

**Investigation into Physicochemical Parameters of Harvested Rainwater with
Respect to Drinking Water Quality Standards**

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Statement of Originality

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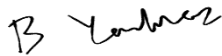
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Abstract

The need for water is gradually increasing due to many factors such as urbanization, climate change and drought. Therefore, interest in rainwater harvesting systems, which have been used for potable and non-potable purposes since ancient times, has been increasing in recent years. Despite this, the low quality of water collected in rainwater harvesting systems poses significant concerns, particularly in the use of drinking. The sources of chemical contaminants and the path of them to reach the storage tank are complicated. The aim of this dissertation was to make recommendations to improve the physicochemical quality of the harvested rainwater for drinking water by examining whether the chemical pollutants in the rainwater harvesting systems are mostly caused by the pollutants picked-up by the rainwater in the atmosphere or the pollutants accumulated on the roof. Secondary data on physicochemical parameters were collected after a detailed literature review to achieve this aim. Eleven different studies in which the data were collected were selected using the Google Scholar engine according to the created study inclusion criteria. Mean levels of physicochemical parameters of direct rain, first-flush and storage tank were compared with WHO drinking water guideline limits and parameters that concern about drinking water were determined. When comparing the parameters in the first-flush and the storage tanks after the first-flush was removed, it was determined that more than 50% of pollutants were in the first-flush, indicating that the pollutants in storage tanks were caused by substances accumulating on the roof rather than direct rain. Also, NO_3 , SO_4 , TDS, TSS, Cu, Mg and Cu concentrations in the storage tank meet WHO drinking water guideline limits in all studies after the removal of the first-flush. In the storage tanks, pH, turbidity, Al, Zn, and Pb concentrations exceeded WHO drinking water guideline limits in many studies, depending on the proximity to pollution sources and the materials of roof, gutter and downpipes in the rainwater harvesting system. In these cases, measures such as cleaning and maintenance after a long period of dry days, using of filter in the point-of-use and using of the non-metallic roof, gutter and downpipes must be taken before using the harvested rainwater for drinking purposes. In addition, in cases where the physicochemical parameters in direct rain exceed WHO drinking water guideline limits, additional treatment was recommended for the harvested water before using of drinking purposes since more first-flush volume or filtration would not be sufficient.

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1.0 Introduction

Water is one of the most important part of life and access to water is a human right (UNESCO, 2019). However, more than 2 billion people in worldwide lack of basic water services, and about 10 % of these people are dependent on surface water for their daily needs (WHO,2019). In addition to this, it is expected that almost half of the world's population will experience severe water shortages by 2030 (SDG Knowledge Platform, 2019) and one of the Sustainable Development Goals (SDG) of the United Nations is to provide the availability and sustainability of water for everyone. However, increasing water demand and water security threats because of the growing population and urbanization, and more frequent droughts and floods due to climate change affect not only water-poor countries but also the future of the whole world (Sazakli et al., 2007).

On the other hand, access to clean water is another major problem facing humanity due to the scarcity of water because the quantity and quality of water are interrelated strongly (Sazakli et al., 2007). Another important problem is that the impermeable surfaces that increase with the effect of urbanization increase the surface water runoff (Lee et al., 2010). Also, the increase of impermeable surfaces cause a decrease in groundwater dependent on the infiltration rate (Quek & Forster, 1993; Lye, 2002). Additionally, excessive consumption and pollution of urban water resources creates additional energy costs due to the transmission of the more distance water resource and increases leakage losses (Zhang et al., 2014). As accessibility and quality decrease in traditional water sources, alternative water sources related to rainwater is becoming more important increasingly.

In many regions, rainwater has been considered and used for potable or non-potable purposes since ancient times during the dry season (Gould, 1999; Gikas & Tsihrintzis, 2012). Rainwater harvesting systems are one of the most important techniques that allow rainwater to be used for these purposes (Nosrati, 2017; Sanchez et al., 2015). The increasing importance of sustainable management of water for future generations further increased the interest in rainwater resources. In addition, the fact that rainwater harvesting systems are cheap and easy to maintain makes these systems attractive. (Helmreich & Horn, 2008). Nevertheless, industrialization and the impact of the growing population have a significant impact on atmospheric pollution (Gikas & Tsihrintzis, 2017). Atmospheric pollution affects either the

water quality in existing water sources or affects the quality of rainwater harvested from different surfaces. Although roof catchments are one of the most important of these surfaces, according to Chang et al. (2004) they are attractive places for contaminants. While the increasing population increased water pollution, it also increased the need for water (Abbasi & Abbasi, 2011).

The quality of rainwater begins to change when it picks up particles and substances in the air. The strong solvent property of water causes it to take up almost all of the substances it encounters (Abbasi & Abbasi, 2011). Capturing and storage of the rainwater are other phases that affect the quality of rainwater in rainwater harvesting systems (Gwenzi et al., 2015). The rainwater reaches the storage tank by washing the microbiologic pathogens, organic substances, dirt, dust and other contaminants such as heavy metals accumulated on the roof on dry days. This phenomenon, known as the first-flush runoff, occurs at the beginning of rain and contains significant amount of pollutants (Gikas & Tsihrintzis, 2017; Martinson & Thomas, 2005). Devices that ensure the removal of the first-flush runoff contribute significantly to improving the quality of the harvested water (Mendez et al., 2010; Yaziz et al., 1989). Also, the materials of the roof surface, storage tank, gutters, and downpipes have an impact on harvested rainwater quality (Dillaha & Zolan, 1985). In addition to these, climatic factors such as rainfall amount, the number of preceding dry days, rainfall intensity, and the temperature affects the quality of harvested rainwater (Yaziz et al., 1989).

Rainwater collected from rainwater harvesting systems may have physicochemical and microbiological pollutants (Abbasi & Abbasi, 2011). Microbiological contaminants are generally caused by animals (Evans et al., 2006; Ahmed et al., 2010) whereas chemical pollutants are caused by human activities such as traffic emissions, industrial pollution, usage of pesticides and fertilizers (Melidis et al, 2007). Microbiological pathogens and chemical contaminants contain risks that threaten human health (Sazakli et al, 2007). For example, Nosrati (2017) said that NO_3 , one of the chemical parameters of drinking water, causes blue baby disease and gastric carcinomas when it is in high concentration in drinking water. Therefore, it is important to analyse the quality of harvested rainwater, which is used especially for drinking purposes.

Generally, many factors such as microbiological pathogens, surrounding activities, weather conditions, the materials of the components of the rainwater harvesting system, water

management, cleaning and maintenance have impact on the quality of rainwater harvested from roofs (Lee et al, 2010; Gikas & Tsihrintzis, 2017; Melidis et al, 2007). Yaziz et al. (1989) and Lee et al. (2012) stated that there were no faecal coliforms or total coliforms in samples taken directly from precipitation, while they encountered these microbiological parameters in samples from storage tanks. In contrast, Mendez et al. (2010) detected total coliform and faecal coliform in samples taken from direct rain and stated that the reason for this was that the sampler where samples from direct precipitation were collected was open during the night and that the birds were causing microbiological parameters. All this supports that microbiological pathogens in storage tanks are caused by the accumulation in the roof and that there is no microbiological pathogen in direct rain.

Investigation of the harvested rainwater quality is complicated by the myriad number of factors affecting rainwater quality. In addition, as mentioned above, the fact that rainwater picks up chemical contaminants in air and on roof surface in rainwater harvesting systems makes it difficult to understand where the chemical parameters affecting rainwater quality have increased. Although it is certain that microbiological pathogens are caused by the accumulation on the roof, it is not known whether chemical pollutants are mostly caused by direct rain or roof accumulation.

1.1 Aim and Objectives

The aim of this dissertation is to make recommendations to improve the physicochemical quality of the harvested rainwater for potable water by examining whether the chemical pollutants in the rainwater harvesting systems are mostly caused by the pollutants picked-up by the rainwater in the atmosphere or the pollutants accumulated on the roof. The specific objectives of the dissertation are:

1. To collect secondary data about physicochemical parameters of direct rain, storage tanks and first-flush of roof-rainwater harvesting systems.
2. To compare the physicochemical parameters obtained from direct rain, first-flush and storage tanks with WHO drinking water standards and determine physicochemical parameters that exceed WHO drinking water guideline limits in rainwater harvesting systems.
3. To examine how concentrations of physicochemical parameters passing through the rainwater harvesting system change.

4. To make some recommendations for the physicochemical quality of harvested rainwater to meet WHO drinking water standards.



2.0 Literature Review

The purpose of the literature review is to examine and analyse past studies and researches related to rainwater quality in rainwater harvesting systems in line with the aim and objectives of the project presented in chapter 1. The objectives of this review are to recognize rainwater harvesting systems, classify pollutants and investigate their causes, identify factors affecting rainwater quality, and examine management types to improving water quality in rainwater harvesting systems. The sub-topics examined;

- Rainwater Harvesting
- Rainwater Harvesting Systems
- Quality of harvested rainwater from roof catchments
- Management of harvested rainwater quality

2.1 Rainwater Harvesting

Although water is the most basic need for humanity, there are always situations when it is not available. Therefore, there are methods and technologies for water supply in many parts of the world. However, the need for water is met with rainwater, especially in regions where water resources are insufficient. Increasing factors such as water scarcity and climate change, and sustainability gaining importance have increased the use of rainwater in almost every region of the world.

Rainwater harvesting is not a new technique. Since ancient times, where access to water is difficult, people have found solutions for dry seasons by collecting and storing rainwater (Gikas & Tsihrintzis, 2012; Despins et al., 2009). One of the main reasons why this method has been used for many years is that rainwater, which is the most important part of the hydrological cycle, is a free and renewable source. Rainwater harvesting is an attractive solution where water resources are inadequate and polluted and contributes to socio-economic development (Zhu et al., 2004; Al-Salaymeh, 2011). In addition, the increase in the demand for water and the increase in the pressure on the existing water resources with the impact of the population growth and urbanisation has increased the interest in the rainwater harvesting systems, which is one of the alternative water resources (Villareal & Dixon, 2005). Therefore, rainwater harvesting is becoming increasingly important, especially in developing countries where water scarcity is intense. In addition to this, rainwater harvesting has been integrated into regions

where traditional water supply systems are insufficient to meet water demand (Handia et al., 2003). Also, having less environmental impacts than other water supply methods makes rainwater harvesting the main alternative water supply (Sazakli et al., 2007; Zhu et al., 2004).

Houston & Still (2002) defined rainwater harvesting as keeping and collecting rainwater runoff from a catchment. According to Gupta (2011), rainwater harvesting refers to the method of catching and storing rainwater. In general, rainwater harvesting can be described that it is a method that meets the needs of potable and not-potable after capturing, collecting and storing rainwater from surfaces such as roof, road, public spaces etc. When regular maintenance and cleaning is made on the catchment surface, rainwater harvesting is a very important alternative method for water need (Lee et al, 2010). The impact of developing technology and the rapid reduction of water resources led to its development and increase in its use worldwide. This dissertation covers only rainwater harvested from roof surfaces.

2.2 Rainwater Harvesting Systems

According to the purposes of use, Rainwater Harvesting Systems (RWHS) can be divided into different sub-techniques. Domestic and agricultural rainwater harvesting is most important rainwater harvesting techniques (Helmreich & Horn, 2009). Furthermore, RWHS can be used to prevent flood risk and to control stormwater runoff in urban areas. While Agricultural RWHS (ARWHS) is used for irrigation purposes, Domestic RWH (DRWHS) provides water harvested from rooftops for potable and non-potable (toilet flushing, car washing, clothes washing etc.) purposes. Rainwater harvested from the roof surface will be the focus of this study (DRWHS).

As seen in figure 1 DRWHS mainly consists of the collection surface (rooftops), gutters and downspouts, storage tank. Rainwater falling on the roof surface flows throughout the surface, then it is transmitted to the water storage tanks via gutters and downspouts. Interest in domestic RWHS has increased with water scarcity and reduced water quality and has caused new components such as first-flush diverters, filters, screens, water treatment to be included in the systems (Gupta, 2011; Che-Ani et al., 2009; Texas Water Development Board, 2005).

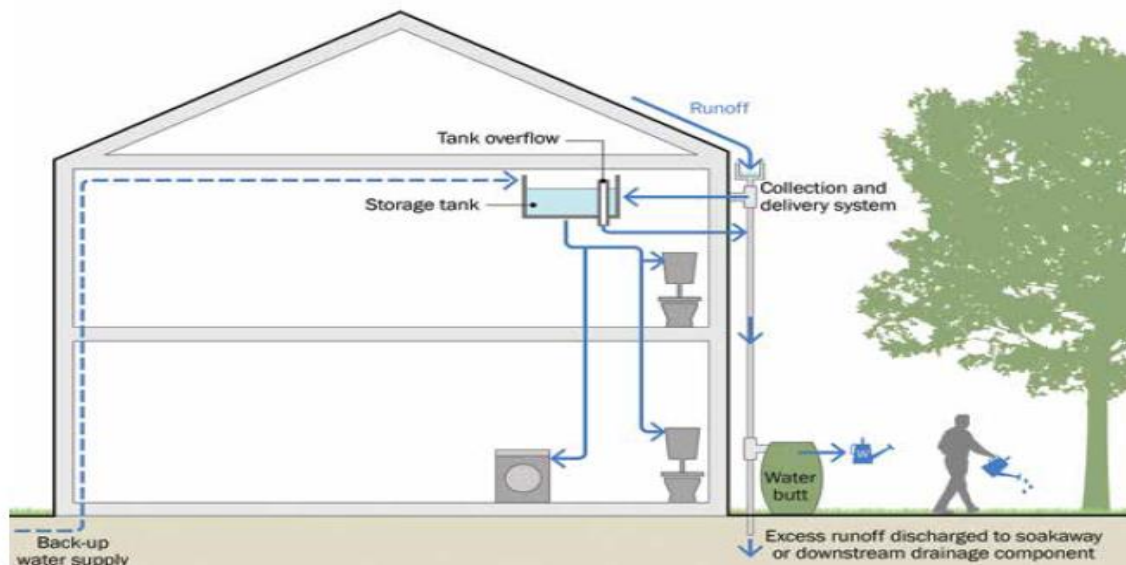


Figure 1 - Schematic Diagram of Roof Rainwater Harvesting System (CIRIA, 2009, p. 210)

Some advantages of rainwater harvesting systems include that they have economic advantages such as reducing water bills and low investment costs, reduce the amount of energy spent on water transmission and decrease the pressure on the main water supply of the city (Rahman et al., 2014; Ahmed et al., 2011; Lye, 2002). According to Zhu et al. (2004), the fact that the owners are fully responsible for the maintenance and operation of these systems also reduces the issues and costs associated with maintenance and operation. Rainwater harvesting systems reduce the amount of water going into the drainage system, thereby extend the life of traditional drainage systems and also decrease the costs required for existing drainage system restoration. Therefore, they are used in urban areas to contribute to conventional drainage systems. Also, the fact that rainwater harvesting systems are easy to install and operate and enable consumption where rain falls, makes this sustainable method attractive (Lee et al., 2010).

One of the disadvantages of RWHS is that they are inefficient for some regions because the amount of rain is uncertain (Zhu et al., 2004; Almdny et al., 2009). At the same time, as uncertain rainfall increases the need for storage, costs increase accordingly. One of the other cons is that although these systems are beneficial in terms of environment and ecology, they also contain potential risks in terms of water quality (Sazakli et al., 2007). Potential risks originate from microbiological and chemical pollutants. These risks are generally caused by factors such as air pollution, catchment surface, local climate, animals, storage tanks (Yaziz et al., 1989; Evans et al., 2006; Lee et al, 2012; Despains et al., 2009). Specifically, microbiological

pollutants are caused by animals and microorganisms in the air, while chemical pollutants are caused by human and human activities such as traffic pollution, industrial pollution (Sazakli et al., 2007; Villarreal & Dixon, 2005).

2.3 Quality of harvested rainwater from roof catchments

In many regions and traditions, rainwater is accepted as pure and clean water (Gould, 1999). For this reason, people have used the rainwater for different purposes such as drinking, cooking, cleaning, irrigation from the past to present. The usage purpose of rainwater collected from domestic rainwater harvesting systems differs depending on many factors such as the socio-economic situation of the region where it is used, climate conditions, the presence of water resources, pollution (Zhu et al., 2004). One of the most important factors that determine the purpose of use is the quality of rainwater. Sazakli et al. (2007), Gikas & Tsihrintzis (2017) and Radaideh et al. (2009) stated that the harvested rainwater is not suitable for drinking purposes due to microbiological parameters, although results have acceptable levels of physicochemical standards. On the other hand, they said that the harvested rainwater can be used for non-potable purposes such as irrigation, toilet flushing, without any treatment. Even though there are many national and local water quality standards, WHO drinking water quality standards are accepted worldwide. In many studies, roof-rainwater quality in many different regions of the world was compared with WHO's drinking water quality standards (Yaziz et al., 1989; Uba & Aghogho, 2000; Thomas & Greene, 1993; Al-Salaymeh et al., 2011). Table 1 shows the WHO guideline limits for some parameters.

