CHALMERS
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# Quantitative Microbial Risk Assessment and Microbial Barrier Analysis for a standard water treatment plant in Ghana

## With the Tano River as a raw water source

Master's thesis in Water Environment Technology

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DEPARTMENT OF Architecture and Civil Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY

MASTER'S THESIS ACEX30

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ABSTRACT

Safe drinking water is essential for human health and has even been declared as a human right. However, this is still a critical challenge in Ghana, Africa. In Ghana, many drinking water sources are microbiologically contaminated, and unsafe drinking water is commonly consumed. There is a need for better water treatment to reduce the health risk for consumers. The overall aim of this master thesis was therefore to perform a Quantitative Microbial Risk Assessment (QMRA) and a Microbial Barrier Analysis (MBA) for a standard water treatment plant in Ghana, with the Tano River as the raw water source.

The MBA analysis evaluate if there are enough microbial barriers in relation to the raw water quality, to guarantee a safe drinking water for the consumer. Three pathogen groups were considered, bacteria, viruses and parasites. In the QMRA, different scenarios were modelled and the annual risk of infection of E.coli O157, Norovirus and Cryptosporidium were compared to the guideline limit of one infected per 10 000 consumers per year (set by the United States Environmental Protection Agency). Due to the lack of studies of microbiological water quality in Ghana, the input data was taken from existing research from Ghana and Sweden, used in combination with some carefully considered estimations and assumptions.

The microbial water quality in the Tano River is affected by wastewater discharge, which increases the risk of microbial contamination. The results from the MBA and QMRA showed that conventional treatment including chemical precipitation and chlorination is not enough to guarantee a safe drinking water. The separation and inactivation of viruses and parasites was not efficient enough, and parasites was especially critical.

Additional treatment with UV-disinfection and ultrafiltration, is recommended for removal of the parasite Cryptosporidium, which the results showed to be of high risk. However, the results differed between the MBA and the QMRA. The MBA addition of UV-disinfection would be sufficient whereas, the QMRA suggested both UV-disinfection and ultrafiltration was needed. The way water quality was characterised for the two methods could explain the different result.

Possible improvements of raw water quality could be better upstream control and improved wastewater collection system. In addition, sampling on pathogen concentrations would be beneficial for further studies.

Key words: Quantitative microbial risk assessment, Microbial barrier analysis, Ghana, Tano River, Microbial contaminants, Microbial barriers, Probability of infection annually

Kvantitativ mikrobiell riskbedömning och mikrobiologisk barriäranalys för ett standard vattenverk i Ghana

Tano River som råvattenkälla

Examensarbete inom mastersprogrammet Infrastruktur och miljöteknik

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## SAMMANFATTNING

Säkert dricksvatten är en mänsklig rättighet och en grundförutsättning för människors hälsa. Tyvärr är dock inte tillgången på rent vatten en självklarhet överallt, i Ghana är bristen på rent dricksvatten en stor utmaning. I Ghana är många dricksvattenkällor kontaminerade av mikrobiologiska föroreningar och osäkert vatten konsumeras dagligen. Det finns ett stort behov av bättre vattenberedning för att minska sjukdomsrisken hos konsumenterna. Därför var det huvudsakliga syftet med detta examensarbete att genomföra en Kvantitativ Mikrobiell Riskbedömning (QMRA) och en Mikrobiologisk Barriäranalys (MBA) för ett vanligt förekommande vattenverk i Ghana, med floden Tano River som råvattenkälla.

En MBA görs för att utvärdera den mikrobiologiska säkerheten på ett vattenverk, i relation till råvattenkvalitén, för att säkerställa säkert dricksvatten. Tre patogengrupper studerades, bakterier, virus och parasiter. I QMRA simulerades olika scenarier och den årliga infektionsrisken för E.coli O157, Norovirus och Cryptosporidium jämfördes med gränsvärdet för maximalt en infekterad människa per 10 000 konsumenter per år, som är bestämt av United States Environmental Protection Agency. Då det råder brist på studier som berör mikrobiologisk vattenkvalitet i Ghana, är indata baserad på litteratur både från Sverige och Ghana i kombination med noga avvägda antaganden och uppskattningar.

Den mikrobiologiska vattenkvalitén i floden Tano River påverkas av utsläpp av avloppsvatten, vilket leder till ökad risk för mikrobiologiska föroreningar. Resultaten från MBA och från QMRA påvisade att en beredningsprocess som innefattar konventionell rening med kemisk fällning samt klorering inte var tillräcklig för att kunna garantera ett säkert dricksvatten. Separeringen och inaktiveringen av virus och parasiter var inte tillräcklig.

Därför föreslogs ytterligare beredningssteg, nämligen UV-desinfektion och ultrafilter, då dessa processer är effektiva mot parasiten Cryptosporidium. Resultatet skiljde sig dock åt mellan MBA och QMRA. För MBA visade resultatet att det var tillräckligt att addera UV-desinfektion, för QMRA krävdes däremot både UV-desinfektion och ultrafilter. Hur råvattenkvalitén var estimerad för de två olika metoderna kan ha varit anledningen till skillnaden i resultatet. Möjliga förbättringsåtgärder av råvattenkvalitén, skulle kunna utgöras av bättre uppströms kontroll och förbättrat

avloppsystem. Ytterligare analyser av patogenhalter skulle också vara mycket värdefullt för framtida studier.

