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Development of monitoring program for water safety in small-scale water treatment plants in rural areas of Ecuador

Tone Sigrell

ABSTRACT

Development of monitoring program for water safety in small-scale water treatment plants in rural areas of Ecuador

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Globally a major health concern according to the World health organization (WHO, 2011) is gastro-intestinal infections caused by fecally contaminated water. The access to drinking water has increased due to international efforts, however the long-term sustainability and safety of the water accessed have gained criticism, and many water sources have proven to be both contaminated (UN, 2016) and badly managed (WHO, 2016a).

This thesis aims to design a monitoring program for small-scale water treatment in order to make the water supply sustainable in terms of providing safe water in a long-term perspective. A case-study was conducted for three treatment systems under constructed in rural Ecuador. The monitoring program design was based on a literature review and conducting a quantitative microbial risk assessment (QMRA). QMRA is a tool for estimating microbial risks, by using quantitative data on microbial contamination and estimating health risks. Data for the QMRA was gathered from literature and in field, and the reference pathogens used in the QMRA were *E.coli* O157:H7, Rotavirus and Giardia. In order to estimate infection risk from drinking water consumption for the community a QMRA-model called MRA, developed by Abrahamsson et al. (2009) was used.

Observations of the catchment areas and measurement of water quality regarding aspects other than microbial contamination indicated that the main risk was microbial contamination from fecal contaminations in the catchment area. The results from the QMRA indicated that the treatment using chlorination reduces *E.coli* O157:H7 under the acceptable risk level of 1/1000 infections per person and year, while the systems using biosand filters (BSF) are more effective in reducing rotavirus and Giardia. If the BSF are combined with chlorination the annual probability of infection caused by consumption of the treated water per year and person was 0.42/1000 for *E.coli* O157:H7, 570/1000 for Rotavirus and 25/1000 for Giardia.

The resulting monitoring program was divided into two parts: one part aimed to prevent contamination and one part designed to measure pH, temperature, conductivity, turbidity on a weekly basis and microbial indicator tests using a presence/absence method monthly. Additional testing is to be done in case of events of such character that the water quality could be effected, for example an extreme weather event.

It was concluded that the designed monitoring program could help improve the water quality in a long-term perspective, but it is dependent on the possibilities to get the necessary support, especially in the implementation phase. Recommended further studies includes collection of more site-specific data to make the QMRA results more representative, and evaluation of the monitoring program design by implementing it and optimizing it in the communities.

Keyword: Safe water, Quantitative microbial risk assessment, QMRA, Sustainable water access, Water quality monitoring

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REFERAT

Utformning av kvalitetsövervakningsprogram för småskaliga vattenreningsverk på landsbygden i Ecuador

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Runt om i världen skapar en otillräcklig tillgång på rent vatten och sanitet mycket lidande. Enlig världshälsoorganisationen WHO (2011) är ett av de ledande världshälsoproblem mag- och tarminfektioner som orsakats av vattenburna fekala patogener. Trots att antalet människor med tillgång till en dricksvattenkälla har ökat till följd av internationella ansträngningar, är hållbarheten och säkerheten för vattenkvalitén problematisk. Många dricksvattenkällor har visat sig vara både förorenade (UN, 2016) och undermåligt skötta (WHO, 2016a). Målet med denna studie är att ta fram ett vattenkvalitetsövervakningsprogram för tre småskaliga vattenreningsverk, för att dessa ska producera säkert vatten i ett långsiktigt perspektiv.

En fallstudie utfördes i byar på landsbygden i Ecuador där systemen planerats. Metoden för att ta fram ett kvalitetsövervakningsprogram var litteraturstudie och mikrobiell riskanalys. Den mikrobiella riskanalysen genomfördes med en metod som kallas Kvantitativ Mikrobiell Risk Analys (QMRA). I QMRA kan hälsorisker från mikrobiell kontamination estimeras med kvantitativdata på mikrobiell förorening. Data för att genomföra QMRA samlades från litteraturen och fältbesök. För att estimera hälsorisker i byarna i fallstudien användes en QMRA-modell som heter MRA framtaget av Abrahamsson et.al. (2009).

Observationer i fält och data på ingående vatten tydde på att de största riskerna för vattenkvalitén var fekal kontamination från djur och människor. Resultaten från QMRA:n visade att reningsverket med klorering reducerade E.coli O157:H7 till en nivå under den accepterade risknivå, satt till 1/1000 infekterade per år och person. Reningsverken med biosandfilter (BSF) var mer effektiva i reduktionen av rotavirus och Giardia. Då klor kombinerades med BSF i modellen blev den årliga infektionsnivån per person 570/1000 för Rotavirus och 25/1000 för Giardia.

Vattenkvalitetsövervakningsprogrammet delades in två delar: en kontaminationsförebyggande och en för att mäta pH, temperatur, konduktivitet och turbiditet veckovis, samt mikrobiella indikatortest med en metod som noterar förekomst av bakteriekolonier (presence/absence metod) månadsvis. Extra tester ska även göras vid sådan händelse som kan komma att påverka vattenkvalitén avsevärt, exempelvis en kraftig storm.

Slutsatsen är att det framtagna vattenkvalitetsövervakningsprogrammet kan göra att vattenkällan blir mer säker och hållbar i ett långsiktigt perspektiv, men att framgången är beroende av att rätt hjälp finns tillhanda speciellt i implementeringsfasen. Fortsatta studier behövs för att göra resultaten från QMRA:n mer representativa, exempelvis genom att samla mer områdesspecifikdata. Vidare skulle det vara intressant att implementera kvalitetsövervakningsprogrammet för att utvärdera och optimera det.

Nyckelord: kvantitativ mikrobiell riskanalys, QMRA, hållbar dricksvattenförsörjning, vattenkvalitétsövervakningsprogram

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PREFACE

Supervisor: Alicia Ortiz, Fundación Altropico
Subject reviewer: Annika Nordin, Department of Energy and Technology, SLU
Examiner: Allan Rodhe, Department of Earth Sciences, Uppsala University

This thesis is my master degree project in Environmental and Water Engineering at Uppsala University and SLU. The idea for the thesis emanated from an internship I did in Ecuador during spring of 2015. The internship was at the environmental organization Altropico, who works with environmental education and preservation as well as with human rights for indigenous groups in Ecuador. In my master I had specialized in environmental management and water resources, which gave me knowledge, both theoretical and practical, that was in line with the work that Altropico does. When I was to conduct my thesis, they were constructing three small-scale drinking water treatment plants in the northwest Ecuador where an earthquake had hit earlier the same year (April, 2016). The treatment plants were to be built in three rural villages and everything was in place for the construction. What the organization was lacking was any form of evaluation and monitoring of the quality of the water that was to be produced. So together with the organization and teachers at my university (Uppsala University and SLU) we elaborated a thesis plan. The original plan was to measure the water quality of the untreated and treated water and model the treatment efficiency and then conduct a quantitative microbial risk assessment (QMRA) for the finished drinking water based on the measured and modelled water quality. From these results and from fieldtrips I was to design a monitoring program and implement it with the local people of the villages, in order to make the drinking water supply safe in a long-term perspective. However, the construction of the treatment plant was delayed and when I had to return to Sweden the construction was still not completed. Therefore I could not test the water quality of the finished water and not implement the monitoring program. However, I had the time to do several visits to the villages and got the opportunity to learn about the difficulties that a project can encounter when it is placed in a rural area without elaborated infrastructure and where different cultures meet. For example, all construction materials for the water treatment system had to be transported by the river in canoe.

I would like to thank my subject reviewer Annika Nordin at SLU for supporting me with her knowledge, her optimism and problem-solving attitude. Thank you also dad and grandparents for reading through and discussing with me throughout the thesis work.

Tambien me gustaria darle la gracias a mis companeros en Quito, a Alicia Ortiz, Samuel Schredinger y Gustavo por assistarme en mi trabajo. Tambien estoy muy agradecida por la bienvendia tan amoroso que me dieron los comunidades Chachi, en San Salvador, San Jose y Mono Manso. Y gracias a Michael Gonzalez por los animos y el suporto!

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POPULÄRVETENSKAPLIG SAMMANFATTNING

Utformning av kvalitetsövervakningsprogram för småskaliga vattenreningsverk på landsbygden i Ecuador

Tone Sigrell

Runt om i världen skapar bristen på rent vatten och sanitet en hel del lidande. Samtidigt som rent vatten i höginkomstländer ses som en självklar rättighet så dör över 800 barn dagligen till följd av botliga sjukdomar som de fått för att de har otillräcklig tillgång till rent vatten, sanitet och hygien (UNICEF, n.d.). Enlig världshälsoorganisationen WHO (2011) så är ett av de ledande världshälsoproblemen mag- och tarminfektioner (vanligt är exempelvis diarré) som orsakats av vattenburna fekala patogener. Patogener är hälsoskadliga mikroorganismer dvs. väldigt små ofta encelliga organismer. De delas in i grupperna bakterier, virus och parasiter såsom protozoer och inälvsmaskar. Fekala patogener kan sprida till vatten via avföring från infekterade människor eller djur (Palaniappan et al., 2010). Just dessa patogener som sprids via avföring är den främsta orsakerna till de vattenrelaterade infektionerna som drabbar folk världen över (Palaniappan et al., 2010). I Ecuador så listades diarré i en statistisk sammanställning som en av fyra av de vanligaste inläggningsorsakerna på sjukhus (INEN, 2015), och 17 % av alla hospitaliseringar av barn under fem år i Ecuador var på grund av diarré (INEN, 2014).

Många internationella initiativ för att öka tillgången på bra vattenkällor har tagits. Ett exempel är FN:s Millenium mål där delmål 7c var att halvera antalet människor som inte har tillgång till rent dricksvatten (UN, n.d.). Initiativen har gett resultat och antalet människor med tillgång på rent vatten ökar, till exempel så nåddes delmål 7c redan år 2015 men hållbarheten och den långsiktiga säkerheten på vattenkvalitén i många av de installerade systemen är under kritik. Det har rapporterats om att dricksvattensystem som installeras både är förorenade (UN, 2016) och undermåligt skötta (WHO, 2016a). Så som med alla tekniska installationer krävs underhåll och drift av systemen. För att garantera att dricksvatten är säkert (inte hälsoskadligt) rekommenderar WHO (2011) att varje dricksvattensystem ska ha en plan för övervakning och bevarande av kvalitén på vattnet. Vidare anses det öka säkerheten hos vattensystemet om det i planen ingår en analys av potentiella och reella risker som hotar vattenkvalitén och därmed hälsan för dess konsumenter.

Målet med denna studie var att ta fram ett vattenkvalitetsövervakningsprogram för småskaliga vattenreningsverk i Ecuador, för att dessa ska producera säkert vatten i ett långsiktigt perspektiv. En fallstudie utfördes i tre byar på landsbygden i Ecuador där systemen planerats. Metoden för att ta fram kvalitetsövervakningsprogram var förutom fältbesök, även en litteraturstudie och en mikrobiell riskanalys. Den mikrobiella riskanalysen genomfördes med en metod som kallas Kvantitativ Mikrobiell Risk Analys (QMRA). I QMRA så kan hälsorisker tex från ett vatten uppskattas genom att infektionsrisken för de som dricker vattnet estimeras. För att genomföra QMRA:n så sammanställdes data på antalet patogener som finns i vattnet innan rening sedan beräknades hur effektiva de olika reningsstegen i vattenreningen är på att döda dessa patogener. Beroende på mängden vatten som en konsument dricker per dag och hur många samt vilka patogener som finns kvar i vattnet efter rening, så kan risken för infektion uppskattas.

För att genomföra dessa beräkningar av infektionsrisk i denna studie så användes en modell framtagen av Abrahamsson et al., (2009). Risken för infektion från en viss mängd patogener är olika för olika patogener då dosen som krävs för infektion och vilka hälsoeffekter den ger varierar. Det är praktisk omöjligt att utvärdera risker till alla patogener i en QMRA eftersom det finns alldeles för många, därför valdes tre så kallade referenspatogener ut. I detta arbete användes *E.coli O157:H7*, som är en patogen bakterie som orsakar alvarliga diarréer, för att representera bakteriell vattenkontaminering. Giardia användes för att representera en parasitkontaminering och Rotavirus användes för att representera virus. Det betyder att den slutliga risken som uppskattas är risken från endast tre referenspatogener, beaktning tas alltså inte till alla potentiella vattenburna patogener. Riskerna som upptäcktes genom att göra QMRA:n användes för att utveckla kvalitetsövervakningsprogram. Programmet utvecklades med hjälp av litteraturstudier, platsspecifika betingelser och identifierade hälsorisker från QMRA:n.

Observationer i fält och data på ingående vatten tydde på att de största riskerna för vattenkvalitén var fekal kontamination från djur och människor. Resultaten från QMRA:n visade att ett av reningsverken som använde klor för desinfektering som enda reningssteg gav 0/1000 infektioner från *E.coli* O157:H7 i dricksvattnet vid normal konsumtion per år. Om förutsättningarna ändras till ett så kallat ”worst-case” scenario vilket betyder att både kontaminationen ökas och reningsförmågan minskas var risken fortfarande inom acceptabla gränser. Acceptabel gräns sattes i detta arbete till 1/1000 infektioner per år. De andra två systemen som använde biosandfilter (BSF) som enda reningssteg klarade inte att nå en acceptabel risknivå utan gav 570/1000 infektioner från *E.coli* O157:H7 per år. Reningsverken med biosandfilter (BSF) var mer effektiva i reduktionen av rotavirus och Giardia jämfört med klorering, men den acceptabla risknivån nåddes inte för någon av referenspatogenerna. Då klor kombinerades med BSF i modellen blev den årliga infektionsnivån per person 570/1000 för rotavirus och 25/1000 för Giardia.

Det slutliga vattenkvalitetsövervakningsprogrammet delades in två delar: en del som ska förebygga kontamination; och en del som ska mäta pH, temperatur, konduktivitet och turbiditet veckovis samt mikrobiella indikatortest med en ”presence/absence” metod månadsvis. Turbiditet är ett mått på halten lösta partiklar i vattnet, ju grumligare vatten ju högre turbiditet. pH och turbiditet mättes främst då dessa kan påverka reningsförmågan hos både BSF och klorering. Blir vattnet dessutom mycket grumlig kan det både vara otrevligt och ohälsosamt att dricka. Konduktivitet är ett mått på ledningsförmågan i vattnet och mäts främst då det fungerar som en indikator för många kemiska föroreningar. De mikrobiella indikatortesterna visar om vattnet är förorenat med patogener, som ger en indikation om fekal kontamination har förekommit. Extra tester ska även göras vid extrema väder eller oförutsedda händelser. Om de parametrar som mäts är utanför de gränser som satts upp eller om det varierar mycket skall åtgärd vidtas. Detta beskrivs i övervakningsprogrammets sista del.

Slutsatsen var att det framtagna vattenkvalitetsövervakningsprogrammet kan göra att vattenkällan blir mer säker och hållbar i ett långsiktigt perspektiv, men att framgången är beroende av att rätt hjälp finns till handa speciellt i implementeringsfasen. Då programmet måste skötas av lokalbefolkningen är det viktigt att alla i byarna är involverade och känner att säkerheten i vattnet är viktig. För att de ska bli ett lyckat system måste även utbildning ges, så att byborna har de förutsättningar som krävs för att sköta och driva ett vattensystem. Övervakningsprogrammet är bara en del i det system som krävs för att driva och sköta systemet.

Fortsatta studier behövs för att göra resultaten från QMRA:n mer representativa, exempelvis genom att samla mer områdesdata. Vidare skulle de vara intressant att implementera kvalitetsövervakningsprogrammet för att utvärdera och optimera det.

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1 INTRODUCTION

Good water quality in high income countries is not seen as luxury, but as a natural right, while over 800 children in low- and middle-income countries die daily due to preventable diseases caused by not having the access to good quality water, lacking sanitation and hygiene (UNICEF, n.d.). It is estimated that 3.1 % of all deaths that occur worldwide are due to insufficient access to clean water, hygiene and sanitation (Palaniappan et al., 2010), and 663 million people do not have access to improved water sources (UNICEF, n.d.).

Waterborne diseases are defined as diseases where water is the common medium for transmission of disease causing agents (Palaniappan et al., 2010). One example of such agents are pathogens (Palaniappan et al., 2010). Globally a major health concern according to the World health organization WHO (2011) is gastrointestinal infections caused by fecally contaminated water. The pathogens causing waterborne diseases are various bacteria, parasites and viruses. Globally, rotavirus, pathogenic *E.coli*, Campylobacter jejuni and protozoan parasites are the most common cause to severe diarrheal diseases (Palaniappan et al., 2010). In Ecuador, the Ecuadorian statistical institute (INEN) (2015) listed acute appendicitis, gallstone, pneumonia, and diarrheal as the most common causes for hospitalization in Ecuador during 2015. In the population under 5 years old almost 17% of hospitalizations during 2014 were due to diarrheal diseases (INEN, 2014).

Many international efforts have been made to address water and sanitation problems. In the Millennium Development Goals (MDG) established by the UN, goal 7.C was to, in 2015, halve the proportion of the population in the world that lack access to clean water and basic sanitation compared to 1990 (UN, n.d.). In 2015 this goal was met with respect to access to improved drinking water sources, were 2.6 billion people gained access from 1990 to 2015 (UN, 2015). Since 2015 the effort to address the global water situation was continued and is expressed in the sustainable development goals, also elaborated by the UN. Goal number 6 is to “Ensure availability and sustainable management of water and sanitation for all” (UN, 2016). With all the global initiatives to improve water and sanitation in the world a lot has improved. Positive progress, like reaching the MDG of improved water sources, is reported around the world. In 2015, 91% of the global population had access to an improved water source, as opposed to in 2000 when it was 84% (UN, 2016). In the Americas (Central and South America) 110 million people gained access to improved drinking water sources between 2010 and 2015 (WHO, 2016a).

The efforts to improve the water situation have resulted in an increased access to potable water. However, the means necessary to make the new water sources sustainable in a long-term perspective has been lacking. In rural water supplies in the region of South and Central America, only seven out of sixteen countries have a moderate to high level of implementation to ensure the sustainability of their water services in a long/term perspective (WHO, 2016a). Problems with contamination of the water sources remain a challenge, for example it was estimated that in 2012, 1.8 billion people had access to an improved water source contaminated with fecal matter (UN, 2016). The problems facing the long-term quality of water sources are therefore given emphasis in the sustainable development goal 6 (WHO, 2016a). Countries are now encouraged to go beyond improving access and also implementing management plans, monitoring and quality improvement (WHO, 2016a). In the Americas only 10% of the water systems in rural areas from community or informal providers (not governmental), are reported to have operational monitoring of the water (WHO, 2016a). In Ecuador, organizations that implement water treatment systems in rural areas normally do not include monitoring or any formal follow-up (pers. com. Scherdinger, 2016).

To provide safe access to water in a long-term perspective an active management of the system is required. The minimum requirements for assuring water safety, recommended in the guidelines for drinking water quality established by WHO (2011), include setting health based water quality targets for the system, having an adequate system and management plan, which includes water quality monitoring, and to have a system of independent surveillance. Furthermore, including risk assessment and risk management adds confidence to the safety of the water (WHO, 2011). The risk management should include identifying risks in all parts of a water supply, from the catchment area for the water source to the final handling in the household before consumption. For community managed treatment systems, which are common in rural areas in low income countries, it is important for the success and sustainability of the water system that the whole community is involved in the planning, implementation and management (WHO, 2011).