Table 1-WHO Drinking-Water Quality Guideline Limits for Some Parameters (WHO, 2017)

Parameter	Unit	WHO Guideline Value	Parameter	Unit	WHO Guideline Value
pH	-	6.5-8.5	Zinc (Zn)	mg/l	0.1
Conductivity	uS/cm	250	Magnesium (Mg)	-	Not Available
Turbidity	NTU	5	Calcium (Ca)	-	Not Available
Nitrate (NO ₃)	mg/l	50	Copper (Cu)	mg/l	2
Sulphate (SO ₄)	mg/l	250	TDS	mg/l	600
Lead (Pb)	mg/l	0.01	TSS	-	Not Available
Aluminium	mg/l	0.1			

2.3.1 Sources and Pathways of Pollutants in Roof-Harvested Rainwater Quality

In order to assess the quality of roof-harvested rainwater, it is necessary to understand the pathways of contaminants in the rainwater harvesting system. Gwenzi et al. (2015) and Sanchez et al. (2015) stated that harvested rainwater quality is affected in 3 different stages in domestic rainwater harvesting systems. Figure 2 demonstrates the source of contaminants and pathways of contaminants in a roof rainwater harvesting system.

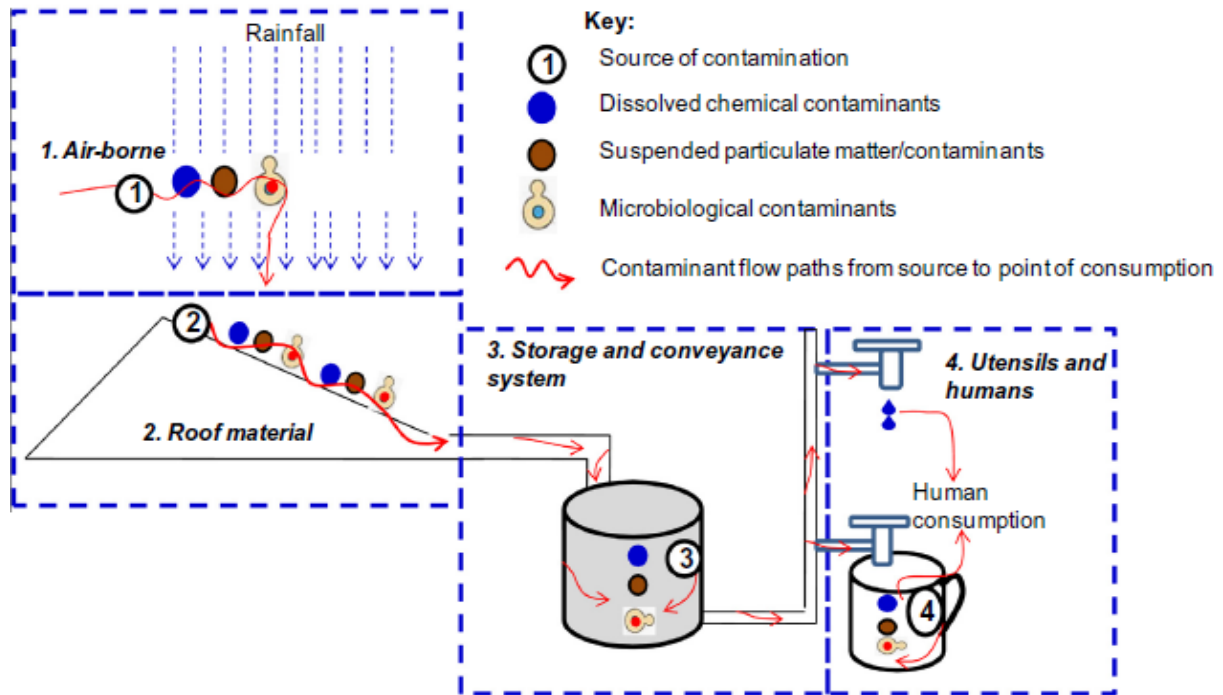


Figure 2 - Source of Contamination and Pathways of Contaminants in a Roof Rainwater Harvesting System (Gwenzi et al., 2015)

Airborne contaminants: Atmospheric deposition occurs by transporting pollutants such as particulate matter including heavy metals, nitrate, sulphate, dust. According to Demirak et al. (2006), the quality of rainwater is associated with the air quality of the atmosphere, where it falls. Rainwater dissolves and adheres to all the pollutants it encounters by using its own solvent properties, thus losing its purity (Abbasi & Abbasi, 2011). Industrial and agricultural activities, traffic emissions affecting air pollution in a region, causes contamination of harvested rainwater (Kwaadsteniet et al., 2013). For example, Demirak et al. (2006) stated that the concentration of NH_4 (ammonium) in the samples they collected was caused by the agricultural activities in the region. Gikas & Tsihrintzis (2012) determined that industrial activities, traffic and central heating emissions led to increasing of concentration SO_4

(Sulphate) and NO_3 (Nitrate). On the other hand, Thomas & Greene (1993) have revealed that fertilizer use in agricultural areas caused NO_3 concentration increase. They found that rainwater harvested from roofs in the rural area contained more nitrate concentrations than rainwater harvested from the urban area. Uba & Aghogho (2000) said that another important problem with rainwater is acid rain, which is caused by increased heavy metal concentrations in industrialized areas. Radaideh et al. (2009) found that the turbidity level, total dissolved solids, NO_3 and heavy metal concentrations were higher in the samples taken from the roofs in the industrial region than the samples collected from the roofs in the agricultural regions. The main causes of poor water quality in industrial areas are atmospheric deposition, air pollution, and traffic emissions (Huston et al., 2002). It is concluded that land use in a region affects air pollution and atmospheric accumulation and thus has a direct impact on rainwater quality.

Settlement of contaminants on the surface: Another important pathway that affects the quality of harvested rainwater is the accumulation of pollutants on the roof surface (Sanchez et al., 2015; Gwenzi et al., 2015). The accumulation of pollutants on the roof surface depends on the location of the roof and air pollution as mentioned above. The difference with atmospheric pollutants is that the pollutants on the roof surface are removed from the roof surface after a while depending on the precipitation intensity and amount (Abbasi & Abbasi, 2011). The most important factor contributing to the accumulation of pollutants on the roof surface is the number of dry days before the rain event (Yaziz et al., 1989; Mendez et al., 2010). Rainwater, along with the pollutants it picks up in the atmosphere, washes the accumulated pollutants on the roof surface and reaches the collection tank (Gikas & Tsihrintzis, 2012). Therefore, one of the most important problems that must be taken into account is the pollutants on the roof surface cause the first-flush effect.

First-Flush and storage of rainwater: In many studies, it was revealed that the water quality of the samples collected at the beginning of the rain was worse than the samples collected later. The reason for this is the first-flush phenomenon. First-flush effect is discussed in detail in section 2.4.1.

On the other hand, It is assumed that storage improves rainwater quality due to the sedimentation of particles during storage with heavy metals and microbiological bacteria (Sanchez et al., 2015; Abbasi & Abbasi, 2011). In addition to this, Sanjeeva & Puttaswamaiah

(2018), Mendez et al. (2010), and Yaziz et al. (1989) determined that pH of the harvested rainwater samples taken from tanks higher than the collected from direct rain. Despins et al. (2009) said that the pH increase in rainwater in the tank reduces the leaching of metals and improve the chemical quality of the water.

2.3.2 Factors Affecting the Quality of Roof-Harvested Rainwater

It is clear that there are several different factors impacting the rainwater quality in domestic rainwater harvesting systems has increased the number of studies conducted in recent years. The fact that the quality of harvested rainwater depends on a large number of factors has made it difficult to examine its quality and differentiates its efficiency. While rainwater quality in rainwater harvesting systems was acceptable in some studies (Dillaha & Zolan, 1985; Handia et al., 2003), physicochemical and/or microbiological parameters were found to exceed the standards in most studies (Simmons, 2001; Chang et al., 2004; Zhu et al., 2004). According to Despins et al. (2009), the main cause of harvested rainwater quality is airborne contaminants, but with proper selection of roof and tank materials, treatment practices improve water quality. Daoud et al. (2011) found that the samples taken from storage tanks met chemical parameters standards, but in some of the samples they detected microbiological parameters such as total coliform and faecal coliform. Lye (2002) revealed that untreated harvested rainwater from roof surfaces poses significant health problems for consumers due to microbiological pollutants such as mosquito larvae. Also, Amin et al. (2013) found that storing the harvested water for at least 1 week before use improved water quality.

Many studies have found different factors affecting the quality of rainwater harvested from roofs. Table 2 summarizes the findings from different studies on factors affecting the quality of harvested rainwater.

Table 2-Factors affecting roof harvested rainwater quality

Author	Findings
Sazakli et al., 2007	- Conductivity, Cl, NO ₃ , Ca, and Mg levels were higher in winter than in other seasons.
Zhang et al., 2014	- Conductivity, Zn and Cu had the highest concentration in the concrete roof in winter, while these parameters in asphalt roof had the highest concentration in spring. - They found that the dry weather significantly influenced conductivity, Ca, SO ₄ , Cu and Mg levels.

	- Strong negative correlation was detected between rainfall volume and conductivity, Na, Ca, Mg, Cl, SO ₄ , Cu, and Zn.
Chang et al., 2004	- Conductivity, Mg and Zn concentrations are affected by roof orientation depending on the wind direction.
Radaideh et al., 2009	- The rainwater harvested from the roofs in the industrial area had higher turbidity, TDS, NO ₃ and Pb levels than the rainwater harvested from the roofs in the rural area. - pH, turbidity, TDS and NO ₃ levels showed differences in concrete and rock tanks.
Farreny et al., 2011	- The significant negative correlation between rainfall height and conductivity, NO ₃ , and SO ₄ . - The flat roof was determined to have more pollutants than pitched roofs.

Apart from the factors summarized in Table 2, effects of different roof materials have been investigated on harvested rainwater quality in many studies. Table 3 summarizes the studies investigating the effects of different roofing materials on harvested rainwater quality.

Table 3-The effect of different roofing materials in different studies on rainwater quality

Author (Study Area)	Roof Material	Results
Mendez et al., 2010 (Austin, Texas)	Asphalt Fiberglass Shingle Roof	- pH was slightly higher in asphalt and galvalume roofs than other roofs. - Conductivity, TSS, lead and, zinc concentrations after First-Flush were significantly higher in green roofs than in other roofs.
	Galvalume Roof	
	Concrete Tile roof	
	Cool Roof	
	Green Roof	
Zhang et al., 2014 (Yubei, Chongqing, China)	Concrete Roof	- Green roof had quite higher Na, Mg, Cl, SO ₄ , Cu concentrations than other roofs' samples.
	Asphalt Roof	
	Ceramic Tile Roof	
	Green Roof	
Olaoye & Olaniyan, 2012 (Ogbomosho, Nigeria)	Asbestos Roof	- All of the samples they collected from different roofs were below the guideline values in terms of physicochemical parameters. -The pH, Al, Cu, NO ₃ and SO ₄ concentrations of the samples taken from the asbestos roof are higher than the other roofs.
	Aluminium Roof	
	Concrete Roof	
	Corrugated Plastic Roof	
Uba & Aghogho, 2000 (Port Harcourt, Nigeria)	Zinc Roof	- The aluminum concentration was higher in the samples collected from the aluminum roof than the samples from other roofs. - Although zinc was not found in samples collected from other roofs, zinc was detected in samples collected from zinc roof.
	Aluminium Roof	
	Asbestos Roof	
	Thatch Roof	
Lee et al., 2012	Wooden Shingle Tile Roof	

(Seoul, South Korea)	Concrete Tile Roof	- While pH has the highest value in concrete roof, zinc and aluminum levels are higher in galvanized steel roof compared to other roofs. Sulphate concentration is higher in wood roofs than other roofs.
	Clay Tile Roof	
	Galvanized Steel Roof	
Sanjeeva & Puttaswamaiah, 2018 (Bengaluru, India)	Reinforced Cement Concrete Roof	- pH, conductivity, TDS, sulphate, and nitrate levels were highest in samples collected from the reinforced cement concrete roof. Aluminum and zinc concentrations were highest in Galvanized iron roof.
	Galvanized Iron Roof	
	Asbestos Cement Roof	
	Galvalume Roof	
Adeniyi & Olabanji, 2005 (Ife, Nigeria)	Thatch Roof	- Although the levels of pH, nitrate, TSS, TDS, sodium, sulphate are similar in all roofs, turbidity and conductivity levels in samples taken from thatch roof are significantly higher than collected from other roofs.
	Concrete Roof	
	Aluminium Roof	
	Fe-Zn Roof	
	Adex Roof	

Generally, as mentioned above, the quality of roof harvested rainwater is affected by:

- Materials of rainwater harvesting system components: Roof, tank and gutter material
- Weather Conditions: Rainfall amount, rain intensity, number of dry days, wind direction
- Location of the roof: Proximity to pollutant sources
- Roof characteristics: Area, slope, age, orientation
- Cleaning and maintenance of the components

Melidis et al. (2007) found that rainwater on the roof surface contained more contaminants than direct rain, and in both cases, potable standards were exceeded and revealed that the harvested water in the storage tank could be used non-potable purposes without any treatment. By contrast, Quek & Forster (1992) determined that direct precipitation samples contain more heavy metal than rainwater samples taken from the roof surface. Abegunrin et al. (2014), Adeniyi & Olabanji (2005), Kim et al. (2005), Chang et al. (2004), Chizoruo & Onyekachi (2016) and Sanjeeva & Puttaswamaiah (2018) collected samples from direct precipitation as well as rainwater samples collected from roof surfaces and examined the effects of rainwater harvesting systems on rainwater quality. They determined that air quality had an impact on rainwater quality because of the surrounding activities (industrial activities, agricultural activities, traffic intensity).

2.4 Management of harvested rainwater quality

Usage of first-flush devices and filters, cleaning and maintenance, appropriate system design are methods that play an active role in the management of water quality in domestic rainwater harvesting systems (Gould, 1999). These methods have advantages such as being cost-effective as well as being easy to operate in improving water quality. Appropriate system design is the first and most important step to protect the water quality, from the selection of components of the rainwater harvesting system to the installation of the system. Cleaning and removing pollutants, debris, leaves etc. accumulated on the roof, in gutters and tanks is another important step in improving the water quality.

2.4.1 First-Flush Systems

Another reason that affects the quality of rainwater in the storage tank is the first-flush runoff caused by the accumulation of airborne contaminants on the roof surfaces on dry days (Yaziz et al., 1989). First-flush refers that the pollutants accumulating on the surface to flow when the rain begins. First-flush flow contains high levels of pollution with the beginning of the rain event. The most important reason of the first-flush phenomenon is the number of dry days and not enough maintenance and cleaning on the surface (Villarreal & Dixon, 2005; Dillaha & Zolan, 1985). The integration of first-flush diverter devices into the RWHS prevents contaminants from reaching the tank, especially after long dry days, and contributes to improving the quality of rainwater in the storage tank (Dillaha & Zolan, 1985; Gikas & Tsihrintzis, 2012; Villarreal & Dixon, 2005). In addition to this, rain intensity reduces the first-flush volume (Yaziz et al., 1989). Also, the first-flush devices significantly reduce the need for treatment and filtration, as they prevent contaminants at the beginning of the rain from reaching the collection tanks (Kus et al., 2010).