Nyckelord: Kvantitativ Mikrobiell Riskbedömning, Mikrobiologisk Barriäranalys, Ghana, Tano River, Mikrobiologiska föroreningar, Mikrobiologiska barriärer, Sannolikheten för infektion per år.

# Contents

# Preface

This thesis is carried out at the Department of Architecture and Civil Engineering within the Division of Water Environment Technology. I would like to thank my supervisor Thomas Pettersson, associate professor at the Division of Water Environment Technology, at Chalmers, for valuable support when performing the Quantitative Microbial Risk Assessment and advice throughout this master thesis process. I also like to thank Dr. Nashita Moona for the initiation of the Study and for great engagement and good knowledge. Furthermore, I like to thank the examiner Oskar Modin, professor at Water Environment Technology, at Chalmers.

Gothenburg May 2023

Stina Zagerholm

# Notations

DW: Drinking Water

MBA: Microbial Barrier Analysis

QRMA: Quantitative Microbial Risk Assessment

UF: Ultra membrane filtration

UN: United Nations

US EPA: United States Environmental Protection Agency

UV: Ultraviolet

WHO: World Health Organization

WSP: Water Safety Plans

WTP: Water Treatment Plant

# 1 Introduction

Safe and clean drinking water was 2010 declared as a human right by the United Nations (UN) General Assembly, this since safe drinking water is essential for human health (WHO, 2017). Despite that, two billion people still live without access to safely drinking water services in 2020 (United nations, 2022). One of UNs Sustainable Development Goals, number 6, *Clean water and Sanitation* is aiming for improvement, one part of the goal is "*6.1 By 2030, achieve universal and equitable access to safe and affordable drinking water for all*" (United nations, 2022). If this goal is going to be reached, the progress needs to increase fourfold the current developing rate, which would save 829,000 people annually according to the UN (United nations, 2022).

Developing countries are facing the hardest challenge, due to high population growth and urbanization, safely managed water supply services is hard to provide, and Ghana is one of these countries (Machdar et al., 2013). In Ghana, 60 % of the water bodies are polluted and it is very common that the drinking water sources are polluted with microbiologically contaminants causing water-related diseases (Ibn & Yeboah, 2022). The microbial contaminants are commonly caused by wastewater discharge that contains faecal contaminants, such as pathogenic bacteria, viruses and parasites (Andersson, 2010).

There is a framework for safe drinking water created by WHO, called Water safety Plans (WSP), which has partly been implemented in Ghana (Vinas Cos & Salinas Niedbalski, 2015). The purpose with WSP is to get a holistic control over the drinking water supply to get negligible risk for consumers and public health both regarding chemical and microbial quality. The WSP focus on control of abstraction, treatment and delivery of drinking water (WHO, 2017). The WSP require a comprehensive risk-based approach, therefore a Quantitative Microbial Risk Assessment (QMRA) is a valuable tool to evaluate drinking water safety, supporting the water safety plan (Petterson & Ashbolt, 2016). Another method to assess human health risks due to waterborne diseases is performing a Microbial Barrier Analysis (MBA) of the drinking water supply system. With the purpose to evaluate if there are enough microbial barriers to safeguard consumer from waterborne diseases, for the current raw water quality (Ødegaard et al., 2014).

In this master thesis, an MBA and a QMRA were performed for a standard conventional drinking water plant (WTP) in Ghana. With the purpose to evaluate the potential risk of infection caused by pathogenic microorganisms due to the consumption of drinking water from such WTP. The result from the QMRA was compared with the health risk value set by US EPA.

## 1.1 Aim

The aim of the thesis is to perform an MBA and a QMRA for a standard drinking water treatment plant in Ghana, with the Tano River as raw water source, and to compare and analyse the results from the two methods. Depending on the result, recommended improvements will also be made.

## 1.2 Specification of research question

- Are the traditional treatment processes for a WTP in Ghana enough to meet the acceptable health risk value set by US EPA, of one infected per 10 000 consumers per year, according to the QMRA analysis?

- Do a traditional treatment processes for a WTP in Ghana provide enough microbial barriers to prevent waterborne diseases according to the MBA analysis?

- How can a QMRA analysis be performed with limited input data available?

- Is there any difference in the result between QMRA and MBA? If so, what is the reason for this?

- What are the health consequences if one treatment step fails in the WTP? How sensitive is the process operation to the health risks? Which treatment process is the most critical one?

- What is the maximum load of microbiological contaminants the standard treatment processes can handle?

- Is there a need for an additional treatment process, and what process would be most suitable?