One method for assessing microbial risks is to conduct a so-called Quantitative Microbial Risk Assessment (QMRA). This risk assessment approach is a broad-spectrum tool but when it is used for assessing health risks regarding portable water consumption, risks are estimated by simulating the health outcome based on contamination level, barriers and exposure rates. The amount of pathogens entering (by contamination) and leaving (by barriers, for example disinfection) a water on its way to the consumer is part of the computation in a QMRA. Then a final risk of infection or illness for the consumer is estimated based on the amount of water consumed, the concentration and pathogenesis of the infectious microorganism (WHO, 2016b).

1.1 GOAL AND SCOPE

The aim of this thesis was to design a monitoring program for small-scale water treatment plants in rural settings to make the water supply sustainable in terms of providing safe water in a long-term perspective. In order to reach this goal a case study was conducted in Ecuador, where the programme was designed for three small-scale drinking water systems providing water for domestic use for 15-70 families. The thesis investigates the following questions:

- Which are the health risks associated with the provided water system?
- How can the water quality be monitored in a rural setting, i.e without access to laboratory?
- How can monitoring programmes make the water supply sustainable with no need for external expertise in a long-term perspective?

In order to evaluate these questions, the thesis work includes:

1) Conducting a quantitative microbial risk assessment (QMRA) for the drinking water from the three water treatment plants.
2) Conducting a literature review on monitoring programmes.
3) Design a monitoring programme based on the risk identified in the QMRA and the literature review of monitoring programmes.

2 BACKGROUND

2.1 MICROBIAL WATER CONTAMINATION

Microorganisms are microscopic one- or multi-celled organisms, which include all forms of bacteria, protozoa and viruses, some one-celled algae and some kinds of fungi (Abrahamsson et al., 2009). Most forms of microorganisms are harmless to humans. Some can however cause infection and even death, and these are called pathogens (Alberts et al., 2002). Health problems related to drinking water are often due to pathogenic bacteria, viruses or protozoans contaminating the water (WHO, 2011). More specifically drinking water contaminated with pathogens from animal or human excreta, *i.e.* fecal sources, is the most common source of waterborne disease. The transmission pathway for most bacteria, virus and protozoa to humans is through ingestion of contaminated water (WHO, 2011).

Bacteria are one-cell organisms that inhabit all types of environments on the planet (Abrahamsson et al., 2009). Bacteria are in general sensitive to disinfection by chlorine for drinking water purposes (WHO, 2011). Viruses are very small units and it is debated whether they shall be defined as organisms since they need a host organism in order to reproduce WHO, 2011). They can survive for long periods in water and have typically a low infection dose. Viruses are supposed to be more persistent to disinfection (like chlorination or UV) compared to protozoa and bacteria. Protozoa are typically >2 µm. They can survive for long periods in water and typically have a low infection dose (WHO, 2011). Because of the size which is larger than both bacteria and viruses, water treatment techniques based on physical removal are effective when reducing protozoa contamination of water.

2.2 GROUND WATER CONTAMINATION

The world’s ground water serves as an important supply of fresh water, often providing good water quality due to natural infiltration processes. It further has resilience against changes in climate making it a valuable potable water resource (Morris et al., 2003). Using groundwater for the purpose of drinking therefore often proves relatively cheap since little treatment is required. Morris et al. (2003) state in their report assessing global groundwater, that it is a resource under threat. They conclude that miss-use due to high demands from population, irrigation etc., improper land-use and spills of chemicals on ground surface are three of the main threats to the sustainability of groundwater. Since contamination of groundwater in most cases origins from deposits or spill on the surface, the contamination can take several years before it reaches the groundwater, e.g. for persistent chemicals. The main sources of chemical contamination are industries, agriculture and waste disposal facilities. Microbiological contamination is mainly derived from human and animal fecal disposal through wastewater irrigation, livestock breeding, on-site disposal etc. (Morris et al., 2003). Tracking the source of a groundwater contamination can in some cases be hard since the contamination can travel with either surface runoff or waste moisture before percolating (Morris et al., 2003). For rural settings, Morris et al. (2003) further mentions the growing concern for nitrogen contamination of groundwater, which may originate from intensified agriculture with nitrogen fertilizers and intensive life stock rearing.

The natural processes that can attenuate, remove and/or reduce contaminations of groundwater depend on the contamination type, soil type and which zone in the ground that is contaminated. In general the unsaturated zone and especially the top layers of soil are the most effective for attenuating both microbiological and chemical contaminants (Morris et al., 2003). In the saturated zones dilution and natural die-off (for pathogens) become the predominating reduction processes as biological activity decreases and flow velocities increase. When assessing water safety for an aquifer it is therefore important to take into account the soil properties, soil structures and thickness of the soil layers.

In order to assess if a water source, for example a borehole, is within safe limits from identified hazards on ground it can be useful to calculate the travel time from identified contamination source to the intake of the well. The flow of groundwater in an aquifer can be calculated by using Darcy's formula together with mass balance calculations which takes into account pumping rates, screen depths, effective porosities and permeability anisotropy ratios (Morris et al., 2003). In general a 50 days travel time is suggested in order to have a low risk scenario, and this can be used as a guideline when evaluating risk from a contamination source.

2.3 WATER TREATMENT TECHNIQUES

Methods of treating water with sand filters are used worldwide in a range of settings, from large-scale water treatment plants like the one supplying London with potable water, to small-scale household treatment systems. Biosand filters (BSFs) are widely recommended and used in low-income countries since they are cheap to construct, can be run by non-professionals and have proven effective in removing pathogens (Sobsey et al., 2008). In a review of water cleaning technologies for use in low-income countries BSF were proven to be the most effective technology according to criteria based on the microbial efficiency, health effects and sustainability (Sobsey et al., 2008).

The BSF technology was developed from traditional slow sand filters (SSF). The method of the treatment is that water percolates through a bed of sand. On top of the sand a layer of solids, microorganisms and algae from the water being treated is formed as the water percolates trough the sand (USEPA, n.d.). This layer, the bio-film, is biologically active and most of the reduction of contaminants takes place in this layer. The BSF combines biological and physical reduction mechanisms in order to clean the water. In the sand layer, suspended solids and pathogens are physically trapped between grains of sand (Dangol and Spuhler, n.d.). Pathogens will also attach to other pathogens, suspended solids and the grains of sand, increasing the possibility of becoming trapped and delaying the travel time through the sand layer. This will then increase the reduction due to natural death of pathogens. In the bioactive bio-film microorganisms degrade pathogens. The effectiveness of this layer develops as it forms and depends on the amount of microorganisms, nutrients and dissolved oxygen available in the raw water (Dangol and Spuhler, n.d.).

Biosand filters are constructed with one layer of fine sand, on top of which the bio-film is formed, and below a layer of gravel. The operation is simple and there is no need for maintenance on a daily basis. Water enters on top of the filter tank and percolates through the layers. As time passes the flow rate decreases as pores become clogged, and the bio-film develops increasing the reduction potential (Stauber et al., 2006). When the flow rate becomes insufficient for the water production need, the tank has to be cleaned. The sand is never replaced, but cleaned by a so-called swirl-and-dump method. It is a simple method, which involves adding water to the filters and stirring the sand and then removing the water. The procedure is repeated until the removed water is clear. It has been pointed out in several studies that the effectiveness of the reduction of pathogens depends on filter maturity, flow rate, size of system (filter bed contact time) and the operation and design of the system (Stauber et al., 2006; Sobsey et al., 2008). Water quality parameters such as temperature and turbidity of the well water will also affect the reduction rates of pathogens. The USEPA (n.d.) recommends that the turbidity should be <10 NTU (Nephelometric Turbidity Units) for the filters to work efficiently, if it is higher the pathogen reduction rates will be slower.

Chlorine is a chemical oxidant commonly used in water treatment for its capacity to disinfect, i.e. reduce the amount of microorganisms in the water (Deborde and von Gunten, 2008). Chlorine has a relative low cost which has made it the most commonly used chemical oxidant globally. It can be added at the beginning of the treatment process in order to pre-disinfect the water, or at the end of the process, which then leaves a residual in the water for continuous disinfection in the distribution system. Due to its oxidation potential and reactiveness it reacts with numerous organic and inorganic contaminants in water (Deborde and von Gunten, 2008).

The sensitivity to chlorine varies among different pathogens. The rate at which chlorine can kill or reduce pathogens depends also on the chlorine concentration in the solution and the contact time between pathogen and chlorine (Petterson and Stenström, 2015). A Ct value is a measure of the potential disinfection capacity of the treatment to reduce a certain pathogen. The Ct value for chlorination is calculated by taking the chlorine concentration (C) in mg/L times the time of contact between free chlorine and the pathogen being treated (t) in minutes. As the chlorine is mixed in the water it will combine with other components, such as microorganism and chemical dissolved in the water. The amount of free chlorine therefore decreases and after a certain time the amount left is called chlorine residual. The residual is the chlorine that still can disinfect pathogens at that specific time. This needs to be accounted for when calculating Ct values in a disinfection process (LeChevallier et al., 2004).

The effectiveness of the oxidation and disinfection from chlorine further depends on several water quality parameters such as pH, temperature and turbidity as mentioned above. The chloride is pH-dependent and will at different pH be present in different forms, which pose different oxidation and disinfection properties due to their differences in reactivity with micro pollutants and microorganisms (Deborde and von Gunten, 2008). As pH increases, the Ct needed for a certain reduction of pathogens increases, and studies have shown that chlorine is more biocidal at low pH (Pickard et al., 2006). In the pH range of 7-8.5, chlorine in the form of HOCl (stronger disinfectant) quickly transforms to OCl^- (less strong disinfectant) and the effectiveness of the chlorine is reduced. Inactivation studies have shown that HOCl was 70 to 80 times more efficient in reducing bacteria compared to OCl^- (Pickard et al., 2006). Pickard et al. (2006) recommend a pH below 8 when using chlorination in water treatment.

The efficiency of the chlorination increases with increasing temperature. The turbidity of the raw water also affects the chlorination efficiency. One study showed that the chlorination efficiency on coliform bacteria reduction was negatively correlated with an increase in turbidity (LeChevallier et al., 1981). Other studies have shown similar results, and point out the protective effect that particles can have as they consume part of the oxidant since it is unspecific and oxidizes all organic material (Pickard et al., 2006).

Chlorine is recommended for disinfection of surface waters and groundwater that have fecal contamination and are intended for drinking water (WHO, 2011). The disinfection capacity for especially bacteria is very high. Studies have shown that *E.coli* O157 amongst other *E.coli* strains is highly sensitive to chlorine (Pickard et al., 2006). The chlorine dosage depends on the aim of the treatment. It is a common practice in drinking water treatment to leave some chlorine residual in order to protect the water quality through the distribution process. If too much is left the water could get an unpleasant taste and therefore the residual should always be monitored (Pickard et al., 2006). The monitoring also gives information to the operator about the quality of the raw water since more residual means less reactions and hence less initial contamination.

2.4 CONSTRUCTING SMALL-SCALE WATER TREATMENT SYSTEMS IN PROJECT FORM

In order for a water treatment system to continue to work after it has been installed some kind of management is needed. This management can range from very advanced involving many professionals, continuous automatized quality monitoring, risk management etc., to small scale with one person in charge of the whole system and the water quality. In order to reach success in a project aiming to give access to potable water in rural areas in low-income countries, there are some key elements that should be considered according to Samuel Schlesinger (pers. com. 2016). Schlesinger is a water engineer with over six years’ experience in construction and management of small-scale water treatment systems in Ecuador. He says the first thing to do is always visiting the community to investigate if there are people that are motivated and willing to engage in the project. It is absolutely vital for the success of the project that the community members are motivated and see a value in the project. Schlesinger concludes, “Don’t start projects if there are no motivated people, it will not work”. Another important factor for a successful project is that the design is feasible for the community. For example, a project unfitted to the economic situation in a community will not succeed.

In order for a drinking water project to reach its goals of serving good quality water in a long-term perspective it should have a water board, i.e. a group of representatives from the community responsible for the water system (pers. com. Schlesinger, 2016). The task of the water board is to manage the system when the construction phase is ended. This management should include making a budget, keeping the system running and clean, seeking help if something is broken and act as local ambassadors for the treatment system. In order for the water board to be functional there are some important aspects that should be implemented (pers. com. Schlesinger, 2016). The group has to work with transparency, involving the community as much as they can. This includes working towards getting a community were as many as possible understand the work that the water board does and why it is important. One example where transparency is vital is in the budget of the water system. The beneficiaries will have more faith in the system if they know how the fee for the water is spent. In order to involve the community one suggestion is that the water board changes in relatively short periods, for example every one or two years. Furthermore, it is important that not too much work or responsibility is put on one single person, making the management more vulnerable and less inclusive. A project leader who has constructed a water treatment system can leave bylaws to the water group in order to support their work. The bylaws can be in form of documentation regarding the system and the management, “this is what we do and why we do it" (pers. com. Schlesinger, 2016). A key factor for this type of documentation is that it is simple and straightforward.

Another important aspect of the success is to include education in the implementation of the project. Management and leadership education is important for the water board system to work. Education on sanitation and health (WASH education) is another form of education suitable for drinking water projects globally that is important to include (UNICEF, n.d.). In practical implementations, these parts are often neglected or insufficient (pers. com. Schlesinger 2016). Schlesinger comments that a lot of water projects don't involve WASH education for the water board and/or the community.

When the project phase is ended there is usually no formal follow up of water projects. Maybe the project organization make a call to the communities to see if everything is working, but follow up is not a part of the project (pers. com. Schlesinger 2016). Schlesinger further comments that it is hard for organizations working with water projects to obtain funding for follow-up work. The organizations have to get on with the next project constructing more systems in order to keep the funding coming in. This means that at the end of the day, improving health is the reason for constructing the systems, but there is no one to keep track of the actual success of the project. Does it work two years after implementation? Not many organizations can answer that.

2.5 THE PLANNED TREATMENT PLANTS

The water treatment systems studied in this thesis are being constructed in the villages San Salvador, Mono Manso and San Jose, in the Parroquia San Gregorio, Cantón Muisne, Provincia de Esmeraldas, which is in the northern coastal area of Ecuador. The number of inhabitants of the villages range between about 100 and 250. The treatment plants in the three villages are designed as piped systems where well water is to be pumped with an electrical pump from a well to an elevation where the water will be treated and stored in water tanks ranging from 2500 liters to 5000 liters (Table 1). The tanks are placed with the first tank as the treatment tank and after treatment the water flows to other tanks used as reservoirs. The water is to be distributed in a network of underground pipes leading to communal taps. The system is driven by gravitation (from the elevated placement of the treatment and reservoir tanks). The distribution system is designed with communal taps. The taps are placed based on the distribution of households in the community in order for the taps to be as close as possible to as many families as possible (Figure 1).

Figure 1 A sketch used to plan the placement of the communal taps in San Salvador. Each colour represents a group of houses that will use one tap and the orange dots represent a communal tap.

Table 1 Design aspects of the wells, treatment systems and distribution in the three communities.

Community	**Well depth, m**	**Water table, m**[a]	**Number of tanks**	**Treatment**
San Salvador	20	2	10 (1 of 5000 L and 9 of 2500 L)	Chlorination
Mono Mano	24	5	7 (2500 L)	Biosand filter
San Jose	18	4	5 (2500 L)	Biosand filter

[a] Distance from ground level to water surface in well measured in December 2016.

The drilled groundwater wells, which will serve as water source for the distribution systems, are about 20 m deep (Table 1). The interior of the wells is made up of plastic perforated tubes. The water treatment systems are designed to have the capacity to provide 80 L of water per person and day.

The treatment in San Salvador will be chlorination only. The technology used in the treatment system is called Waterstep M-100 and is developed to be an affordable way to chlorinate water (WaterStep, 2014). The method uses electrolysis in order to produce chlorine gas from salt and water. It is operated by connecting the chlorine gas generator to the water tank containing the raw water. Clean water and salt is added to the generator and the chlorine gas is circulated with the raw water. When the water reaches a chlorine level of 5 ppm, the generator is disconnected from the tank and the treated water is left for about one hour when the chlorine levels are measured again. If the level is between 2 ppm and 5 ppm the water is judged safe to drink. If the level is below 2 ppm the chlorination process will be repeated.

The treatment in Mono Manso and San Jose is to be done by biosand filters (BSF). The tanks of 2500 L that will be used for the BSF have a diameter of 1.47 m, which gives 1.7 m^2 of surface area and a depth of the sand filters of 60 cm (pers. com. Scherdinger, 2017). During operation the filters are kept saturated.

The tanks that are used for the water treatment are placed on a concrete base in order to create a levelled and easily maintained area. The area is fenced and has a roof constructed above (Figure 2). This infrastructure was created in order to secure the treatment system and prevent contamination.

Figure 2 The treatment system tanks in San Salvador (December 2016).

2.5.1 Environment and climate

All villages are located in the coastal area of northern Ecuador, a country where the climate is influenced by the Amazon rainforest, the Pacific Ocean and the mountain range La Cordillera (Cadeño et al., 2010). The annual mean temperature is 26.8 °C (INAMHI, 2015). The coastal area has two seasons, one humid, reaching from around December to April, and the rest of the year is the so-called dry season. The annual rainfall for the coastal region varies from around 622 mm per year to up to over 2000 mm per year and the area were the studied villages are located has an annual average of about 1000 mm per year (Cadeño et al., 2010).

The topography is hilly ranging from 0 to about 80 m a s l. The villages are centered around a river flowing in low parts of the landscape, from which hills raise behind the small villages. In the area the ground generally has low permeability which makes the transport of water through the soil very slow (Schlesinger, 2016b). The soil has a deep layer of clay and the aquifer is confined, making it resistant against contaminations from the overlaying ground. Thus, the chemical composition of groundwater in the area shows little variation over time (pers. com. Schlesinger, 2016).

According to an initial investigation of the communities done by Schlesinger (2016b), 100% of the population was without access to piped water system or any waste disposal management (Table 2). There were some families that used dry toilets, but the majority of the population disposed their excrement in nature without management. Furthermore, the investigation found no system for garbage collection or management in the communities. On field visits it was noted that garbage was thrown into the river, on ground at random locations or burned.

Table 2 The population in the communities and their access to portable water and sanitation before the water systems were implemented (Schlesinger, 2016b).

Village	Families/ Households	Population	Potable water distribution		Excrete disposal system	
			Piped (%)	Other (%)	Sewage system (%)	Latrines or other[a] (%)
San Salvador	70	259	0	100	0	30
Mono Manso	25	127	0	100	0	no data
San Jose	15	102	0	100	0	50

[a] The latrines in the communities are dry toilets consisting of a hole in the ground, i.e. unlined pit latrines.

[b] There were no data available for latrines in Mono Manso.

