UPPSALA
UNIVERSITET

UPTEC W 24042
Examensarbete 30 hp
Juni 2024

Rainwater harvesting in rural Kenya

How can a sufficient volume of safe drinking water be ensured through rainwater harvesting at schools?

Torun Allansson

Civilingenjörsprogrammet i miljö- och vattenteknik

UPPSALA UNIVERSITET

Rainwater harvesting in rural Kenya. How can a sufficient volume of safe drinking water be ensured though rainwater harvesting at schools?

Torun Allansson

Abstract

One in four people in the world do not have access to safe drinking water. In rural Kenya almost half of the population lack basic service for safe drinking water. Rainwater harvesting is one way to collect the runoff excess in the rainy seasons for use during the rest of the year. Rainwater is usually of better water quality than water from other sources, like surface water or borehole water, which often has high salinity levels in Kenya. However, there are serious risks that rainwater may be contaminated during collection and that the harvested rainwater is not enough for the whole year. This study has therefore investigated the potential rainwater volume that can be harvested at schools in rural Kenya, and how safe drinking water quality can be ensured from the harvested rainwater.

The results show that the harvested rainwater volume is sufficient for covering the drinking water demand of one litre per person per day the whole year, and that the harvested rainwater can cover other water usages as well, if actions are taken against the limiting factors (storage capacity, catchment area, and water consumption) at each school, and that water quality can be improved both through preventive actions and point-of-use water treatment technologies. Regular inspection of the rainwater harvesting systems is recommended to ensure that maintenance and preventive actions are performed. It is also recommended to monitor rainwater quality continuously.

Keywords: drinking water quality, Kenya, MCDA, multicriteria decision analysis, point-of-use water treatment technology, QMRA, quantitative microbial risk assessment, rainwater harvesting, sanitary inspection.

Teknisk-naturvetenskapliga fakulteten

Uppsala universitet, Utgivningsort Uppsala

Handledare: Helfrid Schulte-Herbrüggen Ämnesgranskare: Ekaterina Sokolova

Examinator: Sahar Dalahmeh

REFERAT

Regnvatteninsamling på Kenyas landsbygd. Hur kan tillräcklig volym av säkert dricksvatten säkerställas genom regnvatteninsamling på skolor?

Torun Allansson

Var fjärde människa på jorden saknar tillgång till säkert dricksvatten. På Kenyas landsbygd saknar nästan hälften av befolkningen grundläggande tillgång till säkert dricksvatten. Regnvatteninsamling är ett sätt att ta vara på överflöd av vatten från regnperioder och använda det under resten av året. Regnvatten har ofta bättre vattenkvalitet än vatten från andra tillgängliga vattenkällor, som ytvatten eller brunnsvatten, som ofta har höga salthalter i Kenya. Men det finns stora risker att regnvattnet blir förorenat under insamlingsproessen och att det insamlade regnvattnet inte räcker hela året. Den här studien har därför undersökt den potentiella regnvattenvolym som kan samlas in på skolor på Kenyas landsbygd samt hur säkert dricksvatten kan säkerställas från det insamlade regnvattnet.

Resultatet visar att den regnvattenvolym som kan samlas in är tillräcklig för att täcka dricksvattenbehovet på en liter per person per dag hela året och att regnvattnet även kan räcka för andra vattenanvändningsområden, om åtgärder sätts in mot de begränsande faktorerna (lagringskapacitet, insamlingsyta och vattenförbrukning) på varje skola, samt att vattenkvaliteten kan höjas både genom förebyggande åtgärder och småskaliga vattenreningstekniker. Regelbunden tillsyn av regnvatteninsamlingssystemen rekommenderas för att säkerställa att underhåll och förebyggande åtgärder genomförs. Kontinuerlig provtagning av regnvattnet är också rekommenderad.

Nyckelord: dricksvattenkvalitet, Kenya, kvantitativ mikrobiell riskbedömning, MCDA, multikriterieanalys, QMRA, regnvatteninsamling, sanitetsinspektion, småskaliga vattenreningstekniker.

Institutionen för geovetenskaper; Luft-, vatten- och landskapslära, Uppsala universitet

Villavägen 16, 752 36 Uppsala, Sverige

PREFACE

This Master thesis of 30 credits constitutes the last part of the five years programme in Water and Environmental Engineering at Uppsala University and the Swedish University of Agricultural Sciences (SLU). The thesis project has been carried out through a collaboration between Ecoloop, the Salvation Army and Uppsala University. Helfrid Schulte-Herbrüggen from Ecoloop, and the Salvation Army has been the supervisor. Ekaterina Sokolova has been the subject reviewer, and Sahar Dalahmeh has been the examiner, both at Department of Earth Sciences; Program for Air, Water and Landscape Sciences at Uppsala University. The master thesis was carried out as a part of the WASH and resilience project within the Salvation Army Kenya East Territory.

Special thanks to the WASH and resilience project team within the Salvation Army Kenya East Territory for the warm welcome to Kenya, and for all your support in collecting data during the field visit. I would like to express my gratitude to everyone that participated in the focus group discussions during the field visit, for sharing your stories and broaden my understanding of living in a water scare country. I also want to thank my supervisor, Helfrid Schulte-Herbrüggen, for accompanying me on the field visit to Kenya, and for all your support during the Master thesis, and special thanks to Benson Nyaga Mbarire that drove us safely on the roads in Kenya. I also thank Åforsk for the scholarship that made it possible for me to perform the field visit to Kenya and thank to Kenya Meteorological Department for the provision of rainfall data.

Thanks to my subject reviewer, Ekaterina Sokolova, for your continuous guidance, and for your valuable feedback and helpful structure during the process of writing the Master thesis. Thanks to Anders Larsolle for supporting me in creating the map over Kenya in GIS, and thanks to Allan Rodhe who, without knowing it, inspired me to summarize my work in a song. Finally, I thank each and everyone that has supported med during the Master thesis, and during the five years of engineering studies. Above all, I praise and give thanks to the almighty God. Glory be to the Father, and to the Son and to the Holy Spirit, as it was from the beginning, is now, and ever shall be, world without end. Amen.

Torun Allansson

Uppsala, June 2024

UPTEC W 24042, ISSN 1401-5765
Digitally published in DiVA, 2024, through Department of Earth Sciences, Uppsala University
(http://www.diva-portal.org/)

POPULÄRVETENSKAPLIG SAMMANFATTNING

Föreställ dig en torr sommar. Det kommunala vattensystemet är utslaget. Du behöver hämta ditt dricksvatten direkt från ån en bit bort. Det ser brunt ut och det flyter något grönt på ytan, men det är i alla fall vatten. Du tar med det hem i en vattendunk och låter det stå några timmar så den tyngsta smutsen får sjunka ner till botten. Du blandar i aska från gårdagens grillkväll för att askan kan suga åt sig det bruna i vattnet, så det blir klart. Sedan blir det att starta spisen och börja koka vattnet, för att bakterierna ska dö. Sedan ska vattnet svalna. Så, äntligen, kan du släcka törsten och laga dagens middag.

Nästa dag kom tills slut regnet. Gräsmattan hade blivit gul efter veckor av torka. Du hör hur det smattrar mot taket. Du blir glad för nu kommer regnet från ditt tak rinna ner i stuprännorna och in i den regnvattentank som du har på innergården. Snart, om några dagar med ihållande regn, kommer du kunna gå ut på gården och hämta in klart regnvatten från kranen på tanken. Du slipper gå den långa vägen ner till ån och du slipper hela proceduren men att göra vattnet rent. Regnvatten är ju redan klart och doftar så friskt.

Men lyckan är kortvarig. Regnvattnet i tanken tog slut efter bara några veckor och du känner hur du börjat få en ihållande magvärk. Kan det vara regnvattnets fel? Hur skulle det vara möjligt? Regnvattnet som var så klart och doftade så friskt! Finns det något skadligt i regnvattnet som inte syns? Inte skulle väl regnvattnet behöva renas på samma sätt som vattnet från ån?

För oss i Sverige nu på 2020-talet har vi antagligen inte behövt hämta dricksvatten varken från ån eller från insamlat regnvatten. Vi har ett utbyggt ledningsnät med säkert dricksvatten som renats enligt konstens regler i ett vattenverk innan det kommer till kranarna i våra hem. Eller så har vi egen brunn med tjänligt grundvatten som kommer rätt in i huset. Om vi har kommunalt dricksvatten vet vi ens sällan varifrån vattnet kommer. Det bara finns där. Och det är rent. Men så är det inte för alla.

Var fjärde människa på jorden har inte tillgång till säkert dricksvatten. För många människor är det en självklar del av vardagen att gå långa sträckor för att hämta vatten från en å eller en flod, bära hem det och göra det så rent som möjligt innan det används som dricksvatten och för att laga mat och tvätta och städa och vattna och allt annat som man behöver vatten till. Enligt FN:s globala mål för hållbar utveckling ska alla människor ha tillgång till rent vatten år 2030. Det är många som arbetar för det, både myndigheter och olika företag och organisationer. En av dem är Frälsningsarmén.

Frälsningsarmén i Sverige stöttar lokala utvecklingsprojekt genom Frälsningsarmén i andra länder. I Kenya är Frälsningsarmén en stor kyrka och en viktig aktör i samhället. För femton år sedan började Frälsningsarmén i Kenya arbetet med vattenprojekt på skolor på landsbygden för att förbättra tillgången till rent vatten, sanitet och god hygien. Det arbetet spred sig sedan från skolor till de omgivande hemmen. En del av arbetet är att bygga ut system för regnvatten-insamling för att ta vara på regnet under regnperioderna och på så sätt ha vatten nära till hands under torrperioderna, resten av året.

Syftet med det här arbetet var att undersöka hur tillräcklig mängd säkert dricksvatten kan säkerställas genom regnvatteninsamling från tak på skolor som Frälsningsarmén arbetar med på landsbygden i Kenya. För att komma fram till det har jag läst tidigare forskning om vilka föroreningar som finns i regnvatten och vilka förebyggande åtgärder och reningsmetoder som finns för att göra vattnet säkert. Utifrån de föroreningsnivåer som tidigare studier mätt upp har jag beräknat vilken nivå av rening som behövs för regnvatten, genom en kvantitativ mikrobiell riskbedömning och jämfört olika småskaliga vattenreningstekniker med hjälp av en multikriterieanalys. Jag har också beräknat den potentiella regnvattenvolym som kan samlas in utifrån nederbördsdata. För att bättre förstå det lokala sammanhanget gjorde jag en studieresa till tre av de skolor i Kenya som Frälsningsarmén arbetar med. Där fick jag möta och samtala med lokalbefolkningen, personer från de lokala vattenmyndigheterna, projektpersonal i Frälsningsarméns projekt, skolbarn och lärare på skolorna. Jag genomförde också en risk-inspektion på varje skola där jag utifrån Världshälsoorganisationens formulär observerade risker kopplade till de befintliga regnvatteninsamlingssystemen. Förhoppningen med detta arbete är att presentera konkreta förslag på åtgärder för hur regnvatteninsamlingssystemen kan förbättras, så vattnet kan räcka längre och få högre kvalitet.

Till att börja med är det viktigt att veta att regnvatten inte är säkert att dricka som det är, trots att det ser klart ut. Regnvatten i sig själv är renare än många andra vattenkällor men när det faller på tak tar regnet med sig smuts som hamnat där. Värst är de sjukdomsframkallande mikroorganismer, alltså bakterier, virus och protozoer, som finns i fågelskit och avföring från andra djur. De kan göra oss sjuka så vi får ont i magen och diarré. Eftersom de är så små, kan vi inte se dem med blotta ögat, vilket gör att förorenat vatten kan se rent ut. Men mängden bakterier som finns i regnvatten kan faktiskt vara lika hög som i vatten från sjöar och floder!

Beroende på hur stor mängd bakterier, virus och protozoer det finns i regnvatten, behövs olika stark rening för att vattnet ska bli säkert att dricka. Det finns också flera förebyggande åtgärder man kan göra för att det insamlade regnvattnet ska vara så rent som möjligt. En viktig åtgärd är att använda sig av *first flush*. Det innebär att man låter de första millimetrarna regn rinna av taket utan att det vattnet samlas upp, så den smuts som kommit på taket mellan regnen inte kommer med in i regnvattentanken. Det är också viktigt att regnvatteninsamlingssystemet underhålls regelbundet så risken att sjukdomsframkallande mikroorganismer kommer in i regnvattentanken minskar. Andra förebyggande åtgärder är att ta bort grenar från träd som hänger över taket, så inte fåglar sitter där och skiter och att regnvattentanken rengörs med desinfektionsmedel vid jämna mellanrum. Med förebyggande åtgärder kan man faktiskt minska mängden bakterier i det insamlade regnvattnet med 99,9 %!

Men för att regnvatten ska vara säkert att dricka behöver mängden bakterier och protozoer minska med upp till 99,999999%. Och man behöver ta bort ännu mer virus. Olika typer av sjukdomsframkallande mikroorganismer kan reduceras på olika sätt, både genom olika slags filter som tar bort dem och genom desinfektion med bland annat klor, som inaktiverar dem. Bakterier är känsliga mot klor men vissa protozoer behöver filtreras bort för att man ska få bort tillräckligt stor mängd. Därför är det bra att använda sig av olika småskaliga vattenrenings-tekniker efter varandra, för att få bort tillräckligt stor mängd av alla sjukdomsframkallande mikroorganismer.

Förutom de storskaliga reningsprocesser som finns i våra vattenverk i Sverige finns det flera småskaliga vattenreningstekniker som kan användas lokalt, på platsen där vattnet används. Tack vare samtal med projektpersonal i Frälsningsarmén och lokalbefolkning i byarna på lands-bygden i Kenya kunde jag genomföra en multikriterieanalys där jag jämförde olika småskaliga vattenreningstekniker baserat på kriterier som är viktiga för att dessa ska användas och fortsätta fungera över tid. Det är grundläggande att vattenreningstekniken har en hög rening av sjukdomsframkallande mikroorganismer. Sedan är det också viktigt att den är socialt och kulturellt accepterad och att den kan rena tillräckligt stor mäng vatten samt att tekniken är tillgänglig lokalt. Två beprövade kloreringsmetoder, Aquatabs ® och WaterGuard blev högt rankade. En obeprövad metod i dessa sammanhang, biosandfilter, blev också högt rankad. Ett biosandfilter liknar de sandfilter man har i storskaliga vattenverk men byggs i mindre tunnor av lokala material. Fördelen med biosandfilter är att det kan rena vattnet från protozoer. För att få så hög rening som möjligt är det bra att kombinera reningsmetoder som både tar bort och inaktiverar sjukdomsframkallande mikroorganismer. Man kan till exempel använda klorering med Aquatabs ®, som är bra på att inaktivera bakterier och virus, tillsammans med ett bio-sandfilter, som är bra på att ta bort även protozoer.

Det finns olika åtgärder som kan göras så den insamlade regnvattenvolymen bättre täcker vattenbehoven på varje skola. I ett område med högre nederbörd kan fler regnvattentankar behövas för att kunna samla in mer av det regn som kommer. I områden med lägre nederbörd kan det i stället vara takets storlek som är den begränsande faktorn. Då kan regnvatten-insamlingssystemet behöva byggas ut så fler tak används. Skolans vattenförbrukning är också en avgörande del i om det insamlade regnvattnet räcker. Därför är det viktigt att mäta vattenförbrukningen över tid för att se om den motsvarar den rekommenderade vatten-förbrukningen på skolor i Kenya. Om vattenförbrukningen är orimligt hög kan skolan behöva jobba med hur man använder vatten så det hanteras på ett mer varsamt sätt och på så sätt räcker längre, samt prioritera regnvatten som dricksvatten och använda vatten av lägre kvalitet till städning och likande.

Slutsatsen av arbetet är att åtgärder kan sättas in mot de begränsande faktorerna (lagrings-kapacitet, insamlingsyta och vattenförbrukning) för att det insamlade regnvattnet ska räcka längre samt att vattenkvaliteten kan förbättras både genom förebyggande åtgärder och användning av småskaliga vattenreningstekniker. För att göra det krävs regelbunden tillsyn av regnvatteninsamlingssystemen och samarbete mellan olika aktörer. För att bygga upp ett hållbart arbete för reparationer och underhåll uppmuntras personer från olika skolor att besöka varandra, så de skolor som inte har fungerande underhåll kan lära av dem som har det. Vidare undersökningar kring möjligheten att bygga lokala biosandfilter krävs, för att se om det kan vara en passande småskalig vattenreningsteknik i den lokala kontexten. Precis som Frälsnings-armén jobbar med andra frågor lokalt i dessa vattenprojekt är det viktigt att fortsätta involvera lokalbefolkningen i utvecklandet av nya vattenreningstekniker, så engagemanget att använda dessa tekniker kommer inifrån och blir långsiktigt hållbart.

Föreställ dig en torrperiod som varar i flera månader. Det finns inget kommunalt vattensystem. Du ser rader av människor bära sina gula vattendunkar ner till floden för att hämta dricksvatten. Det är fullt med skräp längs strandkanten. Uppströms släpps avloppsvatten ut i floden utan rening. Tungmetaller från industrier samlas på botten av floden. Vattnet är brunt. Men det är i alla fall vatten. Föreställ dig glädjen över att slippa gå långt för att hämta smutsigt vatten och i stället kunna ta regnvatten direkt från kranen på tanken utanför huset. Föreställ dig besvikelsen över hur det till synes rena regnvattnet gör att man får ont i magen. Tänk om en ökad medvetenhet om att det finns smittoämnen i regnvatten kan bidra till att man börjar arbeta mer aktivt med förebyggande åtgärder och småskaliga vattenreningstekniker för att säkerställa säkert dricksvatten från regnvatteninsamling på skolor på Kenyas landsbygd. Tänk om man kan sätta in åtgärder mot de begränsande faktorerna så det insamlade regnvattnet räcker längre. Tänk om fler kan få tillgång till säkert dricksvatten på jorden.