## 1.3 Limitations

Only microbiological contaminations (pathogens) will be considered in this thesis, no other pollutant types will be considered. The MBA and the QMRA analysis only concern the microbial water quality. In addition, this thesis will not consider the distribution network and its effect on the drinking water quality.

# 2 Background

## 2.1.1 Ghana

In developing countries there is still a critical challenge to reduce water related diseases, due to lack of potable water and good sanitation (Ibn & Yeboah, 2022). In Ghana, 60 % of the water bodies have been evaluated as polluted (Ibn & Yeboah, 2022). In rural communities about 85 % use raw water which is unsafe, most rural dwellers even drink untreated water (Nyantakyi et al., 2013). Harmful substances from agricultural activities, industrial and household waste and domestic use of water in rivers are causing poor water quality (Ibn & Yeboah, 2022). Because of this, several studies have investigated the drinking water quality in Ghana showing that the drinking water sources often are microbiologically contaminated. This led to water-borne outbreaks with diseases such as, diarrhoea, typhoid and dysentery (Ibn & Yeboah, 2022). On contrary, in some areas of Ghana water from boreholes is used as household water, but during dry season most boreholes dry up, while rivers, streams and hand-dug wells become the only option of household water. Therefore, people are extra vulnerable to water related diseases during dry seasons. Because of this, it is of great importance to improve the drinking water quality in general in Ghana (Ibn & Yeboah, 2022).

In this project a hypothetical standard type of drinking water treatment plant is assumed to be built in Ghana, with the Tano River as raw water source, with a design population of 400 000. See the map of Ghana and the Tano River in Figure 1 below.


*Figure 1. Map over Ghana. See the Tano River in the western part of the country* (Osumanu et al., 2010).

### 2.1.2 Tano River

The Tano River flows southward from Tano Boase through the Brong Ahafo Region and then enters the Gulf of Guinea in the Atlantic Ocean (Nyantakyi et al., 2013). The river is an important drinking water source in the area, despite the fact, the water quality is largely affected by surrounding activities, see the photo of the river below in Figure 2. Within the watershed area (Ankobr-Tano Basin) mining (bauxite, gold), palm oil, rubber, copra and timber trading are common activities. In addition, along the riverbanks, construction activities, industrial waste, illegal mining, and bad farming practices affect the river. The consequence of this is that communities in the area that use and drink untreated water are highly exposed to water borne diseases. Sampling of physico-chemical parameters on the river has also shown values above the regulatory safe limit (Nyantakyi et al., 2013).

*Figure 2. Picture of the Tano River, affected by illegal mining activities* (Sakyiabea Gyapong, 2022).

In addition, the wastewater collection system and wastewater treatment are rather absent in Ghana in general (Ghana statistical service, 2022). In Figure 3 below, it can be seen the proportion of households throwing wastewater onto the ground, street, and outside. The Tano River flows through the Ahafo and Bono Region. In urban areas around 81% throws the wastewater right outside and in rural areas, it is even worse around 92% (Ghana statistical service, 2022). This poses a big risk for the drinking water since these contaminants may be transported with surface runoff to the Tano River.