3 THEORY

3.1 QUANTITATIVE MICROBIAL RISK ASSESSMENT

In order to guarantee safe drinking water, risk assessment is used in all water-related WHO guidelines (WHO, 2016b). Risk assessment associated with drinking water often includes identifying and evaluating health risks for consumers. A risk assessment can then support in risk management by indicating whether the identified health risks are sufficiently supervised and controlled or need to be further managed.

The method for conducting risk assessment is by systematically evaluating hazards, hazardous events and examining how the function of possible control measures affects the risk (Figure 3).

Figure 3 The three main steps in risk assessment. Identify hazards, the hazardous events and then evaluate how big the risk is based on the likelihood that the hazardous event occurs and the severity of the damage it can cause.

There are several methods for conducting a risk assessment, for example sanitary inspection, risk matrix or QMRA. WHO (2016b) states that, in order to ensure safe drinking water from a microbial perspective, efforts have traditionally been focusing on examination of fecal indicator bacteria. They argue that this approach is inadequate since studies have shown that other disease-causing pathogens, such as viruses and parasites, can thrive in waters that are safe according to guidelines using fecal indicator bacteria (WHO, 2016b; Smeets et al., 2010). Furthermore, when results from fecal indicator bacteria tests are obtained and a potential health risk can be highlighted, the exposure to consumers has already occurred. Therefore, WHO (2016b) recommends that a preventive, risked-based, water safety management method should be used, and one such method is Quantitative Microbial Risk Assessment, QMRA.

Hazards are in a QMRA defined as pathogens which cause a negative effect on the health of the people exposed. Hazardous events are events that cause exposure to the pathogen or barriers that fail to remove them. The risk is then defined as the likelihood that a hazardous event happens combined with the severity of the hazard. A QMRA can be conducted to evaluate risk from ingestion, respiration or contact with pathogens. There are many possible hazards and hazardous events in most QMRA, therefore, it is a key element in the risk assessment to find the most critical hazards or hazardous events in order make the assessment effective.

A QMRA is usually conducted following four generic steps which are called:
1) Problem formulation, 2) Exposure assessment, 3) Health effects assessment and 4) Risk characterization (WHO, 2016). In the literature, the four steps are named differently even if they describe the same concept. CAMRA, the Centre for Advancing Microbial Risk Assessment, call the first step Hazard identification, the second Dose-Response, the third Exposure Assessment and the fourth is the same, Risk characterization (Rose et al., 2013).

CAMRA defines QMRA as: “A method for assessing risks from microbial agents in a framework that defines the statistical probability of an infection from the environmental pollution of water, soil, food, surfaces and hands.” (Rose et al. 2013, page 6). This is to say that instead of monitoring actual contaminations as they occur, QMRA method can predict the microbial risks and therefore also take preventive actions and avoid disease outbreaks. This is done by combining scientific knowledge about pathogens, their presence and nature, how they travel and interact, exposure routes to humans, and what a certain exposure can cause in terms of health effects. The intervention of barriers and hygiene measures is also considered, i.e. how natural or engineered microbial barriers can have a positive effect (WHO, 2016b).

The WHO (2016b) developed a guide called *Quantitative Microbial Risk Assessment: Application for Water Safety Management, QMRA* in order to provide guidance on how to ensure safe drinking water using this risk-based management approach. In order to conduct a QMRA for drinking water thorough knowledge about the water source, knowledge about the treatment process and the consumer is needed. Often it is conducted with a mix of local data and data from literature. The use of QMRA for water quality assurance is gaining in popularity globally. It has been identified as an important tool to complement monitoring and is recommended by WHO (2011). A range of QMRA-tools is available in literature, but many are based on and developed for European or North American conditions. In a study by Howard et al. (2006) a simplified QMRA method was proven to give valuable results in a setting with limited data, which often is the case for low-income countries.

When assessing the quality of water intended for drinking including all possible pathogens in a QMRA would be time consuming because of the extensive dependency of data, therefore the WHO (2016b) recommends the use of reference pathogens. A reference pathogen is used as substitute for all pathogens of concern by having the same or similar resistance to treatments barriers, the same survival in the water and having the same severity of impact (Howard et al., 2006). That means that if the reference pathogen is controlled, the organisms that it represents are also controlled.

By describing data for a water quality parameter by its probability distribution the risk assessor can take into account the variability of the parameter (Abrahamsson et al., 2009). Describing parameters, for example the amount of a reference pathogen in a water sample, with a probability distribution is useful in QMRA since the variability can be accounted for in the calculations, and the final risk outcome can be presented as a probability distribution. Many water quality parameters are non-normally distributed (Bartram et al., 1996) for example for pathogens in water a lognormal distribution is usually assumed (Abrahamsson et al. 2009; Robertson et al., n.d.).

In Table 3 a suggestion of the four steps of a QMRA conducted in order to assess health risk of drinking water is presented. Typical answers that the risk assessor has to answer and data sources usually needed are also provided.

Table 3 Description of the four steps in QMRA method as described by WHO (2016b) used for assessing microbial risk in drinking water. Examples of typical question to answer and the data needed.

Description	Typical questions to be answered	Data sources needed
Problem formulation		
Here the general scope for the QMRA is **defined**.	- What is the risk management decision that needs to be answered? - Which hazards, exposure pathways and/or hazardous events? -What are the health effects? -What reference pathogen to choose?	Epidemiologic studies, clinical data and outbreak investigations[a]
Exposure assessment		
Depending on definitions in problem formulation, the frequency and magnitude of exposure is determined.	- What are the concentrations at the source? - Which barriers or controls are in the system and what is the reduction of pathogens? - Trough which way is the population exposed?	Quantitative data on pathogen concentrations in source water and reduction of pathogens by barriers. Exposure data for population. Size, nature and frequency of exposure for population.
Health effects assessment		
Define the health impact on the population for which the QMRA is done. Dose-response relationships are determined.	-What is the severity of the health effects? (type of health effect, duration, etc.) - What are the probabilities of health effect from ingested dose pathogens?	Dose-response relationships from literature. Risk models. Demographic data
Risk characterization		
The information from previous steps is combined in order to make a quantitative risk estimation.	-What are the estimated health effects?	

[a] Source data suggestions from (Rose et al., 2013).

In order to quantify the risk in a QMRA the probability of occurrence of a risk (for example infection) and the severity if it occurs (for example illness or death) have to be combined in order to assess the overall risk (WHO, 2016b). Furthermore, a time aspect needs to be considered, is it a risk based on one consumption, one year or a lifetime? The results will be deterministic when point estimates are used in model calculations, or probabilistic when probability functions are used. The risk assessor can then choose to present their results as the probability of infection, illness or DALY. A DALY (disability-adjusted life year) is a measurement of effect on public health, and represents loss of years of "healthy" life (WHO, 2016b). The sum of DALYs in a population thus represents the difference between an ideal situation where the population is healthy, free of disease and illness, living to an advanced age, and the current health situation. QMRA results expressed as DALYs allow for comparison with other risks in the society since many different scientific fields use this unit when describing public health risks.

3.1.1 QMRA model MRA

In order to conduct QMRAs, tools have been developed as computational computer based models, in which the user can compute risks by defining for example (for the case of drinking water QMRA): water source quality, reference pathogens and treatment process (Abrahamsson et al., 2009 and RIVM, n.d.). The model used in this study is called MRA. MRA was developed for assessing health risk from drinking water in Nordic conditions by Swedish researchers (Abrahamsson et al. 2009). The model provides reference concentrations of pathogens in water sources based on studies of European and North American countries. The model has predefined reduction potential for different water treatment steps, dose-response relationships for different pathogens and statistical distributions for describing pathogen concentrations in the water source.

The MRA-model is constructed with six steps, were the user defines their processes from water source to consumer. In the first step the user defines the pathogens to be studied in the QMRA. It is possible to choose one pathogen from each pathogen group, i.e. one bacterial, one viral and one protozoan pathogen. In the second step the user characterizes the source water by defining the initial concentration of the chosen pathogen in the water source. The initial concentrations of pathogens can be represented in the model either as a discrete value or as a statistical distribution. The default setting in MRA for pathogen concentrations in water is a lognormal distribution.

The third step in MRA is to define the treatment process. The reduction of pathogens in each treatment step is defined with the unit $\log_{10}$-reductions and the reduction from each treatment step is then added together to a final reduction of pathogens by the whole treatment system. One $\log_{10}$-reduction represents a reduction to 90% of the pathogen studied. It is possible to calculate the reduction as a discrete number or as a statistical distribution. The default in MRA is a triangular distribution. If the MRA-user has site-specific data on removal potential in each treatment step of the water treatment system they are studying, this data can be entered in the model. If no site-specific data is available the model calculates the reduction based on default values from literature. The user can simulate the process fault free or with some failure rate. Data on failure for the specific system can either be specified if it is available, or a default failure rate based on literature can be used.

In the fourth step the exposure is defined by the amount of water consumed per day, and the model default describes the amount of water consumed as a lognormal distribution. Then in the fifth step the model uses a dose-response relationship to estimate the infections caused by the exposure calculated in previous steps. In the sixth step the results are presented. The user can choose to present their results as a $\log_{10}$ reduction of pathogens in every step of the treatment process, the daily or yearly infection from each pathogen, and/or as DALYs (disability adjusted life years).

3.2 MONITORING PROGRAMMES

Operational monitoring is by the WHO (2011) defined as monitoring based on planned activities and/or measurements with the purpose of determining if the control measures in a treatment system are operating correctly. The control measures are based on implementations in the treatment system that are made in order to protect the quality. Such measures can be actions taken to prevent contamination in the catchment area, filters and disinfection infrastructure, and protecting the area around the well. Operational monitoring generally includes the three following steps, setting control limits, monitoring the control limits, and having a plan for appropriate action to be taken if monitoring shows deviation from the limits (WHO, 2011). Operational monitoring is designed to give fast response to contamination or mal-function of a treatment plant. It is therefore important that it is built on monitoring techniques that are fast and easy to manage and. Verification or surveillance monitoring are the activities or tests carried out in addition to the operational monitoring, in order to ensure the drinking water quality. This means that the water quality meets the health based targets, and therefore is safe for consumption (WHO, 2011).

3.2.1 Monitoring microbial contamination

To minimize risks from microbial contamination of a drinking water system it is important to include preventive measures as part of the monitoring plan. Preventive measures can prevent or reduce pathogens from entering the system and thereby also reducing the dependency of the efficiency of the treatment plant (WHO, 2011). According the WHO (2011) preventive measures should be of highest priority when working to achieve health based targets. Another important aspect of microbial quality of drinking water is that the concentrations of pathogens in water tend to have substantial fluctuations over time and space (WHO, 2011). Sampling the water during a pathogen concentration peak can be misleading, likewise missing to detect a concentration peak. When missing a concentration peak the pathogens may cause diseases without being discovered in operational monitoring.

Furthermore, water quality will not remain stable once it has passed through treatment (Robertson et al., n.d.). This is due to risks of new contamination entering in distribution and storage systems, and bacteria persisting in the water after treatment which may re-grow on residual nutrients. Therefore, a monitoring program designed to monitor pathogen-contaminations should involve risk identification and sampling of the water at the source, after treatment, after distribution, and after it has been stored in households.

As mentioned above the main health risk for a water consumer originates from fecal contamination of the water. Total coliform bacteria and *E. coli* are two frequently used microbial indicators for fecal contamination of drinking water (WHO, 2011 and Robertson et al., n.d.) and many international standards for drinking water are expressed in terms of these indicators (Robertson et al., n.d.). Coliform bacteria and *E. coli* are both highly sensitive to chlorine. Hence the detection of these indicators when chlorine is used in treatment suggests either substantial or recent contamination, and a great health risk (Robertson et al., n.d.). However, since these indicator bacteria are more sensitive than other contaminating microorganism groups as for example viruses and enteric protozoa, absence of the bacterial indicators does not prove the absence of the less sensitive microorganisms.

In order to monitor microbial contamination there are two common types of methods that can detect the indicator organisms mentioned above in a water sample. Frequency-of-occurrence-methods use techniques were the results show if the microorganism that the test is designed for is present or absent in the water sample of a certain volume. The other type provides a quantitative measure, and the results are given in for example CFU (Coliform forming units) per100 mL of water sample or MPN (Most probable number) per 100 mL (Robertson et al., n.d.).

3.2.2 Monitoring chemical contaminants

The main health effects caused by chemical contaminants in drinking water are usually detectable first after long periods of exposure (WHO, 2011). Only a few chemicals can cause direct health effects, however in many cases chemicals cause esthetic problems such as taste, odor or coloring to the water. Generally, if the ground water shows little variation in chemical quality a chemical analysis is only needed once a year or less (WHO, 2011). Chemical and physical parameters are often included in monitoring programs in order to quickly detect changes in water quality. Turbidity, pH and conductivity give useful information as part of operational and verification monitoring (WHO, 2011). Chemical variations in the water quality detected from monitoring provide information about the functionality of the treatment plant and distribution system. In the monitoring it is also important to address problematic chemicals in the specific area, for example if pesticides are used in the area, if there has been a factory nearby the water extraction source etc.

Turbidity is a measure of the cloudiness of the water due to particles suspended in the water. It varies from low turbidity in water that visually appears to be perfectly clear, to high turbidity when the water appears to be colored or cloudy. Turbidity is usually caused by soil particles such as mud, sand and silt, chemical precipitates or organic material. Turbidity can have severe effects on treatment steps. For example, a high turbidity from sand or silt can block filters and even quite low turbidity will hinder chlorine from effectively reducing pathogens. Furthermore, pathogens are often attached to particles, making turbidity an indirect measurement of possible pathogen contamination (WHO, 2011).

Conductivity is a measure of the ability of the water to conduct electric current. The conductivity of water depends on various factors, which include the concentration and mobility of ions in the water, and the water temperature (Oram, n.d.). Conductivity measures for water quality monitoring provide an approximation of the amount of total dissolved solids (TDS) in the water. The TDS can be approximated by Equation (1) (Walton, 1989), but it is a very simplified correlation and should be used only as an approximation.

$TDS = K \cdot EC$ (Equation 1)

where

TDS - total dissolved solids ($\text{mg} \cdot L^{-1}$)
K - Conversion factor between 0.4-1.0 ($\text{mg} \cdot \text{cm} \cdot \text{L}^{-1} \cdot \mu S^{-1}$) (Manual WTW, 2002)
EC - Conductivity ($\mu S \cdot \text{cm}^{-1}$) at 25℃

In general, drinking water with TDS level of 600 mg L^{-1} or less is considered good and levels over 1000 mg L^{-1} are considered unfit for drinking (WHO, 2011). Conductivity or TDS recommendation levels in drinking water are not based on health risks for consumers. It is part of many monitoring programs since an increase in conductivity can cause the water to have a mineral taste and it can damage domestic plumbing, faucets, washing machines etc. Another important aspect of measuring conductivity is as an indicator of a broad array of chemical pollutants and it provides a quick way of detecting changes in the water quality (Oram, n.d.).

The pH value is a measure of the activity of hydrogen (H^+) ions in water. In general if water has a pH value less than 6.5 it is considered acidic and can be corrosive (Oram, n.d.b). Acidic water increases the possible leaches of metal ions, causing an elevated risk of toxic metals in the water. Low pH can also cause for example damage to plumbing, aesthetic problems with a sour or metal taste and staining of laundry. pH-values above 8.5 may indicate hard water (Oram, n.d.b). This poses no direct health risk but can have several esthetic problems such as formations of scales or depositions on piping and dishes, decreased efficiency of electrical heaters, an alkali taste or problems getting soap and detergents to clean as desired (Oram, n.d. b). Changes in pH value can indicate pollution since the pH value alternates depends on the chemical composition of the water. The amount of H^+, thus pH, affects the biological availability and solubility of the chemical constituents of the water (Aquaread, n.d.).

3.2.3 Operational limits, frequency and location of sampling

For every parameter in a monitoring program an operational limit is defined (Table 4). If this limit is exceeded a set of actions are to be implemented. These limits are usually defined by the responsible for a treatment system, following international guidelines or national laws. If national levels are not available the internationally accepted WHO guidelines for drinking water quality can be adopted (WHO, 2011).

Table 4 Guideline values for parameters in monitoring program for health-based targets for human consumption. Maximum acceptable levels according to Ecuadorian potable water regulations.

Parameter	**Guideline value**[b]	**Maximum level Ecuadorian law**[f]
E. coli or thermotolerant coliform bacteria[a]	Must not be detected in any 100 mL samples	Must not be detected in any 100 mL samples
pH	Not a health concern [c]	-
Turbidity	5 NTU or less[d]	5 NTU
Conductivity	Not a health concern [e]	-

[a] For water directly intended for drinking, treated water entering the distribution system and treated water in the distribution system.
[b] From WHO 4th guideline for drinking-water quality (2011).
[c] However important measurement for operational monitoring, since it affect processes in treatment.
[d] Preferably 1 NTU but 5 NTU is acceptable for small-scale treatment plants. Furthermore, for the chlorination processes to be effective a maximum of 1 NTU and desirably much lower.
[e] Aesthetic limits see d 3.2.3.2. Conductivity.
[f] NTE INEN (2014).

WHO (2012) recommends a method of combining fixed and random sample locations for water sampling in a monitoring program designed for drinking water. The fixed positions should be located at each step of the distribution chain from source to consumer. This gives valuable information on where the contamination occurs. For example, whether the contamination origins from reduced quality in the water source or if a part of the treatment system is mal-functioning. Decisions can then be taken whether investigation of possible source contamination is necessary or maintenance of the treatment system is needed. The fixed sampling is done according to a monitoring scheme, the sampling is to be done at the same place and time every scheme iteration. This also allows for comparison of the water quality over time.

The random water samples should be collected from the water consumers when the water has been stored under typical household storage conditions (Robertson et al., n.d., Levy, 2007). The time of storage should be noted for every sample. The cleanliness of the household and the storage method (open container, with lid etc.) should be noted in order to investigate possible sources of a contamination. On a global scale, mishandling in the household is the main source of microbial contamination (Robertson et al., n.d.). If contamination is occurring in the household educational programs on safe, healthy handling of water can be an important addition in order to provide safe drinking water.

In a setting were the water distribution is community based, meaning that water consumers collect their water at a community tap, a monitoring program should include collecting water samples at all steps in the treatment system, also including from the distribution system and households. The monitoring should also combine fixed and random sample collection (Table 5).

Table 5 Locations for sampling for monitoring that is recommended in literature (Robertson et al., n.d.; Levy, 2007) adapted for a rural setting with communal distribution.

Quality parameter	Location of test	Fixed or random
Microbial indicator	At well, at communal taps and in households	Fixed at well and communal taps. Random in households.
pH	At communal taps	Fixed
Turbidity	At well and communal taps	Fixed
Conductivity	At communal taps	Fixed

In general, the sampling frequency should be based on the variability in the water quality and the causes of the variability (World Meteorological Organization, 2013). When sufficient data is gathered on variability a sampling frequency can be decided. The frequency should also reflect the severity of risks linked to the sample. If, for example, a water sample location has shown high levels of a certain pathogen, this sample point should be more frequently tested.

