water treatment should be applied when health is at risk. Abassi & Abassi (2011) state that studies that claim that rainwater harvesting systems provide acceptable water quality are based on incomplete and less than adequate sensitive analysis.

Lee et al. (2010) showed that concentrations of several chemicals and microbial indicators vary with season. This counts both for harvested rainwater (roof-runoff) and reservoir water (Figure 3). Furthermore, Thomas & Martinson (2008) mention that microbial contamination at the water extraction point fluctuates largely over an even smaller time scale (Figure 4). Microbial concentrations increase during rain events, and after time concentrations reduce due to settlement. In three days reductions can be up to 90%. It is important to take this fluctuation into account when measuring contamination in systems.
Thomas & Martinson (2007) and Abott & Caughley (2012) mention the fact that just a limited number of illnesses are reported due to consumption of rainwater. Rainwater harvesting systems are on small scale, and outbreaks are often only reported in case it occurs at a larger scale. Moreover, a proportion of the population exposed can get immune for relevant pathogens (Abbott & Caughley, 2012).

Micro-organisms associated with untreated rainwater include *Salmonella*, *Campylobacter*, *Legionella pneumophila*, *Clostridium*, *Aeromonas hydrophila, Pseudomonas aeruginosa, Staphylococcus aureus, Giardia*, tissue helminths and Cryptosporidium (Ahmed et al., 2009; Ahmed et al., 2014; Lye, 2002; Gould, 1999). Most of the reported cases are of S*almonella* (bacterial diarrhea), which can be spread via faeces and is mainly associated with bad circumstances including bird droppings on the roof or frogs inside the tank (Thomas & Martinson, 2007). *Legionella pneumophila* and *Aeromonas hydrophila* are examples of opportunistic micro-organisms that can grow in drinking water (Wielen & Kooij, 2009). Optimum temperatures for *Aeromonas* spp. are around 28 ˚C, and *Legionella pneumophila* growths at temperatures between 20 and 43 ˚C (Wielen & Kooij, 2009).

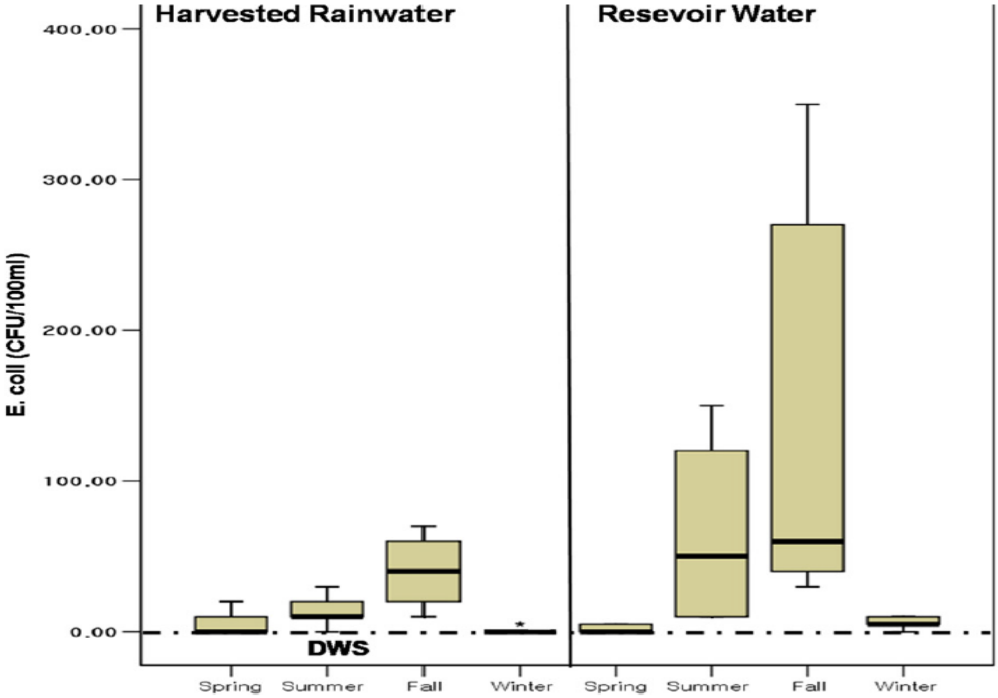


Figure 3: The fluctuation of *E.coli* concentrations (CFU/100 ml) in rainwater per season (Lee et al., 2010).

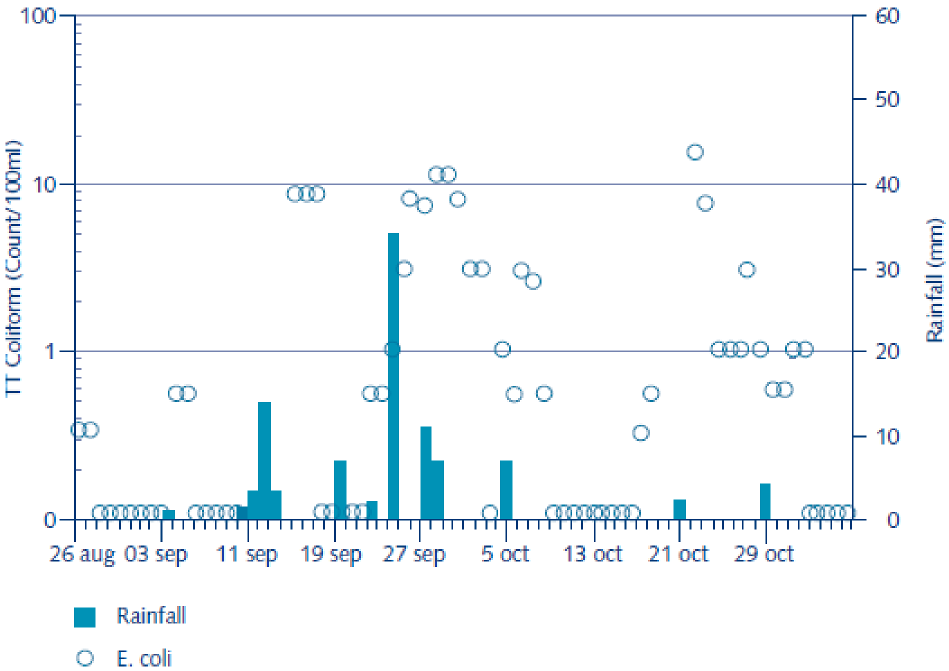


Figure 4: *E.coli* concentrations (count/100 ml) and rainfall (mm) in a rainwater harvesting tank over time (Thomas & Martinson, 2007).

2.3 Treatment options

In the design of a rainwater harvesting system pollution can be prevented in several ways, which can have an important effect on the water quality in the system. Water can be treated either before it enters the tank, after it leaves the tank or at the point of use. Below first the possibilities for pollution prevention are discussed. Furthermore different treatment options are explained.

According Medema (2016) the five most important health aspects of a rainwater harvesting systems include the rainwater quality after collection on the roof, the treatment, the regrowth during storage, mosquito larvae in the stored water (dengue, chikungunya, zika) and recontamination because of insufficient hygiene and the leaching of several substances from the storage reservoir. In the design of a rainwater harvesting system it is important to pay special attention toward these points.

2.3.1. Pollution prevention

Pollution of rainwater harvesting can be prevented by simple measures including the use of first flush devices, the regular cleaning of the roof, gutter and tank, the application of suitable system materials and the installation of an overflow pipe. These measures are discussed below.

System cleaning

The regular cleaning and inspection of the catchment area and gutter can help to ensure good water quality (Worm, 2006; Abdulla & Al-Shareef, 2009). First flush should, when required, be emptied after each storm. Tanks should be cleaned once a year, at the end of the dry season. They should be scrubbed out, screens should be replaced and the water outlet should get some service. Worm (2006) advices to regularly clean the whole domestic rainwater harvesting system in the rainy season (including catchment, gutter, pipe, screens, first flush and overflow). Especially when dry periods longer than a month occur cleaning of the roof and gutter is important, due to the accumulation of dry deposition on the roof and elevated concentrations of air pollution. All time during the year leaks and cracks in the tank should be repaired, also the outlet should not be leaking. The overflow pipe should be free of obstacles.

System design

To prevent both microbial and chemical contamination and mosquitos inside the rainwater harvesting system, attention should be paid toward the system design and the used material. Suitable roof materials include tiles, slates and aluminium sheets. Wooden and bamboo gutters should be prevented, together with thatched roofs, or roofs containing zinc, copper, lead, asphalt or coating (Helmreich & Horn, 2009; Worm 2006). Wood and bamboo can rot away and leak, creating an ideal environment for bacteria to accumulate (Worm, 2006). Aquaplate, plastic and concrete tanks were found to show a similar water quality at the tap, with minimal contributions from the material used for tank construction. However, concentrations of strontium, molybdenum and arsenic were found to be influenced by the tank material (Morrow et al., 2009).Overflow of the tank should be prevented by the installation of an overflow pipe since this can cause pollution (Worm, 2006). Mosquitos should not be able to enter the tank, and ponding water in the gutter, on the roof or after the overflow pipe should be prevented since these can provide growing places for mosquitos.

First flush

First flush, which disregards the first portion of rainfall, can be done manually or automatically. One manual and two automatically working first flush devices are illustrated in Figure 5. The first flush can improve the water quality in the tank because the first portion contains the most dirt, debris, bird droppings and contaminants that accumulated on the roof during the dry period (Abdulla & Al-Shareef, 2009). Although, the installation of a first flush device will improve the physicochemical quality of the collected rainwater, it will not avoid all microbial contamination of the rainwater (Gikas & Tsihrintzis, 2013).

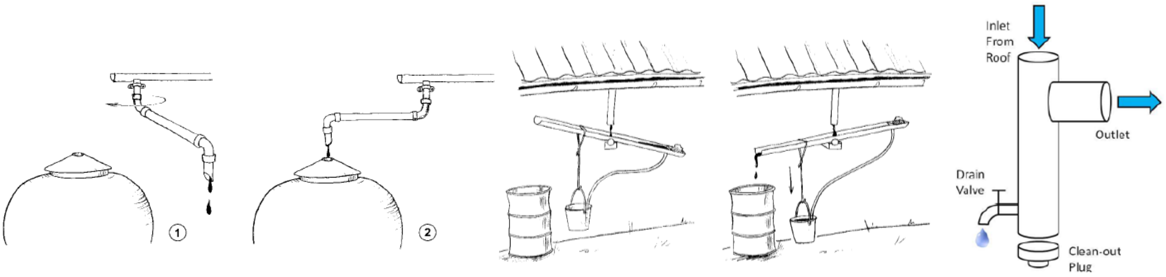


Figure 5: Manually first flush device (left), a fixed mass system (middle) and the SafeRain system (left) (Worm, 2006; Ling & Benham, 2014).

Mendez et al. (2011) found that the concentration of most water quality parameters decreased by using a first flush, as shown in Figure 6. Black bars indicate the quality of the first flush, and grey bars the quality after first flush. To indicate microbial contamination total coliforms (TC) and faecal coliforms (FC) are measured. Standard deviation is given.

The amount of precipitation that should be regarded as first flush depends on the season and the amount of air pollution in the given area (Abdulla & Al-Shareef, 2009). There is debate about the amount of first flush that should be divided. According to Ntale, et al. (2003) the amount of first flush should be 0.83 mm. Martinson & Thomas (2005) gave as a rule of thumb that "the contamination is halved for each millimeter of rainwater that is flushed away". Mendez et al. (2011) used a first flush volume of 0.41 mm. Bertrand-Krajewski et al. (1998) found that in 50% of the rainfall events, 50% of the total pollutant mass was transported in the first 38% of the water volume and 80% of the pollutant was transported in the first 74% of the total volume. However, the M(V) curves they developed were found to be very variable based on the pollutant and the catchment. M(V) curves show the relation between the cumulative mass/total mass with respect to the cumulative volume/total volume.

2.3.2. Household treatment

When it is decided to apply water treatment, this can be done either before the water enters the tank, inside the tank, or just before consumption at the house. Several different low costs water treatment techniques exist that can be applied at a local scale. A distinction is made between point of use systems and point of entry systems. The first only treats water that is used for drinking and cooking, the second treats all water used for a household water and also include small-scale treatment systems that are applied on the scale of a small village (Peter-Varbanets et al., 2009). Some of these small-scale treatment systems are specially designed for rainwater harvesting systems. Factors that should be considered when applying a specific type of treatment includes the effectiveness of pathogen removal, the costs, the availability of materials and system parts, the scale of the treatment, the mode of treatment (continuous or batch) and the time and effort that can be invested by the local population for their water treatment (Brownell et al., 2008).

Peter-Varbanets et al. (2009) mentions different treatment techniques that can be applied at a as household level. Main categories that are discussed include heat and UV based systems (boiling, solar radiation and SODIS and UV light), chemical treatment methods (chemical disinfection, adsorption, ion exchange and coagulation, precipitation, sedimentation) and physical removal processes (sedimentation, granular media filters, aeration and filtration including membranes, ceramic and fiber filters). Also a combination of these techniques is possible. Although Peter-Varbanets et al. (2009) discusses these treatment systems as point of use systems, most of them can also be applied as point of entry treatment.

Different types of treatment require different types of resources during installation and operation. Household treatment systems investigated either require electricity, direct solar energy, natural resources like wood or chemicals, or are gravity based. Gravity based systems have a huge advantage above the others, due to limited operation costs. In Table 2 the resource requirement of different type of treatment systems can be found.

Table 2: Type of resource or mechanism which different treatment methods rely on during operation. √ indicates that the resource is one of the options that could be used, √√ indicates that the resource is required for system operation.

	Boiling and pasteurization	SODIS	UV	Chemical disinfection	Granular media filtration	Ion exchange	Membrane	Paber, fiber and fabric filters	Ceramic filtration
Electricity	√		√√				√		
Direct solar energy	√	√√							
Wood and other resources	√								
Gravity					√√	√√	√	√√	√√
Chemicals				√√		√√			

When comparing the performance (log$_{10}$ removal in the field) of various household treatment options thermal heat is found to have high removal rates for bacteria, viruses and protozoa, a log$_{10}$ removal of six was found (WHO, 2013). Sedimentation was found to be ineffective during baseline circumstances. Hunter (2009) compared different household treatment techniques, including chlorine and safe storage, combined coagulant and chlorine disinfection, SODIS, ceramic filtration and bio-sand filtration. It was found that ceramic filters are, on the long term, much more effective than the other options. The investigated disinfection only interventions (chlorination, coagulation-chlorination, or SODIS) were found to have a poor, if any effect on the long term (Hunter, 2009). In general multi-stage treatment is more effective then single treatment steps. According Schmidt & Cairncross (2009) the tests regarding effectiveness can be biased, and other transmission routes (person to person contact, contact with contaminated soil and surfaces, food, and flies) also play role in the spread of diarrheal pathogens. Hunter (2009) confirms that studies regarding the effectiveness of household water treatment are often poorly designed.

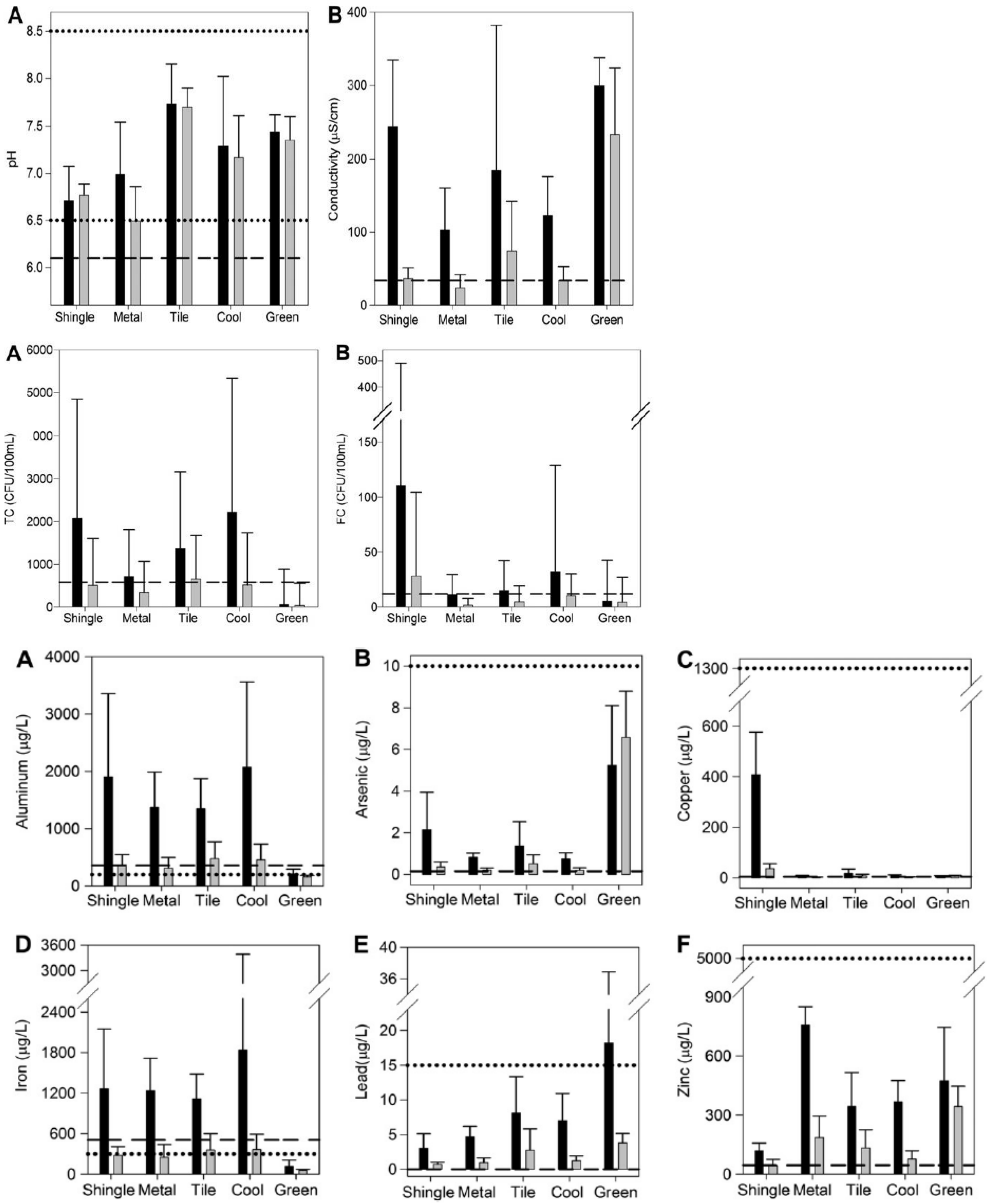


Figure 6: Average concentration of microbial and chemical parameters on pilot scale roofs from different materials (Mendez et al., 2011).

Most household water treatment systems are not designed to remove chemical contamination from the water source. This is most likely linked to the fact that in most developing countries diseases related to microbial contamination are more urgent and visible.
In Table 3 an indication is given of the microbial and chemical effectiveness of several household water treatment systems. In the remaining part of this paragraph these treatment systems are further discussed. In section 2.3.3. there is attention for existing treatment devices that are used in RWH systems.

Table 3: Microbial and chemical effectiveness of several household water treatment options. Low microbial removal (≤ 1 log), medium removal (>1 and <3 log) and high removal (≥ 3 log) are distinguished.

	Boiling and pasteurization	SODIS	UV	Chemical disinfection	Granular media filtration	Membrane	Paber, fiber and fabric filters	Ceramic filtration
Bacteria	High	High	High	High	Low	High	Low	Medium
Virus	High	Medium	High	High	Low	Medium	Low	Low
Protozoa	High	Low	High	High*	Medium	High	Low	High
Chemical contaminants	No	No	No	No	Some	Some	No	Some

2.3.2.1. Heat and UV based systems

Boiling and Pasteurization

Boiling with fuel is a conventional water disinfection technique that is the most used household water treatment over the world, with 21% of the households practicing it (Rosa & Clasen, 2010). Especially in Indonesia, Mongolia, Uzbekistan and Vietnam boiling is widely done. In these countries more than 90% of the households apply this technique (Rosa & Clasen, 2010). However self-reported use as discussed by Rosa & Clasen (2010) can differ quite a lot from actual use. This is confirmed by Brown & Sobsey (2012) in Cambodia, where self-reported use was found to be 90%, and the actual use was 31%. Boiling can effectively destroy all waterborne pathogens, including viruses, bacteria and bacterial spores, fungi and protozoans and helminths (Sobsey, 2002). It can be used to disinfect water with a wide range of physical and chemical characteristics, and is for example effective for water with high turbidity (Clasen et al., 2008). Removal rates above 10 log can be expected when water is boiled for longer than one minute, for bacteria and viruses (Hijnen, 2011). Spores can however be more heat tolerant, for one minute boiling a log removal of 0.1 can be expected for *Clostridium perfringens*, *Clostridium botulinum*, *Bacillus subtilis* and *Bacillus anthracis* (Hijnen, 2011).
In Table 4 the effectiveness of boiling can be found. Measurements are performed at in field. As can be expected removal rates are lower in the field, for example because the boiling is done for insufficient time, or because of recontamination.

Table 4: Effectiveness of boiling against thermotolerant coliforms (TTC), *E.coli* and faecal coliforms.

	Water source	Country	Reduction	Source
TTC	River, streams, open wells	Vietnam	97%	Clasen et al., 2008.
Geometric mean TTC	Unprotected wells or boreholes	India	99%	Clasen et al., 2008.
TTC	Groundwater	Guatemala	82.2%	Rosa et al., 2010.
E.coli	Rainwater	Cambodia	98.7%	Brown & Sobsey, 2012.

Although boiling of water is preferred, pasteurization temperatures of above 60 degrees for a period of minutes to tens of minutes can destroy most waterborne pathogens (Sobsey, 2002). In Figure 7 an overview is given of the survival of several bacteria species at different pasteurization temperatures. Major disadvantages of boiling with fuel like fire wood is that it is often more costly than other treatment methods, requires additional time and energy to collect the (limited available) fuel and is environmentally unsustainable (Clasen et al., 2007; Peter-Varbanets et al., 2009; Mintz et al., 1995). Moreover, boiling with fuel can increase indoor air pollution (Schmidt & Cairncross, 2009). These disadvantages can be overcome by using other treatment techniques or by using solar energy to heat the water. Pasteurization without UV is possible in a vessel that is capable of absorbing heat, in most cases black or metal containers, in which temperatures above 60 degrees can be reached (Peter-Varbanets et al., 2009). Solar reflectors and solar cookers can help to increase water temperatures in containers (Sobsey, 2002). Recontamination should be prevented by storing water in the same and covered vessel in which it is heated (Brown & Sobsey, 2012; Sobsey, 2002).

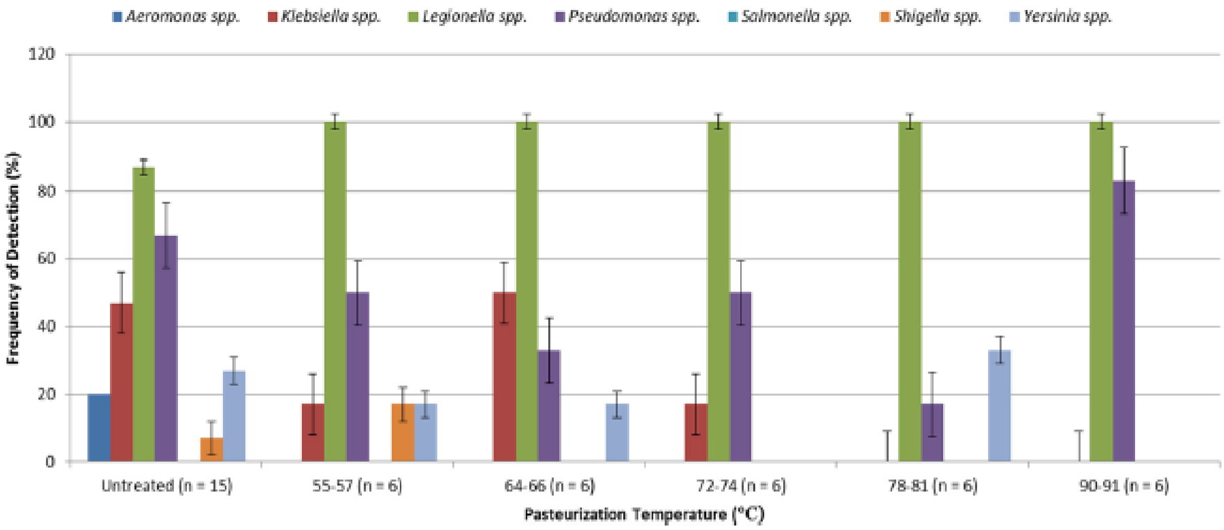


Figure 7: Percentage of unpasteurized rainwater and duplicate pasteurized rainwater samples that is tested positive for various of bacterial genera (Dobrowsky et al., 2015).

In practice boiling as household water treatment does not give a guarantee for the removal of microbial contamination at the point of water consumption. Sodha et al. (2011) tested water quality in 242 random selected households in South Sulawesi, Indonesia. It was found that after boiling, 44% of the samples at the water storage still contained *Escherichia coli*. In case the water was not boiled, 89% of the samples contained *E.coli*. The geometric mean was found to be 0.8 (most probable number estimate of colony counts per 100 mL) in case of boiling, versus 29.9 (MPN/100 mL) in case no boiling was applied.

Solar radiation

By the use of solar energy, one can combine UV-A radiation and heat to treat water. The technique is seen as reliable, and is low cost (Li et al., 2010). Different solar treatment systems are described, from which SODIS is the most practical and economical (Sobsey, 2002).

Microbes are inactivated by absorbing solar rays and sunlight excites molecules present inside cells and turns them into reactive oxygen species, that can damage cell membrane, proteins and DNA (Pandit & Kumar, 2015). According Lagtagne et al. (2006) SODIS can reach high removal rates for bacteria, viruses and protozoa. Sobsey at al. (2008) expects removal rates of 3, 2 and 1 log for bacteria, viruses and protozoa respectively. Water is placed in plastic bottles and bags, temperatures should range between 50-55 and 65 degrees and suspended solids should be low (Sprinks et al., 2006; Helmreich and Horn, 2009; Lit et al., 2010). The user should shake the bottles to aerate the water (Peter-Varabanets et al., 2009). In practice SODIS is not always found to be effective. Meera and Ahammed (2006) still found heterotrophic bacteria after application of SODIS in India, and Amin & Han (2009) found microbial indicators to be above the drinking water standard after rainwater was stored in pet bottles and kept in the sun in South Korea. Methods to optimize SODIS include the use of solar collector disinfection (SOCO-DIS), titanium dioxide, simple dyes like methylene blue or rosebengal or seed treatment (for example M.oleifera) (Kwaadsteniet et al., 2013; Helmreich and Horn, 2009; Pandit & Kumar, 2015).
A system, based on evaporation, that is suggested in combination with rainwater harvesting is a shallow pan with sloping glass cover that can be installed on the roof or on the ground to purify rainwater (Kinkade-Levario, 2013). Undesired contaminants are left in the pan, and should be washed away daily. After treatment water is stored in the rainwater harvesting tank.

UV light (using lamps)
Pathogens can be killed by the exposure of UV light. Bacteria, viruses and protozoa are expected to reach a log 3 removal (WHO, 2016). The least sensitive pathogens for UV light are protozoan (Cheremisinoff, 2001). However the chlorine resistant protozoan *Cryptosporidium parvum* oocyst and *Giardia lamblia* cyst can be inactivated (>3 log) by using UV-light (Peter-Varabanets et al., 2009). Efficiency of UV light treatment decreases for more turbid waters. Flow in the filters must be turbulent and water should not be exposed to visible light since the process can be reversed by photoreactivation (Cheremisinoff, 2001). Point of use water treatment technologies with UV light exist. Disadvantages of UV technology includes the requirement of electricity and the fact that water is not protected against recontamination (Brownell et al., 2008; Peter-Varabanets et al., 2009). Brownell et al. (2008) designed a UV light local treatment tube under 50 US dollar. The tube was tested in the field and found to reduce *E.coli* concentrations to less than 1 per 100 mL in 65 of the 70 samples of 100 mL.

2.3.2.2. Physical/Chemical treatment

Chemical disinfection
Chlorine is a cheap, common and easy chemical disinfection method which inactivates the majority of waterborne pathogens (De Kwaadsteniet, 2013).. Sobsey et al. (2008) excepts removal rates of 3 log for most bacteria, viruses and protozoa. Chlorine is not effective for *Cryptosporidium Parvum* oocysts and *Mycobacteria* species (De Kwaadsteniet, 2013).Chlorine tablets, solution, gas or bleaching-powder can be used (Pieck, 1977; Helmreich and Horn, 2009). An important advantage of chlorination is the residual disinfection capacity (WHO, 2016). The requirement of 0.4-0.5 mg/L free chlorine should be met (Helmreich and Horn, 2009). Disadvantages include that the taste of the

water can be effected, an overdose of chlorine can cause health problems and that it is less effective in turbid or organic rich water (WHO, 2013). Moreover, disinfection byproducts can be formed in case natural organic matter is present in the water (Singer, 1994) which can have possible adverse reproductive effects on humans (Hrudey, 2009). Because of this chlorination should take place after water has left the storage tank to prevent reaction with the organic matter that settles at the bottom of the tank (Helmreich and Horn; 2009). However Mosly (2005) advises to add chlorine to the rainwater harvesting tanks when it is known that there is a bacterial risk, individuals are getting sick because of the water, the tank cannot be cleaned and/or when animals or fecal material has entered the tank.

Other chemicals that can be used for water disinfection include iodine, silver, copper and quaternary ammonium compounds (Sobsey, 2002). However according Sobsey (2002) none of these chemicals are considered suitable for long term use as water disinfectant. Iodine, silver and copper ionization are difficult to deliver to water and copper and silver are bacteriostatic (they stop the reproduction, but do not kill them). Quaternary ammonium compounds are limited available, costly and not effective against viruses. The extent to which silver alone inactivates microbes is limited, bacteria can develop silver resistance. Moreover, many microbes including viruses, protozoan cyst, oocysts and bacterial spores are often not inactivated at the silver concentrations used (Sobsey, 2002). Rohr et al. (1999) for example found that *Legionella* developed a tolerance to silver-copper ionization in a German university hospital. Silver concentrations of 30 µg/L, only gave a 1.3 log reduction in *Legionella*.

Coagulation, flocculation and/or sedimentation

Coagulation, flocculation and sedimentation often occur in combination. First the mainly negatively charged particles in water are destabilized (coagulation), were after they can collide and stick to each other (flocculation) and settle to the bottom (sedimentation) (Beless & Ardner, 2004). This combination is a widely applied water treatment method that can remove turbidity and microbes in water (Sobsey, 2002; Pandit & Kumar, 2015). In water treatment sedimentation is often followed by filtration, which is explained in paragraph 2.3.2.3.

Coagulation and flocculation can be initiated by adding salts of aluminium (aluminium sulphate), iron (ferric sulphate), lime or other inorganic and organic chemicals. For point of use systems alum potash, crushed almonds or beans and the contents of moringa and strychnos seeds have been used (Sobsey, 2002). Moringa oleifera is a coagulant from plant origin that traditionally has been used to clean water, and has been ranked as one of the best extracts of plant origin (Pandit & Kumar, 2015). To get maximum reduction of turbidity and microbes, coagulant dose, pH and the water quality treated should be considered. Furthermore, mixing conditions should be appropriate (Sobsey, 2002). According Sobsey (2002) currently household water treatment by coagulation-flocculation is not highly recommended because more information is needed on effectiveness, reliability, availability, sustainability and affordability. However Peter-Varbanets et al. (2009) states that tablets and powders that combine coagulation, flocculation with disinfection, can extensively reduce bacteria, viruses and protozoa for a relatively low costs of around 0.01 US dollar per liter.

The size of the microbes is very important for sedimentation processes. Viruses and bacteria are generally too small to be removed by sedimentation, were protozoan can be removed (Sobsey, 2002). Helminths (multicellular animals) of concern generally settle fast enough to be removed by sedimentation (Sobsey, 2002). For longer settling times, smaller particles will settle. However, bacteria and viruses are too small to settle, also over longer time spans (Sobsey, 2002).

In rainwater harvesting tanks sedimentation plays a primary role to reduce the contaminant load in the tank (Novak et al., 2014). The microbial water quality improves when water is stored undisturbed and without mixing, for long enough for particles to settle (Sobsey, 2002). Concrete and plastic tanks can facilitate an increase of pH in the tank, thereby facilitating the precipitation and removal of heavy metals (Novak et al., 2014). Settled material include heavy metals such as copper, nickel, zinc and lead and should be removed without disturbing the sedimentation process (Sobsey, 2002;Novak et al., 2014).

Ion exchange

Ion exchange is largely practiced on large scale treatment plants for the softening of water, but can also be applied on household scale. One can distinguish softening resins, deionizing resins, iodine disinfection and adsorbent and scavenging resins (Sobsey, 2002). Softening and scavenging resins are not recommended for household treatment and the effect of long term consumption of deionized water is not totally understood (Sobsey, 2002). Iodine disinfection can be practiced on a household scale to disinfect water (Sobsey, 2002). Water flows through portable systems like cups, pitchers and columns where microbes come into contact with the iodide (Sobsey, 2002). Although this technique is effective and convenient, it is too expensive to use in developing courtries (Sobsey, 2002).

Aeration

Aeration, especially when done manually in a vessel is simple, practical and affordable (Sobsey, 2002). Aeration can remove taste- and odor-producing substances like hydrogen sulphide by physical removal. Chemically it can remove metals (iron, manganese), gases and other organic and inorganic compounds by oxidation and settling (Rajenden, 2000). Aeration can also be used to biologically oxidize domestic and industrial organic waste (Rajenden, 2000).

Microbial water quality can be indirectly influenced by these processes, although there is currently no clear evidence that aeration alone can reduces microbes in water consistently and significantly (Sobsey, 2002). Especially in combination with sunlight or heat aeration can have an effect on microbial water quality (Sobsey, 2002). Aeration pumps are commercially sold, for the use in rainwater harvesting tanks to avoid stagnant water, for example the HP-200 aerating pump.

2.3.2.3. Filtration processes

Filters reduce microbial contamination by both physical and chemical processes. Pore size is very important in determining the performance of a filtration device. Removal depends on size, shape and surface of the particle to be removed compared to the pore size, depth and physical-chemical properties of the filter (Sobsey, 2002). Systems require regular cleaning and maintenance of their parts. Already simple filters that prevent debris from entering the tank can improve the water quality

(Worm, 2006). Filters include granular media, paper, fiber and fabric filters, membrane filters and ceramic or composite filters which are discussed below.

Granular media filters

In a granular media filter particulates and in some cases specific contaminants are removed by a solid-liquid separation process (Boller & Kavanaugh, 1995). Different grain sizes can be used, and filters can be produced from local materials, are simple, easy to use and can have a long life time (Peter-Varbanets et al., 2009). Traditionally vegetables and animal matter have been used in granular media filtration (Sobsey, 2002). Coal-based and charcoal filters, sponges, sand, cotton, wool, linen, and pulverized glass are all materials that could be used (Sobsey, 2002).Palm fiber is another alternative, removing turbidity in water. However this material is also related to a drop in dissolved oxygen and creates odor and taste problems (Galvis, 2002).

Slow sand filtration uses biological treatment to improve the bacteriological quality of the water. A developed schmutzdecke, which takes 30 days to form, can remove 97% of *E.coli*, 99% of protozoa and helminths, 50-90% of the organic and inorganic pollutants, 95% iron and 90% arsenic (Pandit & Kumar, 2015). Biosand filtration, a slow sand filtration on household scale was found to remove 94% of *E.coli* during lab conditions, and 93% reduction in the field in the Dominican Republic (Stauber, 2006). Sobsey et al. (2008) expects removal rates of 1, 0.5 and 2 for biosand filtration in field for bacteria, viruses and protozoa respectively. A constant flow and regular cleaning is necessary to be effective (Helmreich and Horn, 2009; Peter-Varbanets et al., 2009). Micro-organisms are reduced but not totally removed (Li et al., 2010). Because of this additional disinfection is required to supply safe drinking water (Pandit & Kumar, 2015). Slow sand filtration can be incorporated in domestic tanks in done (Thomas, 1998).

Rapid sand filtration can be used to remove hazardous substances that are particle bound (Helmreich and Horn, 2009). Charcoal and activated carbon are extensively used as adsorbents for water treatment all over the world (Sobsey, 2002). These materials can adsorb microbes. However dissolved organic carbon takes adsorption sites, biofilm can growth rapidly and indicator bacteria colonize carbon particles (Sobsey, 2002). Because of this carbon does not remove pathogens on long term. Only charcoal or activated carbon in combination with other treatment should be considered for household water treatment (Sobsey, 2002). For example mixed media filtration in combination with chemical agents are found to be effective for microbial reduction (Sobsey, 2002). Carbon impregnated with silver is used as bacteriostatic agent to reduce microbial colonization and control microbial proliferation (Sobsey, 2002).

Paper, fiber, fabric filters

Paper, fiber and fabric filters are examples of simple filters, which have too large pore sizes to remove bacteria and viruses. However they can be applied at a household level to remove larger water-borne pathogens like free swimming larval forms of *Schistosoma* and *Fasciola* species, Guinea worm larvae within their intermediate crustacean host and bacterial pathogens associated with relatively large zooplankton in water (Peter-Varbanets et al., 2009; Sobsey, 2002). General treatment by the use of these filters is not recommended (Sobsey, 2002).

Membrane filtration

Membrane filtration uses a semi-permeable film and a driving force which can be either a difference in pressure, concentration, temperature or electric potential to treat water (Peter-Varbanets et al., 2009). Dependent on the pore size they can remove parasites, bacteria and viruses (Sobsey, 2002). Different variants of membrane filtration include microfiltration, ultrafiltration, nanofiltration and reverse osmosis. Most membranes require advanced fabrication, special filter holders, supervision and maintenance. Furthermore most of them are relatively costly (Peter-Varbanets et al., 2009; Sobsey, 2002). Microfiltration removes colloidal particles, microorganisms and other particulate material, with a minimal size of ±0.2 µm (Van der Bruggen et al., 2003). Viruses are not removed (Fiksdal & Leiknes, 2006). Ultrafiltration removes suspended particles and colloids, turbidity, algae, bacteria, parasites and viruses (Van der Bruggen et al., 2003). Nanofiltration and reserve osmosis have even smaller pore sizes, and thereby they can even remove smaller contaminants.
Main advantage of membranes with larger pore sizes, is the fact that these can be operated under gravity. Fiksdal & Leiknes (2006) found a limited virus removal from ultrafiltration, with an average log removal of 0.5. Clasen et al. (2009) did a laboratory assessment of a gravity-fed ultrafiltration water treatment device designed for household use in low-income settings. With a test of 20.000, liters log10 reduction values were found of 6.9 for *E.coli* , 4.7 for MS2 coliphage (proxy for enteric pathogenic viruses), and 3.6 for *Cryptosporidium* oocysts. Nanofiltration combines the removal based on size exclusion with charge effects between solution and the membrane (Bruggen & Vandecasteele, 2003).

Point of use systems for membrane filtration, generally require pressure, electricity or solar power or gravitational force. Simpler systems work on gravity, and often require everyday supervision, backwashing and regularly chemical cleaning (Peter-Varbanets et al., 2009). The expensive part of a membrane system, is not the membrane itself but the costs for the pumps, solar powered systems and the measurement and control systems that are often used (Peter-Varbanets et al., 2009) . Ultrafiltration membranes can be bought for around 40 US dollar per m^2. With a water height of 2 meter, 5-10 liter a hour can be produced with a relatively small membrane (0.17-0.42 m^2).

LifeStraw filters are ultra-membrane filters developed for use on a household scale, and do not require any power. Different filter editions have been tested and removal rates ranged from 5-7 log for bacteria, 4-5 log for viruses and 4-5 log for protozoa (WHO,2016). Jansen (2016) is currently testing the performance of an ultrafiltration membrane, based on gravity flow, for the treatment of rainwater in the Netherlands. In the first analysis bacterial and inorganic parameters were found to be below guideline values. Only zinc was found to be higher due to a zinc gutter. Further tests are currently ongoing.

A metal membrane is described by Kim et al. (2004). The membrane is submerged into the tank. Advantages of metal membranes above polymeric micro-filters include that it can be stored in dry forms, which implies that it can be used intermediately. Furthermore the membrane is durable to high pressures, high temperature (up to 350 degrees) and chemical oxidation. Lifetime of the filters is long enough to have a minimal maintenance cost. Ozone bubbling and aeration in the feed side reduced membrane fouling and inactivated micro-organisms. The membrane efficiently removed microorganisms and particles, but removal was found to be dependent on rainwater source, the nominal pore size of the filter, filtration conditions and the operation mode. Water quality was suitable for toilet flushing and gardening. Pore blockage was found to be the main fouling mechanism.

Ceramic filtration
Ceramic filtration physically removes contaminants by size exclusion and adsorption. The technique is found to be effective for bacteria and protozoa, but less effective against viruses (WHO,2016; Van Halem, 2009). Pots can be coated with silver to increase effectiveness (Pandit & Kumar, 2015). Important disadvantages of ceramic filtration includes that there is no protection against recontamination. Moreover, filter quality is variable due to local production and filters are susceptible for breaking (WHO, 2016). A siphon filter uses a ceramic candle to remove pathogens from the water. A field study in Ghana showed a removal of total coliforms of 90.7% and a removal of *E.coli* of 94.1% (Barnes et al., 2009). A commercial ceramic filter currently supplied in Indonesia includes the Nazava filter developed by Lieselotte Heederik. Lab studies indicate large removals for bacteria (100%) were iron, copper, lead, manganese and aluminium were found to be removed between 77.0 and 99.6% (Parentich, 1992). Sobsey et al. (2008) expects removal rates of 2, 0.5 and 4 log for bacteria, viruses and protozoa respectively for porous ceramic filtration.

2.3.3. Existing treatment techniques for rainwater harvesting

In this section existing treatment techniques that are used in rainwater harvesting systems are discussed. Kinkade-Levario (2013) suggested that rainwater harvesting systems intended for potable use require screening, settling, filtering and disinfection before consumption. Additional water treatment includes pH control. Until now there is a lack of rainwater treatment techniques that have a high efficiency to remove contaminants and do not require energy (Vieira et al., 2013).

First of all larger pollutants (like leaves) should be prevented to enter the rainwater harvesting system. Although the largest part of this material is present in the first flush, this will not always be the case (Kinkade-Levario, 2013). Especially when drinking water quality is required, filtering devices should be present on gutters, downspouts and first flush devices. When these devices are placed under an angle, pollutants are forced to the downside of the filter. An illustration of such devices is shown in Figure 8.

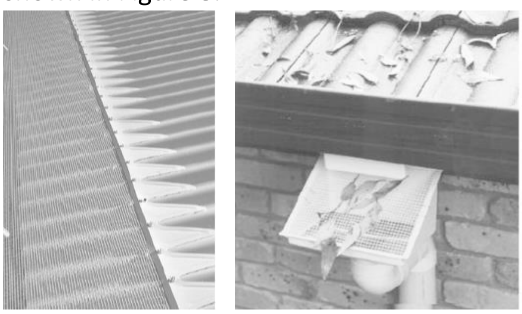


Figure 8: Filter before water enters the gutter (left) and before it enters the downpipe (right) (Kinkade-Levario, 2013)

After this first removal the water still contains a wide variety of pollutants. The chemical, physical, heat and UV techniques described in paragraph 2.3.2. could be used for further treatment. Below treatments systems that are developed for rainwater harvesting systems are discussed.

Vieira et al. (2013) suggest an up flow polypropylene filtration with down flow backwashing system. This can be easily applied in a rainwater harvesting system, possibly with additional treatment. An important disadvantage of regularly used down-flow filtration is the settlement of particles that leads to an increasing maintenance, energy and backwash requirements. The system is independent of electricity, it uses a self-cleaning mechanism and is simple to install. In Figure 9 the system is illustrated, "A" shows the standby situation, "B" the situation of treatment, and "C" the backwash situation where a float valve closes the treated rainwater outlet when the tank is full. Because of the increasing water level, the backwash outlet opens by a magnetic backwash valve, the flow reverses rapidly, causing a hydraulic shock and thereby cleaning the filter. When the system is totally drained as in "D", the backwash outlet closes again. Filters were found to remove 68% of the turbidity. The backwash device was found to bring the head loss over the filter back to the initial head loss.

A treatment unit designed by Naddeo et al., (2013) suggests a combination of filtration, adsorption on granular activated carbon and UV disinfection (FAD) for the treatment of rainwater. It can be found in Figure 10. According to the designers the treatment unit provides a total barrier for pathogens and organic contaminants. The turbidity is reduced. Pre-filtration was found to be effective for the removal of total solids, preserving the performance of the system. The system is of low costs compared to other treatment options (Naddeo et al., 2013).

RainPc is an in the Netherlands developed treatment method for rainwater which consists of a five stage purification process. The system is illustrated in Figure 11 (left). A pre filter takes out particles larger than 5 microns, water passes through a drum cage containing ceramic spheres with silver colloids and then it goes through three activated mineral composite Xenotex-A cartridges, an activated carbon filter with silver particles and a low pressure membrane filter (Kinkade-Levario, 2013).

Dobrowsky, et al. (2015) tested a rainwater harvesting system with pasteurization. The system is illustrated in Figure 11(right). Water is collected in a rainwater harvesting tank (A), from where the cold water is transported via the cold water feed (B) towards the cold water stainless steel tank (D) from which it flows to the main storage stainless 100 liter steel tank (E). From here water flows through the borosilicate glass evacuated tubes (F), and back to the main storage tank. Water can be extracted from the hot water outlet (G). Iron, aluminium, lead and nickel were detected above the drinking water limits at pasteurized tank water samples. The indicator bacteria (heterotrophic plate counts, *E.coli* and total coliforms) were below the detection limit in the tank samples. However, *Yersinia* spp., *Legionella* spp. and *Pseudomonas* spp. were detected in tank water samples pasteurized at temperatures above 72 °C. As alternative for the borosilicate glass evacuated tubes other pasteurization or solar disinfection devices can be used. Amsberry et al. (2015) for example described a simple continuous flow device in which solar thermal pasteurization and solar disinfection are combined.

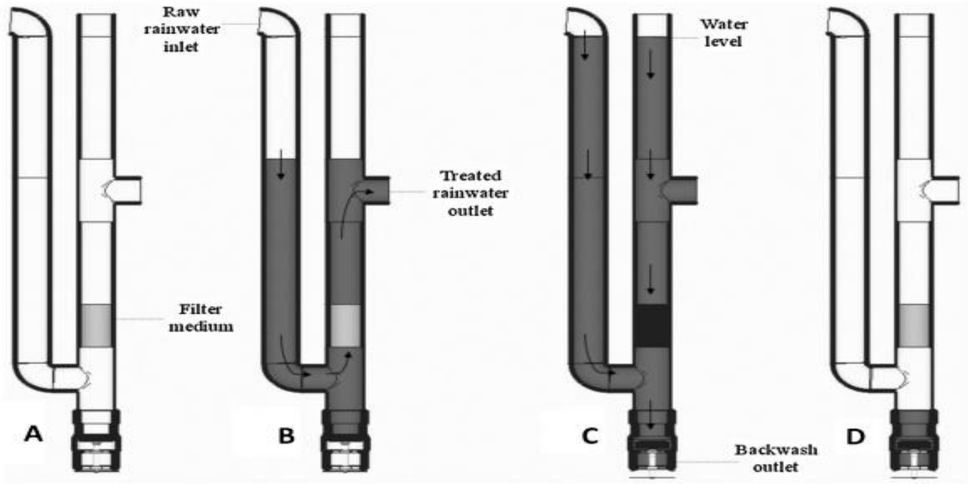


Figure 9: Up flow filtration with down flow back washing (Vieira et al., 2013) .

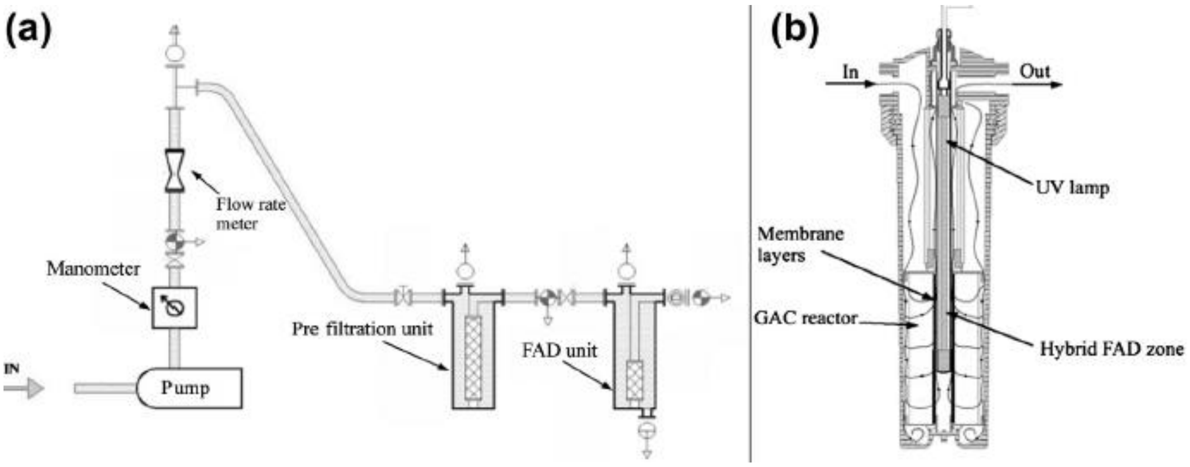
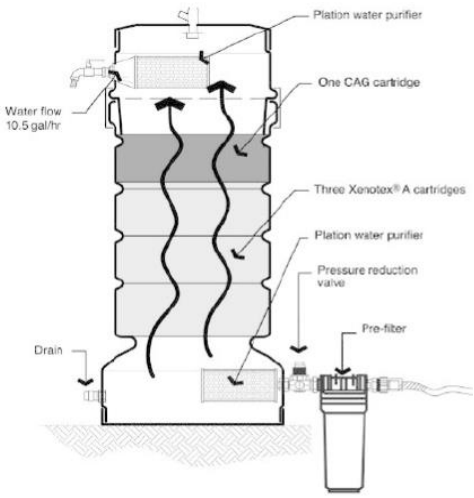


Figure 10: FAD treatment (filtration, adsorption on granular activated carbon and UV disinfection) (Naddeo et al., 2013).



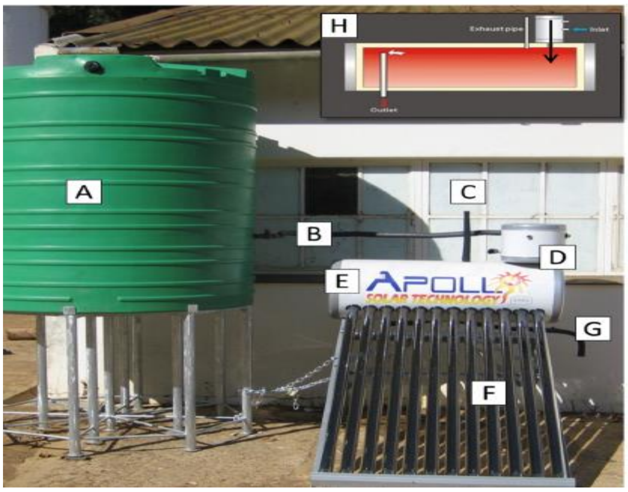


Figure 11: RainPc treatment system (left) and a low pressure solar pasteurization system (right) (Kinkade-Levario, 2013; Dobrowsky, et al., 2015).

2.4. Quantity

In this section the available methods to determine the potential water harvest from a RWH system are discussed. Focus is on DRWH systems.

The feasibility of DRWH depends on the rainfall amount and distribution, the length of the dry period and the possibility to use alternative water sources (Worm, 2006). Tropical climates with a short dry season, are one of the most suitable climates for DRWH (Worm, 2006). As rule of thumb rain should exceed 50 mm/month for at least half of the year (Worm, 2006).

Water losses occur at several parts in a DRWH system. First of all a proportion of the rain evaporates, splashes from the roof or leaks out of the gutter. The proportion of rainfall that actually runs off the roof can be defined as the runoff coefficient (Gould, 2015). The runoff coefficient is really dependent on the roof material. It ranges from 0.24-0.31 for handmade clay tiles, to 0.80-0.85 for corrugated iron, in a specific case study in China (Gould, 2015). For the same case study runoff coefficients in ground catchments were found to be between 0.13-0.19 for compacted loess soil, up to 0.73-0.76 for concrete lined surfaces (Gould, 2015). For a DRWH system with closed tank, the losses in the tank are generally small. This can be very different in case rainwater is stored in reservoirs, or soil and groundwater. Furthermore water can be lost at point of use, due to losses during transport or due to unsustainable water use.

For the sizing of a DRWH system, tank sizes are the main design variable to be determined, in case systems are installed on existing roofs. In Appendix A4 an overview of different methods for tank sizing can be found. There are several methods that can be used to determine the required size of a rainwater harvesting tank. Below some approaches are discussed. By Ward et al. (2008) a distinction is made between design methods based on simple approaches and design by detailed models. According to this research non-academic staff lack awareness of the availability and capabilities of these two type of tools. Existing models that can be applied to size rainwater harvesting tanks include DRHM, Rewaput, RWIN (KOSIM), PURRS, PCSM, MUSIC, Aquacycle, RSR, Raincycle and HWCM (Ward et al., 2008). A short description of these models can be found in Table 5. Computer models that use monthly data include "SimTanka" and the "Rainwater tank performance indicator" (Gould, 2015). Some of these computer models, like SimTanka is freely available on world wide web.

Londra et al. (2015) described two methods for the sizing of a rainwater harvesting tank. The daily water balance method calculates the volume of water in a rainwater harvesting tank on a specific day (S_t) based on the volume in the tank of the day before (S_{t-1}), plus the incoming rainwater (R_t), minus the outgoing water demand (D_t). The dry period method calculates the required tank volume to over bridge the longest dry period in the data.