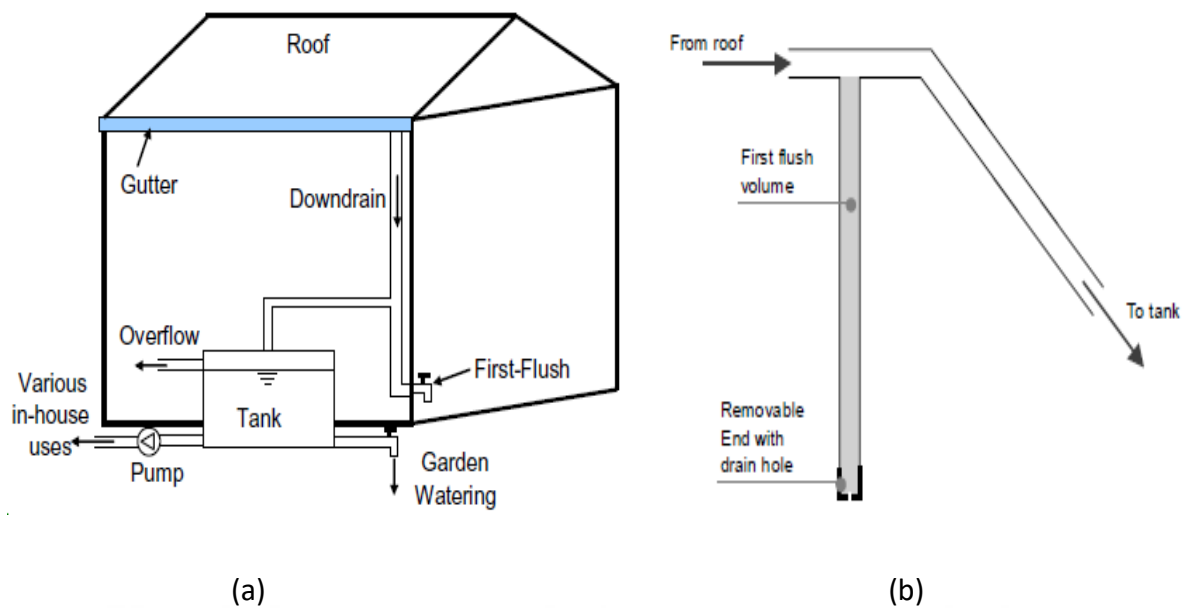


Figure 3.a & b - First-Flush System Schematic Diagram and Integration of a First-Flush System into the Rainwater Harvesting System (Gikas & Tsihrintzis, 2012) (Martinson & Thomas, 2003)

Figure 3.a & b illustrate the schematic diagram of the first-flush system and its integration into rainwater harvesting systems. Gikas & Tsihrintzis (2012), Lee et al. (2012) and Gikas & Tsihrintzis (2017) installed the first-flush diverter and found that the first -flush did not affect the microbiological parameters of the harvested rainwater in the tank and that the chemical parameters were improved. Yaziz et al. (1989) examined the first-flush quality by collecting rainwater from roofs with 2 different material types in 5 bottles of 1 l volume. They found that parameters other than zinc and lead started to decrease after the first 1 l volume. They revealed that zinc and lead concentrations fluctuated after the first 1 volume, and the last samples contained less zinc and lead than the first samples. The reason for this fluctuation is due to the material types of the components in the system.

Although many studies have found that the first-flush diverter improves the quality of harvested water, this amount has been evaluated in different amounts in different studies. However, the fact that separating the first-flush has a significant effect on water quality also makes the amount important. Therefore, the amount of first-flush must be taken into account. Even though there is a consensus that diverting the first flush improves the rainwater quality, there are different opinions about the first flush volume. Gwenzi et al. (2015) said that there is no accepted principle for determining the first-flush volume. Table 4 shows the diverted first-flush volumes in different studies.

Table 4-First-Flush volumes in different studies

Study	First-Flush Volume
Texas Water Development Board, 2005	10 gallons for 1000 ft ² roof area
Lee et al., 2012	5 L
Gikas & Tsihrintzis, 2017	0.18 mm depth for first-flush volume
Van Meter, 2003	2.6 mm depth
Gikas & Tsihrintzis, 2012	0.11 mm depth
Yaziz et al., 1989	0.33 mm

Martinson & Thomas (2005) suggested determining the first-flush volume according to the targeted turbidity. As seen in Table 5, they determined how much rainwater should be diverted according to the initial turbidity of the harvested rainwater and the targeted turbidity after at least 3 dry days.

Table 5-Recommended First-Flush Volumes (Martinson & Thomas, 2005)

Initial runoff turbidity (NTU)	Targeted Turbidity (NTU)			
	50	20	10	5
50	0	1.5	2.5	3.5
100	1	2.5	3.5	4.5
200	2	3.5	4.5	5.5
500	3.5	4.5	5.5	6.5
1000	4.5	5.5	6.5	7.5
2000	5.5	6.5	7.5	8.5

2.4.2 Filters and Screens

These devices are used to improve the quality of water as well as first-flush diverter devices. In a basic domestic rainwater harvesting system, rainwater on the roof surface passes through the gutters to the downpipes and transmitted by the downpipes to the storage tank. According to this flow, it is possible to use filters and screens in gutters, downpipes and tank entrance (Martinson & Thomas, 2003). Despite the fact that each location has its own pros and cons, Abbasi & Abbasi (2011) suggested that filters and screens should be placed in a visible location where easy to clean and maintain. Filters and screens prevent the entry of

leaves and debris, which meet the nutritional needs of microorganisms, into the storage tanks (Mosley, 2005; Abbasi & Abbasi, 2011).

2.4.3 Other Treatment Methods

If the harvested water has not enough water quality due to reasons such as areas where the pollutant concentration in the air is high and the pollutants accumulated on the roof surface etc, a number of treatments are needed (Abbasi & Abbasi, 2011). In addition, it is recommended to treat even rainwater harvested from well-maintained and clean roof surfaces before using it for drinking purposes. Treatment types such as cartridge filters, ultraviolet (UV) light, ozone, membrane filtration, chlorination are generally used in the prevention of microbiological bacteria (Texas Water Development Board, 2005).



3.0 Methodology

The literature review shows that the significant number of research has been done on the quality of rainwater harvested from the roof surfaces. Nevertheless, it also revealed that studies have generally concentrated on the roofing material, rain intensity, seasonal variations, and very little research has been done on where chemical pollutants mainly come from in rainwater harvesting systems. Moreover, very few studies discussed whether the harvested rainwater physicochemical parameters fall below the compared WHO drinking water guideline value after using the first-flush diverter. However, due to the rapid spread of coronavirus and its effects worldwide, it has not been possible to generate primary data by collecting samples and analysing in the laboratory. For this reason, the dataset was collected from published studies in order to examine how the rainwater physicochemical quality in rainwater harvesting systems changed throughout the system.

Google Scholar search engine was used for literature review and data collection. The terms used in Google Scholar when searching studies are (the number of articles produced from search terms):

- Rainwater harvesting (141,000)
- Roof runoff quality (47,000)
- Rainwater quality in rainwater harvesting systems (114,000)
- First-flush in rainwater harvesting systems (17,800)
- Roof catchments rainwater quality (17,300)
- Water quality of domestic rainwater harvesting systems (48,700)

Since the subject of the dissertation is related to the physicochemical water quality in the roof-based rainwater harvesting systems and the topic of the research does not depend on the year, no specific year interval was specified when writing search terms in Google Scholar. Producing too many articles by Google Scholar as a result of search terms made it difficult to review the articles. For this reason, a series of measures were taken to prevent overlooking important articles on the topic of this dissertation. The first of these measures was to reach the studies of the most cited authors in articles on rainwater harvesting systems and water quality in stormwater harvesting systems. In addition, search terms were combined with the "AND" command to narrow down the search results and find more relevant articles. For

example, the combination of "rainwater harvesting" AND "roof flow quality" ensures that articles with these 2 different search terms are found. Since thousands of articles were produced from the search terms, study eligibility criteria were created. Articles that were able to answer "yes" to all of the questions asked in the study inclusion criteria were accepted. Articles that answered "no" to any of these questions were rejected.

Study inclusion criteria for literature review:

1. Are the authors of study professional in their field?
2. Is the journal or site in which the study was published reliable?
3. Is the content of the study compatible with the dissertation?
4. Is the language of the study published in English?

The authors of the studies found were searched in Google Scholar and other studies of them were examined. This was done to see if the authors are experts and professionals in their field. In order to analyse the expertise of the author, it was evaluated whether their articles were published in peer-reviewed journals. Furthermore, refereed journals and professional sites were used for the reliability of the studies. In addition to the Google Scholar search engine, data was also collected from studies found after following-up from key sources. The articles obtained from the reference lists of the initial articles were also checked to see if they complied with the study inclusion criteria. In total, 47 different articles from search terms were found in Google Scholar.

On the other hand, articles in the literature review were used to collect data. Therefore, study inclusion criteria were also generated for data collection.

Study inclusion criteria for data collection:

1. Is the data in the studies the result of the primary study?
2. Do the study have physicochemical parameter data of samples taken from storage tanks of the rainwater harvesting system?
3. Do the study have results of the physicochemical parameter at least one of the direct rain and first-flush samples?

Firstly, the titles and abstracts of the articles were reviewed and the articles that were not in line with the aim and objectives of this dissertation were rejected. After that, studies that did

not meet the study inclusion criteria for data collection mentioned above were rejected by looking at the places where samples were collected from the content of the articles. For example, in many studies, there were the results of physicochemical water quality only in the storage tanks. These articles were rejected because they did not meet the second of the study inclusion criteria. The data collection was stopped when the parameters to be analysed were found in at least 4 different articles. On the other hand, 2 further studies were accepted to analyse the effectiveness of the first-flush diverter in the rainwater harvesting system. Thus, the accuracy of the analyses was tried to be increased. The last 2 studies meet the study inclusion criteria for data collection. Finally, 11 articles were used to ensure data from at least 4 different articles was present for each parameter.

After data collection, charts were plotted using mean values of the same parameters obtained from different studies in Microsoft Excel. At the same time, WHO guideline limits were placed in these charts to ensure that the parameters were compared with the WHO standard guideline value.

In this dissertation, parameters affecting the physicochemical quality of rainwater in rainwater harvesting systems; pH, conductivity, turbidity, sulphate (SO_4), nitrate (NO_3), lead (Pb), zinc (Zn), copper (Cu), total dissolved solids (TDS), total suspended solid (TSS), aluminium (Al), magnesium (Mg) and calcium (Ca) are examined. When determining the physicochemical parameters to be examined, it was decided to collect the tested parameters in 4 or more than 4 studies. This is because it is not possible to make a general opinion from the parameter tested only in one study since it reflects only the area where the study took place and the rainwater harvesting system. Table 6 demonstrates the studies in which the data set was created, and which parameters were tested in the studies.

Table 6-Parameters tested in different studies

Study No.	Author (Study Area)	Parameters												
		pH	Conductivity	Turbidity	NO ₃	SO ₄	Pb	Zn	Mg	Ca	Cu	TDS	TSS	Al
1	Sanjeeva & Puttaswamaiah, 2018 (Bengaluru, India)	+	+	-	+	+	+	+	+	+	+	+	-	+
2	Mendez et al., 2010 (Austin, Texas)	+	+	+	+	-	+	+	-	-	+	-	+	+
3	Yaziz et al., 1989 (Serdang, Selangor)	+	+	+	-	-	+	+	-	-	-	+	+	-
4	Lee et al., 2010 (Gangneung, South Korea)	+	+	-	+	+	+	+	+	+	+	+	-	+
5	Adeniyi & Olabanji, 2005 (Ife, Nigeria)	+	+	+	+	+	-	-	+	+	-	+	+	-
6	Chizoruo & Onyekachi, 2016 (Orlu, Nigeria)	+	+	+	+	-	+	+	-	-	+	+	+	-
7	Chang et al., 2004 (Nacogdoches, Texas)	+	+	-	-	-	-	+	-	-	+	-	-	+
8	Gikas & Tsihrintzis (2012), (North-Eastern, Greece)	+	+	-	+	+	-	-	+	+	-	-	+	-
9	Gikas & Tsihrintzis (2017), (Dialampi, Greece)	+	+	-	+	+	-	-	+	+	-	-	+	-
10	Nosrati, 2017 (Tehran, Iran)	+	+	-	+	+	-	-	-	-	-	+	-	-
11	Lee et al., 2012 (Seoul, South Korea)	+	-	-	+	+	+	+	-	-	+	-	+	+

(+ : Tested, - : Not tested)

As seen in Table 6, studies have tested different parameters and there is no parameter tested in every study except pH. This restricts the in-depth analysis of parameters with few data. Also, it is seen that each parameter has been tested in at least 4 different studies.

On the other hand, the areas, years and seasons in which the studies took place are different. In addition, the studies had only mean values of the physicochemical parameters and not all parameters to be examined in this dissertation were tested in each study. Therefore, it was decided not to perform any statistical analysis.

Table 7-Where samples are collected in the different studies

Study No.	Sample	Acronyms	Study No.	Sample	Acronyms	
1	1 DR	Direct Rainfall	6	6 DR	Direct Rainfall	
	1 AC (FF)	Asbestos Cement (First-Flush)		6 AR	Aluminium Roof	
	1 AC (SF)	Asbestos Cement (Second-Flush)		6 GMR	Galvanized Metal Roof	
	1 AC (TF)	Asbestos Cement (Third-Flush)		6 TR	Thatch Roof	
	1 GI (FF)	Galvanized Iron (First-Flush)		6 AsR	Asbestos Roof	
	1 GI (SF)	Galvanized Iron (Second-Flush)	7	7 DR	Direct Rainfall	
	1 GI (TF)	Galvanized Iron (Third-Flush)		7 WSR	Wood Shingle Roof	
	1 G (FF)	Galvalume (First-Flush)		7 CSR	Composition Shingle Roof	
	1 G (SF)	Galvalume (Second-Flush)		7 AR	Aluminium Roof	
	1 G (TF)	Galvalume (Third-Flush)		7 GIR	Galvanized Iron Roof	
	1 RCC (FF)	Reinforced Cement Concrete (First-Flush)	8	8 CTR (FF)	Clay Tile Roof (First-Flush)	
	1 RCC (SF)	Reinforced Cement Concrete (Second-Flush)		8 CTR	Clay Tile Roof Tank (Rural)	
	1 RCC (TF)	Reinforced Cement Concrete (Third-Flush)		8 CRR (FF)	Concrete Roof (First-Flush)	
2	2 DR	Direct Rainfall		8 CRR	Concrete Roof Tank (Rural)	
	2 SR (FF)	Shingle roof (First-Flush)		8 CR (FF)	Concrete Roof (Suburban)(First-Flush)	
	2 SR (T1)	Shingle roof (Tank 1)		8 CR	Concrete Roof Tank (Suburban)	
	2 SR (T2)	Shingle roof (Tank 2)		8 CRS (FF)	Clay Tile Roof (Suburban) (First-Flush)	
	2 MR (FF)	Metal roof (First-Flush)		8 CRS	Clay Tile Roof Tank (Suburban)	
	2 MR (T1)	Metal roof (Tank 1)		8 CRU	Clay Tile Roof (Urban) (First-Flush)	
	2 MR (T2)	Metal roof (Tank 2)		8 CRU	Clay Tile Roof Tank (Urban)	
	2 TR (FF)	Tile roof (First-Flush)		9	9 CTR (FF)	Ceramic Tile Roof (First-Flush)
	2 TR (T1)	Tile roof (Tank 1)			9 CTR	Ceramic Tile Roof Tank
	2 TR (T2)	Tile roof (Tank 2)			9 CR (FF)	Concrete Roof (First-Flush)
3	3 DR	Direct Rainfall	9 CR		Concrete Roof Tank	
	3 GR (S1)	Galvanized Roof (Sample 1)	10		10 BR (FF)	Bitumen Roof (First-Flush)
	3 GR (S2)	Galvanized Roof (Sample 2)		10 BR	Bitumen Roof	
	3 GR (S3)	Galvanized Roof (Sample 3)		10 MTR (FF)	Mosaic Tile Roof (First-Flush)	
	3 GR (S4)	Galvanized Roof (Sample 4)		10 MTR	Mosaic Tile Roof	
	3 GR (S5)	Galvanized Roof (Sample 5)		11	11 WSR (FF)	Wood Shingle Roof (First-Flush)
	3 TR (S1)	Tile roof (Sample 1)	11 WSR		Wood Shingle Roof Tank	
	3 TR (S2)	Tile roof (Sample 2)	11 CR (FF)		Concrete Roof (First-Flush)	
	3 TR (S3)	Tile roof (Sample 3)	11 CR		Concrete Roof Tank	
	3 TR (S4)	Tile roof (Sample 4)	11 CTR (FF)		Clay Tile Roof (First-Flush)	
3 TR (S5)	Tile roof (Sample 5)	11 CTR	Clay Tile Roof Tank			
4	4 DR	Direct Rainfall	11 GR (FF)		Galvanized Roof (First-Flush)	
	4 GR	Galvanized roof Tank	11 GR		Galvanized Roof Tank	
5	5 DR	Direct Rainfall	5		5 AR	Aluminium Roof
	5 TR	Thatch Roof			5 Fe-ZnR	Fe-Zn Roof
	5 CR	Concrete Roof		5 AAR	Adex/Asbestos Roof	

Table 7 contains information about where rainwater samples were collected from the studies in which data were collected. As can be seen in Table 7, although each study aims to investigate the chemical quality of rainwater, the locations where the samples are collected

differ according to the studies. For example, unlike other studies, samples from direct rain were not collected in studies 8, 9, 10 and 11. In addition to this, the first-flush diverter was not used in studies 4, 5, 6, and 7. Also, the roofing materials used in each study are different.