In this study, the consumer health is the main objective and the frequency of sampling should therefore aim to guarantee that the drinking water is safe for human consumption. As always, economic aspects need to be taken into account by balancing the gain from testing and the cost in material and time for technician. In this study, the water source was groundwater from a well, which should have a water quality with low variability. In general, when monitoring groundwater quality in environmental research, a frequency of one to four times a year is recommended (World Meteorological Organization, 2013) depending on the purpose of the monitoring. For monitoring drinking water quality the sample frequency should be much higher. Frequency recommendations for monitoring microbial contamination in drinking water is based on the number of inhabitants provided by a water treatment system and the specific contamination tested for (WHO, 2011). WHO (2011) recommends in their drinking water guidelines that the minimum sample frequency for fecal indicator testing when serving a population of less than 5000 individuals should be 12 times per year. In the guidelines (WHO, 2011) it is also stated that the parameters such as turbidity and pH should be tested more frequently. Many studies suggest that automatized continuous monitoring of turbidity and pH is good, however in a rural setting with a low budget this is seldom an option.

In addition to monitoring microbial contamination, pH, conductivity and turbidity at a decided frequency, the monitoring should include sampling in case of unexpected activities or extreme events that could affect the water quality (WHO, 2011). These include:

- Unusual or unpleasant smell, colour and taste of the water have been reported to the group responsible for the water system in the villages.
- Land-use changes
- An increase in gastrointestinal infections in the community
- Climate change or extreme weathers

This kind of monitoring after unexpected or extreme events is dependent on a population that has the knowledge to identify the scenarios mentioned above as risks. Monitoring programs should also include supervising the infrastructure of the water system to make sure it is functioning and clean (free from contamination) (WHO, 2012). The area around the water source (well in this study) and its catchment area should also be supervised and maintained free from contamination or contamination sources.

4 METHODS AND MATERIALS

4.1 DEMOGRAPHIC DATA

The construction of the treatment systems in the case study started in September 2016 and was not yet finished in January 2017. The communities, San Salvador, Mono Manso and San Jose, were visited a total of three times during the case-study (October, November and December 2016). During the visits information was gathered from conducting semi-structured interviews and observing the communities' culture, the social setting and the environment. Three semi-structured interviews were held with the presidents of each community to investigate the health status in the communities and the population. Open questions were asked about the general health, how many times each month that they experienced diarrhea and how often the adults and children were sick in general. It was also asked how many children and how many pregnant women that were living in the community. One interview was held with the local doctor at the health clinic in San Salvador. This interview was also based on open questions about the health in the communities, and the most common reasons for people to visit the health clinic, according to the doctor's experience. From the health clinic information about the age and sex of the population was also obtained. This data was used to divide the population in the studied communities into subpopulations in order to map groups that are more vulnerable to exposure of contaminated water. The population in the three communities were divided into four subgroups where one is considered general population between the age of 11 and 60 years and three subgroups were considered sensible: Infants and Children < 10 years; Elderly > 60 years; and pregnant women (Hauchman, 2000). Data on chronic illnesses in the villages was not available why such subgroup could not be identified and enumerated.

4.2 QMRA

The QMRA was conducted based on the four steps of QMRA for drinking water (Table 6) (WHO, 2016b). The method from WHO (2016b) provided a framework in which the scope and the general outline of QMRA was defined. All calculations were done in the model named MRA by Abrahamsson et al. (2009). The four generic steps of QMRA for drinking water outlined the assessment and MRA was the tool used to derive numerical values (Table 6).

Table 6 Procedure to conduct the QMRA for drinking water, with the steps of the framework from WHO (2016b) and the corresponding steps taken in the model MRA by Abrahamsson et al., (2009)

Steps in the WHO (2016) QMRA method for drinking water	Corresponding steps in modelling in MRA
Problem formulation	Selecting reference pathogens
Exposure assessment	Defining the concentration of pathogens in the well water. Defining the reduction of pathogens in the water treatment steps.
Health assessment	Defining the amount of water consumed. Defining the dose-response relationship.
Risk characterization	Defining how to present the resulting health risks.

4.2.1 Problem formulation

The problem formulation in the QMRA was based on a literature review of the health situation in Ecuador and the information gathered about the health in the studied communities. A literature review about pathogens causing health problems in general was also conducted in order to choose reference pathogens. The goal for the QMRA was to evaluate the risk that consumers suffer a negative health impact from consumption of the water generated in the treatment systems studied. This question was investigated by estimating the probability that the water consumers would get infected from drinking the water during the scenarios listed below. The scenarios describe when treatment works perfectly, is not working at all or if water treatment capacity is lowered and this in combination with different quality of the raw water.

Scenarios:

a. Treatment works perfectly (assumed normal condition)
    i. Using water quality data from the wells and literature
    ii. Using water quality data as high contamination scenario

b) Treatment is not working at all
    i. Using water quality data from the treatment system wells and literature

c) Treatment is damaged and is working at low treatment capacities
    i. Using water quality data from the treatment system wells and literature
    ii. Using water quality data from high contamination scenario

The mechanism of exposure is constrained to drinking the treated water. An acceptable risk was defined as 1/1000 yearly infections, this is higher risk then the recommended by the WHO which is 1/10 000 yearly infections. The acceptable risk of 1/1000 was chosen based on literature that argues that the WHO definition is too high leading to over treatment (Abrahamsson et al., 2009).

Reference pathogens

In the MRA the first step was to select reference pathogens. One reference pathogen was chosen from each of the pathogen groups bacteria, virus and protozoa. The selection of reference pathogens was based on literature review, using criteria of selection as listed below (Table 7). Search engines used in order to find research articles and other published reports were Google Scholar and Scopus.

Table 7 Criteria for selection of reference pathogens. The same criteria were used for bacteria, protozoa and virus.

Criteria	Key words used in search engines	Comment
Frequency of use of pathogen in research articles in the field of QMRA and potable water.	QMRA, drinking water, low income country, reference pathogen.	From the literature review of scientific articles published on QMRA and drinking water.
Probability of occurrence	Pathogens in drinking water, Health in Ecuador, Common diseases Ecuador, Water treatment Ecuador, Water treatment low-income countries.	The probability of occurrence was investigated by literature review and by studying the current health status of the population in studied villages, see interviews and observations described in *4.1 Demographic data*.
Persistency to treatment method	Biosand filters (BSF), Chlorination, Efficiency of BSF/Chlorination on bacteria/virus/protozoa. Water cleaning treatment for bacteria/virus/protozoa.	Based on the above-mentioned criteria the efficiency of the treatment with respect to some selected pathogens were studied, these included *E.coli*, Giardia and Rotavirus.

The selected reference pathogens was *E.coli O157:H7* to represent bacterial contamination in the model simulations using MRA. *E.coli O157:H7* is one of the most studied bacteria that cause diarrhea globally, and it is the bacteria that causes the majority of hospitalizations (Lim et al., 2010). To represent a virus contamination in simulations Rotavirus was chosen. According to the CDC (2006) the rotavirus is the virus by which most children are hospitalized due to diarrhea globally. To represent protozoa contamination Giardia was chosen for simulations in the model MRA. Giardia parasites are found in water, soil and food contaminated with feces, causing diarrheal illness. Infection through drinking water is the most common mode of transmission (CDC, 2015).

4.2.2 Exposure assessment

The exposure assessment was conducted in three steps; defining the exposure pathways, quantifying each component of the exposure pathway, and characterizing exposure (Figure 4) (WHO, 2016b). At each step in the exposure assessment the amount of each of the studied reference pathogens are estimated.

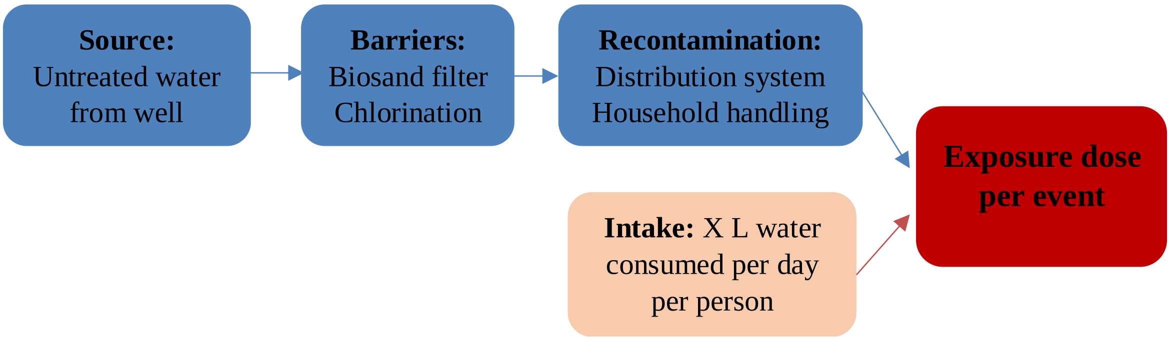


Figure 4 Diagram showing all parts of the water system where pathogens were quantified or analyzed (see blue boxes), and the amount of water consumed per person per day (pink box). Together this gives the exposure dose of pathogens per person per day (red box). Adapted from WHO (2016).

Recontamination was not taken into account in the calculations in the QMRA. However, in the design of the monitoring program possible recontamination in distribution and household systems was accounted for see *4.3 Monitoring program*.

The pathogen concentrations used in the QMRA for scenarios *i)* were based on the water quality data collected from the treatment system wells (three samples) and water quality data, collected in the same region as the communities (ten samples). The only site-specific data available were on *E. coli*, which were used in all the scenarios a, b and c. Note that the site-specific data was sampled as described below and then calculations were made in order to estimate the amount pathogenic *E.coli O157:H7* from the *E.coli* water samples, also described below. To include the possible effects that virus or protozoa contamination could have, an experimental approach was taken in which a virus and a protozoa contamination were simulated. This was done for scenario, *a) i)* Treatment works perfectly(Table 9).

Sampling the wells in the communities for total coliforms and E. coli
In order to determine fecal contamination of the source, samples were taken on site. Water from the wells used for the treatment systems, was hand-pumped and tested for pH, conductivity and turbidity. For all tests three samples were taken at each well. The pH was measured with two types of pH sticks, with the ranges 0-6 and 7-14. The conductivity was measured with the portable conductivity meter WTW Cond 340i. The turbidity was measured with 2100Qis from HACH. The pH, conductivity and turbidity were measured in order to provide general information about the quality of the water and to assure that the samples were representative of the aquifer in accordance with recommendations from Vail (2013). In order to assure that the samples were representative to the aquifer, pumping and sampling was done until pH, turbidity and conductivity were stable, i.e. a minimum of three consecutive measurements show that the pH remains constant within 0.1 SU, specific conductance not varies more than about 5 percent and the turbidity measure are below 10 NTU or stable.

The water samples for microbiological analysis (Fecal coliform bacteria) were taken in pre-sterilized 120 mL glass containers. The sample containers were filled leaving some air space. Two water samples for microbiological analysis were taken from each well. The cap, the container mouth and the inside of the container were not touched in order to not contaminate the samples. Immediately after sample was collected the container was closed and the samples were placed on ice for transport to a laboratory in Quito. The laboratory used a method called PEEMi/LA/19 Standard Methods 9222 D and the results were given as MPN per 100mL. Due to the few samples the resulting concentrations of fecal coliform bacteria could not be described as a probability distribution, instead the mean value of all samples was used in the calculations to estimate the concentration *E.coli* from fecal coliforms and then from coliforms to pathogenic *E.coli O157:H7*.

Preparation of water quality data for E.coli from literature (INAM)
Data from the National Institute of Meteorology and Hydrology in Ecuador, INAM (Pers. com. Megens, 2016) on concentrations of fecal coliform bacteria in surface waters in Esmeraldas, Ecuador was also used in the MRA, hence representing a worst-case scenario. The data was from surface waters at various locations around "Cuenca Esmeraldas" during a period of approximately two years, from around 2014 until 2016 and given as MPN (most probable number) per 100 mL. The data showed great variation in both space and time which motivated investigating which of the locations that was most relevant to the communities in a geographical sense. ArcGis ArcMap program was used in order to plot the sample locations and the locations of the wells used in the three villages. Then data from the 10 closest sampling locations was used in the study. See Appendix 1 for full description of the original data and the methods applied.

Since the samples of the well water and the data from INAM (Pers. com. Megens, 2016) only provided data on fecal coliform bacteria, these concentrations were used to estimate the *E. coli 0157:H7* concentration (Table 8). It was calculated by assuming that 95 % of the fecal coliforms were *E. coli* (Howard et al. 2006) and that 8 % of these were pathogenic (Howard et al. 2006).

Table 8 Concentration of fecal coliform bacteria in the well water (from sampling) and from INAM and estimation of *E. coli 0157 H7* concentration extrapolated from fecal coliform concentrations (Pers. com. Megens, 2016).

Source	**Fecal coliform** (Mean, Max, Min)	***Estimated E. coli O157 H:7***[a] (Mean, Max, Min)	**Number of samples**	**Period of sampling**
Site specific data (CFU/100 ml)	139, 410, <1	10.56, 31.16, 0	3	7/12/2016
Data from INAM (MPN/100 ml)	4745, 13000, 45	360, 988, 3.42	10	09/2014 – 03/2016

[a] Calculated as 95% of fecal coliforms are *E.coli* and 8% of the *E.coli* are Pathogenic, *E.coli O157:H/,* as suggested by Howard et al. (2006).

The concentrations of Giardia and Rotavirus in the well water were approximated with values from literature. Rotavirus was approximated with a lognormal distribution with mean 1 (virus units L^{-1}.) and stdev 3, based on an international review article on Rotavirus in surface waters (Abrahamsson et al., 2009) representing a worst-case scenario. The concentration of Giardia cysts in the well water was approximated to hold a constant value of 0.5 (oocyst L^{-1})(Abrahamsson et al., 2009).

Table 9 Data on concentrations of Rotavirus and Giardia used as water source contamination, i.e. contamination parameters in the wells in the studied communities in the MRA simulations.

Literature Source	**Rotavirus** (virus units L^{-1}.)	**Giardia** (oocysts L^{-1})
Abrahamsson et al. (2009)	mean 1, stdev 3 (Lognormal Distribution)	0.5

Barriers

The treatment barriers (reduction steps) accounted for were BSF in Mono Manso and San Jose, and in San Salvador the treatment was chlorination. Since no site-specific data was available for the pathogen reduction by the treatments, data from literature was used. The reduction rate of microorganisms by BSF in water treatment system used in the MRA model for *E.coli O157:H7* was based on values from a review by Hijnen and Medema (2007). The review had the aim of producing a default value for reduction of microorganisms in water treatments to facilitate QMRA, and is recommended by WHO (2016b). The values were reported as Microbial Elimination Credit (MEC). The MEC are calculated by combining reduction rates reported in different studies and the reduction rates are weighted depending on technical and microbial aspects of the study (Hijnen and Medema, 2007). The average MEC for slow-sand filters (SSF) was 2.7 $\log_{10}$ (±1.1), the range 1.2-4.8 and median value was 2.4 (Hijnen and Medena, 2007). However, the filters used in this study were BSF and the reduction rates for these filters are typically lower (Stauber et al., 2006). The treatment efficiency is further dependent on several design- and operation aspects, including flow rate and size of the system, with efficiency of the filter improving with increasing size (Stauber et al., 2006). Most BSF are designed for household use and therefore are generally smaller than SSFs. The BSFs studied in this project are larger, providing a community of 75 families versus single household, therefore the value for SSF from Hijnen and Medena (2007) was used. To simulate reduction of virus (Rota virus) and protozoa (Giardia), SSF reduction rates from Abrahamsson et al. (2009) were used.

The reduction of pathogens by chlorination was simulated in the MRA model using the initial chlorine concentration and the total time from dosage to reaching consumer tap. Both the initial chlorine concentration of 5 mg L^{-1} and total time from the dosage to the consumer of one hour was based on the manual for the WaterStep M-100 chlorine generator (WaterStep, 2014).

Drinking water consumption in the communities

The amount of drinking water consumed was estimated based on information on water use in the communities and literature values. From a review study of drinking water consumption in low-income countries, including Europa and Austria, the mean value of drinking water consumed was 0.10 to 1.55 liters per person per day (Mons et al., 2007). Mones et al. (2007) further showed that their data on water consumption often was skewed to the left. Therefore, the mean, which will be higher than the median, can be a good “worst-case” estimate for use in QMRA. Furthermore Mons et al. (2007) pointed out that results from different studies on consumption varied a lot depending on the type of study. In the communities in this study one family used about 24 liters of water per day, based on the fact that they gathered about two 12 liters buckets from the river each day (based on observations and informal interviews in the communities). The fetched water was used for drinking, cooking and washing. The families were in average 4.4 people, resulting in 5.4 liters of water per person and day. But since a lot of this water is used for cooking and washing it was hard to approximate the amount that was drunken. The populations in the studied communities were further found to consume less water than expected considering the warm climate (Schelsinger, 2016). In a research article on QMRA for drinking water from Uganda, which has a similar climate as Ecuador 1L per person and day was used (Howard et al., 2006). With respect to the reasoning above this study used a reference value of 1 L per person per day.

Scenarios Water quality and exposure
Based on above presented literature and water sampling, the following values were used as model parameters in MRA to simulate each scenario respectively (Table 9,10 and 11).

Scenarios:

i) Water quality data from wells, and literature
In scenario i) the water quality in the wells was represented with local data and data from INAM to simulate a bacterial contamination. The local data is as a constant value, which was the mean value of the measurements in the wells, 105.6 (CFU L^{-1}). The data from INAM was simulated as a lognormal distribution with mean value 3606 (CFU L^{-1}) and standard deviation 3302 (CFU L^{-1}). To simulate a virus contamination, model parameters for Rotavirus were given mean a value of 3 and a standard deviation of 1 (virus units L^{-1}). The model parameter used for simulations of protozoa was Giardia with mean value 0.5 (oocysts L^{-1}).

ii) Water quality data from high contamination scenario
Scenario ii) was simulated by increasing the concentration of *E.coli O157:H7* in the water source used in scenario i) by 25%, 50% and 75%. This was done in order to investigate how the probability of infection was affected by an increase in *E.coli* concentration in the water source, and to find which concentration in the water source that complied with the acceptable risk level of 1/1000 infected.

iii) Increased drinking water consumption
The consumption of drinking water was doubled, from 1 to 2L. This was done in order to investigate how the infection probability per year was affected by the exposure. This was only done for scenario a).

The scenarios were combined and the probability of infection was simulated with the different inputs (Table 9, 10 and 11).

Tabell 9 Model parameters for simulation of scenario a) Treatment working perfectly. BSF reduction efficiency represented in the simulations as a triangle distribution. Chlorination represented with model parameters to simulate the pathogen reduction.

	E.coli O157:H7	**Giardia**	**Rotavirus**
BSF ($\log_{10}$ reduction)	Range 1.2-4.8 Mode 2.4	Range 0.6-4.0 Mode 2.2	Range 0.3-6.6 Mode 3.8
Chlorination	$Cl_{2\ initial}$ = 5 ppm, $T_{dosage\text{-}consumer}$ = 60 min (for all ref. pathogens)		

Table 10 Model parameters in simulations representing scenario a) and b) for bacterial contamination, *E.coli O157:H7* (CFU L^{-1}).