TABLE OF CONTENT

1. INTRODUCTION ... 1
1.1 AIM AND OBJECTIVES ... 4
1.2 DELIMITATIONS ... 4
2. METHODOLOGY ... 5
2.1 LITERATURE REVIEW ON RISK FACTORS AND RAINWATER QUALITY ... 6
2.2 FIELD VISIT TO MACHAKOS, MAKUENI AND KITUI COUNTIES IN KENYA ... 7
2.3 ASSESSMENT OF WATER USE AND POTENTIAL RAINWATER HARVESTING VOLUME AT SCHOOLS ... 10
2.4 SANITARY INSPECTION FOR RAINWATER COLLECTION AND STORAGE ... 11
2.5 QUANTITATIVE MICROBIAL RISK ASSESSMENT ON REQUIRED TREATMENT FOR RAINWATER ... 12
2.6 MULTICRITERIA DECISION ANALYSIS ON POSSIBLE POINT-OF-USE WATER TREATMENT TECHNOLOGIES ... 14
3. RESULTS ... 17
3.1 WATER USE AND POTENTIAL RAINWATER HARVESTING VOLUME AT SCHOOLS ... 17
3.1.1 Water Use at Schools ... 17
3.1.2 Potential Rainwater Harvesting Volume at Schools ... 18
3.2 MICROBIAL RISK FACTORS ASSOSIATED WITH RAINWATER HARVESTING ... 22
3.2.1 Risk Factors Presented in Previous Research on Rainwater Harvesting ... 22
3.2.2 Risk Factors Observed Through the Sanitary Inspection for Rainwater Collection and Storage During the Field Visit ... 23
3.2.3 Preventive Actions That Can Contribute to Minimizing the Risk of Microbial Contamination ... 25
3.3 TREATMENT FOR RAINWATER ... 27
3.3.1 Required Treatment for Rainwater Based on the Swedish QMRA-tool ... 27
3.3.2 Treatment Performance of Point-of-use Water Treatment Technologies ... 30
3.3.3 Evaluation of Point-of-use Water Treatment Technologies Through the Multicriteria Decision Analysis ... 33
4. DISCUSSION ... 35
4.1 ENSURING A SUFFICIENT VOLUME OF RAINWATER AT SCHOOLS ... 35
4.2 IMPROVING RAINWATER QUALITY THROUGH PREVENTIVE ACTIONS ... 36
4.3 ASPECTS TO CONSIDER WHEN CHOOSING POINT-OF-USE WATER TREATMENT TECHNOLOGIES ... 38
4.4 PRACTICAL IMPLEMENTATIONS AND FURTHER RESEARCH ... 40

5. CONCLUSIONS 42
REFERENCES 43

1. INTRODUCTION

Access to safe drinking water is a basic human right, essential to a good health (World Health Organization 2017a) and part of the 6th Sustainable Development Goal by the United Nations, that shall be achieved in 2030 (UNICEF & WHO 2023). Even though the availability of safely managed drinking water has increased during the last decade, there are still 2.2 billion people globally that are without safely managed drinking water in year 2022. That is one in four people (UNICEF & WHO 2023).

The definition of safely managed drinking water is presented in Table 1, together with the other service levels of drinking water and the definition of an improves source (UNICEF & WHO 2023). The risk of microbial contamination of drinking water comes from faeces from humans and animals (World Health Organization 2017a). Faecal contamination is usually identified through detection of the indicator bacteria *E. coli*. The priority chemicals are arsenic and fluoride (World Health Organization 2017b). Contamination of *E. coli* is the primary reason that safely managed drinking water is not met in low- and middle income countries (Bain et al. 2021).

Table 1. Service levels for drinking water and the coverage of the service levels in Kenya in 2022, together with the definition of an improved source. Modified from UNICEF & WHO (2023) *and* JMP (2022).

Service level for drinking water		Definition	Coverage of the *rural* population in Kenya	Coverage of the *urban* population in Kenya	Coverage of the *total* population in Kenya
At least basic	Safely managed	Drinking water from an improved source that is accessible on premises, available when needed and free from faecal and priority chemical contamination.	53.3 %	86.4 %	62.9 %
	Basic	Drinking water from an improved source, provided collection time is not more than 30 minutes for a round trip, including queuing.			
Limited		Drinking water from an improved source, for which collection time exceeds 30 minutes for a round trip, including queuing.	10.7 %	3.6 %	8.7 %
Unimproved		Drinking water from an unprotected dug well or unprotected spring.	11.5 %	4.0 %	9.3 %
Surface water		Drinking water directly from a river, dam, lake, pond, stream, canal or irrigation canal.	24.5 %	6.0 %	19.1 %
Improved source		Piped water, boreholes or tubewells, protected dug wells, protected springs, rainwater, and packaged or delivered water.			

In Kenya, access to safe drinking water is significantly lower in rural areas than in urban areas, as presented in Table 1. Different sources report that access to safe drinking water is available for slightly more than 60 % of the total population. The WHO/UNICEF Joint Monitoring Programme for Water Supply, Sanitation and Hygiene (JMP) reports that 62.9 % of the total population has access to at least basic service level of water (JMP 2022) and Kenya National Bureau of Statistics reports that 67.9 % of the total population uses safely managed drinking water sources in 2022 (Kenya National Bureau of Statistics 2022).

The climate in Kenya is mainly arid or semi-arid with air temperature at approximately 25 °C during the whole year and two rainy seasons that break into the otherwise dry weather (World Bank Climate Change Knowledge Portal 2021). The country is vulnerable to climate change and has a low readiness to improve resilience (University of Notre Dame 2024). Different drinking water sources are used in the rainy and dry seasons. Rainwater is commonly used during the rainy seasons. Other important drinking water sources are boreholes, kiosk water, wells, springs (Okotto-Okotto et al. 2021), public taps and surface water (Morris et al. 2018). Previous studies from Kenya indicate that the groundwater very often exceeds the water quality thresholds (Nowicki et al. 2023) both regarding high salinity (Araya et al. 2023) and fluoride levels (Gevera & Mouri 2018; Rusiniak et al. 2021; Mwiathi et al. 2022). According to the National Water Master plan 2030 by the Government of Kenya, water demand will increase at a greater rate than water resources during the coming decades, as the population increases (Nippon Koei Co., Ltd. 2013).

In Kenya, the Ministry of Water, Sanitation and Irrigation is responsible for the availability and accessibility of water resources (Ministry of Water, Sanitation and Irrigation 2023). Increased water supply and water quality are parts of the Integrated Development Plans for 2027 for the local county governments in Kenya, and cooperation with stakeholders both within and outside government is encouraged to achieve the goals (County Government of Kitui 2023; County Government of Machakos 2023; County Government of Makueni 2023). The provision of safe water and sanitation in schools relies on the Ministry of Education, the Ministry of Health and the ministry of Water and Sanitation. According to the *Standards and Guidelines for WASH Infrastructure in Pre-primary and Primary Schools in Kenya*, the basic minimum water requirements for non-residential schoolchildren and staff are 5 litres per person per day, and 20 litres per person per day at boarding schools (Ministry of Education et al. 2018). Water in the schools is to be used for drinking, cooking, personal hygiene, cleaning and laundry. Water for drinking, cooking and personal hygiene should meet drinking water standards, while water for cleaning and laundry can be of lower water quality. The schools should aim to perform water quality tests at least once per year and make a budget provision for the sampling and testing. Unless the water has been determined to be free from bacterial contaminants, all water for drinking should be treated (Ministry of Education et al. 2018).

To improve work within water, sanitation and hygiene (WASH) in local schools and communities, the Salvation Army Kenya East Territory have worked with WASH projects since 2009. The projects are running in phases of for four to five years with a focus that has broadened to include more components for each phase. The current, third, phase started in 2019 with a focus on resilience to adapt to the effects of the climate change through WASH and food security. The geographical area for the project covers communities in the Counties Machakos, Makueni, Kitui, Taita Taveta and Isiolo/Samburu. One central focus area for the WASH and resilience project is to improve WASH access in schools and their surrounding communities. The project initially installed rainwater harvesting tanks in the schools and then extended the support to the surrounding households. The focus on rainwater harvesting and storage in the WASH and resilience project is to ease reliance on streams and boreholes since the areas get relatively high rainfalls during the rainy periods (Right Track Africa 2022).

Rainwater harvesting has been practiced throughout history as a way of collecting water. The principle is to capture the excess rainfall runoff and use it as a water supply. Rooftop harvested rainwater is transported from the roof through gutters and drainpipes to a storage system (Mekdaschi Studer & Liniger 2013). Rainwater is less frequently contaminated than unimproved water sources (Bain et al. 2021), but even though rainwater is inherently relatively free from contaminants, faecal droppings from birds and other animals, insects, leaves, wind-blown dirt and litter on the roof can pollute the rainwater from the catchment area (World Health

Organization 2017a). Water from an improved source, like rainwater, is more likely to be free from microbial contamination than water from unimproved sources, but faecal bacteria have been observed in water from both improved and unimproved sources (World Health Organization 2017b). The *E. coli* levels in rainwater have been measured at equally high levels as in unimproved sources (Bain et al. 2021). Water from an improved drinking water source is therefore not necessarily safe (World Health Organization 2016).

A review article on previous studies from different countries confirms that microbial contamination is the main water quality problem in rainwater (Meera & Ahammed 2006). All pathogen groups (bacteria, viruses and protozoa) have been detected in rooftop harvested rainwater (Crabtree et al. 1996; Dobrowsky et al. 2014; Shubo et al. 2021). Risk factors for contamination in rooftop harvested rainwater have been investigated through sanitary inspections, for example, in Bangladesh (Karim 2010; Islam et al. 2011), Fiji (Kohlitz & Smith 2014) and Kenya (Misati et al. 2017). One main finding is that a well-kept rainwater harvesting system reduces the risks of contamination and that treatment is necessary before rainwater is used as drinking water (Meera & Ahammed 2006). A study from Vietnam shows that a well-designed rainwater harvesting system at a school can provide sufficient volume of safe drinking water from rainwater, after applying point-of-use water treatment technologies (Dao et al. 2017).

The performance and acceptability of different point-of-use water treatment technologies have been investigated through multicriteria decision analysis (MCDA) by previous studies. Possible point-of-use water treatment technologies investigated were for example: solar disinfection, boiling, chlorination, coagulation with Moringa seed, ceramic pots and biosand filtration (Santos et al. 2016). Previous studies have also investigated potential onsite water treatment systems for emergency situations (Loo et al. 2012) and different decision making criteria for water and sanitation projects in developing countries (Garfí & Ferrer-Martí 2011).

There is a need to adapt the results of previous research on rainwater harvesting and point-of-use water treatment technologies to local level in Kenya, since there are several problems connected to the current rainwater harvesting practices. According to a study from western Kenya, rainwater is often consumed untreated, since rainwater is considered the safest water source by people from local villages (Okotto-Okotto et al. 2021). Studies from Bangladesh confirm that rainwater is commonly consumed untreated (Karim 2010; Islam et al. 2011). According to a study from Machakos County, Kenya, there are several barriers in adapting rainwater harvesting, for example, costs, lack of support from the local government, and poor quality of the rainwater harvesting technologies (Wekesa et al. 2022). A study from Fiji confirms that limited government resources can be a challenge in adapting rainwater harvesting at household level (Kohlitz & Smith 2014).

This master thesis has collected findings from studies on rainwater harvesting from all over the world and applied relevant aspects in the WASH and resilience project within the Salvation Army Kenya East Territory. One problem in the project is that the implemented rainwater harvesting systems do not function over time. The rainwater volume that is harvested does not last the whole dry periods and rainwater quality is not always ensured through preventive actions or point-of-use water treatment technologies before it is used for drinking.

1.1 AIM AND OBJECTIVES

The overall aim of the Master thesis was to provide practical recommendations that can contribute to ensuring a sufficient volume of safe drinking water from the rainwater harvesting systems. This project investigated rainwater harvesting systems at three schools connected to the WASH and resilience project within the Salvation Army Kenya East Territory and identified the limiting factors in ensuring a sufficient volume of rainwater, preventive actions that can reduce the risk of microbial contamination to rainwater and suitable point-of-use water treatment technologies.

The following objectives were addressed:

1. Investigate how well the water use of the schools corresponds to the basic minimum water requirements and whether this requirement can be reached through the local rainfall, the available rooftop area, and the storage capacity.

2. Identify the microbial risk factors associated with the harvested rainwater based on previous research and the sanitary inspection for rainwater collection and storage, and present preventive actions that can contribute to minimizing the risks.

3. Investigate the required treatment for rainwater based on a quantitative microbial risk assessment through the Swedish QMRA-tool, the treatment efficiency of possible point-of-use water treatment technologies and investigate what point-of-use water treatment technologies are most suitable in the local context through a multicriteria decision analysis.

1.2 DELIMITATIONS

Only the microbial aspect of safely managed drinking water was considered, not the priority chemical parameters arsenic and fluoride, and neither the criteria *accessible on premises* nor *available when needed*. According to the World Health Organization, a majority of the health problems from drinking water comes from microbial contamination (World Health Organization 2017a) and the physio-chemical quality of rainwater generally meets the quality guidelines, with the exception of pH (Meera & Ahammed 2006). The criteria accessible on premises and available when needed are important but not part of the objectives in this study. Harvested rainwater is however usually located on premises, but it differs between countries (World Health Organization 2017b). According to previous research, one advantage of rainwater harvesting is that is it available close to the building where it is collected (Mekdaschi Studer & Liniger 2013). However, investigations on this aspect are outside of the scope of this study.

The required treatment level for rainwater was investigated based on pathogen concentrations in rainwater reported in previous research, since no continuous water quality measurements are performed at the schools connected to the WASH and resilience project. However, one reported sample on *E. coli* as indicator from the WASH and resilience project was found and used together with the literature concentrations.

2. METHODOLOGY

To answer the objectives of this study, several methods were used. Risk factors associated with rainwater harvesting and pathogen concentrations in rainwater were investigated through a literature review. During a field visit to Machakos, Makueni and Kitui counties in Kenya, sanitary inspections on rainwater collection and storage were performed as well as focus group discussions with local communities. An assessment of potential rainwater volume at schools were conducted based on local meteorological data. Trough the Swedish QMRA-tool, a quantitative microbial risk assessment was performed to investigate the required treatment level for rainwater. Finaly, different point-of-use water treatment technologies were compared and evaluated in a multicriteria decision analysis. The connection between the objectives, the methods and the results are visualized in Figure 1.

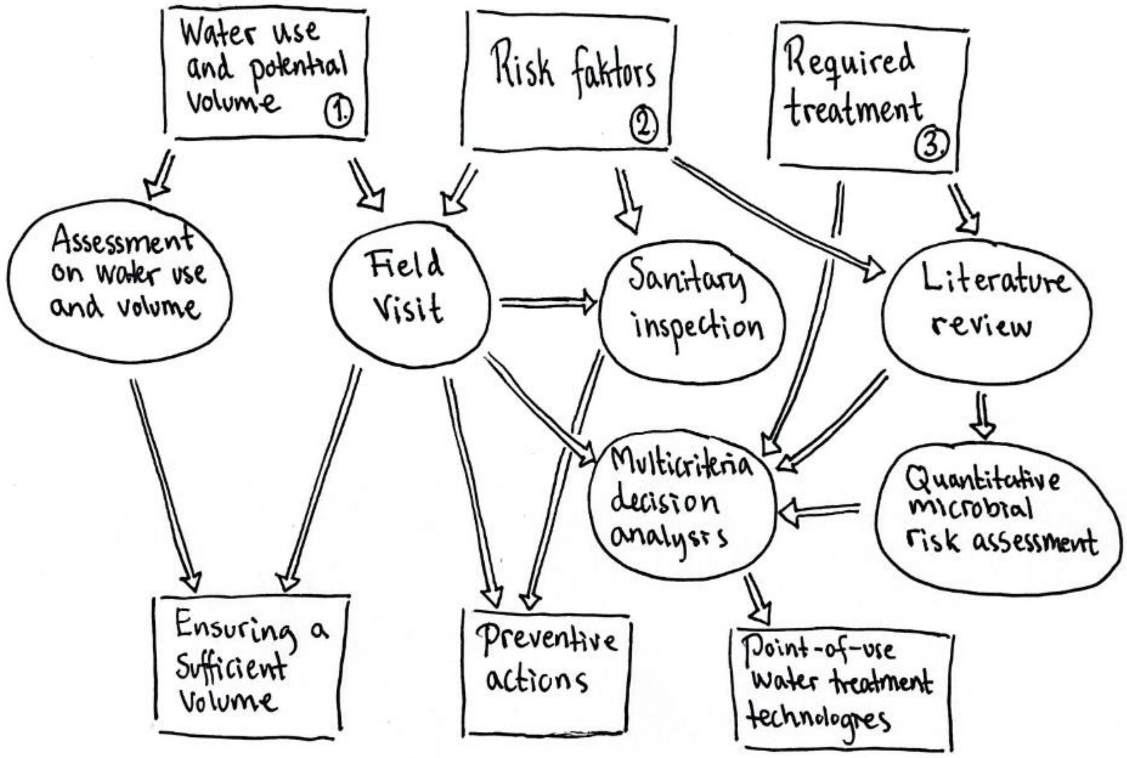

Figure 1. Flow chart over the objectives, methods, and outcomes of the Master thesis. The objectives are presented in boxes, numbered from one to three. The methods are presented in circles. The outcomes are presented in boxes, bellow the objectives they are connected to. The arrows show the connection between the different parts.

2.1 LITERATURE REVIEW ON RISK FACTORS AND RAINWATER QUALITY

The literature review was conducted as an iterative process to find risk factors for contamination of rainwater, pathogen concentrations in rainwater that could be used as input data in the Swedish QMRA-tool, point-of-use water treatment technologies suitable for rainwater, and possible criteria for the multicriteria decision analysis. The database Scopus was used to find academical articles. The document type was limited to *article* and *review*. New articles were also found through the references in the articles.

Key words for the literature search for risk factors included: rainwater harvesting, rainwater, drinking water, potable water, risks, pathogen, contamination, microbial contamination, water quality, Kenya and sub-Saharan Africa and they were used in different combinations in the database searches. Specific names such as *Escherichia coli, E. coli*, EHEC, VTEC, STEC, *Salmonella*, rotavirus and adenovirus were used to find specific concentrations in rainwater from previous research that could be used in the Swedish QMRA-tool.