Santos & Taveira-Pinto (2013) analyzed six different methods for the determination of the size of a rainwater harvesting tanks in Germany, the United Kingdom and Portugal. These tanks only served for non-potable purposes. It is found that the determined tank volume differs a lot (in some cases more than a factor 30) for different methods used. This is mainly because the different methods are based on different criteria and require different performance.

Table 5: Existing models for analysing RWH systems (Ward et al., 2008).

Model	Developer	RWH only?	Functionality
DRHM	Dixon (1999)	Yes	Mass balance with stochastic elements for demand profiling, simulates quantity, quality and costs
Rewaput	Vaes and Berlamont (2001)	Yes	Reservoir model, rainfall intensity-duration-frequency relationships and triangular distribution
RWIN (KOSIM)	Herrmann and Schmida (1999); ITWH (2007)	No	Hydrological-based high resolution (5 minute) rainfall runoff model
PURRS	Coombes and Kuczera (2001)	No	Probabilistic behavioural, continuous simulation, evaluates source control strategies
RCSM	Fewkes (2004)	Yes	Behavioural, continuous simulation, detailed analysis of time interval variation and yield-before/after-spill
MUSIC	CRCCH (2005)	No	Continuous simulation, modelling water quality & quantity in catchments (0.01 to 100 km^2)
Aquacycle	Mitchell (2005)	No	Continuous water balance simulation using a yield-before-spill algorithm
RSR	Kim and Han (2006)	Yes	RWH tank sizing for storm water retention to reduce flooding, using Seoul as a case study
RainCycle	Roebuck and Ashley (2006)	Yes	Excel-based mass balance model using a yield-after-spill algorithm and whole life costing approach
HWCM	Liu et al (2006)	No	Object-based behavioural, continuous simulation using Simulink

Bocanegra-Martínez et al. (2014) discussed a method to optimize rainwater harvesting tanks for domestic use in a residential area based on costs. Costs that are considered include the total annual costs associated with the public connection, the capital costs for catchment areas, storages and pumps and the costs for pumping, maintenance and treatment. It can be chosen to minimize total costs, minimize consumption from the public water supply or to composite both objectives.

Fewkes (2000) investigated how spatial and temporal fluctuations can be incorporated into models. Two models were developed. The first model used daily data and the yield after spill (YAS) operation rules. This is a more conservative estimate of system performance. The second model uses monthly rainfall data, were an storage operating parameter was used to take fluctuations smaller than a month into account. Also this second model, which requires less input data, was found to perform well.

Imteaz et al. (2012) determined the potential for rainwater harvesting in southwest Nigeria by using a daily water balance model. As rainwater input a typical dry year was used. It was found that with a tank size of 7000 liter, a low demand (1.80 m^3/month) can be fulfilled for all days in a year. For smaller tanks, the percentage of days in which the demand is fulfilled becomes smaller. For a higher demand (2.45 m^3/month) larger tank sizes of 10.000 liter were required. Furthermore it was found that an analysis using monthly rainfall data (instead of daily data) overestimates tank sizes.

Su et al. (2009) used a probabilistic approach to design rainwater harvesting systems. An annual deficit rate (DR) was defined as the total deficit volume divided by the total demand. This deficit rate can be calculated for different years of historical data, and afterwards the distribution function of this deficit rate can be found for different storage capacities (and/or roof sizes). The probability density function can be integrated to a cumulative probability density function and afterwards an exceedance probability curve can be constructed.

2.5. Economic aspects

The installation of rainwater harvesting systems comes together with several direct and indirect costs and benefits. Important benefits of rainwater harvesting systems include the fact that they can improve access to water and sanitation and limit the costs for alternative water sources (Aladenola & Adeboye, 2010). Furthermore, several environmental benefits (like decreasing erosion or storm water runoff), social benefits (like limiting time for water collection), economic and health benefits are associated with rainwater harvesting (Rahman et al., 2012; Kahinda et al., 2007; Aladenola & Adeboye, 2010; Barron, 2009). Costs of DRWH systems include the monetary cost required to purchase, construct, operate and maintain the system. Moreover, installation of DRWH can have negative social effects. It can for example cause tension in the community due to unequal distribution of the systems.

Costs of a rainwater harvesting system largely depend on the existing infrastructure (like roofs, gutters and downpipes), the tank material used, the tank size and the local material and labor prices (Worm, 2006). A distinction can be made between investment, operation and maintenance costs. Investment costs include costs for construction materials, labor, transportation, supervision and communication. Operation and maintenance costs include labor, energy and material costs in case something is broken. Costs can be minimized by shape optimization, the use of free materials, function separation (only use waterproof materials when required), mass production or the use of existing containers (Ariyabandu, 2003).

In general the tank is the main part of the total investment costs in case of domestic rooftop rainwater harvesting systems . Furthermore, the treatment device can cover an extensive part of the total costs. An indication of the tank costs for different materials can be found in Table 6. Costs are shown in euros (1 USD = 0.918 euro). When looking at larger tanks (> 1m^3) plastic tanks are found to be the least expensive, followed by ferrocement tanks (Worm, 2006). Gould and Nisselen-Petersen (1999) however found that plastic tanks are relatively expensive compared to tanks from corrugated iron, ferrocement, brick and cement when looking at the price per m^3 of tank. In later research a ground hemispherical tank was found to be one of the cheapest options (Nissen-Petersen, 2007).

Table 6: Examples of costs for storage reservoirs (Worm, 2006).

Type	Volume (m^3)	Indicative costs (euro)	Costs per m^3 (euro/m^3)
Plastic bowl/buckets	0.01- 0.025	1	90
Steel (oil) drums	0.1	10	10
Plastic lined tanks	5	45	10
Water jar or jumbo jar (ferrocement)	3	140	45
Water tank (concrete in situ/formwork)	5	275	55
Water tank build of bricks or blocks	10	460	45
Water tank built of ferrocement	11	505	45
Water tank built of ferrocement	23	690	30
Water tank built of ferrocement	46	1100	25
Sub-surface ferrocement tank	90	1745	20

An indication of the capital (investment), operation and total costs (CapEx, OpEx, TotEx) of different rainwater harvesting systems can be found in Appendix A5. Operational costs are generally much lower than the investment costs (Batchelor et al., 2011). It is found that the investment costs of rainwater harvesting systems is relatively high compared to systems that do not require any storage tank, but low compared to groundwater-based piped water supply (Batchelor et al., 2011). However when taking the lifetime of the system and the number of users into account rainwater harvesting can often be considered less expansive (Batchelor et al., 2011). Total costs of the systems differ a lot for different regions and are found to be higher in Africa, as elsewhere (Batchelor et al., 2011).

Possible finance options for rainwater harvesting systems include donor subsidy, self-contribution, microcredit loans and governmental financing (Heijbroek, 2012). A fast majority of the rainwater harvesting projects until now is based on subsidies for the tanks, gutters and downpipes (Naugle et al., 2011). However people in some areas are willing to invest in rainwater harvesting systems (Hartung, 2006). The systems of these people will have the best performance in case transparent terms and conditions and rules for operation are provided (Hartung, 2006). According to Hartung (2006) microfinance institutions can be important actors for the spread of DRWH systems.

3. Case study area

3.1. General information

Indonesia is an archipelagic nation with 17 508 islands and approximately 258 million people (Nastiti and Widiaty, 2012; World Bank, 2015). Many islands have mountain ranges from volcanic origin over their entire length (AQUASTAT, 2011). The country has 33 provinces, 349 districts (kabupaten), 91 cities (kota), 656 sub-districts (kecamatan) and 71.563 villages (desa kelurahan).

Banten is a province in the most Western part of the Indonesian island Java, which is the highest populated island of Indonesia. On Java, 59% of the Indonesian population lives on 7% of the total land area (AQUASTAT, 2011). The province of Banten is divided in four districts (kabupaten Serang, Tangerang, Pandeglang and Lebak) and has four main cities (kota Serang, Cilegon, Tangerang and Tangerang Selatan). Kaputaten Serang itself is divided into 28 sub-districts and 314 villages (Whitebook Serang, 2010). The Serang district lies between 0 and 1778 meters above sea level. The south part of Serang is a hilly area, where the northern part is relatively flat with a slope between zero and two percent (Whitebook Serang, 2010). The capital of the province Banten is Serang. The research areas Pabuaran, Baros and Tirtayasa are sub-districts in kabupaten Serang. These sub-districts are selected based on current rainwater use, and the availability and quality of the current water supply. In Figure 12 the location of the case study areas can be found. It is found that the availability and quality of the current water supply is not the only health problem in the case study area. Other main problems include sanitation, waste and nutrition.

Information regarding the population, surface area, population density, number of households, average household size, life expectancy and income in Banten province, kabupaten Serang and Tirtayasa, Pabuaran and Baros can be found in Table 7. Life expectancy in kabupaten Serang is 63 years. This is much lower than the average life expectancy of 69 years in Banten province. In 2009 the total population in kabupaten Serang is approximately 1.5 million people (Whitebook Serang, 2010). Average population density in Banten and Serang is found to be 1232 and 1023 inhabitants per km^2 respectively. The population density in Pabuaran and Tirtayasa is found to be relatively low (598 and 466 inhabitants per km^2), were in Baros it is around average (1100 inhabitants per km^2). Population in kabupaten Serang is steadily increasing, between 2014 and 2015 the population growth was 2.1%. An average household has a size of approximately four persons.

Information regarding income, education and land use in Banten Province and in Serang can be found in Table 8. Average annual expenditure per capita in Serang is around the 10 million Rup (€690,-). The largest part of the population follows elementary school (97.7%). The part of population that has followed middle and high school is slightly lower (79.6 and 56.9%). A large part of the land is used as rice field or mixed farm. This is as expected, since a large part of the economically active population in Serang works in agriculture (42%), for example in the food production (rice, maize, cassava, soybean, sweet potatoes and peanut) (AQUASTAT, 2011).

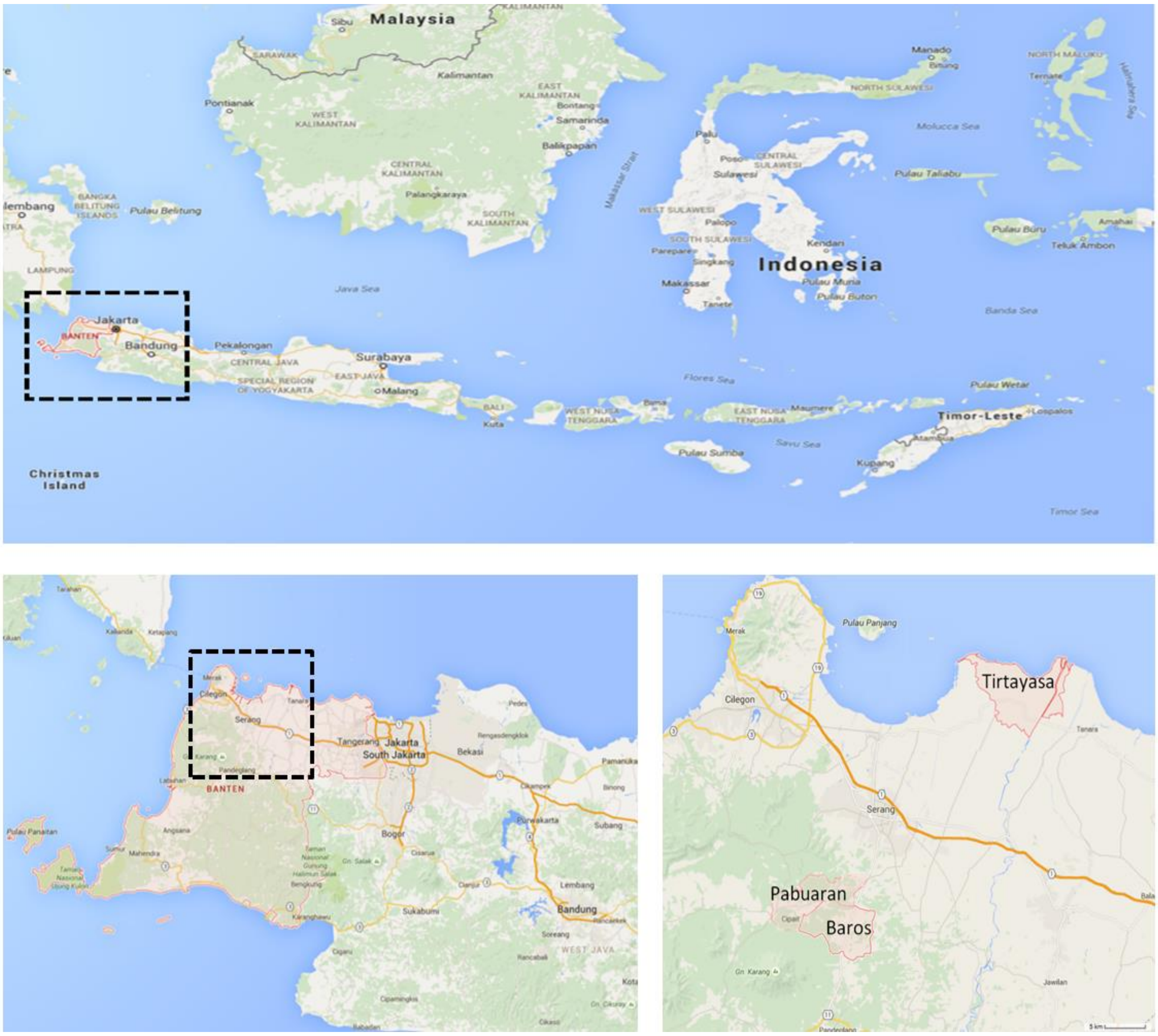


Figure 12: Map of the case study area (Google Maps, 2016).

Table 7: General information for Banten province and kabupaten Serang, Tirtayasa, Pabuaran and Baros (SIB, 2016; Whitebook Serang, 2010; Cakuapn keluarga menurut sumber air minium air minum yang digunakan,2015; Status lingkungan hidup Indoensia, 2010).

	Banten	Kabupaten Serang	Tirtayasa	Pabuaran	Baros
Population	11.9 million (2009)	1.5 million(2009)	38,555 (2015)	36,845 (2015)	48,717 (2015)
Area [km^2]	9663	1467	64	79	44
Population density [inhabitants/km^2]	1232 (2009)	1023 (2009)	598 (2015)	466 (2015)	1105 (2015)
Households	2,861,654 (2009-2014)	366,397 (2015)	10,085 (2015)	8,697 (2015)	11,328 (2015)
Inhabitants per household	4.1 (2014)	4.4 (2014)	3.8 (2015)	4.2 (2015)	4.3 (2015)
Life expectancy [year]	69 (2014)	63 (2014)	N.A.	N.A.	N.A.

Table 8: Income, education and land use in Banten and kabupaten Serang (SIB, 2016; Status lingkungan hidup Indoensia, 2010)

	Banten	Kabupaten Serang
Income		
Expenditure per capita [Rup/year]	11,150,000 (2014)	9,886,000 (2014)
Gross Regional Domestic Product per capita [Rup]	36,606,416 (2014)	35,722,047 (2014)
Minimum income [Rup/year]	19,200,000 (2014)	28,500,000 (2014)
Labor force participation rate [%]	63.8 (2014)	61.3 (2014)
Education		
Elementary school (6-12 year)	96.69% (2014)	-
Middle school (12-15 year)	79.56% (2014)	-
High school (15-18 year)	56.87% (2014)	-
Land use		
primary forest [%]	0.6 (2010)	-
secondary forest [%]	8.4 (2010)	-
mangrove [%]	0.4 (2010)	-
rice fields [%]	25.3 (2010)	-
mixed farm [%]	34.2 (2010)	

3.2. Culture

Indonesia is a country with a wide range of cultures, religions and beliefs. There exist 300 socio-linguistic groups (Nastiti and Widiaty, 2012). The largest part of the population is Muslim, but also Christian, Hinduism and Buddhism can be found. Islam provides certain instructions regarding the use of water. In general the population in Indonesia uses plenty of water. Water should for example be used to clean yourself before praying, and running water should be used in the toilet (Nastiti and Widiaty, 2012). Furthermore, water is used in ceremonial purposes in different cultures.
Besides, it is very common in Indonesia to use a combination of sources and to organize the water supply at a household scale. A large part of the populations applies point of use household water treatment, in which water is boiled before drinking. Only bottled water is not treated.

3.3. Climate

Indonesia has a wet tropical climate. According the Köppen climate classification Banten province has an equatorial climate (Af). Average temperature in Banten province is 27.1 ˚C . Temperatures are quite stable throughout the year. The same counts for the relative humidity, which is around 80%. Average temperature has not changed much the last twenty years.

Annual rainfall in Indonesia ranges between roughly 1300 mm to 4300 mm a year. This large variation of average annual rainfall occurs also on the island of Java, as illustrated in Figure 14. Besides this variation in annual average rainfall the distribution of the rainfall can vary largely. In Banten average annual rainfall is 1722 mm (2005-2014). Rainfall is not stable throughout the year. Most of the rain (±66%) falls in the period between November and March. The temporarily distribution of rainfall can be found in Figure 13. In Serang the southern part is much wetter and colder than the northern part. Open water evaporation varies from month to month and from location to location. Open pan evaporation was found to vary between approximately three mm/day in January and above four mm/day in October in Cipanas (Oldeman, L. R., & Frere, M., 1982).

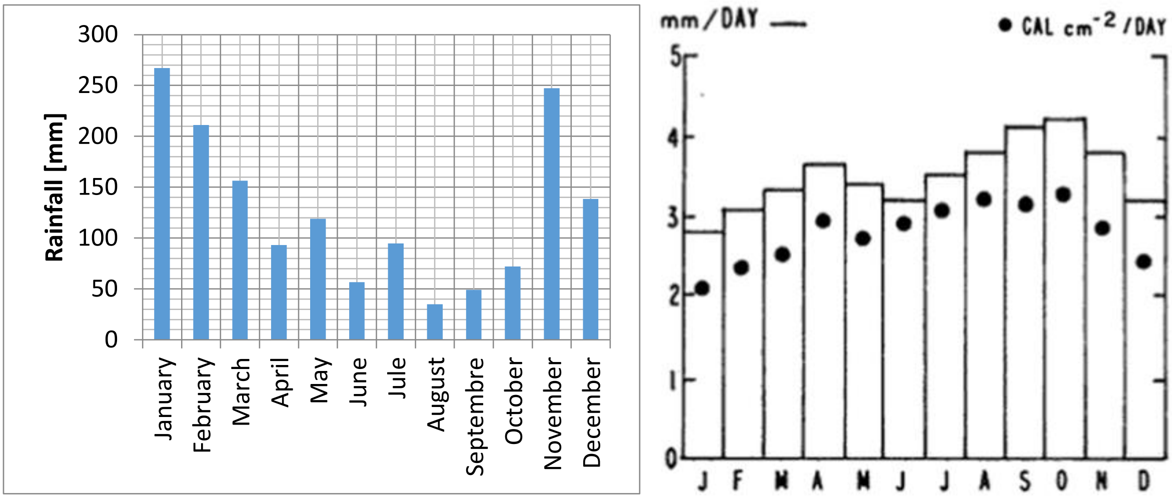


Figure 13: Average monthly rainfall [mm] for Banten province (left), average open pan evaporation [mm/d] and total radiation [cal.cm^{-2}/day] in Cipanas (West-Java) (right) (Oldeman, L. R., & Frere, M., 1982).

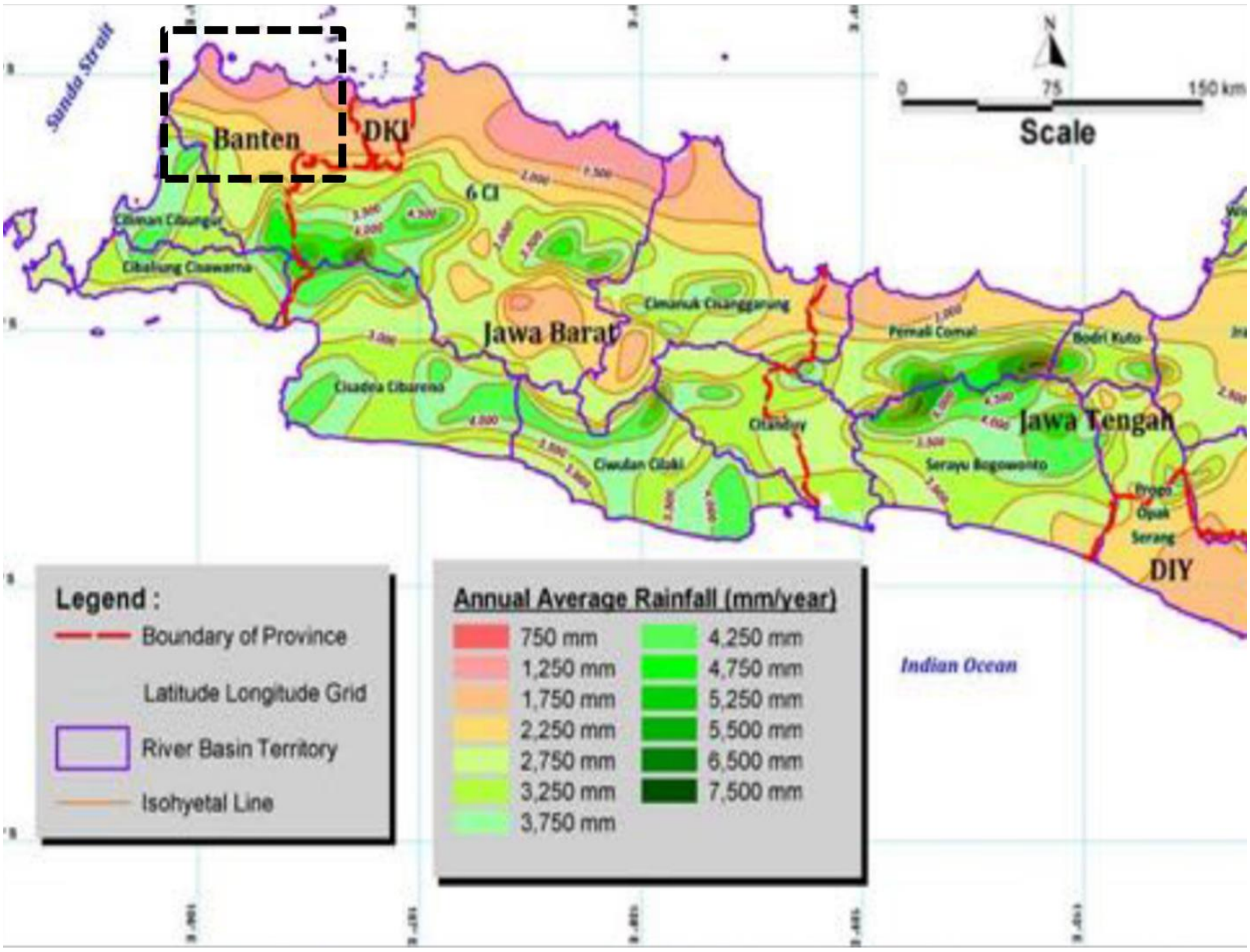


Figure 14: Average annual rainfall in of the Indonesian island Java (Asian Development Bank, 2016).

3.4. Water supply

In Indonesia, thirteen percent of the population had no access to an improved drinking water source in 2015, where in urban areas the access to improved water sources is much higher than in rural areas (WHO & UNICEF, 2015). Twenty percent of the Indonesian population performs open defecation (WHO & UNICEF, 2015). However the quality of this report from the WHO and Unicef is discussable (Bonné, 2016). Defecating in rivers is seen as a hygienic practice and open defecation is largely cultural acceptable (Nastiti and Widiaty, 2012). High water demands exist for sanitation, but when limited water is available ,water tends to be saved for cooking and drinking (Nastiti and Widiaty, 2012).

In Figure 15 the primary water sources for Indonesian inhabitants can be found (World Bank, 2012). Urban areas in Indonesia rely in most cases either on bottled water, piped water, a pump or a protected well. Also in large cities like Jakarta just 25% of the population has access to a water supply system (Cosgrove, 2014). Approximately 25% of the urban population gets water from vendors at high prices (World Bank, 2012). It is found that, in Jakarta, municipal water has a price of between $0.09–0.50 per cubic meter. However water from tanker trucks is already $1.80 per cubic meter and vendors ask prices around $1.50–2.50 per cubic meter (Cosgrove, 2014). Although the price of vendor water is high, the quality is often poor. Rainwater use in Indonesia is limited. Just 2.58% of the Indonesian population is using rainwater as a water sources. From all regions in Indonesia, the use of rainwater is the smallest on Java, were just 0.39% of the population uses rainwater (Lubis, 2016).

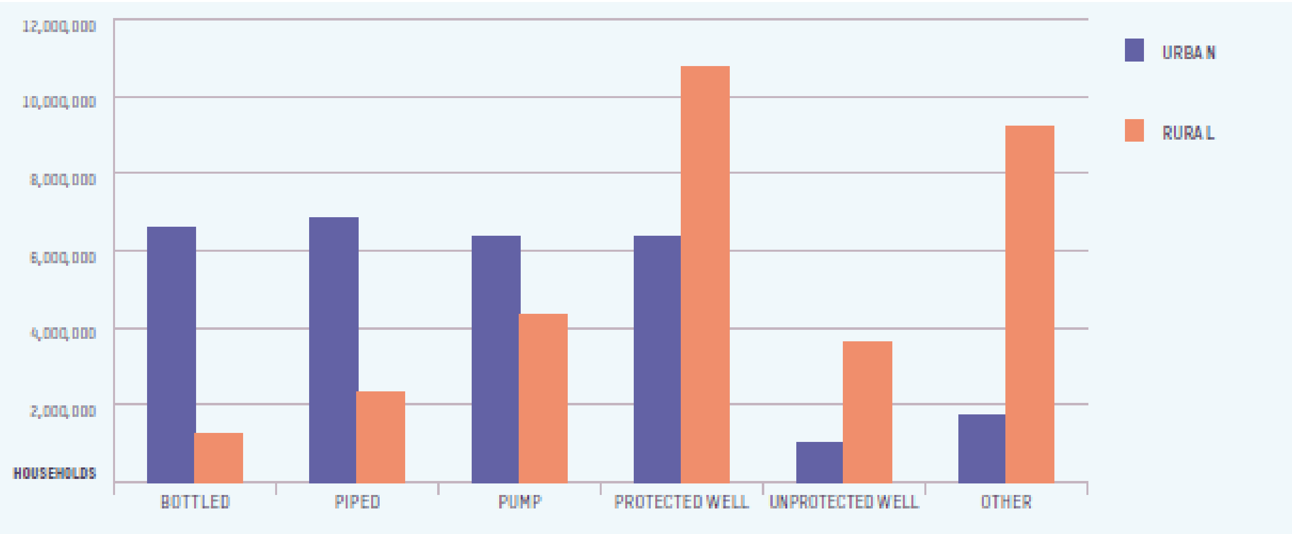


Figure 15: Primary drinking water sources for both urban and rural Indonesia (World Bank, 2012).

Water demand is increasing in some areas because of urbanization, population growth, the intensive development of agriculture, economic and industrial growth and requirements regarding the environment (Fulazzaky, 2014; Fulazzaky & Akil, 2009). Problems like water quality degradation, floods and drought, groundwater depletion, land subsidence, erosion and seawater intrusion are occurring in different areas of Indonesia. An important reason for water quality degradation is the contamination with fecal material (AQUASTAT, 2011). Climate change together with deforestation in the upper part of catchments, increase both the extreme wet periods and floods in the wet season and the droughts in the dry season (Jentsch and Beierkuhnlein, 2008; AQUASTAT, 2011). The Bandung Basin in western Java experiences land subsidence, most likely caused by extensive groundwater extraction which increases the chances for flooding and causes damage to buildings and infrastructure (Abidin et al., 2013). In Greater Jakarta large groundwater extractions, used for drinking water, combined with decreases in infiltration because of land use changes results in groundwater depletion (Delinom, 2008). In Jakarta itself the groundwater level is in some places 30 meters below sea level, and saltwater intrusion and other pollution make this water source unsuitable for drinking water (Cosgrove, 2014). Monsoon droughts, coinciding with El Niño affect the whole country (D'Arrigo et al., 2006).

In kabupaten Serang available water sources include irrigation water, groundwater, bottled water, gallons, refilled jerry cans, spring water and rainwater. In Table 9 the main water sources used in Pabuaran, Baros and Tirtayasa can be found. A distinction is made between water used for potable purposes (like drinking) and non-potable purposes. Beside this a difference is made between bottled water and gallons. Bottles are the small 0.33 to 1.5 liter bottles from commercial brands. Gallons are locally refilled big bottles of approximately 19 liter. Although rainwater is used in all these sub-districts, only in Tirtayasa more than ten percent of the population practices this technique.

Table 9: Main water sources used for potable and non-potable purposes in Pabuaran, Baros and Tirtayasa.

	Potable purposes			Non potable purposes		
	Pabuaran	Baros	Tirtayasa	Pabuaran	Baros	Tirtayasa
Bottled	√					
Gallons	√		√			
Shallow wells		√	√	√	√	√
Borehole	√	√				
Spring	√				√	
Piped water supply (PDAM or no PDAM)		√	√	√		√
Rainwater			√			√

Table 10: Approximation of the installation, operation and administration costs for current water sources (Saputra, 2016)

	Installation [€]	Operation or Use [€/m^3]	Administration costs [€/month]
Bottled (1 liter)	0.00	483.00	0.00
Gallons (19 liter)	unknown	15.00	0.00
Piped (PDAM)	108.00	0.29	0.41
Groundwater	unknown	0.07*	0.00

*electricity costs

Current water supply in Baros, Pabuaran and Tirtayasa is insufficient. In Figure 16 the relevant water related issues in the case study area are represented schematically. In Tirtayasa, there is no spring water and irrigation canals are heavily polluted due to domestic wastewater, industry, agriculture, fish farming and solid waste. However these canals are still used for low end purposes like washing of clothes. Groundwater is brackish and thereby only suitable for non-potable purposes. Bottled water or big gallons can be bought, but are relatively expensive. The piped water network (PDAM) does not cover the entire area and is not expected to increase capacity in short term. In Baros and Pabuaran groundwater levels are deep. Levels can be around fifteen meter (Whitebook Serang, 2010). Springs are available at several places, but the distance to these sources can be a limitation. Rainwater is used as additional water source in all three sub-districts. In Table 10 an approximation of the current costs for bottled, PDAM and groundwater can be found.

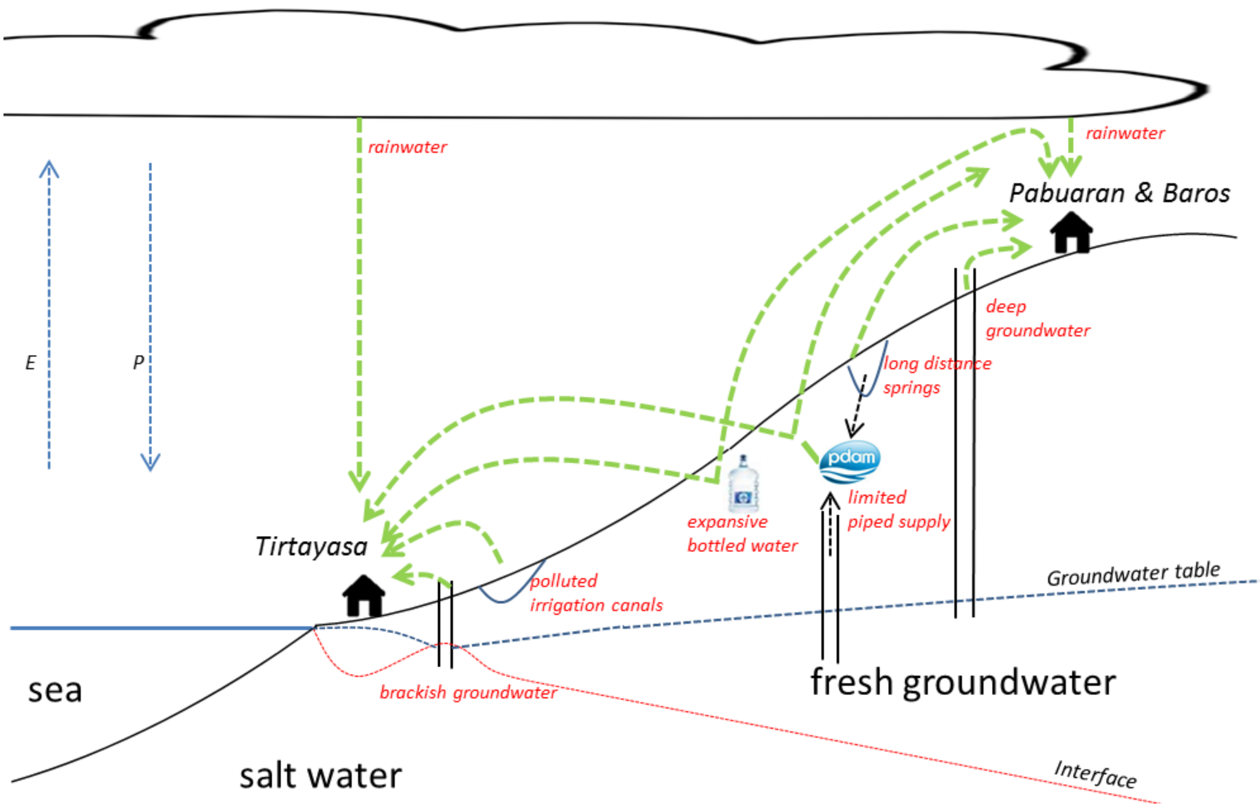


Figure 16: Schematic representation of water sources available in the case study area.

3.5. Water use

In Indonesia annual water withdrawal is 113.3 billion cubic meter per year (AQUASTAT, 2010). The largest part (81.9%) of this water is used for agricultural purposes, 6.5% is used for industrial purposes, and 11.6% is used for municipal use by households (AQUASTAT, 2010).

Municipal water demand varies over time and is dependent on the water price, income and household composition (Arbués et al., 2003). Different water qualities are required for different purposes, which is illustrated in the hierarchy in Figure 17. Only very high water quality is needed for drinking and cooking. Already a lesser water quality is necessary for washing clothes, cleaning, agriculture and sanitation.

Gleick (1998) determined that the average domestic water usage per person in Indonesia was 34.2 liters a day around 1998, which is below the minimal water requirement for human needs of 50 liter per person per day. This is split in 5 liter for drinking water, 15 liter for bathing, 10 liter for cooking and kitchen and 20 liter for sanitation services.

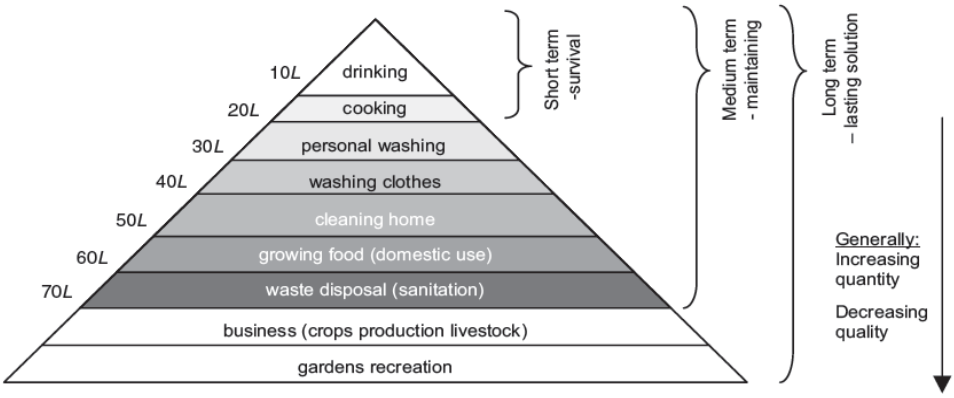


Figure 17: Minimal water requirements needed, shown in the hierarchy of water requirements (WHO, 2005).

This demand is much lower than the water demand determined by Rosetyati Retno Utami, who is looking at average water use in Bandung. Current approximations indicate that 100 liter/person/day is used for bathing, a 120 liter/family/day for washing and approximately 1.5 liter/person/day for drinking. Based on the data provided from AQUASTAT (2010) a domestic water use of 150 liter/person would be expected.
For this research it is assumed that the water requirement for an entire family is 500 liter/day.

3.6. Governance

Law and regulation in Indonesia is according the national statue no. 12/2011 organized at five levels. As explained by Agni (2016) the first level are the Undang-undang (statutes). After this level the Peraturan Pemerintah (government regulation) is made to give a more practical concept to the statute. As third level the Peraturan Presiden (residential regulation) is made by the president to execute the statutes or the government regulations. On the fourth level the Reraturan Dearah Tingkat Provinsi (provincial regulation) contains more detailed information on specific issues. On the last level the Peraturan Daerah Tingkat kabupaten/kota (district/city regulation) has even more elaborated specifications.

The responsibility for water and sanitation in Indonesia is organized at national, provincial and regional government (Wieriks, 2011). Tasks are spread over several ministries, including the Ministry of Public Works, Health, Foresty, Environment, Bappenas, Agriculture and Home Affairs (Wieriks, 2011).

At a national level the National Development Planning Agency (BAPPENAS) is responsible for long and medium term development programs (Witteveen en Bos, 2012). They do policy formulation, coordination, synchronization of the preparation and evaluation of national development planning (Witteveen en Bos, 2012). Also the performance of the water and sanitation sector is evaluated and monitored. It plays an important role for grants and loans from foreign investors.

Regarding water the ministry of public works (MPW) is responsible for national policies and standards regarding water supply and sanitation (Water dialogs, 2008). They work on the development of water resources, road, bridges, water supply, sanitation and special planning (Water dialogs, 2008). They also publish technical regulations, norms, standards, guidelines and manuals (NSGM) (Witteveen & Bos, 2012). Badan Pendukung Pengembangan Sistem Penyediaan Air Minum

(BPP-SPAM) is established by the ministry of public works to give recommendations to the MPW regarding the development of the water supply (Water dialogs, 2008).

The Ministry of Health (MoH) sets standards for water quality which is monitored through the Directorate of Water and Sanitation (Witteveen & Bos, 2012). It provides wastewater facilities, sanitation emergency response systems and promote hygiene (Witteveen & Bos, 2012).

The ministry of Environment regulates water quality management and pollution prevention. Inter-provincial water bodies are monitored. Provincial agencies monitor inter-district water bodies and the district monitors intra-district waters.

On a provincial level the government is headed by a governor with five assistants and one secretary governor (Wieriks, 2011). Under this top level several directorates are situated (called “Dinas”) (Wieriks, 2011). Examples of Dinas that manage water resources include Dinas water resources (SDA) and Dinas public works (PU) (Wieriks, 2011). The Provincial level water management committee (PTPA) is set between the governor and the provincial water management agency (PSDA) (Wieriks, 2011).

The Regional Planning and Development Agency (BAPPEDA) is the main coordinator to budget and develop provincial or local government (Witteveen & Bos, 2012). The Environmental Control Agency (BP LHD) formulates policies and has duties on environmental management (Witteveen & Bos, 2012).

Local governments are responsible for designing and monitoring construction, regional planning, providing facilities and environmental management. Towns and large urban areas are headed by a Walikota (major) and districts are headed by the Bupati (head of district) (Wieriks, 2011). Like at the provincial level, walikota and bupati are assisted by assistant heads and followed by Dinas and sub-Dinas (Wieriks, 2011).The existence of a department (for example public works, health, environmental sanitation, settlements and environment and/or pollution control) is dependent on the district leader or city mayor (Witteveen & Bos, 2012). Drinking water supply is in most cases organized by PDAMs, which are local governmentally owned water supply companies. In cities with a sewer system, this is generally operated by PDAMs. Only ten wastewater treatment facilities exist in Indonesia, from which six are operated by PDAMs.

For the case study area, the kabupaten (especially the Bappeda, Dinas health and Public works) and the PDAM are of main importance in planning and executing improvements in the water supply.

4. Methodology

For the design of a rainwater harvesting system several design choices have to be made. As stated by Studer (2013) general aspects, technical aspects, economic viability, institutional and legal criteria and social and cultural criteria should be taken into account. Technical aspects include both water quality and quantity aspects. In Table 11 these aspects are further elaborated. The approach suggested by Studer (2013) is adapted and implemented in this research with main attention towards the technical aspects. Studer (2013) is, to the best knowledge of the author, the only methodology that takes general, technical, economical, institutional, legal, cultural and social aspects into account in the design of rainwater harvesting systems.

Table 11: Planning of water harvesting projects: summary of key elements (Studer, 2013).

General

- Understand the problems and the specific needs of beneficiaries.
- Keep project designs flexible and aim for realistic project durations.
- Identify the scale at which WH will be implemented.
- Identify and build on existing WH technologies and approaches involving all stakeholders.
- Keep WH technologies simple and manageable.
- Promote technologies that have worked in similar conditions.

Technical feasibility and biophysical criteria

- Rainfall: amount, intensity, duration, distribution, runoff-generating events, evapotranspiration rates.
- Land topography: slope gradients, length of slopes, size and shape of the catchment.
- Soil type: infiltration rate, water holding capacity, fertility, soil depth, texture, structure.
- Collection/ catchment area efficiency and runoff coefficient for the generation of runoff.
- Land use for catchment and application area: cultivated, uncultivated or partially cultivated, under pasture or forests, etc.
- Plant water requirements.
- Level of mechanization required during establishment and maintenance.
- Availability of local material (stone/ earth etc.) when structural measures are applied.
- Alternative water sources and family size (specifically for rooftop and courtyard WH).
- Assurance of good long-term maintenance and management of WH interventions.

Economic viability: economic and financial criteria

- Evaluate and analyse effectiveness, cost efficiency and benefit to cost ratio.
- Consider benefits and disadvantages of incentives.
- Assess availability of labour.
- Assess access to markets for specific WH inputs and products.
- Assess need for and access to financial support.
- Take into account if crop to be grown is 'processable' into value-added products to justify for WH investments.

Institutional and legal criteria

- Mainstream WH into development projects, investment frameworks, national strategies etc.
- Encourage coordination and collaboration among stakeholders.
- Consider legal aspects and land and water use rights.
- Support capacity building and training for effective and well experienced extension and technical advice services.

Socially sound: social and cultural criteria

- Take account of cultural differences and local preferences.
- Integrate socially and economically disadvantaged groups (e.g. women and resource-poor land users).
- Encourage and support local water user groups to organize themselves.
- Determine if collective action is needed in the catchment and application area (consider upstream – downstream relations).

A weakness of the scheme suggested by Studer (2013) is the fact that it is already assumed that rainwater harvesting should be implemented. However multiple solutions exists that can provide improvements in the water supply, for example the installation of a piped water network or individual wells. These solutions are not taken into account in this research. However for policy makers and governments it is important to consider those solutions. Furthermore, existing infrastructure and local best practices should be considered.

In Figure 18 a self-developed alternative and additional framework is shown. First one should check if the water supply does not meet demand with respect to water quality or quantity. The local population should be unsatisfied with the current water supply. When this applies, the case study area should be analyzed. In general it would be the most obvious to increase the capacity of the existing water supply, or to use solutions that are already found to be effective in neighbouring communities. However rainwater harvesting should be considered since it has additional advantages above the use of other sources. Available water sources are used in a sustainable way, and no valuable sources are wasted (circular economy). Furthermore, rainwater harvesting can prevent land subsidence by limiting groundwater extractions. If rainwater harvesting is considered to be a suitable technique, the framework of Studer (2013) comes in which general, technical, economic, institutional, legal, social and cultural aspects are considered.

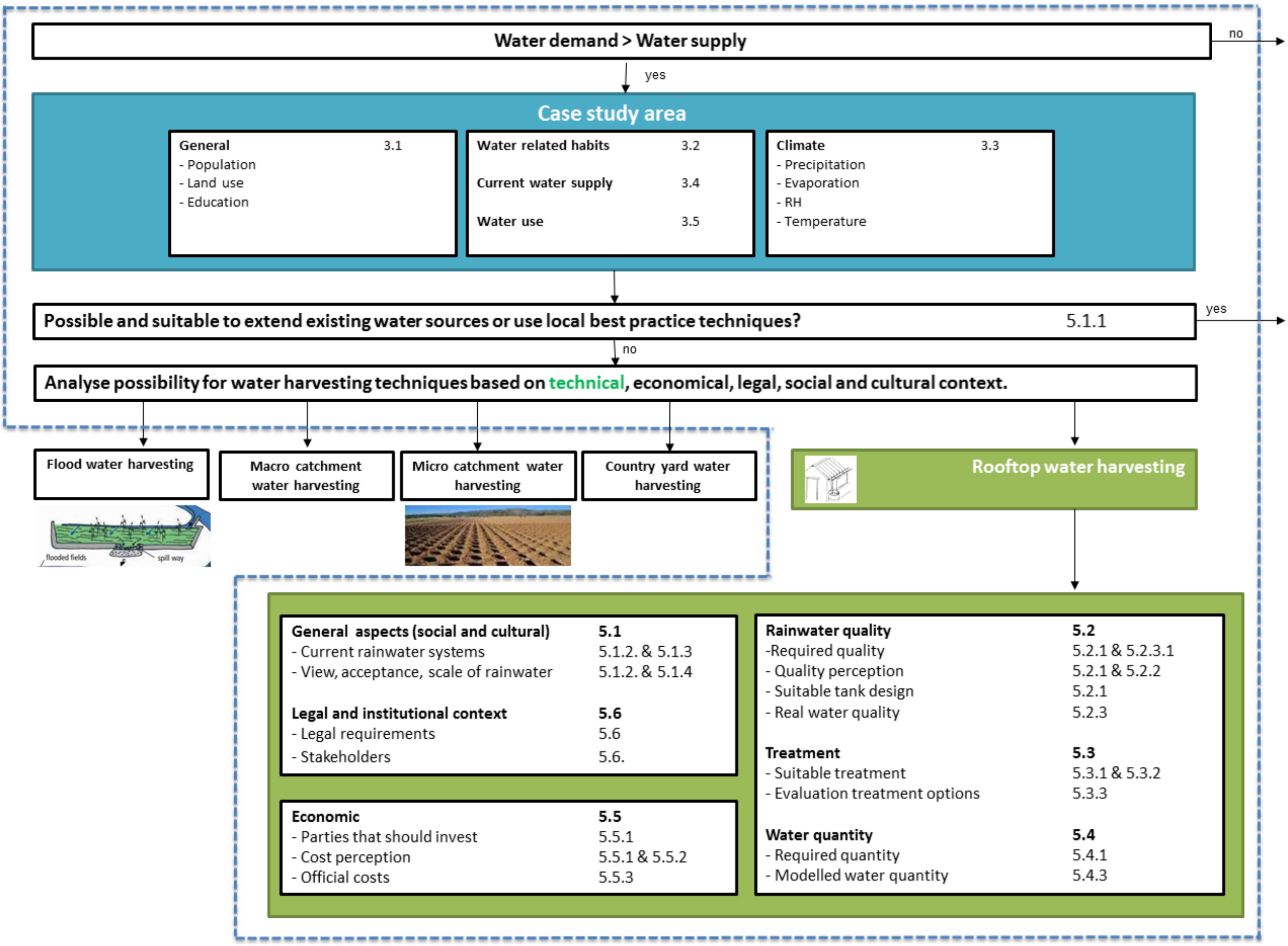


Figure 18: Additional framework for the reflection of rainwater harvesting (numbers refer to paragraphs).

4.1. General aspects

As indicated in the framework presented in Figure 18 one should consider several general aspects in the design of a rainwater harvesting system.
Current rainwater harvesting systems should be evaluated on successes and mistakes. It is important to build on existing technologies in the case study area, or build on systems that have proven to be successful in similar conditions to increase the chance that the system will succeed in practise. The evaluation of existing rainwater harvesting systems is presented in this section.
Furthermore the view and acceptance of rainwater harvesting should be investigated. This information is obtained by interviews with local experts and by the field visits to the case study. More information regarding these aspects can be found in paragraph 4.2.

4.1.1. Evaluation of existing systems

In Indonesia several rainwater harvesting systems exist. A distinction can be made between rainwater harvesting systems installed by individual households and by external organizations. Rainwater harvesting systems installed by individual households in Tirtayasa, Baros and Pabuaran were evaluated. Furthermore the rainwater harvesting projects executed by Unicef, CoRe Solutions and Surdiman Indra were reviewed. Unicef has worked on the installation of several systems in the Indramayu district and on the Ende Island of Ende District (East Nusa Tenggara). CoRe Solutions implemented several rainwater harvesting tanks throughout Indonesia and Surdiman Indra is applying domestic rainwater harvesting in Tangerang.

Individually installed rainwater harvesting systems

Individual rainwater harvesting systems in the case study area have been evaluated based on the design, costs, connected roof area, tank location, water use pattern and system maintenance. Questions are stated below. Question 1 and 2 were answered by observation of the system. The connected roof area (question 3) was determined with a measurement tape. The other questions were directly asked to the local population, during the semi-structured interview.

1. *How is the system designed?*
2. *What is the location of the tank?*
3. *What were the costs of the system?*
4. *How is the maintenance of the system organized?*
5. *How much roof area is connected to the system?*
6. *What is the (rain)water use pattern?*

Externally installed rainwater harvesting systems

Rainwater harvesting systems installed by external organizations have been evaluated on successes and mistakes. This is done to make sure that not the same mistakes will be made in the purposed design in this research. Furthermore, the system choices that are made in these projects were evaluated. System choices include the materials used, the tank size and shape, the installation of the overflow, first flush and the type of treatment. Implementers of these projects are consulted by personal interview, by phone, videoconference and/or electronically regarding the below stated aspects. Question 1 to 4 are similar to the questions asked to the population owning a locally installed system. Additionally some more general questions were asked, since external parties often evaluate their rainwater harvesting projects in a broader sense.

1. *How is the system designed?*
2. *What is the location of the tank?*
3. *What were the costs of the system?*
4. *How is the maintenance of the system organized?*
5. *How is the system implemented?*
6. *What could be improved in the existing system?*
7. *What is unique with respect to this system?*
8. *What is or was the lifetime of the system?*

4.2. Social and cultural criteria

In the design of a system it is important to take social and cultural criteria into account. Social aspects are covered and integrated in this report in all chapters of this report including the chapters regarding general, quality, treatment, quantity, legal and institutional aspects. More information regarding which information can be found where, is provided at the end of this paragraph.

An example of the importance of the inclusion of social and cultural criteria is the fact that rainwater harvesting is not viewed as a safe drinking water source in some cultures and/or religions. If this appears to be the case, the implementation of rainwater harvesting could be very difficult, and possibly impossible. In this situation an alternative solution may be more suitable.

This research tested the acceptance of rainwater harvesting in Serang (Indonesia, Java), based on several interviews with both the local population and experts. Goals of these interviews were the following:
1. Learning from in field experiences from existing rainwater harvesting projects (paragraph 4.1.1).
2. Gathering research in the field of rainwater harvesting.
3. Getting a view on the local situation, culture and habits in Indonesia and in the case study area
4. Getting inside in the view of the population regarding rainwater harvesting with respect to other water supply systems (regarding preference, cost and water quality).
5. Find the reason why rainwater harvesting is currently not practiced frequently in Indonesia.

4.2.1. Interviews with experts

To identify water related habits, the acceptance and perception of rainwater and the suitable design of rainwater harvesting systems experts were interviewed. All experts interviewed are working or studying in Indonesia. These experts either have in field experience with rainwater harvesting, are working in the field of rainwater harvesting in Indonesia, are doing research at a university regarding rainwater harvesting or are working in a governmental institution related to water issues in the case study area. Experts that were contacted, regarding the social- cultural situation in Indonesia are summarized in Table 12.

Main questions included:

1. *What are main water related habits in Indonesia?*
2. *How is the perception and acceptance of rainwater in Indonesia?*
3. *What kind of water quality should such a system provide? Should it meet the drinking water standard or can it be less strict?*
4. *What kind of tank would you suggest? Especially regarding the material, size and shape?*
5. *What kind of treatment would you think of? For example pasteurization, SODIS, copper and silver disinfection, ceramic candle (Nazava) or gravity based ultrafiltration?*
6. *Should the rainwater harvesting system provide a 100% coverage, or can it be a combination of sources?*
7. *What is a suitable system scale of a rainwater harvesting system? Household, family/street or village level?*
8. *Who should investments money and time in the rainwater harvesting system? The population or the government?*

Table 12: Experts that were interviewed regarding the social and cultural aspects of rainwater harvesting in Indonesia.

Who	Function	Use for my research
General experts		
Prof. Wahyoe Hantoro	Indonesian Institute of Science	In field experience rwh
Basja Jantowsk	Employee Aidenvironment / Rain	In field experience rwh
Maarten Onneweer	Employee Aidenvironment / Rain	In field experience rwh
Robby Kamarga	Unicef (old function)	In field experience rwh
Glen Eitemiller	CoRe solutions Indonesia (old function)	In field experience rwh
Anindrya Nastiti	PhD-student, dimensions of access to water, household behavior, equity, and institutions in Indonesia.	Expert water supply
Aidan Cronin	Unicef	Expert water supply
Fany Weda and Maraita Listyasari	World Bank	Expert water supply
Rosetyati Retno Utami	PhD-student regarding water usage in Indonesia (Bandung)	Expert water supply
Ira Lubis	Bappenas	Expert water supply
Indratmo Soekarno	Professor ITB	Expert water supply
Yuniati Zevi	Post-doctoral associate, ITB Bandung	Research rwh
Juliana Imroatul	PhD- domestic rainwater harvesting ITB	Research rwh
Case study experts		
Freddy Sinurat	Kabupaten Serang, Bappeda	Local expert
Erwin Unyil	Kabupaten Tangerang, Bappeda	Local expert
Irfan Saputra	Kabupaten Serang , Dinas Health	Local expert
Pak Suhaemi	Contact person IUWASH	Local expert
PDAM kabupaten Serang	PDAM kabupaten Serang	Local expert
Dr. Betti Haingwak	Puskesmas Tirtayasa	Local expert
Dr Hago	Puskesmas Baros	Local expert
Ida Nariah	Puskesmas Pabuaran	Local expert

Since social and cultural criteria cannot be viewed separately from technical or economic aspects, these are integrated in the report as much as possible. Results of question 1 and 2 regarding water related habits and the acceptance of rainwater harvesting are presented in section 5.1. Question 3 and 4, related to water quality can be found in section 5.2. Question 5, regarding treatment is shown in section 5.3, question 6 and 7, regarding water quantity in section 5.4 and question 8 regarding economic aspects in section 5.5.