4.0 Data Collection

This chapter presents the collected secondary data, which is part of the dissertation. These data are then analysed and discussed in chapter 5. Table 8 contains the mean values of the parameters in the storage tank and the first-flush collected from different studies. The mean values with the highest concentrations in each study are shown in table 8. While the values in the table show the mean values of the parameters, the values shown in parentheses show the minimum and maximum values of that parameters. Red values indicate that the parameter exceeded the WHO drinking water guideline limits. It can be seen from table 8 that the pH, conductivity, turbidity, Pb, Zn, and Al parameters exceeded WHO guideline limits in many samples. While NO₃, SO₄, Cu, and TDS parameters did not exceed WHO drinking water standards in any study, there are no available WHO drinking water guideline limits for Mg and Ca. These parameters that do not exceed the WHO drinking water guideline limits and do not have the WHO drinking water guideline limits are in appendix 1.

Table 8-Comparison of mean, min and max values of physicochemical parameters with WHO drinking water standards

Parameter	Study No.											WHO DWS
	1	2	3	4	5	6	7	8	9	10	11	
pH	5.9	6 (6-6.8)	6.4	7.3 (6.7-7.8)	7	6.65	5.03	6.49	6.48	9.6	6.7	6.5-8.5
Conductivity (uS/cm)	42	14 (9-31)	50.7	170 (50-340)	122.6	22.25	28	394	282.3	256.7	N.A.	250 uS/cm
Turbidity (NTU)	N.A.	8 (7-9)	10	N.A.	24.7	13.19	N.A.	N.A.	N.A.	N.A.	N.A.	5 NTU
NO ₃ (mg/l)	4.1	0.9 (0-1.8)	N.A.	6.8 (2.9-9.8)	4.13	3.68	N.A.	0.83	0.69	9.8	3.3	50 mg/l
SO ₄ (mg/l)	4	N.A.	N.A.	4.1 (2-7.2)	1.49	N.A.	N.A.	16.6	27.13	19.7	5.57	250 mg/l
Pb (ug/l)	4	0.69 (0.1-2)	145	27 (10-40)	N.A.	22.4	N.A.	N.A.	N.A.	N.A.	10	10 ug/l
Zn (ug/l)	150	118 (77-362)	294	160 (120-280)	N.A.	809	9717	N.A.	N.A.	N.A.	135	100 ug/l
Mg (mg/l)	1.2	N.A.	N.A.	1.2 (0.5-2.7)	1.61	N.A.	N.A.	5.24	3.63	N.A.	N.A.	N.A.
Ca (mg/l)	4.9	N.A.	N.A.	6.4 (3.24-15.4)	6.12	N.A.	N.A.	24.92	39.05	N.A.	N.A.	N.A.
Cu (ug/l)	16	2.1 (1-2.8)	N.A.	85 (70-120)	N.A.	187	22	N.A.	N.A.	N.A.	34	2000 ug/l
TDS (mg/l)	28	N.A.	13	88 (40-230)	38.97	7.88	N.A.	N.A.	N.A.	164.3	N.A.	600 mg/l
TSS (mg/l)	N.A.	21 (20-44)	52	N.A.	34.2	92.93	N.A.	39.5	2.1	N.A.	213.9	N.A.
Al (ug/l)	8	337 (73-554)	N.A.	225 (100-400)	N.A.	N.A.	224	N.A.	N.A.	N.A.	227	100 ug/l

(N.A.: Not available, WHO DWS: WHO drinking water guideline limits) (red text indicates values that exceed the WHO guideline limit.)

4.1 pH

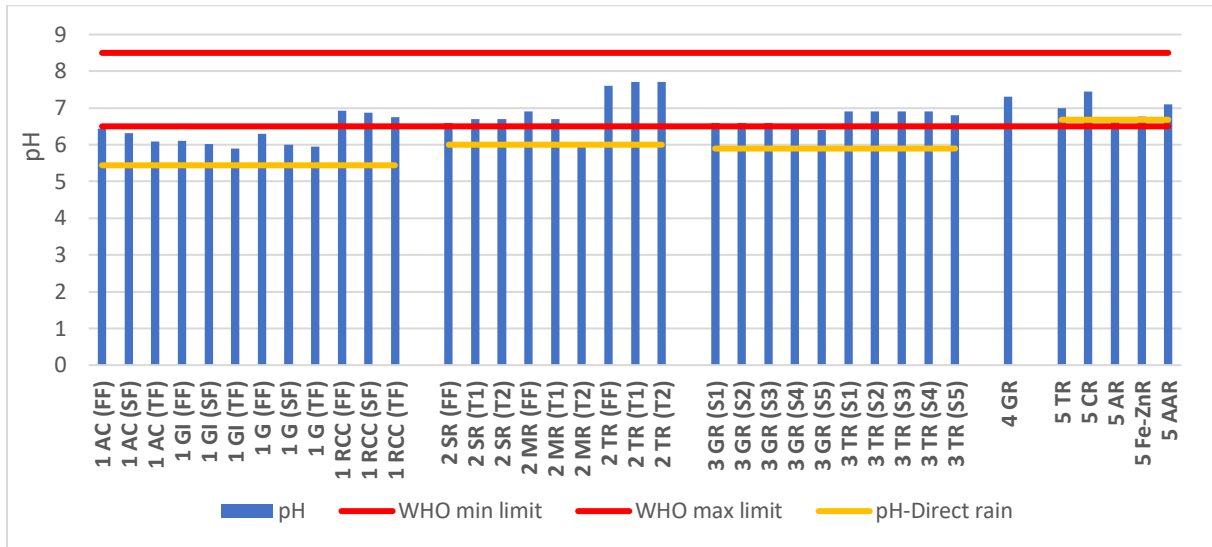


Figure 4 - Comparison of pH levels from 5 rainwater harvesting studies, with minimum and maximum limits shown for the WHO drinking water guideline limits

(FF: First-Flush; SF: Second-Flush; TF: Third-Flush; S1: Sample 1; T1: Tank 1; T2: Tank 2; 1 AC: Asbestos Cement Roof; 1 GI: Galvanized Iron Roof; 1 G: Galvalume Roof; 1 RCC: Reinforced Cement Concrete; 2 SR: Shingle Roof; 2 MR; Metal Roof; TR; 2 Thatch Roof; 3 GR: Galvanized Roof; TR; 3 Tile Roof; 4 GR: Galvanized Roof; 5 TR: Thatch Roof; 5 CR: Concrete Roof; 5 AR: Aluminium Roof; 5 Fe-ZnR: Fe-Zn Roof; 5 AAR: Adex/Asbestos Roof)

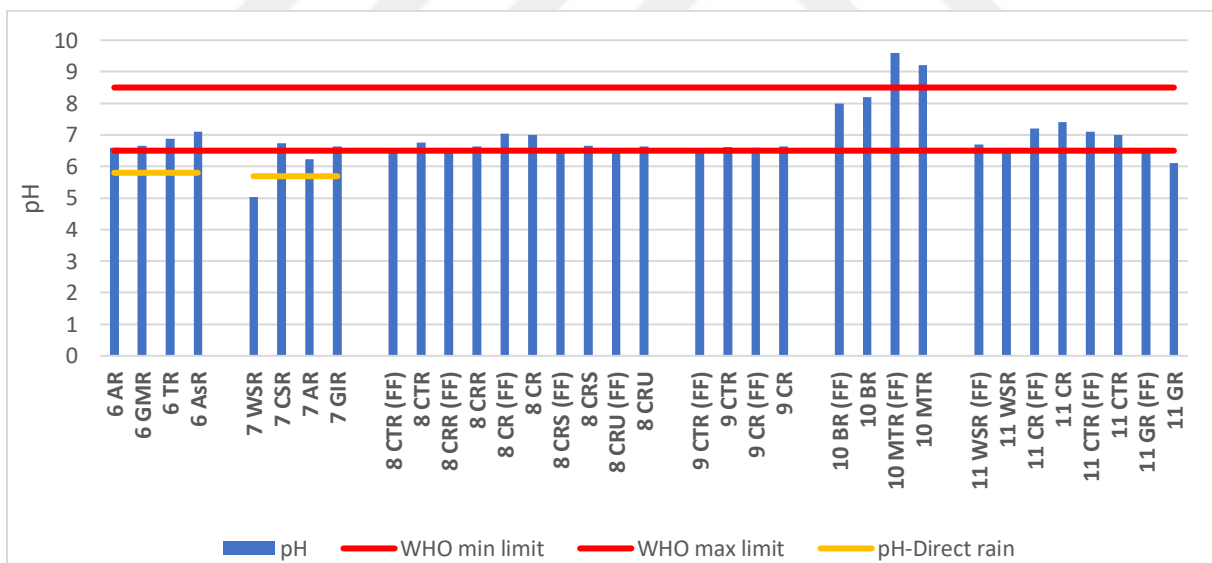


Figure 5 - Comparison of pH levels from 6 rainwater harvesting studies, with minimum and maximum limits shown for the WHO drinking water guideline limits

(FF: First-Flush; 6 AR: Aluminium Roof; 6 GMR: Galvanized Metal Roof; 6 TR: Thatch Roof; 6 AsR: Asbestos Roof; 7 WSR: Wood Shingle Roof; 7 CSR: Composition Shingle Roof; 7 AR: Aluminium Roof; 7 GIR: Galvanized Iron Roof; 8 CTR: Clay Tile Roof; 8 CRR; Concrete Roof; 8 CR: Concrete Roof; 8 CRS: Clay Tile Roof; 8 CRU: ; 9 CTR: Ceramic Tile Roof; 9 CR: Concrete Roof; 10 BR: Bitumen Roof; 10 MTR: Mosaic Tile Roof; 11 WSR: Wood Shingle Roof; 11 CR: Concrete Roof; 11 CTR: Clay Tile Roof; 11 GR: Galvanized Roof)

Figure 4 and 5 illustrate mean pH levels of direct rain, first-flush and storage tank in different studies and also, comparison of these levels with WHO drinking water pH guideline limits. In general, as can be seen in figure 4, the pH of direct rain is acidic in all studies testing the pH level of direct rain. Also, the pH levels of rainwater in first-flush and storage tanks are higher than the pH of rainwater from direct rain. In addition to differences in pH levels in different studies, there were also significant differences in pH levels of samples collected from different roofs used in the same study. For example, although the pH levels in the first-flush and storage tank of the reinforced cement concrete roof in study 1 met the WHO drinking water guideline limits, the pH levels of these samples in the other 3 roofs remained below the WHO drinking water standards.

On the other hand, it is very difficult to talk about the effect of first-flush diverter on pH level. In some studies, after the first-flush was removed, the pH decreased and in some studies it increased. With the exception of a few storage tanks, pH levels are generally within WHO guideline limits.

4.2 Turbidity

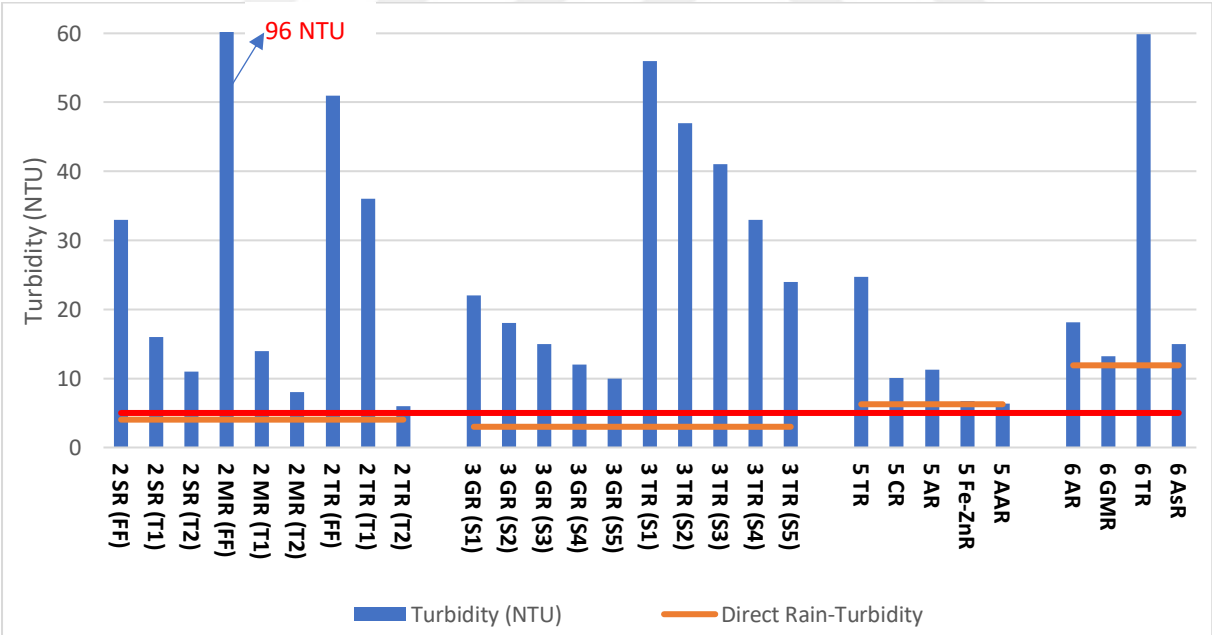


Figure 6 - Comparison of turbidity levels from 4 rainwater harvesting studies, with the WHO drinking water guideline limit

(FF: First-Flush; S1: Sample 1; S2: Sample 2; S3: Sample 3; S4: Sample 4; S5: Sample 5; T1: Tank 1; T2: Tank 2; 2 SR: Shingle Roof; 2 MR; Metal Roof; TR; 2 Thatch Roof; 3 GR: Galvanized Roof; TR; 3 Tile Roof; 5 TR: Thatch Roof; 5 CR: Concrete Roof; 5 AR: Aluminium Roof; 5 Fe-ZnR: Fe-Zn Roof; 5 AAR: Adex/Asbestos Roof; 6 AR: Aluminium Roof; 6 GMR: Galvanized Metal Roof; 6 TR: Thatch Roof; 6 AsR: Asbestos Roof)

Figure 6 shows mean turbidity levels of direct rain, first-flush and storage tank in different studies and also, comparison of these levels with WHO drinking water turbidity maximum value. Turbidity level of direct rainwater is less than first-flush and rainwater in storage tanks in all studies. As the roof washing out with rainwater, the level of turbidity decreases significantly in the storage tanks thanks to first-flush diverter and the turbidity level of harvested rainwater approaches the level of turbidity in direct rainwater. However, in all studies, the turbidity of the rainwater in the storage tank after removal of the first-flush is not below the WHO guideline limits.

On the other hand, there are large differences in different roofs used in the same study at the turbidity level as at the pH level. For example, in study 2, the first-flush turbidity level of the metal roof is about 3 and 2 times higher than the first-flush turbidity level of the shingle roof and the first-flush turbidity level of the tile roof, respectively. Also, the turbidity level in the samples taken in the storage tanks of the thatch roofs used in studies 5 and 6 is significantly higher than in other roofs.