To find possible point-of-use water treatment technologies and possible criteria for the multicriteria decision analysis key words such as multicriteria decision analysis, MCDA, multicriteria analysis, MCA, point-of-use water treatment, household treatment technology, water treatment, drinking water and potable water were used in different combinations in the database searches. Besides academic articles, information on point-of-use water treatment technologies was obtained from reports from the World Health Organization and from the product description of the point-of-use water treatment technologies. The efficiency of different point-of-use water treatment technologies was investigated and compiled.

2.2 FIELD VISIT TO MACHAKOS, MAKUENI AND KITUI COUNTIES IN KENYA

The study sites for this Master thesis were Machakos, Makueni and the lower (southern) parts of Kitui Counties in Kenya. These areas were selected since Machakos has a higher rainfall and Makueni and Kitui a lower rainfall. A field visit was done from the 29th of April to the 3rd of May 2024. The schools investigated were Kawethei Secondary School in Machakos County, Kyumbuni Primary School in Makueni County, and Mwambaisyuko Primary School in Kitui County. Kawethei Secondary School is a boarding school, while the other two are considered non-residential schools, even though there is a minority of residential schoolchildren at Kyumbuni Primary School. The locations of the counties, the investigated schools and the meteorological stations from where rainfall data were obtained are presented in Figure 2.

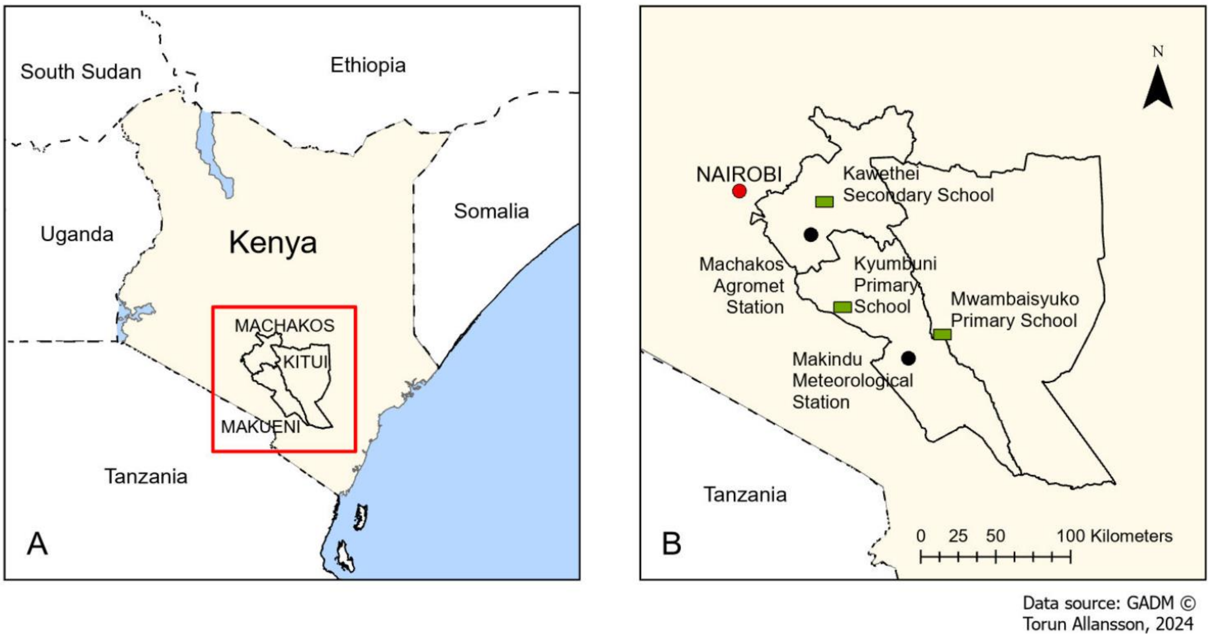

Figure 2. Map of the study area. The map to the right, map A, shows where the counties Machakos, Makueni and Kitui are situated in Kenya. The map to the left, map B, shows where the investigated schools are situated in comparison to the capital, Nairobi, and the location of the meteorological stations, from where rainfall data were obtained. The spatial data is obtained from GADM for Kenya, and the neighbouring countries (GADM 2022).

Machakos County is located east of Nairobi between latitudes 0°45′S and 1°31′S and longitudes 36°45′E and 37°45′E. The county has a semi-arid climate and a great variation in topography. The high-altitude regions have high rainfall and a dense vegetation, while the low altitude regions have less rainfall, open grassland and sporadic trees. The highlands receive the double amount of rainfall than the lowlands (County Government of Machakos 2023).

Makueni County is located at the southeastern part of Kenya between latitudes 1º35′S and 3°00′S and the longitudes 37º10′E and 38º30′E. It borders to Machakos in the north. The county has an arid and semi-arid climate and is prone to frequent droughts. The terrain contains volcanic hills, forests and farmlands. The Athi river forms a natural boarder to Kitui to the east (County Government of Makueni 2023).

Kitui County is located at the eastern part of Kenya between latitudes 0°10′S and 3°0′S and longitudes 37°50′E and 39°0′E. It shares the border with Machakos and Makueni counties to the west. Kitui is one of the largest counties in Kenya. The county has an arid and semi-arid climate with uneven terrain, rocky hills, and flat lands. The flat lands and plateaus are mainly in the central and northern part of Kitui. The rainfall in Kitui is low and unreliable and the county frequently experience droughts and floods, which affect the socio-economic activities. Kitui has a higher level of poverty than average in Kenya (County Government of Kitui 2023).

During the field visit, focus group discussions were held in each community connected to the investigated schools. In the end of the field visit, a workshop on possible point-of-use water treatment technologies and important criteria for the multicriteria decision analysis was held with the project staff within the WASH and resilience project. An overview of the focus group discussions and the workshop is presented in Table 2. In Kawethei, the focus group discussion was held in a private home where the participants had gathered. In Kyumbuni and Mwambaisyuko the focus group discussions were held at the schools together with the participants.

Table 2. An overview of the focus group discussions and the workshop for the multicriteria decision analysis, during the field visit to Kenya.

Place	County	Date	Participants	Type of meting
Kawethei	Machakos	30 April 2024	Kawethei community	Focus group discussion
			Kawethei persons with disability self-help group	
			Project staff from the WASH and resilience project	
			Local officer in the Salvation Army	
Kyumbuni	Makueni	1 May 2024	Kyumbuni community	Focus group discussion
			Representatives from Kyumbuni persons with disability self-help group	
			Schoolchildren	
			Teachers	
			Ministry of Health representative	
			Project staff from the WASH and resilience project	
			Local officer in the Salvation Army	
Mwambaisyuko	Kitui	2 May 2024	Mwambaisyuko community	Focus group discussion
			Youth representatives from Tupande (tree planting group)	
			Teachers	
			Ministry of Health representative	
			The Salvation Army Divisional Education officer	
			Project staff from the WASH and resilience project	
			Local officer in the Salvation Army	
Sultan Hamud	Kajiado	3 May 2024	George Obondo, project manager in the WASH and resilience project	Workshop for the multicriteria decision analysis
			James Nzyimi, water and sanitation engineer in the WASH and resilience project	
			Lilian Lutukai, cluster coordinator in the WASH and resilience project	
			Margaret Musumbi, cluster coordinator in the WASH and resilience project	

According to ethical principals in social science research (Bryman 2018), the people that participate in the focus groups discussions, the sanitary inspections and the workshop for the multicriteria decision analysis during the field visit were informed that the data collection was done for this Master thesis. The people agreed voluntary to participate and that the collected data could be used in this Master thesis.

During the field visit, sanitary inspections, see section 2.4, were conducted at the rainwater harvesting systems at each school. The rainwater harvesting systems investigated at the schools consisted of a catchment area (the roof), guttering channels from the roof to the storage tank, and one or several storage tanks. The design of the storage tanks was the same at all schools. Each storage tank had an inspection hatch lid at the top and an overflow hole at the top of the side of the storage tank so that water could flow out of the storage tank when it was full. The rainwater harvesting systems had a tap for extraction of water ether connected to the storage tank or at a distance from the storage tank. Figure 3 shows parts of the rainwater harvesting system at Kyumbuni Primary School.

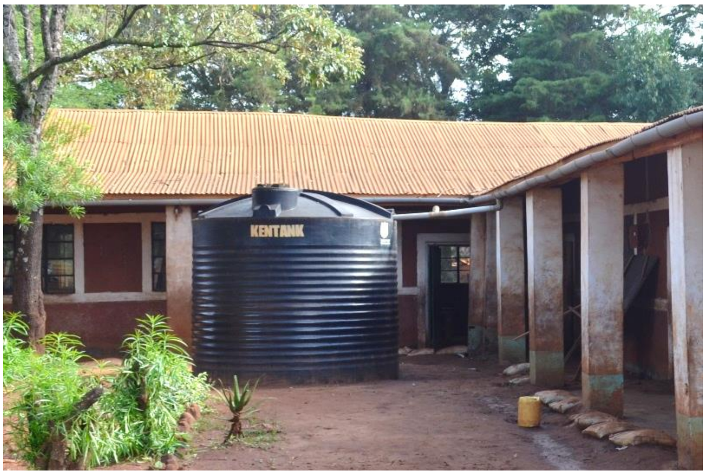

Figure 3. A typical rainwater harvesting system at a school in the study area. The components of the rainwater harvesting system are the catchment area (roof), guttering channels, and the storage tank. The photograph is taken at Kyumbuni Primary School in Makueni County. Photo by Torun Allansson.

2.3 ASSESSMENT OF WATER USE AND POTENTIAL RAINWATER HARVESTING VOLUME AT SCHOOLS

The total water use, the drinking water use, and the number of schoolchildren at each school were obtained from conversations with teachers at the schools during the field visit, and the basic minimum water requirements for schools were obtained from the *Standards and Guidelines for WASH Infrastructure in Pre-primary and Primary Schools in Kenya* (Ministry of Education et al. 2018).

The rainfall data used to estimate the potential rainwater volume were obtained from Machakos Agromet Station and from Makindu Meteorological Station through Kenya Meteorological Department. Monthly rainfall data from the last ten years (2014 – 2023) were used to calculate the potential rainwater harvesting volume for each month.

Machakos Agromet station is situated in Machakos County, 1° 17′S, 37° 25′E, and Makindu Meteorological Station is situated in Makueni County 2° 17′S, 37° 49′E. The rainfall data from Machakos Agromet Station were assumed to represent the rainfall in the whole area of Machakos County and the rainfall from Makindu Meteorological Station was assumed to represent the rainfall from Makueni County and Kitui County. The location of the meteorological stations in comparison to the schools are presented in Figure 2.

A mean value of the monthly rainfall was calculated for each month based on the monthly rainfall data from years 2014 – 2023 for both Machakos Agromet Station and Makindu Meteorological Station. These mean values for each month were plotted to show the rainfall pattern over a year and the difference between the two stations.

The potential rainwater volume that can be harvested was calculated with Equation (1)

$$V_{RW} = R \cdot A \cdot C \qquad (1)$$

where V_{RW} is volume rainwater, in litre; R is the rainfall, in mm; A is the roof area, in m^2 and C is the runoff coefficient, dimensionless. The runoff coefficient was assumed to be 0.8 which represent a loss of 20 % (Zhang et al. 2018; Shiguang et al. 2023) to create the worst-case scenario, compared to the higher runoff coefficient, 0.9, that can also be used (Zhang et al. 2018). The roof area used were a standard area of a roof catchment used for rainwater harvesting at schools in the WASH and resilience project, obtained from conversations with the engineer in the WASH and resilience project. The equation was implemented in Python and was run for the mean monthly rainfall from the two meteorological stations.

The accumulated rainwater volume in the storage tanks, in the end of each month was calculated based on the potential rainwater volume, the limitation in storage capacity and the water abstraction based on the standard drinking water consumption of 1 litre per person per day (World Health Organization 2017a) and the basic minimum water requirements of 5 litres per person per day at non-residential schools (Ministry of Education et al. 2018). The storage tanks were assumed to be empty prior to November and the water use for a month is based on the daily consumption for 30 days, even though the school is not open every day, to create the worst-case scenario. If the potential rainwater volume was greater than the water abstraction, the volume left was accumulated to the next month. If the accumulated volume was greater than the storage capacity, the storage capacity limited the rainwater collection. If the potential rainwater volume was lower than the water use, the percentage of the water demand covered by the potential rainwater volume was shown.

2.4 SANITARY INSPECTION FOR RAINWATER COLLECTION AND STORAGE

Sanitary inspections are a simple and effective tool to identify the most important causes and pathways of contamination for small water supplies, and to evaluate control options to prevent or minimize contamination (World Health Organization 2016). Sanitary inspections are commonly used for point sources with focus on the area around the water source as well as the abstraction and storage. It is also a part of water safety plans for small water supplies. Sanitary inspections often use standardized inspection forms with a systematic checklist and a limited number of questions (World Health Organization 2016). The sanitary inspection form for rainwater collection and storage by the World Health Organization was used in this study together with the management advice sheet for rainwater collection and storage (World Health Organization 2024). Questions regarding the water demand for the schools were added to the sanitary inspection forms.

The sanitary inspection form for rainwater collection and storage with its 16 questions connected to potential risk factors (World Health Organization 2024) was used in this Master thesis during the field visit to Kenya on April 30th – May 2nd 2024 at Kawethei Secondary School in Machakos County, Kyumbuni Primary School in Makueni County and in Mwambaisyuko Primary School in Kitui County. The sanitary inspection forms were filled in together with a teacher at the schools, that explained the conditions regarding the rainwater collection and storage. The data from the sanitary inspections were summarized and analysed after the field visit. Preventive actions were presented based on the corrective actions connected to the sanitary inspection (World Health Organization 2024).

2.5 QUANTITATIVE MICROBIAL RISK ASSESSMENT ON REQUIRED TREATMENT FOR RAINWATER

A quantitative microbial risk assessment is a method in four steps (problem formulation, exposure assessment, health effects assessment, and risk characterization) to evaluate infection risks associated with faecal pathogens, for example in drinking water (World Health Organization 2016). Using quantitative microbial risk assessment, the probability of being infected by water is evaluated based on the concentrations of pathogens in water, the effect of water treatment, how much water is consumed and what health effects are connected to the exposure to the pathogens (World Health Organization 2016).

The online version of the Swedish QMRA-tool for surface water treatment plants was used to conduct the quantitative microbial risk assessment in this study (Chalmers 2020). The Swedish QMRA-tool was used to estimate the required $\log_{10}$ reduction of the pathogen levels in order to achieve the risk level below one infection per 10 000 persons per year, which is an accepted risk level (Ahmed et al. 2010). Log_{10} reduction is a way to present how much the pathogen concentrations were decreased by a treatment technology. The $\log_{10}$ reduction shows the exponent in a logarithmic scale, with the base ten. The reduction of 90 % of the pathogens is equal to 1 $\log_{10}$ reduction, 99 % is equal to 2 $\log_{10}$ reduction, 99.9 % is equal to 3 $\log_{10}$ reduction and so forth (National Food Authority 2023).

There are several different pathogens that can contaminate water from faeces. It is not possible to evaluate the risk from each pathogen. The Swedish QMRA-tool uses some representative pathogens from each category (bacteria, viruses, and protozoa) that have a high risk to remain in drinking water. The pathogens investigated in this study are the representative pathogens used in the Swedish QMRA-tool. The bacteria used are *Campylobacter*, *Salmonella* and *E. coli* O157:H7 (EHEC). The viruses used are rotavirus, norovirus and adenovirus. The protozoa used are *Cryptosporidium* and *Giardia* (Chalmers 2020).

In this Master thesis, pathogen concentrations in rainwater obtained from previous research on rainwater harvesting were used as input in the Swedish QMRA-tool. One measured value of *E. coli* as indicator conducted on one occasion in 2015 at one school in the WASH and resilience project was used together with the literature values. In the cases when *E. coli* were measured as an indicator, both in previous research and the measurement from the WASH and resilience project, 6 % were assumed to be the pathogen *E. coli* O157:H7, based on a study on rainwater from South Africa (Dobrowsky et al. 2014), which corresponds with a study from Nigeria where 7 % of the measured *E. coli* were assumed to be viable and pathogenic (John et al. 2021).

In the Swedish QMRA-tool, the exposure assessment describes the volume of water that a person consumes per day. The consumed volume water was set to two litre based on a study where a quantitative microbial risk assessment was used on rainwater in Nigeria (John et al. 2021). The World health organization uses one litre as daily consumption of unheated drinking water (World Health Organization 2017a), but the higher volume was used in the Swedish QMRA-tool, to create a worst-case scenario. The exposure due to hand washing and other water usages was not included.

The risk characterization in the Swedish QMRA-tool is described by the Beta-Poisson model. It is used to calculate the relationship between the concentration of a pathogen and the probability of infection (Chalmers 2021). The Beta-Poisson model was commonly used in previous studies when quantitative microbial risk assessment has been conducted on harvested rainwater (Ahmed et al. 2010; John et al. 2021).

The required treatment level of rainwater was obtained through several iterations in the Swedish QMRA-tool. The concentration of one pathogen from one previous study was filled in as a point value, together with the water consumption of two litres. Afterwards, the water treatment barrier, expressed as the $\log_{10}$ reduction of a treatment process, was iterated until the Swedish QMRA-tool gave the probability of infection that was less than 1 infection per 10 000 persons per year. The $\log_{10}$ reduction that gave the acceptable level of infection was set as the treatment level needed for that specific pathogen. The process was repeated for each pathogen concentration from the literature review and the measured *E. coli* concentration.

2.6 MULTICRITERIA DECISION ANALYSIS ON POSSIBLE POINT-OF-USE WATER TREATMENT TECHNOLOGIES

The multicriteria decision analysis was used to investigate different aspects of point-of-use water treatment technologies. In this study, the multicriteria decision analysis consisted of the following steps, modified from a manual on multicriteria analysis (Dodgson et al. 2009).