E.coli O157:H7	**i)**	**ii)**			**iii)**
Concentration increase	-	25%	50%	75%	Exposure 2L
INAM[a]	µ: 3606[b] σ: 3302[b]	µ: 4508 σ: 4127	µ: 5409 σ: 4953	µ: 6311 σ: 5778	µ: 3606 σ: 3302
Local[c]	µ: 105.6[b]	µ:132	µ:158.4	µ:184.8	µ:105.6

[a] Simulated in MRA as a lognormal distribution with table values for mean value and standard deviation.

[b] The water quality data for *E.coli O157:H7* used in scenario a) is the same as in scenario b), but in

[c] Model parameter used as constant value.

Table 11 Model parameters representing the barriers in the treatment system, i.e. chlorination and BSF, in simulations for scenario c, when the treatment capacity is reduced for the chlorination and increased for the BSF.

Treatment parameters[a]	**25% reduced treatment capacity for chlorination and increase for BSF**	**50% reduced treatment capacity for chlorination and increase for BSF**	**75% reduced treatment capacity for chlorination and increase for BSF**
Chlorination[b] Cl_2 (mg L^{-1})	3.75	2.5	1.25
BSF Range, Mode (Log reductions)	1.5-6, 3	1.8-7.2, 3.6	2.1-8.4, 4.2

[a] Reduction capacity for Chlorination is presented as mg L^{-1} and BSF as log reductions since it was how the parameters are entered in the MRA model.

[b] The time from dosage to consumer is kept constant at 1 hour, in order to investigate the log reduction dependency on the initial chlorine dosage.

Table 12 The model simulations in MRA, presented with number and the scenario that each simulation represents.

Model simulation #	Scenario for Treatment	Scenario Water quality and exposure **(# : Source : Percent reduction in source quality)**
1-9	a)	**i)** 1: INAM, 2:Local **ii)** 3: 25% INAM 4: 25% Local, 5: 50% INAM, 6:50% Local, 7:75% INAM, 8: 75%Local **iii)** 9:INAM exposure 2 L
10-11	b)	**i)** 10:INAM, 11:Local
12-13	c) 25% reduction (Cl2) increase (BSF)	**i)** 12: INAM 13: Local
14-15	c) 50% reduction (Cl2) increase (BSF)	**i)** 14: INAM 15: Local
16-17	c) 75% reduction (Cl2) increase (BSF)	**i)** 16: INAM 17: Local
18-19	a)	**i)** 18: Rotavirus 19: Giardia
20-21	a) Only BSF	20: Rotavirus 21: Giardia
22-23	a) Only Cl2	22: Rotavirus 23: Giardia

4.2.3 Health assessment and risk characterization

The two last steps in the QMRA are health assessment and risk characterization. The dose-response functions that the model MRA used to simulate infections caused by *E.coli O157:H7* (equation 3), Giardia (equation 4), and Rotavirus (equation 5a, 5b) (Abrahamsson et al., 2009). The dose-response functions cover the entire population, thus the sensitive sub-groups specified in *4.1 Demographic data* are not taken into account in the model simulations.

$$P_{\text{infE.coliO157H7}} = 1 - (1 + (d \cdot 9.16))^{-0.157} \qquad \text{(Equation 3)}$$

$$P_{\text{infGiardia}} = 1 - e^{(-0.0199 \cdot d)} \qquad \text{(Equation 4)}$$

Probability of rotavirus infection was estimated with an exact beta Poisson distribution if dose < 0.1,

$$P_{\text{infRotavirus}} = 1 - e^{(-(\frac{0.167}{0.167+0.191}))} \cdot d \qquad \text{(Equation 5a)}$$

else it was estimated with a beta Poisson approximation,

$$P_{\text{infRotavirus}} = 1 - (1 + \frac{d}{0.191})^{-0.167} \qquad \text{(Equation 5b)}$$

where d is dose.

The dose was calculated by the model using the initial concentration of pathogens in the well water, the reduction that the treatment provides and the volume of drinking water consumed. The results from the model simulations were presented as annual probability of infection per person for all scenarios. Some simulation results were also expressed as daily infections rate in order to compare the results with the infection rates the community experienced before the systems were implemented.

4.3 THE MONITORING PROGRAMME

The final monitoring programme design was based on operational monitoring methodology according to WHO (2011), but simplified due to the rural setting and limited access to materials (both economically and technically). The development of a simplified monitoring program was based on theory for monitoring programs, the results from the QMRA and observations from the field visits.

In a QMRA the step of exposure assessment often includes identifying and quantifying transmission routes for pathogens to exposure, in this case drinking water. In this study this was not done. However, possible hazards or hazardous events that could occur after the water has been treated, and before the water is consumed, were studied. This was studied by field observations and literature review on contamination in distribution system and recontamination after distribution, as described below.

- Study of the reference pathogens from literature.
  Observing the catchment area and identifying potential hazards and hazardous events. All activities and the environment in the catchment area of the well (the extraction point of the water source) can affect the water quality. An approximate catchment area was visually identified for each well by observing the geography in the area, and in the defined catchment area possible hazardous events were identified. Hazardous events included land-use, waste management, and free ranging animals. Topography and soil types of the catchment area were identified in order to estimate possible risk in case of extreme weathers, like heavy rainfall.

- Literature review on recontamination from tap to consumer (household storage).

Due to the poor economic situation in the villages one focus when developing the monitoring program was to make the monitoring possible without or with little materials and/or costs. This focus involved planning so that all the cost that the monitoring generates could be integrated in the already existing budget for the water treatment systems, see *chapter 5.1.1* for explication on how the budget is developed for the systems.

5 RESULTS

5.1 THE COMMUNITIES

The villages studied were all located along the River Sucio. The river was the vein of the communities and its water was used for bathing, washing clothes, as a mean of transport and in the households for cooking and doing dishes. It was the only drinking water source and the only available treatment method was boiling the water before drinking. No data was gathered in order to determine to which extent boiling was used as a water treatment, but it was commented by the community presidents that boiling was a practiced method. The river also served as a gathering point of importance for the communities’ social life (personal observation from field visits). Apart from the main occupation in the villages, which was farming, the community school teacher and small-scale business owners resided in the communities. In San Salvador a local health center was located, with two nurses and a doctor. The villages all have electricity since a couple of years. The electricity was used mainly for private and public lightning. The telephone and internet reception in the villages was poor, but could be found on certain spots on the hills surrounding the villages.

The main access route to the villages was by the river in canoes during the humid season. Families that owned canoes functioned as a type of informal public transport system, transporting people and goods. There was also one dirt road leading to San Salvador, and from there walking, horse or canoes could be used in order to reach the other villages. However, the road was in a very bad condition and is in general inaccessible during a large period of the year. The means of transport available made transport of heavy materials complicated and dependent on weather conditions and season. For example, some of the material necessary for the construction of the water treatment systems could not be transported due to low water levels in the river, and the construction was delayed. The remote location and inaccessibility during periods of the year could create problems for example any repair work on the water systems in the villages.

5.1.1 Water treatment systems project-organization and water boards

The water treatment systems project was initiated by Altropico, an environmental organization from Ecuador, who specializes in leadership training, environmental education and management. In the project to construct water treatment system they worked together with a North American organization called Green Empowerment, to which the water engineer, Samuel Schlesinger, who designed the system belongs. The project was managed by the two organizations and by representatives from the communities. Samuel Schlesinger was responsible for the design of the treatment systems. The communities, under the supervision of Schlesinger, then carried out the constructions of the systems. With the aim of making the water treatment systems self-sustainable, Altropico and Schlesinger worked together to implement water boards with representatives from each community, in parallel to the construction work. The water boards were responsible for the management of the system when the project initiators (Altropico and Green Empowerment) moved on to other projects. The water board consisted of a president, a secretary, a technician and representatives. During the initial state of the project the task of the groups was to organize their communities, inform them about the water system being installed and to make a budget. The technicians would have the responsibilities of the maintenance of the systems, including cleaning the tanks, keeping the area around the well and tanks clean, and also making sure the communal taps are in good condition.

The importance of community involvement became very visible during the case study and the field visits. As explained above, the project implementing the treatment systems was organized so that the community had to help build the treatment system. The organizations managing the project of constructing the water treatment systems worked in the communities for a week or two each month during the project period of about 7 months. During their time in the communities they managed the construction, and made agreements with the community regarding construction plan, time schedules etc. However, the plans were never fulfilled by the locals, and every time the organization returned, expecting for example that the wells would be completed, only parts of the expected work was done. During the periods when the organization was present a lot of work was done and everyone got involved.

The budget for the water treatment systems was constructed by summing all direct and potential costs that the water system would bring per month. The direct costs included payment for technician and maintenance materials, and the potential costs were approximations of repair work and materials. The budget also included saving for further investments such as investments in additional taps or filters etc. When all potential and direct costs had been acknowledged, they were summed up and divided by the number of families using the water from the treatment systems. It was optional for all families if they wished to be part of the water treatment system and thus have access to the potable water. To cover the costs that the treatment systems generate, every family had to pay a monthly fee corresponding to the amount calculated in the budget. An important aspect of the budget was that the water board worked with transparency, communicating the budget to the communities in order for them to understand and accept the monthly fee for the water. In the community of San Salvador (with 70 families) the budget resulted in a price for the water of two US-dollar per month and family when the majority of the families joined.

5.2 QMRA

5.2.1 Risk identification and problem formulation

In this chapter the results of the literature review on health issues related to drinking water in rural areas is presented. Also, the health status and potential microbial hazards identified concerning the water quality in treatment systems studied and the goal and scope of the QMRA conducted are presented.

The Ecuadorian statistical institute INEN (2015) listed acute appendicitis, gallstone, pneumonia, and diarrhea as the most common causes for hospitalization in Ecuador during 2015. In the population under 5 years old almost 17% of hospitalizations during 2014 were due to diarrhea diseases (INEN, 2014).

The health status in the investigated communities was very poor before the water treatment systems were installed. According to the interview with the doctor at the local health clinic, one of the most common reasons for seeking medical advice in the communities is due to health issues related to water (Table 12). The populations in the communities come in contact with contaminated water from ingestion as well as from swimming in the water, cleaning etc. Furthermore, the doctor stated that it is common the patient is treated with medication, but returns re-infected two weeks later.

Table 12 Most common health effects reported by the health clinic for the three villages.

	Organisms	**Health effect**
Parasites	Trichuris trichuria (whip worm)	Diarrhea, lack of energy etc. and skin infections.
Bacteria	Pathogenic *E. coli*	Diarrhea
Viruses	-	Diarrhea, throwing up, stomach-aches, flue etc.

According to the interviews with the presidents of the communities and informal interviews with the local population they suffer from diarrheal every 15 days, with loose stools that last 3-4 days. Furthermore, the most effected are the children who often are sick, with diarrhea, flue and lack of energy.

Based on data from the health clinic in San Salvador and the interviews with the presidents of the communities the demographics for the three villages were determined. As age data was only available for the three villages together the proportion of age groups was assumed to be the same for each village as for the total population (Table 13).

Table 13 Sensible subgroups in the population of the three villages for which the QMRA was conducted. Figures within brackets represent percentage of total population in the village.

	Number of individuals[a]		
	San Salvador *Population 259 individuals*	**Mono Manso** *Population 127 individuals*	**San Jose** *Population 102 individuals*
Infants and children	49 (19)	24 (19)	19 (19)
Elderly	8 (3)	4 (3)	3 (3)
Pregnant woman	1 (0.4)	2 (1.6)	0 (0)

[a] Data was gathered from the president of the villages, respectively.

Goal and scope of the QMRA

The goal of the QMRA was to investigate the health risk for a consumer drinking water from the implemented water systems, and to identify the parts of the water system that are critical for its production of water safe for human consumption. The results were then used to develop a monitoring plan targeting the main risks identified.

Reference pathogens

Research has suggested that *E. coli 0157 H:7*, Rotavirus and Giardia are the most common bacterial, viral and protozoan pathogens respectively, causing diarrhea in the north west coastal Ecuador, the area were the studied communities were (Eisenberg et al., 2006; Bhavnani et al., 2012). Bhavnani et al. (2012) studied pathogenic enteric coinfections, investigating the effect of coinfections on occurrence of diarrheal disease in rural areas. Eisenberg et al. (2006) studied how environmental changes could have an effect on the epidemiology of diarrheal disease also in rural areas. All the pathogens mentioned can be transmitted through drinking water and from the study of the health status in the villages diarrhea was the most common health issue. Based on the above reasoning it was concluded that *E.coli O157:H7*, Rotavirus and *Giardia* were suitable reference pathogens for the QMRA conducted. Furthermore, the identified risks in the catchment area (see below) and the study of the sanitation in the communities (expansive use of on-site disposal, no waste water management etc.) further suggested that fecal pathogens are a risk factor, and therefore further argues that *E.coli*, Rotavirus and *Giardia* were suitable reference pathogens.

Hazards and hazardous events identified in the catchment areas in the communities
In San Salvador there was lush vegetation around the village. The well was situated on one side of the populated area, thus having forest on one side and some vegetation, households and a school on the other side. The well was located at 126 meters distance from the river. The village had little sanitation infrastructure, such as toilets, and no waste management system. Animals such as dogs, cats and horses walked freely and horses were seen pasting close to well during many visits. In Mono Manso the well was located centrally in the village about 50 meters to the closest household and the household had no toilet. On the other side of the well there was a cacao plantation, though no fertilizers or agrochemicals were used. Mono Manso also had little sanitation infrastructure and no waste management system. Dogs and cats were running freely. The well in San Jose is situated on an area in the center of the village where the only vegetation was grass. Dogs, cats, horses and donkeys walked freely in the area. There were grazing cows on a hillside about 500 meters away from the well. The school building was located at about 300 meters distance from the well.

The landscape in the area where the three villages are located is hilly. All catchments areas include steeply inclined surfaces, and a ground that has low permeability. This creates a risk for surface run-off during heavy perception. Run-off can transport loads of particles and pathogens to the flatter areas were the wells are located, creating a potential risk of pathogens reaching the ground water in the wells. The main hazard identified in the catchment areas was fecal contamination from animals and humans. Furthermore, there would be a short distance for the contamination to travel through the unsaturated zone, due to the relatively high groundwater tables in the area. For example, in San Salvador the water table is one meter below ground level. A short distance implies a risk of contamination of the ground water, as natural reduction processes such as reactions or natural die-off of microorganisms are time dependent and get shorter time to act. This risk is however reduced due to the low permeability in the grounds, making other fecal contamination transmission routes, such as direct leakage into the well and contamination of the water after treatment, more probable.

Water quality of the well water in the communities
In-situ measurements were conducted for pH, turbidity and conductivity in the water samples collected in the community wells at time of collection. The sampling results indicated that the water in the wells held a good physical/chemical quality (Table 14). The pH and turbidity were within the guideline limits for drinking water (WHO, 2011). The TDS for the water in San Jose was higher than the recommended guideline value, and this water also had a mineral taste and bad odor.

Table 14 Data on water in the community wells.

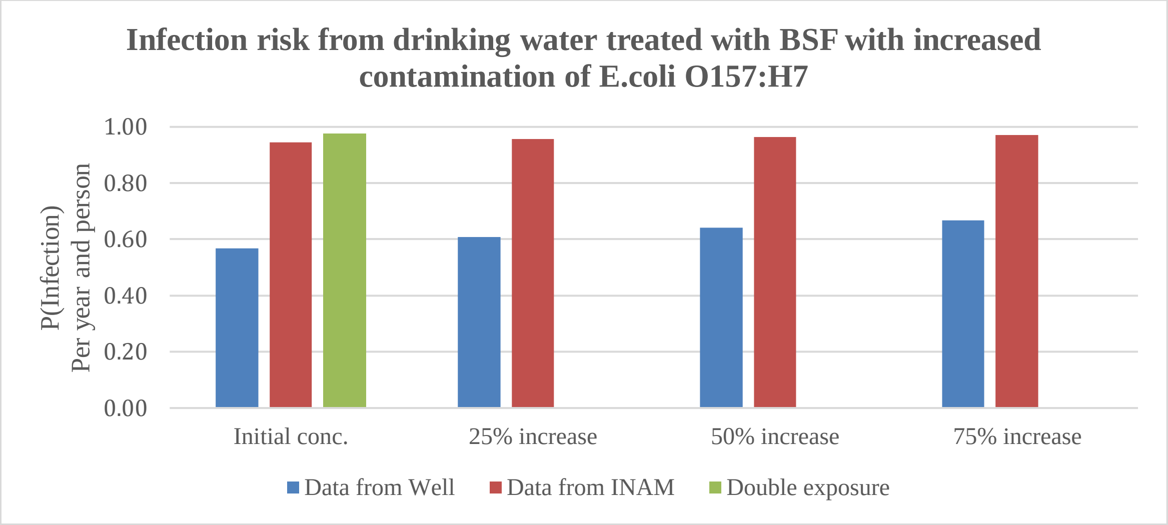
	San Salvador	**Mono Manso**	**San Jose**
Sample date in field (from field to laboratory)	12/07, 07:20 (24 h 40 m)	12/07, 08:15 (23 h 45 m)	12/07, 09:40 (22 h 20 m)
Sampling depth (m)	9	5	8
pH[a]	6-7	6-7	6-7
Turbidity[b] (FNU)	9.95	11.9	9.26
Conductivity (µS/cm)	397	401	880
Water temprature	25 ℃	25 ℃	25 ℃
TDS[c] (mg L^{-1})	278	281	6160
Observations	Turbidity cell a little dirty. Water tasted well, no smell.	Water tasted well, no smell.	Water had a mineral taste and an odor.

[a] The pH was tested with two types of pH sticks, were one set has range 0-6 and the other 7-14.
[b] The turbidity was calculated as the mean for three water samples.
[c] Estimated by equation 1, where k was 0.7.

5.2.2 Infection risks according to the MRA model simulations

Chlorination and E.coli O157:H7 simulations
The QMRA of treatment system in San Salvador, which had chlorination as the main treatment, showed that the chlorination dosage used under assumed normal operation (5mg L^{-1} Cl_2) resulted in zero probability of *E.coli O157:H7* infection per year. The $\log_{10}$ reduction by the initial chlorination exceeded the model's numerical limits and the result was presented as infinite (INF). The simulations showed zero probability of infections independent of the concentration of *E.coli O157:H7* in the well water using a contamination level up to10^8 CFU L^{-1}, which was the highest contamination levels fund in the data from surface waters in the area of Ecuador. The Cl_2 dosage had to be lowered to a concentration of 0.035 mg L^{-1} Cl_2 (from the assumed normal operation concentration of 5 mg L^{-1}) in order to result in an infection rate that exceeded the acceptable risk of 1/1000 infections per year. A concentration of 0.035 mgL^{-1} Cl_2 gave a mean probability of 4.6/1000 infections per year (mean $4.6 \cdot 10^{-3}$ and median $3.4 \cdot 10^{-3}$).

BSFs and E.coli O157:H7 simulations
The simulation of infection risk when drinking water from the system in Mono Manso and San Jose was initially done with biosand filters (BSF) as only treatment step. The risk of infections in Mono Manso and San Jose were 570/1000 infections per year when simulated with the *E.coli O157:H7* concentration calculated from INAM data (concentrations in surface water) and the assumed normal treatment capacity of the BSF (2.85 $\log_{10}$ reduction). This exceeded the acceptable risk of 1/1000 infections per year. Increasing the concentrations of *E.coli O157:H7* in the source water with 75% increased the probability of infections with 3% (Figure 10). Doubling the drinking water consumption from 1 L to 2 L per person and day increased the probability of infection by 0.45% (blue and grey bar Figure 10).