4.2.2. Interviews with local population

Ten semi-structured interviews were done with the local population. Translation was done by an agricultural bachelor student from Tirtayasa University. The student had no experience with translation. Respondents were selected by the sanitarian from the local health center (the puskesmas), who joined the interviews. Without the sanitarian it was not possible to perform interviews in the case study area.

Main goal of the interviews was to understand the view of the population regarding different water sources and to rainwater in particular. To make the interview more interactive and to bridge the language barrier cards with pictures have been used. The cards can be found in Figure 19. The three cards on the top are the raw water sources. The middle twelve cards are methods for water gathering. The emotions on the bottom were used to categorise the cards within the different questions. Cards were specially developed for the local situation. Since it is important that pictures and text do not conflict with the view of the population or with each other the cards were improved by five Indonesian PhD students.

With the use of the cards, questions were asked regarding water sources and methods for water gathering. The choice to evaluate all types of water sources was conscious. When more attention is paid to rainwater in particular it will be more difficult to get a fair view regarding the opinion of the population. Next to the questions regarding raw water sources and water gathering, questions were asked regarding rainwater in particular. Questions are asked in Bahasa Indonesia. Below the questions, and their translation are shown.

Water sources

1. *Sumber air apakah yang Anda gunakan?*
   Which water sources are you using?
2. *Urutkan sumber air berikut mulai dari sumber yang paling Anda sukai.*
   Order water sources to your preference.
3. *Urutkan sumber air berikut dari sumber yang menurut Anda paling bersih hingga paling kotor.*
   Order water sources from clean to dirty.

Water gathering

4. *Bagaimana cara Anda mendapatkan air?*
   How are you gathering your water?
5. *Urutkan sumber air berikut mulai dari cara yang Anda sukai.*
   Order water gathering to your preference.
6. *Urutkan sumber air berikut mulai dari yang menurut Anda paling bersih hingga kotor.*
   Order water gathering from clean to dirty.
7. *Urutkan sumber air berikut mulai dari yang menurut Anda paling mahal hingga murah.*
   Order water gathering methods from cheap to expansive.

Like the results of the interviews with the experts, the results of the above stated questions can be found in different parts of the report. The questions regarding preference (2 and 5) can be found in section 5.1. Questions regarding water quality (3 and 6) can be found in section 5.2. The answers to the questions regarding the type of water use (1 and 4) are shown in section 5.4, were question 7 regarding costs can be found in section 5.5.

Figure 19: Cards used for interviews with the local population.

4.3. Water quality and treatment

In this paragraph the methodology used to investigate rainwater quality at different stages will be discussed. Furthermore there will be attention for the identification of potential treatment options.

As seen in the literature review, water quality in a rainwater harvesting system changes during the various process steps with take place in a DRWH system. The order of these steps can differ, as also indicated in Figure 20. The boxes indicate system parts were the water passes through. Arrows illustrate water flow from one to another system part. Storage and distribution is not relevant when the water is consumed directly out of the tank or the treatment device. During this research the water quality changes during the various steps was investigated.

Raw rainwater, roof runoff, and water quality inside tanks was measured in Tirtayasa (Serang, Indonesia) on 31 May 2016. Analysis were performed by WLN Indonesia.
Below the various process steps, as illustrated in Figure 20 are explained in more detail.

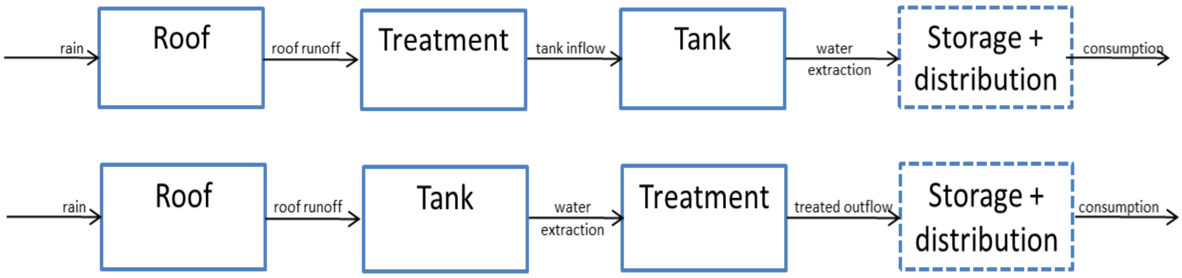


Figure 20: Schematization of the different process steps in rainwater harvesting systems.

- Know rainwater quality
  Information about direct rainwater quality is relevant, to investigate the effect of air pollution on rainwater quality. Furthermore raw rainwater quality can be compared to the quality of roof runoff. This can provide an indication of the pollution on the roof, gutter and downpipe. At a certain point maintenance, redesign or replacement of the roof and gutter system may be more attractive then investing in treatment. Raw rainwater quality in Indonesia was measured in Tirtayasa and Serang. Furthermore some measurements performed by external parties were found. These were compared with the own measurements.
- Know roof runoff quality
  Literature research was done to find the microbial and chemical contamination that can be expected in roof harvested rainwater. It is known that water harvested from the roof has in general more microbial and chemical contaminants then raw rainwater.
  Measurements of roof runoff in the field on relevant microbial and chemical contaminants were performed. *E.coli* is easy to measure and can be used as an indicator for measure microbial contaminants. The microbial indicator *Enterococcus* was also used, because it survives for a longer period. Although these indicators can provide an useful source of information regarding microbial quality, Ahmed et al. (2009) found that both *E.coli* and *Enterococcus* in roof harvested rainwater do not satisfactory indicate the presence of other human enteric pathogens like *Aeromonas hydrophila*, *Campylobacter coli*, *Campylobacter jejuni*, enterohaemorrhagic *E. coli*,

Legionella pneumophila, *Salmonella* species, *Giardia lamblia* and *Cryptosporidium parvum*. *Campylobacter*, associated with the deposits of birds was measured as well. Water quality parameters that were measured include pH, turbidity, DOC (dissolved organic carbon), lead, copper, zinc, aluminium, arsenic, magnesium and calcium. Measurement were performed using a checklist incoming water quality including, as suggested by RAIN (2008). This checklist includes information about roof and gutter material, surface area, presence of animals on the roof, presence of organic matter on the roof and the technical state of the roof. These parameters are relevant, since they influence the quality of the roof runoff. The difference in pollutant load in roof runoff over time is assessed, by measuring in three fold. Factors that could not be taken into account in this research, but will influence the incoming water quality include seasonal fluctuations, wind speed and direction and the length of the dry period before the rain.

- Know the water quality that has to be achieved
  The produced water quality of the system was compared with worldwide and Indonesian water quality standards, and water quality information from current water sources. Water quality guidelines are discussed in paragraph 2.2.1.

Table 13: Checklist incoming water quality that has to be filled in during measurements.

Checklist incoming water quality
What is the roof material?
Flat or tilted roof?
Age of the roof
Damage of the roof?
Vegetation above the roof?
Roof area
Birds present on the roof?*
Dirt, leaves, faecal dropping, insects and litter on the roof?
Gutter and drainpipe present?
Gutter and drainpipe material
Age of the gutter and drainpipe
Damage of the gutter and drainpipe?
Functioning of the gutter and drainpipe (water stagnation)
Dirt, leaves, faecal dropping, insects and litter in the gutter and drainpipe?

*point measurement. Additionally this question will be asked to the local population.

- Determine possibilities for treatment
  Existing possibilities for local rainwater treatment and combinations of those were found during a literature study and several interviews with experts. Treatment devices are tested by others on log removal for bacteria, viruses and protozoa and on chemical removal. An overview of possible treatment methods is given in paragraph 2.3.2.
  Both treatment before water enters the storage tank (point of entry treatment), and treatment just before use (point of use treatment) can be applied. Point of entry treatment that was researched include: cloth filtration, ultrafiltration, copper silver disinfection and fish. Point of use treatment that was evaluated include: biosand filtration, SODIS, chlorine, ceramic pot filtration (with silver/copper) and boiling. The selection is based on technical suitability, applicability for small scale treatment, low tech solutions and costs. An attempt is paid to include different type of treatment techniques. All selected treatment types have been evaluated on costs (investment and operational costs), technical performance (microbial and chemical effectiveness, turbidity

removal and mosquito prevention), social possibilities (availability, time and preference) and possible negative effects. In the results treatment is discussed separate, in paragraph 5.3.

- Determine removal/(re)growth/leaching during storage in tank
  Concentrations of micro-organisms can change in the storage tank due to survival rates. Chemicals can settle or attach to biofilm in the storage tank. The extend of regrowth and removal in the storage tank at one point of time has been determined by comparing the measurement results in the tank with the measurements of the roof runoff.
- Recontamination
  Recontamination during transport and storage can occur because of unhygienic storage and handling practices. Information about the extent of recontamination has been searched in literature.

After all process steps the water quality should meet the water quality objectives that are set. If this is not the case, the system design has to be corrected. In many cases this would implement additional treatment, or safe storage and distribution.
Since in this research just a limited number of point measurements are performed. Own microbial and chemical analysis are compared with measurements done by others in Indonesia. This should provide an indication of the variations in time and space in direct rainfall, roof runoff or in rainwater harvesting tanks.

4.4. Water quantity

4.4.1. General data analysing

Data between 01-01-1990 and 31-12-2015 was extracted from the PUSAT DATABASE – BMKG, for four different stations in the province of Banten (Java, Indonesia). The stations include Stasiun Meteorologi Serang, Stasiun Klimatologi Pondok Betung, Stasiun Geofiskika Tangerang and Stasiun Meteorologi Soekarno Hatta. All selected stations have daily rainfall data available for the selected period. The locations of the stations can be found in Figure 21.

Figure 21: Locations of the precipitation stations in Banten (Google Maps, 2016).

Since the rainwater harvesting system is designed for the Northern part of Serang, the data from the station Serang was used. However the quality of the data from this station was checked by visual data quality analysis and making a double mass plot with the Serang station and the other three stations in Banten province. The number of missing data points has been checked and compared for all four selected stations. This analysis can be found in Appendix C1. Based on this analysis only the data between 01-01-1990 and 31-12-2014 has been used in further analysis.

4.4.2. Distribution functions for missing data

Since a significant amount of the rainfall data for the station of Serang is missing, something has to be done with these data gaps. It was chosen to use a probabilistic analysis to fill up the missing data. Since rainfall is not uniformly distributed throughout the year, but shows a clear seasonality it was chosen to construct cumulative distribution functions (cdf) for every month separately. The decision for the time step is a trade-off between data availability and the correct representation of seasonality. For smaller time steps you will have less data available to construct the cdf, which will make the curve more uncertain. For larger time steps, the seasonality in the computed series will be less representative for the “real” seasonality. The separation in months, implies that it is assumed that rainfall between one day and another in one month is independent. In reality this assumption is not totally correct.

To construct the cumulative distribution functions (cdf) of each month the following steps were taken:

- Collect all rainfall data between 01-01-1990 and 31-12-2014 from the month in consideration.
- Calculate the percentage missing data.

- Calculate the percentage of days without rain, and delete this data. The percentage days without rain will not be used to construct the cdf. However it will be used, during the generation of the rainfall data.
- Generate the cumulative distribution function , which is defined as:
  $F_x(x) = P(X \leq x)$ for x=1,2,3,….,rainmax. In which X is the rainfall observed, and rainmax the maximum rainfall observed within the total data series.
  In empirical cdf is defined as:
  $$F_x(x) = \frac{number\ of\ datapoints\ \leq x}{total\ number\ of\ datapoints}$$
  The problem with the empirical cdf is that this function is not continuous.
- Approximate the cdf by fitting a log-normal distribution, a gamma distribution or a Weibull distribution through the collected points. The distribution functions have been fitted by using the maximum likelihood approximation. The most suitable fit will be selected by visual inspection, the mean square error (MSE), chi-square test and the Lilliefors test.
- Generate a random number between 0 and 1 to determine whatever you have a day with or without rainfall. This is illustrated in Figure 22A. You have no rainfall in case the random generated number is smaller as the fraction of dry days in the corresponding month.
  $$Random\ number \leq \frac{average\ number\ of\ dry\ days\ month\ i}{total\ number\ of\ days\ month\ i}$$
  In case of no rainfall the analysis stops here (Figure 22B).
- Generate random rainfall, by taking a random number between 0 and 1, and reading the corresponding rainfall (in mm) from the cdf for the specific month for which you want to generate rainfall data. This is illustrated in Figure 22C.
- Fill in the data gaps by random generated rainfall for the corresponding month, and use this data series as input for the rainwater harvesting model. For this the percentage of days without rainfall has been taken into account.

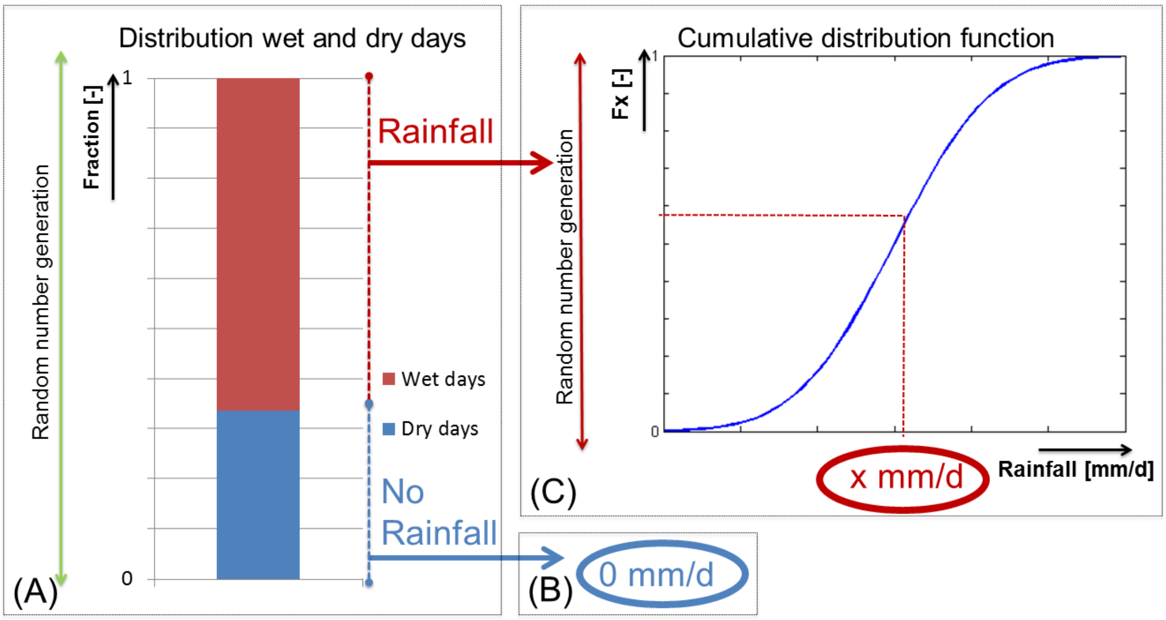


Figure 22: Methodology to fill missing data.

4.4.3. Model

A conceptual model for a rainwater harvesting system was built in which precipitation (P), evaporation (E), splashing from gutter and roof (SPL), first flush (FF), overflow (O) and tap flow (TF) were considered. A visual representation of the conceptual model that was used can be found in Figure 23. In Figure 24 a schematic representation of the model is shown.

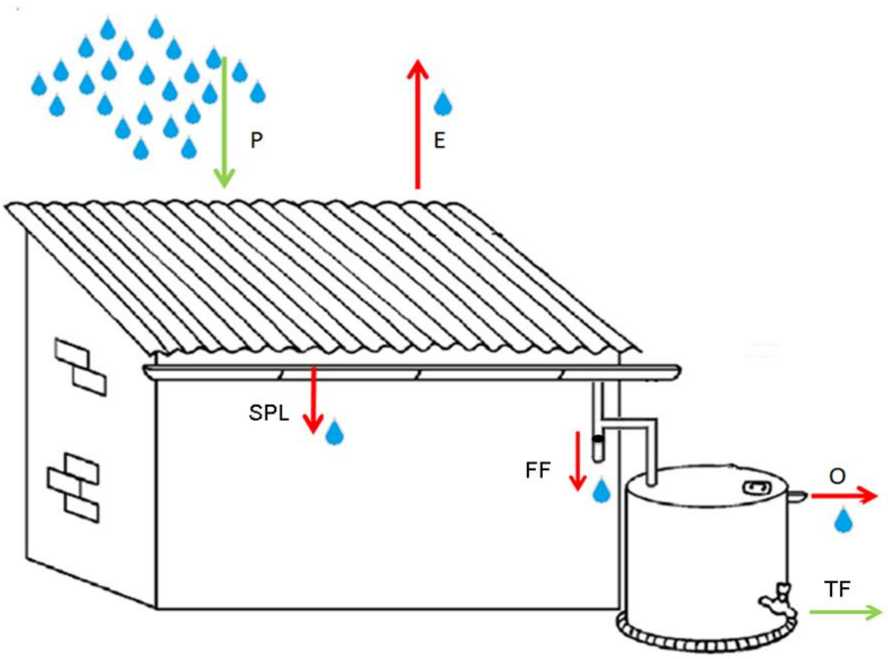


Figure 23: Conceptual model used to represent the rainwater harvesting system.

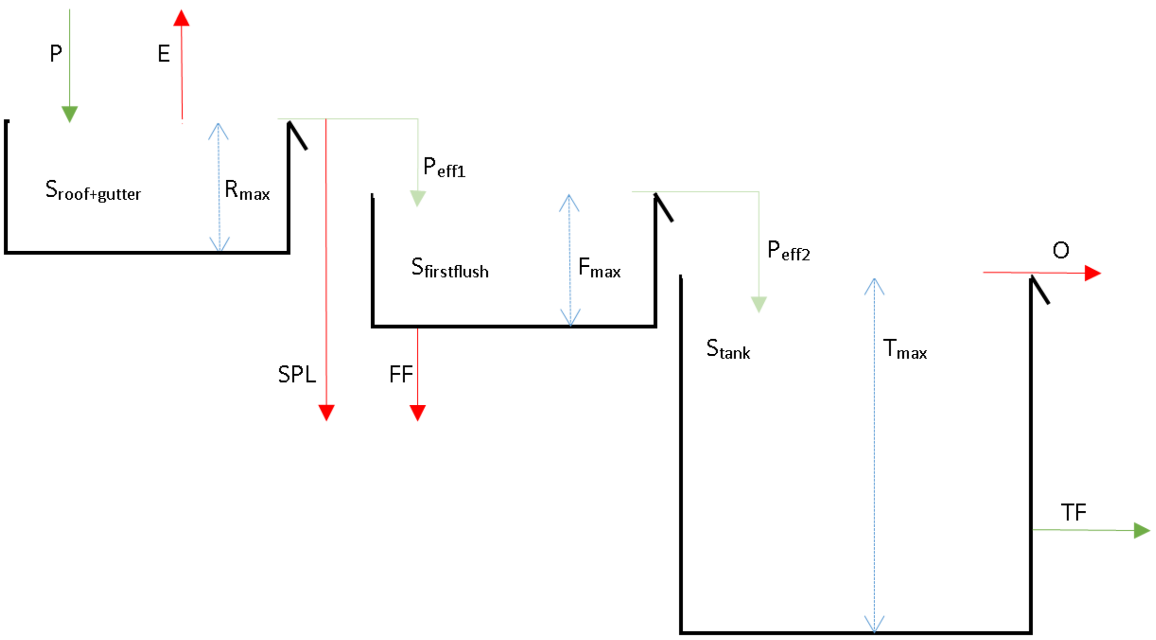


Figure 24: Conceptual model used, for the rainwater harvesting system.

The model is based on a water balance model (ΔS = In – Out), and runs with a daily time step. The model consists of 3 reservoirs which are the roof, the first flush system and the tank itself. All these reservoirs have a certain volume (Rmax, Fmax and Tmax), and incoming and outgoing fluxes. The water balance for this system is shown below.

$$P(i) = \cancel{\frac{dS_{roof+gutter}}{dt}} + SPL(i) + E(i) + \underbrace{Peff1(i)}_{\cancel{\frac{dS_{firstflush}}{dt}} + FF(i) + \underbrace{Peff2(i)}_{\frac{dS_{tank}}{dt} + O(i) + TF(i)}}$$

On day i, a certain rainfall volume falls on the roof, part of this water will stay on the roof and evaporate later that day. The other water flows towards the first flush system, but some water will splash from the roof or from the gutter. The rest of the water will enter the first flush system. Some of the water will stay behind in the first flush system, which will empty again later the same day. The rest of the water enters the storage tank. Here part of the water will overflow, another part will be used, and the storage in the tank may change. One should note that for the rainwater harvesting tank it is decided to first fill the tank with the available rainfall that day (Peff2), then spill (O), and then use the remaining water in the tank (TF).
The water storage in the roof and in the first flush system does not change over a daily time step and are assumed zero at the beginning of each day.
Monthly average open pan evaporation is used. Average open water evaporation is around 3-4 mm/day (see paragraph 3.3). Since this is larger than the possible storage on the roof (±1.5 mm), it is assumed that all water will be evaporated at the end of the day. The same counts for the first flush system, the possible volume of flow out of the first flush system is larger than the volume of the system itself, resulting in an empty system in the beginning of each day. Obviously the storage in the rainwater harvesting tank will change over time.
The formulas that are used in the model to represent the processes can be found in Table 14.

Parameters used in the model are presented in Table 15. Important in the determination of the potential water harvest is the tank and roof size. In this research calculations are performed for tanks of 1,2, 4 and 8 m^3 and roofs of 25, 50, 75, 100 and 150 m^2. However in the calculations in which different operating scenarios are compared (see section 4.4.5), a tank of 2 m^3 and a roof of 100 m^2 is used.

The demand D(i) can be set or optimized based within the model. This demand is a fixed value which can vary within different months, or can be constant throughout the entire year. The demand is the amount of water that is asked for by the consumers. Since the tank can be empty, this is different from the tap flow (TF(i)) which is the actual amount of water which is consumed from the system.

Table 14: Formulas used to represent the processes in the conceptual model.

Flux	Formula
Precipitation volume [L^3/T]	$P(i) = Pm(i) * RS$
Roof loss [L^3]	$L_{roof+gutter}(i) = min(P(i)\Delta t, R_{max} * RS)$
Evaporation [L^3/T]	$E(i) = min\left(\frac{L_{roof+gutter}(i)}{\Delta t}, E_{ow}\right)$
Splash loss [L^3/T]	$SPL(i) = LO * (P(i) - \frac{L_{roof+gutter}(i)}{\Delta t})$
Effective precipitation 1 [L^3/T]	$Peff1(i) = P(i) - \frac{L_{roof+gutter}(i)}{\Delta t} - SPL(i)$
First flush [L^3/T]	$FF(i) = min\left(\frac{F_{max} * RS}{\Delta t}, Peff1(i)\right)$
Effective precipitation 2 [L^3/T]	$Peff2(i) = Peff1(i) - FF(i)$
Overflow [L^3/T]	$O(i) = max\left(0, \frac{S_{tank}(i-1)}{\Delta t} + Peff2(i) - \frac{T_{max}}{\Delta t}\right)$
Available water [L^3]	$S_{available}(i) = S_{tank}(i-1) + Peff2(i)\Delta t - O(i)\Delta t$
Tap flow [L^3/T]	$TF(i) = min\big(D(i), S_{available}(i)\big)$
Storage tank (after tap flow) [L^3]	$S_{tank}(i) = S_{available}(i) - TF(i)\Delta t$

Table 15: Parameters that are used in the model. Demand can be varying within time in months in the model, or it can be constant throughout the entire data set.

Parameter	Process	Range	Value	Unit	SI Unit
$\boldsymbol{S_{tank}(i)}$	Storage in tank	0 - T_{max}	-	[m^3]	[L^3]
$\boldsymbol{Pm(i)}$	Precipitation	-	-	[m/d]	[L/T]
$\boldsymbol{E_{ow}}$	Open water evaporation	3 $*10^{-3}$ - 6 $*10^{-3}$	4 $*10^{-3}$	[m/d]	[L/T]
$\boldsymbol{R_{max}}$	Maximal roof storage	0.50$*10^{-3}$ – 4 $*10^{-3}$	1.50$*10^{-3}$	[m]	[L]
$\boldsymbol{LO}$	Loss fraction	0.15$*10^{-3}$ – 0.65$*10^{-3}$	0.35	[-]	[-]
$\boldsymbol{F_{max}}$	First flush	0 – 4$*10^{-3}$	1.00$*10^{-3}$	[m]	[L]
$\boldsymbol{PDNM}$	Percentage of days demand not met	0 – 100	20	[%]	[%]
$\boldsymbol{T_{max}}$	Tank volume	1 – 8	1,2,4,8	[m^3]	[L^3]
$\boldsymbol{RS}$	Roof size	25 – 150	25,50,75,100,150	[m^2]	[L^2]
$\boldsymbol{D(i)}$, $\boldsymbol{DemandWet}$, $\boldsymbol{DemandDry}$, $\boldsymbol{D1\ untill\ D12}$	Demand Seasonal demand Monthly demand	0.01 – 0.50	Not applicable	[m^3/d]	[L^3/T]

The model can be used in various ways, in which the behavior of a real rainwater harvesting system can be predicted. An important parameter is the system reliability which is expressed as the percentage of days in which the demand is not met (PDNM). In general the percentage of days in which the demand is not met is set to 20%. Very low PDNM result in unnecessary large systems. High PDNM results in very large uncertainty regarding water extraction. Since no guidelines exist regarding this percentage, a decision had to be made. Twenty percent, personally, still seemed acceptable. For scenario 1a results are also calculated for a PDNM of 5% and 50%. For scenario 2a results are calculated for a PDNM between 5 and 100%.

Besides the PDNM, the range of demand is an important parameter that has to be considered. The demand can be either constant or varying per month. The maximum demand is set towards 500 liter/family/day. Of course one should consider the demand D(i) when evaluating the PDNM. With a higher demand, there is a higher chance that the demand will not be met on a certain day.

Finally, the minimum amount of fresh water needed, is an important parameter to evaluate the total water use pattern of a family. This research assumes that one family needs at least 80 liter fresh water per day. Twenty liter per person per day, is the minimum water requirement set by the WHO. With this amount of water some basic hygienic needs and food hygiene can be covered. This can be either rainwater or bottled water. Ground- and surface water cannot be used since this is brackish or heavy polluted. Piped water supply cannot be used is most areas, since it is not available.

4.4.4. Demand optimization

In this research two types of optimization were selected. In the first method optimization is based on a fixed amount of water which is requested from the rainwater harvesting tank. In the second method water use is based on the available amount of water. This is illustrated in Figure 25.

Optimization based on expectation

First a Monte Carlo analysis was performed in which the demand in the wet season, in the wet and dry season or in each month is varied between a certain minimum and maximum value. Only the demand is varied, and all other parameters, including roof sizes and tank sizes have been kept constant within one run. Secondly only the combinations of demands are selected which meet the PDNM criteria (percentage of days demand not met). From these combinations the optimum combination can be selected. This is either the maximum tap flow or a weighted tap flow throughout the season. In case the tap flow is weighted an attempt is played to give relatively more attention to the tap flow in the dry season. Table 16 explains how the maximum tap flow, or the weighted tap flow is calculated for each scenario.

Optimization based on availability

Instead of basing the expected water use (demand) on the time of the year, it can also be based on the water availability inside the tank. The model just has to run once, with a specific operation rule, and the average and monthly tap flows are stored. The operation rules that will be analysed can be found in paragraph 4.4.5. (scenario 2d).

4.4.5. Scenarios

In the demand optimization, multiple scenarios were used. One can distinguish the scenarios which assume water use only in the wet season and the scenarios that assume water use both in the wet and the dry season. Using the rainwater harvesting system only in the wet season can be relevant due to water quality issues.

One can also distinguish the scenarios, whatever they calculate the tap flow based on a fixed demand (expectation) or based on availability as explained in the previous section. The scenarios are summarized in Figure 26. The methodology used to calculate the optimum tap flows is illustrated in Figure 25.

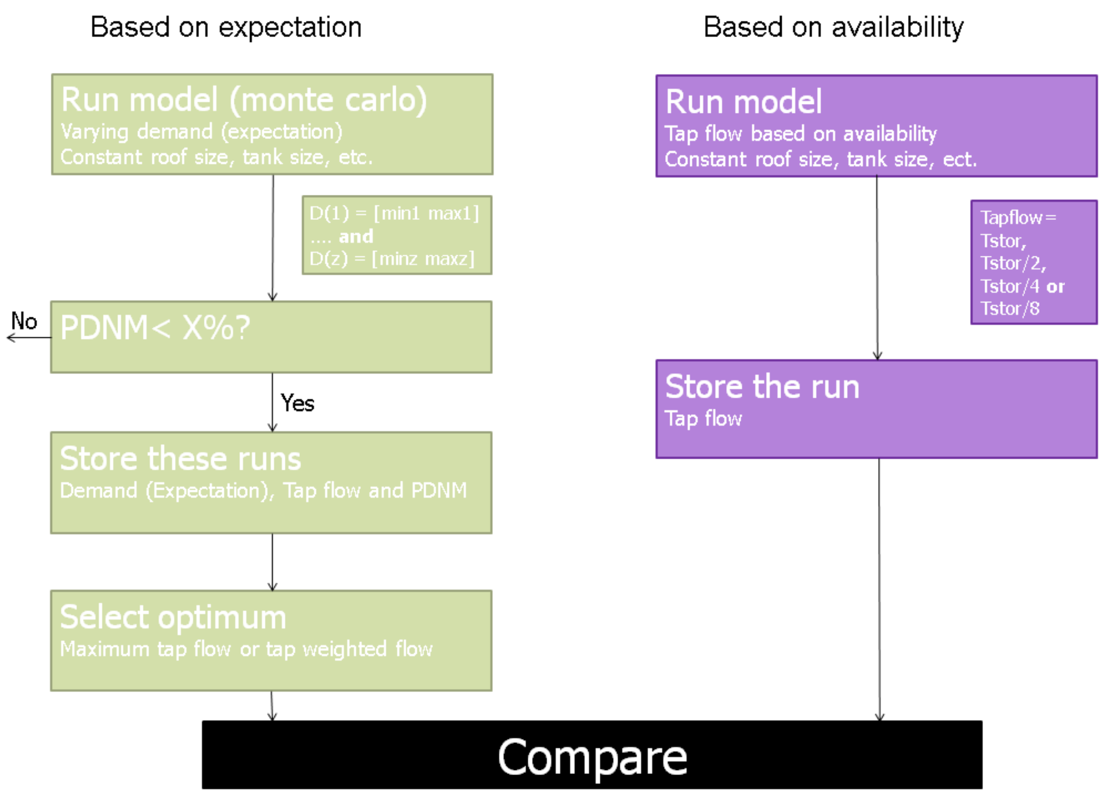


Figure 25: Optimization based on a fixed demand (expectation) or based on available amount of water.

Scenario 1a

In this scenario no water use is assumed in the dry season, which is between 1 June until 31 October. The water demand (or expectation) is kept constant throughout the wet season. After the Monte Carlo runs the highest tap flow is selected which meets the criteria for the percentage of days the demand (expectation) is not met (PDNM).

Scenario 1b

In scenario 1b again no water use is assumed in the dry season. The difference between scenario 1a is that in this case the expected water use (or demand) is fluctuated each month. The percentage of days the demand cannot be met is set to 20%. A roof size of 100 m^2 and a tank size of 2 m^3 was used. To find the optimum demand (expectation) the Monte Carlo run with the highest average tap flow was selected (see Table 16). To calculate the average tap flow, all daily tap flows in the wet season (dw) are added for each Monte Carlo run (n). The sum of these tap flows is divided by the number of days in the wet season (dwmax).

Scenario 2a

For scenario 2a a constant demand is assumed during the entire year. From an user perspective this implies that one requires a similar amount of rainwater both in the wet and the dry season. However in practise the water availability will be less in the dry season compared to the wet season. Different from the other scenarios, this scenario investigates the relation between PDNM and tank size. Roof sizes (50, 100 and 150 m^2) and demands (50, 100, 200, 300, 400 and 500 liter/day) were fixed.

Table 16: Formulas that are used to select the optimum. For each monte carlo run (n) the calculation is made, and the maximum value of all runs is selected.

Scenario	
1a and 1b	$AverageTapWet(n)\ [m^3/d] = \frac{\sum_1^{dwmax} TF(dw,n)}{dwmax}$
2b(i) and 2c(i)	$AverageTapTotal(n)\ [m^3/d] = \frac{\sum_1^{dtmax} TF(dt,n)}{dtmax}$
2b(ii) and 2c(ii)	$WeightedTap(n)\ [-] = \frac{AverageTapWet(n)}{\sum_1^{nmax} \frac{AvTapWet(n)(PDNM<20\%)}{nmax}} + \frac{AverageTapDry(n)}{\sum_1^{nmax} \frac{AvTapDry(n)(PDNM<20\%)}{nmax}}$

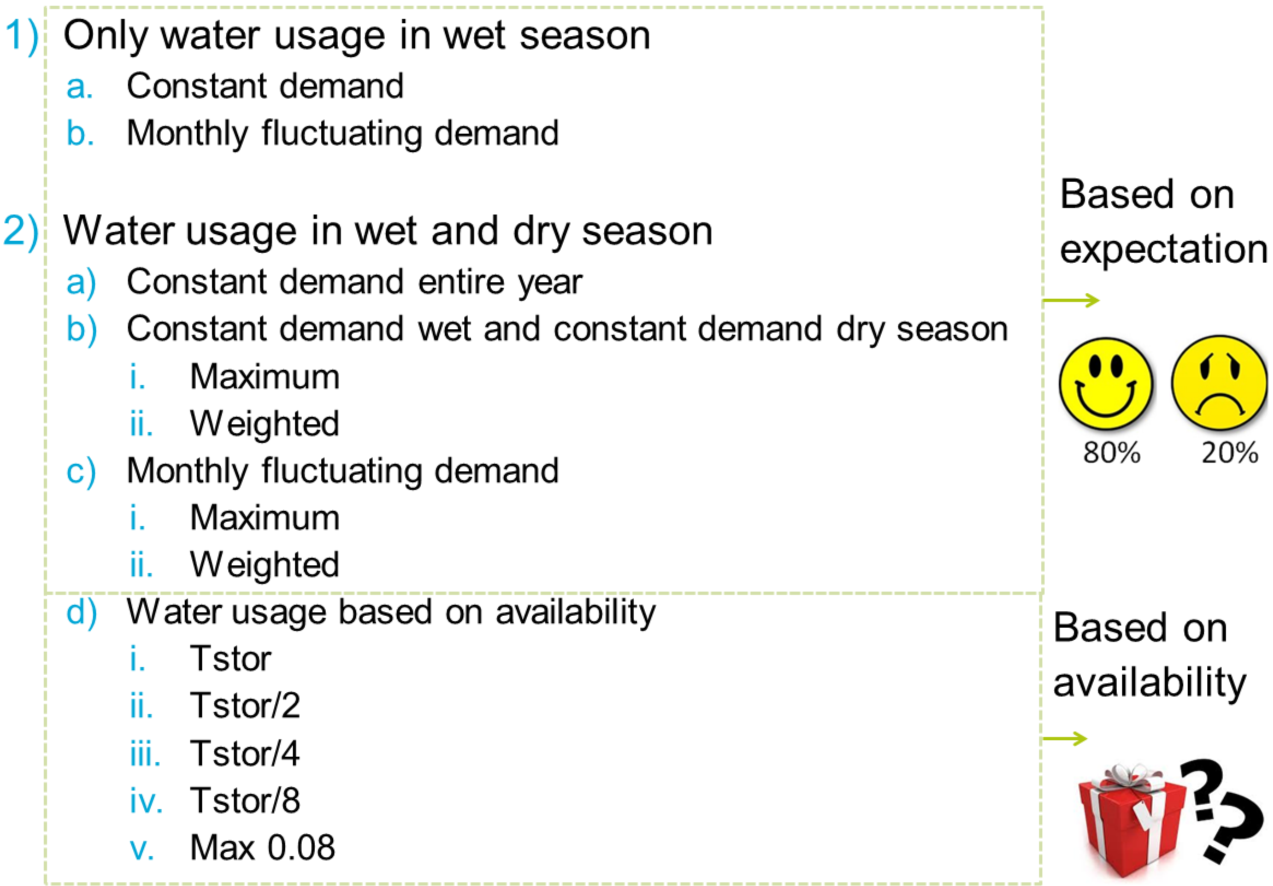


Figure 26: Summary of the scenarios that are used in the optimization of the tap flow.

Scenario 2b

In this scenario the rainwater harvesting tank is used throughout the entire year. The expected amount (demand) is different for the wet and the dry season, but does not differ between the months. The percentage of days the demand cannot be met is set to 20% and a roof and tank size of respectively 100 m^2 and 2 m^3 was used.

In this scenario the optimum can be selected in two ways. Either the maximum average tap flow can be selected, or one can find a weighted tap flow (see Table 16).The average tap flow is calculated by summing all daily tap flows (dt), and dividing it by the number of days (dtmax). The weighted tap flow is calculated by summing a weighted tap flow in the wet season with a weighted tap flow in the dry season.

Scenario 2c
In this scenario the demand (expected water use) is fluctuated per month. Again PDNM, tank and roof sizes are 20%, 2 m^3 and 100 m^2 respectively. Optimum demand (expected water use) is selected by finding the highest average tap flow, or the highest weighted tap flow.

Scenario 2d
Instead of basing the demand on the time of the year, it can also be based on the water availability inside the tank. For this scenario, three operating rules have been developed. In the first operating rule one will use all water available in the tank, with a maximum of the required amount of water which is 0.5 m^3/d. For the second operating rule one will use half of the water available in the tank still with a maximum of 0.5 m^3/d. In the third scenario one fourth of the water available in the tank is used, still with a maximum of 0.5 m^3/d. In the fourth scenario one eight of the tank is used, still with a maximum of 0.5 m^3/d. However in case a tank size of 2 m^3 is used the maximum water usage will become one eight of the tank size which is 0.25 m^3/d. The last scenario assumes rainwater is only used for drinking, and thereby the maximum water use becomes 0.08 m^3/d.

i) Water usage(i) = min(Tstor(i), 0.5);
ii) Water usage(i) = min(Tstor(i)/2, 0.5);
iii) Water usage(i) = min(Tstor(i)/4, 0.5);
iv) Water usage(i) = min(Tstor(i)/8, 0.5);
v) Water usage(i) = min(Tstor(i), 0.08);

4.4.6. Sensitivity analysis

In the sensitivity analysis the effect of parameter uncertainty on final model results are investigated. The parameters Rmax, SPL and FF is approximated as good as possible, for the model runs. Values were based on literature research and the field visit done. The values used, together with the expected range of the parameters can be found in Table 15. In the sensitivity analysis model outcomes were tested in case the parameters were varied within the expected range.

4.5. Economic aspects

To evaluate the economic aspects of rainwater harvesting the total cost of a rainwater harvesting system and the costs per cubic meter were calculated. These cost were compared with the costs for PDAM and bottled water. Moreover, the most economic operating scenario was determined. This calculation only considers operational costs. Finally the payback period was calculated. Below these steps are explained in more detail.

4.5.1. Calculate the total costs of a rainwater harvesting system

To calculate the total costs of a rainwater harvesting system installation, operation and maintenance costs were considered. Calculations have been performed both for plastic and ferrocement tanks. Installation costs include the price of the tank, tank transport, pipes, elbows, a tap, a gutter, a gutter filter, soil excavation and labor. Operation costs are not considered since the rainwater harvesting system operates on gravity. Maintenance costs were assumed to be a fixed percentage of the installation costs. For the plastic tanks, maintenance is assumed to be 4% of the installation costs and for plastic tanks 2% is used. Lifetime of the tanks were assumed to be 25 and 15 years for the ferrocement and plastic tank respectively. For the maintenance costs the net present value (NPV) is taken into account. The net present value is calculated by using the yearly maintenance costs (r) and a discount rate (i) of 6%. The net present value of the maintenance of all years (t) within the lifetime are added to find the total NPV of the maintenance.

$$NPV_{maintenance} = \sum_{t=0}^{lifetime} \frac{r}{(1+i)^t}$$

Material requirements were determined based on the authors best knowledge and compared to research performed by Imroatul (2016). For the material required for ferrocement tanks the method of Sharma & Gopalaratnam (1980) was used, as can be found in Appendix D1. Material costs were found by personal communication with Imroatul (2016). By adding the total installation costs and the net present value of the maintenance costs, the lifetime costs of the system were determined.

4.5.2. Calculate the water costs per m^3 of rainwater

The water costs per m^3 are found by dividing the lifetime costs with the total tap flow that can be achieved over the entire lifetime of the system.

$$Water\ costs_{euro/m3} = \frac{Lifetime\ costs}{\sum_{t=0}^{lifetime} tapflow(t)}$$

The water cost was calculated for a tank of 2 m^3, for scenario 2c, 2c and 2d. Furthermore, the water costs was calculated for a range of system sizes for scenario 2d(Tmax/2).

4.5.3. Comparing the price of rainwater, with bottled and PDAM water

The cost per cubic meter of rainwater was compared with the costs for bottled and PDAM water. Costs of bottled and PDAM water were found during the field work. A shop selling refilled bottled water was visited and employees of the Dinas Health and PDAM were interviewed. To calculate the costs for PDAM, water installation, administration and operation costs are taken into account.

4.5.4. Most economic water use pattern

The most economic water use pattern is defined (in this research) as the most economical way to use the available water sources (rainwater, refilled gallons and groundwater). It is assumed that the rainwater harvesting system, groundwater tanks and gallons are already present. This implies that only operation costs were taken into account. Calculations were performed for scenario 2c, 2c and 2d as explained in section 4.4. A tank size of 2 m^3 is assumed, combined with a roof size of 100 m^2.

For all considered scenarios the volume of water used from each source was calculated. The total volume of rainwater can be determined by using the average tap flow. The volume of bottled water, depends on the number of days rainwater that rainwater is not available in the tank. This depends on the percentage low flow, which is the percentage of days the amount of extracted water from the rainwater harvesting system is less than 80 liter (the fresh water need) and the average low flow, which is the average flow in case the flow is less than 80 liter. The amount of groundwater is calculated by subtracting the rainwater and groundwater use from the daily water requirement of 500 liter a family a day. Formulas that are used to perform these calculations can be found in Appendix D4.

After the amount of water for each considered scenario is calculated, it is multiplied with the operation costs of the water source. Operation costs of the rainwater harvesting system are assumed to be negligible since gravity flow is used. Operation costs for bottled water are the costs required to buy the gallons in a local shop. Operation costs for groundwater are the costs for pumping. It is assumed that groundwater has to be pumped for 5 meter, with an efficiency of 33.3%.

4.5.5. Payback period

Based on the amount of money that can be saved by installing a rainwater harvesting system the payback period was calculated. The formula to calculate the payback period is shown below. To determine the payback period the investment costs are divided by the yearly savings based on the investment. An important note is that the payback period does not take the lifetime of the system into account. When evaluating the results one should take into account that the lifetime of the ferrocement is expected to be higher than the lifetime of a plastic tank.

$$Payback\ period = \frac{Investment\ costs}{Yearly\ saving\ based\ on\ investment}$$

$$Yearly\ saving\ based\ on\ investment = New\ annual\ expenditure\ for\ water - Old\ annual\ expenditure\ for\ water$$

$$New\ annual\ expenditure\ for\ water = bottled_{\ new} \left[\frac{m^3}{year}\right] * price \left[\frac{euro}{m^3}\right] + gw_{new} \left[\frac{m^3}{year}\right] * price \left[\frac{euro}{m^3}\right]$$

$$Old\ annual\ expenditure\ for\ water = bottled_{\ old} \left[\frac{m^3}{year}\right] * price \left[\frac{euro}{m^3}\right] + gw_{old} \left[\frac{m^3}{year}\right] * price \left[\frac{euro}{m^3}\right]$$

For the old annual expenditure two scenarios are taken. In the first scenario it is assumed that one family currently pumps 420 liter groundwater a day and buys 80 liter of refilled gallons a day. In the second scenario it is assumed that one family currently pumps 480 liter groundwater and buys 20 liter of refilled gallons a day. For groundwater costs only the electricity costs required for pumping were taken into account. It should be noticed that both scenarios simplify the current water use.

4.6. Institutional and legal criteria

From a legal viewpoint it has been checked whatever it is legally allowed to install a rainwater harvesting system on a household level. Furthermore, it is investigated whatever their exists support for rainwater harvesting at a governmental or non-governmental level. Finally ongoing scientific research is identified. Governmental institutions contacted include the Bappenas, Bappeda, Dinas Health, PDAM and Puskesmas. Non-governmental institutions include Aidenvironment, Unicef and CoreSolutions. Research institutions include ITB Bandung and the Indonesian Institute of Sciences.

Focus was on the questions as stated below.

1. *Is there any legislation that discourages or limits the use of rainwater harvesting systems?*
2. *Are there governmental institutions that support rainwater harvesting? And if so, how?*
3. *Are there non-governmental institutions that support rainwater harvesting? And if so, how?*
4. *Is there any scientific research contribution to knowledge regarding rainwater harvesting?*

Questions were asked to the relevant stakeholders, who have knowledge regarding the question.

5. Results

5.1. General aspects

General aspects regarding the characteristics of the case study area, like catchment characteristics, the current water supply and population data can be found in chapter 3 of this report. In this section the existing rainwater harvesting systems that are installed by professional parties within Indonesia and by individuals in kabupaten Serang are discussed.

5.1.1. Need for rainwater harvesting

The current water supply in Tirtayasa, Pabuaran and Baros as discussed in paragraph 3.4. is not sufficient. Prices for bottled or refilled gallons are high, groundwater is brackish or located very deep, PDAM connections are not present and springs can be located relatively far. This results in a population that is unsatisfied with the current water supply, and thereby action is needed. The Dinas Health and the Bappeda, confirm that the current water supply in these areas is not sufficient.

In Tirtayasa, the use of groundwater or irrigation water cannot be extended due to water quality issues. Treatment will require high technological solutions, which will generally come with high costs. Costs for bottled water will remain high, and thereby it is not realistic to increase the use of this source. Although it is theoretically possible to increase the water supply of the PDAM, in practise this is not realistic in short term, because it will require time, support of the population and innovation of the facilities. As stated above, increasing the capacity of groundwater, irrigation water , PDAM, bottled or refilled water is not feasible, is short term. Thereby rainwater is an interesting option.

Like in Tirtayasa, in Pabuaran and Baros, the use of bottled water is too expensive and the PDAM network cannot be extended in short therm. However it would be possible to optimize the use of spring water, although the capacities of these sources are often limited and currently some springs are polluted. Also the use of groundwater could be increased, although this would result in even deeper groundwater levels and pumping costs. Hereby rainwater use in not the only option, to improve the water supply in Pabuaran and Baros, but considered as one of the options.

5.1.2. Professionally installed rainwater harvesting systems

Unicef, Core Solutions and Sudirman Indra have been implementing rainwater harvesting projects in Indonesia. From these projects some important lessons can be learned, as presented in Table 17. It is found beneficial to involve the community, to let professionals assist in tank installation, to build individual systems and to use financing that is provided by the development of new housing. In the text below these main lessons are discussed.

Community participation

It is of large importance to involve the community in all steps of the implementation of rainwater harvesting systems. The community should invest, either in money or time, in the rainwater harvesting system, to make sure they feel responsible for the system. This will increase the chance that the population will operate and maintain the system correctly. Unicef for example, requires the population to gather local materials, and to install the tank themselves, with help of professionals. Core solution requires a minimal financial contribution of 20%. In the project of Sudirman Indra, the population will pay the total installation costs, in most cases with a loan.

Table 17: Characteristics of existing rainwater harvesting projects in Indonesia.

	Unicef	Core Solutions	Sudirman Indra
Project type	non-profit organization	Commercial	commercial - pilot
Location	above ground	above ground	below ground
Material	reinforced concrete	Ferrocement	reinforced concrete
Tank volume	4 m^3	9 m^3	8 m^3
Shape	cylinder	Cylinder	rectangular
Overflow	yes	Yes	yes + infiltration
First flush	yes	Yes	no
Treatment	no	palm fiber and nazava	palm fiber
Installation costs	1,750,000 Rup	7,000,000 Rup	11,000,000 Rup
Installation time	3 – 4 days	5 days	unknown
Water quality	mosquito and algae expected.	clean, cool and clear. no algae.	not in operation yet.
Scale	individual	Individual	individual
Type of supply	drinking, cooking dry season	household water	unknown
Population investment	labor and material collection	materials cost (>20%) and 2 family members for labour.	full costs

Professional assistance in tank installation

The quality and lifetime of a DRWH system is largely dependent on its design. Therefore it is important to involve professionals in the installation of the system. The importance of this is can be explained by the projects of Unicef. In projects where the local population was building the tanks, the tanks were often not uniform, causing leakages and thereby decreasing the system lifetime. In later projects in which professionals assisted the local population in the building of the tank, this problem was solved.

Build a system on household scale

In projects of Unicef in which large tanks (10 m^3) were built for four families, it appeared difficult for the families to share their water source. Also the maintenance of these systems was found to be difficult. In the end only one family was generally using the system. Because of this reason rainwater harvesting systems are advised on a household scale.

Get financing by joining new developments

In practise it is sometimes difficult to obtain microfinancing for investments in water supply.

Experience with microfinancing for the installation of a piped water supply (at kabupaten Serang) shows that it is often not possible to get such financing. This is due to the fact that the population often does not comply with the requirements. Although it remains unclear which requirements are not met, it has most likely to do with the fact that the population has no high and regularly income, from an official registered job and/or that the population has no payback model, in which the initial investment done (with the microcredit) will be earned back by the investment itself. In this last example, microcredits are used to invest in a private company, from which the profit is likely to increase because of the investments.
An interesting possibility is to join new housing developments. This population already obtains a microcredit, and the additional costs for a rainwater harvesting system can be added to the micro-credit.

5.1.3. Individual existing rainwater harvesting systems

Based on initial communication with the health agency and the planning agency of the kabupaten Serang rainwater harvesting was expected to be very limited. However several different individual rainwater harvesting systems were found in kabupaten Serang, in sub-district Tirtayasa, Pabuaran and Baros, which are shown in Figure 27. Systems include small plastic buckets (A), larger plastic buckets (B), open concrete tanks placed outside (C), shallow wells refilled with rainwater (D), open concrete tanks placed inside (E), larger closed concrete tanks placed inside (F) and large plastic tanks placed outside (G).

In the evaluation of the existing systems some interesting points and customs were found which are discussed in detail below. The key findings include that the local government provides limited guidance in the installation, operation and maintenance of DRWH systems. The design of the population is based on own knowledge, creativity and preference. Currently water use based on water availability. Local materials are used, limited roof areas are connected and tanks are placed inside the house. Water quality is not monitored and small fishes and cloth filters are used as treatment. Systems are designed based on the ability and willingness of the population to pay for the system. These key findings are summarized in Figure 28.

Available materials and the knowledge, creativity, preference, ability & willingness to pay
Since there is no direct support for rainwater harvesting systems at the governmental institutions with direct contact with the population, the population uses their own knowledge, creativity and preference to build rainwater harvesting systems at their private ground. System design is based on the ability and willingness to pay of the local population. Materials are used that are easily available locally. In general cement and plastic tanks are common in the case study area. Both plastic and cement tanks are also used for water storage in families not practising rainwater harvesting. Often similar type of tanks can be found within a street level. On larger scale multiple types of systems can easily be found. In general the installation of a rainwater harvesting system is seen as last choice, and only done in case water is scare. Main complain regarding rainwater as water source has to do with quality concerns.

No system monitoring and water quality improvements based on experience
No monitoring network for rainwater harvesting systems exist in Baros, Pabuaran and Tirtayasa, and no advise is given regarding possible improvements of rainwater harvesting systems. Because of this the population implements water quality improvements based on their own experience. Fishes are placed in open tanks to eat mosquito larvae and systems are cleaned when dirty. In some cases a cloth filter is used to prevent debris and other larger particles to enter in the tank. In case water is used for potable purposes, it is boiled before consumption. This is a wide spread practise in Indonesia.

Water use based on availability
Current rainwater use is based on rainwater availability. In general no longer term planning exist to overbridge (part of) the dry season by using rainwater. Systems are generally only used in the rainy season, when the roof is relatively clean. In case the rainwater systems are empty, rainwater is substituted by other water sources.

Figure 27: Individual rainwater harvesting systems that are found in kabupaten Serang.

System location
In general most rainwater harvesting tanks are placed inside the house, although the surface area of some houses is relatively limited (small houses are around 50 m^2). The population itself does not experience this requirement for space as a limitation of the system. Main advantages are the fact

that there is no need to go outside to collect water. Part of the population is afraid to go outside at night, or do not want to share their water with their neighbours. Furthermore, it is very common to have an open water tank inside the house in the bathroom, also for people not practising rainwater harvesting. People use this water for cooking, bathing and sanitation and in some cases also for drinking. Another main advantage of locating the tank inside the house concerns algae growth. Inside the house there is no sunlight and it is more cool, which limits algae growth.

Connected roof area
In most cases just a limited roof area is connected to the rainwater harvesting system. This implies that gutters are not present around the entire roof. However people are generally satisfied with the amount of water they are able to harvest, during heavy rain. This can also be related to the fact that not all systems are equipped with a good functioning overflow system. In some cases an overflowing system will cause flooding of the house. However this is not mentioned by the population.