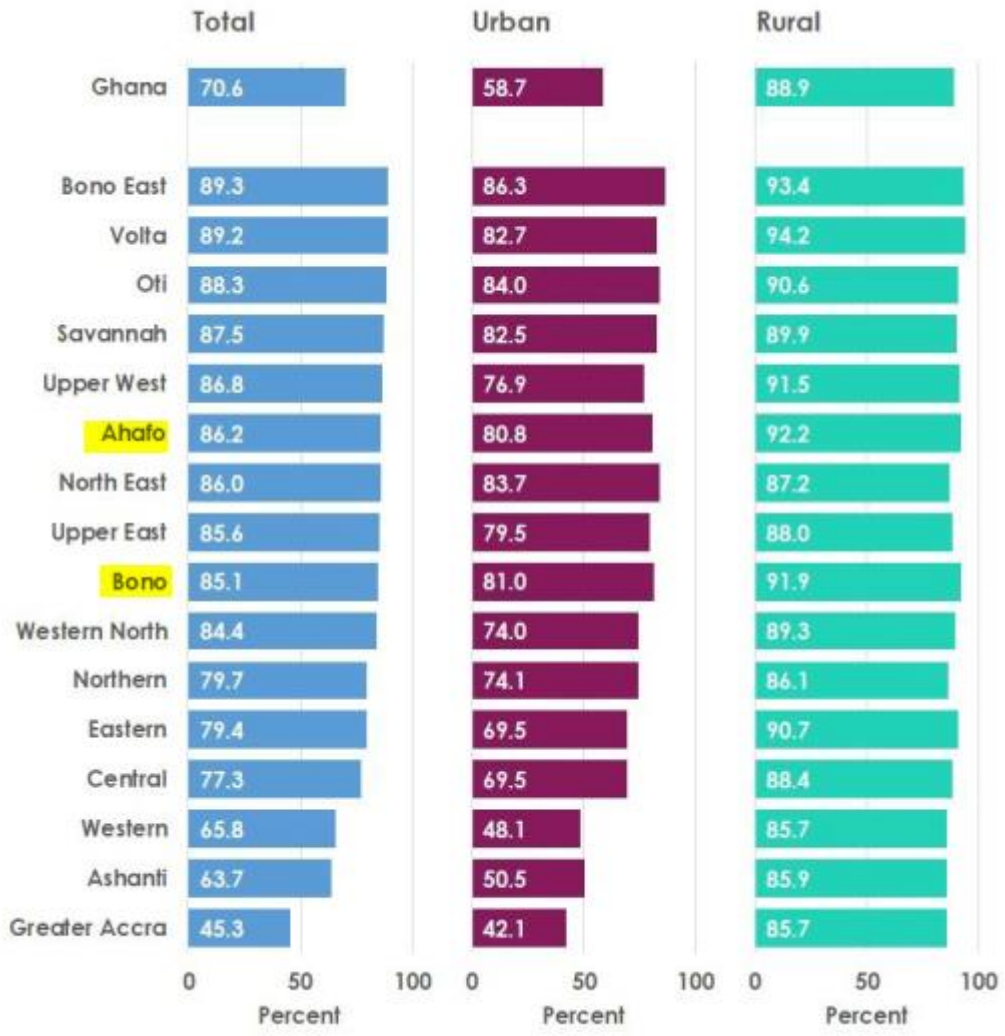


*Figure 3. Proportion of households throwing wastewater onto the ground/street/outside* (Ghana statistical service, 2022).

#### 2.1.2.1 Comparison with another River in Ghana

A research study investigating the microbial water quality of the river Wiwi in Kumasi (see Figure 1) found that the highest mean faecal coliform was detected when the weather was warm and dry, during December (Amisah & Nuamah, 2014). This is because during warmer temperatures faecal coliform bacteria are at their highest concentration, probably because of the favourable environment for reproduction (Amisah & Nuamah, 2014). In addition, during January and February the coliform counts was also relatively high, probably due to the low river flow. Decreased precipitation led to less dilution in the river and higher concentration of solids waste, and therefor also higher coliform count (Amisah & Nuamah, 2014). The faecal component of bacteria counts, and the high occurrence of coliform is a result of human sewage. The discharge of untreated wastewater is a significant portion of the domestic pollutants in the river Wiwi (Amisah & Nuamah, 2014).

### 2.1.3 Water quality

#### 2.1.3.1 Microorganisms in drinking water

Microorganisms are constantly present in our surroundings, some of them are essential for us humans and most of them are harmless (Andersson, 2010). However, some microorganisms can cause diseases, and these are called pathogenic microorganisms. Waterborne diseases are most often caused by faecal contamination, from wastewater or manure for example. In this report three different microorganisms, bacteria, viruses and parasites will be considered (Andersson, 2010).

*Bacteria*
There are several types of bacteria in water, and they can benefit from different conditions (Ødegaard et al., 2014). Bacteria have cell machinery and genetic material and that are fold up in a protein coating. Examples of pathogenic bacteria that can cause illness are *Campylobacter, Escherichia coli (E. coli), Salmonella, Legionella* and *Yersinia*. Spore forming bacteria, including *Bacillus* and *Clostridium*, are very resistant to extreme conditions (Ødegaard et al., 2014).

*Viruses*
Viruses require a host cell to multiply, they consist of genetic material in a protein folder. Examples of viruses are *Noroviruses, Adenovirus, Rotavirus, Poliovirus,* and *Hepatitis A viruses*. Depending on which type of virus, the disinfection method varies in efficiency (Ødegaard et al., 2014).

*Parasite*
The parasites *Giardia* and *Cryptosporidium* are the main protozoan in drinking water systems that can cause severe illness. Parasites also rely on a host cell to multiply, however during the inactive stages outside the host cell they are very resistant to commonly used disinfection methods, apart from UV (Ødegaard et al., 2014).

### 2.1.4 Microbial barrier

Some countries have a detailed description of the required number of microbial barriers depending on the raw water source quality. A microbial barrier can either be the removal of pathogens or the inactivation (disinfection) of pathogens (Ødegaard et al., 2014). In Table 1 and 2 below, the efficiency of commonly used microbial barriers for pathogens are shown. In the MBA-guideline the removal effectiveness of a microbial barrier is given in $\log_{10}$-reduction, where a 90 % removal equals 1 $\log_{10}$ reduction, 99 % removal equals 2 $\log_{10}$ reduction and 99,9 % removal equals 3 $\log_{10}$ reduction and so on.