Figur 10 Probability of infection per year and person from drinking water simulated with the initial *E.coli* O157:H7 concentrations in the well and with 25%, 50% and 75% increase in contamination. The green bar shows the probability of infection with the initial *E.coli* O157:H7 concentration and an exposure of 2 L drinking water per day.

Maintaining the contamination concentration from the INAM data set and the water sampling from the wells in the villages, and increasing the reduction capacity for the BSF with 25%, 50% and 75%, reduced the probability of infection per year (Figure 11). When the capacity of the BSFs was increased by 75%, they achieved 4.9 $\log_{10}$ reduction. The probability of infection was then decreased by 57% when simulated with the concentrations from INAM, and by 84% when simulated with the concentrations from the well. In the "best-case-scenario", i.e. when the lowest contamination concentration and highest treatment reduction was used, the mean probability of infection was 0.093, which is 9.3/1000 infections per year.

If chlorination was added after the BSFs filters, using a chlorine dosage of 0.02 mg L^{-1}, the probability of infection per year was decreased to 0.42/1000 which would then be within the acceptable risk of 1/1000 used in this study.

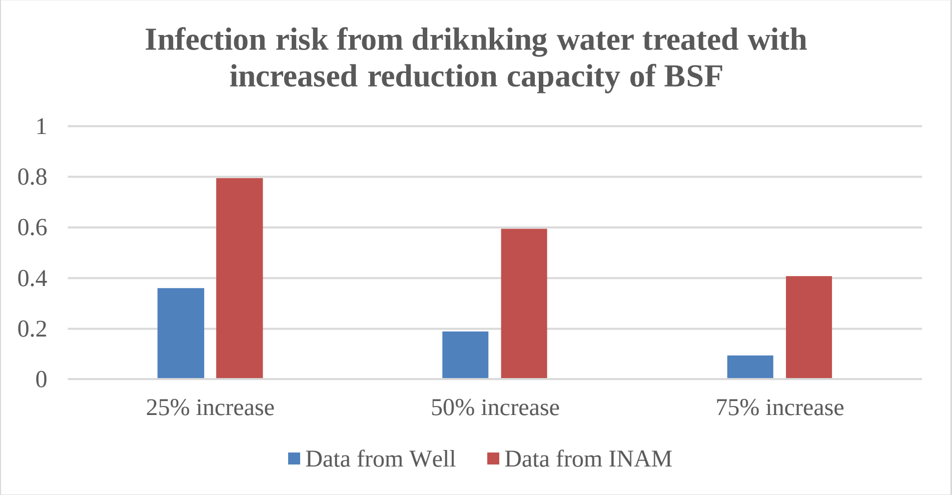


Figure 11 The probability of infection per year and person from drinking water, simulated with the initial *E.coli O157:H7* concentrations in the well when the reduction potential in the BSF was increased by 25%, 50% and 75%.

E.coli O157:H7 and no treatment

Simulating the treatment system as in scenario b), that no treatment is working, yielded a probability of 1000/1000 infections per year. This result was regardless if *E.coli O157:H7* concentrations were based on the INAM data or the local well data. The mean probability of infection per day with data from INAM (surface water data) was 0.59 (min 0.33 and max 0.75). The daily infection probability, when simulated with data from the local well, was 0.33.

Rotavirus and Giardia simulations

When simulating a treatment system with both BSF and chlorination, the Rotavirus contamination in the well water resulted in an annual probability of infection of 0.52 and with *Giardia* the probability was 0.025 infections (per year and person) (Figure 12). Annual infection probability was over 70% higher when Rotavirus was treated with chlorination instead of BSF. The probability of *Giardia* infection was 36 times bigger when treated with chlorination instead of BSF. The $\log_{10}$ reduction from the BSF was 2.26 and 3.53 for Rotavirus and *Giardia* respectively. The log reduction from chlorination was 0.15 and 0.012 for Rotavirus and *Giardia* respectively.

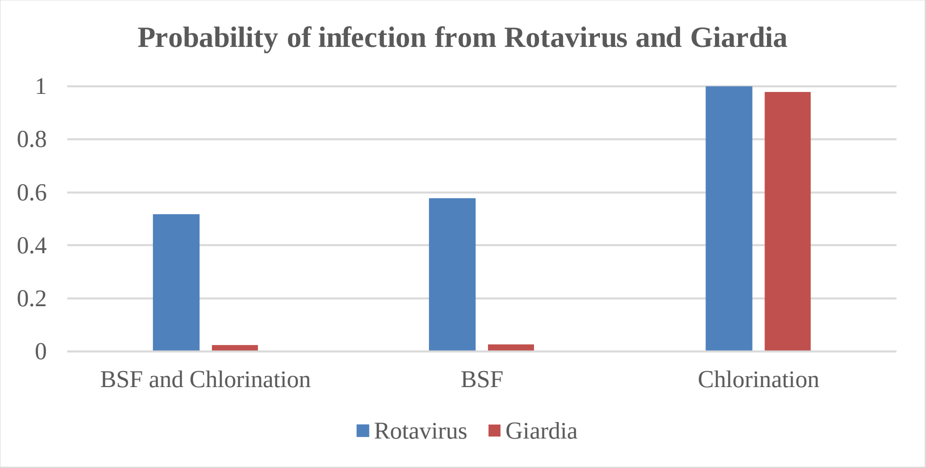


Figure 12 The probability of infection from drinking water, simulated with Rotavirus and Giardia contamination and BSF, chlorination, and BSF and chlorination.

5.3 MONITORING PROGRAM FOR THE COMMUNITIES

The monitoring program is divided into three parts: Precautionary monitoring, continuous monitoring and action to be taken when irregularities in the water quality are identified. The program takes into account the risk scenarios for the two different treatment systems, and one monitoring program was designed for all three communities.

Precautionary monitoring

Precautious monitoring is important from a feacal pathogen perspective since it reduces the risk of feacal pathogen contamination of the well water in Mono Manso and San Jose, while the treatment with BSF was insufficient in reducing the *E.coli O157:H7* and Rotavirus to such extent that acceptable rate of infection was met (Figure 10 and 12). The main hazard identified in all communities was feces from humans and animals. In order to reduce risks of fecal contamination of the water animals should be kept out of the area surrounding the well. Animal feces are to be removed from the catchment area and safety measures, such as fences or roofs protecting the wells and the treatment system, are to be supervised and maintained. In order to avoid contaminations from entering the water the monitoring program recommend:

- The catchment area, the well, the treatment system and the water distribution system are to be kept clean. Daily supervision should be part of the monitoring in order to promote a safe environment and reduce risks of contamination.
- Make sure all families that collect water practice safe handling of the water, which includes using clean vessels and always keeping the water covered (i.e. use a lid or equivalent). Clean vessels refer to vessels washed with soap and water, free from contamination.
- The storage time should be kept short, and the recommendation is to only collect the water you are going to use the same day.

Continuous monitoring
The continuous monitoring is divided into two main parts, regular monitoring of water quality parameters, and monitoring of extreme or sudden events that can deteriorate the drinking water quality. A schedule for the water quality monitoring is proposed (Table 15). The water samples should be taken only at the communal taps in order to make the monitoring simple, and so increasing compliance with the program. Furthermore, it is recommended that all monitoring results should be catalogued (in booklet or equal) to permit the assessment of trends in the water quality. Assessing trends in the water quality allows the community to get to know their water, and link quality alternations to events. The monitoring plan is accompanied by instructions for the instruments used. All instrument taken into account in this monitoring program are easy to use, and are relatively affordable with the exception of the turbidity meter. The pH is measured mainly due to its effect on the efficiency of the chlorination treatment. The critical limit for the water system is pH<8 (Table 15), ensuring the chlorination to work efficiently. The turbidity for drinking water has a specified limit of 5 NTU in the water act for potable water from Ecuador (INAM, 2011). If turbidity increases above this limit the effect of the treatment will decrease. The conductivity is measured mainly in order to detect changes in water quality and an esthetical limit for drinking water is defined as less than 1000 total dissolved solids (TDS) (mg L^{-1}). The TDS can be estimated from the conductivity measure (equation 1), were K is estimated to be 0.7 and EC is the conductivity measured in μS cm^{-1}.

Table 15 The critical limits for the monitoring program designed.

Water quality parameter	Frequency	System critical limits
pH	Weekly	<8
Turbidity (NTU)	Weekly	5
Conductivity (mg L^{-1})	Weekly	TDS <1000
Microbial Indictor (CFU in any sample)	Monthly	0

The monitoring of extreme or sudden events shall be based on observations of the surroundings and reacting on possible hazardous situation. The area is prone to heavy rainfalls in the wet seasons, and then the surface runoff can contaminate the drinking water. Including this “observation based monitoring” has no economical cost, since it should be undertaken during normal communal activity when the community members observe their surroundings as part of their everyday life. This type of monitoring can further help to build an understanding of water quality, and if possible risk scenarios can be identified they can in turn be managed in order to prevent or minimize harm from risk situations. The following situations should be associated with possible risk by the communities:

- Unusual or unpleasant smell, colour and taste of the water are to be reported to the group responsible for the water system in the villages
- Land-use changes
- An increase in gastrointestinal infections in the community
- Extreme weather events

If any of the situations stated above occur, the quality monitoring (Table 15) should be conducted in order to determine if the situation has affected the water quality.
All monitoring should, as stated above, be catalogued in order to generate a knowledge database for the water quality in the communities. For all the monitoring the following data should be noted: date and time, temperature, weather conditions (dry, wet, recent heavy rainfall), comment (activities such as construction work, agriculture etc.) and the data for the quality parameter measured (Table 16). The template in Table 16 can be used for the weekly monitoring of pH, turbidity and conductivity. The samples taken for microbial analysis and the total time from analysis to laboratory should be added.

Table 16 An example of the data that should be collected at every sampling in the monitoring program for samples taken weekly on pH, Turbidity and Conductivity.

Sample date and location:	
Sample conditions	**Sample data**
Water temperature:	pH:
Weather conditions:	Conductivity:
Comment:	Turbidity:
Signature technician:	

The continuous monitoring is to be done by the technician in the water board. The precautionary and "in case of extreme or sudden events" monitoring is to be done by everyone in the community. If a risk situation is encountered it should be reported to the water board who are the group outmost responsible for the water treatment system and the quality of the water produced.

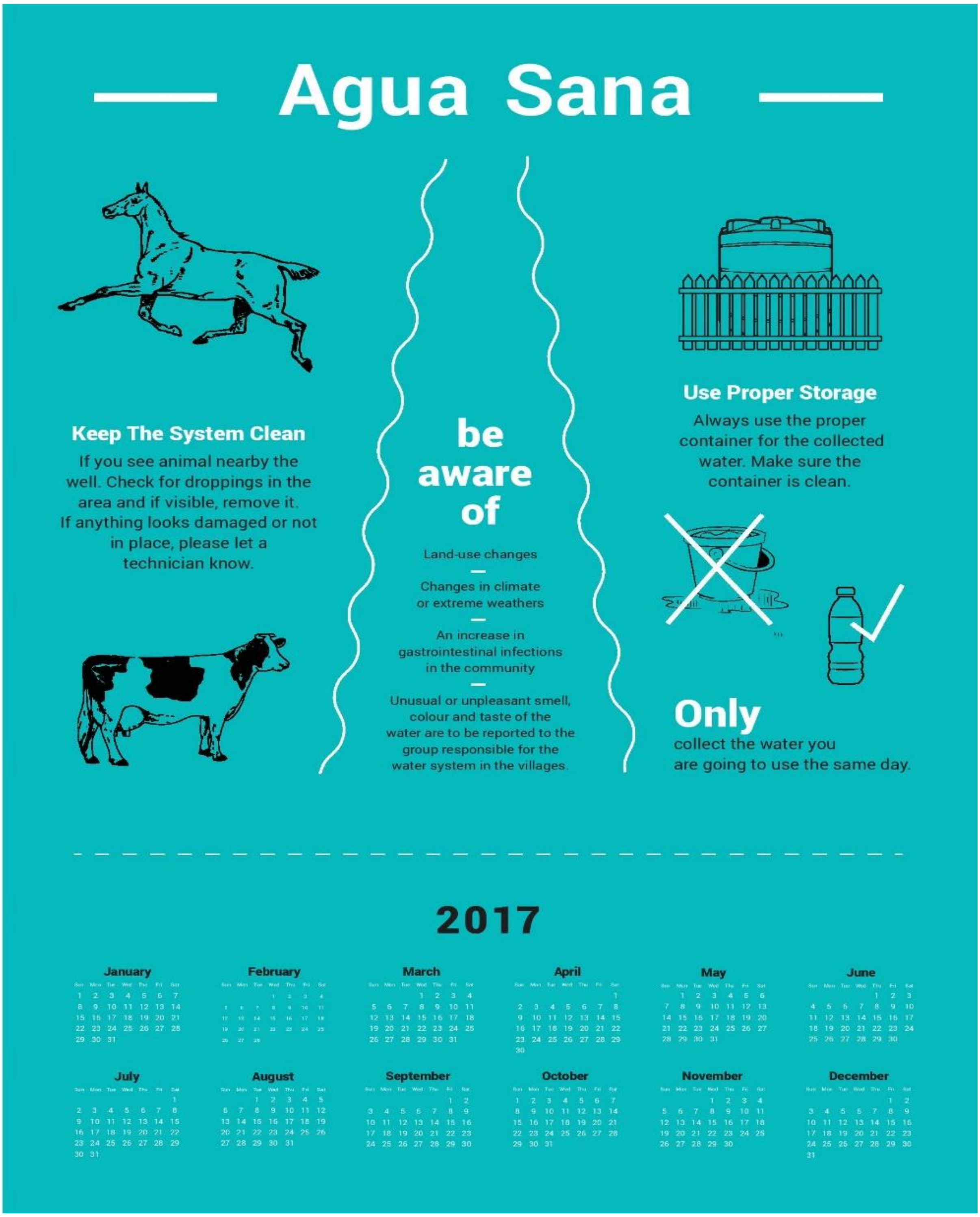
The action to be taken, if monitoring parameters do not fall within given critical limits, depends on the technical knowledge of the responsible technician. Assuming the technician does not have any technical knowledge about the treatment system the following actions should be taken:

- If the bacterial indicator tests detect *E. coli* or coliform bacteria, a boil advisory for the drinking water should go out to the community. The water should be boiled for at least one minute (CDC, 2015). Then the technician needs to make sure nothing in the system is broken, and check for unusual activities in the catchment area. If it is found and he/she cannot fix it a professional should be contacted. If nothing is found a professional should be consulted.

- If any of the other tests shows deviation from the limits (Table 15), the first thing to do is to search the system and the catchment area if something is broken or contaminated. If nothing is found and the problem still is present a professional should be contacted.

5.4 IMPLEMENTATION OF THE MONITORING PROGRAMME

The monitoring program suggested in the present study will be handed over to the organizations in charge of the treatment systems. It will be presented in two parts, one part that includes all information in Chapter 5.3. That part of the monitoring plan is for the water board and the technician. The other part is a summary of the monitoring of extreme or sudden events and this part will be presented as a calendar for everyone in the community (Figure 13). It is presented as a calendar for marketing reasons. Calendars are popular and they are viewed as something useful (Pers. com. Schlesinger, 2016). Hence making this part of the monitoring program in form of a calendar was in order to increase the community participation and engagement in the monitoring and their water treatment system.



Agua Sana

Keep The System Clean

If you see animal nearby the well. Check for droppings in the area and if visible, remove it.
If anything looks damaged or not in place, please let a technician know.

be aware of

Land-use changes
–
Changes in climate or extreme weathers
–
An increase in gastrointestinal infections in the community
–
Unusual or unpleasant smell, colour and taste of the water are to be reported to the group responsible for the water system in the villages.

Use Proper Storage

Always use the proper container for the collected water. Make sure the container is clean.

Only collect the water you are going to use the same day.

2017

January

Sun	Mon	Tue	Wed	Thu	Fri	Sat
1	2	3	4	5	6	7
8	9	10	11	12	13	14
15	16	17	18	19	20	21
22	23	24	25	26	27	28
29	30	31				

February

Sun	Mon	Tue	Wed	Thu	Fri	Sat
			1	2	3	4
5	6	7	8	9	10	11
12	13	14	15	16	17	18
19	20	21	22	23	24	25
26	27	28				

March

Sun	Mon	Tue	Wed	Thu	Fri	Sat
			1	2	3	4
5	6	7	8	9	10	11
12	13	14	15	16	17	18
19	20	21	22	23	24	25
26	27	28	29	30	31	

April

Sun	Mon	Tue	Wed	Thu	Fri	Sat
						1
2	3	4	5	6	7	8
9	10	11	12	13	14	15
16	17	18	19	20	21	22
23	24	25	26	27	28	29
30						

May

Sun	Mon	Tue	Wed	Thu	Fri	Sat
	1	2	3	4	5	6
7	8	9	10	11	12	13
14	15	16	17	18	19	20
21	22	23	24	25	26	27
28	29	30	31			

June

Sun	Mon	Tue	Wed	Thu	Fri	Sat
				1	2	3
4	5	6	7	8	9	10
11	12	13	14	15	16	17
18	19	20	21	22	23	24
25	26	27	28	29	30	

July

Sun	Mon	Tue	Wed	Thu	Fri	Sat
						1
2	3	4	5	6	7	8
9	10	11	12	13	14	15
16	17	18	19	20	21	22
23	24	25	26	27	28	29
30	31					

August

Sun	Mon	Tue	Wed	Thu	Fri	Sat
		1	2	3	4	5
6	7	8	9	10	11	12
13	14	15	16	17	18	19
20	21	22	23	24	25	26
27	28	29	30	31		

September

Sun	Mon	Tue	Wed	Thu	Fri	Sat
					1	2
3	4	5	6	7	8	9
10	11	12	13	14	15	16
17	18	19	20	21	22	23
24	25	26	27	28	29	30

October

Sun	Mon	Tue	Wed	Thu	Fri	Sat
1	2	3	4	5	6	7
8	9	10	11	12	13	14
15	16	17	18	19	20	21
22	23	24	25	26	27	28
29	30	31				

November

Sun	Mon	Tue	Wed	Thu	Fri	Sat
			1	2	3	4
5	6	7	8	9	10	11
12	13	14	15	16	17	18
19	20	21	22	23	24	25
26	27	28	29	30		

December

Sun	Mon	Tue	Wed	Thu	Fri	Sat
					1	2
3	4	5	6	7	8	9
10	11	12	13	14	15	16
17	18	19	20	21	22	23
24	25	26	27	28	29	30
31						

Figure 13 Proposal for calendar to be handed over to the community as part of the implementation of the monitoring plan.

6 DISCUSSION

6.1 QMRA

Pathogen data on water contamination

To simulate a bacterial contamination in the villages wells two data sets were used, one from INAM and one from water samples in the wells. The data from INAM was on fecal coliform bacteria from which an *E.coli* O157:H7 concentration was calculated. The sampling of the INAM data was done in surface waters in the same area of Ecuador as the studied treatment systems were located. Using not site-specific data to describe the water quality in the wells adds insecurity to the results. However, the present author argues that the assumption serves as a good estimate of a worst-case scenario.