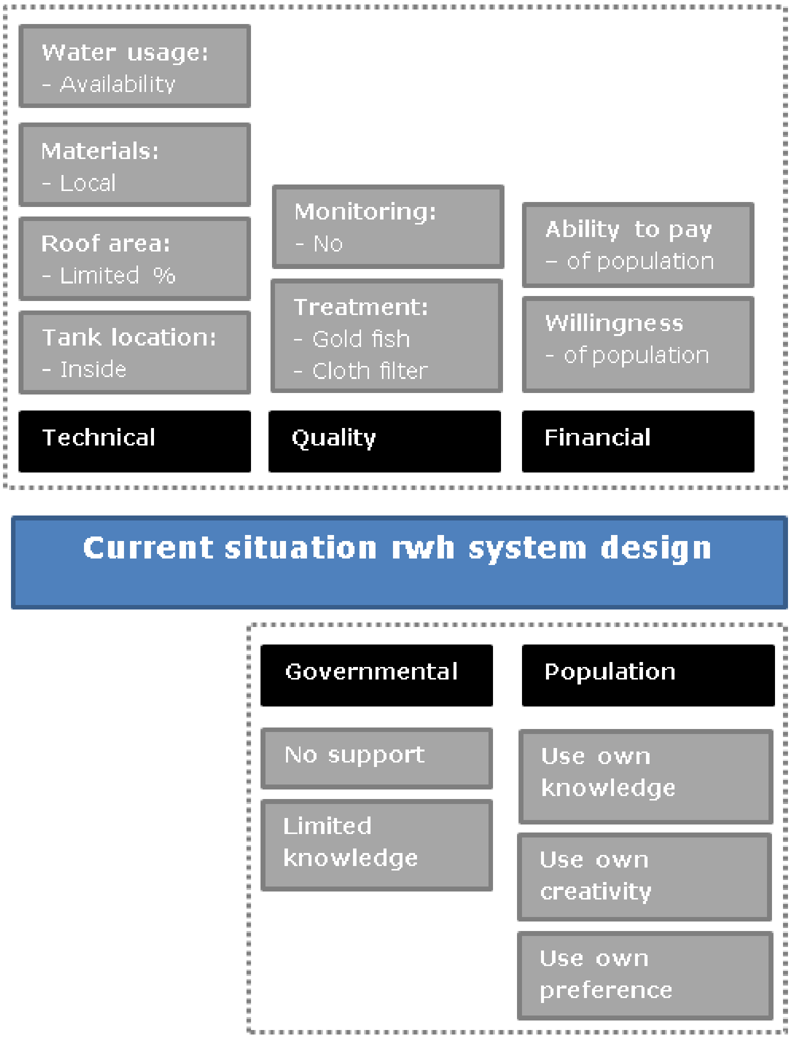


Figure 28: Current situation regarding the design of rainwater harvesting systems.

5.1.4 View on rainwater harvesting

5.1.4.1. Expert view on rainwater harvesting

The suitability of rainwater harvesting within a specific area depends on several factors including culture and social factors. In this paragraph the support for rainwater harvesting and the expert view on the use of rainwater harvesting in Indonesia in particular will be discussed. In general rainwater harvesting is not very common in Indonesia. However in some areas it is practised frequently. Especially on small islands or in coastal areas with polluted surface water and brackish groundwater, rainwater harvesting systems can be found (Kamarga, 2016). More information regarding existing rainwater harvesting projects in Indonesia and in Serang can be found in paragraph 5.1.2 and 5.1.3.
Water related habits in Indonesia are in several points different from in the Netherlands. It is very common, especially outside the big cities (like Jakarta) to use a combination of water sources, and to organize water supply on a household scale. For praying clean water is required, which should meet several criteria. Water is cooked before drinking and at the toilet water is used extensively. Sewer systems are limitedly present, increasing the risk of contamination of other water sources.

During the implementation of rainwater harvesting one can define three important phases. First of all, one has the facilitating condition that should provide the opportunity to implement rainwater harvesting. Afterwards design choices have to be adapted to the local situation. Finally, there should be attention to operation and maintenance of the system, together with quality control.

To implement rainwater harvesting, it is important to make sure that there is a the facilitating condition. Most important the population should be unsatisfied with the current water supply (Imroatul, 2016), should accept the technique (Listyasari, 2016), be aware of it and have sufficient knowledge regarding rainwater harvesting (Jantowski, 2016).
It is clear that the perception and acceptance of rainwater harvesting is not uniform throughout Indonesia (Saputra, 2016; Eitemiller,2016). This also explains the fact why experts do not agree regarding the acceptance of rainwater harvesting in Indonesia.
According to Aidan Cronin (2016), who did some rainwater harvesting projects in remote islands, the perception of rainwater in Indonesia is in general good, although you need proper education to inform the population about the use of rainwater. In some of his projects people even prefer rainwater above other water sources for some kind of tasks, like hair washing, because of the low hardness.
However according both Maraita Listyasaria (2016) and Yuniati Zevi (2016), both living in big cities, the perception about rainwater in Indonesia is less positive. Rainwater is not viewed as a clean source (Zevi, 2016) and in general groundwater is preferred. Kamarga (2016) agrees with this and states that rainwater is viewed as last option, which is only used in case no other sources are available (Kamarga, 2016). Glen Eitemiller (2016) remarks that rainwater harvesting is often seen as a poor village alternative, in case no piped water supply is available. Water quality concerns are present at a community level, but can be diminished by the installation of prototypes (Eitemiller, 2016).

When the facilitating conditions are met, the implementation of rainwater harvesting systems can start. In this phase several design choices have to be made. These include the suitable scale of the system (household, and communal a village level), the desired water quality and water quantity, the tank material, the type of treatment and the parties that will invest time and money in the system. These decisions are not independent, for example the choice regarding tank material will have influence on the water quality in the system. For all these decisions the local situation should be taken into account and their water related habits. It is very important to always listen to the wants and needs of the local population (Cronin, 2016; Listyasari, 2016; Kamarga, 2016). However this can be very different from the view of external stakeholders about the needs.

Finally, operation and maintenance is important to consider already at an early stage of the design, and appropriate follow up should be organized. An important factor is whatever the community takes own responsibility for their water sources (Cronin, 2016). In this case operation and maintenance will be much easier to organize.

5.1.4.2. Case study expert view on rainwater harvesting

The Bappeda and the Dinas Health are relatively neutral regarding rainwater harvesting. It is important to take the interest of the local population into account, which can vary largely on small spatial scale (Saputra, 2016). In case the population shows interest in rainwater use, knowledge regarding the system could be provided by the kabupaten.
Although the distance between the sub-districts Tirtayasa, Baros and Pabuaran is small (±40 km), the water supply is organized differently (chapter 3).Moreover the opinion at the puskesmas (local health center) regarding several water and sanitation issues varies widely, as can be seen in Table 18. Furthermore, the attention points are not similar.

Table 18: View of the head of the puskesmas and the sanitarian regarding water and health in their region (kecemantan).

	Tirtayasa	Pabuaran	Baros
Attention points	Water quality, sanitation and garbage	Domestic waste	Bad nutrition
Water problems	Saline groundwater and polluted irrigation canals	High iron & magnesium [2] close to rice fields	Walking to source
Usage of rainwater	Relatively often (20%)	Not often	Unknown
Preference society	Use water that is available (no choice)	Spring or groundwater is preferred	Groundwater is preferred
View sanitarian / head of puskesmas on rainwater	Quality problems (air pollution)	Can be used, with appropriate treatment	Quality problems (no minerals/ ions)
Reason of limited stimulation of rwh	Capacity problems	Knowledge quality to limited	Unknown

Were in Tirtayasa the puskesmas focusses on water quality, sanitation and waste this is not the case for Pabuaran and Baros were main focus is on domestic waste and nutrition respectively. Knowledge regarding rainwater harvesting at the puskesmas is relatively limited, and dependent on the individual sanitarian. Because of this limited knowledge and because of capacity problems of the puskesmas, rainwater harvesting is not stimulated actively by these local health centers. In Pabuaran the sanitarian argues that rainwater can be used with appropriate treatment, where in Tirtayasa and Baros the use of rainwater is not advised due to quality concerns. Main concerns are related to the lack of minerals in rainwater or to the link with air pollution.

[2] It is most likely that due to language barier or unsufficient knowlegde magnesium is confused with manganese.

5.1.4.3. Population view on rainwater harvesting

The opinion of the population regarding rainwater harvesting was investigated by using cards of raw water sources (groundwater, surface water and rainwater) and cards with water collection methods (bottled water, refilled bottled, shallow wells, deep wells, PDAM, rainwater, ect). For several questions the population had to place these water sources in three categories (section 4.2.2). Respondents were selected by the sanitarian of the puskesmas, are currently practising rainwater harvesting and were at house during the time of the interview.

Figure 29: Interviews with the local population.

It is found that the view of the population on rainwater harvesting regarding quality and preference is variable between the different case study areas. The view of the population regarding rainwater as raw water source, and rainwater as way of water gathering can be found in Table 19. Clean, cheap and preferred refers to the fact that the largest part of the population categorised rainwater in the happy green face category. Neutral refers to the neutral yellow face, where not preferred refers to the sad red face. In Appendix A6 the game is further explained.
In general the view in Tirtayasa regarding rainwater is more positive as in Pabuaran and Baros. However in both cases rainwater is seen as last option, which is only used in case no other water source is available.

Table 19: Perception of rainwater in Tirtayasa and Pabuaran and Baros based on social research. Clean, cheap or preferred refers to , neutral to and not preferred to .

	Tirtayasa	Pabuaran - Baros
Rainwater as raw water source		
Preference (Q2)	Neutral	Neutral – Not preferred
Clean to dirty (Q3)	Clean	Neutral
Rainwater as supply system		
Preference (Q5)	Preferred - Neutral	Not Preferred
Clean to dirty (Q6)	Neutral	Neutral
Costs (Q7)	Cheap	Cheap

Rainwater in Tirtayasa is used for cooking, bathing, washing clothes, and for some cases for drinking or for coffee and tea. Since the surface water (irrigation channels) are heavily polluted and the groundwater is brackish, rainwater is the only “freely available” and suitable fresh water source. As alternative gallons can be used as free water source. However, as one of the inhabitants mentioned

“I use rainwater because gallons are too expensive and the groundwater is saline.”
The population is positive regarding rainwater and prefers it as raw water source together with groundwater. As water supply method only bottled water and refilled gallons are preferred more. One respondent even mentioned that rainwater is also used for coffee and tea “since I like the taste of the rainwater“. Another respondents mentioned “the rainwater has no taste and we can use it without any problem for cooking”.

In Pabuaran and Baros groundwater levels are deep. Although spring water is available, which is free and viewed as very clean water, one needs to walk to collect water from this source. Because of this some part of the population is using rainwater for washing and bathing, or in some cases also for drinking and cooking.
In Pabuaran and Baros the use of rainwater is less preferred, compared to Tirtayasa. Many respondents described rainwater as “oily”. Another respondent was concerned about the fact that the population gets sick when starting to use a rainwater harvesting system. However it is still used because one has no choice or because it is “easier, more effective and more suitable” then other water sources.

5.1.5. Summary

In some sub-districts in Serang the current water supply is not sufficient and action should be taken. Rainwater harvesting is one possibility to improve this situation. Rainwater harvesting is already practised throughout Indonesia, especially in areas were the current water supply is lacking. Only in these areas rainwater harvesting can successfully be implemented. Furthermore, it is found important that there is awareness, knowledge and acceptance regarding the technique.

External parties often install tanks from reinforced concrete or ferrocement. Tanks are placed outside or below ground, are closed and of large capacity (around 9 m^3). It is found that for these projects the community should be involved, professionals should assist during the installation, tanks should be individual and preferable tanks should be installed in new developments. In contrast individually installed systems in Serang are found to be placed inside, are not always closed and exist in a wide variety of sizes. Often just a limited roof area is connected and water use is based on availability. Systems are built with local materials, knowledge, creativity, preference and the ability and willingness to pay of the population. Cloth filters can prevent the entering of large organic material and in some cases fishes are used to eat mosquito larvae. Systems are not monitored with respect to quality.

It is found that the view regarding rainwater harvesting varies largely from location to location at national, regional and local scale. In Serang it is found that at the kabupaten the employees are neutral regarding the idea of rainwater harvesting, although concern regarding minerals exist. At the puskesmas the sanitarian mentions concern regarding air pollution, lacking minerals, or the limited knowledge regarding the technique. For the local population rainwater harvesting is viewed as neutral or not preferred.

5.2. Water quality

In this paragraph the water quality aspects from rainwater harvesting are discussed. First the expert view on rainwater quality is discussed, followed by the view of case study expert and the population. Finally the water quality analysis of rainwater that was done is presented and compared to the Indonesian and World Health Organization water quality guidelines.

5.2.1. Experts and case study expert view

Required water quality

Experts[3] have a non-uniform view regarding the required quality for rainwater harvesting systems. One can distinguish two main views; the first suggests that rainwater should not necessary comply with the drinking water standards at point of extraction and the second argues that rainwater should either meet the drinking water standard, or it should not be used for potable purposes. Below both views are shortly discussed. Furthermore, the quality concerns regarding rainwater are presented.

Regarding several experts, rainwater harvesting systems should not necessary comply with the drinking water standards because a very limited number of alternative water sources comply with these standards (Kamarga, 2016) and one can develop resistance against microbial contamination (Jantowski, 2016). Furthermore households have their own method to improve the water quality when required (Kamarga, 2016; Soekarno, 2016; Lubis, 2016).

However according other experts rainwater harvesting systems should comply with the drinking water guideline. For example Cronin (2016) states the water should meet the drinking water standard when no other or alternative drinking water source is available. Otherwise it can be less strict. Imroatul (2016) has a similar view and suggests that rainwater is only used for non-potable purposes, for which it should meet the clean water standard. This standard is presented in paragraph 5.2.3.3. Listyasari (2016) gave the suggestion that one should consider the use of alternative sources of drinking water to limit treatment cost for rainwater. A very important limitation for self-supply systems like rainwater harvesting systems in practise is that it is difficult to ensure the water quality of such systems since they have no regular monitoring (Listyasari, 2016). This could be another reason to limit the use of rainwater harvesting systems for potable purposes.

Like general experts, the opinion of case study experts regarding the required water quality from rainwater harvesting systems is not well defined. Attention is for the fact that available water sources, do not comply with the drinking water standards (Lamhot Sinuarat, 2016; Saputra, 2016). Lamhot Sinuarat (2016) from the Bappeda states that there is knowledge available to install good quality rainwater harvesting systems, which implies that quality will be no problem for rainwater harvesting systems. Also the PDAM is relatively positive regarding the quality of rainwater, only bottled water, PDAM water (piped and refilled jerry cans) and spring water are viewed as more clean water sources.

[3] Experts, all have in field or scientific knowledge in the field of water supply in Indonesia. They include employees from non-governmental organizations (World bank, Unicef, Aidenvironment), employees from the national government (bappenas) and PhD and professors at universities (ITB Bandung and Indonesian research institute of science)

Concern regarding water quality of rainwater harvesting systems
Regarding the real quality of rainwater concern exists of the correlation between rainwater quality and air quality (Listyasari, 2016; Soekarno, 2016). In case the pH of the rainwater is low it cannot be used for drinking, cooking or washing (Soekarno, 2016). Next to this algae growth is relatively common in the current plastic tanks which are mainly used for groundwater storage (Kamarga, 2016; Zevi, 2016; Imroatul, 2016). Mosquitos also occur in these tanks, but can be prevented by using a tight tank and which is regularly cleaned (Imroatul, 2016; Kamarga, 2016; Zevi, 2016). Next to this microbial contamination can be of concern (Imroatul, 2016).

At the Dinas Health concern exists regarding the mineral content in rainwater, related to the limited diet of the population with is mainly rice, chicken, white fish and oil. In the local health centre (puskesmas) in Baros this concern regarding the minerals and ions present in rainwater also exist, as can be seen in Table 18 in paragraph 5.1.4. This is most likely related to the bad nutrition in Baros. In the puskesmas Tirtayasa, there is also concern regarding rainwater quality, but this is related to the influence of air pollution on rainwater quality. In the puskesmas Pabuaran one assumes that rainwater can be used, when appropriate treatment is applied. However one admits that the knowledge regarding rainwater quality is limited.

Suitable tank design
The water quality in a rainwater harvesting system is directly linked to the design, material and location of the rainwater harvesting tank and roof. However an important factor in the decision for the tank material is material availability (Cronin, 2016; Soekarno, 2016; Listyasari, 2016; Lubis, 2016; Zevi, 2016; Imroatul, 2016; Kamarga, 2016). Moreover, the suitable tank material depends on the community (Cronin, 2016). Their preference and knowledge regarding the use of different materials is of main importance. Costs are another important factor that should be considered in the decision of tank design (Zevi, 2016; Soekarno, 2016).

According case study experts, plastic tanks are easy to use, since in Serang a large part of the population (±80%), already uses these tanks to store their groundwater (Lamhot Sinurat, 2016). However in case plastic is used, algae growth can occur (Lamhot Sinurat, 2016). Saputra (2016) prefers round and big rainwater harvesting tanks (of cement) with a capacity of approximately 14 m^3, which can be placed outside. The round one is preferred because it is stronger. However, like the general experts, Saputra (2016) states that the preference of the population is of main importance in the design of the tank.

5.2.2. Population view
It is found that the population view regarding rainwater quality varies largely from location to location. Were in Tirtayasa rainwater is viewed as a relatively clean source, the perception regarding rainwater quality in Baros and Pabuaran is less positive, as can be seen in Table 19 in paragraph 5.1.4.
In Tirtayasa rainwater as raw water source is viewed as the most clean water source. Groundwater is viewed dirty because it is saline. Compared to the other water supply systems rainwater is seen as medium clean. Bottled and refilled water is viewed as more clean, were surface water is seen as more polluted. PDAM, well and spring water are ranked similar as rainwater. One respondent mentioned “in some cases we find some algae in the tank, but this is not really a problem”. Another

respondent experienced rainwater as less clean “rainwater is dirty source because the roof may be dirty (with dust), but in case the rainwater is directly cached, rainwater is more clean.”

In Pabuaran raw rainwater and rainwater as supply system is seen as medium clean. As raw water source, groundwater is viewed more clean and surface water is seen as more dirty. As water supply system only shallow wells and surface water are seen as more polluted water sources (from the total twelve water supply systems discussed). Several respondents describe rainwater as “oily”. The exact meaning of this term remained unclear.

5.2.3. Technical results

5.2.3.1. Required water quality

To determine the required water quality for the system one can either use available water quality guidelines, as presented in section 5.2.3.3., or one can determine the required water quality based on the local situation. In this last case one should evaluate the quality of alternative water sources, and the local health situation. In case the new system improves the current situation, it can be considered a valuable option.

In Serang, most available sources do not comply with the drinking water standards. Even improved groundwater wells and water from the PDAM often contain microbial contamination and high levels of manganese. Water quality data from these water sources can be found in Appendix B1. Groundwater sources in Tirtayasa are often brackish. Surface water is visually already heavily populated. Although bottled water is relatively clean, it is still not always totally free from microbial contamination and it is very expensive. Water quality, sanitation and garbage are important health problems in the area.
Currently arsenic concentrations in groundwater are not measured. However it is possible that water sources will be contaminated with arsenic. In West-Java for example arsenic is found related to volcanic activities (Ilyas et al., 2009). However in general limited is known regarding arsenic in Indonesia (Ilyas et al., 2009).

Based on the health situation, the interviews with experts, case study experts and the quality of other sources it is decided that the water quality should comply with the drinking water standards, only in case it is used for potable purposes. For non-potable purposes it can be less strict.
In this case the use of rainwater is not advised for young children, elderly of sick or weak individuals as will be further discussed in paragraph 5.3.3.5.

5.2.3.2. Measurement results

Water quality was measured from two different roofs, at three different moments in time to measure the first flush. Furthermore raw rainwater (in duplicate) and water quality inside two tanks was measured. For the roofs from which the measurements were taken the checklist incoming water quality is performed, which can be found in Table 20. More information regarding the measurement locations and pictures of the situation can be found in Appendix B2.

Table 20: Checklist incoming water quality: roof characteristics.

Checklist incoming water quality	Roof A (closed tank)	Roof L
What is the roof material?	**Tiles**	**Tiles**
Flat or sloped roof?	**Sloped**	**Sloped**
Age of the roof	**16 years**	**28 years**
Damage of the roof?	**No**	**No**
Vegetation above the roof?	**Yes, a tree**	**No**
Vegetation close to the roof?	**Yes, a tree**	**Yes, a tree**
Roof area	**108 m^2**	**170 m^2**
Area connected to tank	**30 m^2**	**7.5 m^2**
Birds present on the roof?*	**No**	**No**
Dirt, leaves, faecal dropping, insects and litter on the roof?	**No**	**No**
Gutter and drainpipe present?	**No**	**No**
Material connection to tank	**Metal (zinc/iron) plates and pvc**	**Metal (zinc/iron) plates and pvc**
Age of the gutter and drainpipe	**16 years**	**4 months**

* based on a short visit of approximately 30 minutes

In Table 21 the results from the water quality measurements can be found. In the results presented below attention will be towards the change in water quality within the different steps in the rainwater harvesting system (direct rainfall, roof runoff t=0, roof runoff t=4, roof runoff t=8 and tank). Furthermore the results of the analysis are compared to other analysis performed. These include direct rainfall measurements from Imroatul (2014) in East Bandung and West Semarang, long term direct rainfall measurements from EANET (2014) in Jakarta and Bandung, measurements by Song et al. (2009) in Banda Aceh, and measurements from Eitemiller (2013) in Denpasar (Bali).

5.2.3.2.1. Physical characteristics

Temperature, conductivity, turbidity, and pH of water in all stages was measured, as can be found in Table 21. Temperature of the water in all stages is found to be between 25-27 °C. Temperatures in the tanks are slightly higher than temperatures of direct rainfall or roof runoff (Figure 30). The pH of rainfall is found to be around 7.18. In Alang-Alang the pH increases after contact with the roof, which is not the case in Lontar. Conductivity in all stages of the rainwater harvesting system is found to be between 19 and 72 µS/cm. In the raw rainwater measurement the conductivity is 41 µS/cm (50 and 32 µS/cm). In Lontar conductivity in the other steps in the rainwater harvesting system increases slightly (around 51 µS/cm). In Alang-Alang the conductivity first decreases in the roof runoff to 20 µS/cm, and increases in the tank towards 72 µS/cm. Turbidity is found in a range between <0.5 NTU and 2.4 NTU. The average turbidity measured in Lontar (0.6 NTU) is lower as the average turbidity in Alang-Alang (1.8 NTU) and in a similar range as the turbidity of raw rainfall (<0.5 and 1 NTU). No first flush can be observed for turbidity.

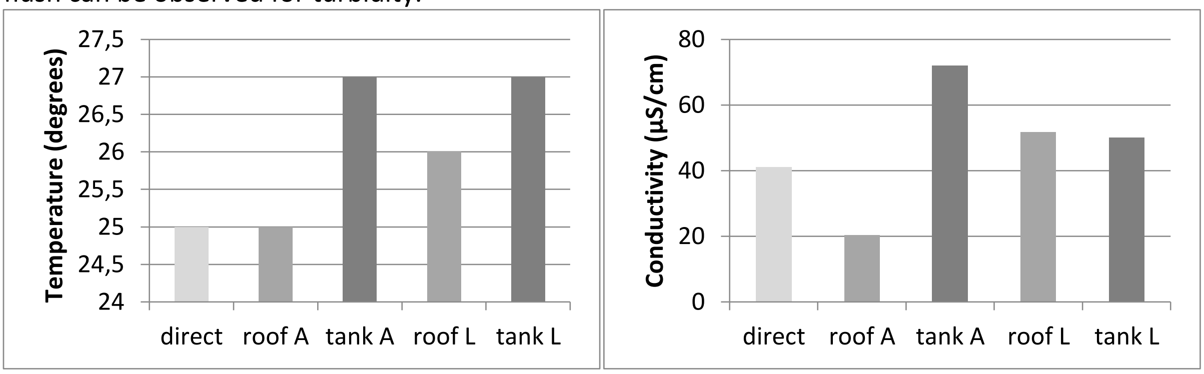


Figure 30: Average temperature and conductivity of direct rainfall (direct) and in the roof and tank in Alang-Alang (A) and Lontar (L).

Table 21: Water quality measurements from direct rainfall , from a roof in Alang-Alang and a roof in Lontar (at t=0, 4 and 8 minutes) and from a closed cement tank in Alang-Alang and an open cement tank in Lontar.

	Alang-Alang	Alang-Alang	Alang-Alang	Alang-Alang	Alang-Alang	Alang-Alang	Lontar	Lontar	Lontar	Lontar	
	direct	direct	roof, t=0	roof, t=4	roof, t=8	tank	roof, t=0	roof, t=4	roof, t=8	tank	
Physical Test											
Conductivity	50	32	19	20	22	72	53	51	51	50	uS/cm
Turbidity	< 0.5	1,0	2,1	0,7	2,4	2,0	0,6	0,5	0,6	0,6	NTU
Temperature (Water)	25	25	25	25	25	27	26	26	26	27	°C
pH in situ	7,17	7,19	7,63	7,51	7,69	7,45	6,87	6,76	6,78	6,93	n/a
N											
Total Nitrogen	1	1	2	1	2	2	2	2	2	2	mg/L
Total Kjeldahl Nitrogen	0,9	1,1	1,6	1,2	1,3	0,8	0,9	1	0,8	1,2	mg/L
Nitrate (N-NO3)	0,085	0,096	0,209	0,215	0,234	0,893	0,921	0,922	0,909	0,972	mg/L
Nitrite (N-NO2)	0,021	0,015	0,019	0,02	0,022	0,167	0,008	0,008	0,008	0,007	mg/L
Ammonia (N-NH3)	0,06	0,18	0,74	0,74	0,79	0,14	0,22	0,22	0,21	0,21	mg/L
Microbiology											
E.coli	1550	< 1	>2420	>2420	1410	730	690	550	390	390	MPN/100mL
Enterococcus sp.			>2420		>2420	160					MPN/100mL
Campylobacter spp.*			Negative		Negative	Negative					Per 25mL
Human nutrients											
Fluoride	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	0,02	mg/L
Calcium-Dissolved (Ca)	3,1	1,9	0,5	0,6	0,6	11,6	7,1	6,7	6,7	5,5	mg/L
Magnesium-Dissolved (Mg)	0,33	0,31	0,05	0,07	0,08	0,10	0,23	0,22	0,22	0,17	mg/L
Metals											
Aluminum-Dissolved (Al)	0,521	0,320	< 0.005	< 0.005	< 0.005	< 0.005	0,023	0,016	0,029	0,016	mg/L
Arsenic-Dissolved (As)	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	mg/L
Copper-Dissolved (Cu)	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	mg/L
Iron-Dissolved (Fe)	0,82	0,52	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	mg/L
Manganese-Dissolved (Mn)	0,017	0,010	< 0.005	< 0.005	< 0.005	< 0.005	0,007	0,006	0,007	0,006	mg/L
Sodium-Dissolved (Na)	5,35	3,25	1,32	1,44	1,40	1,68	1,93	1,98	1,84	1,52	mg/L
Lead-Dissolved (Pb)	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0,008	mg/L
Zinc-Dissolved (Zn)	0,021	0,020	0,08	0,085	0,091	0,008	0,211	0,208	0,206	0,206	mg/L
Organic											
Dissolved Organic Carbon	3	< 1	2	3	7	1	< 1	4	3	1	mg/L

Regarding the abundance of nitrogen in rainwater several parameters are measured. Total Nitrogen (TN), Total Kjeldahl Nitrogen (TKN), nitrite (N-NO2), nitrate-N (N-NO3), and ammonia (N-NH3), are determined (*TKN = organic nitrogen + N-NH3 and TN = TKN + N-NO2 + N-NO3*).
No clear first flush effect is observed regarding nitrogen compounds. In direct rainfall, a large fraction of the total nitrogen is present as organic nitrogen. As expected the roof and tank contain larger fractions of ammonia, nitrite and nitrate as can be seen in Figure 31.

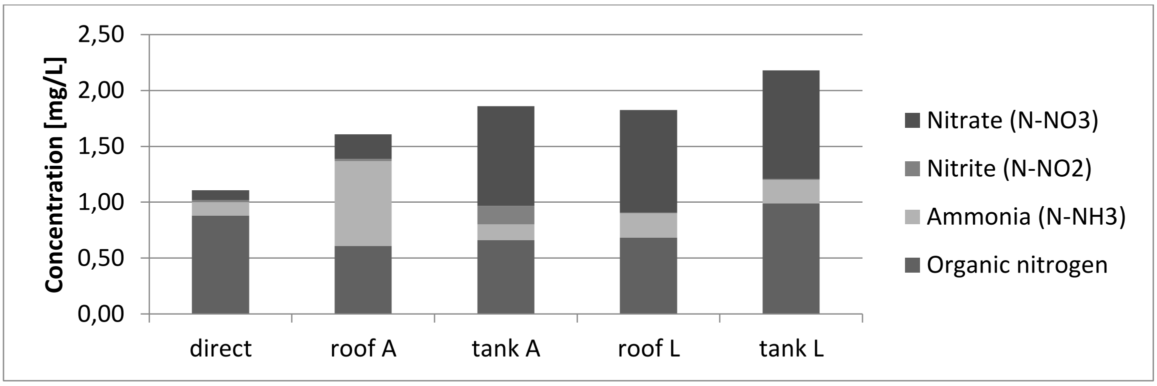


Figure 31: Organic nitrogen, ammonia, nitrite and nitrate concentrations of direct rainfall (direct), the roof and tank in Alang-Alang (A) and Lontar (L).

5.2.3.2.2. Metals

Concentration of dissolved metals in direct rainwater is found to be relatively high. Especially high concentrations of aluminium (0.320-0.521 mg/L) and iron (0.52-0.82 mg/L) are found.
The high concentrations could be explained by air pollution. Lead and zinc for example are often associated with traffic (Herngren et al., 2005). High concentrations of aluminium can be explained by mineral dusts (Prospero et al., 1987). However it is unclear if this is the case in Indonesia.

The concentrations of aluminium, iron and manganese are found to decrease after contact with the roof in all cases. Iron, as Fe^{3+} (which exists in aerobic conditions, unlike Fe^{2+}) forms a complex after it touches the roof. For example Fe_2O_3 can be formed, but multiple possibilities exists. As soon as this occurs iron is not present in dissolved form, and not included in the measurements. A similar process is suggested for manganese and aluminium. Zinc is found to increase after contact with the roof, most likely due to the leaching of this metal from the roof.

5.2.3.2.3. Microbial contamination

Microbial indicators show the presence of large amounts of microbial contamination. In nine out of the ten samples taken *E.coli* is present. Measured concentrations of *E.coli* are higher in Alang-Alang, which could be linked to the fact that a tree was present above the roof at this location

Only in one of the two direct rainwater measurements *E.coli* is found to be smaller than 1 MPN per 100 mL. Although the measurements took place on a day with a lot of small drizzle, a clear first flush effect is found in the *E.coli* measurements as shown in Figure 32. This indicates contamination of the roof. For both locations the lowest concentrations are found within the tank. *E.coli* concentrations in Alang-Alang were found to be larger than 2420 MPN/100 mL but are shown as a concentration of 2420 MPN/100mL in the Figure. *Enteroccocus* spp, only measured in Alang-Alang, is found in large concentrations (above 2420 MPN/100 mL) both at t=0 and at t=8 min. In the tank a lower concentration of *Enteroccocus* is found (160 MPN/100 mL). *Campylobacter* is not detected in any of the three samples taken in Alang-Alang (roof and tank).

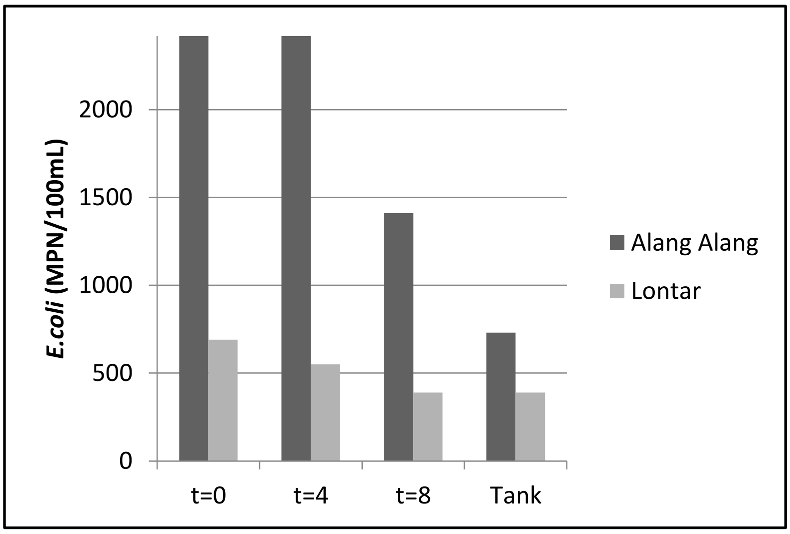


Figure 32: Contamination of samples with *E.coli* over time and inside the tank for Alang-Alang and Lontar.

5.2.3.2.4. Dissolved organic carbon

Dissolved organic carbon (DOC) is found in concentrations between <1 to 7 mg/L. No first flush effect is observed for DOC. In the measurements performed DOC concentrations in roof runoff are found to be highest, followed by direct rainfall. In Figure 33 the average DOC concentrations at the different stages can be found. Microbial growth is not only dependent on the amount of DOC, but also on its composition. However some pathogens can grow already at low concentrations organic carbon (AOC < 1 µg/L), which is expected always to occur in rainwater harvesting systems. In general concentrations are found below the aesthetic objective of 5 mg/L.

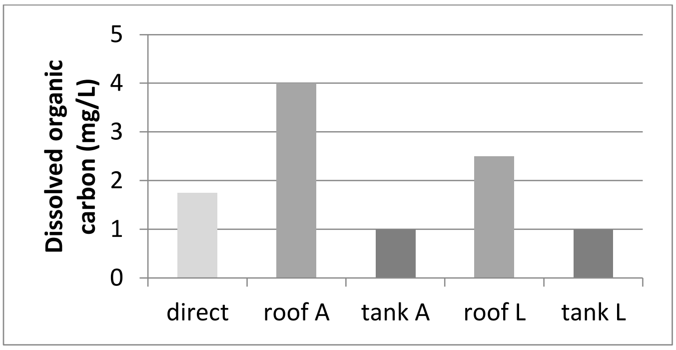


Figure 33: Average DOC concentrations (mg/L) in direct rainfall, in roof runoff and tanks in A (Alang-Alang) and L (Lontar).

5.2.3.2.5. Minerals (or human nutrients)

As explained in section 5.2.1 and 5.2.2 concern exists regarding the limited intake of essential minerals during rainwater consumption. Calcium, magnesium and fluoride are essential minearals for human health, but are very limitedly present in rainwater as confirmed by the measurements. Evidence between the presence of minerals and health benefits is strongest for calcium, magnesium and fluoride.

For calcium and magnesium intake mainly occurs via food. Calcium can mainly be found in dairy products, but also in legumes, green leafy vegetables, broccoli. Magnesium is found in dairy products, vegetables, grain, fruits and nuts. In contrast to calcium and magnesium, main fluoride intake normally occurs via drinking water. But intake can also occur via certain types of food (fish and rice) and tea.

The WHO advises a daily intake of 1000 mg calcium and 350 mg of magnesium for an adult. For fluoride the daily intake should be around 3.5 mg/day. The fluoride intake in Serang seems sufficient. Tea can contain large amounts of fluoride, were black tea contains 1 to 9 mg of fluoride per litre (Medical college of Georgia, 2010). Moreover, rice contains fluoride. Research in Ethiopia found fluoride concentrations between 0.1 and 5.5 mg/kg in rice (Tegegne et al., 2013).

The daily intake of calcium and magnesium is calculated based on the average daily kcal consumption of an average inhabitant of Banten province, as shown in Table 22. Projected daily intake of calcium and magnesium is around 314 and 242 mg respectively. This implies that the intake of calcium and magnesium via food is not sufficient to meet the WHO guideline.

Rainwater consumption does not add large amounts to the daily calcium and magnesium intake. Calcium and magnesium concentrations are around 8 mg/L and 0.14 mg/L. Total hardness of the rainwater in Tirtayasa is around 0.2 mmol $CaCO_3$ per liter. Assuming a daily drinking water consumption of 2 liter, one can predict around 15 mg/day calcium intake via harvesting rainwater and less than 1 mg/day magnesium intake.

Table 22: Daily intake for magnesium and calcium, based on the daily kcal consumption of an inhabitant in Banten province.

Category	Daily kcal	Assumed product	Kcal per gram product	Daily consumption (gram)	Daily calcium intake (mg)	Daily magnesium intake (mg)
rice	848	cooked rice	0.93	912	20	112
tubers	15	Potato	1.19	13	1	2
fish	46	Halibut	1.05	43	7	3
meat	58	Chicken	1.11	52	7	4
eggs and milk	67	Milk	0.46	145	247	16
vegetable	34	green beans	0.26	132	16	64
nuts	55	Peanut	6.29	9	5	18
fruit	36	Banana	0.83	44	4	9
oils and fats	233	-		-	-	-
beverage ingredients	73	-		-	-	-
herbs	21	red pepper	0.40	53	7	12
other	445	-		-	-	-
total	1931	-		-	314	242

Most data regarding groundwater sources in Tirtayasa, show a total hardness of around 1.2 mmol $CaCO_3$/L. PDAM water has a hardness of around 0.5 mmol $CaCO_3$/L. One of the six well measurement shows a total hardness of 6.7 mmol $CaCO_3$/L, but this well is not taken into account.

Although hardness is closely related to the magnesium and calcium content in water, it does not tell anything about the ratio between calcium and magnesium. In general the Ca:Mg ratio in groundwater is larger than one. Kousa et al. (2006) found an average Ca:Mg ratio of 5.39. A ratio of 5.6, 4.9 and 4.8 is found for three drinking water companies in the Netherlands (DZH, Waternet and Asselt) (Lenntech, 2001). Assuming the ratio to be five, one can expect a calcium and magnesium concentration in groundwater of 35 and 7 mg/L respectively. In PDAM water this would be 15 and 3 mg/L.

When comparing the total intake of calcium and magnesium by using different water sources in Tirtayasa it becomes clear that the type of water consumption does not change the total intake of these minerals largely (see Table 23). In any case the population experience a shortage for the intake of these minerals, especially for calcium. When consuming groundwater approximately 38.4% of the daily requirement of calcium is fulfilled, were this is 32.9% in case rainwater is consumed. For magnesium this is 73.1% when consuming groundwater compared to 69.1% when rainwater is consumed.

Table 23: Approximation of the intake of calcium and magnesium via water and food for calcium and magnesium [mg/d].

	Calcium			Magnesium		
	GW	**PDAM**	**RW**	**GW**	**PDAM**	**RW**
Food [mg/d]	314	314	314	242	242	242
Water (2L) [mg/d]	70	30	15	14	6	<1
Total intake [mg/d]	384	344	329	256	248	242
Percentage of total required intake [%]	38.4	34.4	32.9	73.1	70.9	69.1

5.2.3.3. Compliance drinking water standard

The performed measurements are compared to WHO and Indonesian drinking water standards, as can be found in Table 24. Standards are found to be very similar, were the Indonesian guideline provides additional values for water temperature, ammonia and *E.coli*. The WHO uses health outcome targets exists, and no water quality targets for microbial contamination. However the WHO recommends that no *E.coli* is found in a 100 mL sample. Also *Enterococcus* should not be found. Both *E.coli* and *Enterococcus* give an indication of faecal contamination, and detection in drinking water should lead to further action (WHO, 2011). With respect to microbial contamination rainwater clearly does not comply with the drinking water standards, were huge numbers of *E.coli* and *Enterococcus* are found. Treatment can decrease microbial contamination, as explained in section 5.3. For heavy metals, the water quality of roof harvested or tank stored rainwater meets both the WHO and the Indonesian drinking water guidelines.

Table 24: Comparison of the water quality parameters measured in the tanks in Alang-Alang and Lontar and the WHO and Indonesian drinking water quality guidelines.

	Alang-Alang (tank)	Lontar (tank)	Indonesian Drinking Water standard 2010	WHO Drinking Water	Indonesian Clean Water standard 1990	
Physical Test						
Conductivity	72	50	NA	NA	NA	uS/cm
Turbidity	2,0	0,6	5	5*	25	NTU
Temperature (Water)	27	27	Room temp. + 3	NA	Room temp. + 3	°C
pH in situ	7,45	6,93	6,5 - 8,5	6,5 - 8,5*	6,5 – 9,0	n/a
Nitrogen						
Total Nitrogen	2	2	NA	NA	NA	mg/L
Total Kjeldahl Nitrogen	0,8	1,2	NA	NA	NA	mg/L
Nitrate (N-NO3)	0,893	0,972	11,3***	11,3***	2,3**	mg/L
Nitrite (N-NO2)	0,167	0,007	3	0,9	0,3**	mg/L
Ammonia (N-NH3)	0,14	0,21	1,5	NA	NA	mg/L
Microbiology						
E.coli	730	390	0	Not detectable*	NA	MPN/100 mL
***Enterococcus* sp.**	160	-	NA	NA	NA	MPN/100 mL
Campylobacter* spp.	Negative	-	NA	NA	NA	Per 25mL
Minerals						
Fluoride	< 0.02	0,02	1,5	1,5*	1,5	mg/L
Calcium-Dissolved (Ca)	11,6	5,5	NA	NA	NA	mg/L
Magnesium-Dissolved (Mg)	0,10	0,17	NA	NA	NA	mg/L
Metals						
Aluminium-Dissolved (Al)	< 0.005	0,016	0,2	0,2*	NA	mg/L
Arsenic-Dissolved (As)	< 0.005	< 0.005	0,01	0,01	0,05	mg/L
Copper-Dissolved (Cu)	< 0.005	< 0.005	2	2	NA	mg/L
Iron-Dissolved (Fe)	< 0.02	< 0.02	0,3	0,3*	1,0	mg/L
Manganese-Dissolved (Mn)	< 0.005	0,006	0,4	0,4*	0,5	mg/L
Sodium-Dissolved (Na)	1,68	1,52	200	200*	NA	mg/L
Lead-Dissolved (Pb)	< 0.001	0,008	0,01	0,01	0,05	mg/L
Zinc-Dissolved (Zn)	0,008	0,206	3	3*	15	mg/L
Organic						
Dissolved Organic Carbon	1	1	NA	NA	NA	mg/L

* No official guideline, often based on acceptance of the water source

** The guideline value for clean water from 1990 with respect to nitrate and nitrite is found to be more strict as the drinking water standard in 2010. However in 1990 the drinking water standard for nitrate and nitrite was more strict.

*** 50 mg/L as nitrate-NO3 or 11.3 mg/L as nitrate-N

5.2.3.4. Comparison with other measurements

In Table 25 the field measurements are compared with measurements done by other parties in Indonesia. In general results are found to be comparable, and give an indication regarding variation in time and space. When evaluating this table it should be taken into account that water quality is fluctuating with time, space and type of system.

In direct rainfall sodium concentrations generally increase as one moves towards the coast (Carroll, 1962; Junge & Werby, 1958). This explains the high sodium concentrations in Tirtayasa, which is located very close to the coast. However in West Semarang, which is located close to the coast, a surprisingly low concentration was found. Sodium concentrations are generally higher in urban areas, compared to more rural areas (Gatz, 1991). However this cannot be observed in the measurements.

In contrast, calcium concentrations in rainwater, coming from both oceanic salt and land surfaces, should increase when moving land inward (Carroll, 1962; Junge & Werby, 1958). In Bandung (more land inwards) higher concentrations of calcium are found as in Jakarta. However the concentrations of calcium found in Tirtayasa are relatively high.
Nitrate concentrations are higher in small rain showers then in larger rain showers (Jones, 1971; Pio et al., 1991). This could be an explanation for the fact that the measured nitrate concentration is relatively low, however information regarding the size of the showers measured in not available. Furthermore, nitrate concentrations are higher in urban areas as in more rural areas (Gatz, 1991). This can possible (partly) explain the lower concentrations of sodium found in Tirtayasa.

Acid rain is mainly caused by sulphur dioxide, oxides of nitrogen and ozone that are emitted into the air by automobiles and during the combustion of burnable waste or fossil fuels (Singh & Agrawal, 2007). Furthermore, pH is largely dependent on the history of the air mass (Pio et al., 1991). This can explain the relatively high pH found in Tirtayasa.

Water quality of roof runoff and inside tanks depends on the water quality of the direct precipitation and on several characteristics of the system including the material used and trees and animals near the tank and system maintenance. The high concentration of microbial contamination found in Tirtayasa can be explained by a relatively high contamination of the roof, and by possible recontamination in the tank.

5.2.4. Summary

It is debated by experts whatever the water quality in rainwater harvesting systems should meet the WHO and Indonesian drinking water quality guidelines. This uncertainty exists since other water sources do not meet these guidelines, the population can develop resistance against some (microbial) contamination and the population can apply end of pipe treatment when required.

In the measured rainwater harvesting systems the drinking water guidelines are met with the exception of microbial parameters. Different from expected the pH is found to be around 7. Dissolved concentrations of aluminium, iron and manganese decrease after contact with the roof, most likely due to the formation of complexes.

Although concern consist of the influence of air pollution on rainwater quality, measured heavy metals in tanks do not increase guideline values. However in direct rainfall measurements guideline

values are exceeded for iron and aluminium, possibly due to air pollution. Moreover, some relevant parameters including PAHs, phthalate ester, pesticides and polychlorinated biphenyls have to be measured to draw final conclusions regarding the effect of air pollution.
Another concern of local health authorities includes the limited mineral intake due to rainwater consumption. Although the intake of calcium and magnesium via rainwater is found to be low, in the case study area, this is mainly due to the limited diet of the population. It is approximated that rainwater use decreases the calcium intake from 38.4% towards 32.9% of the recommended daily intake. For magnesium the daily intake decreases from 73.1 to 69.1% of the recommended intake.

Table 25: Comparison of own direct and tank measurements, with other water quality measurements performed

	Average direct	Direct	Direct	Direct	Direct	Average tank	Tank	Tank	Tank	Tank	
Location	Serang	East Bandung	West Semarang	Jakarta	Bandung	Serang	Banda aceh	Banda aceh	Banda aceh	Bali	
Conductivity	41.0			16.7	21.4	61.0				85.0	uS/cm
Turbidity	1.0	5.2	2.0			1.3		3.5		4.6	NTU
Temperature (Water)	25.0	25.6	28.0			27.0				27.0	°C
pH in situ	7.2	5.7	7.0	4.7	5.2	7.2		7.5		7.2	n/a
Nitrate (N-NO3)	0.09	0.49	0.28	1.24	1.72	0.93				2.65	mg/L
Nitrite (N-NO2)	0.02	0.05	<0.005			0.09				0.01	mg/L
Ammonia (N-NH3)	0.12					0.18					mg/L
E.coli	776					560				0	MPN/100mL
Fluoride	< 0.02	0.28	<0.002			< 0.02				0.02	mg/L
Calcium-Dissolved (Ca)	2.5			0.60	0.91	8.55					mg/L
Magnesium-Dissolved (Mg)	0.32			0.09	0.18	0.14					mg/L
Aluminium-Dissolved (Al)	0.42					0.02	0.03		0.17	0.02	mg/L
Arsenic-Dissolved (As)	< 0.005					< 0.005	ND		0.001	ND	mg/L
Copper-Dissolved (Cu)	< 0.005					< 0.005				0.78	mg/L
Iron-Dissolved (Fe)	0.67	0.22	0.04			< 0.02				0.10	mg/L
Manganese-Dissolved (Mn)	0.01	0.07	1.05			0.01	ND		0.002	0.18	mg/L
Sodium-Dissolved (Na)	4.30	0.33	<0.01	0.49	0.30	1.60					mg/L
Lead-Dissolved (Pb)	< 0.001					0.005	0.001		0.002		mg/L
Zinc-Dissolved (Zn)	0.02					0.11	0.35		0.04	0.95	mg/L

5.3. Treatment

In this section the suitable treatment options for rainwater harvesting in Indonesia will be discussed. First there will be attention for the suitable treatment according experts and case study experts. Second the treatment currently applied by the population will be discussed. Finally the selected treatment options will be evaluated.

5.3.1. Expert and case study expert view

Suitable treatment for rainwater harvesting systems

Suitable treatment for rainwater harvesting systems largely depends on the local situation. According several experts treatment should be reflected on the costs, maintenance and acceptability (Listyasari, 2016; Cronin, 2016). Attention should be to the operation and maintenance and especially the availability of spare parts, since this is the main failure mechanism (Cronin, 2016).

In general boiling is widely applied in Indonesia (Listyasari, 2016; Zevi, 2016; Lubis, 2016, Imroatul, 2016; Lamhot Sinurat, 2016; Saputra, 2016). This behaviour is difficult to change (Lubis, 2016) and besides this the main water consumption takes place with coffee and tea (Saputra, 2016; Listyasari, 2016). For this boiling is required in any case. Because of this most experts advise no additional treatment next to boiling (Zevi, 2016; Lubis, 2016, Imroatul, 2016; Lamhot Sinurat, 2016; Saputra, 2016; Listyasari, 2016). However perhaps minerals (like calcium, magnesium, fluoride) have to be added to the water source to secure the mineral intake of the population (Saputra, 2016).

As alternative treatment UV disinfection is suggested by Zevi (2016), the ceramic filtration by Lubis (2016) and the biosand filtration by Imroazul (2016) and Soekarno (2016). Biosand makes use of easily available materials and costs of such systems are low (Soekarno, 2016). According to Cronin (2016) SODIS is too low tech and time requirement is a main limitation (Saputra, 2016). Zevi (2016) states that projects that use ultrafiltration, nazava filters and other ceramic filters will not work well in Indonesia.

Saputra (2016) mentions several disadvantages for alternative treatment technologies. There is concern regarding carcinogenic substances in case SODIS is used. The problem with commercial ceramic filters such as Nazava and Purit (Unilever) are the initial investments (Saputra, 2016). Ceramic filters were implemented in Binuang (kabupaten Serang), but did not succeed because the flow rate was too low (Saputra, 2016).
Ultrafiltration and pasteurization are not common in kabupaten Serang (Saputra, 2016). Most likely there will be issues regarding costs of such systems. Moreover, the fact that it is not common makes it more difficult to find support for such a technology (Saputra, 2016).

5.3.2 Population practice

In general the population boils the groundwater, surface water or rainwater before consuming it as drinking water. Bottled water is not boiled before consumption. As explained in section 5.1.3. the population sometimes uses additional treatment for their rainwater. Small fishes are placed in open tanks to eat mosquito larvae, a cloth filter can be used to prevent debris or other larger particles from entering the tank. Furthermore, rainwater is generally only used in the rainy season when the roof is relatively clean and systems are cleaned when dirty. In section 5.3.3 more information regarding the performance of these treatment techniques can be found.

5.3.3. Scientific review

As explained in section 5.2.3, water quality in current tanks complies with the WHO and Indonesian standards with the exception of microbial contamination. Direct rainfall does not comply with the standards for several metals, but the relevant dissolved metals decrease in concentration on the roof and inside the tank. In this paragraph first the treatment techniques that are currently used in Indonesia are discussed. This includes boiling, cloth filtration and fishes. Second these treatment techniques are evaluated together with the other selected treatment techniques. Selection is based on technical suitability and possible applicability for small scale treatment. Only technologies which are low tech and have low costs are included. An attempt is paid to include different type of treatment techniques. Third the possibilities for recontamination during distribution and storage are quickly discussed. Finally there is attention for the remaining health risk after treatment.

5.3.3.1. Evaluation of currently practised treatment techniques

Boiling

Boiling is currently already frequently practiced in Indonesia and Banten province in particular. One can consider this practice as automatic behavior which cannot easily be changed in a short time frame. Although various alternative treatment methods are available with their own advantages and disadvantages, boiling is because of these social reasons one of the most appropriate treatment methods in the case study area. However one should keep in mind that in general boiling is not the most sustainable or cheap water treatment method. Moreover, boiling inside on an open fire can cause indoor air pollution, which can cause serious health risks.

Enteric pathogens are killed within seconds when boiling (Ericsson et al., 2002). However bacterial spores like *Clostridium botulinum* are heat tolerant (Ericsson et al., 2002). Spores are general harmless, but when spores grow out to active bacteria, a dangerous situation can occur. This can occur is small children (<1 year), so in case your water supply is contaminated with the spores of C*lostridium*, one should be careful to use it as drinking water for small children. The link between *Clostridium* spores and infant botulism is suggested for rainwater harvesting systems in Australia (Lye, 2002).

A major disadvantage of boiling as end of pipe household treatment is the fact that it is, although boiling is effective against *Legionella*, ineffective against *Legionella* development inside the tank. This is a serious risk since the circumstances in Serang for the development of *Legionella* are favorable. Temperature of the water is between 25-45 degrees, water is stagnant and in some cases stored for a longer period of time, nutrients are present for the development of biofilm and dissolved iron is present in raw rainwater. Iron is of key importance for replication of *Legionella pneumophila* (Cianciotto, 2008).

Bacterial pneumonia due to *Legionella* often occurs due to inhalation of the bacteria. This is not prevented by end of pipe treatment or by limiting rainwater use to non-potable purposes. Effective treatment for *Legionella* includes chlorine, copper and silver ionization, periodic flushing with hot water (50-60 degrees) or UV (WHO,2007). Next to treatment several preventive measures could be taken against *Legionella* including storing water as cold as possible (<25 or ideally <20 degrees). One can also limit the maximum storage time of water inside the tank, the presence of nutrients and scale and corrosion (WHO,2007). These measures either limit the growth of *Legionella* and also the growth of biofilm, closely interlinked to *Legionella*.