4.3 Conductivity

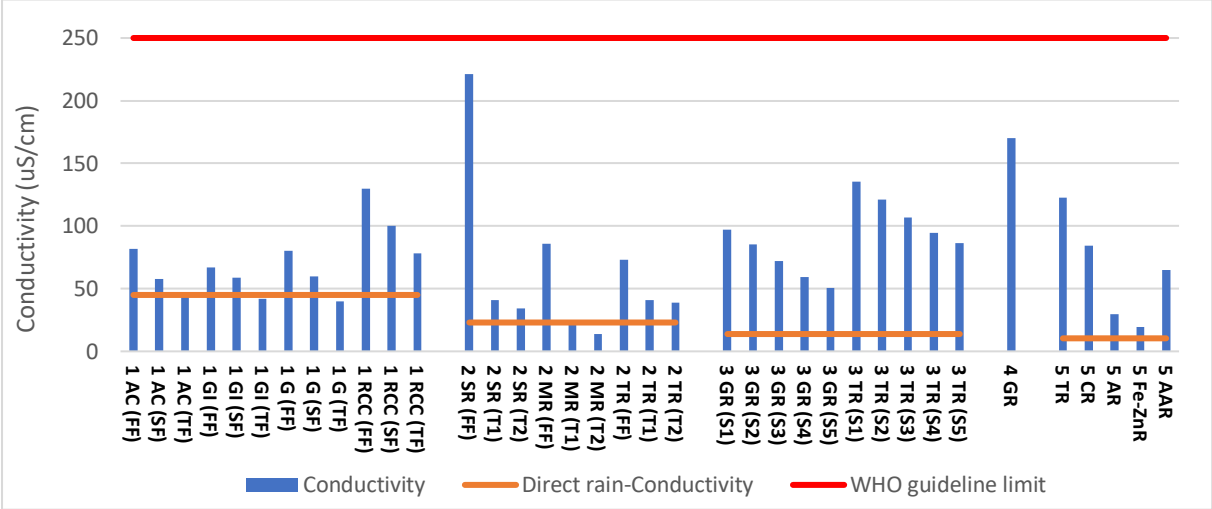


Figure 7 - Comparison of conductivity levels from 5 rainwater harvesting studies, with the WHO drinking water guideline limit

(FF: First-Flush; SF: Second-Flush; TF: Third-Flush; S1: Sample 1; T1: Tank 1; T2: Tank 2; 1 AC: Asbestos Cement Roof; 1 GI: Galvanized Iron Roof; 1 G: Galvalume Roof; 1 RCC: Reinforced Cement Concrete; 2 SR: Shingle Roof; 2 MR: Metal Roof; TR: 2 Thatch Roof; 3 GR: Galvanized Roof; TR: 3 Tile Roof; 4 GR: Galvanized Roof; 5 TR: Thatch Roof; 5 CR: Concrete Roof; 5 AR: Aluminium Roof; 5 Fe-ZnR: Fe-Zn Roof; 5 AAR: Adex/Asbestos Roof)

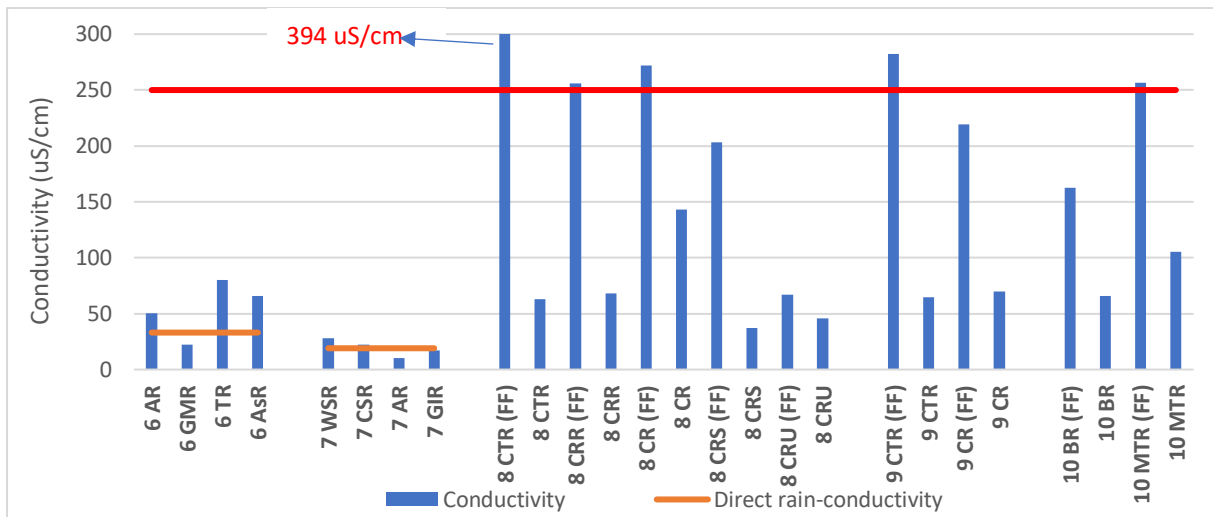


Figure 8 - Comparison of conductivity levels from another 5 rainwater harvesting studies, with the WHO drinking water guideline limit

(FF: First-Flush; SF: Second-Flush; 6 AR: Aluminium Roof; 6 GMR: Galvanized Metal Roof; 6 TR: Thatch Roof; 6 AsR: Asbestos Roof; 7 WSR: Wood Shingle Roof; 7 CSR: Composition Shingle Roof; 7 AR: Aluminium Roof; 7 GIR: Galvanized Iron Roof; 8 CTR: Clay Tile Roof; 8 CRR: Concrete Roof; 8 CR: Concrete Roof; 8 CRS: Clay Tile Roof; 8 CRU: ; 9 CTR: Ceramic Tile Roof; 9 CR: Concrete Roof; 10 BR: Bitumen Roof; 10 MTR: Mosaic Tile Roof)

Figure 7 and 8 demonstrate mean conductivity levels of direct rain, first-flush and storage tank in different studies and also, comparison of these levels with WHO drinking water conductivity guideline limits. Similar trend in turbidity is also seen in conductivity concentration. The conductivity levels of direct rain were lower than conductivity levels of first-flush in all studies testing the conductivity level of direct rain. The first-flush conductivity levels of some roofs used in studies 8, 9, and 10 have exceeded the WHO drinking water conductivity guideline limits. However, after removal of the first-flush, the conductivity levels of rainwater in the storage tank dropped below the WHO drinking water guideline limits.

In addition, there are large differences in the conductivity level between different roofs used in the same studies. For instance, in study 1 the first-flush conductivity level of the reinforced cement concrete roof is nearly 1.5 times higher than other roofs. In Study 2, the shingle roof first-flush conductivity level is about 3 times higher than other roofs.

4.4 Lead

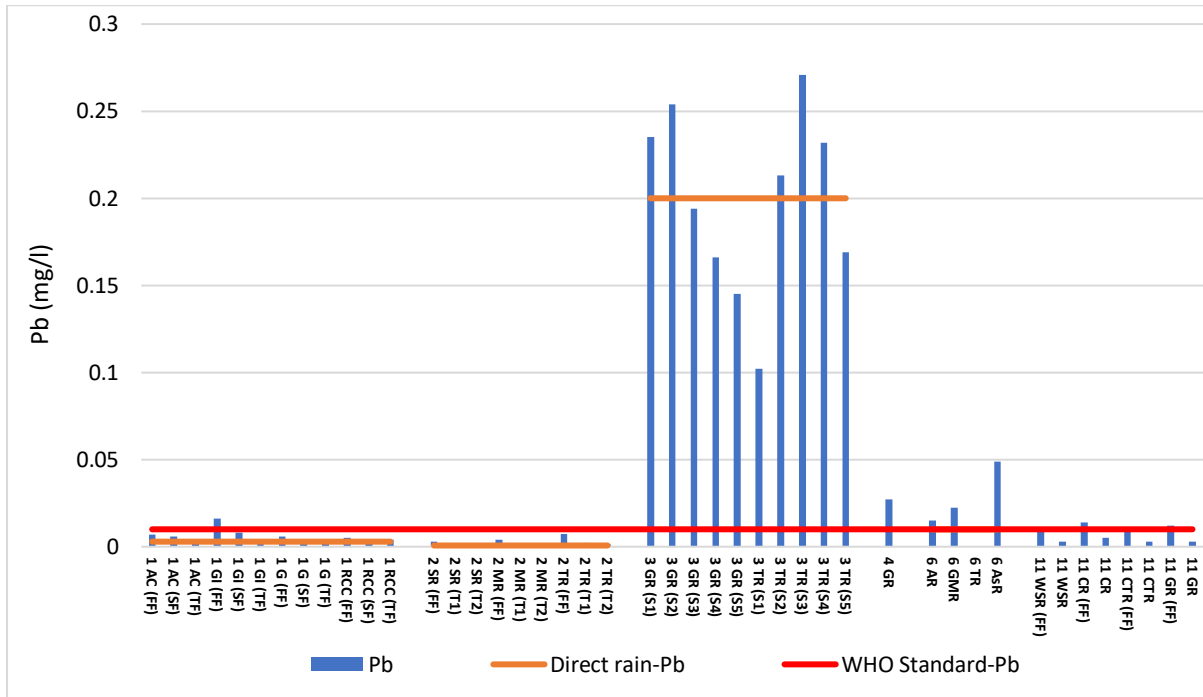


Figure 9 - Comparison of Pb concentrations from 6 rainwater harvesting studies, with the WHO drinking water guideline limit

(FF: First-Flush; SF: Second-Flush; TF: Third-Flush; S1: Sample 1; T1: Tank 1; T2: Tank 2; 1 AC: Asbestos Cement Roof; 1 GI: Galvanized Iron Roof; 1 G: Galvalume Roof; 1 RCC: Reinforced Cement Concrete; 2 SR: Shingle Roof; 2 MR: Metal Roof; TR: 2 Thatch Roof; 3 GR: Galvanized Roof; TR: 3 Tile Roof; 4 GR: Galvanized Roof; 6 AR: Aluminium Roof; 6 GMR: Galvanized Metal Roof; 6 TR: Thatch Roof; 6 AsR: Asbestos Roof; 11 WSR: Wood Shingle Roof; 11 CR: Concrete Roof; 11 CTR: Clay Tile Roof; 11 GR: Galvanized Roof)

Figure 9 shows mean Pb concentrations of direct rain, first-flush and storage tank in different studies and also, comparison of these levels with WHO drinking water conductivity maximum value. There were no major differences between studies in Pb levels except for study 3. The Pb concentrations of direct rain were lower than Pb levels of first-flush in all studies testing the Pb concentration of direct rain. In studies (studies 1, 2, 11, and 3) using the first-flush diverter, the first-flush Pb concentrations of some roofs exceeded the WHO drinking water guideline limits. Pb concentrations dropped below the WHO drinking water guideline limits after removal of the first-flush in Studies 1, 2, and 11. However, in study 3 the samples were taken in chronological order and showed an increase in Pb over time from sample 1 to 3. The average Pb rainwater concentration in study 3 was 0.2 mg/l, whereas the average Pb rainwater concentration reported in all the other studies was 0.0001 mg/l. Also, In studies without first-flush diverter, Pb levels in harvested rainwater exceed WHO standards.

4.5 Zinc

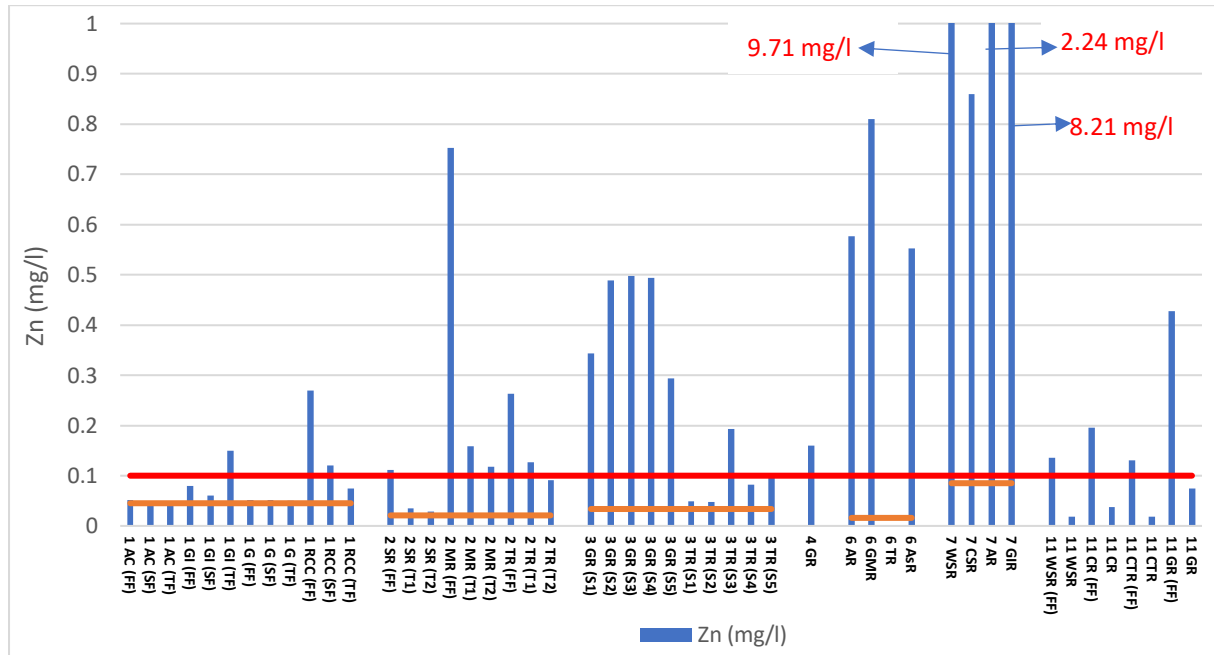


Figure 10 - Comparison of Zn concentrations from 7 rainwater harvesting studies, with the WHO drinking water guideline limit

(FF: First-Flush; SF: Second-Flush; TF: Third-Flush; S1: Sample 1; T1: Tank 1; T2: Tank 2; 1 AC: Asbestos Cement Roof; 1 GI: Galvanized Iron Roof; 1 G: Galvalume Roof; 1 RCC: Reinforced Cement Concrete; 2 SR: Shingle Roof; 2 MR: Metal Roof; TR: 2 Thatch Roof; 3 GR: Galvanized Roof; TR: 3 Tile Roof; 4 GR: Galvanized Roof; 6 AR: Aluminium Roof; 6 GMR: Galvanized Metal Roof; 6 TR: Thatch Roof; 6 AsR: Asbestos Roof; 7 WSR: Wood Shingle Roof; 7 CSR: Composition Shingle Roof; 7 AR: Aluminium Roof; 7 GIR: Galvanized Iron Roof; 11 WSR: Wood Shingle Roof; 11 CR: Concrete Roof; 11 CTR: Clay Tile Roof; 11 GR: Galvanized Roof)

Figure 10 demonstrates mean Zn concentrations of direct rain, first-flush and storage tank in different studies and also, comparison of these levels with WHO drinking water Zn guideline limits. There was no significant differences between studies in Zn concentrations except for study 7. The Zn concentrations of direct rain were lower than Zn levels of first-flush in all studies testing the Zn concentration of direct rain. The harvested rainwater Zn concentrations fall below the WHO guideline limits after removal of the first-flush in some studies using the first-flush diverter. In studies without first-flush diverter (study 6 and 7), the harvested rainwater Zn levels still continue to exceed the WHO standard guideline value. Also, in figure 10, it can be seen that the concentration of rainwater Zn in the storage tanks of different roofs varies significantly. In roof types such as zinc-containing metal and galvanized, Zn concentrations appear to increase in the storage tank as the flow on the roof continues.