In order to characterize a microbial contamination in a water source there are many aspects that should be taken into account. *E.coli* bacteria concentrations in surface waters have been shown to be variable, depending on season, weather, sanitation and handling of possible sources such as livestock etc. (Levy et al. 2007). Levy et al. (2007) surveyed the variability of presence of *E.coli* in surface waters in rural villages in the North West Ecuador. Sampling on an hour-to-hour basis, weekly and during wet and dry season, at various points following a river, Levy et al. (2007) derived a geometrical mean value for the presence *E.coli* in the water. The results showed that the geometrical mean varied from 100 to 1000 CFU 100 mL^{-1} over a one year sample period. The geometrical mean for *E.coli* concentration in CFU 100 ml^{-1} was; 375 (n=1,251) for all weekly samples, 293 (n=541) during dry season and 451 (n=710) during wet season. Levy et a. (2007) used a method for counting *E.coli* that had an upper detection limit of 45 000 CFU $100ml^{-1}$ and samples from both the dry and wet season had extreme values above detection limit. These extreme values indicate that concentrations in the area can be very high. The data from INAM had an *E.coli* mean value of 4500 CFU 100 ml^{-1} (calculated as 95 % of total feacal coliforms) and the geometrical mean was 1750 CFU $100ml^{-1}$. The samples were collected during a two-year period, during dry and wet season. Since the objective of conducting the QMRA was to identify risk and possible health threats it was a planned decision to use a worst-case scenario in order to exaggerate risks rather than omitting them. Comparing the surface water data on *E.coli* from Levy et a. (2007) and the INAM data suggests, in accordance with the intention, that the INAM data can serve as a worst-case estimate.

The data from the village wells used in the simulations was based on water samples gathered on one day and with one sample from each well (by the present author). Considering that bacteria tend to cluster creating occasional concentration peaks and vary depending on seasonal and environmental circumstances, these samples cannot be seen as representative but rather as a point estimate. Collection of samples from the wells during a period of time, preferably during wet and dry season and on different times on the day, would have been desired in order to make the results more representative. The measured E. coli concentrations in the well was considerably lower than the INAM data. This is most likely due to the fact that INAM data is from surface waters. No literature values were found from studies sampling ground water in the region (North West Ecuador).

The INAM data was compared to suggested reference values in different types of water from WHO (2011) (Table 17). The simulations for the treatment in San Salvador that used chlorination showed that when the treatment works normally it will effectively reduce all *E.coli O157:H7* for concentrations up to 10^8 CFU L^{-1}. WHO (2011) states that occurrence of *E. Coli* in untreated waste waters range from 10^6-10^{10} CFU L^{-1}. The concentration levels of coliform bacteria from INAM used in this study were in the range typical for raw waters (Table 17). It should also be commented that Table 17 shows values for *E.coli* and for *E.coli* O157:H7. The later was calculated by assuming that pathogenic *E.coli* concentration was 95% of the fecal coliform (INAM data) and then 8% was *E.coli* O157:H7.

Reduction capacities of chlorination and the BSF from MRA simulations were used to compare the presence of pathogens in the water (data from INAM) after assuming normal capacity of each of the barriers (Table 17). Only the chlorination could reduce the *E.coli* O157:H7 to the target from WHO (2011) of no presence in any 100 mL sample. The infective doses of this *E.coli* (Enterohaemorrhagic) are 1-10^2 organisms (WHO, 2011). The BSF could reduce the *E.coli* to a level of $5 \cdot 10^{-2}$ CFU 100ml^{-1}, suggesting that the risk for infection after the BSF treatment is low. Both Rotavirus and Giardia are like *E.coli* O157:H7 classified as having relatively high infection risk, i.e. infection may occur from low doses. Even though all results are well under the infective dose of 1-10^2 organism (Table 17), people in general consume more than 100 mL of water. No other barrier than chlorination reducing *E.coli* reached the WHO (2011) target that *E.coli* most not be detected in any 100 mL sample.

Table 17 Occurrence of *E. coli*, Rotavirus and Giardia in untreated waste water and raw water (WHO 2011). Presence of the pathogens before and after treatment in water treatment system was simulated in MRA with treatments assumed to work at normal capacity.

	Microorganism concentration				
Microorganism	**untreated waste water**[a]	**raw waters**[a]	**before treatment**[b]	**treatment**[c]	
				CL_2	**BSF**
E. coli (CFU 100 ml^{-1})	10^5 -10^9 (*E.coli*)	10 -10^4 (*E.coli*)	360 (*E.coli* O157:H7)	absent	$5 \cdot 10^{-2}$
Rotaviruses (Virus units 100 ml^{-1})	5–500	0.01–10	0.1	$7 \cdot 10^{-3}$	$5 \cdot 10^{-5}$
Giardia intestinalis (Ocysts 100 ml^{-1})	1–10^3	0–100	0.05	$5 \cdot 10^{-3}$	$1 \cdot 10^{-6}$

[a] Values from WHO (2011)

[b] The presence of *E.coli* O157:H7 calculated from INAM data, the presence of Rotavirus and Giardia from literature.

[c] Assumed log reduction for Chlorination from model simulations were 15, 0.15, 0.012, for *E.coli* O157:H7, Rotavirus and Giardia respectively. For BSF the log reduction were 2.89, 2.26, 3.54 for *E.coli* O157:H7, Rotavirus and Giardia respectively. The log reductions were under assumed normal capacity for Chlorination and BSF.

Regarding the concentrations used when simulating Rotavirus and Giardia contamination in the water there was no site-specific data and only data from literature was used. Therefore the simulation results using Rotavirus and Giardia contamination are to be viewed primarily as a comparison on how the treatment techniques, Chlorination and BSF, differ in their efficiency in reducing contamination of different pathogen groups. The concentrations of Giardia and Rotavirus are in the lower range of raw waters according to WHO (2011) (Table 17), this indicates that<< the simulations input, and thus the results, are not a worst-case scenario.

The barriers

The reduction rates used for the different treatment steps are data gathered from literature. In order to improve the accuracy in the calculations of the probable risk, it would have been preferred to calculate the reduction rate by taking samples before and after the treatment. However, since the systems were not yet finished during the case-study, this was not possible. The literature values for reduction capacities were mainly based on QMRAs developed in Europe and North America (Abrahamsson et al., 2009). The treatment efficiency, and thus the reduction, is dependent on environmental factors such as temperature. The fact that the treatment systems are located in Ecuador then adds uncertainty to the results. BSF and chlorination work more efficiently with higher temperatures. The reduction rates used in MRA are mainly based on European and North American literature were water temperatures used usually are between 5-15 °C. The water in the study had a temperature of about 25 °C, which thus suggests that the reduction capacities could be higher in Ecuador then when simulated in MRA.

The dose-response relationships from literature that are used in MRA are also developed for Nordic conditions, and based on European studies. Probably the population in the studied communities has a better defense, i.e. is less sensitive to many pathogens, as suggested above. The accuracy of the QMRA would have been better if the local dose-response relationships could have been used.

6.1.1 Infection probabilities in the communities and treatment optimization

In San Salvador the chlorination effectively reduced the bacteria, but not virus or protozoa. In Mono Manso and San Jose the BSFs could not reduce any of the pathogens to the acceptable risk level, however it was more efficient in reducing Rotavirus and Giardia than the chlorination was. When both BSF and chlorination were used there were still a high risk for Rotavirus infection, with the probability of 0.52 infections per person and year. Viruses in general are hard to remove by physical methods such as filtration since they are so small (Gall et al., 2015). Thus, if there are high levels of Rotavirus or other virus in the well water in the villages, a method including UV-light would be recommended (Gall et al., 2015).

Simulations were done assessing the risk of *E.coli O157:H7* infection when increasing the filter capacity by 75%, using a low contamination situation, i.e. simulating well water with the site-specific data and a reduction capacity of the BSF of $\log_{10}$ reduction of 4.9. Then the filters resulted in an annual infection probability of 0.093 per person, which is close to the acceptable risk level. If this scenario is compared to values reported in the literature review by Hijnen and Medena (2007), which reached a $\log_{10}$ reduction of maximum 4.8, it could be possible that the BSFs actually perform at a level of 4.9 $\log_{10}$ reductions. Especially considering that the sampling of the water in the wells showed little turbidity (~ 10 NTU) and a neutral pH (~6-7), and a temperature of ~25 C°, which are all favorable conditions for the efficiency of BSF (Stauber et al., 2006). The BSFs were furthermore effective in reducing virus and protozoa. Another opportunity would be to complement the sand filter treatment with chlorination. For example if chlorination is added with an initial chlorine dosage of 0.02 mg L^{-1}, the probability of infection per year caused by *E.coli O157:H7* is 0.00042, which is within the acceptable risk level. The probability of infection estimated with the data on *E.coli* O157:H7 from the well treated with the assumed normal capacity of the BSF was 0.0069 per person and day. This means that the treatment system, even though it does not reach the acceptable risk, decreased the probability of daily infections by over 96% (compared to a simulation with no treatment).

When conducting the QMRA and estimating the health risks in the villages, the transmission route (pathogen to human) was constrained to ingestion through drinking water that had been treated by the system. The concentrations used in MRA to estimate the risk were based on estimates of presence of pathogens in the well water that had been reduced by the treatment system. The possible transmission routes in terms of other forms of ingestion was investigated by Penakalapati et al. (2017) in their review article examining human health impacts of exposure to animal feces in low- and middle-income countries. They identified that pathogens from livestock, domestic animals and rodents were transmitted directly to food or water, or via the secondary pathways, soil (in fields), flies, fingers and fomites such as clothes or kitchen utilities. Penakalapati et al. (2017) found evidence of diarrheal illness caused by pathogens transmitted by the secondary pathways food, flies, fingers and fomites. They also found that cohabitation of human and animals, which is common in low-income countries, was a primary risk factor in terms of human health when exposed to animal feces. A study of fecal transmission routes in rural Bangladesh using *E.coli* as indicator showed that *E.coli* was transmitted in a domestic setting despite on-site sanitation, where transmission routes were identified to be by hands, in soil, ponds and source water (Ercumen et al., 2017). Ercument et al. (2017) also showed an increase in *E.coli* in domestically stored water when *E.coli* was increased in soil, ponds, source waters and on hands. The results from the above-mentioned studies indicates that using only ingestion as a possible transmission route for pathogens when estimating illness risk implies underestimation of the risk. In the simulations made in this study the risk was estimated only with ingestion of water as transmission route.

The simulations in MRA with no treatment showed that the daily infections caused by the level of *E.coli* O157:H7 calculated from the INAM data had the probability of 0.59 infections per person and day. The interviews conducted in the villages suggested that the probability of diarrheal was 0.2 per person and day. The fact that other transmission routes than ingestion of the water treated by the system were not accounted for in this study makes it difficult to compare the simulation results and the health situation in the villages. It should also be commented that a person could be infected without symptoms. Furthermore, the infection probability of 0.59 per person and day was estimated with only *E.coli* O157:H7 and the studies mentioned above suggest that there are many pathogens from animal feces and other transmission routes then ingestion that cause diarrheal. This insinuates that the results from the simulations exaggerate the risks of infection of *E.coli* O157:H7.

In the MRA an infection probability was estimated, and the estimation from the health status in the villages were on illness which is a result of the infection, but could originate from any diarrheal causing pathogen. *E.coli* O157 H:7 infections are linked to illness such as diarrhea and stomach cramps. The infectivity of the *E.coli* O157:H7 is low, with doses over 100 organisms are needed to infect a human (WHO, 2011). Evidence has shown that a person infected with *E.coli* O157:H7 develops antibodies to O157 that may prevent colonization and thus infection (Li et al., 2000). Researchers have further found evidence suggesting that some humans have genes that might make them resilient to enterotoxigenic *E.coli* infections (Yang et al., 2016). This may be part of a reason why the health status in the studied population showed less probability of illness than the MRA estimates of infection.

6.1.2 MRA-model

The model MRA was developed by Nordic researchers and optimized for surface waters under Nordic conditions. It was recommended by the Swedish national food agency (Livsmedelsverket) to be used by Swedish drinking water producers as a tool to assess microbial risks in drinking water in their report on hazard analysis for drinking water (Tollin, 2016). Furthermore, several thesis projects evaluating microbial risks from drinking water have used the MRA model with satisfactory results (Johansson, 2015; Högberg, 2010; Dahlberg, 2011; Westermark 2011). One aspect of the model, which is true for QMRAs in general, is a critique of the rigid need for site-specific data needed in order to make simulations realistic for a specific site. Gathering large amounts of site-specific data is generally very time consuming. Involving sampling the well water, the actual treatment capacities, if there is any recontamination, failure rates for the system etc. However, in the model it is easy to change variables and thus simulate different scenarios, making it possible to detect risk scenarios, areas of interest for further studies or optimize the treatment in order to provide safe drinking water. These simulations can be done with little site-specific data. The present author argues that this can be used to make valuable comparisons and estimations of future and present risks associated with drinking water. Johansson (2015) used MRA to predict possible risk associated with drinking water in a Swedish municipality, with pathogen concentrations associated with present climate and predictions of changes in concentrations due to climate change. The results from Johansson (2015) QMRA were intended to be used as part of the municipality resilience work to secure good potable water quality.

Using the MRA model under ”non-Nordic conditions” and for a treatment system using groundwater instead of surface water should not affect the comparison between different contamination scenarios or treatment efficiency steps. It will, to some extent, affect the exact value of the probability of infection. However, as stated above, this does not hinder a valuable comparison between treatments or contamination scenarios.

6.2 USING QMRA IN A PLANNING PHASE OF A PROJECT

Even if the QMRA is based on many assumptions, it raises interesting questions. When engineers plan treatment systems, standard designs are often used independently of the local setting (pers. com Scherdinger, 2016). The QMRA in this study showed that neither one of the planned treatment systems reached an acceptable level of infection risk. When planning for a treatment system, a QMRA based on local data on raw water and literature data on treatment possesses can be conducted. Design aspects could then be reconsidered before final design and construction. Before a treatment is chosen, the required log reduction for any treatment can be estimated, and thus the selection of treatment can be done accordingly. This could save both health and money. Furthermore, if a QMRA model is available the process of developing a pre-QMRA would not be very time consuming. One such model was the one used in this project. However, the more details put into the QMRA, the more accurate it will be. This said, it could be a good complement in the planning process of small-scale treatment systems to include a QMRA. This could indicate possible weak points in the system and give an opportunity to optimize the system before it is constructed.

6.3 MONITORING PROGRAM

The most important aspect of the monitoring program was to make it achievable for the communities. The challenge was to make it simple and cheap without compromising too much on the quality of the monitoring. If it is too complicated, it will not work in a setting where professionals are not available, and if it is too expensive it will never be implemented. Therefore, the idea is to create something simple, implement it, learn by doing it, and optimizing it. The question is if a simplified monitoring actually could improve the water quality in a long-term perspective? In this sense, this study serves as a pre-study, looking at the theoretical possibilities and challenges.

One important aspect that was observed during the case-study was the importance of the involvement and engagement of the community in the project. If the community is not involved and the project manager closes the project and leaves, the system will be more vulnerable. Clasen et al. (2007) studied effectiveness of interventions to improve water quality to prevent diarrheal. In reviewed literature Clasen et al. (2017) found evidence suggesting that if receivers are involved, informed or engaged, interventions were more effective in reducing diarrhea. From the field visits it was observed that during the construction of the systems, the community was engaged and contributed in form of participation in meetings and construction work when the NGOs, Altropico or Green empowerment, were present in the villages. However, agreements made upon the work that was to be done by the community in absence of the NGOs was seldom fully completed. In order to obtain community engagement and involvement, a constructive communication between the community and the project manager is necessary. This is especially important for the precautionary monitoring, since it is dependent on everyone in the community being involved in the water treatment system.

Having this is mind, having a representative from the NGOs present for at least a couple of weeks during the start-up phase of the monitoring could make it more sustainable. This is done in order for the routine of monitoring to be well implemented and to give opportunity finding solutions to possible difficult situations that occur.

If the monitoring were to be functioning as intended, it should contribute to an improved microbial water quality for the end users. A review article examining interventions aimed at preventing diarrheal by improving water quality showed that interventions to improve microbial quality of drinking water effectively reduce the occurrence of diarrhea (Clasen et al., 2007). The review was based on 42 controlled trials with about 56 000 participants. Water quality interventions were defined as any measure to improve the microbial quality of drinking water. Clasen et al. (2007) also compared water quality interventions only versus compounded environmental interventions such as hygiene instructions, improved storage vessels or improved sanitation. They, somewhat contradictory, found no evidence that water quality interventions were more effective in reducing diarrheal when implemented with any of the other components mentioned above compared to alone. Clasen et al. (2007) further found that household interventions, such as chlorination at household level, were more effective than for example improved sanitation or improved water supply. This could be compared to the results from Penakalapati et al. (2017) that suggested that fecal pathogens use various transmission routes. Indicating that even if one route is blocked by an intervention contamination can still occur through other routes, and with more possible infection situations that the water has to pass before ingestion the higher the risk of infection. This might explain the somewhat contradictive results from Clasen et al. (2007). The results from the QMRA suggest that the water quality will be improved by the water treatment system. Combining this improvement with a monitoring program that includes various interventions, at household level, at source and storage, could improve the quality. If the monitoring works as intended it should then be possible to block various transmission routes and therefore it might have an effect in contradiction to the results from Clasen et al. (2007).

6.4 USING QMRA AND LITERATURE REVIEW AS A METHOD FOR DESIGNING A MONITORING PLAN

Did the results from the QMRA contribute to the monitoring program, and will the monitoring program contribute to the safety of the water quality of the systems? In order to evaluate this, the best would be to do further studies (Chapter 6.5). If a QMRA yield results that are representative for the treatment system, then it contributes to the design of the monitoring program. By estimating risks with different scenarios, the QMRA results can be used to optimize a monitoring program, and make it more effective, since acknowledged risks can be prioritized. For example, as part of the QMRA simulations showed that BSF could not reduce the assumed well water concentration of *E.coli* O157:H7 (from INAM data) to an acceptable risk level. The literature review together with observations made in the field implied that one key risk factor in the communities was fecal contamination of the well water or during household storage. Further literature review suggested that *E.coli* O157:H7 infections are often caused by exposure to animal and human feces from infected individuals, via water, food or contact. In regard to this the precautionary monitoring in the program could be added in order to prevent fecal contamination of the water source, and as a guidance towards safe household handling of the water. In this sense using a QMRA method is believed to add value to monitoring program. When the best-case scenario was simulated, i.e. *E.coli* O157:H7 concentration from well sampling data and the BSF capacity increased by 75%, the risk was 9.3/1000 infections per person and year which is almost 10 times higher than the acceptable risk level. Furthermore, the MRA results indicated that chlorination was more effective against bacteria whereas the BSF reduced protozoa and virus to a higher degree compared to chlorination. This is something that further enhances the vulnerability of the systems, taking into account that all pathogen concentrations could go up.