Cloth filters
Cloth filters will not remove significant amounts of micro-organisms, due to the relatively large pore sizes. However they will remove larger organic materials which decreases the nutrient availability in the tank. This has a positive influence on the water quality. However the current way of installation of cloth filters allows organic material and dead animals to accumulate before entering the tank. Because decaying material goes together with bacterial growth, this situation is not desirable. Possible solutions are illustrated in Figure 34 and include the use of a transparent pipe (a), installing the cloth filter just before the water enters the tank (b), or using a partly self-cleaning filter with slope (c).

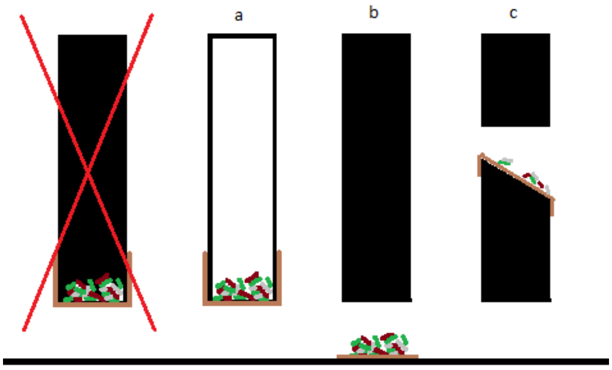


Figure 34: Current use of the cloth filter (left), use of a transparent pipe (a), installing the cloth filter just before water enters the tank (b) or installing the cloth filter on a slope (c).

Fishes
Mosquitos in water storage tanks can be controlled by several methods. These include good coverage of storage tanks, the use of insecticide curtains, lethal ovitraps, the cleaning and removal of breeding sites, the addition of predators to water tanks (biological control measure) and integrated methods of control (Seng et al., 2008). The use of larvivorous fish, which feed on the immature stages of mosquitoes, is one of the biological control measures that has been used extensively all over the world (Chandra et al., 2008). Almost 200 fish species have been found to be effective in decreasing mosquito larvae in water bodies (Howard et al., 2007). Several studies found that larvicolous fish, like *Poecilia reticulata* (guppies), were effective in controlling mosquito larvae in water storage tanks (Seng et al., 2008; Wang et al., 2000; Martinex-Ibarra et al., 2002; Nam et al., 2000). Thereby limiting the diseases like dengue and malaria that are spread by mosquitos.

However the introduction of biological control measures in water storage tanks may also add a potential source of pathogenic micro-organisms. Zoonosis are diseases that can be transmitted from animal to humans (Haenen et al., 2013). Zoonotic infections can occur by either contact with aquatic animals or their products or by the consumption of insufficient heated fish (Haenen et al., 2013). Bacteria are the main fish-borne zoonotic agents, and beside this some zoonotic parasites are reported (Boylan, 2011; Jacobs, 2015). Fish borne zoonotic viral, fungal or protozoal pathogens are not reported in literature (Boylan, 2011). Parasite zoonosis is mainly transmitted via the consumption of raw, undercooked, under salted, or insufficiently pickled fish meats (Boylan, 2011). This only leaves bacterial zoonotic infections relevant for rainwater harvesting systems.

The bacteria can infect humans through abrasions, cuts or penetrating wounds in the skin when dealing with infected fish or fomites (like water) with can carry infectious organisms (Boylan, 2011; Haenen et al., 2013). Reported bacteria include *V. vulnificus, M. marinum, S. iniae, E. tarda, Aeromonas hydrophila and Erysipelothrix rhusiopathiae* (Haenen et al., 2013). Outbreaks of these bacteria are often associated with water quality, the quantity of the nutrients and the stocking density of fish (Haenen et al., 2013). In general fish borne zoonoses are rare (Boylan, 2011). Highest risk groups include fish culturists, processors and handlers and commercial fishermen and women (Haenen et al., 2013). Especially immunocompromised individuals with open skin injuries or pierced by fish spines are at risk (Haenen et al., 2013).

Table 26: Bacterial zoonosis related to fish.

Bacteria	Fresh, brackish or marine water	Causes of infection (fish related)
V. vulnificus	Brackish and marine water$_1$	Skin comes into contact with infected seawater, fish or shellfish$_2$ Consumption of shellfish$_1$
M. marinum	Fresh and marine$_2$	Injury by aquarium fish, aquarium/fish tank exposure, injury during bathing in seawater (by fish spines or sharp edges on shellfish) and exposure to water$_2$
S. iniae	Fresh, brackish and marine$_1$	Contact with living or dead fish$_1$
E. tarda	Fresh water fish$_1$	Consumption of raw fish or intake via water$_1$
Aeromonas hydrophila	Fresh water fish$_3$	Exposing wounds to water containing *A. hydrophila*.$_{5 \text{ and } 8}$ Exposure to fresh water$_6$
Erysipelothrix rhusiopathiae	Fresh and marine fish$_4$	Infection via injuries coming into contact with infected animals, their secretions, wastes or products, or organic matter contaminated by any of these.$_7$

1. Jacobs (2015), 2. Haenen et al. (2013), 3. Lowry et al. (2007), 4. Roboli & Farrar (1989), 5. Hazen et al. (1978), 6. Gold & Salit (1993), 7. Brooke & Riley (1999), 8. Vally et al. (2004)

5.3.3.2. Evaluation of selected treatment techniques

Based on the analysis of the currently practiced treatment techniques (paragraph 5.3.3.1) and the literature review in paragraph 2.3.2 the selected treatment techniques were evaluated. Parameters taken into account include costs (investment, operation and maintenance), social acceptance (availability, time requirement and preference) and technical performance (microbial, chemical, turbidity and mosquito). Treatment technologies that were found to have a relatively low (additional) cost and high social acceptability include fiber or cloth filtration, the use of fish and boiling. When these techniques are combined one could reach a relatively high technical effectiveness since boiling is highly effective for microbial contamination, fiber or cloth filtration will remove turbidity and fish[4] will prevent mosquito breeding. The use of these techniques is not expected to have any social resistance since the techniques are already practiced as indicated by experts, case study experts and observed by the population itself.

5.3.3.3. Recontamination during distribution and storage

Recontamination of the water source should be prevented by safe transport and storage of water. In safe storage devices the water is protected from any possibly fecal contaminated objects, and well closed against mosquitos. Several research confirms the importance of safe storage after water is treated. Sodha et al. (2011) found that water stored in wide-mouthed or uncovered containers in Indonesia were more likely to contain *E.coli*. Furthermore water touched by the respondents hand was also more likely to contain *E.coli*. Quick et al. (2002) found that diarrhoea disease in a community in Zambia reduced significantly by using water treatment, safe storage and education.

[4] A mosquito tight system is preferred above the use of fish, due to microbial risk.

Sobsey et al. (2003) found similar results in Bolivia. Community diarrhoea decreased with 43% by applying point of use treatment and safe storage. Based on these researches it can be stated that safe storage is of main importance. Containers with narrow openings and dispensing devices are found to protect water sources relatively well (WHO,2016).

Table 27: Evaluation of several point of entry and point of use treatment techniques.

	Costs		Social			Technical				Other
	Investment	Operation & mainten.	Availability	Flow limitation	Preference	Microbial	Chemical	Turbidity	Mosquito	
Fiber or cloth	low	low	high	low	high	low	low	high	yes	no
Ultrafiltration	high	medium	low	medium	low	high	medium	high	yes	yes (1)
Copper silver disinfection	medium	medium	low	low	low	medium	low	low	no	no
Fish	low	low	high	low	high	low	low	low	yes	yes (2)
Biosand	medium	low	high	medium	medium	low-medium	low	medium	no	no
SODIS	low	low	high	high	low	medium-high	low	low	no	yes (3)
Chlorine	low	medium	medium	medium	low	high	low	low	no	yes (4)
Ceramic pot	medium	low	medium	high	low	medium-high	low	high	no	no
Boiling	low	medium	high	medium	high	high	low	low	no	yes (5)

(1) requires total redesign of the system, (2) fish zoonosis, (3) softeners, (4) disinfection by products, (5) air and environmental pollution.

5.3.3.4. Selected treatment chain

As discussed in the previous paragraphs it is advised to treat rainwater before use. However high quality water is not required for all purposes. In case water is stored both turbidity should be removd and mosquito prevention is required. First flush water can still be used for low end non-purposes like the watering of plants. After the first flush water contains less microbial contamination, although it still will be present. This water could be used for other non-potable purposes such as the washing of cloths and personal washing (but not for showering). In case water is planned to be used for drinking or cooking all treatment steps are required including turbidity removal, mosquito prevention, first flush and boiling. In Appendix B3 the treatment chain is visualized.

5.3.3.5. Remaining health risks after treatment

By using the system with a leaf strainer and/or cloth filter to remove turbidity, a well tight system and/or fish to prevent mosquitos and boiling to remove microbial contamination in drinking water still some health risks remain. In this paragraph these health risks will be discussed. In Figure 35 the exposure pathways for contamination are shown. Microbial or chemical contamination can be ingested in large volumes in case the water is used for potable purposes, or in smaller volumes in case it is used for non-potable purposes. Microbial contamination can also be inhaled via aerosols or enter via (wounds in) the skin.

Health risk for potable purposes

For potable purposes the main health risks occurs due to the ingestion of microbial and chemical contamination. Since boiling is very effective against microbial contamination the health risk associated with this is small. However is certain health risk is present for young children (< 1 year), since infant botulism can occur due to spores of *clostridium botulinum*, which are not removed during boiling. In this research chemical contaminants measured were found below guideline values, but more rainwater harvesting systems should be checked in time and space and especially from other roof materials. These measurements should confirm that the health risk regarding chemicals like copper, zinc, aluminium, manganese and lead is small. Furthermore, the presence of organic pollutants like PAHS, phthalate ester, pesticides and polychlorinated biphenyls should be checked.

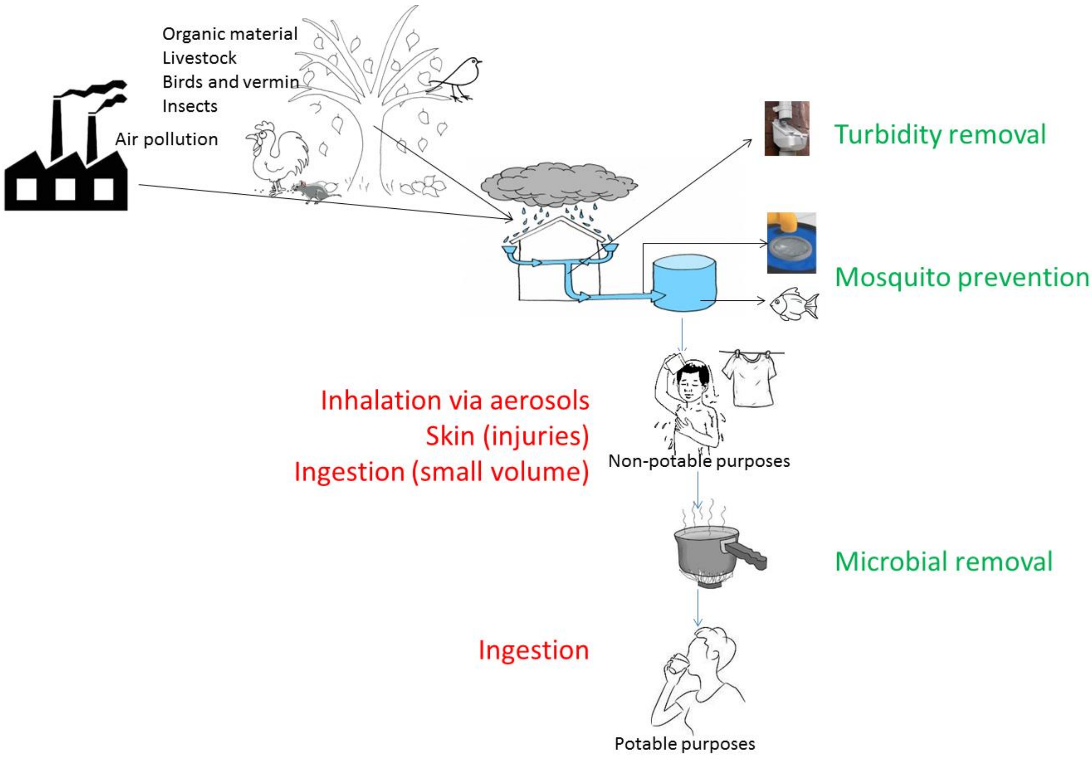


Figure 35: Exposure pathways for microbial and chemical contamination

Health risk non-potable purposes

For non-potable purposes main exposure roots are via the inhalation of aerosols or via skin(injuries) which are exposed to contaminated water. Furthermore, ingestion of water can occur in small volumes, especially during washing. Water used for non-potable purposes is not cooked and thereby microbial contamination will be present. This can be present due to direct sources, like feacal material from birds, vemin or lifestock. Moreover, microbial contamination like *Legionella pneumophila* and *Aeromonas hydrophila* can grow in drinking water systems (Wielen & Kooij, 2009). However, these opportunistic micro-organisms can only be transmitted via aerosols or via the skin (Wielen, 2012). Viruses and protozoa can only grow in a host (Medema, 2016).

From the micro-organisms found in rainwater harvesting systems *Legionella pneumophila* and

Pseudomonas aeruginosa can spread via aerosols. However since the use of aerosol forming devices (like showers, bubble baths and air condition) is very limited, the chance to get infected by these diseases is relatively small (CDCab, 2016; PHAC, 2016). *Pseudomonas aeruginosa, Aeromonas hydrophila* and *Staphylococcus aureus* can cause infections in open wounds (Dermnetnz, 2016; Mekkes, 2012; PHAC, 2016). These diseases often occur for patients with skin injuries. Other risk groups include individuals with weakened immune systems and young children. Fish in rainwater harvesting tanks can possibly increase the chance of wound infections. Until know it is unclear how large this risk is, for example compared to the risk of working in rice fields.

Salmonella, *Campylobacter*, *Clostridium botulinum*, *Aeromonas hydrophila, Staphylococcus aureus, Giardia*, tissue helminths and *Cryptosporidium*, transmission can occur via ingestion. Symptoms often include diarrhea (with the exception of the tapeworm *Echinococcus granulosus*) and in general effects are most severe for young children, elderly and/or people with weakened immune systems (CDCab, 2016) .

5.3.4. Summary

Water used for different purposes requires different water quality. For potable purposes, strict water quality requirements are required. To reach these requirements fiber and cloth filtration, ultrafiltration, copper and silver disinfection, fish, biosand, SODIS, chlorine, ceramic pot and boiling were evaluated against technical, social and economic aspects. Based on this analysis it is found that boiling, cloth filtration and fish are currently a suitable treatment combination for Serang, tackling the microbial contamination present in rainwater, preventing turbidity and dealing with mosquitos. An important consideration taken into account is the fact that boiling is a very common and preferred treatment technique. This suggested treatment chain is accompanied with a certain health risk, both for the boiled water which is used for potable purposes (via ingestion), and the unboiled water which is used for non-potable purposes (via ingestion, aerosols and wounds). Pathogens of concern are spores of *clostridium botulinum* which can cause infant botulism in case water is ingested by young children. Other relevant micro-organisms which are spread by aerosols or wounds include *Legionella pneumophila* and *Aeromonas hydrophila, Pseudomonas aeruginosa* and *Staphylococcus aureus.*

5.4. Water quantity

In this paragraph the water quantity aspects of rainwater harvesting are discussed. First there is attention for the view of experts and case study experts and the current practice of the population. Second the characteristic of the rainfall data and selected cumulative distribution functions are discussed. Third the model results for the different operational scenarios as discussed in paragraph 4.4.5. are presented. Finally there will be attention for the sensitivity of the model results to the selection of model parameters.

5.4.1. Expert and case study expert view

Experts and case study experts were asked about the required coverage of rainwater harvesting and the suitable system scale for a rainwater harvesting systems. Results are summarized below.

As experts mention, it is very common in Indonesia to use a combination of different water sources for different purposes (Lubis, 2016; Listyasari, 2016). Which source is used for which purpose depends on the local situation (Listyasari, 2016; Soekarno, 2016). Rainwater cannot easily supply 100% of the total water need (Jantowski, 2016). Because of these reasons it is advised to use a combination of different water sources (Kamarga, 2016; Lubis, 2016; Imroatul, 2016; Jantowski, 2016). When rainwater is used in the dry season the population should be educated, to make sure that no water is wasted (Cronin, 2016). Interesting enough some communities have higher priorities for easy clean water in the wet season, compared to the dry season (Jantowski, 2016). During the wet season they have to work on the land the whole day and have no additional time to spend on water collection (Jantowski, 2016).

The water quantity that can be supplied is largely linked to the system scale and size. One can expect that a larger scale system can more easily overcome fluctuations in rainfall or demand. The suitable system scale should be decided based on dynamics, cohesion and teamwork within the community (Cronin, 2016; Jantowski, 2016). Focus group discussions can be used to find the attitude of the population (Listyasari, 2016). Furthermore it is important to take the house type into account (Zevi, 2016). Some roofs are unsuitable for a rainwater harvesting system (Kamarga, 2016). Ground availability may limit the possibilities for the installation of tanks (Jantowski, 2016; Listyasari, 2016). Also the financial situation of the population can be important (Jantowski, 2016; Imroatul, 2016). However according Cronin (2016) the financial situation is of less importance compared to the motivation of the population.

In general one advices to build small scale rainwater harvesting systems on household level (Cronin, 2016; Kamarga, 2016; Imroatul, 2016, Lubis, 2016; Zevi, 2016). For larger scale systems, the maintenance is a critical point and fights with the neighbours can occur (Lubis, 2016; Zevi, 2016; Cronin, 2016; Kamarga, 2016). Moreover, a communal tank is not very common in Indonesia, and it can also be difficult to find a good location for the tank (Imroatul, 2016; Soekarno, 2016). Also case study expert Lamhot Sinurat (2016) advices to start with a system on a household scale. Experience with sanitation projects in kabupaten Serang learns that maintenance costs is one of the main reasons not to join communal systems. Projects should always be based on the wishes of the local population. In case of a larger system one should organize regular payment to maintain the system (Kamarga, 2016).

Case study expert Lamhot Sinurat (2016) states that the main problem with rainfall is the fact that it is unpredictable. Previous year the rainy season just lasted for one month and quite some rainwater harvesting systems were left behind. However this year has a long rainy season, and it is a waste that some of the rainwater harvesting systems are closed.

5.4.2. Population practice

The population is using a wide variety of water sources, which are selected based on availability and the local opinion regarding their quality. In Tirtayasa bottled, refilled gallons, rainwater, shallow wells, shallow wells with pumps, deep wells, piped water (not from PDAM) and refilled jerry cans where used by respondents. On average one family used four (3.7) water sources. In Pabuaran refilled gallons, rainwater, shallow wells, shallow wells with pumps, deep wells and springs are used by the local population. On average one family uses three (2.9) different types of water sources.
Tis research assumes a total water need of 500 liter per family a day and a total fresh water need of 80 liters a family a day.

5.4.3. Modeling

5.4.3.1. General data analyzing

After the extraction of the daily rainfall data from the PUSAT DATABASE – BMKG, the data for the station in Serang was plotted against time (Figure 36). Rainfall shows a clear seasonality. Cumulative missing data and cumulative rainfall of the four stations in Banten province can be found in Appendix C1. Based on this analysis the last year of data is disregarded, and data between 01-01-1990 and 31-12-2014 was used. For this period the station in Serang misses 10.1% of the data.

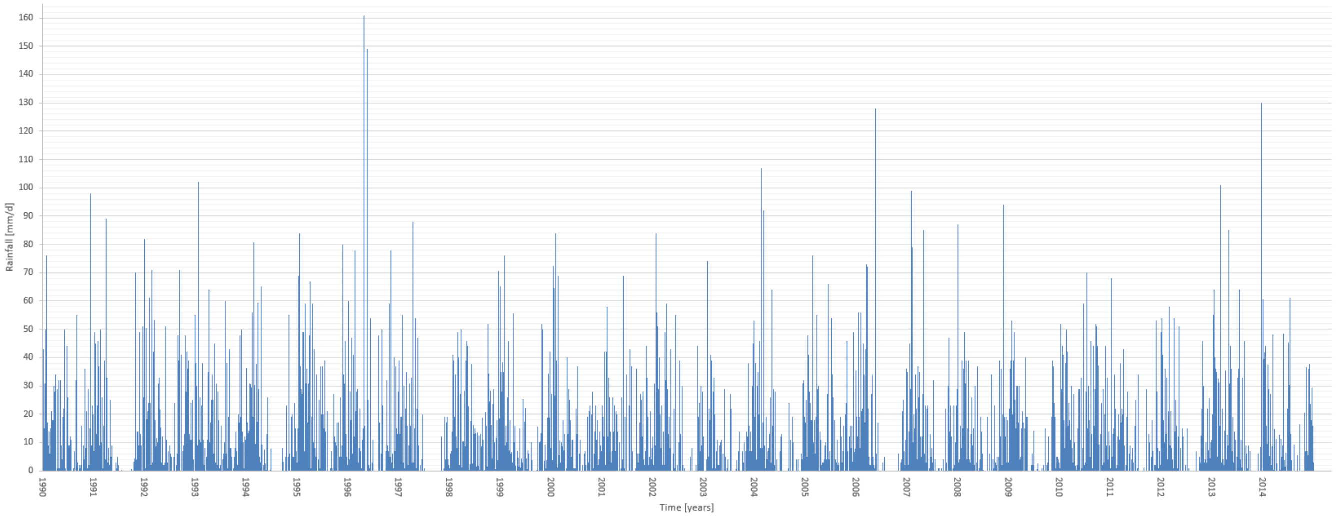


Figure 36: Daily rainfall (in mm) between 1990 and end 2014 for the measuring station in Serang.

Average annual rainfall in Serang was found to be 1722 mm. On average 58.1% of the days had no rainfall and the maximum amount of rainfall in one day was found to be more than 160 mm. In Table 28 the characteristics of the used data can be found. As can be seen the percentage of missing data varies between 4.4% in August to 14.9% in November. January is found have the least dry days (33.7%) were in August much more dry days occur (85.4%).

Table 28: Data characteristics per month.

Month	Total data points (+ missing data) [day]	Missing data [day]	Percentage missing [%]	Days in analysis [day]	Wet days [day]	Dry days [day]	Percentage dry [%]
Januari	744	90	12.1	654	489	165	33.7
Februari	678	63	9.3	615	444	171	38.5
March	744	84	11.3	660	368	292	44.2
April	720	69	9.6	651	306	345	53.0
May	744	82	11.0	662	253	409	61.8
June	720	66	9.2	654	186	468	71.6
Juli	744	46	6.2	698	162	536	76.8
August	744	33	4.4	711	104	607	85.4
September	720	50	6.9	670	110	560	83.6
October	744	94	12.6	650	203	447	68.8
November	720	107	14.9	613	275	338	55.1
December	744	98	13.2	646	400	246	38.1
Total	8766	882	10.1	7884	3300	4584	58.1

Table 29: Average rainfall during event and average monthly rainfall for all months separately.

Month	Average rainfall during event [mm]	Average monthly rainfall [mm/month]
Januari	14.80	294
Februari	14.47	267
March	11.55	193
April	10.95	154
May	10.76	123
June	9.10	78
Juli	10.07	70
August	10.17	45
September	10.90	54
October	11.36	106
November	11.09	149
December	9.63	179

As indicated in the methodology the points on the cumulative distribution functions were constructed empirically. Afterwards a log-normal distribution, a gamma distribution and a Weibull distribution were fitted. The goodness of fit of these three methods was checked by visual comparison and by goodness of fit tests. The visual comparison shows that all three distributions perform relatively well. The log-normal distribution performs slightly better for low rainfall intensities where the gamma and Weibull distribution perform better for higher rainfall intensities, as can be seen in Figure 37.

In Table 30 the MSE calculation and the results of the chi-square and Lilliefors test are shown. A higher MSE implements that the fit is worse. One should note that the mean square error is calculated until the length of the data series, which varies per month. For the chi-square test and the Lilliefors test an one indicates that one can reject the hypothesis that the data fits the distribution with 5% significance, a zero indicates the hypothesis cannot be rejected.
The MSE calculations show that in the wet season (November until May), the Weibull generally fits the rainfall data better. In the dryer months the log-normal distribution has a slightly better fit. This is not confirmed by the Lilliefors test and the chi-square test. The Lilliefors test rejects the null hypothesis at the five percent significance level that the rainfall data fits either the log-normal distribution or the Weibull distribution in any month. The chi-square test shows that the Weibull

distribution fits the monthly data the best. For this distribution the test shows that the hypothesis that the data fits the Weibull distribution, cannot be rejected in nine of the twelve months.

Based on above described analysis, the Weibull distribution is selected to fill missing data gaps. As seen in the visual inspection all distribution functions perform relatively well. The log-normal distribution overestimates high rainfall amounts, and performs bad for the chi-square test. The Weibull and gamma distribution show visually very similar results, but according the MSE and the chi-square test the Weibull distribution performs better.

Table 30: MSE and the result of the chi square test and the Lilliefors test for the different distribution functions.

	Mean square error (MSE)			Chi-square test			Lilliefors test	
	log-normal	Weibull	gamma	log-normal	Weibull	gamma	log-normal	Weibull
Januari	0.0005	0.0004	0.0005	1	1	1	1	1
Februari	0.0006	0.0003	0.0005	1	0	0	1	1
March	0.0005	0.0003	0.0005	1	0	0	1	1
April	0.0002	0.0003	0.0005	0	0	1	1	1
May	0.0003	0.0007	0.0013	1	0	0	1	1
June	0.0010	0.0013	0.0020	1	0	0	1	1
Juli	0.0008	0.0008	0.0012	0	0	1	1	1
August	0.0009	0.0016	0.0024	0	1	1	1	1
September	0.0005	0.0008	0.0012	0	0	0	1	1
Oktober	0.0006	0.0007	0.0010	0	0	1	1	1
November	0.0005	0.0005	0.0008	1	0	0	1	1
December	0.0002	0.0003	0.0006	1	1	1	1	1
Average	0.0006	0.0007	0.0010	7/12 (no fit)	3/12 (no fit)	6/12 (no fit)	12/12 (no fit)	12/12 (no fit)

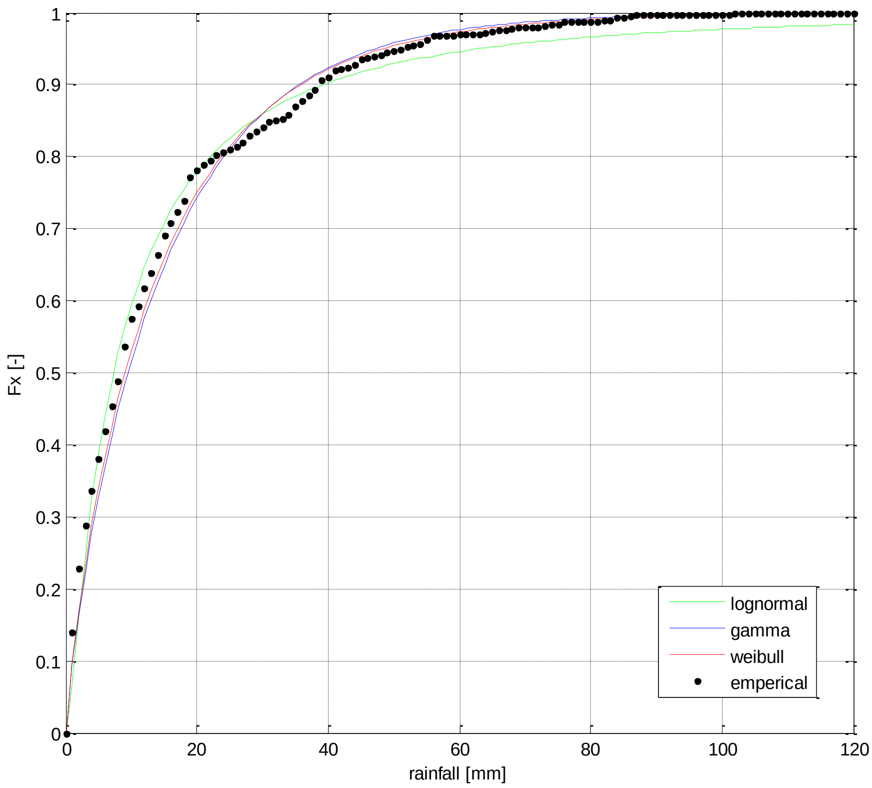


Figure 37: The empirical cdf and the fitted log-normal, gamma and Weibull distribution for January.

5.4.3.2. Model results water use in wet season

In this paragraph the results of the model can be found in case there is only water usage in the wet season. Results for the scenarios in which the tank is used over the entire year can be found in section 5.4.3.3 and 5.4.3.4.

Scenario 1a(i): One equal demand in the wet season (PDNM=20%)

In scenario 1a the rainwater harvesting tank is only used in the wet season. A constant amount of water is requested from the tank during this entire period. The maximum expected and real water use (tap flow) for this scenario can be found in Figure 38 for different tank and roof sizes. Different colours represent different tank sizes, solid lines are expected amounts and dashed lines represent the real water use (tap flow). The expected amount of water cannot be harvested in 20% of the days as a maximum. In this calculation the tap flow is on average 82.6% of the expected amount of water. Even if the expectation is not met, still some water can be taken from the system, which explains the fact that the tap flow is more than 80% of the expectation.

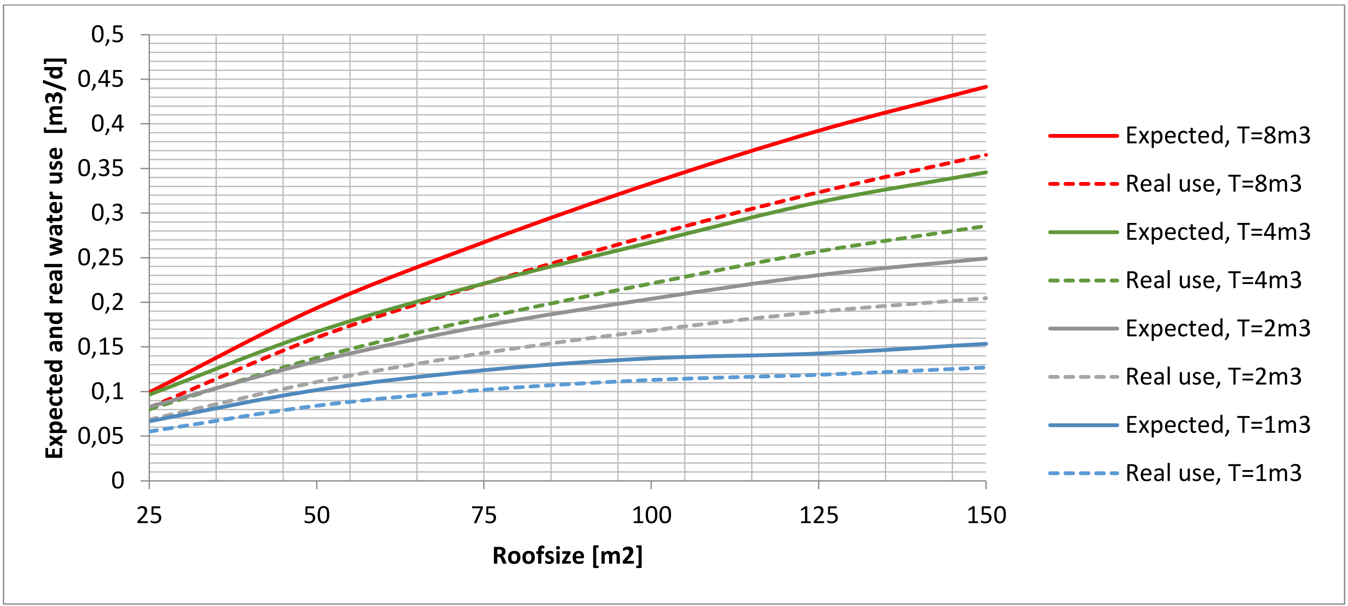


Figure 38: Maximum expected and real water use in the wet season, considering that in 20% of the days in the wet season the expectation is not met (PDNM [-]).

As can be seen in Figure 38 the possible amount of water that could be used from the rainwater harvesting system is not sufficient to meet the demand of the population in Serang, which is assumed to be 500 liter a family a day. This implies that an additional water source will be needed in any case, even in the wet season.

A realistic tank size for Serang is 2 m^3 with a connected roof area of 100 m^2. For this system size it is found that the expected amount and average tap flow are 0.204 m^3/d and 0.169 m^3/d respectively. Average tap flow fluctuates per month, although the same amount of water is requested from the system. Since the population needs 80 liter per family per day of fresh water, bottled water has to be bought in the dry season. In Figure 39 the water use pattern of one family for this scenario can be found.

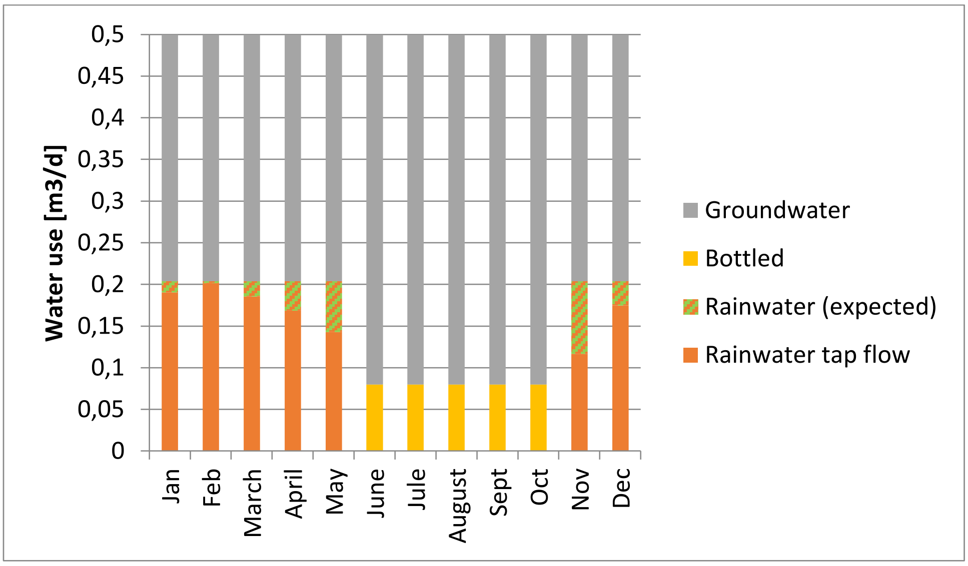


Figure 39: Water usage pattern for a family in Serang, Tirtayasa in case rainwater harvesting system operation occurs according scenario 1a(i).

Scenario 1a(ii): One equal demand in the wet season (PDNM=5%, 20% and 50%)
In Figure 40 the expected water use and the real water use is shown for different system reliabilities (PDNM) for a tank size of 2 m^3. The difference between the expected and the real use is small for low PDNM. Furthermore, a low PDNM also go together with low average tap flows. High PDNM, go together with high tap flows. This implies that in case high amounts of water are asked to the system, one on average can expect higher water withdrawals. However the uncertainty that one can extract this larger amount of water increases.

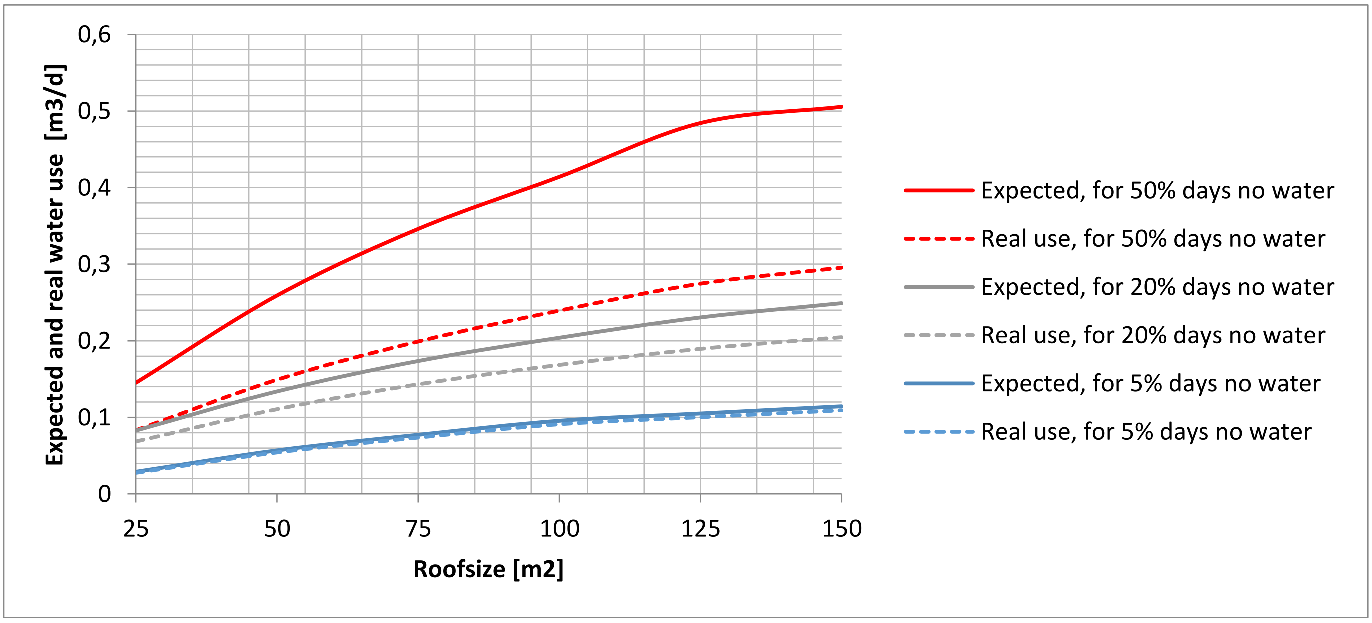


Figure 40: Maximum expected water withdrawal and real use (tap flow) in the wet season for a tank of 2 m^3, considering that in 50, 20% and 5% of the days in the wet season the expectation is not met (PDNM [-]).

Scenario 1b: Fluctuating expectation (or demand) per month in the wet season (PDNM=20%)
In scenario 1b the expectation (or demand) is fluctuated per month in the wet season. In the monte carlo runs the monthly demand is varied between 50% and 200% of the demand found in scenario 1a(i). It is found that the possible demand increases, by fluctuating the demand monthly.
In Figure 41 the optimization is shown for a tank of 2 m^3 and a roof size of 100 m^2. Average demand is found to be 0.223 m^3/d, and average tap flow is 0.188 m^3/d. Compared to scenario 1a(i) this is an increase of 9.5% in the expected amount of water, and an increase of 11.6% in the amount of water that is extracted in reality (the tap flow).

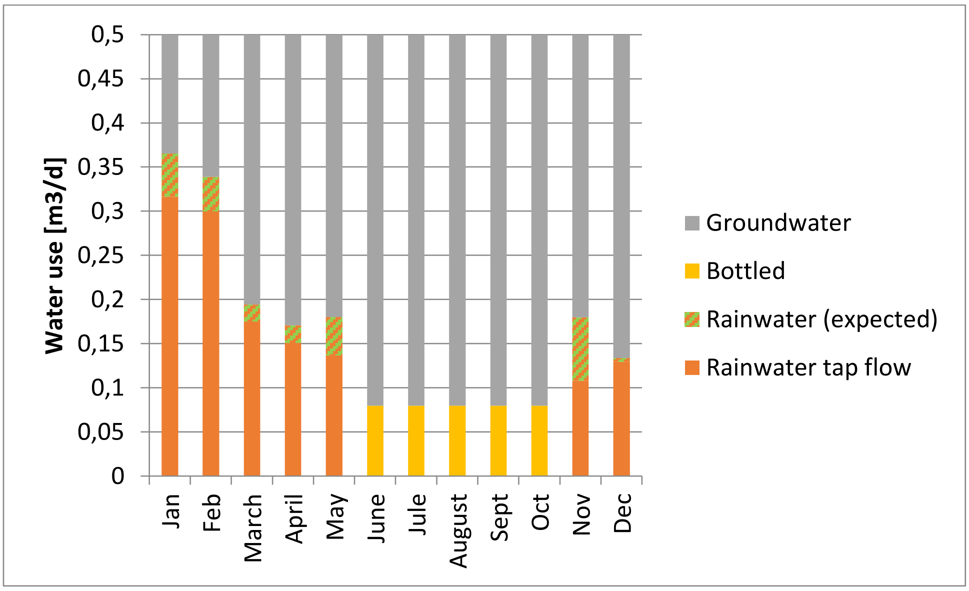


Figure 41: Visualization of the water use by one family, for scenario 1b.

In Figure 42 the selected tap flow and demand is visualized by scatter plots, both in case of a constant demand in the wet season and in case of a monthly changing demand in the wet season for a tank of 2 m^3 and a roof of 100 m^2.
The selected (or optimum) tap flow is the maximum tap flow, taking into account that the PDNM should smaller than 20%. The optimum demand (expected flow) is the demand that results in the highest average tap flow. This is not necessary the highest demand. In case one fluctuates per month points are more scattered due to the multiple combinations of monthly demands that lead to a similar average demand in the wet season.

5.4.3.3. Model results water use in the entire year

In this paragraph the system behaviour is analysed in case the rainwater tank is used in both the wet and the dry season. First there will be attention for constant demand during the entire year. Second the demand is changed between the wet and dry season. Last the possibility of a monthly fluctuating demand will be investigated.

Scenario 2a: One demand
In this scenario it is assumed that the population has a constant demand throughout the entire year. This demand will not be met in a certain percentage of the days, depending on the tank size that is used and the demand that is requested from the system. In case the roof size and the demand is

known, a decision has to be made regarding suitable tank size and failure probability of the system (expressed as percentage of days the demand is not met). In Figure 43 the relation between tank size and failure probability is plotted for different demands. Calculations are performed for a roof size of 100 m^2. Similar figures for a roof size of 50 and 150 m^2 can be found in Appendix C4.

For a percentage demand not met of 20%, a demand of 0.1026 m^3/d is found for a roof of 100 m^2 and a tank of 2 m^3. Average tap flow is not equality distributed per month. In the dry season a high percentage of the demand is not met, were in the wet season almost 100% of the demand is met. The average tap flow per month for scenario 2a can be found in Appendix C5.

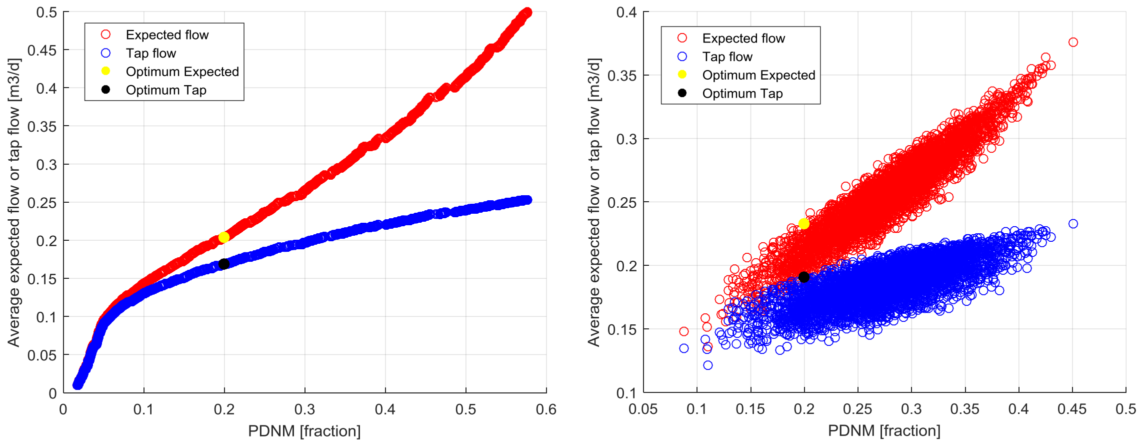


Figure 42: Selected (optimum) tap flow and demand for scenario 1a(i) (left) and scenario 1b (right).

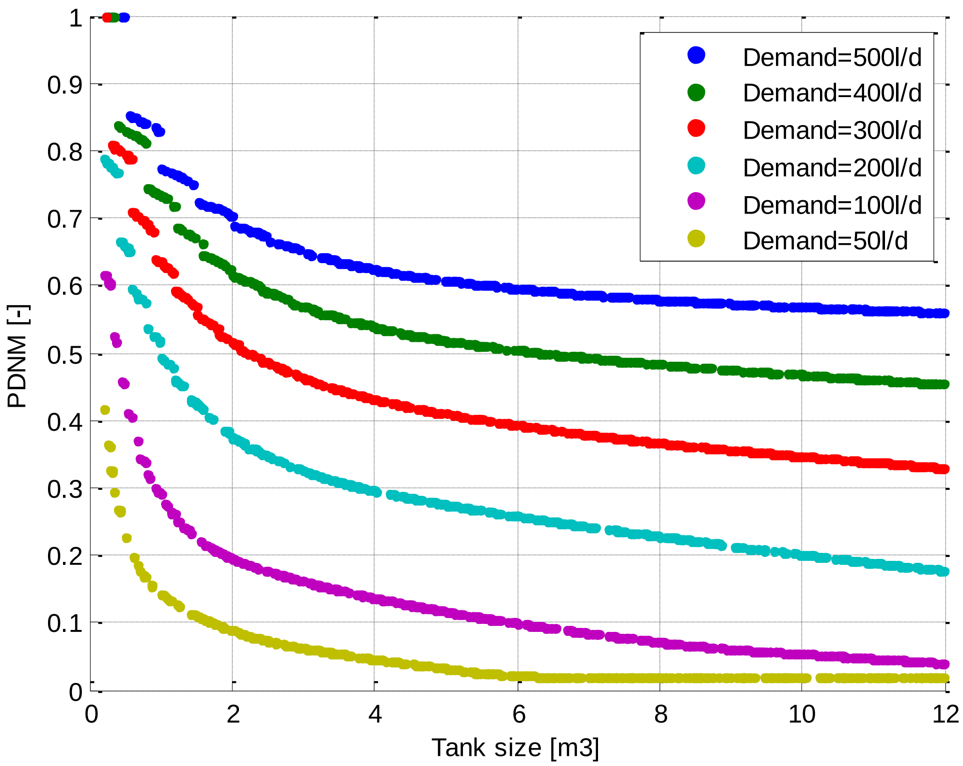


Figure 43: Relation between tank size and percentage demand not met for different demands (RS=100 m^2).

Scenario 2b: One demand in the wet season and one demand in the dry season(PDNM=20%)
In case the rainwater harvesting tank is used in both the wet and the dry season, optimization can be done in two ways, first by maximizing the total tap flow, and secondly by finding a weighted optimum, which gives more priority to the dry season. In Figure 44 the optimization is illustrated in scatter plots for a tank size of 2 m^3 and a roof size of 100 m^2. Optimization can be done by maximizing the average tap flow (red circles). However is case this is done, a relatively low average flow in the dry season will be reached (middle Figure 44). In case the tap flow will be weighted (red squares) a relatively high average tap flow can be reached, combined with a higher tap flow in the dry season.

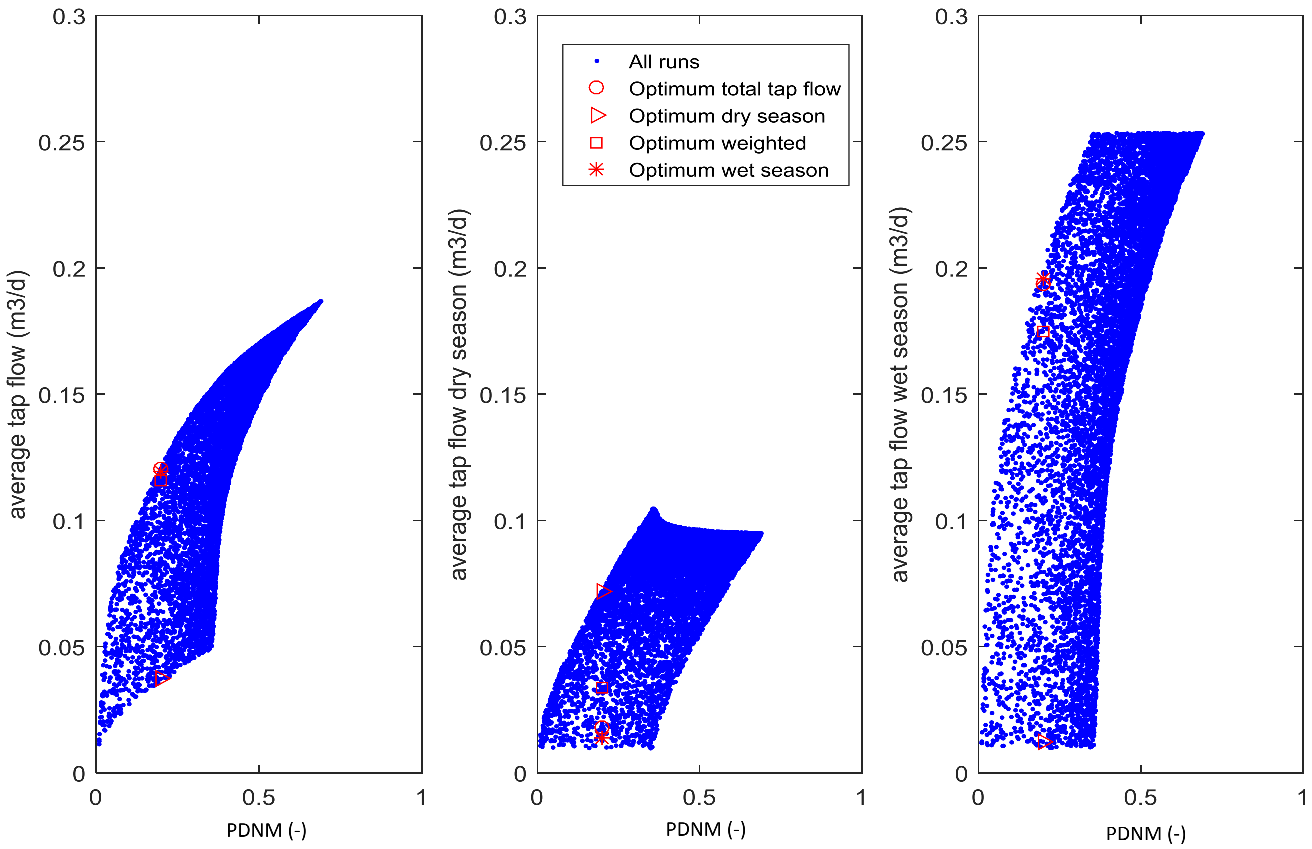


Figure 44: Optimization towards total average tap flow, average tap flow in the dry season, a weighted optimum and maximum tap flow in the wet season (T=2 m^3 and R=100 m^2).

When analysing Figure 44 it should be clear that the fraction of the demand that is not met and tap flow have no direct relationship. Both are calculated during model runs, for which a certain expectation or demand is used as input. Since this demand is not always met, but just in a certain percentage of the days (PDNM), the tap flow will be lower as the demand. In Figure 45 the relationship between demand or expectation and tap flow is shown. Ranges are wide in case one looks to total average demand or tap flow in the left figure. This is due to the fact that the same average demand can be generated with multiple combinations of a demand in the wet and a demand in the dry season. Demand and tap flow in the wet season have a one to one relationship (Figure 45, left). This is due to the fact that the tank is emptied in the beginning of the wet season. Because of this the tap flow in the wet season is independent on the demand in the dry season. This is not the case for the relation between demand and tap flow in the dry season. The tap flow in the dry season depends on the volume of water in the tank at the start of the dry period. This can change the average tap flow up to 0.013 m^3/d (2 m^3 / 152 days). In the figure it is also illustrated that only for relatively small demands the boundary regarding the percentage of days demand not met is reached (green versus blue dots).

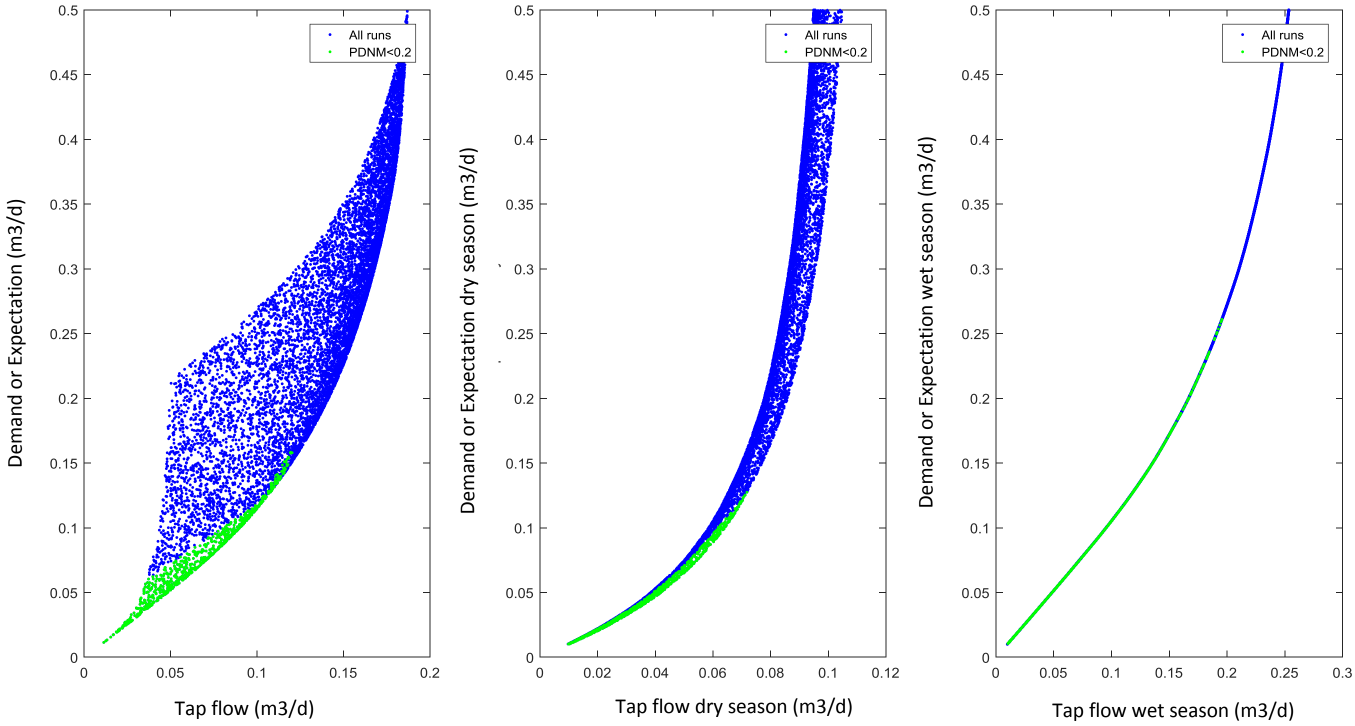


Figure 45: Relationship between demand or expectation (m^3/d) and tap flow (m^3/d).