1. Establish the aim and identify key players.
2. Identify the options that will be investigated.
3. Identify categories and criteria.
4. Score the options on the criteria.
5. Weigh the criteria, to reflect their relative importance to the decision.
6. Combine the weights and scores for each option to derive a weighted score.
7. Examine the results and conduct a sensitivity analysis.

The aim of the multicriteria decision analysis in this study was to compare different-point-of use water treatment technologies that can be used in schools connected to the WASH and resilience project within the Salvation Army Kenya East Territory. The key players from the WASH and resilience project that took part in the workshop on the 3rd of May 2024 were George Obondo, project manager, James Nzyimi, water and sanitation engineer, Margaret Musumbi, cluster coordinator, and Lilian Lutukai, cluster coordinator.

The options for point-of-use water treatment technologies were inspired by previous studies through the literature review (Santos et al. 2016; John et al. 2021) and decided together with the key players in the WASH and resilience project at the workshop during the field visit. Most of the point-of-use water treatment technologies that were identified had been mentioned during the focus group discussions during previous days of the field visit. The key players also added biosand filtration as a possible point-of-use treatment solution for schools, beside already practiced technologies.

The categories and criteria used in this study were based and modified from previous studies using multicriteria decision analysis for water treatment technologies (Garfí & Ferrer-Martí 2011; Hamouda et al. 2012; Loo et al. 2012; Santos et al. 2016; Jones et al. 2019; Sadr et al. 2020) and decided together with the key players in the WASH and resilience project. The categories were: technology, economic aspects, sustainability and social aspects. Each category was defined by two or three criteria. The criteria were: treatment performance, volume capacity, ease of use, initial cost, operation and maintenance cost, local environmental impact, local availability, social and cultural acceptability and perceived cleanliness. The categories and criteria can be found in Table 3 together with the description and previous studies from which the criteria are modified.

Table 3. Categories and criteria used in the multicriteria decision analysis.

Categories	Criteria	Description	Data source
Technology	Treatment performance	The effectiveness of reducing pathogens.	(Garfi & Ferrer-Martí 2011; Loo et al. 2012; Santos et al. 2016)
	Volume capacity	The time it takes to produce the water volume required.	(Loo et al. 2012; Santos et al. 2016; Sadr et al. 2020)
	Ease of use	Training and maintenance required to use and maintain the technology.	(Garfi & Ferrer-Martí 2011; Hamouda et al. 2012; Loo et al. 2012; Santos et al. 2016; Jones et al. 2019; Sadr et al. 2020)
Economic aspects	Initial cost	How high the initial cost is and how well the cost corresponds to the willingness and ability to pay for the users.	(Garfi & Ferrer-Martí 2011; Hamouda et al. 2012; Santos et al. 2016; Jones et al. 2019; Sadr et al. 2020)
	Operation and maintenance cost	How high the continuous costs (energy, chemicals, material replacement and maintenance) are and how well they correspond to the willingness and ability to pay.	(Garfi & Ferrer-Martí 2011; Hamouda et al. 2012; Loo et al. 2012; Santos et al. 2016; Jones et al. 2019; Sadr et al. 2020)
Sustainability	Local environmental impact[a]	The amount of waste, and hazardous byproducts produced.	(Garfi & Ferrer-Martí 2011; Loo et al. 2012)
	Local availability	Availability of the treatment technology and replacement material on the local market.	(Garfi & Ferrer-Martí 2011; Santos et al. 2016; Sadr et al. 2020)
Social aspects	Social and cultural acceptability	The cultural acceptance to use the technology, including if there are any myths regarding the technology.	(Garfi & Ferrer-Martí 2011; Sadr et al. 2020)
	Perceived cleanliness	The perceived level of water quality after treatment regarding taste, colour, and microbial content.	(Loo et al. 2012; Santos et al. 2016; Sadr et al. 2020)

[a] The criterion *Local environmental impact* was added by the key players during the workshop.

The scoring of the options was done qualitatively by the key players on all criteria except efficiency, that was scored based on the effectiveness of reducing pathogens based on the literature review. The scoring was done on a three-step scale, where 1 represents poor, 2 represents fair and 3 represents good. Regarding cost, 1 represent a high cost and 3 represent a low cost. The criteria were ranked from the most important to the least important, reflecting their relative importance to the decision on point-of-use water treatment technology. The key players ranked the criteria during discussion at the workshop, based on their local knowledge. The criterion regarding treatment performance, that was added after the workshop, was later ranked as the most important criterion.

The ranking of the criteria were transformed into weights by the Rank Sum method (Ngubane 2024) according to Equation (2)

$$w_i = \frac{2(n+1-r_i)}{n(n+1)} \qquad (2)$$

were w_i is the weighting factor of the i^{th} criterion of n, r_i is the ranking of the i^{th} criterion and n is the number of criteria.

A weighted score for each point-of-use water treatment technology was obtained by a combination of the score and the weighting factor of each criterion through Equation (3)

$$S_i = \sum w_i x_i \qquad i = 1, 2, 3, 4, 5, 6, 7, 8 \tag{3}$$

were S_i is the weighted score of each point-of-use water treatment technology, w_i is the weighting factor of the i^{th} criterion and x_i is the score for the i^{th} criterion.

The point-of-use water treatment technologies, categories, criteria, scores, ranking of the criteria, weighting factors and the total weighted score were combined in a decision matrix in Excel. When there was no consensus from the key players regarding the score or when an option could be on two steps of the scoring scale, two different scores were given for the same criterion. The weighted score was calculated for the different scoring alternatives, showing the final score for each point-of-use water treatment technology. The total scores without weights were also calculated, showing the sensitivity of the analysis, regarding the weighting factor.

3. RESULTS

The results on water use and potential rainwater volume at schools addressed the first objective of the Master thesis. The second objective on microbial risk factors associated with rainwater harvesting is answered through the literature review and the sanitary inspections conducted during the field visit. The third objective on the required treatment for rainwater and point-of-use water treatment technologies is answered through the quantitative microbial risk assessment through the Swedish QMRA-tool and the multicriteria decision analysis.

3.1 WATER USE AND POTENTIAL RAINWATER HARVESTING VOLUME AT SCHOOLS

Information concerning the water use at the schools was obtained from conversations with teachers during the field visit and compared with the basic minimum water requirements at schools (Ministry of Education et al. 2018) and the standard drinking water use per person per day (World Health Organization 2017a). The potential rainwater harvesting volume which it is possible to collect at each school was calculated based on local rainfall data and available rooftop area, to investigate if the monthly accumulated rainwater volume is sufficient to cover the drinking water demand and the basic minimum water requirements.

3.1.1 Water Use at Schools

The water demand at the schools is presented in three different ways: the basic minimum water requirements at schools according to the *Standards and Guidelines for WASH Infrastructure in Pre-primary and Primary Schools in Kenya* (Ministry of Education et al. 2018), the drinking water use and the total water use reported from the teachers at the schools during the field visit. The basic minimum water requirements provide an indication on how high the water consumption at a school can be expected to be at a minimum level, and the reported water use from the teachers provides a reference on the actual water consumption. The basic minimum water requirements for a school depends on how many schoolchildren[1] there are and if the school is a residential[2] school or not. In Table 4 the number of students at each school is presented together with the basic minimum water requirements and the reported water use.

[1] In this study only the number of schoolchildren was used for the calculation of the water demand since the number of staff was not reported at each school during the field visit, but the total water consumption at a school depends both on the number of schoolchildren and the number of staff.

[2] Kawethei Secondary School is a residential school while Kyumbuni Primary School and Mwambaisyuko Primary School are assumed to be non-residential schools, even though there is a minority of residential schoolchildren at Kyumbuni Primary School.

Table 4. The number of schoolchildren at each school, the basic minimum water requirements (Ministry of Education et al. 2018), the reported total water use per schoolchild per day, the standard drinking water use per person per day (World Health Organization 2017), and the reported drinking water use per schoolchild per day at the schools. The total water use at Kyumbuni Primary School and the drinking water use at Mwambaisyuko Primary School were not obtained from the field visit. The blue colour indicates the area with a higher rainfall and the yellow colour indicates the area with lower rainfall.

	Kawethei Secondary School	Kyumbuni Primary School	Mwambaisyuko Primary School
Number of schoolchildren	569 schoolchildren	350 schoolchildren	116 schoolchildren
Basic minimum water requirements per schoolchild per day	20 litres	5 litres	5 litres
Reported total water use per schoolchild per day	26.4 litres	-	9.0 litres[b]
Standard drinking water use per person per day	1 litre	1 litre	1 litre
Reported drinking water use per schoolchild per day	1.3 litres	0.7 litres	-

[b] The total water use reported at Mwambaisyuko Primary School includes drinking and hygiene but not cooking, since cooking is not frequently practiced at the school.

The reported total water use at both Kawethei Secondary School and Mwambaisyuko Primary School is above the basic minimum water requirements per schoolchild per day. The drinking water use at both Kawethei Secondary School and Kyumbuni Primary School is about 1 litre per person per day, which corresponds to the daily drinking water consumption per person used by the World Health Organization (World Health Organization 2017a).

3.1.2 Potential Rainwater Harvesting Volume at Schools

The potential rainwater volume that can be harvested each month primarily depends on the local rainfall pattern over the year. Rainfall data from Machakos Agromet Station is used for Kawethei Secondary School in Machakos County and rainfall data from Makindu Meteorological Station is used for Kyumbuni Primary School in Makueni County and Mwambaisyuko Primary School in Kitui County. The peaks in Figure 4 show the rainy seasons. The long rains are in March – May and the short rains are in November – December. The rainfall is slightly higher at Machakos Agromet Station than at Makindu Meteorological Station during most months of the year. Each monthly rainfall is a mean value for the monthly rainfall data during 2014 – 2023.

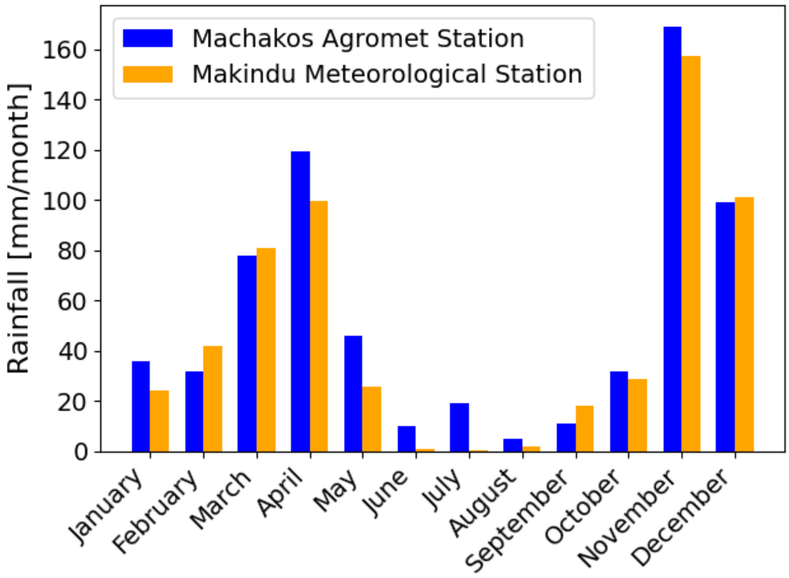

Figure 4. Monthly rainfall at Machakos Agromet Station and Makindu Meteorological Station based on monthly rainfall data during 2014 – 2023.

Besides the rainfall, the potential rainwater volume that can be harvested each month also depends on the area of the roof and the runoff coefficient, presented in Equation (1). The area of the roof used in the calculations for the potential rainwater volume was obtained from the engineer in the WASH and resilience project and is the same for each school. It is the catchment area over eight classrooms, $576\ m^2$. The runoff coefficient, 0.8, is also the same for all schools, and indicate a water loss of 20 %. The potential rainwater volume that can be harvested each month is presented in Table 5 and indicates the volume that can be harvested if the storage capacity were unlimited. The potential rainwater volume is the same at both Kyumbuni Primary School and Mwambaisyuko Primary School since both the rainfall data and the catchment area used are the same for these two schools.

Table 5. Potential volume rainwater per school based on monthly average rainfall data from 2014 – 2023 from Machakos Agromet Station and Makindu Meteorological Station, the roof area over eight classrooms per school and the runoff coefficient. The blue colour indicates the area with a higher rainfall and the yellow colour indicates the area with lower rainfall.

Month	Potential rainwater volume at Kawethei Secondary School [litre]	Potential rainwater volume at Kyumbuni Primary School [litre]	Potential rainwater volume at Mwambaisyuko Primary School [litre]
January	16 600	11 200	11 200
February	14 700	19 200	19 200
March	35 900	37 200	37 200
April	55 000	45 900	45 900
May	21 000	11 700	11 700
June	4 530	292	292
July	8 730	96.8	96.8
August	2 300	945	945
September	5 070	8 290	8 290
October	14 700	13 200	13 200
November	77 900	72 500	72 500
December	45 600	46 700	46 700

The accumulated rainwater volume in the storage tanks in the end of each month not only depends on the potential rainwater volume that can be harvested but also on the rainwater abstraction and the storage capacity. The accumulated rainwater volume for the schools investigated is presented in Table 6. The water abstraction is based on the daily drinking water consumption of one litre per person per day (World Health Organization 2017a) and the basic minimum water requirements at schools (Ministry of Education et al. 2018) except for Kawethei Secondary School where only the standard drinking water consumption of one litre is presented due to the other water source that covers the rest of the demand. The storage capacity of Kawethei Secondary School is 64 000 litres, the storage capacity for Kyumbuni Primary School is 90 000 litres and the storage capacity for Mwambaisyuko Primary School is 48 000 litres. The first month presented is November, assuming that the storage tanks are empty for cleaning prior to November. November is chosen as the first month since it is the month with the highest rainfall and the rainfall during November can, without accumulated water from previous months, fill the water requirements.

Table 6. The accumulated rainwater volume in the storage tanks in the end of each month, after the abstraction of the water use. When the accumulated volume would be greater than the storage capacity, the storage capacity that limits the rainwater collection. If the storage capacity were unlimited the accumulated rainwater would be the volume presented in parenthesis. When the potential rainwater volume is lower than the water use, negative numbers show the volume lacking for reaching the water demand, and the percentage next to is shows the rainwater coverage of the water demand. The blue colour indicates the area with a higher rainfall and the yellow colour indicates the area with lower rainfall.

School	Accumulated rainwater volume at Kawethei Secondary School [litre]	Accumulated rainwater volume at Kyumbuni Primary School [litre]			Accumulated rainwater volume at Mwambaisyuko Primary School [litre]		
Water use per child per day	1 litre/ child/ day	1 litre/ child/ day	5 litre/ child/ day	Rainwater coverage of water demand	1 litre/ child/ day	5 litre/ child/ day	Rainwater coverage of water demand
Water use per school per month	17 070 litre/ month	10 500 litre/ month	52 500 litre/ month		3 480 litre/ month	17 400 litre/ month	
November	60 800	62 000	20 000	100 %	48 000 (69 020)	48 000 (55 100)	100 %
December	64 000 (89 360)	90 000 (98 200)	14 200	100 %	48 000 (91 220)	48 000 (77 300)	100 %
January	63 500	90 000 (90 700)	-27 100	48.4 %	48 000 (55 720)	41 800	100 %
February	61 200	90 000 (98 700)	-33 300	36.6 %	48 000 (63 720)	43 600	100 %
March	64 000 (79 990)	90 000 (116 700)	-15 300	70.9 %	48 000 (81 720)	48 000 (63 400)	100 %
April	64 000 (101 930)	90 000 (125 400)	-6 600	87.4 %	48 000 (90 420)	48 000 (76 500)	100 %
May	64 000 (67 930)	90 000 (91 200)	-40 800	22.3 %	48 000 (56 220)	42 300	100 %
June	51 500	79 800	-52 200	0.556 %	44 800	25 200	100 %
July	43 100	69 400	-52 400	0.184 %	41 400	7 900	100 %
August	28 400	59 800	-51 600	1.80 %	38 900	-8 570	50.8 %
September	16 400	57 600	-44 200	15.8 %	43 700	-9 110	47.6 %
October	14 000	60 300	-39 300	25.1 %	48 000 (53 424)	-4 200	75.9 %

At Kawethei Secondary School, rainwater is only used for drinking water and treated borehole water covers the rest of the water demand. Threated borehole water also covers 60 % of the drinking water use which means that the rainwater use is less than the standard drinking water use of one litre per person per day. The accumulated rainwater volume should however be enough the whole year, even if the whole drinking water use of one litre per person should be taken from the harvested rainwater (Table 6). The harvested rainwater at the school does however run out approximately three months after the rainy seasons, according to a teacher at the school. The rainwater use at the school is therefore likely to be higher than the estimated drinking water use. Since the potential rainwater volume that can be harvested during the rainy seasons is above the storage capacity, the harvested rainwater volume can be increased by installing additional storage tanks.

At Kyumbuni Primary School, rainwater is used for all purposes and water from other sources is used when the rainwater runs out. The high number of schoolchildren at the school makes the basic minimum water requirements per month higher than the potential volume of rainwater that can be harvested most of the months (Table 6). The drinking water demand of one litre per person per day can however be covered by the potential rainwater volume (Table 6). To make the harvested rainwater last the whole year, the water consumption should therefore be well thought through such that rainwater is prioritized for drinking, cooking and personal hygiene and other water sources of lower quality should be used for cleaning and laundry. The potential volume of rainwater that can be harvested each month can also be increased by increasing the catchment area for rainwater harvesting.

At Mwambaisyuko Primary School, rainwater is used for all purposes, and when the rainwater runs out, water is collected from a nearby river. The accumulated rainwater should cover the basic minimum water requirements all months except in August – October where rainwater only covers approximately half of the water demand (Table 6). During the months with the highest rainfall (November – December and March – April) the rainwater harvesting is limited by the storage capacity (Table 6). Increasing the storage capacity would make it possible to harvest more rainwater during these months. However, during the field visit, a teacher at the school reported that the harvested rainwater runs out already in June. The reason can be that the reported total water use is almost double the volume than the basic minimum water requirements. The teacher also said that the schoolchildren misuse the water, which can indicate that the actual water use is even higher. Broken gutters were also observed during the field visit, which reduces the potential rainwater volume that can be harvested.