*Table 1. Commonly used particle separation methods and their efficiency regarding microorganism removal* (Ødegaard et al., 2014).

| Particle removal method | Bacteria | Viruses | Parasites |
|---|---|---|---|
| Sand filtration (no coagulants) | Poor | Very poor | Poor |
| Coagulation/sand filtration | Good | Moderately good | Good |
| Membrane filtration[1)] | | | |
| RO and NF | Very good | Very good | Very good |
| UF | Good | Moderately good | Very good |
| MF | Moderately good | Poor | Good |
| Coagulation/UF(MF) | Very good | Good | Very good |

1) RO- reverse osmosis, NF-nanofiltration (< 5 nm), UF- ultrafiltration (< 40 nm), MF-microfiltration (< 100 nm)

*Table 2. Commonly used disinfection methods and their efficiency regarding microorganism inactivation* (Ødegaard et al., 2014).

| Disinfection method | Bacteria | Viruses | Parasites |
|---|---|---|---|
| Chlorination | Very good | Good | Inadequate |
| Ozonation | Very good | Very good | Good/Inadequate[1)] |
| UV-disinfection | Very good | Good/Inadequate[2)] | Very good |

1) Quite good with respect to Giardia, inadequate with respect to Cryptosporidium at ozone dosages normally used
2) Good with respect to most viruses in water of health related significance - inadequate with respect to Adenovirus at the UV-dosages normally used.

In Sweden, Livsmedelsverket recommends a combination of separation barrier and inactivation barrier for a better total microbial barrier effect (Livsmedelsverket, 2023). This is since the different barrier often supplement each other in efficiency against different pathogens.

The international drinking water quality framework for Ghana recommend that preventive measurements in form of multiple barriers always should be applied (Ministry of Water Resources, 2015). To safeguard that if one barrier fails, the remaining barriers will cover, and that the risk of harm for consumer will be minimised. Traditional barriers used in preventive intensions include the following (Ministry of Water Resources, 2015):

- "*Catchment management and source water protection;*
- *Detention in protected reservoirs and storages;*
- *Extraction management;*

- *Coagulation, flocculation, sedimentation and filtration;*
- *Disinfection;*
- *Protection and maintenance of the distribution system*
- *Household water treatment and safe storage*"

Which barrier used depend on the current circumstances for each water supply, the characteristics of the water source and the catchment area. In addition, which barrier applied should be determined by identifying hazards and risks (Ministry of Water Resources, 2015).

## 2.2 MBA – Microbial barrier analysis

To provide a safe drinking water, microbial barriers are essential as mentioned above. To evaluate if a water utility has sufficient microbial barriers, an MBA can be performed. This qualitative analysis considers the whole process, the conditions in the catchment area all the way to the last step in the water treatment. The Microbial Barrier Analysis (MBA)-a Guideline (2014) is written by Hallvard Odegaard, Stein W.Osterhus and Britt-Marie Pott. The guideline explains the barrier concept and is intended to help water utilities to evaluate their treatment. The guideline provides an outlined procedure for the numerical analysis of the different barrier status in the water system (Ødegaard et al., 2014). The steps included in an MBA can be seen in Figure 4 below.

| Step | Determination of | Dependent on |
|---|---|---|
| 1. | Raw water quality | • Historic data for raw water quality<br>• New data from risk-based sampling program |
| 2. | Barrier level required | • Raw water quality<br>• Size of water supply system |
| 3. | Catchment area and water source barriers | • Barrier actions in catchment area/water source<br>• Surveillance of raw water quality |
| 4. | Particle removal barriers | • Water treatment methods<br>• Surveillance of water treatment |
| 5. | Disinfection barriers | • Disinfection methods<br>• Dosage in disinfection processes |
| 6. | Overall barrier status (total protection provided) | • Barrier level requred ÷ barrier credits<br>• Step 2 ÷ step 3 ÷ step 4 ÷ step 5 |

*The steps of the MBA procedure*

*Figure 4. Summary over the steps of the MBA procedure* (Ødegaard et al., 2014).

The structure for step 1-6 is illustrated in Figure 5 (Ødegaard et al., 2014). The barrier actions value, in the calculations, is given in log-credits. Each step gives a specific $\log_{10}$-reduction for the different microorganism groups.

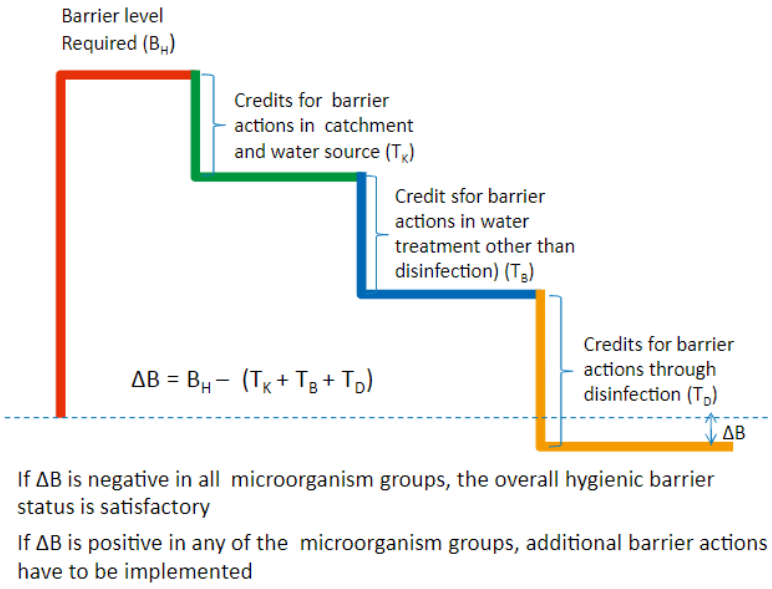


*Figure 5. The MBA procedure* (Ødegaard et al., 2014).