Average tap flow for the maximum optimization was found to be 0.194 m^3/d in the wet season and 0.018 m^3/d in the dry season. For the weighted optimization this was found to be 0.175 and 0.034 m^3/d respectively. As expected, the tap flow in the dry season is higher for the weighted optimization. The visualisation of the total water use both for the maximum tap flow as the weighted tap flow for one family can be found in Appendix C2. Bottled water use decreases compared to scenario 1a since water is also harvested in the dry season.

As can be seen in Table 31 the demand and tap flow in the wet season increases for scenario 2b(i) with respect to scenario 1b. This although in scenario 1b only water is used in the wet season. This can be explained by the fact that in scenario 1b, the PDNM should be 20% of the days in the wet season. In scenario 2b(i) it is possible that this percentage is larger in the wet season, in case the percentage is smaller in the dry season. The only requirement given to the model is that the average PDNM is lower than 20%.

Table 31: Summary of optimum average demands and tap flows for different scenarios (tank=2 m^3, roof=100 m^2).

Scenario	Expectation or demand wet [m^3/d]	Expectation or demand dry [m^3/d]	Tap flow average [m^3/d]	Tap flow wet [m^3/d]	Tap flow dry [m^3/d]
1a	0.204	-	-	0.169	-
1b	0.223	-	-	0.188	-
2a	0.103	0.103	0.083	0.098	0.063
2b(i)	0.257	0.020	0.120	0.194	0.018
2b(ii)	0.216	0.041	0.116	0.175	0.034
2c(i)	*0.293	*0.024	0.131	0.192	0.046
2c(ii)	*0.246	*0.044	0.128	0.178	0.059
2d (Tstor)	-	-	0.186	0.253	0.093
2d (Tstor/2)	-	-	0.182	0.247	0.092
2d (Tstor/4)	-	-	0.167	0.224	0.087
2d (Tstor/8)	-	-	0.124	0.160	0.074
Max(0.08)	-	-	0.068	0.077	0.055

*Average demand wet and dry is less relevant since in these scenarios demand fluctuates per month

Scenario 2c: Fluctuating demand in the wet season and dry season(PDNM=20%)

For this scenario maximum and weighted tap flow are determined in which the expectation (or demand) is fluctuated per month. For the maximum scenario, average tap flow is found to be 0.192 m^3/d and 0.046 m^3/d in the wet and dry season respectively. In Figure 46 the water use per source is illustrated for this scenario. The weighted tap flow is found to be 0.178 and 0.059 m^3/d for the wet and dry season respectively, as illustrated in Figure 47. As can be seen in Table 31 in scenario 2c the average expectation and tap flow increases even further compared to the scenarios which are previously discussed.

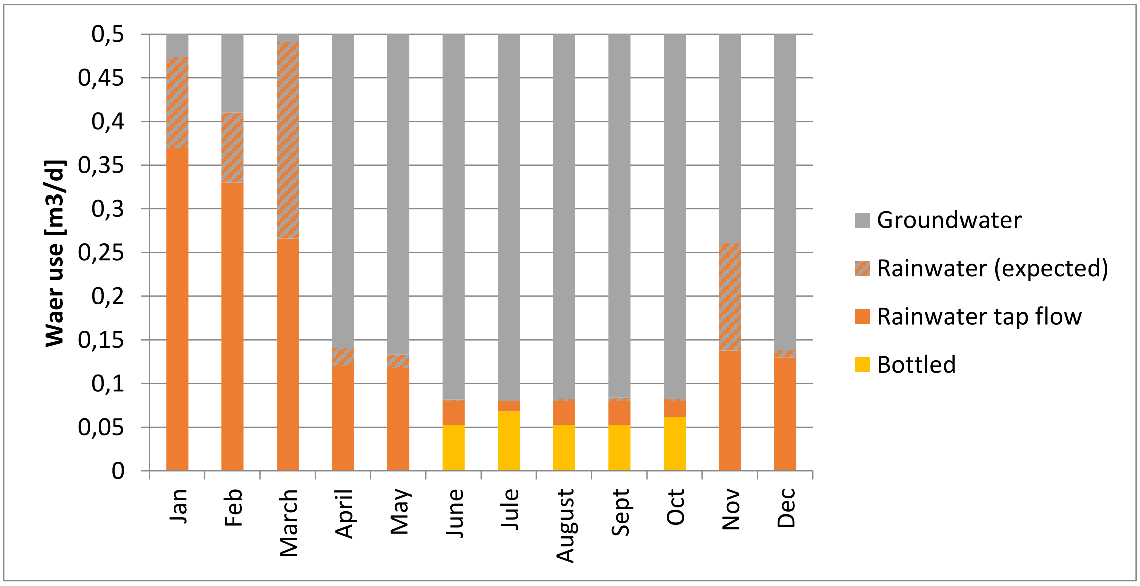


Figure 46: Water use for scenario 2c, optimized towards a maximum tap flow. Roof size = 100 m^2 and tank size is 2 m^3

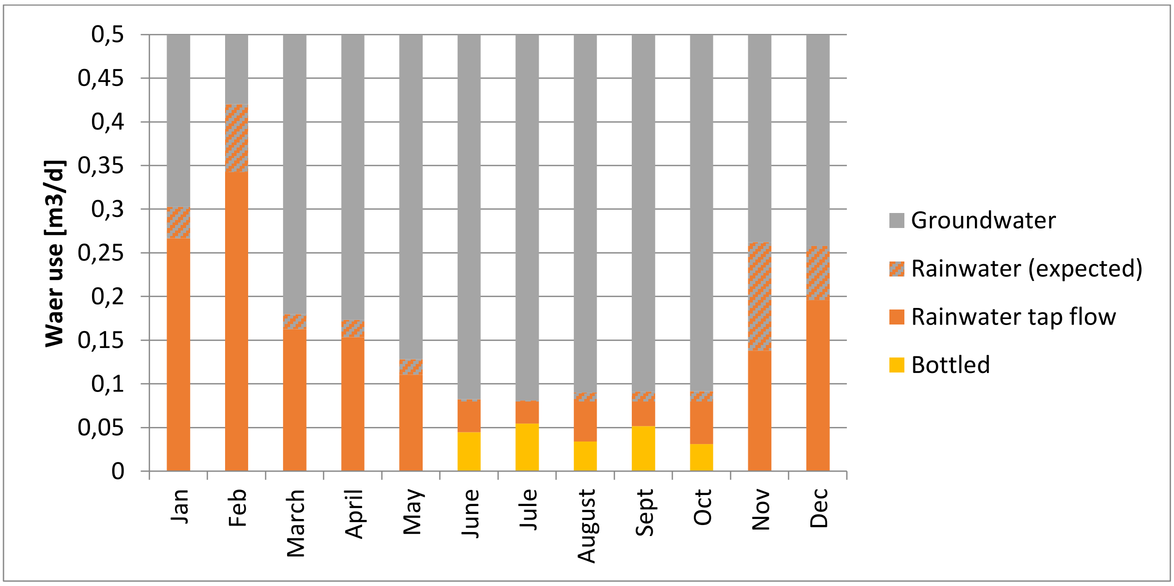


Figure 47: Water use for scenario 2c, weighted optimization. Roof size = 100 m^2 and tank size is 2 m^3.

5.4.3.4. Model results based on availability

Scenario 2d: Water use based on availability

In this scenario water use is based on the availability of water inside the tank. The water use at day "i" is determined based on the amount of water in the tank at the beginning of this day. This makes it is uncertain how much water can be extracted at a certain day. In Figure 48 the average tap flow per month is summarized for several operation rules for a tank of 2 m^3, a roof of 100 m^2 and a maximum water use of 500 liter per family per day. As can be seen more storage of water does not lead to higher average tap flows. This can be explained by the fact that storage will increase the chance of system overflow.

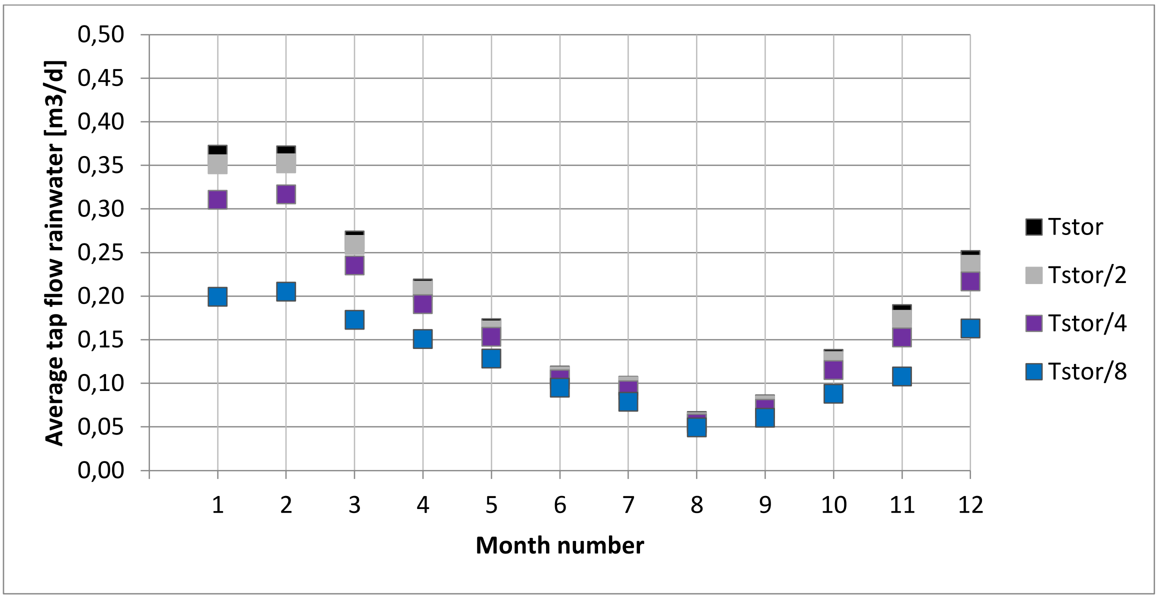


Figure 48: Average tap flow per month for different operation rules (T=2 m^3, RS=100m^2).

Although average tap flow is higher in case water is used directly, this also results in higher percentages low flow and lower averages low flow. Low flow is defined as a tap flow below the 80 liter per day. In this case the family will need to use an alternative fresh water source. This could be refilled bottled water, which is an expensive water source. In Table 32 the average tap flow and the percentage and average low flow can be found. The percentage low flow decreases from 57.9% towards 36.1% in case water just one eight of the tank is used instead of the entire tank (with a maximum of 500 liter a family a day). It can even decrease to 15.7% in case the maximum amount of daily water use is set to 80 liter/day.

Table 32: Average tap flow, percentage low flow (<0.08 m^3/d) and average low flow for different scenarios.

	Tstor	Tstor/2	Tstor/4	Tstor/8	Max(0.08)	Sc. 2b(i)	Sc. 2b(ii)	
Average tap flow	0.19	0.18	0.17	0.12	0.07	0.13	0.13	[m^3/d]
Percentage low flow	57.9	50.3	42.1	36.1	15.7	54.4	52.6	[%]
Average low flow	0.002	0.015	0.023	0.030	0.003	0.018	0.030	[m^3/d]

* rounded numbers are similar. However, differences exist.

By increasing roof or tank sizes, the average tap flow is expected to increase as well. The average tap flow for different roof and tank sizes is shown in Figure 49 for scenario 2d(Tstor/2). At high tank sizes or at high roof sizes an asymptote will be finally reached. The vertical asymptote represents the situation in which a volumetric increase harvested rain, will overflow due to limited tank size. The horizontal asymptote represents the situation in which the tank is large enough to catch all rainfall, and thereby an increase in tank size will not result in higher tap flow.

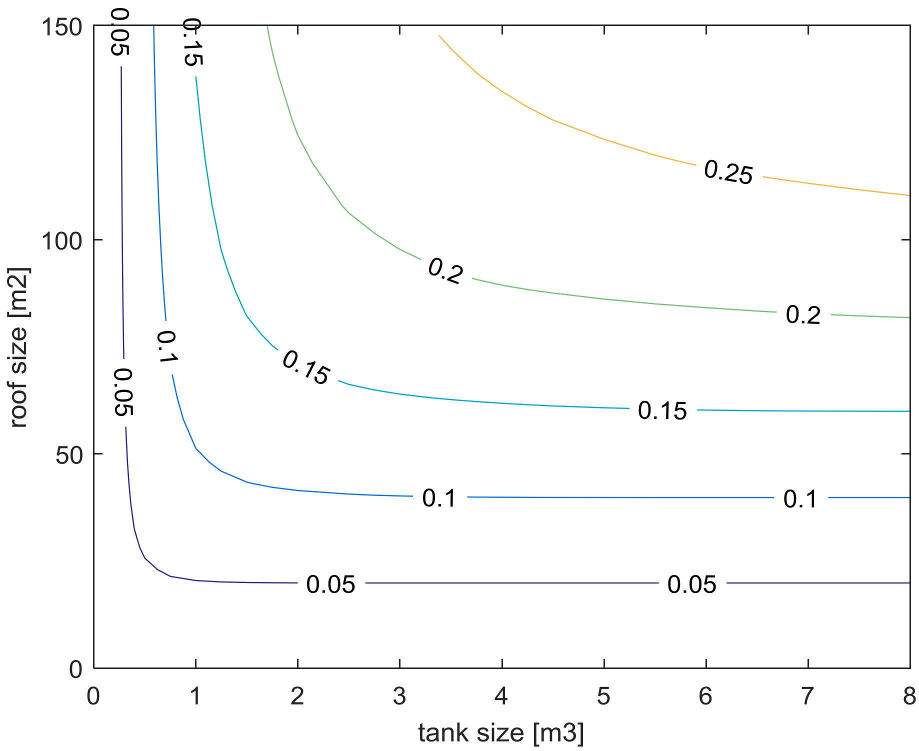


Figure 49: Average tap flow [m^3/d] for scenario 2d(Tstor/2) for different tank and roof sizes.

5.4.3.5. Sensitivity analysis

In this paragraph there will be attention for the sensitivity of the results towards the choice of Rmax, FF and SPL for scenario 2b(i) and 2b(ii). The existence of multiple optima will be discussed, in which scenario 2c(i) is taken as an example.

Sensitivity due to varying Rmax, FF and SPL

The sensitivity for different parameter values is checked for a tank size of 2 m^3 and a roof size of 100 m^2. Parameters are varied within realistic ranges as presented in Table 15 in paragraph 4.4.3.

As presented in paragraph 5.4.3.3 average tap flow for scenario 2b(i) and scenario 2b(ii) is 0.120 m^3/d and 0.116 m^3/d respectively. These points are indicated as a red dot in Figure 50 and Figure 51. The figures illustrated the sensitivity of the tap flow for the selection of model parameters.

For scenario 2b(i) the possible range of tap flow (by varying FF, Rmax and SPL) is found to be between 0.048 and 0.139 m^3/d. This implies that the expected tap flow can decrease 60% or increase 16% in case Rmax, FF and SPL are not predicted correctly.

For scenario 2b(ii) tap flow the possible range is found to be between 0.050 and 0.131 m^3/d. Which implies that the predicted tap flow could change by something between a decrease of 57% and an increase of 13%.

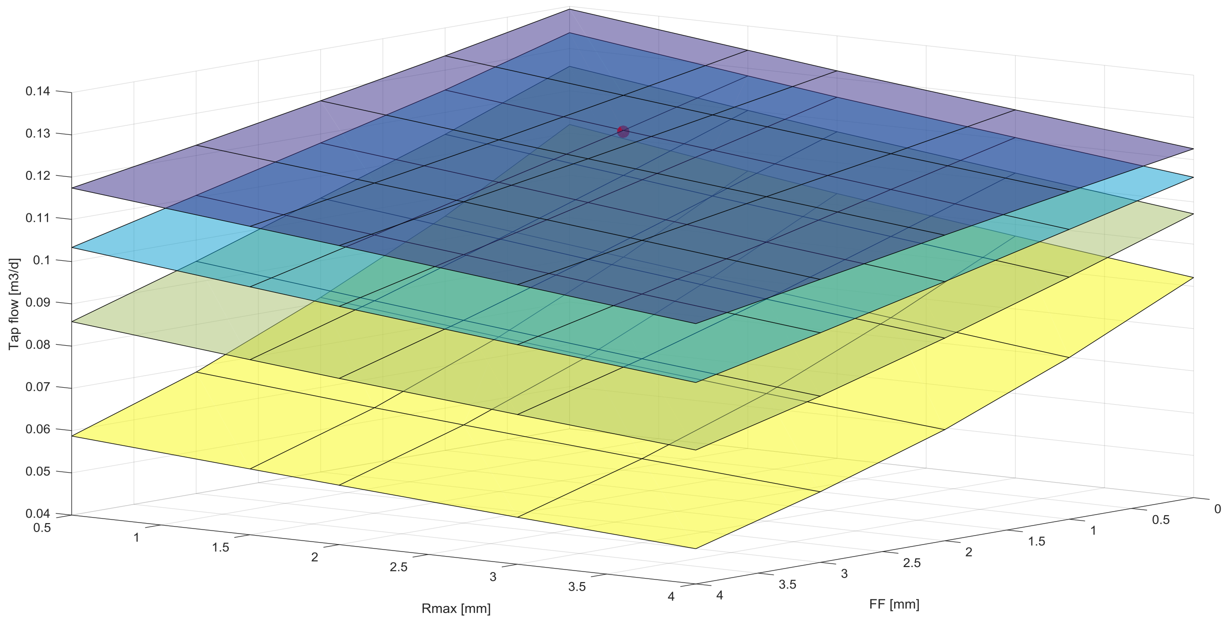


Figure 50: Sensitivity for parameter selection for the calculated maximum demand (scenario 2b(i)). Different colours represent different loss fractions (SPL) with are 0.15, 0.35, 0.50 and 0.65 for purple, blue/green, green and yellow respectively.

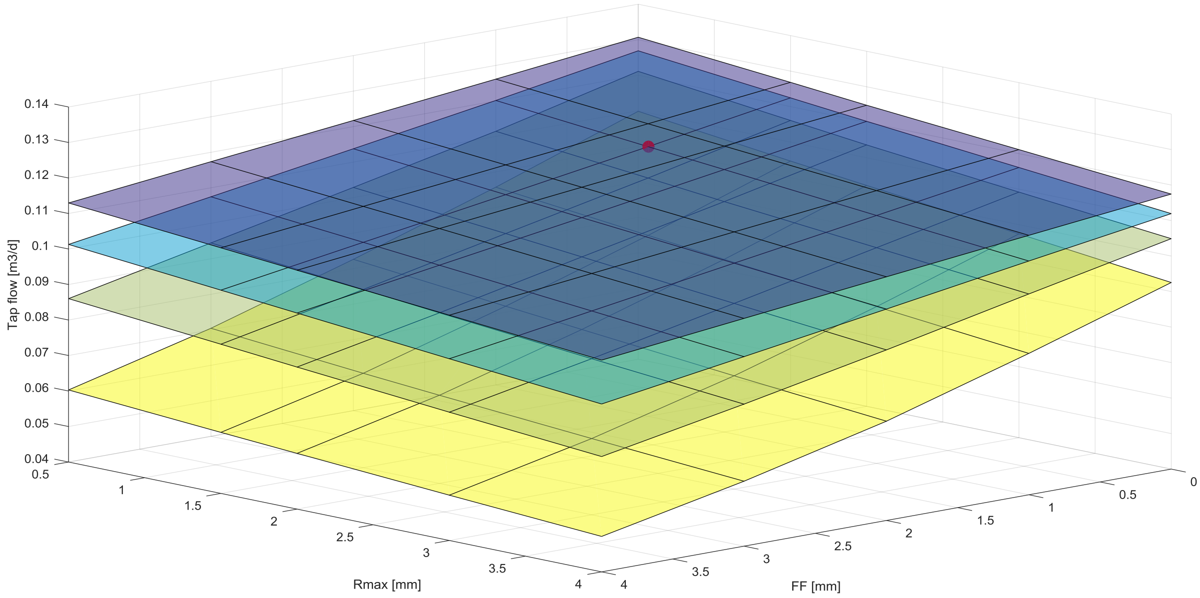


Figure 51: Sensitivity for parameter selection for the calculated weighted demand (scenario 2b(ii)). Different colours represent different loss fractions (SPL) with are 0.15, 0.35, 0.50 and 0.65 for purple, blue/green, green and yellow respectively.

Sensitivity for predicted demands/expected amount of water and tap flow
Since optimum demands/expected amounts of water and the tap flow are generated by monte carlo, one should realize that in above analysis, just one local optimum is shown, which is not necessary the global optimum. This is illustrated in Figure 52 in which three possible optimums are shown for scenario 2c(i). The runs optimize the maximum possible tap flow (right) and the corresponding expectation. Multiple combinations of expectations (or demand) can give high average tap flows. However monthly average tap flows can be very different. Important to notice is that the average tap flow does not change much within different runs (less then ±1%).

The existence of multiple optima has to do with the fact that with twelve parameters (months), a huge number of combinations are possible. Allowing three different demands for each month will already give more then 500.000 (3^{12}) possible combinations. Since the computation time of this will become too large, this research searches local optimum point in relatively limited boundaries. In Appendix C3 the selection of the optimum tap flow is visualized by plotting monthly average tap flows against yearly average tap flows.

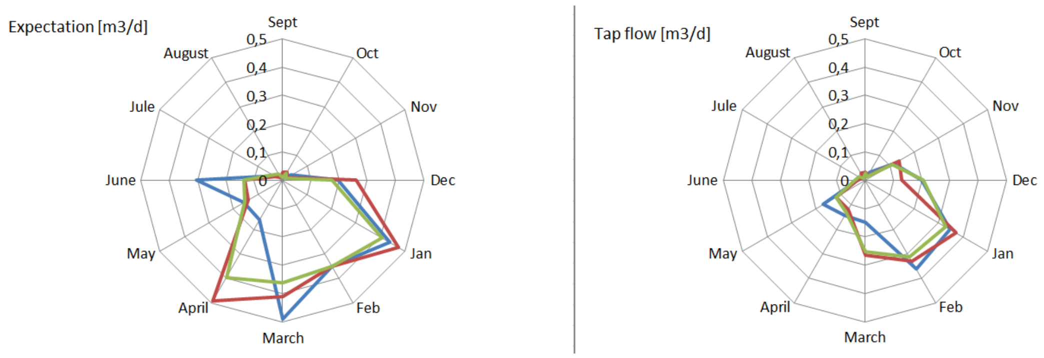


Figure 52: Multiple optimum demands (left) and tap flows per month (right) for scenario 2c(i).

5.4.4. Summary

Experts and case study experts state that a harvesting system at household scale is most suitable Indonesia, compared to systems on larger scales. This is mainly due to system maintenance. At the population level, only individual rainwater harvesting systems were found in Serang.

When looking at systems at a household scale it is found that systems of realistic sizes cannot supply a sufficient amount of water to cover the entire water demand. Depending on the tank and roof size and the (operating) scenario a certain tap flow can be reached. In this research several operating scenarios were considered. A distinction is made between scenarios based on a certain expectation (or demand) and scenarios based on availability. Furthermore, a differentiation is made between scenarios in which water is used in the wet season or during the entire year.

Highest tap flows can be reached in case the maximum amount of water is extracted from the tank directly. So in the case one wants to harvest as much water as possible, saving does not help. This can be explained by the fact that saving of water, increases the chance that the tank will overflow. Fixing the demand or expectation (so decreasing the adaptation capacity of the population) leads to lower average tap flows, due to increasing overflows.

For the no saving scenario an average tap flow of 187 liter/day can be expected (T=2 m^3; RS=100 m^2). In the dry season the tap flow is 90 liter a day on average, where in the wet season it is 250 liter a day. A lower average tap flow of 125 liter a day is found in case maximum 12.5% of the tank volume is used, thereby losing more water but also saving more water for later. This last can be seen in the percentage low flow (<80 liter/day), which is found to be 58% and 36% for the no saving and the maximum 12.5% of the tank scenario respectively.

Finally one should note that for systems with large roofs and small tanks, a further increase in roof size will not lead to a significant increase in tap flow due to the fact that all additional water harvested will overflow. Similarly the harvest of systems with small roofs and large tanks does not increase in case tank sizes are further increased, since the previous tank volume already was capable of storing all harvested water.

5.5. Economic aspects

In this paragraph the view of experts and case study experts is discussed. These were asked regarding the installation costs of rainwater harvesting systems and regarding the stakeholders that should invest in these systems. Second the cost perception of the population is discussed. Finally there will be attention for the total costs for rainwater harvesting systems, the costs per cubic meter and the expected payback period.

5.5.1. Expert and case study expert view

Costs for local available tanks

The largest investment for a rainwater harvesting system is generally the water storage tank. Experts suggest tanks from plastic, cement, ferrocement or steel. Below an indication is given regarding the costs and suitability for different types of tanks.

In general plastic tanks are easily available, since they are already frequently used for the storage of groundwater (Soekarno, 2016; Lubis, 2016; Imroatul, 2016; Zevi, 2016). A 600 or 1000 liter plastic tank can be bought for €28,- and €55,- respectively (Zevi, 2016; Soekarno, 2016; Lamhot Sinurat, 2016). Including installation the 1000 liter tank will cost around €83,-, which can be afforded by the middle class (Zevi, 2016). To limit algae growth the tank can be painted in a dark colour or a steel tank can be used (Listyasari, 2016; Lamhot Sinurat, 2016). Costs for a 600 litre steel tank are around €245,-.

Alternatively to plastic or steel a cement tank can be used. Raw materials are easy available and tanks can provide good quality water (Listyasari, 2016; Lubis, 2016, Soekarno, 2016). Disadvantage of cement tanks could be the fact that ready to use tanks are rarely sold (Soekarno, 2016). Furthermore, the required materials and tanks itself are heavy, which makes it more difficult to transport (Zevi, 2016). However in some remote islands the use of cement may be easier due to the fact that they can locally be produced (Kamarga, 2016). In other cases brick may be easy available (Cronin, 2016). Underground rainwater harvesting tanks can be very interesting, especially for new developments (Jantowski, 2016; Soekarno, 2016). A disadvantage of an underground system are the energy costs which are required for the pumping.

Stakeholders that should invest in rainwater harvesting systems

For the installation, operation and maintenance of a rainwater harvesting system investments have to be made both in time and in money. Investments could be done by the population itself, by governmental bodies or by non-governmental organizations. The opinion regarding the parties that should do these investments is scattered between different stakeholders.

Whatever the population will invests in the water supply depends on the willingness to pay and the affordability of the system (Listyasari, 2016). In general the willingness of the population will be larger in case they understand the benefit of the system and in case no other water sources are available. The affordability can be approximated as percentage of the income that can be spend on water and sanitation. In general it will be easier to invest money in urban areas, where in rural areas it will be easier to invest time. When the rainwater harvesting system is installed out of an external initiative it is important that the community is involved in the project, the process is clear and that the administrative and religious head of the community is involved (Cronin, 2016).

Experts give no unambiguous opinion regarding the parties that should make the initial investments for rainwater harvesting systems. Cronin (2016) and Listyasari (2016) suggest that initial financial investments are shared between the population and the local government. For Unicef projects the population has to pay a minimum amount of 50 dollars and in general the population pays ten percent of the total costs (Cronin, 2016). When the population is not able to pay, microfinance can be done (Cronin, 2016). Kamarga (2016) suggests that initial investments are totally paid by the government, especially in case the population is poor. On the other hand Imroatul (2016), Soekarno (2016) and Lubis (2016) suggest that initial financial investments are done by the population. However the ability to pay has to be checked (Imroatul, 2016; Lubis, 2016). In some cases the government can provide some support (Soekarno, 2016; Lubis, 2016).
Experts agree that initial investments in time should mainly be done by the local population (Kamarga, 2016; Soekarno, 2016). Professionals should however assist the installation to make sure the installation is done in a correct way (Kamarga, 2016).

Operation and maintenance costs should be taken by the local population (Kamarga, 2016; Lubis, 2016; Listyasari, 2016). Time should be invested by the local population as well (Kamarga, 2016; Lubis, 2016; Imroatul, 2016; Soekarno, 2016). In most cases the population can easily repair the system themselves (Soekarno, 2016). However assistance of the sanitarian can make sure that the quality of the repair is sufficient (Kamarga, 2016). Some people will not invest time in the repair of the system and in this case a professional repairer can be hired (Imroatul, 2016).

Case study experts are unclear regarding the stakeholders that should invest in rainwater harvesting systems. Currently the kabupaten is investing around 20-30 million Rup/year (±1800 euro/year) for drinking water and sanitation (Lamhot Sinurat, 2016). However when the national goal of 100% universal access to clean drinking water and sanitation and no slump area in 2019 has to be met, much more investments will be needed (Lamhot Sinurat,2016). These investments could possibly come from local, provincial and national governments (Lamhot Sinurat,2016).

Important to realize is that currently the water supply in kabupaten Serang is often for free, for example from local springs or wells which is installed a long time ago (Saputra, 2016). This implies that for a certain part of the population investments in the water supply will be difficult. Some other available water sources are not for free, like bottled water or water from the PDAM.

5.5.2. Local population view

In general the population views rainwater as a low cost water supply method as shown in Table 19 in paragraph 5.1.3.3. In Tirtayasa rainwater is seen as the most cheap water source. Surface water and groundwater are seen as more expensive water sources. This is most likely related to the fact that rainwater can be already harvested with the available infrastructures. Irrigation channels (surface water) are limitedly used in Tirtayasa, due to heavy pollution and the distance towards the source.

In Baros and Pabuaran rainwater is viewed as least expensive water source, together with spring and surface water. This comes together with the fact that local materials are used to build the rainwater system. The collection of rainwater can be done with similar buckets as the collection of rainwater, and in this sense rainwater has a similar price.

5.5.3. Model results

5.5.3.1. Total costs of a rainwater harvesting system

The total costs of a rainwater harvesting system exist of investment, operational and maintenance costs. In Appendix D1 the material requirements and material prices for ferrocement tanks can be found. In Table 33 the installation costs of a ferrocement and a plastic tank of 2 m^3 are summarized. Total installation costs are around 455 and 550 euro for a ferrocement and plastic tank respectively. These costs are between 23 and 28% of the minimum annual income. Real costs for the population will be lower since they disregard costs for soil excavation and labor. Moreover, gutter installation is not required in case already present.

Table 33: Total installation costs [euro] for a ferrocement tank and a plastic tank of 2 m^3 on a roof of 100 m^2.

Costs [Euro]	Ferrocement	Plastic
Tank	215.04	331.03
Tank transport	-	6.90
Pipes	34.48	34.48
Elbow	2.69	2.69
Gutter filter	2.07	2.07
Tap	3.45	3.45
Gutter	154.48	154.48
Soil excavation	5.41	5.41
Labour	39.08	11.49
Total	456.71	552.01

The expected lifetime of a plastic tank is around fifteen years, where ferrocement tanks can last around twenty-five years. Maintenance is assumed to be annually four and two percent of the investment costs for the ferrocement and plastic tank respectively. The tanks have no operation costs. Taking this into account one can find annual costs of around 30 and 45 euro for the ferrocement and the plastic tank respectively. Costs for other sizes of tanks can be found in Appendix D2.

Table 34: Total lifetime costs and yearly costs for a ferrocement and plastic tank

Costs [Euro]	Ferrocement	Plastic
Investment [euro]	456.71	552.01
NPV Maintenance [euro]	233.53	107.23
Total lifetime costs [euro]	690.24	659.24
Lifetime [year]	25	15
Annual costs [euro/year]	27.61	43.95

5.5.3.2. Water costs per m^3 of rainwater

The costs per cubic meter of water of the rainwater harvesting system depends on the tank and roof size and the amount of water extracted from the system. Larger tank sizes go together with higher investment costs, but also higher water withdrawals. Higher withdrawals lead to lower costs per cubic meter.

Table 35 shows the total costs per cubic meter, for the different scenarios in case a tank size of 2 m^3 is used. The scenarios with the highest tap flow have the lowest water cost. Depending on the operation of the system the cost ranges between €0.40/m^3 and €1.11/m^3 for ferrocement tanks and between €0.63/m^3 and €1.77/m^3 for plastic tanks.

Table 35: Costs [euro/m^3] over the entire lifetime of the rainwater harvesting system for (T=2 m^3, RS=100 m^2).

	Scenario 2c(i)	Scenario 2c(ii)	Scenario 2d(Tmax)	Scenario 2d(Tmax/2)	Scenario 2d(Tmax/4)	Scenario 2d(Tmax/8)	Scenario 2d (D=0.08)
Costs ferrocement system [euro/m3]	0.58	0.60	0.40	0.42	0.44	0.63	1.11
Costs plastic system [euro/m3]	0.93	0.95	0.63	0.67	0.71	1.00	1.77

The water cost for scenario 2d (Tmax and Tmax/2) is investigated for ferrocement tanks of different tank and roof sizes. In Figure 53 the results can be found for scenario 2d(Tmax/2). The lowest water cost can be found for larger connected areas, in case available. For roofs of 50 m^2 or larger the lowest costs can be achieved for rainwater harvesting tanks of 2 m^3. In case a roof of 25 m^2 is used the lowest water costs are found for a tank of 1 m^3.

It is found that the water costs are lower in scenario 2d(Tmax) compared to scenario 2d(Tmax/2) due to a higher average tap flow. For this scenario tanks of 1 m^3 lead to lowest water costs for roofs of both 25 and 50 m^2. For larger roof sizes a tank of 2 m^3 is the least expensive option.

The water costs for plastic tanks can be found in Appendix D3 (scenario 2d(Tmax/2). Cost per cubic meter of harvested water, are higher for plastic tanks then for ferrocement tanks for any size. A tank of 1 m^3 is found to result in the lowest water costs for all roof sizes. This is different for the ferrocement tanks as discussed above. This can be explained by the fact that a ferrocement tank of 2 m^3 is on average 14% more expansive as a tank of 1 m^3. For a plastic tank this is 43%.

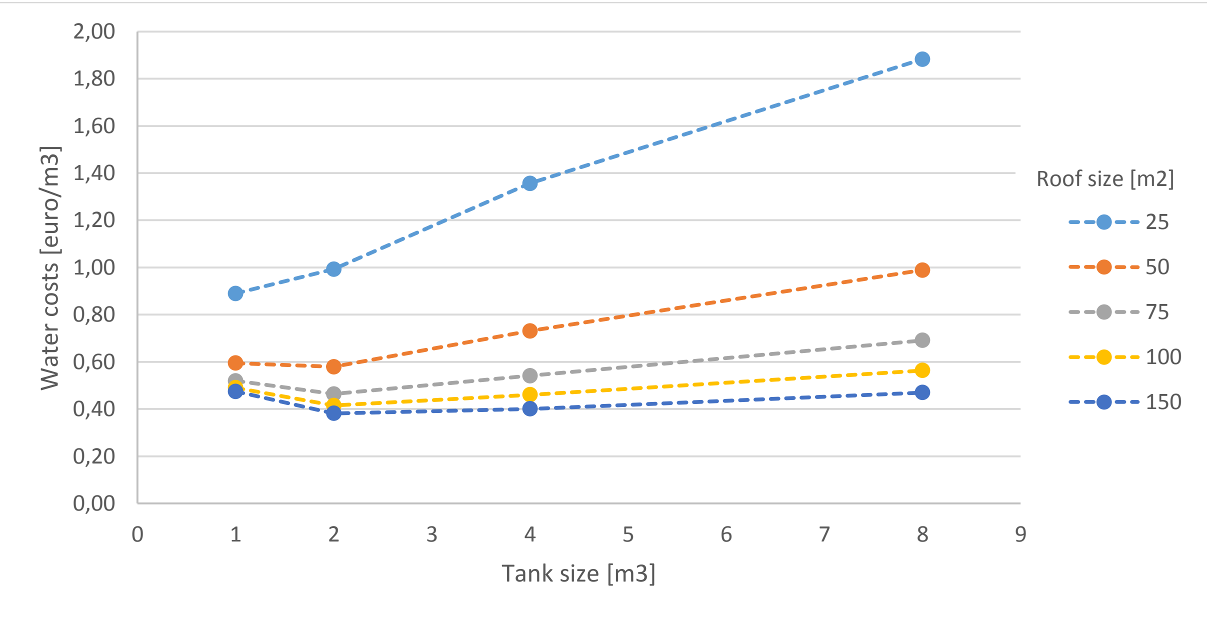


Figure 53: Water costs for scenario 2d (Tmax/2) for different tank sizes and roof sizes for ferrocement tanks.

5.5.3.3. Comparing costs per m^3, PDAM and rainwater harvesting systems

As discussed in the previous paragraph, a ferrocement rainwater harvesting system of 2 m^3 with a normal size roof (50 m^2 or higher) in a financial attractive option. In this section the costs for rainwater will be compared with the costs at a drinking water company (PDAM) and the costs of bottled water.

In the research area there is currently no PDAM. However in this section, the cost difference between a PDAM connection and a rainwater harvesting system will be investigated. To install a PDAM connection, the client pays €107.72 (once). Monthly a client pays €0.41 administration costs and a water tariff of €0.29/m^3. Bottled water is available in the area for a price of €0.28 per 19 liter. In Figure 54 the water costs for bottled, PDAM and rainwater (2 m^3 tank and 100 m^2 roof) are shown.

Maximum average tap flow for a rainwater harvesting system of 2 m^3 is 0.19 m^3/day for scenario 2d (Tmax). The cost of the rainwater harvesting system is comparable as the cost for the PDAM in case the water use is higher than approximately 0.1 m^3/d. Bottled water is found much more expensive than rainwater. However in this calculation one should realize that bottled water will never be bought for all purposes, and has a certain maximum use. Furthermore, the capacity of the PDAM is limited. With the current capacity maximum supply would be around 0.07 m^3 per day for one family.

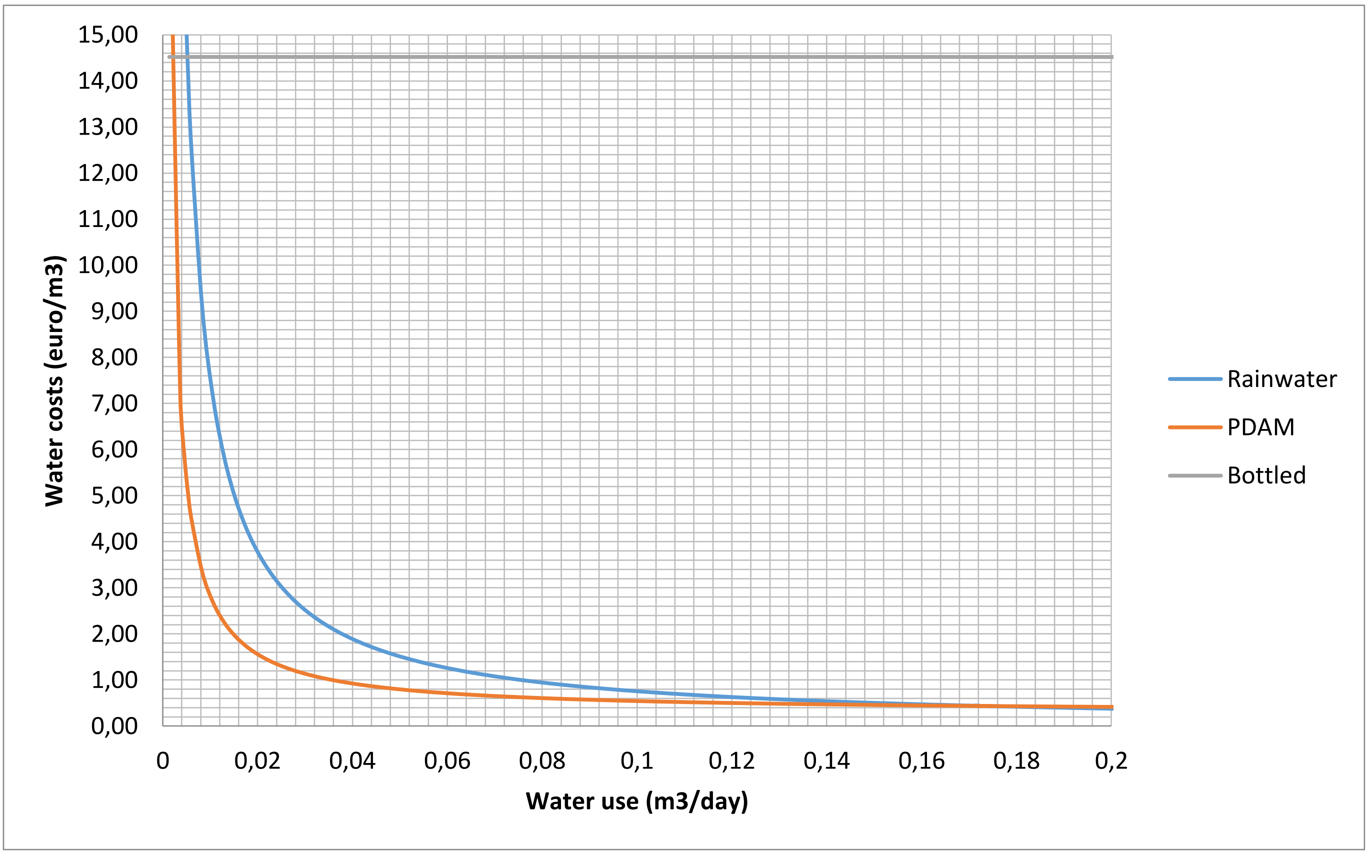


Figure 54: Water costs (euro/m^3) for different amounts of water use.

5.5.3.4. Most economic water use pattern

As shown in paragraph 5.4. most water can be obtained from a rainwater harvesting system by using water from the system directly, before it can overflow, as modeled by scenario 2d(Tstor). However even in this case the rainwater harvesting system cannot provide sufficient volume to be used as only water source. In this section it will be investigated which water use pattern is most economical. In Table 36 the water use per source for different scenarios is summarized. To evaluate water use patterns only operational costs are taken into account. It is assumed that initial costs are already made for both the rainwater harvesting system (2 m^3, 100 m^2), the groundwater well and the gallon for the bottled water.

Table 36: Average annual amount of water use per family per source for different scenarios (T=2 m^3, RS=100 m^2).

	No rainwater	Scenario 2c(i)	Scenario 2c(ii)	Scenario 2d(Tmax)	Scenario 2d(Tmax/2)	Scenario 2d(Tmax/4)	Scenario 2d(Tmax/8)	Scenario 2d (D=0.08)
Bottled [m^3/year]	29.2	13.0	8.6	16.5	11.9	8.7	6.6	4.4
Groundwater [m^3/year]	153.4	121.0	126.5	98.1	104.2	113.0	130.6	153.4
Rainwater [m^3/year]	0.0	48.7	47.6	68.0	66.5	60.9	45.4	24.81

In Table 37 the annual operation costs for the different scenarios is presented. Scenario 2d(Tmax/8) is found to be the most economical scenario in case all systems are already installed and only operational costs are taken into account. Because the price of bottled water is high, the most economical scenario is the scenario that provides the least amount of water on average, but replaces the highest amount of the expensive bottled water. However one can argue about the non-monetary value of the availability of additional fresh rainwater.

Table 37: Operation costs for different scenarios.

	No rainwater	Scenario 2c(i)	Scenario 2c(ii)	Scenario 2d(Tmax)	Scenario 2d(Tmax/2)	Scenario 2d(Tmax/4)	Scenario 2d(Tmax/8)	Scenario 2d (D=0.08)
Bottled [euro/year]	424.25	188.15	124.46	239.23	172.54	126.28	96.19	64.08
Groundwater [euro/year]	5.45	4.30	4.49	3.49	3.70	4.01	4.64	5.45
Rainwater [euro/year]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total [euro/year]	429.70	192.45	128.95	242.72	176.24	130.29	100.83	69.53

5.5.3.5. Payback period of rainwater harvesting system

A rainwater harvesting system cannot fully replace the existing water sources which include the use of bottled and groundwater. Both groundwater wells and bottled water have to be continued in use, since rainwater can only provide a part of the total water need. Calculations of the payback period assume that the maintenance costs and the lifetime of the groundwater well is independent of the amount of use in a year. Furthermore, the total water need of 500 liter per family per day is used and the fresh water need of 80 or 20 liter a family a day. Results can be found in Table 38.

One should note that although the cost per m^3 was the lowest for the scenarios with the highest tap flow, the payback period is shorter for the scenarios in which you save more water. In these scenarios less expensive gallons have to be bought. Next to this one should note that the payback period for plastic tanks is longer for all scenarios although the lifetime of these tanks is shorter.

Table 38: Payback period [year] for ferrocement and plastic tanks of 2 m^3 for different water use scenarios.

	Scenario 2c(i)	Scenario 2c(ii)	Scenario 2d(Tmax)	Scenario 2d(Tmax/2)	Scenario 2d(Tmax/4)	Scenario 2d(Tmax/8)	Scenario 2d (D=0.08)
Payback period ferrocement	2.1	1.6	2.7	1.9	1.6	1.5	1.3
Payback period plastic	2.4	1.9	3.1	2.3	1.9	1.7	1.6

The found payback period is sensitive for the operating scenario (the water use pattern). This operating scenario influences the amount and percentage of low flow. However the payback period is also dependent on the assumption regarding the amount of bottled water that is currently bought. Although 80 liter of fresh water per family per day is the recommended minimal amount of fresh water, it may be unrealistic that the population buys approximately four refilled gallons daily. Because of this the payback period is also calculated by assuming that 20 liter of bottled water is bought on a daily basis. Results are presented in Table 39. The payback period is found to increase largely (towards between 5.9 and 14.6 years). Next to this, for some cases payback periods for the plastic system are shorter. This is explained by the fact that yearly savings are larger for plastic tanks then for ferrocement tanks due to lower maintenance costs.

Table 39: Payback period [year] for ferrocement and plastic tanks of 2 m^3 for different water use scenarios.

	Scenario 2c(i)	Scenario 2c(ii)	Scenario 2d(Tmax)	Scenario 2d(Tmax/2)	Scenario 2d(Tmax/4)	Scenario 2d(Tmax/8)	Scenario 2d (D=0.08)
Payback period ferrocement	6.3	6.3	14.6	7.8	6.4	5.9	6.3
Payback period plastic	6.9	6.9	14.4	8.4	7.1	6.6	6.9

5.5.4. Summary

The local population currently views rainwater harvesting as cheap water source which can be easily harvested in available buckets or locally made infrastructure. However experts and case study experts think of more advanced rainwater harvesting systems which come with higher costs. According experts operation and maintenance costs should be carried by the population itself, but for initial investment some support by government or microcredit may be required. Total installation costs for a rainwater harvesting system of 2 m^3 were found to be around 460 and 550 euro for a ferrocement and plastic tank respectively. This is higher than the costs indicated by experts and case study experts and is between 23 and 28% of the minimum annual income. Total annual costs for a rainwater harvesting system are around 28 and 44 euro for a ferrocement and plastic tank respectively. This would be between 1.4 and 2.2% of the minimum annual income. However these costs will not be the only costs needed for the water supply, since rainwater has to be combined with other sources. Rainwater costs per m^3 (€0.40 to €1.11) are found to be similar to current prices of PDAM water. Although the water costs are lowest for the situation in which a maximum volume is harvested payback times are found to be lowest, in case more water is saved. In this last case more of the expansive bottled water can be replaced. Expected payback periods are around two years, in case the assumption is made that a family currently buys 80 liter of bottled water (gallons) each day. In case it is assumed that the population currently buys 20 liters of gallons each day, payback periods are around 8 years.

5.6. Institutional and legal aspects

Important stakeholders in the implementation of rainwater harvesting are present at national, province, district, sub-district and village level. They include governmental and non-governmental organizations and knowledge institutes. As presented in paragraph 3.6 almost all departments or ministries have some responsibility relevant to the water sector. In Figure 55 the most important stakeholders identified are shown.

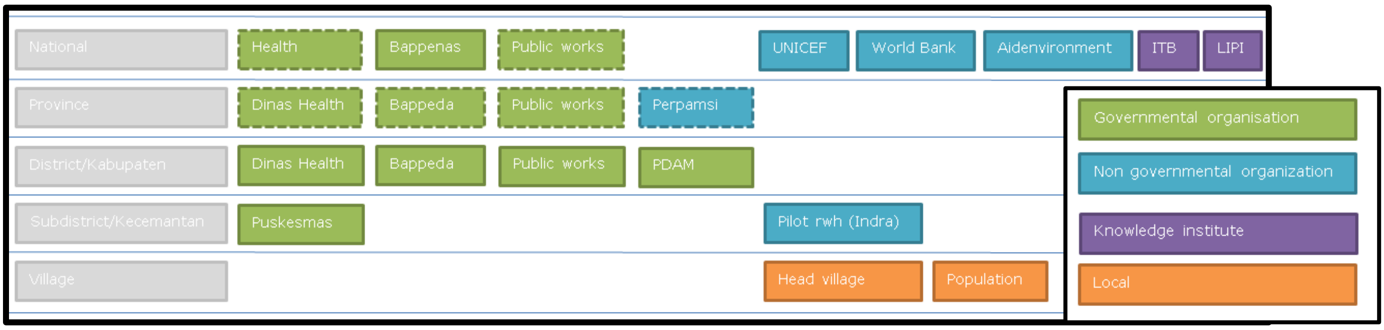


Figure 55: Overview of the important stakeholders, that are related to the implementation of rainwater harvesting at different levels.

5.6.1. Governmental support and legislation

There is no national limiting legislation in Indonesia that hinders the wide-spread use of rainwater harvesting technologies in Indonesia (Eitemiller, 2016). Local governments may have their own regulation regarding rainwater harvesting (Lubis, 2016). In general there is quite some interest in rainwater harvesting at governmental level (Eitemiller, 2016).
At the national government there is support for rainwater harvesting at the Bappenas (Lubis, 2016). Guidelines for the implementation of rainwater harvesting exist. In these guidelines there is attention for the planning, general requirements, technical conditions, the construction and the operation and maintenance of the rainwater harvesting tanks. The Bappenas is working on a program, which should increase the awareness with respect to rainwater harvesting, enhance the community capacity in utilizing and managing sustainable rainwater harvesting systems and increase the availability of the technology by using affordable methods according the local needs. Moreover, it should enable the environment to ensure the sustainability of the systems. The program will be active between 2015-2019. However recently the program seems not very active, although the reason for this remains unclear (Cronin, 2016). At a district level (kabupaten) the knowledge and implementation of rainwater harvesting varies largely. It is hard to reach the kabupaten (districts) from a national level, although this is necessary since the kabupaten takes most decisions in the area were they are working (Cronin, 2016). At the kabupaten Tangerang a rainwater infiltration pilot is installed and biopori systems are promoted. Biopori systems increase infiltration and produce compost. On the other hand, at the kabupaten Serang the attention to rainwater infiltration or usage seemed to be more limited, since no ongoing projects were discussed. The PDAM (water supply and distribution company) in Serang views rainwater harvesting as a possible solution for the water supply, although currently they are not seriously considering this option.

Promoting of hygienic behaviour and education regarding water related habits takes place by the puskesmas. The sanitarian is responsible for water and sanitation in the kecamatan (sub-district) in which the puskesmas is located. It is found that the head and sanitarian of puskesmas Baros, Pabuaran and Tirtayasa have limited knowledge regarding the quality and suitable rainwater harvesting system, although the population is practising rainwater harvesting in these areas.

5.6.2. Scientific research

At the ITB Bandung research regarding rainwater infiltration and rainwater for domestic purposes is ongoing. The Indonesian research institute of science works on rainwater infiltration in deep aquifers and also supports these systems, for example at the kabupaten Tangerang. Research regarding rainwater harvesting in other universities is, to the best knowledge of the writer, limited.

5.6.3. Non-governmental organisations

UNICEF has been working on rainwater harvesting projects in the past, but currently the focus is shifted. World Bank has a huge portfolio regarding water supply projects in rural areas (PAMSIMAS). However in this program groundwater or surface water is used as raw water source. Focus is on a water supply system on community scale with a piped network. Aidenvironment has done a variety of domestic rainwater harvesting projects in Timor and Flores but current focus is on palm oil. Glen Eitemiller has implemented several rainwater harvesting systems at remote islands in Indonesia, but also this program has come to an end. More information regarding the rainwater harvesting programs that are executed by non-governmental organizations can be found in paragraph 5.1.2.

5.6.4. Summary

Important stakeholders identified for the implementation of rainwater harvesting include governmental and non-governmental organizations, knowledge institutes, the head of the village and the local population. In field guidelines are developed by the national government, non-governmental organizations have practical knowledge regarding implementation of rainwater harvesting at larger scale, knowledge institutes have ongoing research regarding rainwater harvesting and local governmental organizations have practical knowledge regarding local best practise techniques.

It is found that knowledge exchange between any of these stakeholders is very limited and has to be improved, to make sure that at a local level sufficient knowledge exists to give advice regarding rainwater harvesting.