3.2 MICROBIAL RISK FACTORS ASSOSIATED WITH RAINWATER HARVESTING

Previous research on rainwater quality, obtained from the literature review, reports several microbial risk factors associated with rainwater harvesting. Observations of risk factors associated with the rainwater harvesting system, through the sanitary inspection for rainwater collection and storage, were done at the inspected schools during the field visit. Preventive actions which can contribute to minimizing the risk of microbial contamination, are based on previous research through the literature review and the suggestions for preventive actions from the sanitary inspection for rainwater collection and storage (World Health Organization 2024).

3.2.1 Risk Factors Presented in Previous Research on Rainwater Harvesting

Rainwater is not significantly polluted before it reaches the catchment, but it can be polluted during the collection. Contamination can occur in any part of the rainwater harvesting system, from the roof through the pipes and in the storage tanks. Risk factors include matter on the roof, roof material, roof size, location of the roof, meteorological factors, storage, bad routines in collection and maintenance (Meera & Ahammed 2006), and bad routines in sanitation and hygiene (John et al. 2021). Previous research indicates that rainwater does not meet the drinking water quality standards due to the microbial content (Meera & Ahammed 2006).

The main source of microorganisms in rainwater is faeces from birds and mammals in the surrounding area (Ahmed et al. 2012; Chubaka et al. 2018), but faecal matter can also reach the roof through dust and windstorms (Chubaka et al. 2018). Pathogens detected in rooftop harvested rainwater are bacteria, viruses and protozoa. The bacteria detected in rooftop harvested rainwater are, for example, *Salmonella, Legionella, Campylobacter* (Ahmed et al. 2010), *Vibrio, Aeromonas* (Meera & Ahammed 2006), and pathogenic *E. coli* strains (Malema et al. 2018). The viruses detected in rooftop harvested rainwater are, for example, adenovirus, rotavirus, norovirus, and parvovirus (Shubo et al. 2021). The protozoa detected in rooftop harvested rainwater are, for example, *Giardia* (Ahmed et al. 2010), and *Cryptosporidium* (Meera & Ahammed 2006).

As well as loose matter on the roof, small particles from the roof itself can contribute to contamination of the collected rainwater. Chemical characteristics, roughness, surface coating, age and weatherability of the roof are therefore contributing factors to the water quality (Meera & Ahammed 2006). The size of the roof as well as the location of the roof regarding the distance to pollution sources are also risk factors that can affect to the quality of the rainwater (Meera & Ahammed 2006). In a study on pathogenic *E. coli* in rainwater from South Africa, different concentrations were shown depending on the location. At the location where the highest *E. coli* levels were measured, a constant presence of birds were observed, which could have contaminated the roof with faecal matter (Malema et al. 2018).

Meteorological factors, such as the intensity of the rain, the wind, and the concentrations of pollutants in the rain affect the rainwater quality as well as the season, and dry periods (Meera & Ahammed 2006). Contamination in rainwater increases in rain after long dry periods due to the accumulation of deposition on the roof (Meera & Ahammed 2006; Amin et al. 2013). On the other hand, the concentration of particles, aerosols, and gases in the rain itself is decreasing with increasing rainfall depth (Meera & Ahammed 2006).

Previous research does not agree on what influence the storage of the rainwater has on the water quality. Some studies show that the concentration of bacteria increase during storage, while others show that the concentration of bacteria decrease during storage. The different results are likely to depend on the availability of nutrients and the conditions for bacterial growth in the storage tank (Meera & Ahammed 2006). According to a study from rural Australia, the storage tank size was an important parameter in rainwater quality, where small storage tanks show higher bacterial contamination and a higher risk of accumulation of sludge on the bottom of the storage tank (Meera & Ahammed 2006). If the storage tank is situated under the ground, faeces can enter through surface runoff, if the storage tank is improperly designed, broken or unsealed (Chubaka et al. 2018). On the other hand, according to a study in South Korea, rainwater stored in underground storage tanks shows a better microbial quality than open weirs because of the dark storage and low temperature that reduce the bacterial growth (Amin et al. 2013). In a study from Nigeria, *E. coli* were present in both open and closed storage tanks (Tenebe et al. 2020).

Bad routines in collection and maintenance of the rainwater reduce the water quality significantly (Meera & Ahammed 2006). A study on rainwater quality from South Korea shows higher water quality regarding microbial parameters from a roof that is easier to clean and more frequently cleaned than a roof that was cleaned less frequently (Amin et al. 2013). A study from Bangladesh shows that rainwater harvested in households was less contaminated than community based rainwater harvesting systems in schools, probably because the regular cleaning of the roof and pipes, and the use of first flush systems and taps for extraction of water in the households, compared with the schools where the maintenance was probably lacking (Karim 2010). Improper installation of rainwater harvesting systems as well as poor design by local technicians that are not adequately trained, together with effects from extreme weather, lead to rainwater harvesting systems breaking after a short time, according to a study from Machakos County, Kenya (Wekesa et al. 2022).

The probability of transmittance of microorganisms from greywater and toilets increases with bad sanitation and hygiene routines close to the rainwater harvesting system (John et al. 2021). Bad hygiene can also result in post contamination of treated water (Loo et al. 2012).

3.2.2 Risk Factors Observed Through the Sanitary Inspection for Rainwater Collection and Storage During the Field Visit

Sanitary inspections for rainwater collection and storage (World Health Organization 2024) conducted during the field visit show that there are several risk factors connected to the rainwater harvesting systems at the schools. Out of sixteen risk factors, six were observed at Kawethei Secondary School in Machakos County, eleven were observed at Kyumbuni primary school in Makueni County and ten were observed at Mwambaisyuko Primary School in Kitui County.

Some of the sanitary inspection questions did not apply to the rainwater harvesting systems that were inspected. The design of the storage tank used in all schools had a fixed cover and only the storage tank inspection hatch lid is possible to open, so the question regarding storage tank cover was not applicable, nor the question regarding air vents, since the only hole in the storage tank was the overflow hole, that also functions as an air vent. The sanitary inspection questions together with the answers for the three investigated schools can be found in Table 7.

Table 7. Questions and answers from the sanitary inspection for rainwater collection and storage (World Health Organization 2024) for the three schools inspected during the field visit. NA (Not Applicable) indicates that the question does not apply to the rainwater harvested system inspected. The answer No tells that the question applies to the rainwater harvesting system, and the risk factor is not present. The answer Yes tells that the risk factor is present.

Sanitary inspection questions		Kawethei Secondary School, Machakos County			Kyumbuni Primary School, Makueni County			Mwambaisyuko Primary School, Kitui County		
		NA	No	Yes	NA	No	Yes	NA	No	Yes
1.	Are there any visible contaminants on the roof or in the guttering channels?		X				X			X
2.	Do the roof or guttering channels have an inadequate slope for drainage?		X				X			X
3.	Is there any vegetation or structures above the roof?		X				X		X	
4.	Is the filter box absent, damaged or blocked?		X				X			X
5.	Is the first flush system absent, damaged or blocked?		X			X			X	
6.	Are there any signs of contaminants inside the storage tank?			X			X			X
7.	Is the storage tank cover absent or in poor condition?	X			X			X		
8.	Is the storage tank inspection hatch lid missing or in poor condition?			X			X			X
9.	Are the storage tank walls cracked or leaking?		X			X				X
10.	Does the overflow pipe lack adequate protection from vermin?			X			X			X
11.	Are the air vents poorly designed so that contaminants could enter the storage tank?	X			X			X		
12.	Is the storage tank tap dirty or in poor condition?		X				X			X
13.	Is drainage inadequate, which could allow water to accumulate in the collection area?		X				X		X	
14.	Is the fence or barrier around the water collection area missing or inadequate so that animals could enter the collection area?			X			X			X
15.	Can other sources of pollution be seen in the water collection area (e.g. open defecation, animals, drinking troughs for livestock, rubbish, commercial activity, fuel storage)?			X			X			X
16.	Is there a local activity (e.g. industry, agriculture) that could contaminate the roof?			X		X			X	
Total number of Yes responses				6			11			10

The most common risk factors that were observed at all three schools were lack of or not properly closed inspection hatch lid of the storage tanks, open overflow hole to the storage tanks were vermin can enter, lack of fence or barrier around the water collection area so animals could enter, and other sources of contamination such as the presence of animals and animal faeces around the storage tanks. Other contamination sources identified at one or two of the schools were contaminants on the roof, broken gutters, vegetation above the roof or the storage tanks, absence of the filter box, cracks in the storage tank, broken storage tank taps, inadequate drainage and the presence of a local agriculture activity that could contaminate the roof.

It was not possible to look inside the storage tank so the presence of contamination inside the storage tank could not be inspected. According to the instructions for the sanitary inspections (World Health Organization 2024), the Yes box should be ticked when a question could not be answered because of lack of access to the investigated component. The question regarding signs of contamination inside the storage tank was therefore marked with Yes and further investigated through conversation with teachers at the schools. At Kawethei Secondary School in Machakos County, the teacher could tell that plastic parts had loosen from the inner walls of the storage tanks due to the heat from the sun and that dust usually is found in the storage tanks when they are cleaned. At Mwambaisyuko Primary School in Kitui County, the teacher said that mosquitos and bats has been seen in the storage tanks. Based on this information, together with the observation that a majority of the storage tanks are not properly closed and that all of the storage tanks lack a vermin proof screen for the overflow hole, it is very likely that there is contamination inside the storage tanks.

3.2.3 Preventive Actions That Can Contribute to Minimizing the Risk of Microbial Contamination

According to previous studies, there are several ways to improve water quality of rooftop harvested rainwater by preventive actions. The use of a first flush device improves the water quality significantly (Meera & Ahammed 2006). The choice of roof material and storage tank size can also improve the water quality (Meera & Ahammed 2006). Improved collection and maintenance reduces the risk of contamination to the rainwater (Meera & Ahammed 2006).

The use of a first flush device increases the quality of the harvested rainwater significantly, since the first two millimetres of runoff height of every rain event shows a higher concentration of contaminants due to matter on the roof and products of the roof material that is dissolved and washed off by the rain and because of the higher contaminant concentrations in the rain itself during the first millimetres of runoff (Meera & Ahammed 2006). First flush can be practiced through an automated first flush device but also through different practices, such as waiting several minutes into a rainfall or waiting several rainfall events into a rainy season before collecting the rainwater (John et al. 2021). Diverting the first flush is suggested by several studies (Meera & Ahammed 2006; Amin et al. 2013; Malema et al. 2018; John et al. 2021).

The preventive action that was practiced at all schools was the use of first flush by waiting several rainfall events into a rainy season before collecting the rainwater. The gutters were manually disconnected from the storage tanks during the first rainfall events in every rainy season before the rainwater was collected in the storage tanks. The time it takes for the rain to clean the roof from contamination depends on the frequency and the intensity of the rainfall event, but it takes approximately two days. None of the schools had a first flush device installed in the rainwater harvesting system. Using a first flush device can further minimize the risk of microbial contamination, since a first flush device diverts the first millimetres of rainfall from every rain event.

The use of metal roofs in tropical countries increases the water quality since the heat on the metallic roofs kills many of the organisms (Meera & Ahammed 2006; Mendez et al. 2011). Besides metal roofs, concrete tile and cool roofs (made of reflective material) give similar rainwater quality as metal roofs, regarding the influence of the catchment area. On the other hand, rainwater harvested from shingle and green roofs contain high concentrations of dissolved organic carbon that can lead to high concentrations of disinfection byproducts when chlorination is used for treatment of the water (Mendez et al. 2011). All the investigated schools have galvanized iron sheet roofs where the rainwater is harvested, which can contribute positively to the water quality.

Since poor collection and maintenance is a risk for rainwater quality, proper design and established maintenance practices are important to minimize the contamination in rooftop harvested rainwater (Meera & Ahammed 2006; Malema et al. 2018). Maintenance is important both for the roofs and the pipes (Ahmed et al. 2010). Constant cleaning of the roof is one suggested practice by previous research (Malema et al. 2018). Operation and maintenance should take place on a regular basis to prevent contaminants to enter the water supply according to the management advice sheet connected to the sanitary inspection for rainwater collection and storage (World Health Organization 2024). Proposed daily to weekly activities are checking and cleaning the surrounding area of the rainwater harvesting system, checking that the inspection hatch lid is in place, checking that the inside of the storage tank is clean, checking that the drain is clear, and checking that the fence is in good condition. Proposed weekly to monthly activities are checking that the filter box, first flush system, guttering channels and the roof are clean, checking that the storage tank overflow pipe is in good condition. An annual detailed inspection of the hole rainwater harvesting system and reparations of damaged parts should be conducted. This guidance for operation and maintenance is a minimum recommendation and the frequency of activities may need to be increased depending on the local context (World Health Organization 2024).

Another preventive action that can contribute to minimizing the risk of microbial contamination is improving the design of the rainwater harvesting system. The storage tank model that is used at all the schools does not have a vermin proof screen for the overflow hole, and the overflow hole is recommended to be a pipe that faces downwards, not only hole into the storage tank. Furthermore, the filter box was absent at two of the schools and the drainage was inadequate at one school, and there was no fence around the water collection area at none of the three schools. By using the recommendations in the sanitary inspection for rainwater collection and storage (World Health Organization 2024) prior to installing a rainwater harvesting system, the design of the rainwater harvesting system can be improved in the installation phase.

3.3 TREATMENT FOR RAINWATER

To ensure safe drinking water from harvested rainwater, previous research agree that treatment is essential (Meera & Ahammed 2006; Ahmed et al. 2010, 2012; Kim et al. 2016; Malema et al. 2018; John et al. 2021; Shubo et al. 2021). The required treatment level for rainwater depends on the pathogen concentrations. The pathogen concentrations in harvested rainwater used in this study are based on previous research from the literature review, and the required treatment level was obtained through a quantitative microbial risk assessment using the Swedish QMRA-tool.

Water treatment can be applied in a centralized drinking water treatment plant with a pipeline network or at the point-of-use (World Health Organization 2017a). In rural areas, where there is no access to a pipeline network, point-of-use water treatment technologies can be implemented with a lower investment cost than extending the pipeline network, and with less complex maintenance (Santos et al. 2016). Point-of-use water treatment systems are designed for households or small-scale applications and treat relatively small volumes of water compared with a water treatment plant. The point-of-use water treatment technologies investigated in this study are either used at schools today in the WASH and resilience project or would be possible to use.

The World Health Organization has a system where the efficiency of different point-of-use water treatment technologies is ranked (World Health Organization 2019). This ranking is used for scoring the point-of-use treatment technologies on their efficiency in the multicriteria decision analysis. Other criteria for evaluating the treatment options in the multicriteria decision analysis were decided together with key players in the WASH and resilience project at the workshop during the field visit and scored based on their local knowledge. The multicriteria decision analysis identified the most favourable treatment options that can be used at schools based on the set criteria.

3.3.1 Required Treatment for Rainwater Based on the Swedish QMRA-tool

The assumptions regarding the microbial concentrations in rainwater were made from previous research on pathogens in rooftop harvested rainwater, gathered from the literature review, together with one measurement of *E. coli* as indicator conducted in the WASH and resilience project at one place on one occasion in 2015. The investigated pathogens are the representative pathogens for each pathogen group (bacteria, viruses and protozoa) that are used in the Swedish QMRA-tool. The highest literature values from each study were used, creating the worst-case scenario, an approach that has been used in a previous quantitative microbial risk assessment study on rainwater (Ahmed et al. 2010). The virus concentrations are however mean concentrations of each virus (Shubo et al. 2021). In the cases when *E. coli* were measured as an indicator, 6 % were assumed to be the pathogen *E. coli* O157:H7 (Dobrowsky et al. 2014).

The required treatment for each representative pathogen was presented as the $\log_{10}$ reduction needed to reduce the concentration of the pathogen in rainwater, so that the probability of infection would be lower than 1 infection per 10 000 persons per year, based on the 95-percentile. Some pathogens were more frequently found in the literature review than others. In general, more studies on bacteria and protozoa than viruses were found. The measurement from the WASH and resilience project and the highest concentrations of each representative pathogen from previous research are presented in Table 8, together with the required $\log_{10}$ reduction and the country where the measurements were taken. Beside the highest concentration, the lowest concentration of *E. coli* O157:H7 from the same study (Ahmed et al. 2011) is also presented to compare the required treatment on different rainwater qualities.

Table 8. Required treatment for rainwater, based on the highest concentrations of each representative pathogen in harvested rainwater in previous research. The bacteria are marked in green, the viruses in red and the protozoa in blue. The lowest concentration in one study is presented in dark green as a comparison to the highest concentration from the same study (Ahmed et al. 2011). The concentrations are presented with the same precision as reported in the original studies.

Pathogen	Concentration [Number/litre]	Required treatment level [Log_{10} reduction]	Country	Data source
E. coli O157:H7	45[c]	7	Kenya	Schulte-Herbruggen (2015)
	150[d]	7	South Africa	Dobrowsky et al. (2014)
	591.6[e]	8	Australia	Ahmed et al. (2011)
	0.6[f]	5	Australia	Ahmed et al. (2011)
Salmonella	380[g]	5	Australia	Ahmed et al. (2010)
	252.6[h]	5	U.S.	Alja'fari et al. (2022)
Campylobacter	3.8[i]	7	U.S.	Alja'fari et al. (2022)
Rotavirus	80[j]	9	Brazil	Shubo et al. (2021)
Norovirus	1940[k]	10	Brazil	Shubo et al. (2021)
Adenovirus	1200[l]	10	Brazil	Shubo et al. (2021)
Cryptosporidium	0.703[m]	7	U.S.	Crabtree et al. (1996a)
	53.5[n]	8	American Samoa	Kirs et al. (2017)
Giardia	3.6[o]	6	Australia	Ahmed et al. (2010)
	15[p]	7	U.S.	Alja'fari et al. (2022)
	0.038[q]	4	U.S.	Crabtree et al. (1996a)

[c] A measurement on *E. coli* as indicator was conducted in the WASH and resilience project on one occasion in May 2015 at a school in Kitonyoni, Kenya. The pathogenic *E. coli* O157:H7 is assumed to be 6 % of the detected E. coli. The concentration is presented in CFU/litre.