When performing an MBA the raw water and the WTP is analysed by evaluating each step according to tabulated values, to investigate if the barriers are enough for the specific raw water quality. If all microorganisms' groups (bacteria, viruses and parasites) get sufficient treatment and ends up below zero ($\Delta B<0$, Figure 5), then the hygienic barrier status is sufficient enough. However, if the final value is positive, additional barrier action is needed (Ødegaard et al., 2014).

## 2.3 QMRA – Quantitative microbial risk assessment

QMRA is an internationally established method to evaluate the health risk of consuming drinking water from a specific drinking water system and is recommended by WHO to be performed (Pettersson et al., 2017). It is obvious that water of poor quality requires more treatment than water of good quality, however, exactly how much more treatment that is required to achieve safe drinking water is not obvious. For this purpose, the QMRA framework is a good approach defining the required treatment based on the current raw water quality (Petterson & Ashbolt, 2016).

QMRA supports decision making regarding improvements to specific operational requirements for a WTP and can provide a general system understanding (Petterson & Ashbolt, 2016). There are several QMRA tools developed to calculate health risks in water supply systems, and in this project the Swedish QMRA tool is used.

The QMRA process is divided into five steps (Pettersson et al., 2017):

1. Choose of reference pathogen
2. Characterization of raw water and pathogen concentration
3. Define treatment process
4. Exposure, i.e., volume of drinking water consumed
5. Dose-response calculations and characterization of risk

Pathogen data from analyses of raw water is rarely available, but indicator organism data is more commonly measured (Pettersson et al., 2017). However, unfortunately, the concentrations of indicator organism do not correlate well with the concentration of pathogens in the water. This might make it difficult to use the QMRA tool, however with relevant estimations and scenarios of discharges of faecal loads to the water source, reasonable assumptions can be made (Pettersson et al., 2017). This is a common obstacle that need to be carefully considered since the input data is crucial to getting an accurate result (Pott, 2014). The following pathogens are considered when performing a QMRA and are inserted into the QMRA tool (Pott, 2014):

- Campylobacter
- Salmonella
- E.coli

- Rotavirus
- Norovirus
- Adenovirus

- Cryptosporidium
- Giardia

When pathogen concentration in raw water, the removal efficiencies of treatment processes, water consumption (l/day) are defined the risk characterisation based on dose-response relationship the health risk can be estimated. Scenarios with failures in the barriers and accidents is easy to model and then the health risk is estimated (Pott, 2014).

The result from the QMRA tool provides several results in different ways (Pott, 2014). First, the $\log_{10}$-reduction for each barrier and pathogenic group can be presented, which gives a good overview and understanding of how efficient the different barriers are. Secondly, the main results are the risk characterization, where the probability of infection ($P_{inf}$) is presented, both annually and daily infection risk are presented of the water being consumed. Lastly the tool also provides results being presented as Disability Adjusted Life Years (DALY) (Pott, 2014).

## 2.4 Microbial treatment

The standard (traditional) microbial barriers used at WTPs in Ghana are the following (Ministry of Water Resources, 2015)

- Coagulation, flocculation, sedimentation, and filtration (conventional treatment)
- Disinfection, chlorination

Based on these microbial barriers a treatment proposal has been made, which is presented below.

**Chemical dosing and coagulation**
In conventional treatment, the first step is to add a chemical reagent for dissolved organic matter and particles will flocculate and forming flocs that then will be easily removed by sedimentation and/or filtration (Svenskt Vatten, 2010b). In order to get good coagulation and growing flocs, rapid mixing is needed to promote particle to collide and grow. The primary coagulant proposed will be aluminum sulphate and then the chemical regent polyelectrolyte as coagulant aid and two rapid mixer tanks in series. In this step pH adjustment is also performed. Firstly, aluminum sulphate is added to lower pH and form aluminum complexes. Further, lime is used to adjust pH and aluminum hydroxide is formed (Svenskt Vatten, 2010b).

**Flocculation**
By gentle mixing the particle size will increase further, agglomeration of small microflocs into greater macrofloccs (Svenskt Vatten, 2010b). Three flocculation tanks in series are common and is assumed to have a plug flow. A standard residence time of 20-40 minutes is common, followed by a sedimentation step.

**Sedimentation in lamella settlers**
To remove the flocs produced in the previous steps, a physical separation step is needed, and for this lamella settlers is proposed. For lamella settler the flow needs to be calm and smooth to be efficient (Svenskt Vatten, 2010b).