4.6 Aluminium

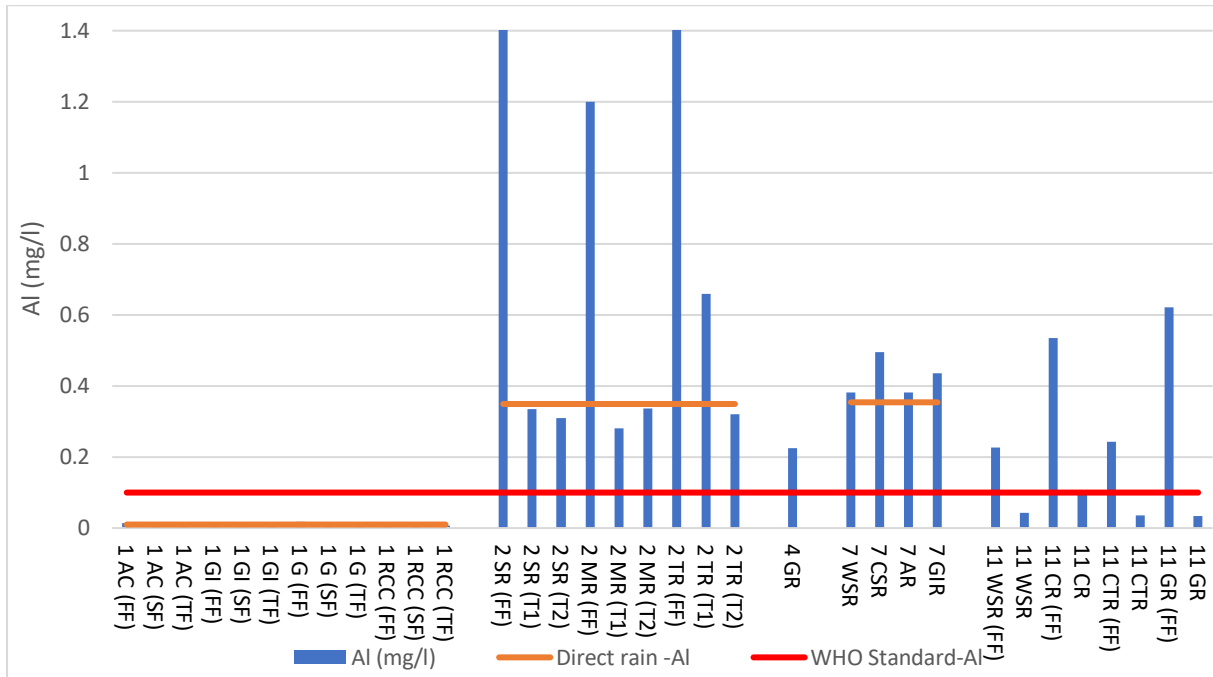


Figure 8 - Comparison of Al levels from 5 rainwater harvesting studies, with the WHO drinking water guideline limit

(FF: First-Flush; SF: Second-Flush; TF: Third-Flush; T1: Tank 1; T2: Tank 2; 1 AC: Asbestos Cement Roof; 1 GI: Galvanized Iron Roof; 1 G: Galvalume Roof; 1 RCC: Reinforced Cement Concrete; 2 SR: Shingle Roof; 2 MR; Metal Roof; TR; 2 Thatch Roof; 4 GR: Galvanized Roof; 7 WSR: Wood Shingle Roof; 7 CSR: Composition Shingle Roof; 7 AR: Aluminium Roof; 7 GIR: Galvanized Iron Roof; 11 WSR: Wood Shingle Roof; 11 CR: Concrete Roof; 11 CTR: Clay Tile Roof; 11 GR: Galvanized Roof)

Figure 11 illustrates mean Al concentrations of direct rain, first-flush and storage tank in different studies and also, comparison of these levels with WHO drinking water Al guideline limits. Al concentrations differ considerably between studies and the Al concentrations of direct rain were lower than Al levels of first-flush in all studies testing the Al concentration of direct rain. Except study 1, the first-flush and some storage tank Al concentrations in other studies are above the WHO drinking water guideline limits. First-flush diverter significantly reduces Al concentration. However, in study 2, although the first-flush diverter reduced the Al concentration in the storage tanks below Al concentration of direct rainwater, Al concentrations of rainwater in storage tanks still exceed WHO guideline limits. In study 11, the first-flush diverter reduced the Al concentration of rainwater in storage tanks below WHO guideline limits. On the other hand, in studies 4 and 7 without first-flush diverter, the storage tank Al concentrations were above the WHO drinking water guideline limits.

Table 9-% Reduction of parameters in the storage tanks after removal of the first-flush

Parameter Sample	Conductivity	Turbidity	NO ₃	SO ₄	Pb	Zn	Mg	Ca	Cu	TDS	TSS	Al
1 AC (FF)	43.90	-	37.14	46.84	42.86	21.57	95.79	50.00	40.63	48.28	-	50.00
1 GI (FF)	37.31	-	28.07	50.62	75.00	46.67	7.69	45.56	48.39	44.00	-	38.46
1 G (FF)	50.00	-	48.84	44.05	50.00	3.85	33.33	44.44	29.63	55.93	-	44.44
1 RCC (FF)	40.00	-	33.33	34.43	20.00	72.22	26.32	36.88	92.86	36.78	-	33.33
2 SR (FF)	84.62	66.67	85.19	-	80.69	75.00	-	-	92.33	-	68.52	83.68
2 MR (FF)	83.72	91.67	67.86	-	82.31	84.33	-	-	77.42	-	91.63	71.92
2 TR (FF)	46.58	88.24	63.89	-	82.67	65.40	-	-	55.83	-	78.62	78.67
3 GR (FF)	47.73	54.55	-	-	38.30	14.29	-	-	-	53.57	42.86	-
3 TR (FF)	36.02	57.14	-	-	-65.69	48.96	-	-	-	51.06	37.91	-
8 CTR (FF)	84.01	-	44.58	35.84	-	-	68.13	59.55	-	-	93.42	-
8 CRR (FF)	73.44	-	19.05	39.03	-	-	57.80	56.95	-	-	83.81	-
8 CR (FF)	47.43	-	6.45	49.13	-	-	40.51	39.96	-	-	85.26	-
8 CRS (FF)	81.77	-	49.30	30.30	-	-	52.16	52.53	-	-	67.44	-
8 CRU (FF)	31.34	-	10.61	-2.43	-	-	17.78	8.73	-	-	58.82	-
9 CTR (FF)	77.15	-	5.80	50.13	-	-	57.02	67.68	-	-	-50.00	-
9 CR (FF)	68.15	-	29.91	37.43	-	-	50.29	42.14	-	-	30.70	-
10 BR (FF)	59.54	-	61.94	83.05	-	-	-	-	-	59.62	-	-
10 MTR (FF)	58.90	-	54.08	35.53	-	-	-	-	-	58.92	-	-
11 WSR (FF)	-	-	90.91	88.33	70.00	86.67	-	-	73.53	-	83.33	81.06
11 CR (FF)	-	-	89.02	89.56	64.29	80.61	-	-	74.14	-	85.44	81.50
11 CTR (FF)	-	-	92.59	93.23	72.73	85.50	-	-	67.57	-	81.03	85.19
11 GR (FF)	-	-	99.29	96.17	75.00	82.71	-	-	72.88	-	94.71	94.69
Average	58.42	71.65	50.89	56.48	62.82	60.09	46.07	45.86	65.93	51.02	72.23	67.54

(FF: First-Flush; 1 AC: Asbestos Cement Roof; 1 GI: Galvanized Iron Roof; 1 G: Galvalume Roof; 1 RCC: Reinforced Cement Concrete; 2 SR: Shingle Roof; 2 MR: Metal Roof; 2 TR: 2 Thatch Roof; 3 GR: Galvanized Roof; 3 TR: 3 Tile Roof; 8 CTR: Clay Tile Roof; 8 CRR; Concrete Roof; 8 CR: Concrete Roof; 8 CRS: Clay Tile Roof; 8 CRU: Clay Tile Roof in Urban Area ; 9 CTR: Ceramic Tile Roof; 9 CR: Concrete Roof; 10 BR: Bitumen Roof; 10 MTR: Mosaic Tile Roof; 11 WSR: Wood Shingle Roof; 11 CR: Concrete Roof; 11 CTR: Clay Tile Roof; 11 GR: Galvanized Roof)

Table 9 shows the reduction of physicochemical parameters in storage tanks after the capture and removal of the first-flush. From the table 9, the average reduction of 58.42%, 71.65%, 50.89%, 56.48%, 62.82%, 60.09%, 46.07%, 45.86%, 65.93%, 51.02%, 72.23%, and 67.54% in parameters conductivity, turbidity, NO₃, SO₄, Pb, Zn, Mg, Ca, Cu, TDS, TSS, and Al, respectively.



5.0 Analysis and Discussion

This chapter consists of 2 different parts. In the first part, parameters that do not exceed WHO drinking water guideline limits or do not have WHO drinking water guideline limits are analysed. In the second part, parameters exceeding the WHO drinking water guideline limits are analysed and the effect of the first-flush diverter on these parameters are discussed. Also, the reduction in the parameters of the storage tank after the first-flush are removed are examined, and thus whether the contaminants in the storage tank are mainly caused by direct rain or accumulation in the roof are discussed and analysed. In addition, some suggestions are made for parameters that exceed the WHO drinking water guideline limits.

5.1 Parameters below WHO Guideline Limits and do not have WHO Guideline Limits

When physicochemical parameters collected from rainwater harvesting systems were placed on the same chart together with WHO drinking water guideline limits, it is clearly seen that NO_3 , SO_4 , Cu and TDS concentrations did not exceed WHO drinking water guideline limits (see appendix 1). In addition, Ca and Mg do not have any WHO drinking water guideline limits.

The first-flush diverter reduces NO_3 and SO_4 concentrations in storage tanks. Also, NO_3 and SO_4 concentrations in the storage tanks reach to or below levels of NO_3 and SO_4 in the rainwater collected from the direct rain after the removal of first-flush. Also, in study 10 the first-flush NO_3 and SO_4 concentrations were 2 times higher than in other studies. Tehran, where the study takes place, is an industrialized region with a high traffic volume (Nosrati, 2017). Moreover, Melidis et al. (2006) stated that NO_3 and SO_4 are products of fossil fuels. The high concentrations of these parameters can be associated with industrialization and traffic density. The rainy season of the study may have caused lower concentrations of these parameters. For this reason, it is important to clean the pollutants that accumulate on the roof on dry days in areas with high industrialization and traffic density for NO_3 and SO_4 .

In studies using first-flush diverter, after the removal of the first-flush, Cu concentrations of the rainwater in storage tanks are significantly reduced. After the removal of the first-flush, the 65.93% reduction in the Cu concentration of the harvested rainwater in the storage tank indicates that the Cu in the collected rainwater is due to the Cu accumulated on the roof surface rather than the direct rain. In addition, Cu concentrations in all studies met WHO drinking water standards. Therefore, it can be concluded that Cu does not cause concern in terms of drinking water standards in rainwater harvesting systems.

TDS and TSS concentrations have similar trend and decrease significantly after the removal of the first-flush. TDS and TSS levels were reduced by 51.02% & 72.23% in storage tanks after the removal of the first-flush, respectively. These reductions in TDS and TSS concentrations in storage tanks indicate that the TDS and TSS originate from accumulated materials on the roof rather than from direct rain. Also, there is no need to worry about WHO drinking water standards in rainwater harvesting systems for these two parameters because their concentrations are lower than the WHO drinking water guideline limits and using of the first-flush diverter is enough for TDS and TSS.

Mg and Ca have similar trends. The significant reduction of Mg and Ca concentrations in the harvested rainwater in the storage tanks after the removal of the first-flush shows that they come from materials accumulated on the roof. On the other hand, while these parameters do not have WHO drinking water guideline limits, cleaning of the roof surface after a long period of dry days and use of the first-flush diverter reduce concentrations of these parameters in the storage tank.

As a result, NO_3 , SO_4 , Cu, TDS concentrations, among other parameters examined, were found to have not exceeded WHO drinking water guideline limits in any study. Since TSS, Ca and Mg parameters did not have any drinking water guideline limits, it was determined that there was no concern for these parameters. It was also found that concentrations of these parameters in the storage tank dropped to direct rain levels after the first-flush was removed. Thus, it can be concluded that the first-flush diverter not only prevents large parts such as debris, leaves and other substances from reaching the storage tank, but also reduces the physicochemical parameters and plays an important role in improving the quality of the harvested water.

5.2 Parameters Exceeding WHO Guideline Limits

In this part, chemical parameters that exceed WHO guideline limits in rainwater harvesting systems are analysed and the effect of the first-flush diverter on these parameters is discussed.

When levels of these parameters were compared with WHO drinking water standard data, parameters such as pH, turbidity, conductivity, Pb, Zn, Al were found to exceed WHO drinking water guideline limits in many studies.

In all studies testing the pH of the direct rain, rainwater was acidic, and this points out the presence of acidic substances in the air. Also, It is understood from Figure 4 and 5 that in all studies testing the direct precipitation pH level, the direct rain pH level is higher than the pH level of rainwater in the first-flush and storage tank. This may be caused by contaminants on the roof when rainwater comes into contact with the roof surface. Dust, dirt, organic substances on the roof surface reduce the acidity of rainwater (Yaziz et al., 1989). In addition, Sanjeeva and Puttaswamaiah (2018) said that the pH level of rainwater collected from the roof is higher than the pH level of rainwater collected from direct rain, due to cations accumulating on the roof surface on dry days. On the other hand, in regions with acidic rain, the first-flush diverter reduces the pH level in the storage tank to the direct rain level, so the harvested rainwater falls below the minimum limit of WHO drinking water guideline. In addition, the pH level was lower in samples collected from metal roofs compared to samples collected in other roofs. In figure 4, it can be seen that the pH levels of reinforced cement concrete roof storage tank in study 1 and thatch roof storage tank in study 2 are higher than other roofs and met WHO drinking water guide values. Therefore, it can be concluded that rainwater harvested in acidic rainy areas requires additional treatment for pH before use for drinking water, and metal roofs should be replaced with materials that do not have metallic properties.

After the first-flush, it was determined that the level of turbidity in the storage tank decreased by 71.65% on average in the studies. This points out that substances accumulating on the roof surface have a significant effect on the level of turbidity. Despite the use of the first-flush diverter, the turbidity level in the storage tank exceeding WHO drinking water standards indicates that harvested rainwater requires additional treatment before its use for drinking water. Martinson & Thomas (2005) suggested first-flush volumes based on the initial turbidity level and target turbidity level and found that the turbidity level in the storage tank decreased thanks to the increase in the first-flush volume. Therefore, it is recommended to increase the first-flush volume when the turbidity level in the storage tank exceeds the WHO drinking water guideline limits, especially in cases where the direct rain turbidity level does not exceed the WHO drinking water guideline limits. However, in cases where the turbidity level does not fall below the WHO drinking water guide limits with a high first-flush volume, water filter jug can be recommended that provides the point-of-use treatment. Also, Gikas & Tsihrintzis (2017)

revealed that the accumulation of chemical parameters, dust, dirt on the roof surface increased due to the increase in the number of antecedent dry days. Therefore, cleaning and maintenance on the roof surface after a long period of dry days is another important recommendation in terms of turbidity as it prevents the accumulation of substance on the roof. However, the larger first-flush volume can do the same job as cleaning on the roof surface, so it can reduce all the effort and expense of having to go up on the roof all the time.

In figure 7, it is seen that the conductivity level was different between the roofs with different materials used in the same study. In addition to the material effect, it was determined from the information given in the studies that the conductivity level may change depending on different factors. For instance, Sanjeeva and Puttaswamaiah (2018) stated that the reinforced cement concrete roof used in study 1 has an angle of 0.4o (other roofs have an angle of 20o) and this may be the reason for the higher conductivity level than other roofs. Egodawatta et al. (2009) stated that due to the fact that TDS and conductivity are related, and the angle of the roof affects the flow, thus the runoff occurs slowly in flat roofs, which affects the level of TDS and conductivity. This reveals that the material and sloping of roof have an effect on the conductivity level. On the other hand, conductivity is related to the amount of dissolved material in water (Nosrati, 2017). As seen in figure 7, as the runoff on the roof surface continues, the conductivity level of the harvested rainwater in the storage tank decreases, indicating that the amount of material, which can be dissolved in the water, decreases with this runoff. The reduction in conductivity level in storage tanks by 58.42% on average compared to the first-flush conductivity level supports this view. The difference between turbidity and conductivity is that the turbidity levels in storage tanks exceeded WHO standards, and conductivity levels in storage tanks fall below WHO standard guideline value by diverting the first-flush. Therefore, it is concluded that the harvested rainwater used for drinking water does not require additional treatment in terms of conductivity and the use of the first-flush diverter is sufficient.

Figure 8 shows that Pb concentrations in study 3 are remarkable. The biggest difference that distinguishes study 3 from other studies is that Pb concentration in direct rain is high. Yaziz et al. (1989) stated that the building with rainwater harvesting system used in study 3 was close to the highway (the study site was 2 km away). In addition, Gunawardena et al. (2013) found in their study that Pb concentration increases depending on traffic density. Thus, the reason

for the direct rain Pb concentration in study 3 was much higher than in other studies is that study 3 took place close to the highway and therefore the Pb particles that are the result of the emission of vehicles were washed by the rain. Also, the removal of the first-flush resulted in an average reduction of 62.82% of Pb concentration in storage tanks, which indicates that the accumulation of Pb particles on the roof surface. Therefore, it is concluded that the harvested rainwater requires using of water filter jug before the use of Pb for drinking in regions with high traffic volume (especially in areas where the rainwater harvesting system is less than 2 km from the highway). However, in cases where Pb concentrations in direct rain exceed WHO drinking water guideline limits, water filter jug use may not be sufficient and therefore harvested rainwater requires additional treatment before using drinking purposes. In addition, as the number of antecedent dry days increased, cleaning and maintenance are required to prevent the accumulation of Pb particles on the roof surface.

As seen in figure 9, although there are differences in Zn concentrations between studies, rainwater Zn levels in the storage tanks of the roofs of study 7 are quite high compared to other studies. Chang et al. (2004) stated that the gutters and downpipes in the rainwater harvesting system in study 7 were galvanized. Therefore, The reason for high Zn concentrations in study 7 can be attributed to the use of galvanized gutters and downpipes. In addition, in study 3, it is seen in figure 9 that Zn concentration increased in samples 2 and 3, respectively in galvanize roof. Looking at figure 4, it is seen that direct rainwater samples show acidic properties in study 3. Acidic rainwater interacts with the galvanized roof, causing Zn to leak from the roof into the tank. In general, the Zn concentrations in the storage tank are 60.09% less than the Zn concentrations in the first-flush, indicating that substances accumulated on the roof are washed at the beginning of the rain.