[d] In the study from Kleinmond, South Africa (Dobrowsky et al. 2014), a total of 80 rainwater samples were taken from ten different domestic rainwater harvesting tanks on eight occasions during low and high rainfall periods during March to August 2012. Of the 92 *E. coli* strains detected, 6 % were identified as *E. coli* O157:H7. The concentration of *E. coli* O157:H7 is presented in CFU/litre.

[e] In the study from Southeast Queensland, Australia (Ahmed et al. 2011), a total of 200 *E. coli* isolates from 22 tanks were tested for 20 virulence genes. The highest *E. coli* concentration was detected in a 12 000 litres tank without a first flush diverter and with overhanging trees and evidence of animal droppings on the roof. The water in the tank was used for non-potable purposes. The pathogenic *E. coli* O157:H7 is assumed to be 6 % of the detected E. coli. The concentration is presented in CFU/litre.

[f] The lowest *E. coli* concentrations in the same study from Southeast Queensland, Australia (Ahmed et al. 2011) were detected in eight tanks, where the *E. coli* concentration were <1 CFU/100 ml. All these tanks had a first flush diverter or no signs of faecal droppings or trees above the roof. The concentration used for estimating the required $\log_{10}$ reduction is 6 % of 1 CFU/100 ml water, transformed to and presented in CFU/litre.

[g] In another study from Southeast Queensland, Australia (Ahmed et al. 2010), a total of 214 samples from 82 tanks were taken. The concentration of *Salmonella* is presented in cells/litre.

[h] In the study from four cities in the U.S. (Alja'fari et al. 2022), a total of 72 rainwater samples were taken during 13 rainfall events by seven participants in each city from May 2018 – October 2019. The concentration of *Salmonella* is presented in cells/litre.

[i] In the study from four cities in the U.S. (Alja'fari et al. 2022), a total of 72 rainwater samples were taken during 13 rainfall events by seven participants in each city from May 2018 – October 2019. The concentration of *Campylobacter* is presented in cells/litre.

[j] In the study from Rio de Janeiro, Brazil, a total of 100 rainwater samples were taken from the first 10 mm rainwater from 10 rainfall events from April 2015 – March 2017. The concentration of rotavirus is presented in gene copies/litre.

[k] In the study from Rio de Janeiro, Brazil, a total of 100 rainwater samples were taken from the first 10 mm of rainwater from 10 rainfall events from April 2015 – March 2017. The concentration of norovirus is presented in gene copies/litre.

[l] In the study from Rio de Janeiro, Brazil, a total of 100 rainwater samples were taken from the first 10 millimetres of rainwater from 10 rainfall events from April 2015 – March 2017. The concentration of adenovirus is presented in gene copies/litre.
[m] In the study from U.S. Virgin Islands (Crabtree et al. 1996), a total of 44 rainwater samples were taken from 13 different cisterns over one year. The detected concentration of *Cryptosporidium* is presented in oocysts/litre.
[n] In the study from American Samoa (Kirs et al. 2017), a total of 14 rainwater samples were taken at different places during a three day period in 2016. The detected concentration of *Cryptosporidium* is presented in oocysts/litre.
[o] In the study from Southeast Queensland, Australia (Ahmed et al. 2010), a total of 214 samples from 82 tanks were taken. The concentration of *Giardia* is presented in cysts/litre.
[p] In the study from four cities in the U.S. (Alja'fari et al. 2022), a total of 72 rainwater samples were taken during 13 rainfall events by seven participants in each city from May 2018 – October 2019. The detected concentration of *Giardia* is presented in cysts/litre.
[q] In the study from U.S. Virgin Islands (Crabtree et al. 1996), a total of 44 rainwater samples were taken from 13 different cisterns over one year. The detected concentration of *Giardia* is presented in cysts/litre.

The results from the quantitative microbial risk assessment show that the required treatment of rainwater regarding bacteria is a $\log_{10}$ reduction of 5 – 8, the required treatment for viruses is a $\log_{10}$ reduction of 9 – 10 and the required treatment for protozoa is a $\log_{10}$ reduction of 4 – 8. The range of the required $\log_{10}$ reduction depends on how high the pathogen concentration in the untreated rainwater is, with lower concentration requiring a lower reduction.

In a study from Australia (Ahmed et al. 2011), both the highest and the lowest concentration of *E. coli* transformed into *E. coli* O157:H7 are presented. The highest concentrations are from a storage tank without a first flush diverter and with overhanging trees and evidence of animal droppings on the roof, while the lowest concentrations are from storage tanks with a first flush diverter or no signs of faecal droppings or trees above the roof. The required treatment for the highest concentration is 8 $\log_{10}$ reduction while the required treatment for the lowest concentration is 5 $\log_{10}$ reduction. The preventive actions did in this case reduce the pathogen concentration in untreated rainwater with 3 $\log_{10}$ reduction.

3.3.2 Treatment Performance of Point-of-use Water Treatment Technologies

The quantitative microbial risk assessment performed in this Master thesis, based on the highest pathogen concentrations in rainwater from previous studies, results in relatively high required treatment. The World Health Organization has another ranking system for point-of-use[3] water treatment technologies, where the treatment performance in removing the different pathogens is evaluated, also through a quantitative microbial risk assessment, but not based on rainwater specifically (World Health Organization 2019). In the ranking system, the performance of a point-of-use water treatment technology is ranked on a three-step scale, represented by stars. A comprehensive protection is reached by two – three stars, targeted protection is reached by one star and little or no protection is reached if the point-of-use treatment technology fails to meet the criteria for one star. The $\log_{10}$ reduction needed for the different performance levels is presented in Table 9.

Table 9. The required log_{10} reduction for the performance levels, according to WHO performance criteria for point-of-use water treatment technologies (World Health Organization 2019). The Table is modified from the World Health Organization (World Health Organization 2019).

Performance classification	Bacteria [required $\log_{10}$ reduction]	Viruses [required $\log_{10}$ reduction]	Protozoa [required $\log_{10}$ reduction]	Interpretation
★★★	≥ 4	≥ 5	≥ 4	Comprehensive protection
★★☆	≥ 2	≥ 3	≥ 2	
★☆☆	Meets at least two-star criteria for two classes of pathogens			Targeted protection
-	Fails to meet criteria for one-star			Little or no protection

During the field visit, information on point-of-use water treatment technologies that are practiced currently in schools or technologies that could be practiced in schools was collected. The following technologies were used currently, either at schools or in households connected to the WASH and resilience project: boiling, WaterGuard, Aquatabs ®, P&G Purifier of Water, and LifeStraw Community ®. In conversation with the staff in the WASH and resilience project, biosand filtration came up as a possible solution that is not yet practiced in the project.

Three of the investigated point-of-use water treatment technologies have been evaluated by the World Health Organization through the ranking system (World Health Organization 2019). Lifestraw ® Community is ranked with three-star (World Health Organization 2015c), P&G Purifier of Water is ranked with two-star (World Health Organization 2015d), and Aquatabs ® is ranked with one-star (World Health Organization 2015b). The other point-of-use water treatment technologies investigated in this study have not been evaluated by the World Health Organization but are ranked according to Table 9 based on the manufacturer information. Each point-of-use water treatment technology is presented with its efficiency and the estimated number of stars in Table 10.

[3] In the ranking system by the World Health Organization, the products are called *household water treatment technologies*, which is the same as *point-of-use water treatment technologies*.

Table 10. The treatment performance of the point-of-use water treatment technologies. Boiling is a heating method and is presented in blue. WaterGuard, Aquatabs ®, and P&G Purifier of Water are chlorination products, and they are presented in red. Lifestraw ® Community and biosand filter are filtration technologies, and they are presented in green. The number of stars is based on the ranking system by the World Health Organization (World Health Organization 2019).

Water treatment technology	Log_{10} reduction of Bacteria	Log_{10} reduction of Viruses	Log_{10} reduction of protozoa		Number of stars	Data source
			Crypto-sporidium	*Giardia*		
Boiling	> 99.999 % ($5 \log_{10}$)	> 99.999 % ($5 \log_{10}$)	> 99.9 % ($3 \log_{10}$)	> 99 % ($2 \log_{10}$)	2	(World Health Organization 2015a)
WaterGuard	99 % ($2 \log_{10}$)	99 % ($2 \log_{10}$)	99.9 %[r] ($3 \log_{10}$)		1[s]	(Engineering For Change 2024)
Aquatabs ®	99.9999 % ($6 \log_{10}$)	99.99% ($4 \log_{10}$)	($0.2 \log_{10}$)	99.9 % ($3 \log_{10}$)	2	(World Health Organization 2015b; Aquatabs 2024a)
P&G Purifier of Water	99.999 % ($5 \log_{10}$)	99 – 99.99 % ($2 – 4 \log_{10}$)	99 – 99.9 %[t] ($2 – 3 \log_{10}$)		2	(World Health Organization 2015d; P&G Purifier of Water 2024)
Lifestraw Community ®	99.999999 % ($8 \log_{10}$)	99.999 % ($5 \log_{10}$)	99.999 % ($5 \log_{10}$)		3	(World Health Organization 2015c; LifeStraw 2024)
Biosand filter	96.5 % ($\approx 2 \log_{10}$)	99% ($2 \log_{10}$)	99.9 % ($3 \log_{10}$)		1[u]	(Sustainable Sanitation and & Water Management Toolbox 2024)

[r] The removal of protozoa with WaterGuard is reported as $3 \log_{10}$ (Engineering For Change 2024), but since this is a chlorination product, the efficiency for reducing *Cryptosporidium* is likely to be lower (World Health Organization 2017a).
[s] The one-star ranking for WaterGuard is based on a $3 \log_{10}$ reduction for protozoa. If this is not the case, no star would be given.
[t] The removal of protozoa with P&G Purifier of Water is likely to be higher than the removal of protozoa with WaterGuard or Aquatabs ®, since P&G Purifier of Water not only is a chlorination product but also a coagulant.
[u] The one-star ranking for biosand filter is based on a $2 \log_{10}$ reduction for bacteria, since the reduction for bacteria is approximately $2 \log_{10}$. If not $2 \log_{10}$ reduction is reached, no star would be given.

The reduction of pathogens through boiling depends on the time and the temperature for the boil. The longer the time and the higher temperature, the higher the $\log_{10}$ reduction. Bacteria are sensitive to heat, and it takes less than one minute per $\log_{10}$ reduction when water is boiling at temperatures above 65 °C. Viruses are inactivated at a slower rate than bacteria. When the boiling temperature is above 70 °C, viruses are inactivated by $5 \log_{10}$ reduction in less than a minute. *Cryptosporidium* is also inactivated in less than a minute, but the data for Giardia is limited, but inactivation have been detected (World Health Organization 2015a). The recommendation from the World Health Organization is to heat the water to a rolling boil, let it cool naturally and protect is from post contamination. Different studies report different efficiency for boiling (World Health Organization 2015a), so the $\log_{10}$ reduction used in this study is an approximation of these studies based on boiling for five minutes at 70 °C (World Health Organization 2015a).

WaterGuard is a chlorination product based on a dilute sodium hypochlorite solution. For a higher turbidity, a higher dosage is needed. WaterGuard provides a free disinfectant residual, which continues to protect the water from contamination after the treatment (Engineering For Change 2024).

Aquatabs ® is a chlorination product that is available in different products like Tablets and Granules. The Aquatabs Tablets dissolves in water and releases hypochlorous acid (HOCl) and monosodiumcyanurate. It is a combination of free and combined chlorine (Aquatabs 2024b). The $\log_{10}$ reduction presented are within 30 minutes, when the product is used in non-turbid water. Turbid water should be filtered through a cloth before Aquatabs ® is used (Aquatabs 2024a).

P&G Purifier of Water is a powder with a multi-barrier approach which contains both coagulants and chlorine. When the powder is added to water, the coagulants remove turbidity, and the chlorine inactivates pathogens. A free chlorine residual is present in the treated water to protect against recontamination. The flocculation is effective in removing protozoa such as *Cryptosporidium* and *Giardia*. The $\log_{10}$ reduction used in this study are based on laboratory efficiency (P&G Purifier of Water 2024).

LifeStraw ® filter (Vestergaard) is an ultrafiltration technique that is available in different products. The product Lifestraw Community is a portable product that is enough for 75 people for 3 – 5 years. The ultrafilter has the capacity of removing viruses due to its small pore size (LifeStraw 2024). The technology is designed to operate without electricity (Clasen et al. 2009).

Slow sand filtration is practiced at drinking water plants for larger communities. Depending on the presence of a biofilm layer, grain size, the flow rate, operating conditions (temperature and pH), and turbidity of the water, different levels of pathogen removal are possible. The removal of bacteria is 2 – 6 $\log_{10}$ reduction, the removal of viruses is 0.25 – 4 $\log_{10}$ reduction and the removal of protozoa is 0.3 – >5 $\log_{10}$ reduction (World Health Organization 2017a). The biosand filter has been developed for household, school, or community level based on the traditional slow sand filter. The biosand filter is built with locally available material in a filter container. The water is poured on the top of the biosand filter and travels slowly down through the sand and gravel bed. The treated water is collected from a pipe in the bottom of the biosand filter. The $\log_{10}$ reduction used in this study show the highest removal of pathogens, based on laboratory results for biosand filter (Sustainable Sanitation and & Water Management Toolbox 2024).

3.3.3 Evaluation of Point-of-use Water Treatment Technologies Through the Multicriteria Decision Analysis

The point-of-use water treatment technologies were investigated based on the criteria used in the multicriteria decision analysis. They were inspired by previous studies through the literature review and decided together with the key players in the WASH and resilience project at the workshop during the field visit. The scoring of the options was done qualitatively by the key players on all criteria except treatment performance. The scoring of the options on treatment performance is based on the ranking system of the efficiency of point-of-use water treatment technologies by the World Health Organization, where the number of stars corresponds to the score in the multicriteria decision analysis. The decision matrix for the multicriteria decision analysis is presented in Table 11.

Table 11. Decision matrix for comparing point-of-use water treatment technologies suitable at schools. Each point-of-use water treatment technology is scored according to each criterion on a scale from 1 – 3, where 1 represents poor, 2 represents fair, and 3 represents good. The rank of the criteria shows the relative importance of the criteria, where 1 is most important. The weighting factor shows the obtained weight for each criterion, based on the rank of the criteria. The result is presented in weighted score and score without weighs. The numbers in parathesis show an alternative scoring. The higher the score, the more favourable is the point-of-use water treatment technology.

Categories	Criteria	Rank of criteria	Weighting factor	Boiling	Water-Guard	Aqua-tabs ®	P&G Purifier of Water	Life-straw Com-munity ®	Bio-sand filter
Technology	Treatment performance	1	0.20	2	1	2	2	3	1
	Volume capacity	3	0.16	1	3	3	3	1	3
	Ease of use	7	0.07	3	2	2	2	2	1
Economy	Initial cost[v]	5	0.11	2	3	3	3	1	1
	Operation and maintenance cost	6	0.09	2	2	2	1	1	2
Sustainability	Local environmental impact	9	0.02	1	3	3	2 (3)	3	3
	Local availability	4	0.13	1	3	2	1 (2)	1 (2)	3
Social aspects	Social and cultural acceptability	2	0.18	3	2	2	2	3	3
	Perceived cleanliness	8	0.04	2 (3)	3	3	2 (3)	3	3
Weighted score				1.93 (1.98)	2.27	2.33	2.04 (2.24)	1.96 (2.09)	2.16
Score without weights				17 (18)	22	22	18 (21)	18 (19)	20

[v] The scores for the three chlorination products WaterGuard, Aquatabs ® and P&G Purifier of Water were set to Not Applicable during the workshop, since there is no initial cost, but only operation and maintenance costs when the product is bought, but this was transformed to the score 3 in the decision matrix, since it is advantageous when there is no initial cost.

The results from the multicriteria decision analysis, based on the weighted score, show that the most favourable point-of-use water treatment technology is the chlorination product Aquatabs ®, followed by chlorination product WaterGuard and the filtration technology biosand filter. When the alternative scoring is used, presented in the parentheses in Table 8, the chlorination and coagulation product P&G Purifier of Water gets a higher weighed score than the biosand filter. The alternative scoring increases the weighted score for both Boiling and LifeStraw Community ®, but they stay in the same place compared to the other point-of-use treatment technologies. The change in weighed score is higher for P&G Purifier of Water than for Boiling and LifeStraw Community ®, since there are changes in the scores regarding more criteria for P&G Purifier of Water.

The scores without weights, show that Aquatabs ® and WaterGuard share the first place, when the rank of the criteria is not accounted for. The biosand filter stays at the third place according to the scores without weights, and the alternative scoring, presented in the parenthesis, makes the score for P&G Purifier of Water higher than the scoring for biosand filter, as shown in the weighted score too.

The efficiency of the investigated point-of-use water treatment technologies does not reach the required treatment for rainwater based on the Swedish QMRA-tool. However, if different treatment options are used in combination, the $\log_{10}$ reduction for each point-of-use water treatment technology are added together, so the combination of the treatment technologies in a treatment train can reach the required treatment level together. To use a combination of point-of-use water treatment technologies not only gives a higher $\log_{10}$ reduction, but also the benefit from the advantages of complementary water treatment technologies. Since chlorination is not effective against *Cryptosporidium* (World Health Organization 2017a), chlorination alone would not ensure safe drinking water. Therefore previous research recommends filtration to reduce *Cryptosporidium* (Crabtree et al. 1996). A combination of a chlorination and a filtration technology therefore creates a double barrier, with the advantage of a free disinfectant residual after chlorination, that continues to protect the water from contamination after the treatment, and the advantage of filtration in its efficiency in removing protozoa.