For optimal operation process regarding the chemical precipitation (including the chemical dosing, coagulation, and sedimentation), an optimal pH and chemical dose need to be used in relation to the raw water quality, to get an efficient removal (Blom & Furuberg, 2013). If the pH and chemical dose is not right, it can led to a reduction in efficiency of removing viruses by 50 %, even if the turbidity in the outflow is still low. The flocculation, which depends on the chemical reagent dose and the pH, has proven to be the most important part in this treatment step. This since the viruses are very small, down to 20 nm, the chemical pretreatment needs to work well to get good separation (Blom & Furuberg, 2013).

To a certain extent a correlation between the removal effect from chemical precipitation and the turbidity in the outflow can be drawn, but not regarding the removal of viruses. However, online-monitoring of turbidity and particle content can be of importance. Further, measuring of coagulant complex and/or particles can be suitable to also trace the efficiency in virus removal. The variations in log-removal in relation to other parameters like turbidity can give an indication of how well the process works (Blom & Furuberg, 2013).

**Rapid sand filter**
The rapid sand filter captures remaining suspended flocs from the previous sedimentation. It happens due to particles are sieved by the pore space between the sand grains, but also by adsorption due to electrical charge (Svenskt Vatten, 2010b). The rapid sand filter works as the final polishing step.

**Chlorination disinfection**
By gravity, the cleared, filtered flow reaches the contact tank where calcium hypochlorite, providing free chlorine, is proposed to be used as disinfection and for final pH adjustment lime is added before distribution. The contact tank volume will be

designed to ensure that the contact time will be sufficient for disinfection (Svenskt Vatten, 2010b).

The disinfection effect is dependent on the dose free chlorine added, the contact time, temperature and pH (Svenskt Vatten, 2011a). Depending on the dose free chlorine concentration in the contact tank and the contact time, i.e. the time chlorine is in contact with the water in the tank, it will determine the degree of pathogen inactivation. Integrating the concentration (in mg/L) over time (min) gives us the Ct-value (Svenskt Vatten, 2011a).

When chlorine is added to the water an instant reaction of the free chlorine will appear with the remaining organic material in the water, which is called initial consumption (IC), followed by a slower decay process of the disinfection substance (Blom & Furuberg, 2013). This is illustrated in Figure 6 below. The Ct-value is the area under the chlorine concentration curve and depending on Ct-value the $\log_{10}$-reduction value can be calculated. However, some faecal microorganisms have a very high tolerance to chlorination, regardless of Ct-value, where Cryptosporidium are more or less unaffected by chlorination (Blom & Furuberg, 2013).

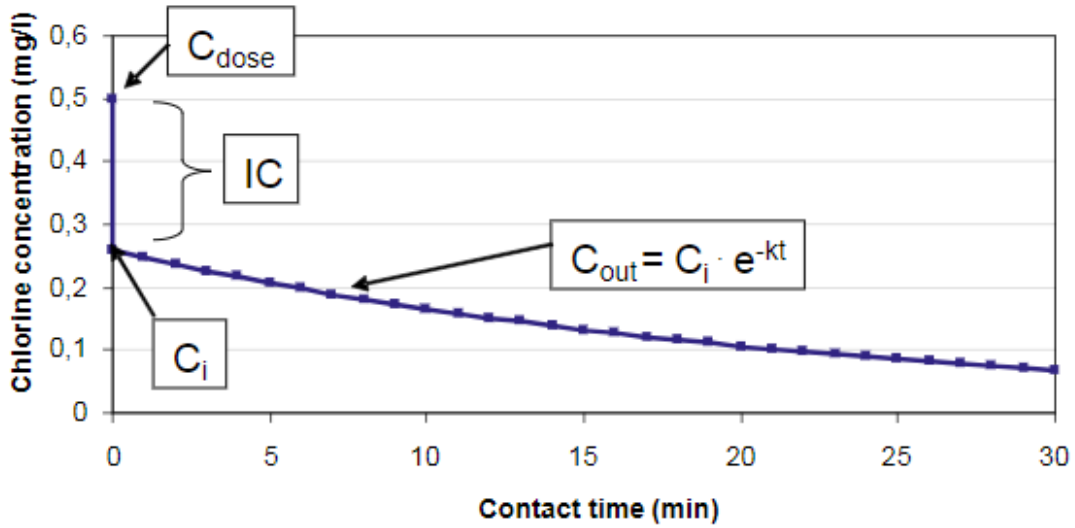


*Figure 6. For the calculation of Ct, initial consumption (IC) and chlorine degradation ($C_i$).* (Ødegaard et al., 2014)

The effect of disinfection is most effective at low pH, why disinfection should be placed before the final pH adjustment (Blom & Furuberg, 2013). The temperature affects the inactivation of viruses, the biochemical activity increases if the temperature increases and viruses will be inactivated faster, and the other way round. Good pre-treatment before disinfection is also important, since too much chlorine will be consumed by high concentration of organic material residual. Therefore, it is important to monitor the water quality variation and adjusting the disinfection doses thereafter (Blom & Furuberg, 2013)

# 3 Method

Firstly, the method for the MBA will be presented, and thereafter the method for the QMRA.