6. Discussion

This study identified the possibilities for rainwater harvesting in Serang (Tirtayasa) by looking at technical, social, economic and legal aspects. In this discussion there will be attention for the following aspects:

1. The main findings, with attention for the difference between the results of the population, general experts, case study experts and literature.
2. The simplifications and assumptions made and uncertainties present in this research.
3. The possible improvements that could be made to the methodology in further research.
4. The extent to which the used method and the results can be generalized to other locations.

The discussion is framed along eight specific topics which were addressed in this research. These topics coincide with the research questions. Additionally there is attention to the methodology applied in this research, which is inspired by the methodology of Studer.

6.1) What are the main experiences with the methodology applied in this research?

6.1.1) Main findings

It is found very useful to consider social, economic, quantity, quality and legal aspects of rainwater harvesting together, since many aspects interfere and influence each other. As example one can look at the decision for tank size. Larger tanks provide more water, and is thereby positive for the quantity. However this goes together with higher costs, and longer retention times. Socially specific tank sizes may not be accepted by the population, since it requires too much of the available space. In some situations these (large) tanks could also provide a legal problem. By not considering one of these aspects, a proposed design could totally fail.

6.1.2) Simplifications, assumptions and uncertainty

The boundary conditions of this research, limits this report to domestic rainwater harvesting. However it is of main relevance to also consider other types of rainwater harvesting, or combinations of those, which can provide interesting opportunities. The same counts for possibilities, other than rainwater harvesting, to increase the availability of quality of the water sources. Although these were outside the boundary conditions of this research, these are of main importance in the improvement of current water supply systems.

6.1.3) Improvements in the methodology

The adjusted framework of Studer (2012), can be improved by having more attention toward operation and maintenance and system sustainability. These aspects are of main relevance for rainwater harvesting systems, and both determine system performance in long term. Furthermore, the different aspects considered in this research could be further integrated. This could for example be done by developing a tool that supports decision making regarding the design of rainwater harvesting systems, from multiple perspectives.

6.1.4) Generalization to other locations

The proposed framework applied in this research can be used in any location. It can provide valuable insights, whatever rainwater harvesting is suitable at a specific area. One should note that the boundary conditions applied in this research are not suitable for decision, since main attention is towards (domestic rooftop) rainwater harvesting. In decision making all possible techniques to improve the water supply should be considered.

6.2) What are dominating social and cultural preferences regarding water supply, use and the acceptance of rainwater harvesting in particular that need to be considered in the development of a rainwater harvesting system?

6.2.1) Main findings

Important factors to consider in the development of a rainwater harvesting system include the acceptance and support of the population. It is found that rainwater is not always accepted as water source. For successful implementation the population should both be unsatisfied with the current water supply and aware and knowledgeable regarding rainwater harvesting, according experts and case study experts. Case study experts state that rainwater in Serang is only used as last option, in case no other sources are available. At the population level the opinion regarding rainwater is more positive in Tirtayasa, which is as indicated by the (case study) since in this area the population is more unsatisfied with the current water supply.

Dominating social and cultural preferences that should be taken into account in the design of a water supply system in general include the clean water that is required for praying and the plenty of water that is used at the toilet. Furthermore it is found that some social and cultural preferences are less important than expected. An important example is the fact that the use of multiple different water sources is very common, and not seen as a main limitation.

6.2.2.) Simplifications, assumptions and uncertainty

Although several stakeholders are interviewed at various levels, the (case study) experts interviewed are not selected randomly, but all work in the field of water supply and are often connected with rainwater harvesting. Moreover, they were interested to join the interview, and available within a limited time span. Also the population was not selected randomly, but chosen by the sanitarian of the puskesmas. The largest part of the interviewed population had a rainwater harvesting system, which also influences their opinion regarding the use of rainwater.

This issue regarding the random selection of respondents does not solely apply for this research question, but for all components of the research in which interviews were taken.

6.2.3.) Improvements in the methodology

For further research it is advised to select respondents randomly, to make further generalization of the results possible. All stakeholders should be included, which was not possible in this research due to limited time, and difficult relations with some stakeholders. Translation for the interviews with the population and some case study experts was performed by a bachelor student, and literate translation was not possible because of the language barrier. By using more professional translation more information could be obtained during the interviews.

6.2.4) Generalization to other locations

The methodology of interviewing stakeholders at all levels is certainly advised for research in other areas. It provides useful information about the view, acceptation and cultural preferences regarding a new technology and provides very valuable knowledge gained in field. For the population itself the cards used for the interview should obviously be adapted to local available water sources. In case there is no language barrier, semi-structured interviews with the population can possibly give more additional information, and in this case it can be interesting to ask similar questions to all interviewed stakeholders. The results found in this research cannot be generalized, since social and cultural aspects are very location dependent. However interviews with stakeholders on a national level, give an impression regarding the national wide opinion of rainwater harvesting. Based on these interviews, similar findings regarding social and cultural preferences are expected in other semi-urban off-grid locations in Indonesia.

6.3) What is the required outgoing water quality for the rainwater harvesting system?

6.3.1) Main findings

Taking the situation in the case study area into account, in which other water sources are not (always) complying with the WHO and Indonesian drinking water standards and in which the population is exposed to a relatively large variety of health risks (from water, sanitation and domestic waste, food, etc.) it can be stated that only the water used for potable use has to comply with the drinking water standard. For other purposes it can be less strict, especially with respect to microbial contamination. These other purposes include all types of non-potable use like personal washing, the washing of clothes and irrigation. An exception has to be made for small children (<1 year), elderly, sick, weak and injured people, for who drinking water quality is required for all purposes. The growth of mosquitos and algae in the systems has to be prevented.

6.3.2) Simplifications, assumptions and uncertainty

One should realize that this question is not solely answered technical, but related to personal judgements from experts and case study experts. These judgements are largely based on the current health situation and the quality of current water sources. However this information contains uncertainty, since monitoring and registration at the local institutions still can be improved. Moreover, the quality of household water sources largely fluctuates in space and in time, making it even more difficult to trust the limited point measurements from alternative water sources that are collected in this research.

6.3.3) Improvements in the methodology

The required water quality is determined by interviewing experts and case study experts, by considering local treatment practices and by taking the quality of other sources into account. This method can be generalized to other situations. It can even be improved by evaluating all main health risks in the society, by taking measurements of all used sources, and by evaluating the effectiveness of the applied treatment (boiling) in the field. A main limitation will remain that it is time and money intensive to monitor individual water systems, and thereby almost impossible to ensure the water quality of these systems.

6.3.4) Generalization to other locations

This advice is not generalizable to other countries and even not in time. In case the health situation or the general water quality in the case study area improves, it will become more realistic and advised to use water that complies with the standard for both potable and non-potable purposes. The same counts for the situation in which sufficient money and time is available to further improve the water quality.

6.4) What is are possible treatment options that meet the requirements regarding water quality, economic, legal and social and cultural aspects?

6.4.1) Main findings

The required treatment is largely dependent on the required quality, which in turn is dependent on the purpose for which the water is used. Water could be extracted at different points in the water treatment chain, dependent on the purposes and the required quality (paragraph 6.3).

For high end potable purposes, several treatment options exist that could be suitable to remove the (mainly) microbial contamination in harvested rainwater. Since the indicator bacteria measured in this research are of the order of 10^2 and 10^3 MPN/100 mL, a log removal of at least three will be required to reach undetectable levels, in case the water is used for potable purposes. Suitable treatment techniques to remove microbial contamination include boiling, SODIS, chlorine and ultrafiltration. Ceramic filtration is another option, although log removals for bacteria are expected to be slightly lower than three. With respect to economic criteria all these options are feasible with the exception of ultrafiltration. Legally all these treatment options are possible. However from a social-cultural viewpoint boiling is widely accepted, in contrast to other treatment systems, as confirmed by (case study) experts interviewed. This leaves boiling the most suitable treatment option for the case study area.

Next to this point of use treatment some preventive measures are required. Obviously regular cleaning is required for all system parts. For aesthetic water quality and to limit regrowth one should remove larger organic materials with a filter, which can be for example a cloth filter or leaf strainer. First flush can prevent the most contaminated water to enter the tank, although not all pollutants show a clear first flush. In this research only microbial contamination is found to show a clear first flush. To prevent mosquitos the most preferred option is to design a mosquito tight tank. However in case this is not possible, fish can eat mosquito larvae in the tank. To prevent algae growth, light penetration through the tank should be prevented and preferable the tank should be placed inside.

6.4.2) Simplifications, assumptions and uncertainty

Possible treatment systems are evaluated against various criteria including technical, economic and social and cultural aspects. This last criterion plays a key role in the selection of boiling combined with some preventive measures as most suitable treatment in the case study area. Technically other treatment options could be advised. For example a point of entry system could be preferred above a point of use system since all water is treated, decreasing health risks. Moreover, boiling is very resource intensive and increases indoor air pollution. Of course social and cultural preferences could be changed by for example education and promotion, and in case this option is considered the treatment devices should be reevaluated.

More research has to be done regarding the water quality in rainwater harvesting systems, and regarding major factors that influence this quality. A major assumption in this research is that the water quality in rainwater harvesting systems complies with chemical water quality guidelines. Although this is true for the measurements done in this research, more measurements are required to confirm this result in time and space.

Furthermore, the effects of taking certain measures, like the use of fish or cloth filters should become more clear. Current research confirms that fish have a positive influence on the amount of mosquito larvae in the tank, and thereby limiting diseases that are spread by mosquitos. However the negative influence (on microbial growth) of increasing nutrients in the tank, and the chance for zoonotic diseases are uncertain, and more research regarding this topic has to be done. The same counts for cloth filters. Although this simple treatment device is known to be ineffective against most microbial contamination the possible positive effects of decreasing organic material on water quality are not well researched.

Furthermore, the mechanism that decreases the concentration of iron, aluminium and manganese between raw rainwater and roof runoff is not fully understood. More measurements are required to confirm this result. In this case it is advised to measure these metals both in dissolved and solid phase.

6.4.3) Improvements in the methodology

Treatment options are evaluated against various criteria. It would be the best to determine weights of these criteria based on discussion with several experts. More treatment options could be considered, and more criteria can be included. Relevant criteria include for example the sustainability of the treatment technique.

6.4.4) Generalization to other locations

Although boiling combined with some preventive measures can be applied at any location, it is not likely to be the most suitable treatment at other locations. First of all roof runoff may contain chemical contamination, which is not removed by boiling. Second the economic, social and cultural situation may differ. The applied method in which several possible treatment options are discussed with experts, and evaluated on technical capacity by literature review can be generalized. However the treatment techniques that are selected to discuss may differ from location to location. For further research it could be interesting to test and evaluate the technical effectiveness and social acceptance of several treatment options for rainwater harvesting in the case study area itself.

6.5) What are the main remaining health risks of using rainwater at a household level in case the advised treatment is applied?

6.5.1) Main findings

As described above it is advised to boil rainwater before drinking, use a filter to remove larger organic material, apply first flush, close the tank well and prevent light penetration. However even in case this is all done, some risks remain. Recontamination after boiling is possible and spores like *Clostridium botulinum*, with are resistant against boiling, can cause infant botulism. Although, for the chemicals measured, rainwater in the tank did not exceed guideline values, individual rainwater harvesting systems should be monitored more frequent in time and space to confirm that this is the case. Moreover, carcinogenic organic compounds (like PAHS) need to be measured.

In case water is used for non-potable purposes, microbial contamination is present in the rainwater harvesting system due to direct contamination or due to growth inside the tank. For non-potable purposes infection by pathogens can occur by inhalation of aerosols or by contact with (wounds in) the skin. Relevant micro-organisms that are spread via aerosols include *Legionella pneumophila* and *Pseudomonas aeruginosa*. Micro-organisms that have been found inside rainwater harvesting systems, and can be spread via the skin include *Pseudomonas aeruginosa, Aeromonas hydrophila* and *Staphylococcus aureus*.

In general the infection risk, and/or the consequences of infection are largest for vulnerable groups which include very young children, elderly, individuals with weakened immune systems and people with skin injuries. Because of this vulnerable groups should prevent the use of unboiled rainwater for non-potable purposes. Children below 1 year, should not drink boiled rainwater, to prevent infant botulism.

6.5.2) Simplifications, assumptions and uncertainty

Even if the above stated advise is followed, a health risk will remain, since all decisions are linked to a certain risk. Although it is expected that the health risk of using rainwater harvesting in Serang is not dominating compared to other health risks in the area, more research is needed to confirm this.
In general it will be difficult to reach a very high safety level at a household level for the lowest possible costs. This is mainly due to the fact that the costs for elaborated treatment and frequent monitoring are not shared at a household level. Because of these reasons, individual rainwater harvesting systems as long term solution may be debated. However as short time solution, that can be started bottom up, individual rainwater harvesting systems can improve water quality.

6.5.3) Improvements in the methodology

To define the health risk of using rainwater in households more information has to be present regarding the type and extent of the pollution present in rainwater harvesting systems. If this information is available a qualitative microbial risk assessment could be performed to translate the concentration of pollutants and pathogens to a certain risk.

6.5.4) Generalization to other locations

The remaining health risk will depend on the incoming water quality, the system characteristics and the treatment applied. In this sense the results presented in this research cannot be generalized to other locations. However the relevant micro-organisms that can be present in rainwater harvesting systems, which are obtained by literature review and communication by experts may also be present in other locations.

6.6) What is the optimal system size for a rainwater harvesting system that is able to link supply and demand by considering the total demand?

6.6.1) Main findings

There is no optimal system size for a rainwater harvesting system. Optimum system size is determined by local roof sizes, and the availability of space for a tank. For realistic system sizes, a rainwater harvesting system cannot deliver the total water need of a family. This implies that in any case additional water sources will be necessary. However the use of multiple water sources is very common in Indonesia, and not seen as a main limitation. In general larger tanks and larger roof sizes will result in a larger possible tap flow. However in case of extreme combinations (large tank-small roof or small tank-large roof) an increase in the larger system part is not resulting in higher tap flow. These combinations can be considered as non-ideal. The model shows that systems that can be placed inside the house (T=2 m^3, RS=100 m^2) can provide between the 0.12 and 0.19 m^3/d on average depending on the type of operation.

6.6.2) Simplifications, assumptions and uncertainty

Uncertainty of model results are related to uncertainty in input data (rainfall), parameter uncertainty and uncertainty in the model structure. No calibration or validation of the model could be performed, because of a lack of available data, which increases the uncertainties in both the model structure and model parameters. Uncertainty in tap flow because of parameter uncertainty is expected to be in the order of ±50% (see paragraph 5.4.3.5). The uncertainty in input data can be caused by observational uncertainty but also by the approach to fill missing data. One of the goodness of fit tests (the chi-square test) has some limitations, since it requires huge datasets, and uses discrete data intervals. Next to the uncertainties in input data, parameters and model structure future changes can largely influence the performance of rainwater harvesting systems. Water availability can change due to climate change (rainfall and evaporation), and on the other hand water demand can change due to population change or a shift in water use patterns.

6.6.3) Improvements in the methodology

For further research it is advised that the model is calibrated and validated, and that changes in water availability and demand are taken into account. Furthermore, it would be interesting to consider yearly fluctuations of average tap flow. Another interesting possibility is to investigate to which extent and in which way, tap flow can be optimized by taking not only considering the current situation in the tank, but also future rainfall expectations (weather predictions).

6.6.4) Generalization to other locations

In case the model is calibrated and validated, and climate change is included, the model can be applied to other locations, in case parameters are adjusted to the local situation.

6.7) What is the optimal system size for a rainwater harvesting system by minimizing water costs per volume ?

6.7.1) Main findings

The water costs per cubic meter, is investigated for tank sizes of 1, 2 ,4 and 8 m^3 and roof sizes of 25, 50, 75, 100, 150 m^2. Calculations are performed for ferrocement and plastic tanks. From these combinations the lowest water costs can always be reached for ferrocement tanks by connecting the largest roof area available. For scenario 2d(Tstor), in which all available water is used directly (with a maximum of the total water requirement of 500 liter) the lowest water costs are reached. This can be explained by the fact that this scenario results in the highest average tap flow. In case a small roof is connected (25 or 50 m^2) a tank of 1 m^3 results in the lowest water costs per cubic meter. For the larger roof sizes, water costs are lowest for a tank of 2 m^3. The minimum costs found is €0.37 per m^3 for a ferrocement tank of 2 m^3.

6.7.2) Simplifications, assumptions and uncertainty

To calculate water costs assumptions have been made regarding material requirements, material costs, system lifetime, maintenance requirements and the discount rate. Moreover, the projected tap flow used to calculate the water costs, contains certain uncertainties.

Real costs are expected to be lower as the calculated cost in this research since some costs, for example for labor, will not be considered as real costs by the local population. Costs shown in this research did not take roof installation into account, since this is assumed to be already present, but consider the installation of gutters.

This implies that the lower water costs for larger roof size can be misleading, and is only the real costs in case a suitable roof area is available.

6.7.3) Improvements in the methodology

Although the calculation of the water costs is useful, one should realize that initial investments for a rainwater harvesting system are high, which is one of the main limitations of implementing a rainwater harvesting system. Possibilities for microfinance can be further researched. Furthermore, one should realize that in case more water is obtained from the system on average, less water is saved for next days. This increases the chance that the system is empty, thereby increasing the amount of bottled water that has to be bought, which will result in a higher pay back period.
The methodology could be further improved by considering next to ferrocement and plastic tanks other type of systems. Furthermore one could investigate the difference between costs for the population and official costs.

6.7.4) Generalization to other locations

Costs are very location dependent, and thereby cannot be generalized to other locations. However the methods used to express the costs can be applied in other areas. In addition one should realize that the type of rainwater harvesting systems (size, material, ect.) for which the costs will be calculated can be totally different for different locations.

6.8) Is there legislation regarding other aspects then water quality, that should be taken into account in the design of a rainwater harvesting system?

6.8.1) Main findings

There is no limiting legislation regarding rainwater harvesting in Indonesia. Support for rainwater harvesting however could be improved at all governmental levels. Although knowledge is available at a national level this is not adequately spread towards the local levels.
Further research can investigate how governmental institutions and possibly legislation could actively support rainwater harvesting. It is believed that increasing knowledge at a local level can hugely increase the spread of rainwater harvesting systems throughout Indonesia.

6.8.2) Simplifications, assumptions and uncertainty

It is assumed that the interviewed experts, have sufficient knowledge regarding the legislation in Indonesia, and the legislation regarding rainwater harvesting in specific. However none of the interviewed experts has a background in legislation, and thereby this result contains some uncertainty.

6.8.3) Improvements in the methodology

To get a better overview of relevant legislation, it is recommended to interview some experts in water legislation. Next to this the role of different stakeholders can better be identified by interviewing them all. During these interviews more attention should be towards the responsibility of different stakeholders, and the fact whatever these responsibilities are currently taken.

6.8.4) Generalization to other locations

Existing legislation cannot be generalized to other countries and even not to other locations within Indonesia, since local legislation can discourage the use of rainwater harvesting systems. However a similar methodology can be applied to find the existing governmental structure and legislation. Although knowledge regarding rainwater harvesting at the local level is stated to be limited, it is possible that the persons interviewed were not probably selected within the organization. Results at a local level cannot be generalized to other locations in Indonesia, for which other institutions will be responsible.

7. Conclusion

In this chapter the answer to the main research question as stated below, is given.

How can a domestic rainwater harvesting system in an off-grid urban area in a developing country (with case study Serang, Indonesia) be designed to have an optimal/sufficient performance regarding technical (water quality and water quantity), economic, social and cultural and legal criteria?

First the possibilities for rainwater harvesting and the proposed design in Serang will be presented, together with the expected performance of this system and the strength, weaknesses, opportunities and threats. Second there will be focus on factors that should be considered in a design in any urban poor infrastructure area. Furthermore, the applicability of the used methodology for other areas will be discussed. Finally, recommendations will be provided for the population in Serang, for governmental institutions and for further research.

7.1. Case study area

7.1.1. Possibilities for rainwater harvesting

This research shows that rainwater harvesting could be a suitable technique for improvement of the water supply in Serang. Although unrealistic system sizes are required to solely rely on rainwater, it can provide significant volumes of water of sufficient quality, for reasonable costs. Legally rainwater harvesting system is permitted. However more research and pilots are required to draw final conclusions regarding the possibilities of rainwater harvesting, as discussed in paragraph 7.3.

Suggested optimal system

Based on this research a rainwater harvesting system at a household level is suggested. During the installation the community should be involved, but professionals should make sure that the installation is done properly. A closed (ferrocement)tank of 2 m^3 is suggested which is installed above ground and inside the house. The system should have an overflow, tap, first flush, cloth filter and lid. The entire roof should be connected to the tank. Roofs with tiles are suitable. Thatched roofs are less suitable due to higher concentrations of microbial contamination. Roofs containing zinc, copper, lead, asphalt or a coating can lead to chemical contamination. For quality control the entire system should be cleaned regularly, at least once a year, preferable at the end of the dry season. In case the water is used for potable purposes, it should be treated before consumption. Boiling is a very common technique which is suitable. Although it is preferred to prevent mosquitos from entering the rainwater harvesting system by using fine wire mesh, small fishes can also be used to eat mosquito larvae.

Performance of the suggested system

Depending on external factors, like (local) air pollution, the above described rainwater harvesting system with treatment is expected to provide water complying with the WHO and Indonesian water quality standards. Only for non-potable purposes the microbial guideline will not be met, since this water will not be boiled before use. With a tank of 2 m^3 and a roof of 100 m^2 one can expect an average tap flow of between 120 and 190 liter/day. In the dry season the supply is around 10 to 90 liter/day, and in the wet season between 170 and 250 liter/day. Installation costs for a ferrocement tank are expected to be around €450,-. Taking the entire system lifetime and the expected operation and maintenance costs into account, water costs are expected to be around €0.40 to €1.11 per cubic meter. From a social cultural viewpoint, the system is expected to be accepted when the population is not satisfied with the current water supply. Currently rainwater is often considered as last option and often described as oily, without minerals or polluted by the air. This image has to be changed before rainwater harvesting systems can be implemented successfully.

Strengths, weaknesses, opportunities and threats

The above proposed design comes together with certain strengths, weaknesses, opportunities and threats which are described below.

The main strength of the suggested system is the fact that people can take their own responsibility for their water supply. Independently of the current system or external parties they can improve their fresh water availability and/or quality. The system is legal and it can provide water for a relatively low cost (over the entire lifetime).

Weaknesses of the system include the relatively high installation costs, which are not easy affordable for the local population. Moreover, the system cannot provide 100% coverage of the total water demand. The proposed system still has some health risks. Vulnerable groups include young children, elderly, sick, weak or injured people. Risk groups should boil rainwater both for potable and non-potable purposes and young children should not use rainwater for potable purposes. Another weakness of the system is the fact that boiling is not the most sustainable type of treatment,. Furthermore it can cause significant indoor air pollution in case wood is used.

New opportunities and threats can be caused by external factors. Both water availability and demand can change in the future, for example due to climate change or shifting water use patterns. Rainwater quality can change due to changing air pollution. Changing quality, coverage or price of alternative water supplies (like the PDAM) can shift the preference for specific water sources. In case the overall health situation in the case study area changes, the accepted health risk may change as well, which would modify the view on the current system. A very interesting opportunity can occur, when money will be available to solve the problem of large investment costs.

7.2. Urban poor infrastructure areas in developing countries

It is found that it is not always possible to design a well-functioning rainwater harvesting system in any off-grid urban area. There are certain boundary conditions that have to be met, before rainwater harvesting can be installed successfully. These boundary conditions can be social, economic, technical and legal. It is found that there is no optimum design for a rainwater harvesting system, since the requirements following from the boundary conditions are largely location and situation dependent.

However the adjusted methodology from Studer (2013) applied in this research is proven very useful to identify these location specific boundary conditions. Main strength of this methodology is the system approach in which technical, social, economic and legal aspects are considered. However it remains a challenge to integrate these different viewpoints and to make decisions taking all aspects into account. The applied methodology can be improved by further integrating all aspects of rainwater harvesting and by including operation and maintenance and system sustainability in the design considerations. When applying the methodology of Studer (2013) at any location it is of large importance to evaluate the technical possibilities of rainwater harvesting at an early stage. In areas

with long dry periods, limited rainfall, heavy air pollution, no location to install storage tanks, small roofs, or unsuitable roofing materials rainwater harvesting may be not be one of the most suitable solutions.
The boundary conditions for domestic rainwater harvesting that are found in this research, and that are expected to apply on a larger spatial and temporal scale will be discussed below.

7.2.1) Facilitating conditions

For successful implementation of a rainwater harvesting system there should be a certain need to improve the water supply, within the area of interest. The population should be unsatisfied with the current situation, because their water demand with respect to quality or quantity is not met. Furthermore, the population and other stakeholders should be aware of the possibilities of rainwater harvesting. They have to accept the technique and have sufficient knowledge. It is expected that acceptance and knowledge can be correlated, and that a lack of knowledge can cause fear regarding the functioning of the technique.
In case water demand is not met and awareness, acceptance and knowledge regarding rainwater harvesting systems exists, rainwater harvesting can be considered as a suitable technique to increase or improve the current water supply.

7.2.2) Social requirements

Next to the required facilitating conditions, other social factors are of mayor importance as well. Examples of technical decisions, that can fail due to social reasons include unsuitable system scales (individual, street or village), unsuitable types of treatment, required materials, and/or tank locations (inside or outside). Depending on the potential water harvest from the system it should be investigated if it is accepted to use multiple water sources, or if the storage tank could be filled with other sources in the dry period.
To ensure proper use and maintenance of the rainwater harvesting system the population should be involved from the start. It is difficult to predict factors that are important for the population, and involvement will guarantee that the system works according to their preferences.

7.2.3) Quality requirements

The water quality that can be provided by a rainwater harvesting system is dependent on the system design. This includes the materials used and the measures taken to prevent microbial contamination. Next to this air pollution influences rainwater quality. As discussed in paragraph 7.1 the tank should be closed, with overflow, tap, lid and first flush. Large organic material should be removed before entering the tank. The system should be cleaned at least once a year and should be regularly inspected. Systems should be checked for chemical contamination that can already be present in direct rainfall due to air pollution and/or in roof runoff due to contamination from the roof or gutters. To meet microbial water quality guidelines additional treatment will be needed. Mosquito growth should be prevented (when applicable), preferable by a well closed tank and alternatively by small fishes. Vulnerable groups should be careful with the use of rainwater.

7.2.4) Quantity requirements

The amount of water a rainwater harvesting system can provide is related to the rainfall intensity and distribution. Furthermore the tank and roof sizes used, are of main importance. The main factor determining the volume of water that can be supplied by the system is the tank size. This is the case since rainfall patterns cannot be influenced by humans, and since roofs are often already present. The conceptual model used in this research could provide interesting information regarding the water quantity one can expect for a specific system size in case daily precipitation data is available.

7.2.5) Economic aspects

Large part of the investment costs for a rainwater harvesting system is related to the purchase of the tank. Other investment costs include guttering, piping, labor, transport and treatment costs. Costs and thereby the economic optimum design is very location dependent, since material and labor prices vary from location to location. Besides these investment costs, operational and maintenance costs should be considered. Furthermore the availability of materials and spare parts is of large importance for the lifetime of the system and as a result also the economic performance of the system.

7.3. Recommendations

In this section recommendations will be given, for improvement of the individual rainwater harvesting systems currently installed in Baros, Pabuaran and Tirtayasa (paragraph 5.1.3.). Furthermore, there will be attention for possible improvements that can be implemented at a governmental level. Finally suggestions for further research are given.

7.3.1. Recommendation for the operated rainwater harvesting systems in Serang

The quality and quantity provided by the individual rainwater harvesting systems in Serang can be improved by taking several (simple) actions as described below.
First of all the tanks which are currently open, should be closed. This prevents material from falling inside the tank, and contamination due to direct handling of the water. In addition, it limits mosquito breeding and decreases the amount of light inside the tank, and thereby limits algae growth.
A well closed tank requires a tap and overflow pipe, to hygienically extract and dispose water. Moreover, the installation of an overflow pipe will prevent flooding of the house.
In case not already used, a cloth filter should be installed to remove large organic material from the water. It is advised to regularly clean the filter, and/or install a self-cleaning filter under an angle. Installation of first flush is advised. This can be done relatively easily with a pipe, with a small hole in the bottom and a (floating) ball. Fine wire mesh can be installed at the overflow and inlet pipe to limit the entry of mosquitos. In case this is not possible, a limited number of small fishes can be used. However, these should directly be removed when sick or dead. Feeding should be limited. In case water is used for potable purposes boiling is required. The entire system should be inspected regularly and cleaned at least once a year.
For quantity aspects it is always advised to connect the entire roof. This can largely increase the water harvest, compared to the current situation, in which just a limited roof area is connected. For normal roof sizes (≥50 m^2), a tank of 2 m^3 is found to be a realistic and economically optimal option, in case the water costs per cubic meter are considered. Depending on the user goal, different types of system operations are advised. In case one seeks to extract the highest possible volume of water, one should extract as much water as possible directly (scenario Tstor). In case one wants to limit the purchasing of the expensive bottled water, one should save more water for later. From the investigated scenarios it is found to be most economical to limit water use to the fresh water requirement of 80 liters per family per day. Also, the fluctuating weighted scenario 2c(ii) and the scenario which uses maximal 12.5% of the tank (Tstor/8) are relatively economical and allow much more water extraction.

7.3.2. Recommendation for the local governmental institutions

On governmental level, several actions can be taken. These measures can either increase the knowledge regarding rainwater harvesting, share the available knowledge between stakeholders or support or inform the community regarding rainwater harvesting. It is of major importance that knowledge regarding the possibilities of rainwater harvesting increases, since a lack of knowledge at local level can cause fear, which prevents the use of rainwater harvesting systems. For governmental institutions it is advised to first improve and share knowledge. After this is done, this information can be communicated with the population. In case further research confirms that rainwater harvesting is suitable, it can be further supported by the government.
Recommendations are stated below and are all focused on rainwater harvesting systems in particular and not on any other tasks of the institutions mentioned above.

7.3.2.1) Increasing knowledge

To increase knowledge regarding rainwater harvesting several actions can be taken. Rainwater harvesting systems should be included in water quality monitoring programs. Hereby microbial and chemical contamination in different types of rainwater harvesting systems will be measured regularly in a professional way. These measurements should be performed which a clear goal in mind and should be stored and analyzed in an appropriate way. A pilot can be done, to get information regarding the real performance of the system suggested in paragraph 7.1. Next to knowledge regarding the technical performance of rainwater harvesting systems, more knowledge has to be gained regarding the financing options for rainwater harvesting systems. Possibilities for microcredit have to be further investigated. Finally, it is important to stay open minded, innovate and analyze different possibilities to improve the current water supply.

7.3.2.2) Sharing knowledge

The obtained and existing knowledge should be shared between all parties. These include the national government, local governments (province, kabupaten, kecamatan and the puskesmas), knowledge institutes and non-governmental organizations. To start, the national government could share rainwater harvesting guidelines. Good communication starts with well-organized and online databases, which are shared with all stakeholders. In case a online database will be used, analyzing and interpretation of result will require less effort.

7.3.2.3) Support and inform the community

The obtained knowledge should be shared with the local population. The kabupaten could inform all sanitarians from the local health centers regarding the current knowledge with respect to rainwater harvesting. The sanitarian can be responsible to communicate this with the local population. System improvements can be promoted and assistance can be given for system changes. Focus should be on the potential improvements in water quality and the potential increase in water extraction due to other types of operation. In the process of improving the current water supply it is mainly important to involve the community and to listen to their needs or desires. A change in the current situation has more chance for success in case the population is interested to change. This implies that information should not only be shared top down (from the government to the population) but also bottom up.

7.3.3. Recommendation for further research

Further research regarding rainwater harvesting in Indonesia is necessary and can focus on the following knowledge gaps related to all aspects of rainwater harvesting in Serang and elsewhere. Below some recommendations for further research are provided regarding the social, quality, quantity, economic, legal and institutional aspects as discussed in this research. Finally, some broader recommendations for further research are given.

7.3.3.1) Social aspects

Regarding the social aspects of rainwater harvesting, professional research by social scientists is required. It should be investigated to which extend the behavior of the population can be changed, for example regarding the water use or treatment pattern.

It is found that the awareness, acceptance and local knowledge of rainwater harvesting are important for the implementation of rainwater harvesting systems. However, further research should confirm this by investigating other relevant aspects, involving more and randomly selected respondents and by using professional translation. Furthermore, additional research is required regarding the flexibility of the population with respect to current water related habits, like boiling.

7.3.3.2) Water quality aspects

With respect to water quality more measurements have to be done, the immunity of the population against microbial contamination should be better understood, the effect of fishes and cloth filters should be further analyzed and water related risks should be placed in the context of other risks that are faced by the population. These aspects are explained in more depth below.

First of all more measurements are required in time and space. Systems should be measured during an entire year (at least every week) for all parameters, to get an indication of water quality fluctuations. It is known that these quality fluctuations exist, but the extent and shape of these fluctuations are not well known. Furthermore, multiple rainwater harvesting systems should be measured, especially in case other roof materials or tank types are used.
It is advised to analyze some additional water quality parameters. Especially organic compounds like polycyclic aromatic hydrocarbon, phthalate ester, pesticides, polychlorinated biphenyls and relevant microbial contamination including *Legionella* and spores of *clostridium* should be further researched.

Second, the extent to which the population gets immune for microbial contamination present in the tank should be further investigated. This is a possible explanation for the fact that expected health risks due to microbial contamination in rainwater harvesting systems often do not match real health risks. More information regarding this phenomenon is required.

Third, the effect of cloth filters and fishes need more investigation. There is limited scientific research related to the water quality improvement related to the use of cloth filters, which minimizes the amount of organic material inside tanks. Especially in case organic material or dead animals are accumulated due to the use of a cloth filter, negative effects for water quality can occur.
Furthermore the effects of fishes in tanks is not well understood. It is unknown how the increasing microbial risk due to the use of fishes is related to the decreasing risk for vector-borne diseases (related to mosquitos). Further research on this topic is advised.

Finally, one should note that clean and sufficient drinking water is not the only health related problem in Serang. It should be investigated to which extent the health risk related to drinking water is proportional to other risks. For example the risk related to sanitation, waste or nutrition.

7.3.3.3) Quantity aspects

Regarding quantity aspects the used conceptual model and input data used can be further improved, the possibility to use monthly rainfall data can be investigated and other operating scenarios could be considered. These recommendations for further research will be elaborated below.

Due to limited data availability it was not possible to calibrate and validate the model parameters used in this research. For further research it is advised to not only collect data regarding rainfall, but also regarding the water level inside tanks and tap flow. This will enable model calibration and validation, resulting in more certainty regarding model parameters and model structure. Other improvements to model results can be reached by taking external factors, like a changing demand or supply into account. Demand can change due to shifting water use patterns or changes in family size. Supply can change for example due to shifting precipitation patterns or changing roof sizes.
This research, filled missing input (or rainfall) data by using a probabilistic approach. Monthly cumulative distribution functions from precipitation are used, to fill data gaps. An underlying assumption for this approach it that the amount of rainfall on day 'i', is independent of the rainfall before or after day 'i'. This assumption is not totally correct. Although the influence of this dependency is expected to be small for the final result, this should be investigated.

This research included a limited number of operational scenarios, to investigate the possible tap flow from rainwater harvesting systems. Other operational scenarios could be included. The possibility to further optimize rainwater harvesting systems by using weather predictions or past rainfall data should be investigated. Another possible operational scenario includes a scenario in which the tank is refilled by another water source. In case rainwater harvesting tanks could be refilled by external water supply system, the system could potentially be used as independent water supply. In this case the quantities and economical optimization of tank sizes would change. Since the refilling of household tanks is currently already done in some areas in Indonesia, it would be interesting to investigate optimum tank sizes for this scenario.

The current model requires daily rainfall data. It can be investigated, how monthly rainfall data (combined with for example the percentage of dry days) can be used to predict the performance of rainwater harvesting systems with a sufficient accuracy. A big advantage of the use of monthly rainfall data, would be an easier application for data scare locations.

7.3.3.4) Economic aspects

With respect to the costs for rainwater harvesting systems, better input data is required to perform more accurate calculations. Furthermore the use of other tank materials should be investigated and solutions for the large investment costs have to be found. These points are discussed in more detail below.

To improve costs calculations, first of all better information regarding material requirements, prices and system lifetime is required. Input data used regarding material requirements, prices and expected lifetime contains relatively high uncertainty. Better information regarding these prices can be found for example by local implementation of a pilot.

Second, cost calculations should be performed for different rainwater harvesting systems. This research only calculated costs for ferrocement and plastic (pinguin) tanks. Costs for other tank materials and designs should be investigated. In case multiple tanks are build a mall could be used, to construct cement tanks. This mall will limit the material requirement with respect to reinforcement. This is an interesting option for large scale projects, since the mall can be reused. Other opportunities for limiting costs should further be analyzed.

Furthermore, research should pay attention to methods to overcome the large investment costs of rainwater harvesting systems. This is an important problem for the implementation of rainwater harvesting systems. The possibilities for financial structures that can bridge these costs (like microfinance) should be further investigated.

7.3.3.5) Legal and institutional aspects

More research is required to understand all legal requirements regarding individual water supplies in Indonesia. Since local governments can have their own regulation, it could be interesting to check the possibilities of rainwater harvesting national wide. As discussed in paragraph 7.3.2 the local government should increase and share knowledge regarding rainwater harvesting. Moreover, they should support and inform the community. Scientific research can focus on the most appropriate method to increase and share this knowledge. Beside this it should be investigated how the population can be most effectively supported and informed regarding rainwater harvesting.

7.3.3.6) Other aspects

First of all it should be mentioned that the current research focuses mainly on rainwater harvesting and not on the other water supply options. However, for practical applications it is recommended that one evaluates all possible methods to improve the water supply. In this sense the methodology used in this research cannot be used for decision making. An interesting possibility to improve the water supply in Serang is for example the improvement of the piped network with respect to both quality and quantity.

Second, further integration of the technical, social, economic and legal aspects is still required. This research still discusses the different aspects relatively separately. However for many decisions multiple aspects should be taken into account.

To conclude, it would be interesting to map the possibilities for rainwater harvesting worldwide based on relevant parameters found in this research. Areas should be selected based on the fact whatever current or future demand is met. Next to these social parameters (acceptance, knowledge and awareness regarding rainwater harvesting), technical parameters (expected water quality and quantity), economical parameters (costs, for example as percentage of average income) and legal parameters should be taken into account. These maps would provide interesting insight of areas where rainwater harvesting could create new opportunities.

8. Literature

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9. Appendix

A1. Chemical drinking water guidelines from the WHO

In this Appendix the chemical drinking water guidelines from the World Health Organization can be found. Guidelines are given in milligram per liter. Water quality targets are generally formulated for chemicals and not for microbial or radiological contamination. Because of this only the chemical drinking water guidelines are given.

Table 40: Chemical drinking water guidelines (WH0, 2011).

Chemical	Guideline [mg/l]	Chemical	Guideline [mg/l]
Acrylamide	0.0005	Edetic acid	0.6
Alachlor	0.02	Endrin	0.006
Aldicarb	0.01	Epichlorohydrin	0.0004
Aldrin and dieldrin	0.00002	Ethylbenzene	0.3
Antimony	0.02	Fenoprop	0.009
Arsenic	0.01	Fluoride	1.5
Atrazine and its chloro-s-triazine metabolites	0.1	Hexachlorobutadiene	0.0006
Barium	0.7	Hydroxyatrazine	0.2
Benzene	0.01	Isoproturon	0.009
Boron	2.4	Lead	0.01
Bromate	0.01	Lindane	0.002
Bromodichloromethane	0.06	MCPA	0.002
Bromoform	0.1	Mecoprop	0.01
Cadmium	0.003	Mercury	0.006
Carbofuran	0.007	Methoxychlor	0.02
Carbon tetrachloride	0.004	Metolachlor	0.01
Chlorate	0.7	Microcystin-LR	0.001
Chorine	5	Molinate	0.006
Chlorite	0.7	Monochloramine	3
Chloroform	0.3	Monochloroacetate	0.02
Chlorotoluron	0.03	Nickel	0.07
Chlorpyrifos	0.03	Nitrate (NO_3^-)	50
Chromium	0.05	Nitrilotriacetic acid	0.2
Copper	2	Nitrite (NO_2^-)	3
Cyanazine	0.0006	N-Nitrosodimenthylamine	0.0001
2,4-D	0.03	Pendimethalin	0.02

2,4-DB	0.09	Pentachlorophenol	0.009
DDT and metabolites	0.001	Selenium	0.04
Dibromoacetonitrile	0.07	Simazine	0.002
1,2-Dichlorobenzene	1	Sodium dichloroisocyanurate	50
1,4-Dichlorobenzene	0.3	Sodium dichloroisocyanurate (as cyanuric acid)	40
1,2-Dichloroethane	0.03	Styrene	0.02
1,2-Dichloroethene	0.05	2,4,5-T	0.009
Dichloromethane	0.02	Terbuthylazine	0.007
1,2-Dichloropropane	0.04	Tetrachloroethene	0.04
1,3-Dichloropropene	0.02	2,3,6-Trichlorophenol	0.2
Dichlorprop	0.1	Trifluralin	0.02
Di(2-ethylhexyl)phthalate	0.008	Uranium	0.03
Dimethoate	0.006	Vinyl chloride	0.0003
1,4-Dioxane	0.05	Xylenes	0.5

A2. Water safety plan for small community water supply

The water safety plan, which are part of the framework for safe drinking water from the World Health Organization consist of six steps, which are explained below.

In the first step the community should be engaged, and a water safety plan team should be developed. Aspirations and needs with respect to the water supply should be identified, water supply needs should be compared to other needs of the population, community resources should be identified, a dialogue should exist between the community and other stakeholders and awareness regarding a safe water supply should be created.

In the second step the community water supply system, including the catchment, possible treatment, storage and distribution and the consumer, should be described. A map should be drawn, supporting information should be gathered and community objectives should be identified.

In the third step hazards, hazardous events, risks and existing control measures are identified. Important hazards include microbial organisms, agricultural and industrial chemicals and natural chemicals.

The fourth step an improvement plan is developed and implemented. This improvement plan should be based on the identified risks in the third step. For control measures, a multiple barrier approach should be considered.

In the fifth step control measures are monitored, to test the effectiveness of the water safety plan. For this a distinction is made between operational monitoring (day to day checking of the water supply) and verification monitoring (checking fecal indicator organisms and hazardous chemicals, internal and external auditing and the checking of consumer satisfaction).

The last step all aspects of the water safety plan implementation should be document, reviewed and improved.

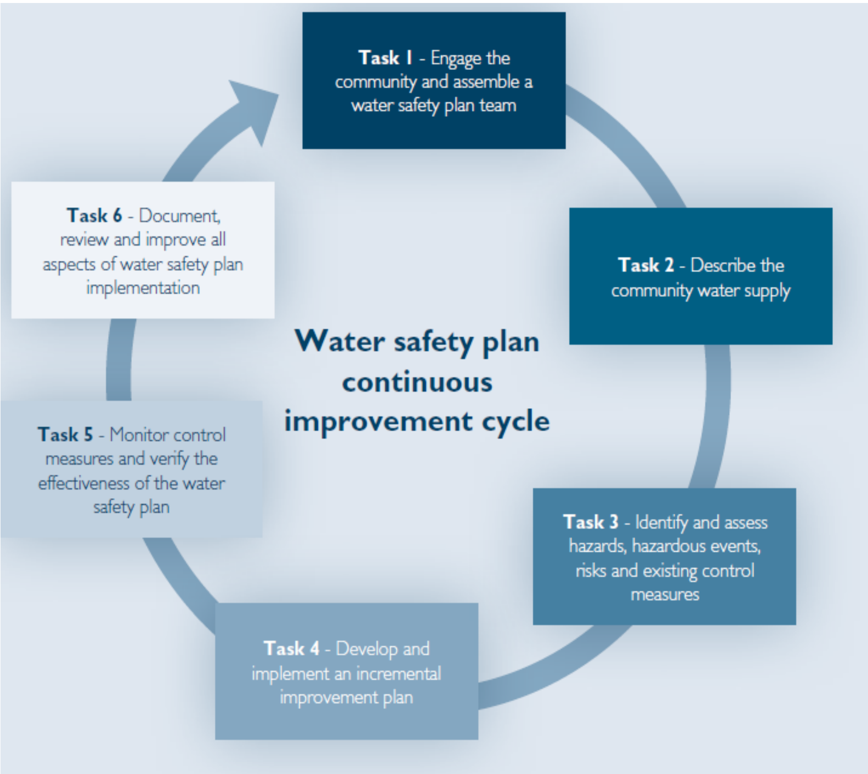

Figure 56: The six tasks to develop and implement a water safety plan in small community water supplies (WHO, 2012).

A3. Chemical and microbiological quality of harvested rainwater

In Table 41 the percentage samples that is tested positive (>1 CFU/100 mL) for bacteria and faecal indicators is shown (together with the number of samples selected). In Table 42, the chemical water quality in several rainwater harvesting tanks is shown.

Table 41: Total bacteria and fecal indicators from harvested rainwater (De Kwaadstenied et al., 2013).

Country	Total bacteria	Total coliforms	Fecal coliforms	E.coli	Entcrococci	Reference
Australia	NR	52 (100)	38 (100)	NR	NR	Verrinder and keleher (2001)
Australia	NR	90 (49)	NR	33 (49)	73 (49)	Spinks et al. (2006)
Australia	NR	NR	NR	63 (27)	78 (27)	Ahmed et al. (2008)
Australia	NR	NR	NR	58 (100)	83 (100)	Ahmed et al. (2010)
Australia	NR	NR	NR	63 (15)	92 (22)	Ahmed et al. (2012a)
Australia	100 (67)	91 (46)	78 (41)	57 (67)	82 (67)	CRC for Water Quality and Treatment (2006)
Australia	NR	NR	83 (6)	NR	NR	Thomas and Greene (1993)
Australia	100 (77)	63 (81)	63 (81)	NR	NR	Evans et al. (2006)
Canada	NR	31 (360)	14 (360)	NR	NR	Despins et al. (2009)
Greece	NR	80 (156)	NR	41 (156)	29 (156)	Sazakli et al. (2007)
Denmark	100 (14)	NR	NR	79 (14)	NR	Albrechtsen (2002)
Micronesia	NR	70 (176)	43 (155)	NR	NR	Dillaha and Zolan (1985)
New Zealand	NR	NR	56 (125)	NR	NR	Simmons et al. (2001)
Nigeria	100 (6)	100 (6)	ND	NR	ND	Uba and Aghogho (2000)
South Korea	NR	92 (90)	NR	72 (90)	NR	Lee et al. (2010)
Thailand	NR	NR	NR	40 (86)	NR	Pinfold et al. (1993)
USA	100 (30)	93 (30)	NR	3 (30)	NR	Lye (1987)
US Virgin Islands	86 (45)	57 (45)	36 (45)	NR	NR	Crabtree et al. (1996)
US Virgin Islands	NR	NR	59 (17)	NR	NR	Ruskin and Krishna (1990)
Bermuda	NR	90 (102)	NR	66 (102)	NR	Levesque et al. (2008)
Palestine	NR	95 (100)	57 (100)	NR	NR	Al-Salaymeh et al. (2011)
Palestine	NR	49 (255)	NR	17 (255)	NR	Abo-Shehada et al. (2004)
Hawaii, USA	NR	NR	89 (9)	NR	NR	Fujioka et al. (1991)
Zambia	NR	100 (5)	100 (5)	NR	NR	Handia (2005)

* NR is not reported, ND not determined

Table 42: Chemical water quality of water collected from Domestic Rainwater Harvesting Tanks (De Kwaadstenied et al., 2013).

Table 2 A summary of the reports on the chemical quality of water collected from DRWH tanks

Location/ country	No. of samples	Average pH	Average concentrations of cations	Average concentrations of anions	Reference
Korea	5	7.5	Fe: 0.033 mg/L; Cu: 0.054 mg/L; Zn: 0.15 mg/L	PO_4: 0.2 mg/L; N_2: 1 mg/L	Kim et al. (2005)
Mexico	9	6.6	Ca: 7.58 mg/L; K: 1.52 mg/L; Mg: 0.36 mg/L; Na: 3.23 mg/L;	F: 0.23 mg/L; Cl: 1.48 mg/L; NO_3: 3.84 mg/L; SO_4: 4.51 mg/L	Adler et al. (2011)
Hebron, Palestine	100	8.2	Ca: 94.6 mg/L; Mg: 64.6 mg/L; NH_4: 1.4 mg/L	NO_3: 4.2 mg/L; Cl: 42.3 mg/L	Al-Salaymeh et al. (2011)
Northern Jordan	90		Pb: 0.01 mg/L, Fe: 0.01 mg/L, Cr: 0.012 mg/L; NH_4: 0.06 mg/L	NO_3: 1.56 mg/L; PO_4: 1.27 mg/L	Radaideh et al. (2009)
Bermuda	112	7.81	Ca: 13 mg/L; K: 0.61 mg/L; Mg: 1 mg/L; Na: 7.7 mg/L; Fe: 7.8 μg/L; Al: 110 μg/L; Ba: 4.2 μg/L; Mo: 0.13 μg/L; Pb: 0.15 μg/L; Sb: 0.82 μg/L; Sr: 110 μg/L; V: 2 μg/L; Zn: 9.2 μg/L	Cl: 15 mg/L; NO_3: 1.6 mg/L; SO_4: 6.4 mg/L	Peters et al. (2008)
Kefalonia Island, Greece	156	8.31	Ca: 15.2 mg/L; Mg: 0.6 mg/L; Na: 6 mg/L: K: 2.4 mg/L; Fe: 11 μg/L; Mn: 1 μg/L; Cd: 0.05 μg/L; Zn 10 μg/L	NO_3: 7.04 mg/L; NO_2: 0.013 mg/L; PO_4: 0.09 mg/L; SO_4: 8 mg/L; Cl: 7 mg/L	Sazakli et al. (2007)
Northern China	76	7.39	Na: 3.02–11.2 mg/L; K: 3.36–8.658 mg/L; Ca: 11.2–31.15 mg/L; Mg: 0.930–1.143 mg/L; B: 0.011–0.056 mg/L; Fe: 0.01–0.083 mg/L; Mn: 0.048–0.112 mg/L; Cu: 0.0011–0.016 mg/L; Al: 0.093–0.336 mg/L; Pb: 0.003–0.041 mg/L; NH_4: 0.01 mg/L	Cl: 6.13–79.20 mg/L; SO_4: 2.4–15.62 mg/L; F: 0.071–0.163 mg/L; P: 0.247 mg/L; N: 1.188 mg/L	Zhu et al. (2004)
Batoka, Zambia	2	7.15	Zn: 0.645 mg/L	SO_4: 1.675 mg/L; Cl: 10.5 mg/L; NO_3: 4.63 mg/L	Handia et al. (2003)
Ayudhaya, Thailand	10	6.4	Ca: 10.30 mg/L; Cu: 0.03 mg/L; Fe: 0.54 mg/L; Mn: 0.001 mg/L; Pd: 0.017 mg/L; Zn: 0.15 mg/L	NO_3: 14.1 mg/L; Cl: 1.45 mg/L; SO_4: 3.24 mg/L; PO_4: 0.86 mg/L	Areerachakul et al. (2009)
Dertig Village, South Africa	13	6.85	Fe: 0.013 mg/L; Al: 0.014 mg/L	NO_3: 2.40 mg/L; NO_2 0.006 mg/L; F: 0.270 mg/L	Nevondo and Cloete (1999)
Gangneung, South Korea	90	7.3	NH_4: 0.02 mg/L; Ca: 1.6 mg/L; Na: 1.1 mg/L; K: 2.1 mg/L; Mn: 40 μg/L; Pb: 20 μg/L; Cu: 35 μg/L; Cr: 1 μg/L; Zn: 60 μg/L; Al: 100 μg/L	NO_3: 2.2 mg/L; Cl: 3 mg/L	Lee et al. (2010)
Auckland, New Zealand	125	7.3	Pd: <0.01 mg/L; Cu: 0.06 mg/L; Zn: 0.4 mg/L	–	Simmons et al. (2001)
National Survey, Australia	70	6.7	Ca: 3.7 mg/L; Mg: 0.6 mg/L; K: 0.6 mg/L; Na: 3.5 mg/L; NH_4: 0.0074 mg/L; Al 41.6 μg/L; Ar: 1 μg/L; Ba: 6.4 μg/L; Cd: 0.9 μg/L; Cr: 9.8 μg/L; Co: 0.7 μg/L; Cu: 18.4 μg/L; Fe: 44.8 μg/L; Pb: 3.8 μg/L; Li: 3.5 μg/L; Mn: 10.2 μg/L; Zn 1,790 μg/L	SO_4: 3.2 mg/L; NO_2: 0.006 mg/L; NO_3: 1.2 mg/L	Chapman et al. (2008)

A4. Available methods for sizing rainwater harvesting tanks.

In Table 43 some available methods to size rainwater harvesting tanks are presented. More information can be found in the referred articles.

Table 43: Available methods for the sizing of rainwater harvesting tanks.