4. DISCUSSION

In this study rainwater harvesting was investigated at a local level at three schools in rural Kenya, connected to the WASH and resilience project within the Salvation Army Kenya East Territory. Limiting factors in ensuring a sufficient volume of rainwater have been identified as well as preventive actions that can improve rainwater quality, and aspects to consider when choosing point-of-use water treatment technologies. Based on the findings, practical implementations and suggestions for further research are presented at the end of this section.

4.1 ENSURING A SUFFICIENT VOLUME OF RAINWATER AT SCHOOLS

If rainwater is only used for drinking, based on the standard drinking water use of one litre per person per day (World Health Organization 2017a), the harvested rainwater should be sufficient at the three schools investigated in this study, based on the local rainfall, the standard catchment area, and the current storage capacity. However, water is needed not only for drinking but also for cooking, personal hygiene, cleaning, and laundry. This should be covered by the basic minimum water requirements for non-residential schoolchildren of five litres per person per day and 20 litres per person per day at boarding schools. Water for cleaning and laundry can, however, be of lower quality than drinking water quality (Ministry of Education et al. 2018).

The potential rainwater volume that can be harvested at schools differs depending on whether a first flush device, that leads away the first two millimetres of rain from every rain event, is used or not. The equation on potential rainwater volume used in this study does not include the water loss of a first flush device, since first flush was practiced manually in the beginning of the rainy seasons and not at every rain event, at the schools investigated. The water loss of the manually practiced first flush could, however, be accounted for in the volume calculations for the first months of the rainy seasons to get the actual available water volume. On the other hand, the rainfall is relatively high in the beginning of the rainy seasons and often it is not possible to harvest it all, so the water loss from manually practiced first flush may not affect the available rainfall volume significantly. If the school starts to use a fist flush device, the potential rainwater volume should be calculated through an equation that takes first flush into account (Zhang et al. 2018), since it will affect the potential rainwater volume that can be harvested each month.

The limiting factors for ensuring a sufficient volume of water at the schools are storage capacity, catchment area, and water consumption. To ensure a sufficient volume of water through rainwater harvesting, it is important to investigate each school regarding the limiting factors and the local rainfall, so actions can be taken against the limiting factors at each school. In this study the same standard catchment area was used for all schools investigated. For more accurate calculations, the actual catchment area for each school should be measured more carefully. Depending on whether the school is situated in an area with higher or lower rainfall, the limiting factors can differ. If the potential rainwater volume must be higher to ensure a sufficient volume of rainwater, it is possible to increase the catchment area, but if the potential rainwater volume is higher than the storage capacity, more storage tanks are needed. If the harvested rainwater volume runs out faster than expected, the actual water use needs to be investigated further.

The reported total water use at the investigated schools is higher than the basic minimum water requirements; this indicates that actions can be done to minimize the water use. Reducing the total water use and prioritizing rainwater for drinking, cooking and personal hygiene can require a behaviour change. According to previous research, the issue of motivation is the key to any behaviour change (Curtis et al. 1997). Further work on identifying motivation factors for a water saving mentality in the local context is therefore recommended.

4.2 IMPROVING RAINWATER QUALITY THROUGH PREVENTIVE ACTIONS

Microbial risk factors identified in previous research (Karim 2010; Misati et al. 2017) correspond well with the observed risk factors through the sanitary inspection for rainwater collection and storage, performed during the field visit. The lack of or not properly closed cover, contamination on the roof, broken gutters, and broken storage tank taps observed at the investigated schools are all consequences of the lack of maintenance. Previous research through sanitary inspections on rainwater harvesting systems in Kenya shows that the lack of cover and visible contamination of the roof are commonly detected risk factors (Misati et al. 2017). Additionally, a study from Bangladesh confirms that poor maintenance is responsible for contamination of rainwater (Islam et al. 2011).

Maintenance on a regular basis is the overall preventive action that can contribute to minimizing the risk of microbial contamination to the harvested rainwater, and it can usually be carried out by a trained user or caretaker (World Health Organization 2024). Of the three investigated schools, the school with the lowest number of risk factors had maintenance on a regular basis, according to the responsible teacher, while the maintenance and the responsibility for the rainwater harvesting system were less organized at the two other schools. Previous research shows that community participation is important in maintaining the rainwater harvesting systems, and that a protocol for construction, operation, maintenance and water quality should be adopted (Karim 2010).

The rainwater quality can be improved by proper design and maintenance of the rainwater harvesting system (Meera & Ahammed 2006). The required treatment for rainwater obtained from the Swedish QMRA-tool shows that preventive actions can reduce the pathogen concentration in untreated rainwater with 3 $\log_{10}$ reduction. This calculation is based on a comparison between the highest detected *E. coli* concentration, and the lowest detected *E. coli* concentration from the same study, where the rainwater harvesting systems with the highest concentrations did not have a first flush diverter but overhanging trees, and evidence of animal droppings on the roof, while the rainwater harvesting systems with the lowest concentration had a first flush diverter or no signs of faecal droppings or trees above the roof (Ahmed et al. 2011). The lowest reported *E. coli* concentration of < 1 CFU/100 ml, was assumed to equal to 1 CFU/100 ml. However, the pathogen concentration may be below the detection limit, indicating that the preventive actions may reduce more than 3 $\log_{10}$ reduction, compared to the worst-case scenario. Even though the exact $\log_{10}$ reduction of preventive actions can differ, the result indicate that rainwater quality can be improved by preventive actions.

The sanitary inspections on rainwater collection and storage conducted during the field visit show the status of the rainwater harvesting system at three schools at the occasion of the inspection. To get a broader understanding of the most common risk factors connected to rainwater harvesting systems at the schools in the WASH and resilience project, more schools should be investigated. Repeated sanitary inspections are recommended by previous research (Islam et al. 2011), and data from the sanitary inspections can highlight potential key investments and should be linked to actions to improve the water sources (Misati et al. 2017). The sanitary inspection on rainwater collection and storage is therefore recommended to be used on a regular basis at schools connected to the WASH and resilience project, together with actions to minimize the identified risks.

Previous studies show different correlations between sanitary inspections and the microbial contamination of rainwater. According to a study from Kenya, sanitary surveys cannot be a substitute for microbial water quality testing, since there is no significant correlation between the sanitary risk scores and the level of indicator bacteria (Misati et al. 2017). On the other hand, a study from Bangladesh shows good correlation between the sanitary inspection scores and the microbial contamination (Karim 2010). The different results indicate that performing water quality tests is an important practice, and that sanitary inspections and water quality testing can function well together and answer different questions. While the water quality tests give the answer of the level of contamination, which is important regarding the level of treatment required, the sanitary inspection identify the risk factors and should be used to develop a comprehensive risk management approach to reduce the microbial contamination in the untreated rainwater.

4.3 ASPECTS TO CONSIDER WHEN CHOOSING POINT-OF-USE WATER TREATMENT TECHNOLOGIES

Previous research on rainwater harvesting agrees that it is essential to treat harvested rainwater prior to drinking to ensure safe drinking water (Meera & Ahammed 2006; Ahmed et al. 2010, 2012; Kim et al. 2016; Malema et al. 2018; John et al. 2021; Shubo et al. 2021), but there is a difference in how effective different point-of-use water treatment technologies are in reducing pathogens. Careful consideration is therefore needed when choosing among the treatment technologies (World Health Organization 2017a). A multicriteria decision analysis is constructed to serve as a decision support when choosing between different options (Dodgson et al. 2009), and the strength of the multicriteria decision analysis in this study was the involvement of key players from the WASH and resilience project, that have local knowledge on which point-of-use treatment technologies are suitable and which criteria are most important in the local context.

The sensitivity analysis in the multicriteria decision analysis show that the order of the most favourable point-of-use water treatment technologies changes slightly when the rank of the criteria not is accounted for. Without the weighting factor, Aquatabs ® and WaterGuard share the first place, while Aquatabs ® is more favourable when the weighting factor is accounted for. This reflects the importance of the highest ranked criterion, treatment performance, since Aquatabs ® provides a higher $\log_{10}$ reduction than WaterGuard.

The required $\log_{10}$ reduction obtained from the Swedish QMRA-tool contains uncertainties stemming from the previous studies from which the pathogen concentrations were taken and from the tool itself. The worst-case scenario, based on the highest pathogen concentrations, is likely to result in a too high required treatment level, especially for viruses, since the study on virus concentration were from the first ten millimetres of rainfall, which includes the more contaminated first flush (Shubo et al. 2021). The worst-case scenario, concerning the consumption of two litres per person per day, is likely to overestimate the exposure, since the reported drinking water use per schoolchild per day is about the standard drinking water use of one litre per person per day (World Health Organization 2017a), also used in the volume calculations. On the other hand, the exposure due to hand washing and other water usages is not included in the Swedish QMRA-tool, which the higher exposure volume, in the worst-case scenario is likely to cover. The accepted risk level of one infection per 10 000 persons per year is also likely to be too high, regarding the local rural context.

When comparing the required $\log_{10}$ reduction obtained from the Swedish QMRA-tool with the ranking system for point-of-use water treatment technologies by the World Health Organization (World Health Organization 2019), the required treatment level is lower according to the ranking by the World Health organization than the required treatment obtained from the Swedish QMRA-tool. However, the $\log_{10}$ reduction needed, according to the World Health Organization, is not based on rainwater quality specifically, which makes it a more general ranking system. On the other hand, a two-star or three-star point-of-use water treatment technology should give comprehensive protection under most water quality conditions according to the World Health Organization (World Health Organization 2019). While choosing between point-of-use water treatment technologies, the $\log_{10}$ reduction presented to give a comprehensive protection by the World Health Organization may therefore be a sufficient aim for the treatment performance, since the required $\log_{10}$ from the Swedish QMRA-tool is likely to be an overestimation. While choosing between two-star and three-star point-of-use water treatment technologies, the focus should be on the product that is most likely to be used in a correct way, and other criteria, similar to the ones accounted for in the multicriteria decision analysis in this study (World Health Organization 2019), showing that a multicriteria decision analysis is a suitable methodology when choosing between different point-of-use water treatment technologies, since several important criteria are accounted for. However, ensuring that the treatment level is sufficient, water quality measurements are recommended on a regular basis at the schools.

Regular water quality test at schools, at least annually, as well as treatment for all drinking water should be performed according to the Kenyan governments (Ministry of Education et al. 2018). It is therefore important to actively involve teachers, local communities, Ministry of Health representatives and potentially local Salvation Army staff in routines in conducting water quality tests as well as in good maintenance and preventive actions at an early stage, so that they are fully familiar with the procedures in commissioning and hand-over. Previous research on rainwater harvesting in Kenya shows that successful water and sanitation supply is obtained when stakeholders from non-governmental organizations, communities, private sector, and the government work together (Christian Amos et al. 2016). The Salvation Army Kenya East Territory is therefore recommended to continue the good work in engaging school staff, schoolchildren, and local communities, and to continue the dialogue with the local governments, in ensuring a sufficient volume of safe drinking water through rainwater harvesting at schools.

4.4 PRACTICAL IMPLEMENTATIONS AND FURTHER RESEARH

The overall aim of the Master thesis was to provide practical recommendations that can contribute to ensuring a sufficient volume of safe drinking water from the rainwater harvesting systems at schools connected to the WASH and resilience project within the Salvation Army Kenya East Territory. According to previous research on behavioural change on improving hygiene practices, it is important not to send too many messages at the same time, in order not to confuse and exhaust the people involved (Curtis et al. 2000). The following recommendations are therefore presented as an overview of possible actions based on the findings from this study, and the staff in the WASH and resilience project are best suited to prioritize these and decide on the order of implementation, according to their context.

Ensuring a sufficient volume of rainwater at schools

- Identify the limiting factors at each school and take actions against these (limiting factors identified in this study were: storage capacity, catchment area, and water consumption).
- Conduct water consumption records to investigate the actual water use and the purpose of water used.
- Explore a water saving mentality in order to not exceed the basic minimum water requirements.
- Prioritize rainwater for drinking, cooking, and hygiene, and use water of lower quality for cleaning and laundry.
- Repair broken gutters not to lose water.

Improving rainwater quality through preventive actions

- Conduct sanitary inspections on a regular basis and follow up with the suggested corrective actions (World Health Organization 2024).
- Encourage inspection to ensure that repairs and maintenance is done.
- Use a first flush device for every rain event.
- Ensure that the storage tanks have adequate protection from vermin.

Aspects to consider when choosing point-of-use water treatment technologies

- Inform the schools that rainwater needs treatment to be safe for drinking (Ministry of Education et al. 2018).
- Conduct water quality tests, at least annually, at each school, according to the *Standards and Guidelines for WASH Infrastructure in Pre-primary and Primary Schools in Kenya* (Ministry of Education et al. 2018).
- Use several point-of-use water treatment technologies in combination to get a higher $\log_{10}$ reduction and the benefit from the advantages of different treatment technologies.
- Explore whether it is possible to develop local biosand filters (Sustainable Sanitation and & Water Management Toolbox 2024).
- Consider investigating other possible point-of-use treatment technologies, beside the ones investigated in this study, and ensure that the technologies at least have comprehensive protection according to the World Health Organization (World Health Organization 2019).

Overall recommendations

- Encourage peer learning, by for instance, allowing staff from different schools to visit each other to learn from what other schools are doing well.
- Actively involve school staff, schoolchildren, local communities, and potentially local Salvation Army staff in good maintenance, preventive actions and the use of point-of-use water treatment technologies for rainwater at an early stage, so that they are fully familiar with the procedures by project commissioning and hand-over.
- Continue engaging local Ministry of Health representatives to develop and implement policy in ensuring a sufficient volume of safe drinking water through rainwater harvesting at schools.

Suggestions for further research

- Conduct more studies based on rainwater quality measurements from Kenya to contribute to the understanding of the local quality of harvested rainwater.
- Conduct more studies on viruses in harvested rainwater worldwide to contribute to the understanding of the presence of viruses in harvested rainwater.
- Conduct specific studies on pathogen concentrations in harvested rainwater after different preventive actions, to quantify the pathogen reduction of different preventive actions.

5. CONCLUSIONS

The findings on how well rainwater can cover the water use at the schools show that the harvested rainwater volume is sufficient for covering the drinking water demand of one litre per person per day but may be insufficient for the basic minimum water requirements in which cooking, personal hygiene, cleaning, and laundry are included. The harvested rainwater can last longer if actions are taken against the limiting factors (storage capacity, catchment area, and water consumption).

The outcomes on microbial risk factors associated with harvested rainwater show that faecal matter from animal droppings is the main source of microbial contamination in rainwater. The most common risk factors that were observed at the schools during the field visit were lack of or not properly closed inspection hatch lid of the storage tanks, open overflow hole to the storage tank, were vermin can enter, and lack of fence around the water collection area, so animals could enter. The rainwater quality can however be improved by preventive actions. The use of a first flush device, that leads away the first millimetres of rainfall, increases the quality of the harvested rainwater significantly. Proper design of the rainwater harvesting system and established maintenance practices are important to minimize the contamination in rooftop harvested rainwater. It is recommended to conduct sanitary inspections on regular basis and follow up with the suggested corrective actions.

The required treatment for rainwater, based on the highest pathogen concentrations in rainwater from previous studies, show that bacteria need 5 – 8 $\log_{10}$ reduction, viruses need 9 – 10 $\log_{10}$ reduction, and protozoa need 4 – 8 $\log_{10}$ reduction, to achieve the risk level below one infection per 10 000 persons per year. However, according to a ranking system from the World Health Organization, a lower $\log_{10}$ reduction is sufficient for reaching a comprehensive protection. While choosing among different point-of-use water treatment technologies, criteria such as social and cultural acceptability, and volume capacity are important beside the treatment performance, in the local context. According to the multicriteria decision analysis, the most favourable point-of-use water treatment technologies, based on the weighted score, are the chlorination products Aquatabs ® and WaterGuard followed by the filtration technology biosand filter. It is recommended to use several point-of-use water treatment technologies in combination to get a higher $\log_{10}$ reduction and the benefit from the advantages of complementary water treatment technologies.

REFERENCES

Ahmed, W., Hodgers, L., Masters, N., Sidhu, J.P.S., Katouli, M. & Toze, S. (2011). *Occurrence of Intestinal and Extraintestinal Virulence Genes in Escherichia coli Isolates from Rainwater Tanks in Southeast Queensland, Australia*. https://doi.org/10.1128/AEM.06047-11

Ahmed, W., Sidhu, J.P.S. & Toze, S. (2012). An Attempt to Identify the Likely Sources of Escherichia coli Harboring Toxin Genes in Rainwater Tanks. *Environmental Science & Technology*, 46 (9), 5193–5197. https://doi.org/10.1021/es300292y

Ahmed, W., Vieritz, A., Goonetilleke, A. & Gardner, T. (2010). *Health Risk from the Use of Roof-Harvested Rainwater in Southeast Queensland, Australia, as Potable or Nonpotable Water, Determined Using Quantitative Microbial Risk Assessment*. https://doi.org/10.1128/AEM.00944-10

Alja'fari, J., Sharvelle, S., Brinkman, N.E., Jahne, M., Keely, S., Wheaton, E.A., Garland, J., Welty, C., Sukop, M.C. & Meixner, T. (2022). Characterization of roof runoff microbial quality in four U.S. cities with varying climate and land use characteristics. *Water Research*, 225, 119123. https://doi.org/10.1016/j.watres.2022.119123

Amin, M.T., Kim, T., Amin, M.N. & Han, M.Y. (2013). Effects of Catchment, First-Flush, Storage Conditions, and Time on Microbial Quality in Rainwater Harvesting Systems. *Water Environment Research*, 85 (12), 2317–2329. https://doi.org/10.2175/106143013X13706200598433

Aquatabs (2024a). *Aquatabs | FAQ*. https://www.aquatabs.com/faq.php [2024-05-14]

Aquatabs (2024b). *Aquatabs | Products*. https://www.aquatabs.com/products.php [2024-05-14]

Araya, D., Podgorski, J. & Berg, M. (2023). Groundwater salinity in the Horn of Africa: Spatial prediction modeling and estimated people at risk. *Environment International*, 176. https://doi.org/10.1016/j.envint.2023.107925

Bain, R., Johnston, R., Khan, S., Hancioglu, A. & Slaymaker, T. (2021). Monitoring Drinking Water Quality in Nationally Representative Household Surveys in Low- and Middle-Income Countries: Cross-Sectional Analysis of 27 Multiple Indicator Cluster Surveys 2014–2020. *Environmental Health Perspectives*, 129 (9), 097010. https://doi.org/10.1289/EHP8459

Bryman, A. (2018). Chapter 6 Ethics and politics in social science research. In: *Samhällsvetenskapliga metoder*. 3. ed.