The high Al concentrations in direct rainwater in studies 2 and 4 are directly proportional to the Al particles in the air. However, it can be seen in figure 10 that the Al levels in the first-flush in study 2 are very high compared to other studies. This is because the gutters and downpipes used in this study are aluminium. The acidic rainwater in study 2 may cause aluminium to dissolve and increase the concentration of aluminum in the storage tanks as it passes through the aluminum gutter and downpipes. Also, 67.54% reduction in Al concentrations in storage tanks compared to first-flush is an indication that the accumulation on the roof surface rather than direct rain is more effective on Al levels.

Abbasi and Abbasi (2011) and Mendez et al. (2010) stated that the acidity of the direct rainwater caused the chemicals in the roofing material to reach the storage tank. This supports why Zn and Al concentrations increase in the storage tank depending on the material of roof, gutter and downpipes after the first-flush has been removed. Depending on the intensity of rain at the beginning of the rain, although the substances accumulated on the roof surface are removed with the first-flush diverter, the acidic direct rainwater tends to react with the materials of the components in the rainwater harvesting system and leak these materials into the storage tank. In addition, Chang et al. (2004) stated that the temperatures on the roof surface are higher than other surfaces due to solar radiation and the shadow effect of the surrounding trees, and this temperature effect can accelerate the reaction of the acidic rainwater with the roofing material.

It was determined that metals such as Al and Zn increased after removal of the first-flush due to the material of the roof, gutter and downpipes and the acidity of the rainwater. In regions where rainwater is acidic due to urbanization and industrialization, it is necessary to take precautions regarding these materials to ensure WHO drinking water guideline limits before the installation of rainwater harvesting systems. Replacing metallic gutters and downpipes with acidic water-resistant gutters and pipes, or using a membrane covering on the roof surface are among these measures. However, if Al and Zn concentrations in direct rain exceed WHO drinking water guideline limits, it may not be sufficient to replace the roofing material, increase the first-flush volume or using filter in the point-of-use, and therefore additional treatment is required for harvested rainwater before drinking purposes.

As a result, concentration of parameters in the first-flush and in the storage tank data after the removal of first-flush were compared to determine where the pollutants in the harvested rainwater came mainly from. When these data were compared, it was found that the parameters in the storage tank decreased more than 50% compared to the first-flush. As can be seen in table 8, although the efficiency of the first-flush diverter varies between studies, it is clear that overall the first-flush diverter is able to remove those contaminants effectively. This reduction variability between studies can be attributed to the difference of the first-flush volume used, the roof surface area and the roofing material in the studies. This reveals that the chemical contaminants in the storage tank of rainwater harvesting system arise directly from the substances that accumulate on the roof rather than direct rain. On the other hand,

while the first-flush diverter reduced some of the parameters exceeding WHO drinking water standards below the WHO drinking water guideline limits, in some studies it could not. This is due to environmental factors in the study area or the material of the components such as roof, gutter, and downpipe. It is clear that the harvested rainwater chemical parameters can be reduced with cleaning and maintenance after a long period of dry season, the use of the first-flush diverter, use of water filter jug providing the point-of-use treatment, additional treatment where pollutants in direct rain exceed WHO drinking water guideline limits, proper system design and material selection.



6.0 Conclusion

This dissertation was designed to make some suggestions to improve the quality of collected rainwater by understanding whether the physicochemical quality of the rainwater harvested from the roof-based rainwater harvesting systems is mostly due to direct rain or the contaminants accumulated on the roof surface. Whether the physicochemical parameters in harvested rainwater meet WHO drinking water standards were also examined.

After detailed literature review, secondary data were collected from studies in which physicochemical parameters were tested. Parameters were collected from studies examining samples in direct rain, the first-flush and storage tank. The physicochemical parameters whose mean values were collected and analysed were pH, conductivity, turbidity, NO₃, SO₄, Cu, Al, Zn, Pb, Mg, Ca, TDS and TSS. The parameters collected of mean values were placed on the same graph together with WHO drinking water guideline limits and if it was examined that they met WHO drinking water guideline limits.

A series of main conclusions were determined from the results of this dissertation. These are:

- Comparing the levels of physicochemical parameters in the first-flush and the storage tank after the first-flush is removed, the majority of the pollutants in the first-flush is because the contaminants in the harvested rainwater are mostly due to accumulation on the roof rather than direct rain.
- The pH level of rainwater increases as the rainwater harvesting system passes due to the substances accumulated on the system. However, although the first-flush device reduces contaminants in the storage tank, in some studies the pH level increases after the first-flush is removed. However, the pH level is within the WHO drinking water guideline limits in many studies. Non-metallic roofs were suggested in areas where direct rain is acidic.
- NO₃, SO₄, TDS, and Cu in the harvested rainwater do not exceed the WHO guideline limits. Although there is no need to worry about drinking purposes for these parameters in harvested rainwater, cleaning after a long period of dry days prevents the accumulation of them on the roof surface and also using of the first-flush diverter reduces the concentration of these parameters in the storage tank.
- In terms of conductivity, the use of the first-flush device is sufficient to meet WHO drinking water guideline limits, while harvested rainwater in the storage tank requires

filtering for turbidity. Cleaning and maintenance after a long period of dry days are other necessary measures to reduce conductivity and turbidity levels. In addition, additional treatment can be required for Pb as rainwater harvesting systems in areas with high traffic density tend to exceed WHO drinking water standards in terms of harvested rainwater Pb.

- The concentration of Al and Zn metals in the storage tank increases due to acidic rainwater if the roof, gutters and downpipes in the rainwater harvesting systems are metallic. Therefore, it is recommended to replace metallic rainwater harvesting systems with acidic water-resistant materials if possible or to cover the components with a membrane. On the other hand, if the concentrations of Al and Zn in direct rain are above of the WHO drinking water guideline limits, increasing the first-flush volume will not be sufficient to decrease these concentrations, so the harvested rainwater requires additional treatment for Al and Zn before use for drinking purposes.

6.1 Recommendations for Further Studies

The cost/benefit of treatment options for the problematic pollutants would be a key area for further research. Investigating how these contaminants change with more first-flush volume and whether the filtering in the storage tank or treatment in the point-of-use reduce the parameters exceeding WHO drinking water guidelines limits below these limits should be included in the further study. At the same time, the costs of these measures should be compared with the costs of cleaning and maintenance. On the other hand, the examination of which chemicals increase depending on the traffic volume and how close to the highway in the rainwater harvesting systems would be a key area of another further study. Thus, it may be easier to take measures against these chemicals in the harvested rainwater. Examining how the pH level of the rainwater changes in the storage tank after the first-flush has been removed, can be the topic of further study using different types of materials of roof, gutter and downpipe. Also, in this dissertation, the change of metals such as Fe, Ni and Cd in rainwater harvesting systems could not be analysed due to lack of data. In further studies, it could be analysed whether these parameters exceed WHO drinking guideline limits in rainwater harvesting systems and the effect of the first-flush diverter on Fe, Ni and Cd. In particular, the widespread use of iron-containing galvanized roofs is important for examining how Fe changes throughout the system. In addition, the harvested rainwater used for drinking purposes passes through the plumbing system and taps after the storage tank. Depending on

the material used in the plumbing system and taps, the physicochemical quality of harvested rainwater may be another subject of further study.



7.0 References

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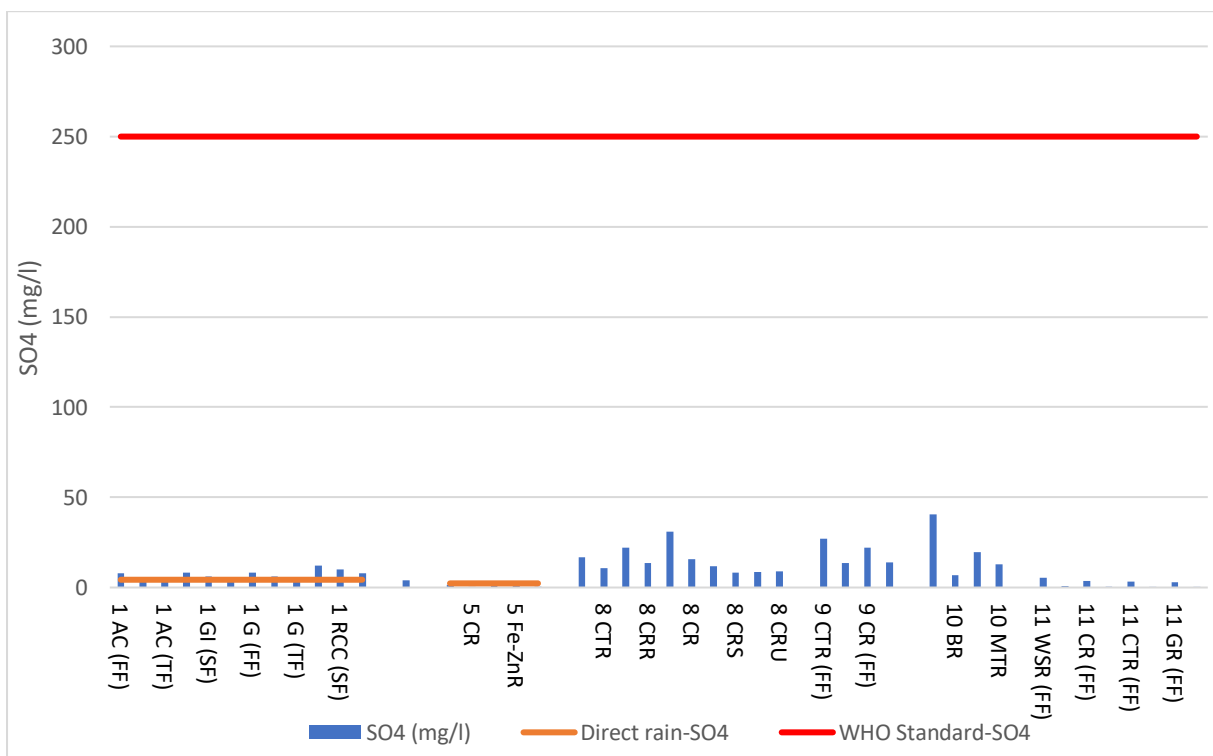
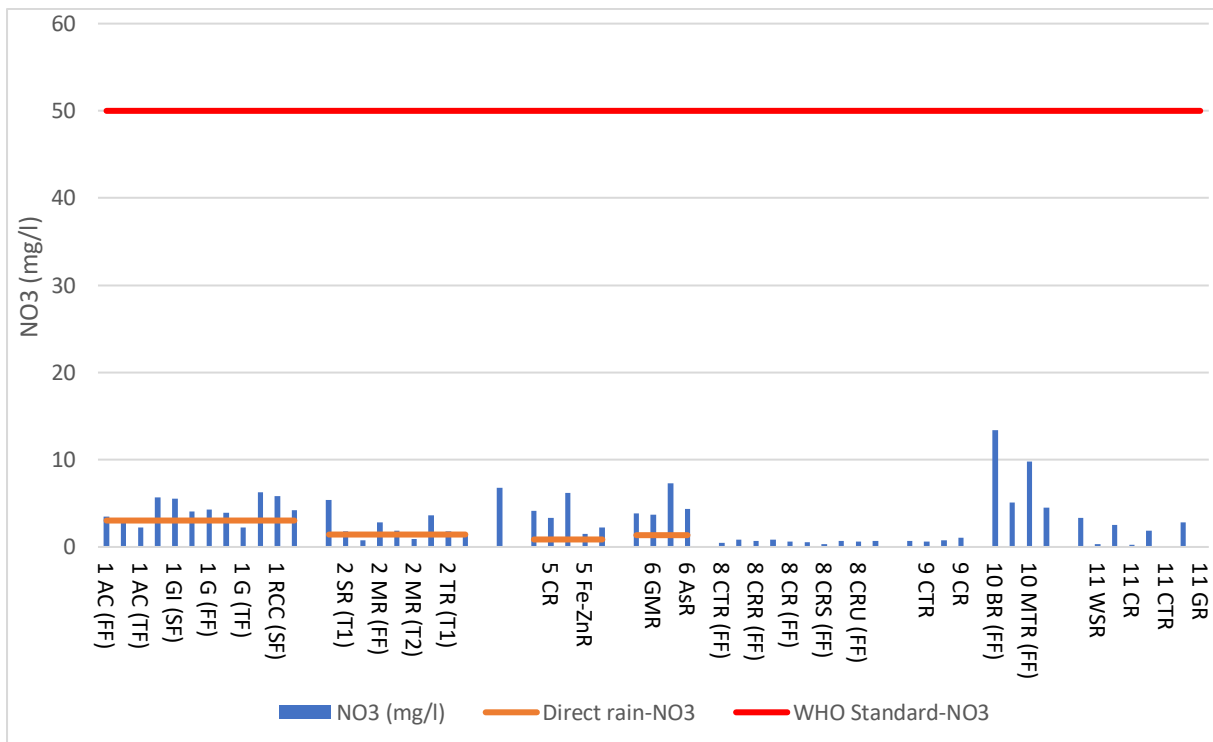
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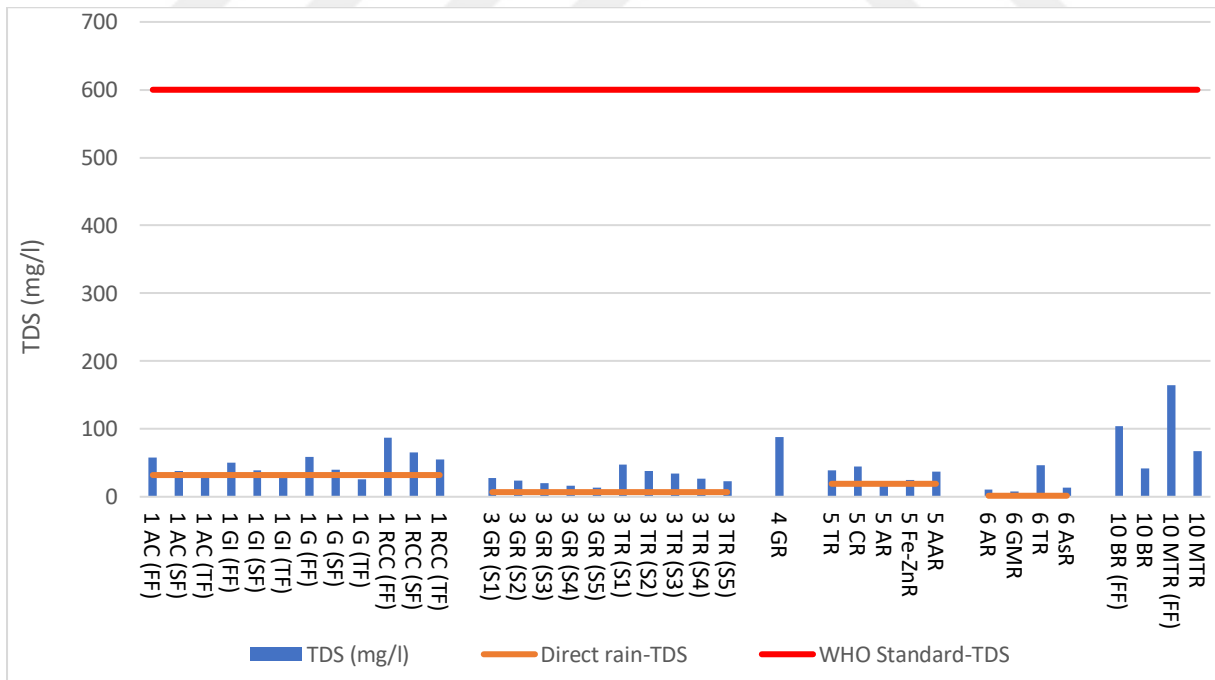
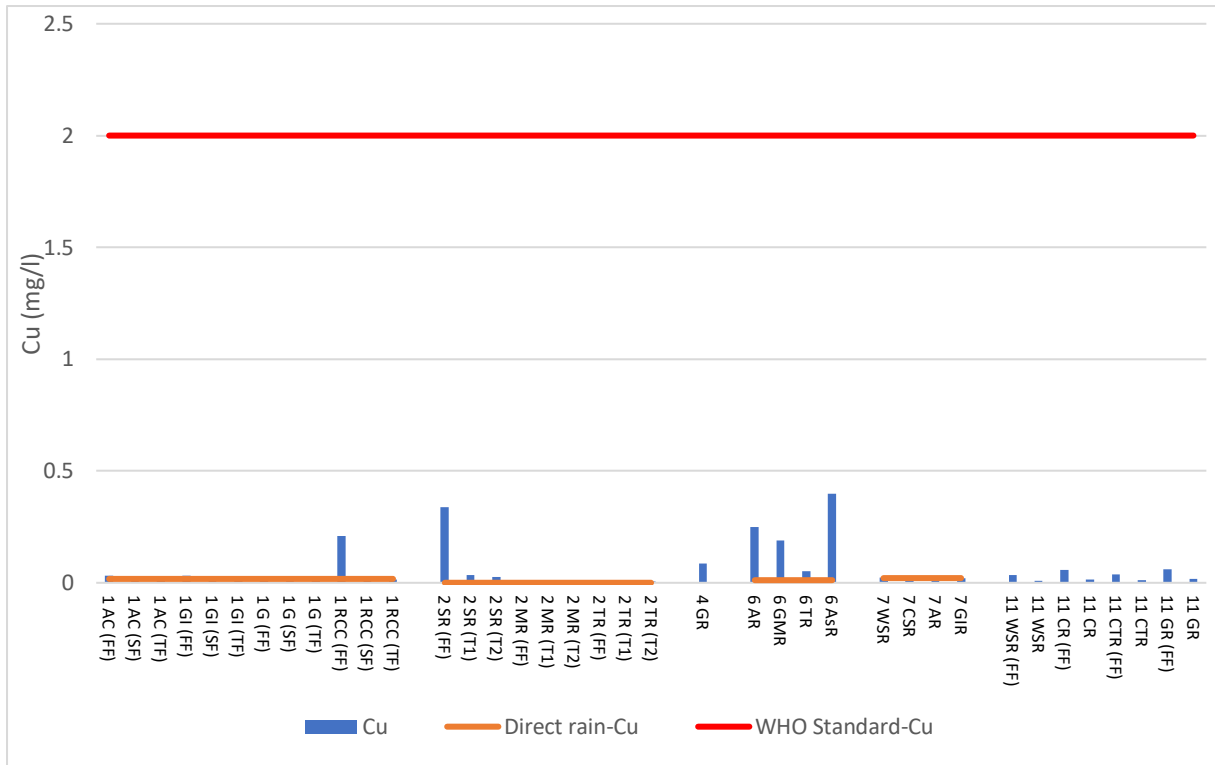
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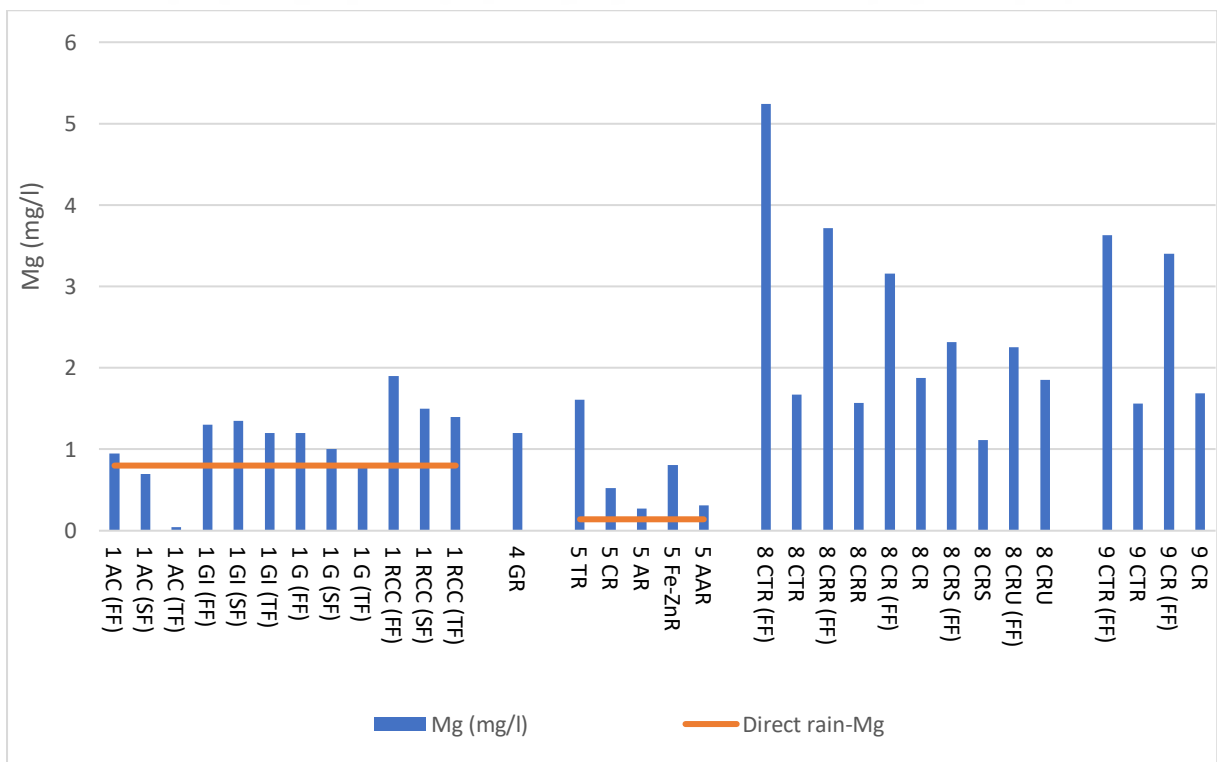
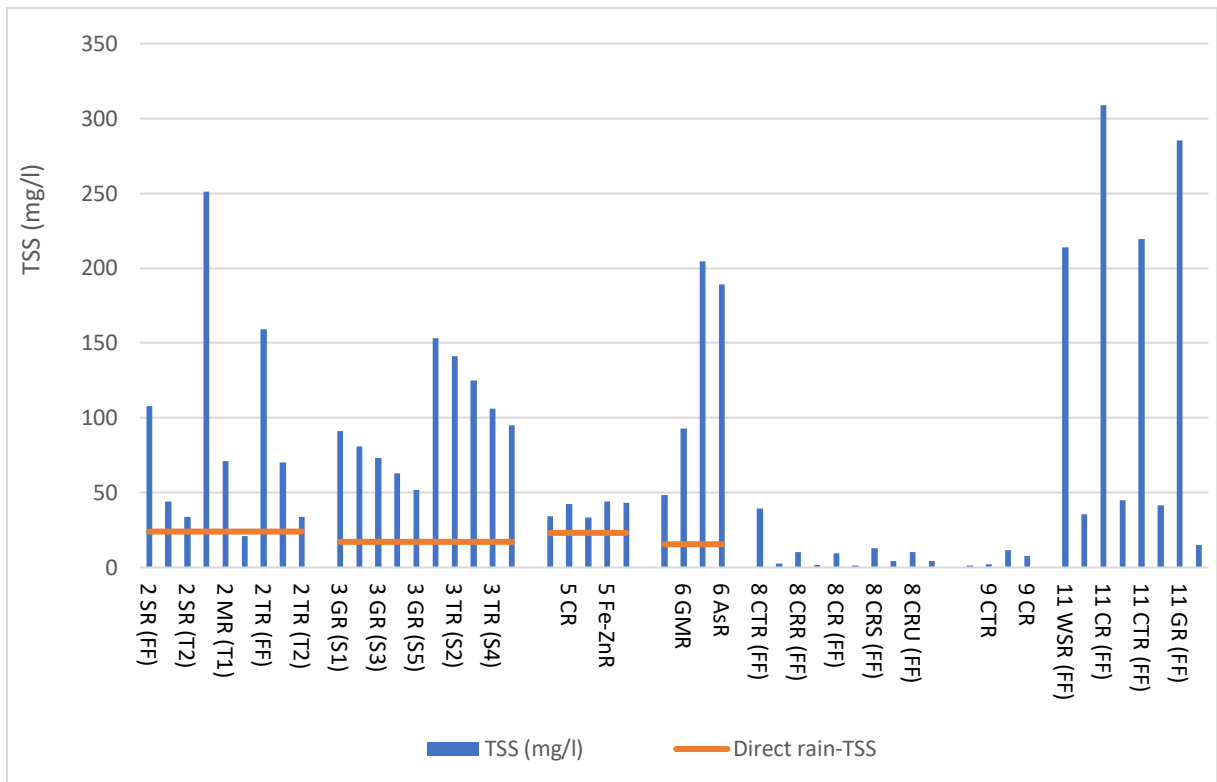