Even though this study suggests that it would be valuable in the design of a monitoring program to include a QMRA, the question if it is realistic remains. It is important to take into consideration the extra workload and knowledge needed to do a QMRA that is representative for the system. The fact that a majority of projects implementing water treatment in rural areas don’t even have funding to do simple follow ups makes it questionable if including a QMRA is realistic. As many things in our society it comes down to money. If an organization that works with implementing water treatment systems wanted to include a monitoring program, they would have to spend more time and more funds. This could mean that instead of making two systems in two different communities without the program, they would do one system with a monitoring program. Then the question is how much value does the monitoring add to the system? Will the system work sufficiently well without it, then maybe it is better to make two systems?

In order to get the answers to these questions, more studies are needed. In the field of developing work there is an interesting paradigm shift where focus is shifted from counting implementation of technical solutions to measuring if they achieve their purpose, i.e. a more target based evaluation. This shift of focus could support the idea of including QMRAs when developing water treatment systems.

6.5 FURTHER STUDIES AND OPTIMISATION OF THE MONITORING PROGRAMME

One valuable optimization could be to quantify pathogen concentrations for different risk scenarios, such as animal excrements near the well, and use the data to simulate the outcome in a MRA model. One way of doing so is by modelling the spreading of pathogens.

This could be done by for example by estimating the concentration load that would reach the well (i.e. the source) if the animal left excrements at certain distances from the well. Another possibility would be to run simulations with different contamination loads due to climate change and/or extreme weather events.

The following studies would improve the accuracy in the QMRA:

- Taking site specific water source samples during wet and dry season, after extreme events etc. to get to know the source water.
- Measuring the actual reduction rates from the barriers in the systems during the different scenarios and simulating the treatment system using other barriers.
- Monitoring the treated water and the water after typical household storage.

6.5.1 Implementation and evaluation of the monitoring program

In order to evaluate how much a monitoring program can improve the overall safety of the water, conducting a study evaluating the frequency of infections in a community before and after a monitoring program has been installed would be useful. Economical calculations of possible values that the monitoring program could generate would also be interesting. One such value could be the income gained due to less sick days without being able to work and hospital expenses saved due to less medical bills. The value generated could then be compared to the costs for implementing and running a monitoring program.

7 CONCLUSIONS

The studied communities and key water quality risks
The studied communities did not have waste or water management systems. The population had diarrhea 3 to 4 days every 14 days. The majority of the population practice open defecation, and horses, cats, dogs and other animals roamed freely in the communities. The above-mentioned observations made in the studied communities suggested that fecal pathogens contaminating the water after treatment constitutes a water quality risk. The function of the treatment systems was also identified as a key risk factor for the water quality.

Reduction capacity in the treatment system and infection probabilities
The treatment system in San Salvador only used chlorination and in Mono Manso and San Jose only BSFs were used. The risk assessment showed that when chlorine treatment works normally, it reduced all *E.coli O157:H7 H:7*, independent of the concentration (for concentrations up to 10^8 CFU L^{-1}). But the reduction of Giardia and Rotavirus did not reach the acceptable risk level of 1/1000 infections per person and year. The BSFs was most effective in reducing Giardia, but did not reach the acceptable risk level for any of reference pathogens. When a treatment system was simulated as having both chlorination and BSF (under assumed normal capacity) the probability of infection per year and person from Rotavirus and Giardia was reduced by 47% and 97% per person and year, respectively. Therefore, based on the QMRA results it was recommended to use both chlorination and BSF in San Salvador, Mono Manso and San Jose.

The monitoring program and further studies
The monitoring program was divided into two parts, precautionary monitoring and continuous monitoring. The precautionary monitoring was aimed at reducing fecal pathogens from entering the drinking water in the well, treatment and at household level. This included keeping the catchment area clean, using proper water storage containers and keeping storage time short. The continuous monitoring should measure pH, turbidity, and conductivity weekly. These parameters are measured in order to detect quality variations that affect the water quality directly and/or treatment capacities. A microbial indicator test should be taken monthly in order to detect contamination or malfunction of the treatment system. The sampling and testing is to be done by the community water technician. In the continuous monitoring an observational based monitoring, consisting in taking notice of extreme or sudden events that could affect the water quality, should also be undertaken on a daily basis by the community members.

Recommended further studies include implementation of the monitoring program in the communities, followed by evaluation and optimization.

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PERSONAL COMMUNICATION

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APPENDIX 1 – PREPARATION OF INAM DATA

The estimate of E. coli concentration is surface water representing a worst-case scenario for the QMRA was based on data on the faecal coliform bacteria in surface waters in Esmeraldas, Ecuador. The method used to determine the concentrations was a qualitative dilution method and the results are presented as most probable number per 100 ml of sample (MPN/100ml). This means that the data is quantitative estimation of the true concentration. The prediction of the concentration for most MPN methods is based on the assumption that the bacteria is randomly distributed (Poisson) in the sample and the outcome is the average concentration often given with a confidence interval (WHO, 2016). MPN methods become more accurate in predicting the concentration when more dilution are made, in this case the method and number of dilutions were unknown, therefore also the confidence interval. Data derived by MPN methods used in QMRA are often assumed to be continuous even though they are categorical (because of the MPN method), and the severity of this simplification depends on the need of accuracy in the QMRA (WHO, 2016). For this project this simplification was used for two reasons: the data used is not site specific but used as a worst-case scenario and the results are meant to be used for comparing different treatment and contamination scenarios.

In order to use the data in the model MRA a distribution to fit the data was needed since the input for pathogen concentration in MRA is defined with a probability distribution. In order to determine which statistical distribution gave the best fit for this data some calculations were made using Excel and Matlab. The first hypothesis tested was that the data was lognormally distributed, since pathogens found in surface waters often are and the MRA model uses lognormal distribution as a default distribution if no other is chosen. In order to test this the natural logarithm of the data was calculated and then it was investigated if the logarithmised data was normally distributed.

Further some graphical tests including a histogram (Figure A.1.1) and a QQ-plot (by calculating the z-score from a standard normal distribution and then comparing it to the data) (Figure A.1.2). These showed somewhat normality, however had some deviations that suggests that the data not is normally distributed. This is since in order to get a “normal distribution looking” histogram the bin sizes had to be changed and in the histogram fewer bins than what is recommended for the amount of data were used. The QQ-plot also showed signs of non-normality with a deviation from the straight line for the low concentrations (the left end of the figure).

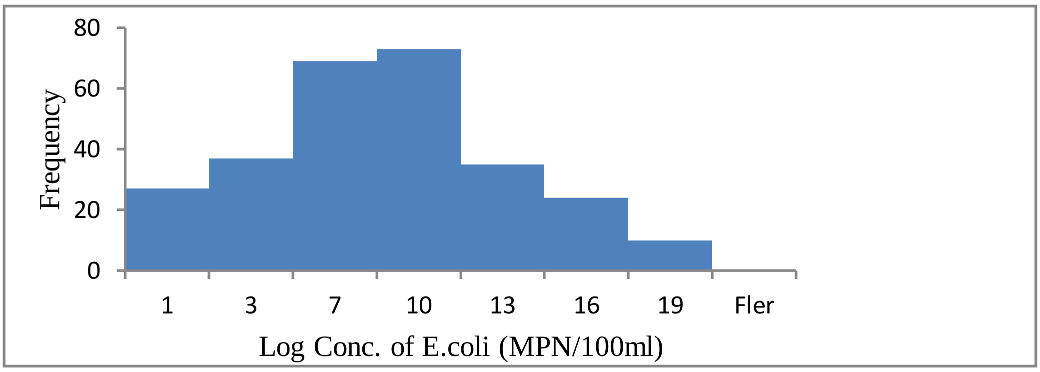


Figure A1.1 Histogram of log of all the data from INAM.

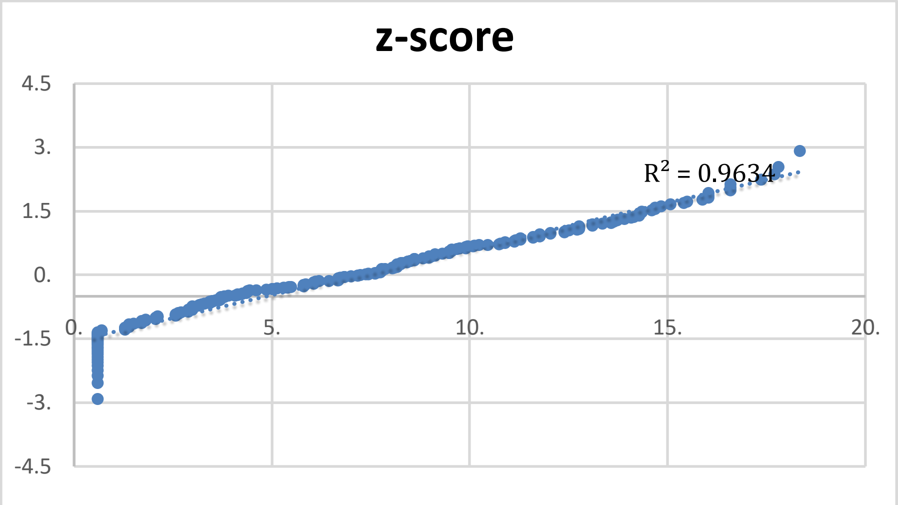
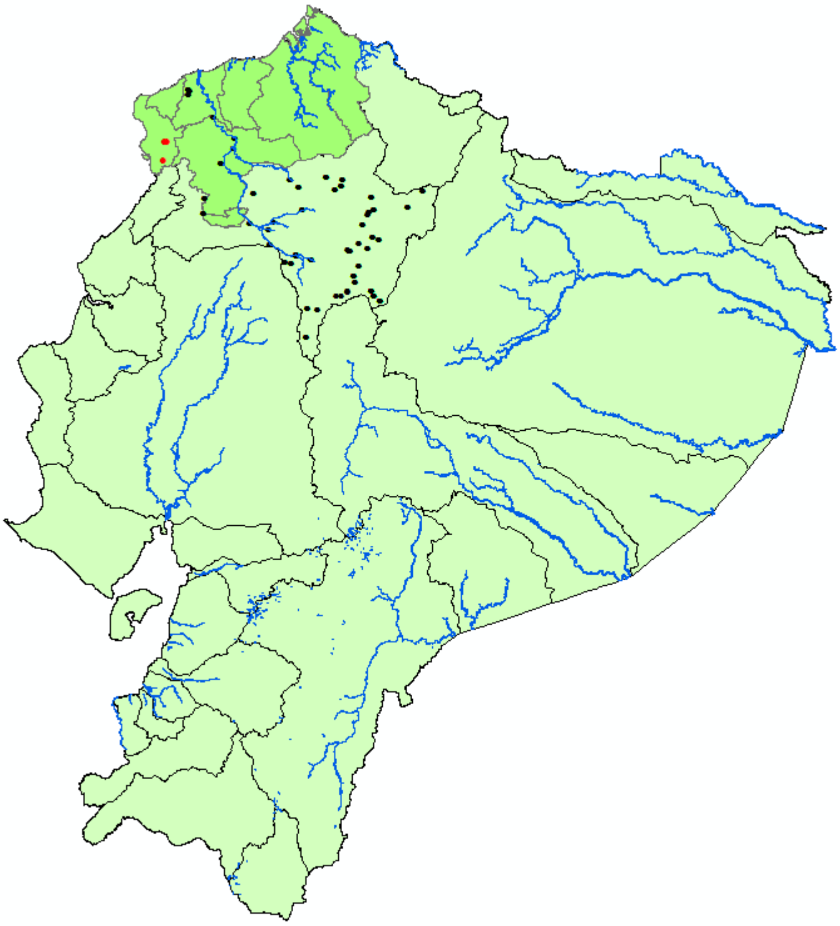


Figure A1.2 QQ plot for the faecal coliform water quality data from INAM on.

In order to reject the hypothesis that the data would be normally distributed two tests for normality were carried out using Matlab 2012b, the Lilliefors test and the Jarque Bera test. The null hypothesis (H0) in both tests was: The data from the population studied are normally distributed. That is there is no significant (at a 5% significance level) difference between a normal distribution and the data being tested. And the alternative hypothesis (H1) is that the observation is non-normally distributed. Both tests rejected the H0 and in concurrence with the graphical test the data is not normally distributed. This suggested that the data need to be transformed to fit a distribution or some data could be more relevant to the wells. The later option was investigated.

The data was gathered from various locations around “Cuenca Esmeraldas” during a period of approximately two years, from around 2014 until 2016. The data showed to have great variation in both space and time, this motivated investigating on which of the locations that was most relevant to the communities in a geographical sense. That is which of the sample locations were the closest to the wells. This was evaluated using ArcGis ArcMap programme. A shape file of the provinces of Ecuador was downloaded, the coordinate system was defined as UTM, GSM 1984 Zone 17S. The data for bacteria concentration had x and y coordinates specifying the sampling location. This data was imported to ArcMap using the import XYdata function, creating a shapefile with the sample locations. The same thing was done with the coordinates of the wells in the two communities San Salvador and San Jose. The two shapefiles with locations were then put on top of the shapefile with the provinces (Figure A1.3). In order to determine which of the sampling points that were closest to the wells a tool called Proximity tool in the Analyst toolbox was used. In *Proximity* the function *Nearest Table* was used to calculate the ten closest sampling points to each well (Table A1.1.)



Figur A3.3 Map of Ecuador. The greener area on top of map show Esmeraldas the province where the water systems are located. The red points are the wells (the two red points closed together on top are two of the wells in this study). The black points are the water sampling locations used by INAM.

Table A1.1 Distance from wells in the communities to sampling points used by INAM to collect the data used in this study.

Coliform Bacteria			Sampling date	Distance to wells[b]
MPN/100ml	Log MPN/100ml	Pat. E.coli		(m)
2.40E+03	3.38		2015-03-20	42610
1.30E+04	4.11		2016-03-14	42610
7.80E+03	3.89		2015-03-20	39910
7.90E+03	3.90		2016-03-13	39910

8.40E+03	3.92		2015-08-26	39910
3.90E+03	3.59		2015-08-26	42610
3.30E+03	3.52		2015-03-21	40416
4.50E+01	1.65		2015-03-27	40416
7.80E+01	1.89		2014-09-10	40416
6.30E+02	2.80		2015-08-27	43753

[a] The two wells for which an GPS point was available (San Salvador and San Jose) gave the same ten closest points. The wells are also relatively closed compared to the distances to the sampling points, for these reasons only the distance from the well in San Salvador is shown.

The ten closest sampling collection points were exported to Excel, the logarithm was calculated and plotted over time (the concentration and the date of sampling). The data showed no specific trend over time and so it was concluded that it could be clumped together even though it came from different locations (Figure A.1.4). In order to test if the data followed a lognormal distribution it was imported to Mathlab, were a Lilliefors normalty test and a Jaque barre test was runned. Both test showed that the logarithm of the data was normally distributed.

Table A1.2 Results from the normality tests conducted in Mathlab.

Test	**H**	**P**
Lilliefors	0	0.701
Jaque Barra	0	-

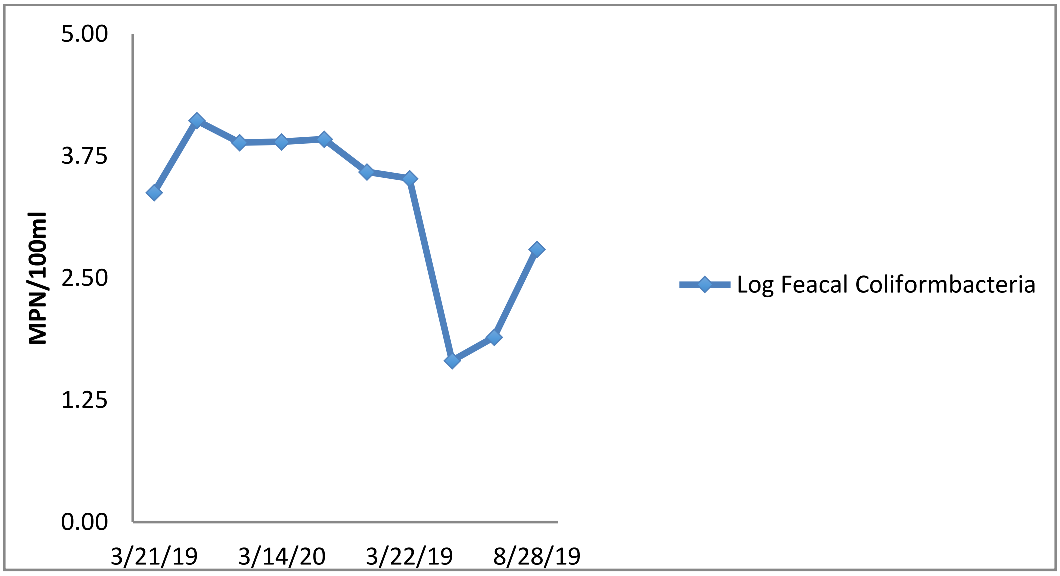


Figure A.1.4 Logarithm of the ten samples closest to the wells, plotted against time.

APPENDIX 2 – RESULTS FROM SIMULATIONS IN MRA MODEL

Data source Water quality	**# Model run**	**BSF**		**Chlorine**		**Scenario**	**Comment**
		Log_{10} reduction	Pinf_year	Log_{10} reduction	Pinf_year		
INAM	1	2.85	9.45E-01	INF	0	a	Inititial bact. Conc.
INAM	3	2.85	9.56E-01	INF	0	a	25% increase conc.
INAM	5	2.85	9.64E-01	INF	0	a	50% increase conc.
INAM	7	2.85	9.70E-01	INF	0	a	75% increase conc.
INAM	9		9.75E-01		0	a	Double exposure
INAM	10		1.00E+00		1	b	No treatment
INAM	12	3.49	7.95E-01	716	0	c	25% increase/decrease treatment
INAM	14	4.19	5.95E-01	477	0	c	50% increase/decrease treatent
INAM	16	4.89	4.08E-01	238	0	c	75% increase/decrease treatment
Local	2	2.85	5.68E-01	INF	0	a	Initial conc.
Local	4	2.85	6.09E-01	INF	0	a	25% increase conc.
Local	6	2.85	6.41E-01	INF	0	a	50% increase conc.
Local	8	2.85	6.67E-01	INF	0	a	75% increase conc.

Local	11		1.00E+00		1	b	No treatment
Local	13	3.40	3.59E-01	716.3101	0	c	25% increase/decrease treatment
Local	15	4.19	1.88E-01	429.7861	0	c	50% increase/decrease treatent
Local	17	4.89	9.26E-02	238.77	0	c	75% increase/decrease treatment

Data source Waterquality	**# Model run**	**BSF**		**Chlorine**		**Scen-ario**	**Comment**
Abrahamsson et al., (2009)		Log_{10} reduction	Pinf_year	Log_{10} reduction	Pinf_year		
	18	2.26	5.17e-001	0.15	5.17e-001	a	
	19	3.53	2.53e-002	0.012	2.53e-002	a	
	20	2.26	5.76e-001	-	-		Only BSF
	21	3.53	2.59e-002	-	-		Only BSF
	22	-	-	0.15	9.99e-001		Only CL2
	23	-	-	0.01	9.70e-001		Only CL2