Chalmers (2020). *Swedish QMRA-tool for surface water treatment plants*. https://analyticacloud.com/view0?invite=4447&code=2411957530316893328 [2024-04-08]

Chalmers (2021). *Wiki for the Swedish QMRA-tool*. http://wiki.qmra.se/doku.php?id=start [2024-04-08]

Chubaka, C.E., Whiley, H., Edwards, J.W. & Ross, K.E. (2018). A Review of Roof Harvested Rainwater in Australia. *Journal of Environmental and Public Health*, 2018, 1–14. https://doi.org/10.1155/2018/6471324

Clasen, T., Naranjo, J., Frauchiger, D. & Gerba, C. (2009). Laboratory Assessment of a Gravity-Fed Ultrafiltration Water Treatment Device Designed for Household Use in Low-Income Settings. *The American Journal of Tropical Medicine and Hygiene*, 80 (5), 819–823. https://doi.org/10.4269/ajtmh.2009.80.819

County Government of Kitui (2023). Kitui County Integrated Development Plan 2023-2027

County Government of Machakos (2023). Machakos County Integrated Development Plan 2023-2027

County Government of Makueni (2023). Makueni County Integrated Development Plan 2023-2027. https://repository.kippra.or.ke/xmlui/bitstream/handle/123456789/4356/Revised-

Final-CIDP-2023-27%28Makueni%29%20%281%29.pdf?sequence=1&isAllowed=y [2024-05-15]
Crabtree, K.D., Ruskin, R.H., Shaw, S.B. & Rose, J.B. (1996). The detection of Cryptosporidium oocysts and Giardia cysts in cistern water in the U.S. Virgin Islands. *Water Research*, 30 (1), 208–216. https://doi.org/10.1016/0043-1354(95)00100-Y
Curtis, V., Cairncross, S. & Yonli, R. (2000). Review: Domestic hygiene and diarrhoea – pinpointing the problem. *Tropical Medicine & International Health*, 5 (1), 22–32. https://doi.org/10.1046/j.1365-3156.2000.00512.x
Curtis, V., Kanki, B., Cousens, S., Sanou, A., Diallo, I. & Mertens, T. (1997). Dirt and diarrhoea: Formative research in hygiene promotion programmes. https://doi.org/10.1093/heapol/12.2.122 [2024-05-06]
Dao, A.D., Nguyen, D.C. & Han, M.Y. (2017). Design and operation of a rainwater for drinking (RFD) project in a rural area: case study at Cukhe Elementary School, Vietnam. *Journal of Water, Sanitation and Hygiene for Development*, 7 (4), 651–658. https://doi.org/10.2166/washdev.2017.055
Dobrowsky, P.H., van Deventer, A., De Kwaadsteniet, M., Ndlovu, T., Khan, S., Cloete, T.E. & Khan, W. (2014). *Prevalence of Virulence Genes Associated with Pathogenic Escherichia coli Strains Isolated from Domestically Harvested Rainwater during Low- and High-Rainfall Periods*. https://doi.org/10.1128/AEM.03061-13
Dodgson, J.S., Spackman, M., Pearman, A.D. & Phillips, L.D. (2009). *Multi-criteria analysis: a manual*. Communities and Local Government.
Engineering For Change, <img Alt=” (2024). *WaterGuard*. *Engineering For Change*. https://www.engineeringforchange.org/solutions/product/waterguard/ [2024-05-14]
GADM (2022). *GADM data*. https://gadm.org/data.html [2024-07-02]
Garfì, M. & Ferrer-Martí, L. (2011). Decision-making criteria and indicators for water and sanitation projects in developing countries. *Water Science and Technology*, 64 (1), 83–101. https://doi.org/10.2166/wst.2011.543
Gevera, P. & Mouri, H. (2018). Natural occurrence of potentially harmful fluoride contamination in groundwater: an example from Nakuru County, the Kenyan Rift Valley. *Environmental Earth Sciences*, 77 (10). https://doi.org/10.1007/s12665-018-7466-7
Hamouda, M.A., Anderson, W.B. & Huck, P.M. (2012). Employing multi-criteria decision analysis to select sustainable point-of-use and point-of-entry water treatment systems. *Water Supply*, 12 (5), 637–647. https://doi.org/10.2166/ws.2012.035
Islam, Md.A., Sakakibara, H., Karim, Md.R., Sekine, M. & Mahmud, Z.H. (2011). Bacteriological assessment of drinking water supply options in coastal areas of Bangladesh. *Journal of Water and Health*, 9 (2), 415–428. https://doi.org/10.2166/wh.2011.114
JMP (2022). WHO/UNICEF Joint Monitoring Programme for Water Supply, Sanitation and Hygiene (JMP) [Data Household Kenya]. https://washdata.org/data/household#!/table?geo0=country&geo1=KEN [2024-01-23]
John, C.K., Pu, J.H., Moruzzi, R. & Pandey, M. (2021). Health-risk assessment for roof-harvested rainwater via QMRA in Ikorodu area, Lagos, Nigeria. *Journal of Water and Climate Change*, 12 (6), 2479–2494. https://doi.org/10.2166/wcc.2021.025
Jones, C.H., Meyer, J., Cornejo, P.K., Hogrewe, W., Seidel, C.J. & Cook, S.M. (2019). A new framework for small drinking water plant sustainability support and decision-making. *Science of The Total Environment*, 695, 133899. https://doi.org/10.1016/j.scitotenv.2019.133899

Karim, M.R. (2010). Microbial contamination and associated health burden of rainwater harvesting in Bangladesh. *Water Science and Technology*, 61 (8), 2129–2135. https://doi.org/10.2166/wst.2010.031

Kenya National Bureau of Statistics (2022). Kenya National SDG Indicator Framework 2023. https://www.knbs.or.ke/download/kenya-national-sdg-indicator-framework-2023/ [2024-01-23]

Kim, Y., Dao, A.D., Kim, M., Nguyen, V.-A. & Han, M. (2016). Design and management of rainwater harvesting systems to control water quality for potable purposes in Cu Khe, Vietnam. *Water Supply*, 17 (2), 452–460. https://doi.org/10.2166/ws.2016.154

Kirs, M., Moravcik, P., Gyawali, P., Hamilton, K., Kisand, V., Gurr, I., Shuler, C. & Ahmed, W. (2017). Rainwater harvesting in American Samoa: current practices and indicative health risks. *Environmental Science and Pollution Research*, 24 (13), 12384–12392. https://doi.org/10.1007/s11356-017-8858-z

Kohlitz, J.P. & Smith, M.D. (2014). Water quality management for domestic rainwater harvesting systems in Fiji. *Water Supply*, 15 (1), 134–141. https://doi.org/10.2166/ws.2014.093

LifeStraw (2024). *LifeStraw Community*. *LifeStraw Water Filters | Europe*. https://eu.lifestraw.com/products/lifestraw-community [2024-04-11]

Loo, S.-L., Fane, A.G., Krantz, W.B. & Lim, T.-T. (2012). Emergency water supply: A review of potential technologies and selection criteria. *Water Research*, 46 (10), 3125–3151. https://doi.org/10.1016/j.watres.2012.03.030

Malema, M., Abia, A., Tandlich, R., Zuma, B., Mwenge Kahinda, J.-M. & Ubomba-Jaswa, E. (2018). Antibiotic-Resistant Pathogenic Escherichia Coli Isolated from Rooftop Rainwater-Harvesting Tanks in the Eastern Cape, South Africa. *International Journal of Environmental Research and Public Health*, 15 (5), 892. https://doi.org/10.3390/ijerph15050892

Meera, V. & Ahammed, M.M. (2006). Water quality of rooftop rainwater harvesting systems: a review. *Journal of Water Supply: Research and Technology-Aqua*, 55 (4), 257–268. https://doi.org/10.2166/aqua.2006.0010

Mekdaschi Studer, R. & Liniger, H. (2013). *Water Harvesting Guidelines to Good Practice*. https://www.wocat.net/documents/85/WaterHarvesting_lowresolution.pdf [2024-01-26]

Mendez, C.B., Klenzendorf, J.B., Afshar, B.R., Simmons, M.T., Barrett, M.E., Kinney, K.A. & Kirisits, M.J. (2011). The effect of roofing material on the quality of harvested rainwater. *Water Research*, 45 (5), 2049–2059. https://doi.org/10.1016/j.watres.2010.12.015

Ministry of Education, Ministry of Health & Ministry of Water and Sanitation (2018). Standards and Guidelines for WASH Infrastructure in Pre-Primary and Primary Schools in Kenya

Ministry of Water, Sanitation and Irrigation (2023). *The Ministry - Ministry of Water, Sanitation and Irrigation*. https://water.or.ke/the-ministry/ [2024-01-29]

Misati, A.G., Ogendi, G., Peletz, R., Khush, R. & Kumpel, E. (2017). Can Sanitary Surveys Replace Water Quality Testing? Evidence from Kisii, Kenya. *International Journal of Environmental Research and Public Health*, 14 (2), 152. https://doi.org/10.3390/ijerph14020152

Morris, J.F., Murphy, J., Fagerli, K., Schneeberger, C., Jaron, P., Moke, F., Juma, J., Ochieng, J.B., Omore, R., Roellig, D., Xiao, L., Priest, J.W., Narayanan, J., Montgomery, J.M., Hill, V., Mintz, E., Ayers, T.L. & O'Reilly, C.E. (2018). A randomized controlled trial to assess the impact of ceramic water filters on prevention of diarrhea and cryptosporidiosis in infants and young children—western Kenya, 2013. *American*

Journal of Tropical Medicine and Hygiene, 98 (5), 1260–1268. https://doi.org/10.4269/ajtmh.17-0731
Mwiathi, N.F., Gao, X., Li, C. & Rashid, A. (2022). The occurrence of geogenic fluoride in shallow aquifers of Kenya Rift Valley and its implications in groundwater management. *Ecotoxicology and Environmental Safety*, 229. https://doi.org/10.1016/j.ecoenv.2021.113046
National Food Authority (2023). *Microbiological Safety Barriers - Control Wiki*. https://kontrollwiki.livsmedelsverket.se/artikel/339/mikrobiologiska-sakerhetsbarriarer [2024-05-23]
Ngubane, Z. (2024). *Development of a multi-criteria decisionsupport tool for improving water quality to assist with engineering infrastructure and catchment management*
Nippon Koei Co., Ltd. (2013). *National Water Master Plan 2030 Exec. Summary Vol. 1 Main 1*. https://wasreb.go.ke/downloads/National%20Water%20Master%20Plan%202030%20Exec.%20Summary%20Vol.%201%20Main%201.pdf [2024-01-23]
Nowicki, S., Birhanu, B., Tanui, F., Sule, M.N., Charles, K., Olago, D. & Kebede, S. (2023). Water chemistry poses health risks as reliance on groundwater increases: A systematic review of hydrogeochemistry research from Ethiopia and Kenya. *Science of The Total Environment*, 904, 166929. https://doi.org/10.1016/j.scitotenv.2023.166929
Okotto-Okotto, J., Yu, W., Kwoba, E., Thumbi, S.M., Okotto, L.G., Wanza, P., Trajano Gomes Da Silva, D. & Wright, J. (2021). A mixed methods study to evaluate participatory mapping for rural water safety planning in western Kenya. Masese, F.O. (ed.) (Masese, F. O., ed.) *PLOS ONE*, 16 (7), e0255286. https://doi.org/10.1371/journal.pone.0255286
P&G Purifier of Water (2024). *P&G Purifier of Water*. https://www.hwts.info/products-technologies/e0baff7f/pandg-purifier-of-water/technical-information [2024-05-14]
Right Track Africa (2022). Mseto Resilience WASH and Food Security Project External Mid-term Evaluation Report 28 April 2022. Right Track Africa.
Rusiniak, P., Sekuła, K., Sracek, O. & Stopa, P. (2021). Fluoride ions in groundwater of the Turkana County, Kenya, East Africa. *Acta Geochimica*, 40 (6), 945–960. https://doi.org/10.1007/s11631-021-00481-3
Sadr, S.M.K., Johns, M.B., Memon, F.A., Duncan, A.P., Gordon, J., Gibson, R., Chang, H.J.F., Morley, M.S., Savic, D. & Butler, D. (2020). Development and Application of a Multi-Objective-Optimization and Multi-Criteria-Based Decision Support Tool for Selecting Optimal Water Treatment Technologies in India. *Water*, 12 (10), 2836. https://doi.org/10.3390/w12102836
Santos, J., Pagsuyoin, S.A. & Latayan, J. (2016). A multi-criteria decision analysis framework for evaluating point-of-use water treatment alternatives. *Clean Technologies and Environmental Policy*, 18 (5), 1263–1279. https://doi.org/10.1007/s10098-015-1066-y
Schulte-Herbrüggen, H. (2015). Unpublished data from data collection for the Salvation Army Kenya East Territory
Shiguang, C., Haoxin, Z., Hongwei, S., Song, L. & Yongmin, Y. (2023). How to determine the cistern volume of rainwater harvesting system: an analytical solution based on roof areas and water demands. *Environment, Development and Sustainability*,. https://doi.org/10.1007/s10668-023-03480-x
Shubo, T., Maranhão, A., Ferreira, F.C., Fumian, T.M., Pimenta, M.M.A., do Rosário Vaz Morgado, C., Toze, S., Ahmed, W., Sidhu, J. & Miagostovich, M.P. (2021). Virological Characterization of Roof-Harvested Rainwater of Densely Urbanized Low-Income Region. *Food and Environmental Virology*, 13 (3), 412–420. https://doi.org/10.1007/s12560-021-09484-y

Sustainable Sanitation and & Water Management Toolbox (2024). *Biosand Filter | SSWM - Find tools for sustainable sanitation and water management!* https://sswm.info/sswm-solutions-bop-markets/affordable-wash-services-and-products/affordable-water-supply/biosand-filter [2024-05-14]

Tenebe, I.T., Emenike, P.C., Nnaji, C.C., Babatunde, E.O., Ogarekpe, N.M., Dede-Bamfo, N. & Omole, D.O. (2020). Bacterial characterization and quantification of rainwater harvested in a rural community in Nigeria. *Environmental Nanotechnology, Monitoring & Management*, 14, 100370. https://doi.org/10.1016/j.enmm.2020.100370

UNICEF & WHO (2023). *Progress on household drinking water, sanitation and hygiene 2000-2022: special focus on gender*. https://data.unicef.org/resources/jmp-report-2023/

University of Notre Dame (2024). *Rankings // Notre Dame Global Adaptation Initiative // University of Notre Dame*. *Notre Dame Global Adaptation Initiative*. https://gain.nd.edu/our-work/country-index/rankings/ [2024-01-23]

Wekesa, P.M., Nzioka, J.M. & Mutune, J.M. (2022). Barriers and Enablers of adoption of Rain Water Harvesting Technologies at County Levels: A Case of Matungulu Sub-County, Machakos County Kenya. *East African Journal of Science, Technology and Innovation*, 3 (2). https://doi.org/10.37425/eajsti.v3i2.411

World Bank Climate Change Knowledge Portal (2021). *Climate Change Overview Country Summary Kenya*. https://climateknowledgeportal.worldbank.org/ [2024-01-23]

World Health Organization (2015a). *BOIL WATER WHO/FWC/WSH/15.02*. https://iris.who.int/bitstream/handle/10665/155821/WHO_FWC_WSH_15.02_eng.pdf?sequence=1 [2024-04-04]

World Health Organization (2015b). *WHO International Scheme to Evaluate Household Water Treatment Technologies Aquatabs® Product evaluation report*. https://cdn.who.int/media/docs/default-source/wash-documents/regnet/products/whoscheme_r1_productreport_aquatabs.pdf?sfvrsn=6435c012_5 [2024-05-14]

World Health Organization (2015c). *WHO International Scheme to Evaluate Household Water Treatment Technologies LifeStraw® Community Product evaluation report*. https://cdn.who.int/media/docs/default-source/wash-documents/regnet/products/whoscheme_r1_productreport_lifestrawcommunity.pdf?sfvrsn=615f4820_5 [2024-05-14]

World Health Organization (2015d). *WHO International Scheme to Evaluate Household Water Treatment Technologies P&G Purifier of Water Product evaluation report*. https://cdn.who.int/media/docs/default-source/wash-documents/regnet/products/whoscheme_r1_productreport_pgpurifierofwater.pdf [2024-05-14]

World Health Organization (2016). *Quantitative Microbial Risk Assessment: Application for Water Safety Management*. World Health Organization. https://iris.who.int/handle/10665/246195 [2024-02-06]

World Health Organization (2017a). *Guidelines for drinking-water quality: fourth edition incorporating first addendum*. 4th ed + 1st add. World Health Organization. https://iris.who.int/handle/10665/254637 [2024-02-22]

World Health Organization (2017b). *Safely managed drinking water: thematic report on drinking water 2017*. World Health Organization. https://iris.who.int/handle/10665/325897 [2024-02-20]

World Health Organization (2019). *Results of round II of the WHO international scheme to evaluate household water treatment technologies*. World Health Organization. https://iris.who.int/handle/10665/325896 [2024-06-17]

World Health Organization (2024). *Sanitary inspection packages - a supporting tool for the Guidelines for drinking-water quality: small water supplies.*

Zhang, S., Zhang, J., Jing, X., Wang, Y., Wang, Y. & Yue, T. (2018). Water saving efficiency and reliability of rainwater harvesting systems in the context of climate change. *Journal of Cleaner Production*, 196, 1341–1355. https://doi.org/10.1016/j.jclepro.2018.06.133