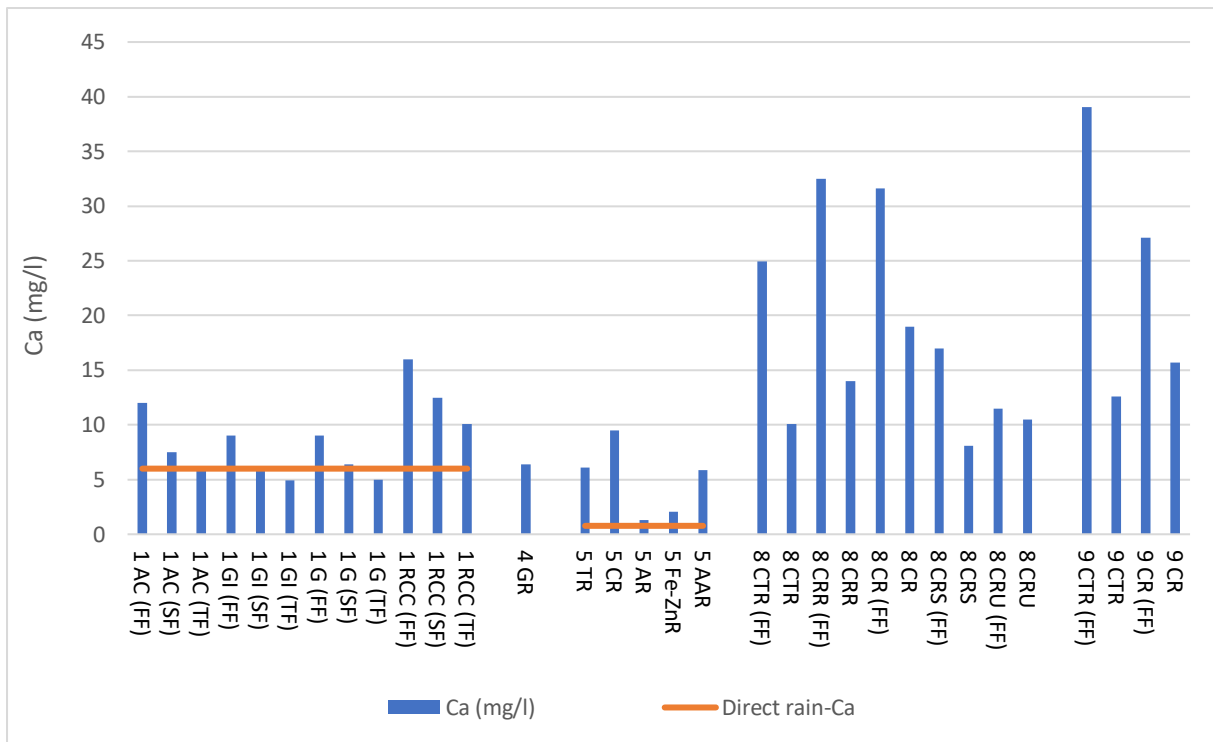
8.0 Appendices

Appendix A- Parameters below WHO Guideline Limits and do not have WHO Guideline Limits











Certificate of Ethics Review

Project Title: Investigation into Physicochemical Parameters of Harvested Rainwater with Respect to Drinking Water Quality Standards

Name: Bektas Berkay Yanilmaz

User ID: 946017

Application Date: 10-Aug-2020 09:23

ER Number: ETHIC-2020-770

You must download your referral certificate, print a copy and keep it as a record of this review.

The FEC representatives for the School of Civil Engineering & Surveying are [Tim Whitehead](#) and [John Williams](#)

It is your responsibility to follow the University Code of Practice on Ethical Standards and any Department/School or professional guidelines in the conduct of your study including relevant guidelines regarding health and safety of researchers including the following

- [University Policy](#)
- [Safety on Geological Fieldwork](#)

It is also your responsibility to follow University guidance on Data Protection Policy:

- [General guidance for all data protection issues](#)
- [University Data Protection Policy](#)

Which school/department do you belong to?: **SCES**

What is your primary role at the University?: **Postgraduate Student**

What is the name of the member of staff who is responsible for supervising your project?: **Peter Cruddas**

Is the study likely to involve human subjects (observation) or participants?: **No**

Are there risks of significant damage to physical and/or ecological environmental features?: **No**

Are there risks of significant damage to features of historical or cultural heritage (e.g. impacts of study techniques, taking of samples)?: **No**

Does the project involve animals in any way?: **No**

Could the research outputs potentially be harmful to third parties?: **No**

Could your research/artefact be adapted and be misused?: **No**

Does your project or project deliverable have any security implications?: **No**

Please read and confirm that you agree with the following statements: **Confirmed**

Please read and confirm that you agree with the following statements: **Confirmed**

Please read and confirm that you agree with the following statements: **Confirmed**



Supervisor Review

As supervisor, I will ensure that this work will be conducted in an ethical manner in line with the University Ethics Policy.

Supervisor signature: *P. A. Cruddas*

Date: *10/8/20*

Appendix C- Risk Assessment

 UNIVERSITY OF PORTSMOUTH		UNIVERSITY RISK ASSESSMENT FORM		<table border="1"> <tr><td style="background-color: red; color: white;">HIGH</td></tr> <tr><td style="background-color: orange;">MEDIUM</td></tr> <tr><td style="background-color: green;">LOW</td></tr> </table>		HIGH	MEDIUM	LOW	Calculate: Probability multiplied by Severity for No/Post control scores. NB For scores of 12 (High), or more contact the Health & Safety Office for further advice. Due to the seriousness of the 'Permanent Disability / Sight Loss and Fatal / Fatalities' factors this has been given a medium rating on the 'Unlikely' probability.				
HIGH													
MEDIUM													
LOW													
Site/Department: School of Civil Engineering and Surveying				Severity →		Minor injury 1	Lost time/ Ill Health 2	Major / >7 days 3	Perm Disability/ Sight Loss 4	Fatality/ Multiple fatality 5			
Task/Activity/Area: Collecting secondary data/ Study Room				Probability ↓		Highly Unlikely 1	Unlikely 2	Possible 3	Probable 4	Certain 5			
Notes:						1	2	3	4	5			
(Including details of previous accidents/incidents)						2	4	6	8	10			
Risk Assessment Team: Peter Cruddas and Bektas Berkay Yanilmaz						3	6	9	12	15			
(People completing the risk assessment, minimum of 2 people)						4	8	12	16	20			
						5	10	15	20	25			
				Risk assessment start date:		03/05/2020							
Highly unlikely: Slight chance of an accident happening		Unlikely: An unusual combination of factors would be required for an accident to happen		Possible: Not certain to happen but multiple additional unforeseen factors may result in an accident happening		Probable: Not certain to happen but one additional unforeseen factor may result in an accident happening		Certain: A high probability of an accident happening					
Minor injury: Injury requiring basic first aid i.e. Plaster or cold compress		Lost time / Ill health: Injury that requires medical treatment at hospital or GP		Moderate / > 7 days off work: An injury or work related illness reportable under <i>The Reporting of Injuries, Diseases and Dangerous Occurrences Regulations 2013</i>		Perm Disability / Eye Sight loss: Likely permanent disability Acute/ Chronic health effects		Fatality / Multiple fatality: An injury/ Ill health that results in a fatality or fatalities					
Dept. Manager (Print Name):		P Cruddas		Signature:									
Review Date:				Reviewed by:									
Reason for review:													
Dept. Manager (Print Name):				Signature:									

General Risk Assessment Form - The University of Portsmouth Health & Safety Office: Issue 4

Page 1

Ref No or Task-step	Identified hazards or injury causes, highlighting risks (Injury focused - see checklist)	People at risk i.e. Staff, students, visitors, contractors or the public	Score - No controls (Probability x Severity = calculation)	Controls/Procedures/Key Behaviours (Existing controls, information, training etc.)	Score - Post Controls (Calculation)	Further action required	Action Priority (H/ML)
Collecting Data	Back pain caused by sitting in front of the screen for a long time	Self	2 x 2 = 4	Make sure the screen is at the user's eye level to avoid any twisting.	1 x 2 = 2	None	Low
Collecting Data	Eye injuries because of computer screen	Self	2 x 2 = 4	Wear glasses and use screensaver	1 x 2 = 2	None	Low

General Risk Assessment Form - The University of Portsmouth Health & Safety Office: Issue 4

Page 2