Method	Formulas	Parameters/Explanation	Article
Daily water balance method	$S_t = S_{t-1} + R_t - D_t$ $S_t = S_{t-1} + C * A * P_{eff,t} - N_{cap} * q * (p/100)$ $0 \le S_{t-1} \le V_{tank}$	S_t = Storage at time t [m^3] S_{t-1} = Storage at time t-1 [m^3] R_t = Incoming rainfall [m^3/d] D_t = Water demand [m^3/d] C = Runoff coefficient [-] A = Catchment area [m^2] $P_{eff,t}$ = Effective rainfall at time t [m/d] N_{cap} = Number of users [-] q = Waterconsumption per person [m^3/d] p = Percentage of total water demand that should be provided by rainwater [%] V_{tank} = Tank volume [m^3]	Londra et al. (2015)
Dry period method or Rippl method	"Volume required to ensure a regular flow during the longest period of drought" $V_{tank} = N_{dd} * N_{cap} * q * (p/100)$	V_{tank} = Tank volume [m^3] N_{dd} = Longest dry period [days] N_{cap} = Number of users [-] q = Water consumption per person [m^3/d] p = Percentage of total water demand that should be provided by rainwater [%]	Londra et al. (2015) Santos & Taveira-Pinto (2013)
Technical specification	$V = Min(V_{NP} \text{ or } V_{RY}) * 0,06$	V = Tank volume [L] V_{NP} =Annual non potable demand [L/year] V_{RY} = Rainwater yield [L/year]	Santos & Taveira-Pinto (2013)
Technical specification	$V = ((V_{NP} + E_R)/2) * (30/365)$	V = Tank volume [L] V_{NP} =Annual non potable demand [L/year]	Santos & Taveira-Pinto (2013)
100% Efficiency	$V = V_{Eff100\%}$ $Ef = (V_{NP} - V_{pot})/V_{NP} * 100$	V = Tank volume [L] V_{NP} =Annual non potable demand [L/year] V_{pot} =Potable water consumed [L/year] Ef = Efficiency	Santos & Taveira-Pinto (2013)
80% Efficiency	$V = V_{Eff80\%}$ $Ef = (V_{NP} - V_{pot})/V_{NP} * 100$	V = Tank volume [L] V_{NP} =Annual non potable demand [L/year] V_{pot} =Potable water consumed [L/year] Ef = Efficiency	Santos & Taveira-Pinto (2013)
Maximum Rainwater used	An optimization criteria that provides the tank volume from which "cumulative water savings approaches to a constant value".	See Mierzwa et al, 2007 and Imteaz et al, 2011	Santos & Taveira-Pinto (2013)
Optimalization based on costs (domestic use in residential areas)	Min{TAC; Freshtotal} TAC = K_f(pipecosts + storagecosts + storagecostsT + capitalcosts) + (pumpingcosts + treatmentcosts + freshcosts) <u>Note:</u> it can be chosen to minimize total costs, total consumption from the public connection or to composite both these objectives.	TAC = total annual costs of the system Freshtotal = water consumption from public network K_f = conversion factor [1/year] pipecosts = capital costs for pipes Storagecosts = capital costs for storage devices Storagecosts T= capital costs for elevated reservoir capitalcosts = capital costs for collection area pumpingcosts= annual pumping costs treatmentcosts = annual treatment costs freshcosts= annual costs for public network	Bocanegra-Martínez et al. (2014)

A5. Costs for rainwater harvesting systems

In Table 44 the capital, operation and total costs (CapEx, OpEx, TotEx) of different rainwater harvesting systems can be found. A lifespan of 20 years was used for all systems when annualising CapEx and the annualised costs per m^3 are based on the volume of storage rather than volume of water supplied.

Table 44: Capital, operation and total costs (CapEx, OpEx, TotEx) of different rainwater harvesting systems.

RWH System	CapEx (US$ PPP 2008)				OpEx (US$ PPP 2008)			TotEx (US$ PPP 2008)	
	Total	Annualised	Annualised per m^3	Annualised per capita	Annual	Annual per m^3	Annual per capita	Annual per m^3	Annual per capita
Nepal									
Stone masonry (10 m^3)	680	34	3.4	4.8	4.4	0.5	0.6	3.9	5.4
Ferrocement jar (6.5 m^3)	638	31.9	4.9	6.4	5.6	0.9	1.1	5.8	7.5
RCC tank (60 m^3)	5730	287	4.8	0.5	8.9	0.2	0.02	5.0	0.5
Ferrocement tank (20 m^3)	4082	204	10.2	1.1	6.7	0.3	0.03	10.5	1.1
Ethiopia									
Sand dam (400 m^3)	12144	607	1.5	-	-	-	-	-	-
Kenya									
Sand dam (1750 m^3)	17966	898	0.5	6	89.8	0.05	0.6	0.55	6.6
Mali									
Ferrocement jar (13.6 m^3)	1388	69	5.1	-	-	-	-	-	-

A6. Interviews with the population

1.1. Introduction

The interviews done with the local population, were done by using a "game". This made it possible to overbridge the language barrier. In this appendix the game is explained in further detail. Goal of the game is to get an impression regarding the use, acceptance and perceived cleanness of different water sources. It is not developed to create awareness at a population level. However it can facilitate a process in which the available water sources are critically assessed. The game can provide valuable information regarding the current concerns and views of the respondents. It does not provide information regarding the real costs and cleanness of water, but it provides information regarding the cost and cleanness perception.

In paragraph 1.2 the questions that could be asked are stated. In paragraph 1.3 these questions are further explained. The game itself, is presented in the main report in paragraph 4.2.2. For both the questions and the cards a distinction is made between water sources (groundwater, surface water and rainwater) and methods for water gathering.

1.2. Questions that can be used

Below the questions that could be asked to the respondent are stated. Additional questions could be added when necessary. For question 1-3 the water source cards should be used (top three cards in Figure 19 in the main report). For question 4-7 the water gathering cards should be used (middle twelve cards in Figure 19). Questions are stated in paragraph 4.2.2 of the report, but repeated here.

Water sources

8. *Sumber air apakah yang Anda gunakan?*
   Which water sources are you using?
9. *Urutkan sumber air berikut mulai dari sumber yang paling Anda sukai.*
   Order water sources to your preference.
10. *Urutkan sumber air berikut dari sumber yang menurut Anda paling bersih hingga paling kotor.*
    Order water sources from clean to dirty.

Water gathering

11. *Bagaimana cara Anda mendapatkan air?*
    How are you gathering your water?
12. *Urutkan sumber air berikut mulai dari cara yang Anda sukai.*
    Order water gathering to your preference.
13. *Urutkan sumber air berikut mulai dari yang menurut Anda paling bersih hingga kotor.*
    Order water gathering from clean to dirty.
14. *Urutkan sumber air berikut mulai dari yang menurut Anda paling mahal hingga murah.*
    Order water gathering methods from cheap to expansive.

1.3. Further explanation regarding the questions

In this paragraph the questions that can be asked are further explained. For each question a new "round" of the game starts in which all cards are collected on one pile.

Question 1-3:

- For question one the respondent can select the water sources that are currently practised.
- For question two the respondent should order the three water sources cards to their prefference. For this the cards with the smileys can be used. The green happy smiley should be coupled to the water source that is most prefered. The yellow neutral smiley to the water source which is preceived neutral. The red sad smiley to the water source which is less preferred.
- For question three the respondent should sort the three water sources from clean to dirty. The green happy smiley should be coupled with the cleanest water source. The yellow smiley should be coupled to the medium clean water source and the red sad smiley should be coupled to the dirty water source.

Question 4-7:

- For question four the respondent can select the water gathering methods that are currently practised.
- For question five the respondent should order the twelve water gathering cards to their prefference. For this the cards with the smileys can be used. The green happy smiley should be coupled to the water gathering methods that are most prefered. The yellow neutral smiley can be coupled to the water gathering methods which is preceived neutral. The red sad smiley can be coupled to water gathering methods which are less preferred.
- For question six the respondent should sort the twelve water gaterhing methods from clean to dirty. The green happy smiley should be coupled with the clean water gathering methods. The yellow smiley should be coupled to the medium clean water gathering methods. The red sad smiley should be coupled to the water gathering methods that are previeved most durty.
- For question seven the water gathering methods are sorted from cheap to expansive. Water gathiring methods that are preceived cheap can be coupled with the green happy smiley. Expensive water sources are coupled with the red sad smiley. The yellow smiley is used for water gathering methods that are inbetween cheap and expensive.

B1. Water quality alternative water sources in Serang

In Table 45 the average water quality in households and from PDAMs in Tirtayasa, Pabuaran and Baros are compared with the Indonesian and WHO water quality guidelines. Both type of water sources do not comply with the standards for microbial contamination and for manganese. Averages are constructed by using data from 17 households and 4 PDAM measurements in Tirtayasa, Pabuaran and/or Baros. Selection is not random. For quality measurements at households, "low risk" locations are selected.

Table 45: Comparison of current water sources to the Indonesian and WHO water quality standards.

	Household**	PDAM	Indonesian Drinking Water standard 2010	WHO Drinking Water	Indonesian Clean Water standard 1990	
Physical Test						
Conductivity	-	-	NA	NA	NA	uS/cm
Turbidity	2.5	1.4	5	5*	25	NTU
Temperature (Water)	29	29	Room temp. + 3	NA	Room temp. + 3	°C
pH in situ	6.89	6.78	6.5 - 8.5	6.5 - 8.5*	6.5 – 9.0	n/a
Nitrogen						
Total Nitrogen	-	-	NA	NA	NA	mg/L
Total Kjeldahl Nitrogen	-	-	NA	NA	NA	mg/L
Nitrate (N-NO3)	3.09	1.55	50	50	10**	mg/L
Nitrite (N-NO2)	0.04	0.01	3	3	1**	mg/L
Ammonia (N-NH3)	-	0.23	1.5	NA	NA	mg/L
Microbiology						
E.coli	-	120	0	Not detectable*	NA	MPN/100mL
***Enterococcus* sp.**	-	-	NA	NA	NA	MPN/100mL
Campylobacter* spp.	-	-	NA	NA	NA	Per 25mL
Total coliform	1215	0	0	NA	10 - 50	MPN/100mL
Minerals						
Fluoride	-	-	1.5	1.5*	1.5	mg/L
Calcium-Dissolved (Ca)	-	28.3	NA	NA	NA	mg/L
Magnesium-Dissolved (Mg)	-	19.6	NA	NA	NA	mg/L
Metals						
Aluminium-Dissolved (Al)	-	-	0.2	0.2*	NA	mg/L
Arsenic-Dissolved (As)	-	-	0.01	0.01	0.05	mg/L
Copper-Dissolved (Cu)	-	-	2	2	NA	mg/L
Iron-Dissolved (Fe)	0.09	0.10	0.3	0.3*	1.0	mg/L
Manganese-Dissolved (Mn)	0.52	0.75	0.4	0.4*	0.5	mg/L
Sodium-Dissolved (Na)	-	-	200	200*	NA	mg/L
Lead-Dissolved (Pb)	-	-	0.01	0.01	0.05	mg/L
Zinc-Dissolved (Zn)	-	-	3	3*	15	mg/L
Organic						
Dissolved Organic Carbon	-	-	NA	NA	NA	mg/L

*, no official guideline value
**, household water is in general groundwater
NA, not available
-, not measured

B2. Measurement locations

Rainwater samples are taken at three different spots. Measurements are performed at different moments. Water inside tanks, roof runoff and direct rainfall is measured. Below the locations of the sampling will be explained in more detail. During the measurements the rain was of low intensity, and measurements are performed at 4 AM in the morning. The day before characterized itself by drizzle followed by some dry periods. No heavy rain was experienced.
With the bucket for raw rainfall measurements the first 10 litre is collected in the first 5 minutes. The second 10 litre is collected in the second 4 minutes of the rain event.

Measurement location Alang-Alang

Measurement location

The house located in Alang-Alang is parallel to the main road. The street is narrow and has houses on both sides. The house is relatively rich for the area, and looks slightly better maintained then most of the other houses in the street. A tree (just slightly higher as the house) is located in front of the house.

The roof

Main roof material are roof tiles, combined with some zinc sheets and a wooden construction. The roof is approximately 16 years old. Leakages occur rarely, and are repaired in case they occur. According the house owner no leaves are found on the roof, because the trees in the area are too low. However as can be seen on the pictures the tree just in front of the house is overlaying the roof. The roof is cleaned every year before the rainy season. According the owner this is the custom for people that use rainwater harvesting in this area. The owner tells us that no birds are present on the roof, and these (or the sigh of these) are also not detectable during the visual inspection of the roof. In general the roof looks a bit old due to the age, but also relatively clean.

Guttering

Water is directed towards the tank by a zinc or iron plates. Afterwards the water is transported towards the tank with a plastic (pvc) funnel and pipe. The guttering system is told to be 16 years old, which is the same age as the roof. According to the house owner, the water flows always easily through the gutter towards the tank.

The tank

This house uses a closed tank of approximately 1.6 by 2.0 meter and 2.0 meter high. The tank is told to be closed with cement at the top but it was not possible to check this visually. The general impression of the tank is clean, and well maintained. The tank has a hole at the top, to make sure it can be cleaned before the rainy season starts. This is stressed out by the owner, which gives the impression that cleaning is really done.

 

Figure 57: House at Alang-Alang were measurements will be performed (left) and a picture of the roofing material (right).

 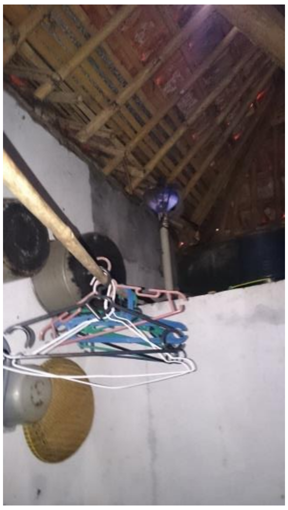

Figure 58: Tank (left) and guttering (right) for the house in which measurements are performed in Alang-Alang.

Measurement location in Lontar

Measurement location

In Lontar measurements were performed in an average sized house, located approximately 50 to 100 meter from the main road (which is also relatively small). The house is connected to the main street with a very small street (2 meters wide), and has neighbours at both sides and behind the house. Also in front of the house you find other houses (with just the small street in between). In the street a high tree (approximately 7 meter high) is located on the other side of the street in front of the house. According to the owners no birds are found on the roof, and also with visual inspection no direct signs of animals were found.

The roof

The main roofing material are roof tiles. However people in the area are very creative in adding different roof materials. Flat and corrugated iron is a common alternative roofing material. Zinc is also used to make gutters inside the house. Wood is mainly used for the construction of the roof, but can also be in contact with the rainwater is some cases.
Visual inspection indicates that the roof is of a relatively bad quality. The roof tiles look old, and show some colour changes. This is also as you would expect, since the roof of this house is already 28 years old. When leakages occur they will be repaired at a certain point. The roof is in general cleaned before the rainy season, and leaves are told to be removed, when seen on the roof. The roof is

connected to the roof of the neighbours. They have a gutter, but possibly some of the rainwater will also come in the rainwater harvesting system of this house. This house of the neighbours uses relatively new roof tiles. Not the entire roof is connected to the tank, maybe just 7.5 m^2 of roof area is connected. It is difficult to approximate exactly, because the water flow on the roof cannot be predicted exactly.

The guttering

The main gutter is currently made from plastic (pvc). It consists of a funnel connected to a pipe, which is directed towards the tank. Metal sheets (iron/zinc) are used to regulate the water flow towards the tank. The piping system is relatively new (4 months old).

The tank

In the house an open rainwater harvesting system is used. Water quality inside this tank is measured. A picture of the tank can be found in Figure 59.

Figure 59: Measurement location Lontar. House from the outside (left) and open rainwater harvesting tank (right).

Figure 60: Roofing material of the house. On the left the view from outside and on the right the view from inside.

Figure 61: Guttering used in the rainwater harvesting system. The gutter is connected with a funnel to the roof, and afterwards the water is transported with a pipe towards the tank.

Direct rainfall measurements

Direct rainfall measurements are performed in front of the head of the village building in Alang-Alang as shown in Figure 62. Rainfall is collected in big buckets of 43 cm diameter at the top, 37 cm diameter at the bottom and 23 cm height. After collection of the rainwater in the big buckets it is stored in the sampling buckets.

Figure 62: Location of the direct rainfall measurements (Alang-Alang).

B3. Treatment chain

In Figure 63 the treatment chain as discussed in paragraph 5.3.3.4 is visualized. Main point is that different types of water use require different water qualities. Potable purposes like drinking and cooking require water that does not exceed the water quality guidelines. For several non-potable purposes the water quality can be less strict. More research is needed to regarding the water quality requirements that should be met for water used for different purposes.

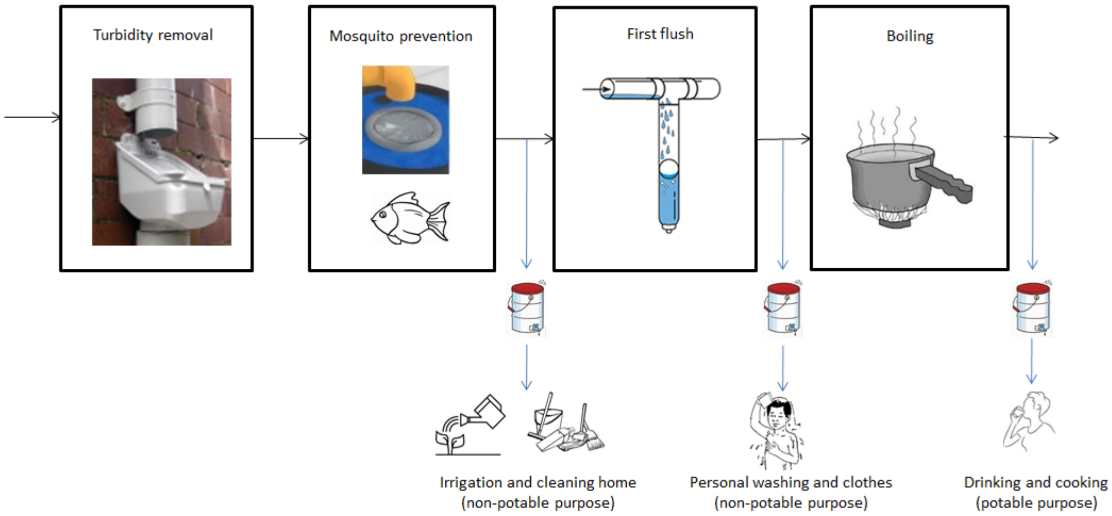

Figure 63: Visualization of the suggested treatment chain.

C1. Cumulative missing data and double mass plot for the four rainfall stations in Banten

To check the rainfall data between 01-01-1990 and 31-12-2014 the cumulative missing data was plotted against time, and double mass plots were constructed.
As can be seen in Figure 64 the cumulative missing data is a relatively straight line for all stations until end 2013. After this period the cumulative missing data for the station in Serang and Soekarno Hatta in Tangerang increases. Because of this data from 2014 is disregarded in the analysis.

In Figure 65 the double mass plots are shown, which are relatively straight lines. Based on this it can be concluded that there are no large mistakes in the data. In the figure it can also be seen that the rainfall in Tangerang and Serang is relatively similar qua amount, were in Tangerang Seleta the total rainfall is in generally more as in Tangerang and Serang.

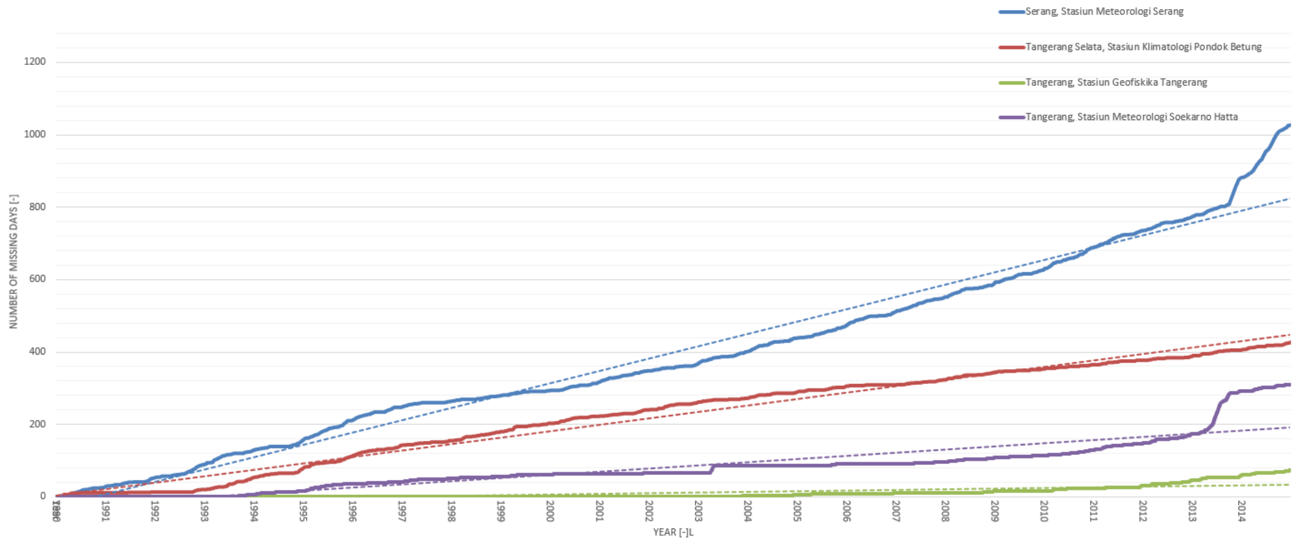

Figure 64: Cumulative missing data (in days) for the four selected stations.

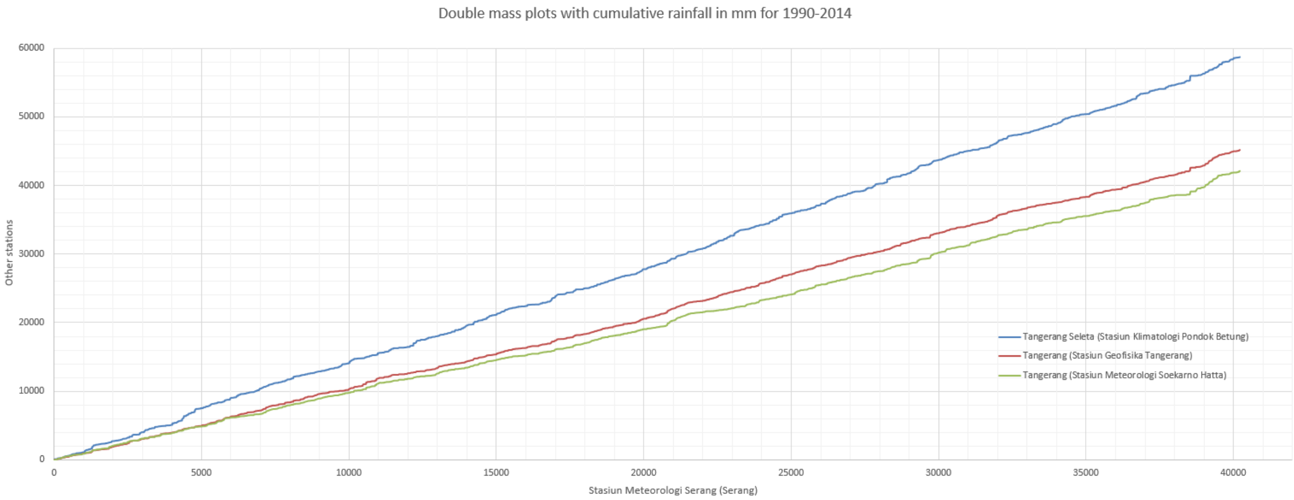

Figure 65: Double mass plots for the cumulative rainfall [mm] of all stations. On the x-axis the cumulative rainfall for the station in Serang is shown, and on the y-axis the cumulative rainfall of the other stations. The amount of rainfall in the stations in Tangerang is similar to the rainfall in Serang. In Tangerang Seleta there is in general more rainfall as in Serang.

C2. Water use pattern for scenario 2b

In Figure 66 and Figure 67 the water use pattern for scenario 2b can be found for the optimum with the maximum total tap flow, and for the weighted optimum respectively. Calculations are performed for a tank size of 2 m^3 and a roof size of 100 m^2.

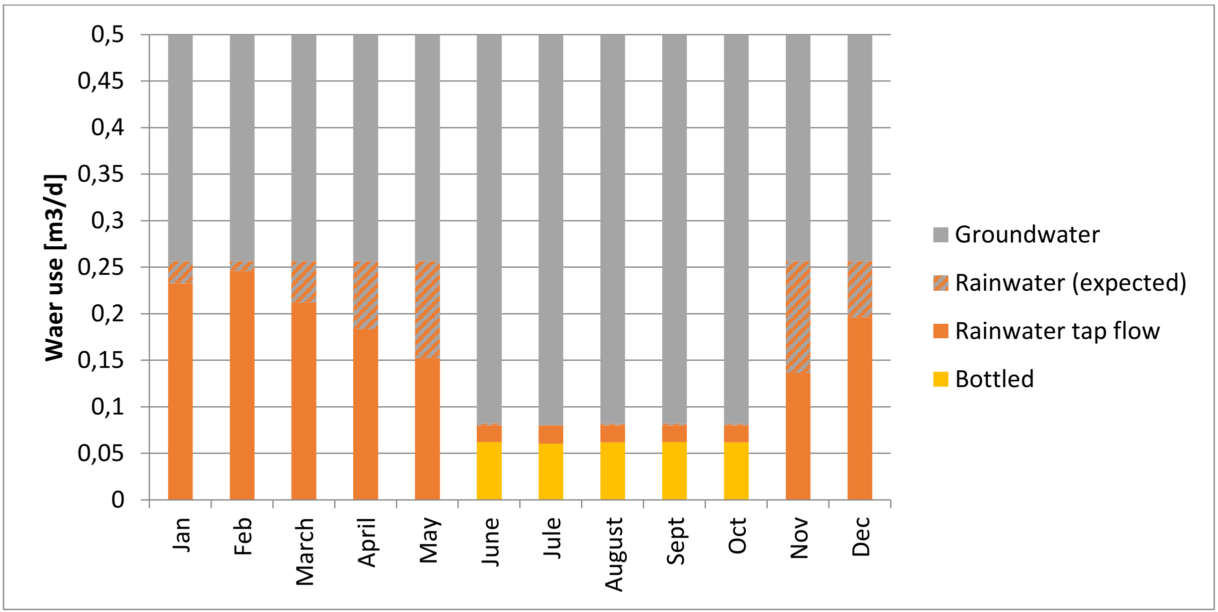

Figure 66: Water use for scenario 2b, optimized towards a maximum tap flow. Roof size = 100 m^2 and tank size is 2 m^3.

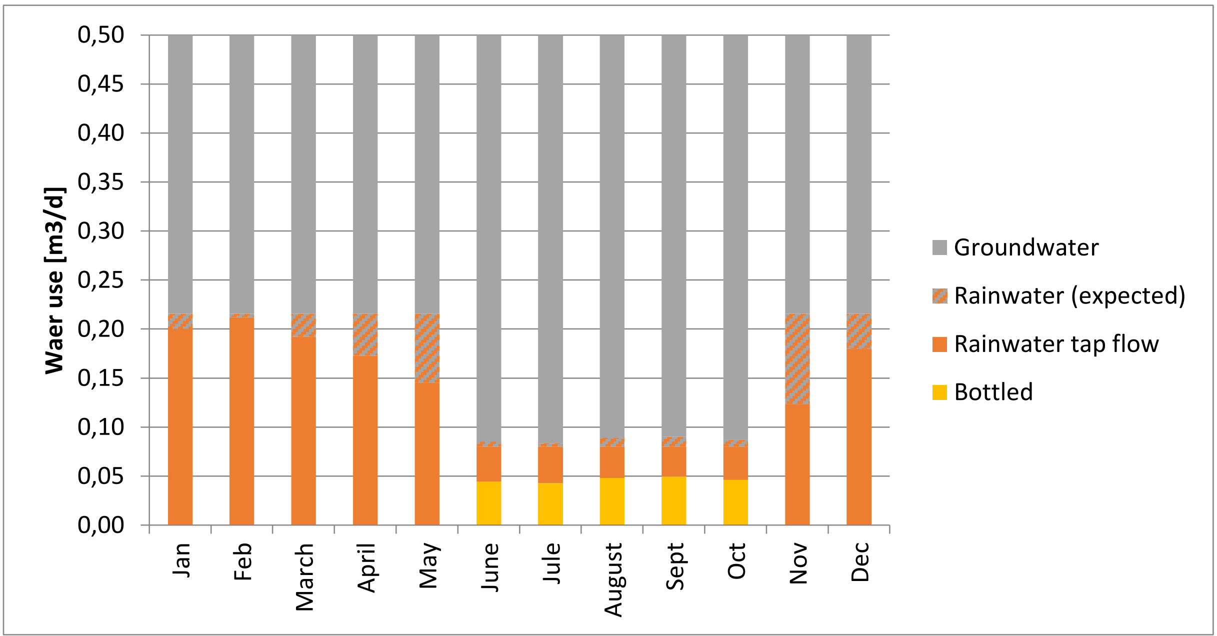

Figure 67: Water use for scenario 2b, weighted optimization. Roof size = 100 m^2 and tank size is 2 m^3.

C3.Relation between average tap flow over all months and monthly tap flow

In Figure 68 the selection of the maximum average tap flow is visualized per month. As can be seen especially January and February have large influence on the average tap flow which is used for the optimization in scenario 2c(i).

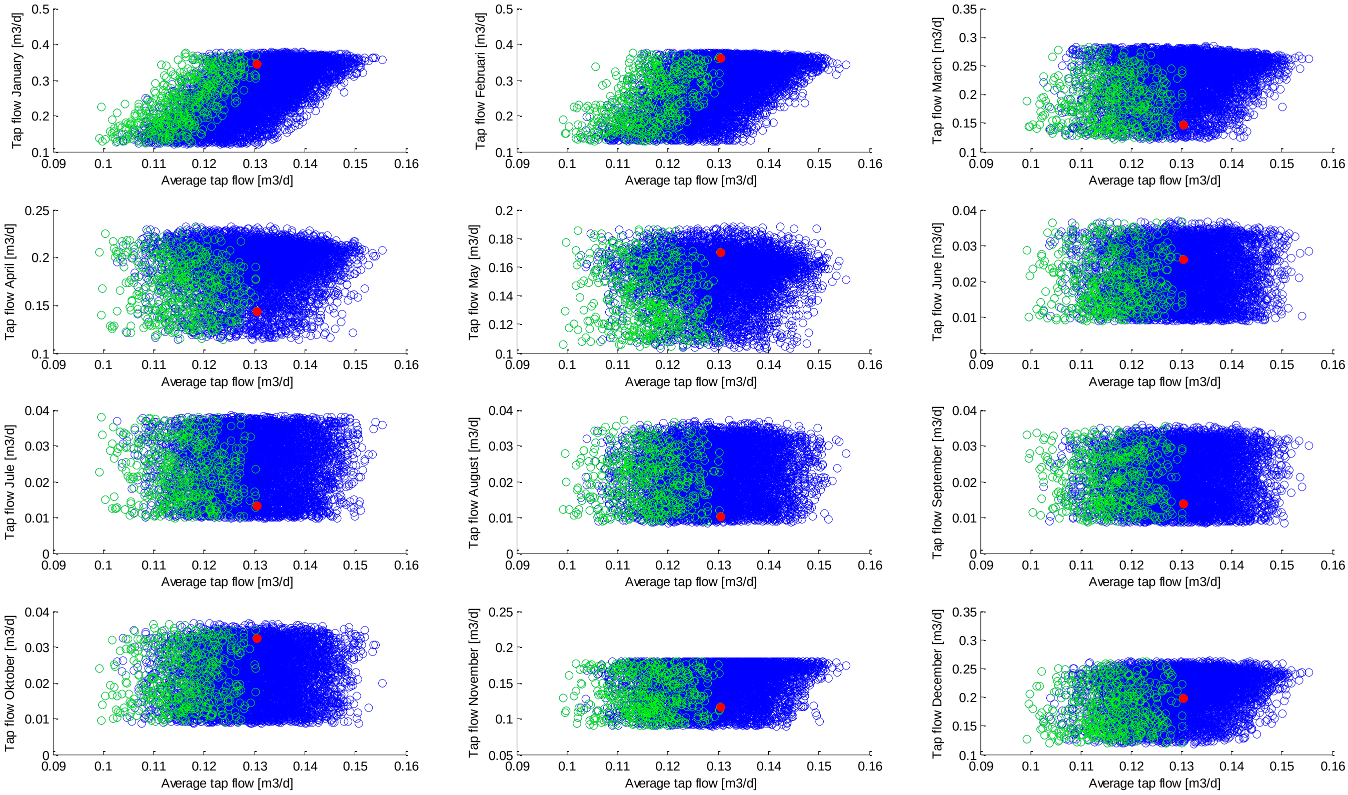

Figure 68: Relation between average tap flow [m^3/d] and monthly average tap flow [m^3/d]. Green dots meet the 20% requirement for the percentage of days the demand is not met. Blue dots, don't meet this requirement.

C4. Results for scenario 2a

In paragraph 5.4.3.3 the results for scenario 2a are presented for a roof size of 100 m^2. In this paragraph the same results are presented for roof sizes of 50 and 150 m^2. Figures show the relation between the percentage of days the demand is not met (failure probability) and the tank size for different demands. Note that these demands are not always met (which is shown on the vertical axis).

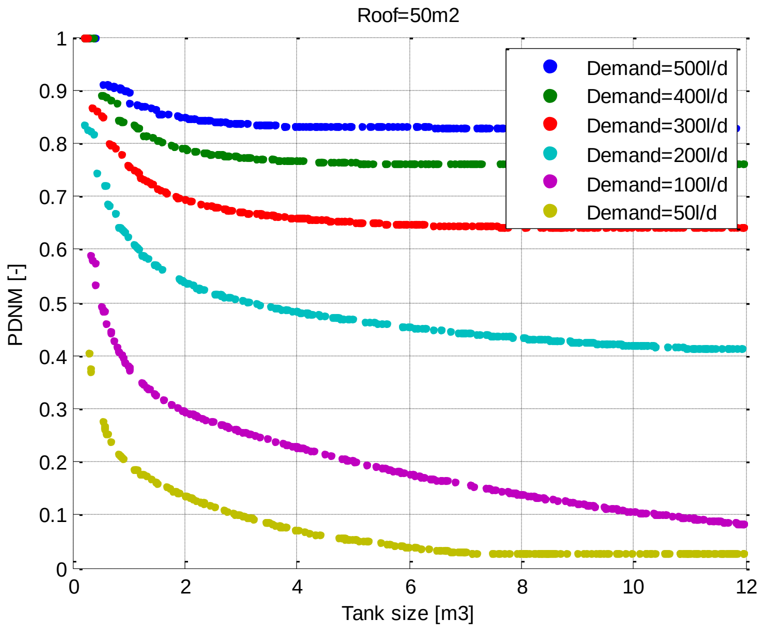

Figure 69: Relation between PDNM and tank size for a roof of 50 m2 and different demands.

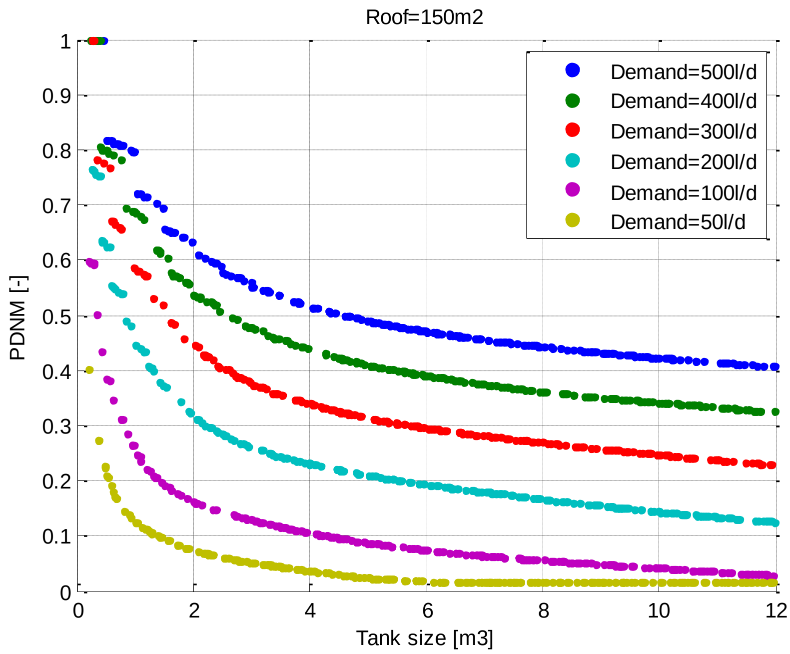

Figure 70: Relation between PDNM and tank size for a roof of 150 m2 and different demands.

C5. Tap flow per month for scenario 2a

In Figure 71 the tap flow distribution can be found for scenario 2a. Taking into account that maximum 20% of the days the demand cannot be met, a demand of 0.1026 m^3/d is found. As can be seen in the figure this demand is met in the wet months, but not in the dry months.

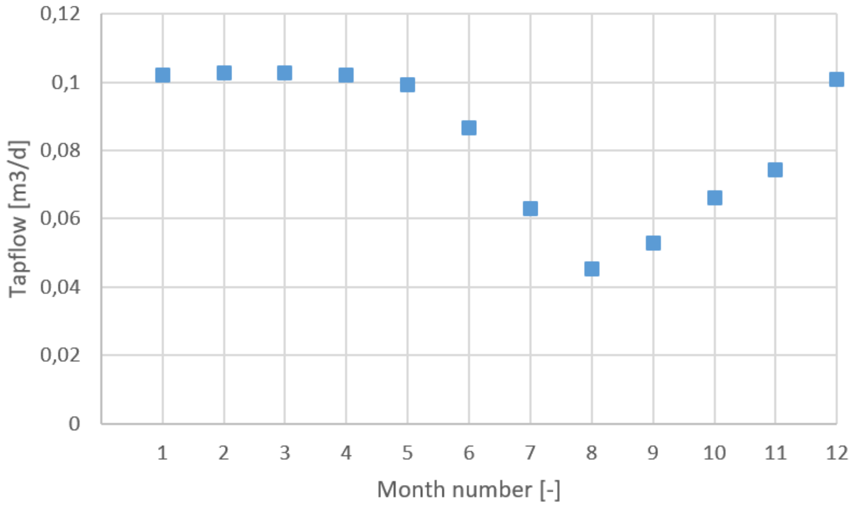

Figure 71: Tap flow distribution for scenario 2a.

D1. Material requirement and prices for rainwater harvesting tanks

In Table 46 the formulas used to calculate the material requirements for the ferrocement tanks can be found. By applying these formulas for different tank sizes the material requirements can be found (Table 47). Standard diameter and heights are used for the tank, which are presented by Sharma & Gopalaratnam (1980).

Table 46: Formulas used to calculate material requirements for the ferrocement tanks (Sharma & Gopalaratnam; 1980).

Formulas for the calculation of material requirements for the ferrocement tank	
Mesh	A_{mesh} [m2] = $1.1*2*(\pi r^2+2\pi rh+1.2\pi r^2)$
Sand	M_{sand} [kg] = $1.1*(A_{base}*t_{base}+A_{wall}*t_{wall}+A_{roof}*t_{roof}+A_{lid}*t_{lid})*2000$ [kg sand/m3 mortar]
Cement	M_{cement} [m3] = $1.1*(A_{base}*t_{base}+A_{wall}*t_{wall}+A_{roof}*t_{roof}+A_{lid}*t_{lid})*1000$ [kg cement/m3 mortar]
Iron/Steel reinforcement	$L_{reinforcement}$ [m] = $1.1*(L_{base}+L_{vertical}+L_{ringwalls}+L_{radailroof}+L_{ringroof}+L_{lid})$

Table 47: Indication material requirements for a ferrocement tank of different sizes (Sharma & Gopalaratnam; 1980).

Volume [m^3]	Mesh [m^2]	Sand [m^3]	Cement [kg]	Iron/Steel bar 6 mm [m]	Labour [day]
1	13	0.26	184	74	4
2	21	0.41	285	95	5
4	32	0.73	512	135	6
8	50	1.45	1016	194	7

In Table 48 the used materials prices can be found. Prices are based on personal communication with Imroatul (2016), who found price indications on the world wide web.

Table 48: Indication of the prices used for the different materials.

	Price (Rup)	Unit	Formula
Ferrocement tanks			
Mesh	28,000	per m^2	A_{mesh} [m2]
Sand	135,000	per m3	M_{sand} [kg]
Cement	71,000	per 50 kg	M_{cement} [m3]
Iron/Steel	24,000	per meter (6 mm)	$L_{reinforcement}$ [m]
Plastic tank			
Pinguin	2,500,000; 4,800,000 9,300,000; 20,000,000	for a tank of 1,2,4 and 8 m^3 respectively	[-]
Ferrocement and plastic tanks			
Pipes	25,000	per m	20 [m]
Elbow	6,500	per unit	6 [-]
Gutter	56,000	per 5 m	SQRT(RS)*4 [m]
Gutter filter	30,000	per unit	1 [-]
Soil excavation	78,5000	per m3	0.5+TS/4 [m3]
Labour	100,000	per person day	X* + RS/150
Maintenance	2 (plastic) 4 (ferro)	% of initial costs a year	$NPV_{maintenace} = \Sigma\, r / (1+i)^t$

* Labour requirement depends on tank type and size. For plastic tanks a basic labour requirement (X) of 1 day is assumed. For ferrocement tanks of 1,2,3 and 8 m3 a labour requirement (X) of 4,5,6,7 days is used.

D2. Costs and tap flow for different system sizes

To calculate the costs per m^3 of tap flow the lifetime costs for different system sizes have been calculated. These prices can be found in Table 49.

Table 49: Total lifetime costs for different tank [m^3] and roof sizes [m^2] for ferrocement and plastic tanks.

Lifetime costs ferrocement tank [euro]				
	1 m^3	2 m^3	4 m^3	8 m^3
25 m^2	486.83	568.29	779.83	1082.28
50 m^2	536.92	618.38	829.92	1132.37
75 m^2	575.76	657.22	868.77	1171.21
100 m^2	608.78	690.24	901.78	1204.23
150 m^2	664.73	746.18	957.73	1260.17
Lifetime costs plastic tank [euro]				
	1 m^3	2 m^3	4 m^3	8 m^3
25 m^2	371.83	562.87	936.73	1824.47
50 m^2	411.41	602.46	976.32	1864.05
75 m^2	442.10	633.15	1007.01	1894.74
100 m^2	468.19	659.24	1033.10	1920.83
150 m^2	512.40	703.45	1077.31	1965.04

For the calculation of water costs total lifetime costs are taken into account. Costs for the installation of the roof are not taken into account, since this is assumed to be already present.
Prices per m^3 of tank decrease for larger systems, as can be seen in Figure 72. However also the tap flow per m^3 of tank decreases for larger tanks, as visualized in Figure 73. Because both decrease for larger system sizes there is a certain optimum point at which the lifetime costs / total tap flow are the lowest.

The reason why the tap flow per m3 tank decrease can be explained by the fact that the system (in the investigated boundaries) is roof size limited. Investigated roofs are not large enough to always fill the tank, and if the tank becomes even larger this becomes even more difficult.
However, one should also consider the two asymptotes of the system. Asymptote 1 is their due to the maximum water use of 1 family is restricted towards 0.5 m^3/day. This also holds for large tank sizes, and this gives the asymptote (0.5 / Tmax). Asymptote 2 is related to the point at which an increase in roof size will not further lead to an increase in tap flow, since all the water that will be additionally harvested will overflow. This asymptote is solely reached at unrealistic roof sizes (for example a roof size of 53.763 m^2 for a tank size of 1 m^3). However at very small tank sizes, this asymptote can become relevant.

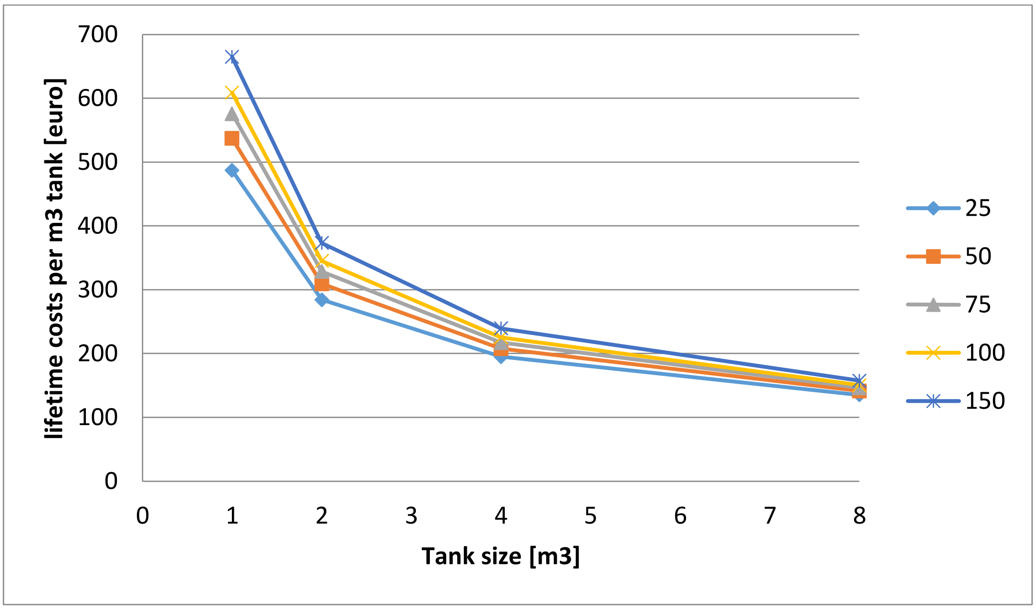

Figure 72: Lifetime system costs for ferrocement tanks per m3 of tank for different roof sizes (scenario 2d(Tmax/2)).

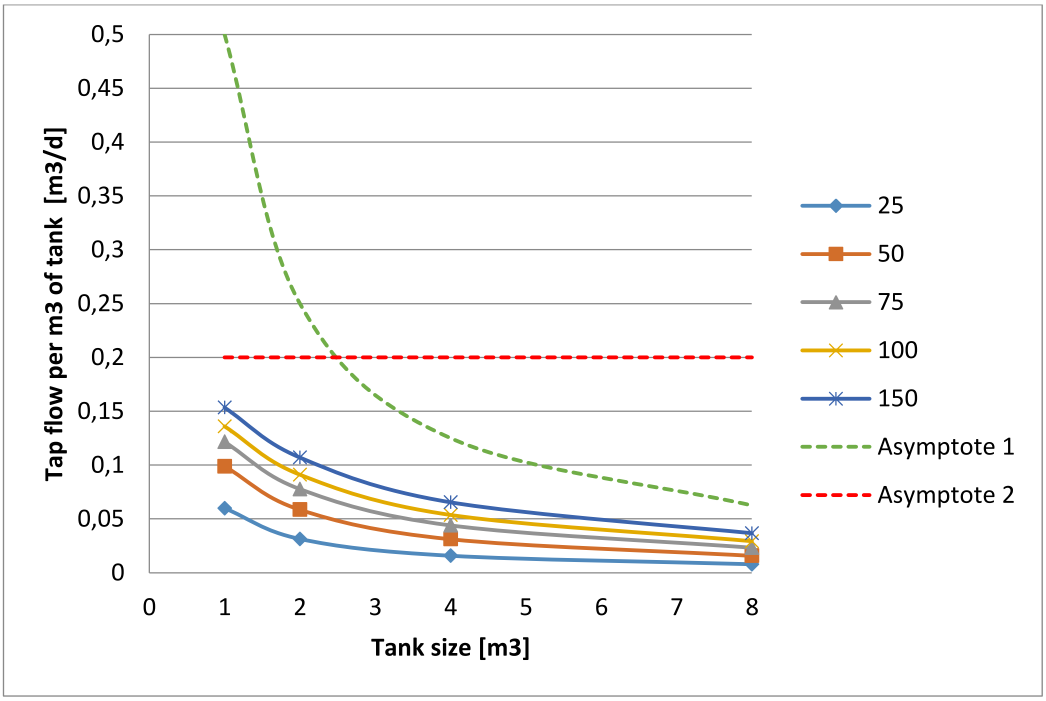

Figure 73: Tap flow per m3 of tank for different roof sizes (scenario 2d(Tmax/2)).

D3. Costs per m3 of water for ferrocement tanks (Tstor) plastic tanks

In Figure 74 the water costs per m^3 can be found in case all scenario 2d(Tmax) is used. Prices are slightly lower, but not much compared to scenario 2d(Tmax/2) for the ferrocement tanks.

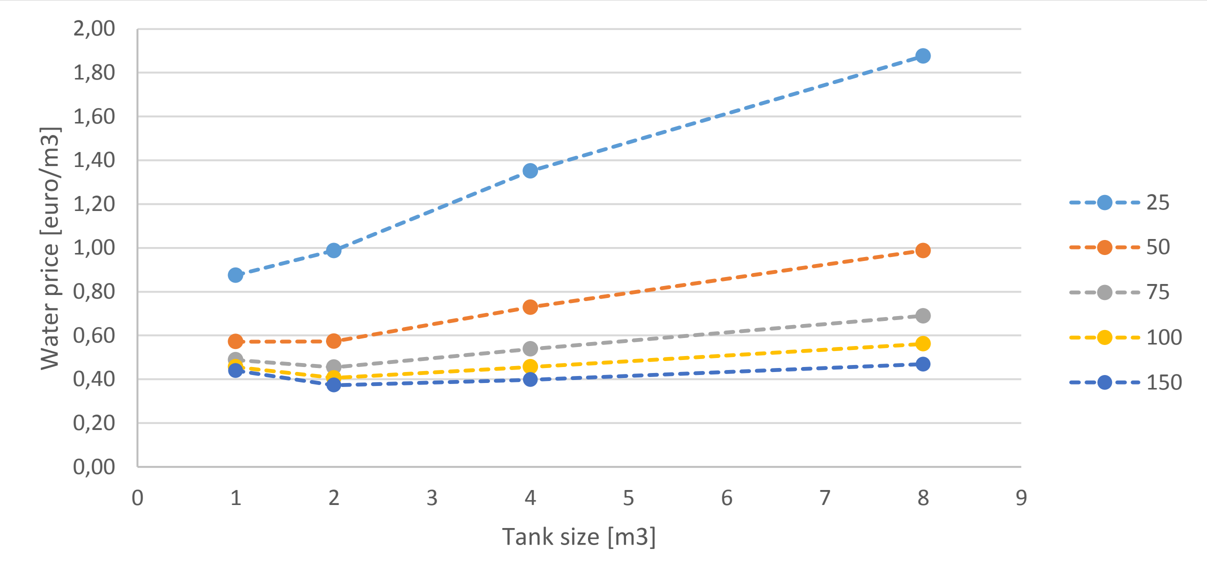

Figure 74: Water costs for scenario 2d (Tmax) for different tank sizes and roof sizes for ferrocement tanks.

In Figure 75 the water costs per m^3 can be found for plastic rainwater harvesting tanks. In general the small tanks of 1 m^3 give the lowest water costs. Only in case a roof of 150 m^2 is used a slightly lower water costs can be found for a tank of 2 m^3. In any case the water costs for plastic tanks is found to be higher as the water costs for ferrocement tanks.

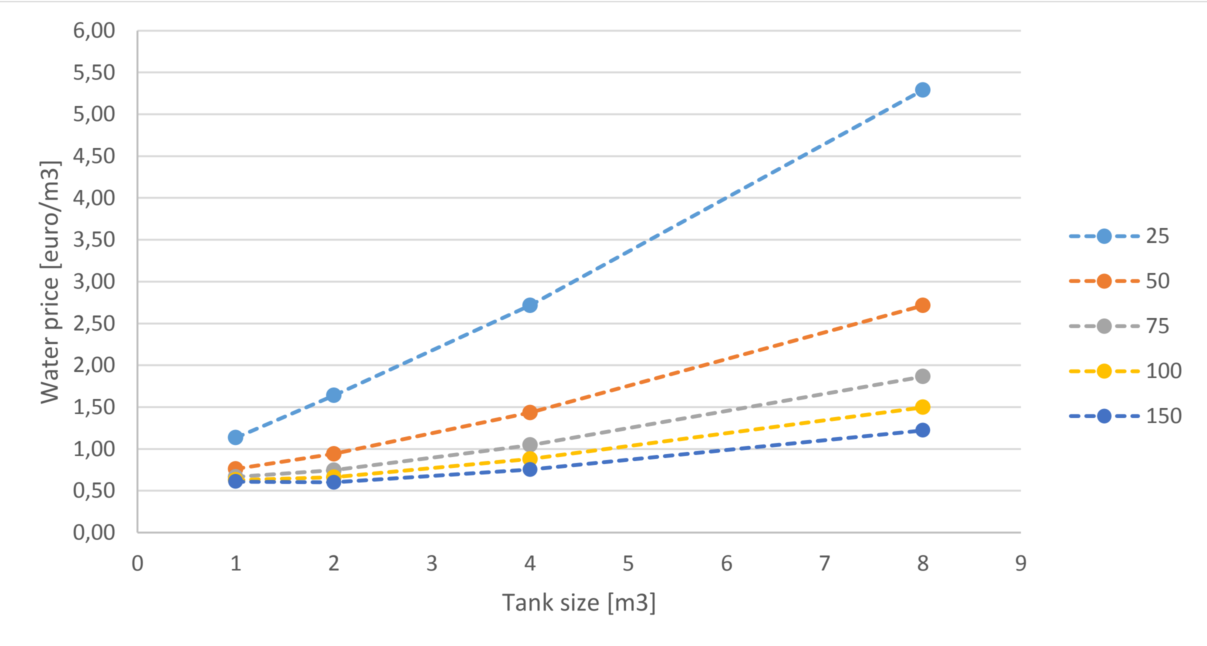

Figure 75: Water costs for scenario 2d (Tmax/2) for different tank sizes and roof sizes for plastic tanks.

D4. Formulas used to determine the amount of water used from each source

With the formulas presented below one can calculate how much rainwater, bottled water and groundwater is used for a specific scenario, annually.

$$Rainwater_{new}\ [m^3/year] = 365.25\ [\frac{d}{y}] * Average\ tap\ flow\ [\frac{m3}{d}]$$

$$Bottled_{new}\ [m^3/year] = 365.25\ \left[\frac{d}{y}\right] * \frac{Percentage\ low\ flow\ [\%]}{100} * (Fresh\ water\ need\ [\frac{m3}{d}] - Average\ low\ flow\ [\frac{m3}{d}])$$

$$Groundwater_{new}\ [m^3/year] = \left(365.25\ [\frac{d}{y}] * 0.50\ \left[\frac{m^3}{d}\right]\right) - Rainwater[\frac{m^3}{y}] - Bottled[\frac{m^3}{y}]$$