## 3.1 MBA - method

The MBA method contains six steps, see Figure 4 in chapter 2.2. These six steps will in this chapter be described for the current study.

### 3.1.1 Raw water quality

The determination of raw water quality is ideally determined by the result from routine sampling from the last 3 years for the indicator organism E.coli (EC) and Clostridium perfringens (CP), and thereafter using Figure 7 to determine the raw water quality (Ødegaard et al., 2014). However, for the current study no data from sampling is available, although information about wastewater discharge is known, and then the following reasoning can be applied "*If there are wastewater discharges (treated or untreated) directly to the water source one should go directly to the D-category path whatever is the findings of E.coli and Clostridium perfringens from the routine analysis sampling program*" (Ødegaard et al., 2014). Since the microbial raw water quality of the Tano River is assumed to be low, Dc is chosen.

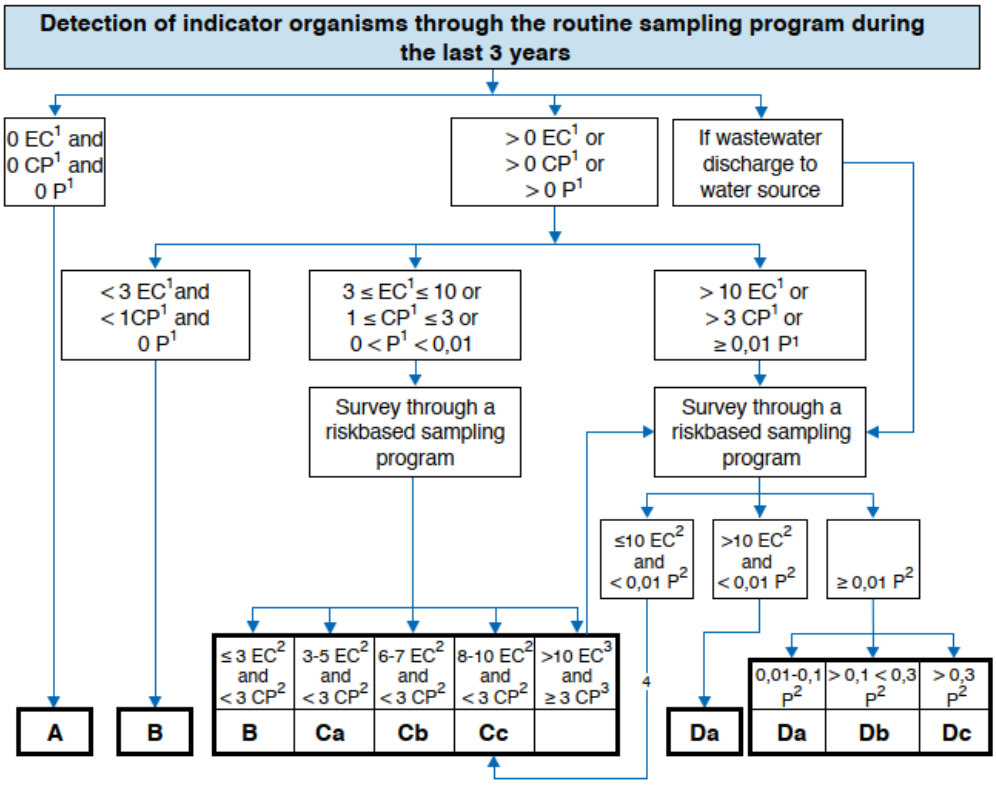


*Figure 7. Determination of raw water quality level* (Ødegaard et al., 2014) .

### 3.1.2 Barrier level required

Depending on the number of persons connected to the drinking water system and on the raw water quality level from the previous step, the barrier level can be determined from the Table 3 below (Ødegaard et al., 2014). Since the current WTP will have 400 000 persons connected, and Dc is chosen from previous steep, the barrier level marked in green in Table 3 is chosen. This barrier level required means that 6 log reduction of bacteria, 6 log reduction of viruses and 5 log reduction of parasites are required in total, and this will be achieved by various barrier through the WTP system.

*Table 3. Barrier level required depending on raw water quality and number of consumers, b stand for bacteria, v for viruses, p for parasites.*

| Size of water system | | Raw water quality level | | | |
|---|---|---|---|---|---|
| | | A | B | C | D |
| < 1000 persons connected | Barrier level required | 3.0b + 3.0v + 2.0p | 4.0b + 4.0v + 2.0p | a. 4.5b + 4.5v + 2.5p<br>b. 4,5b + 4,5v + 2,75p<br>c. 4,5b + 4,5v + 3,0p | a. 5.0b + 5.0v + 3.0p<br>b. 5.0b + 5.0v + 3.5p<br>c. 5.0b + 5.0v + 4.0p |
| 1000 - 10.000 persons connected | | 3.5b + 3.5v + 2.5p | 4.5b + 4.5v + 2.5p | a. 5,0b + 5,0v + 3,0p<br>b. 5,0b + 5,0v + 3,25p<br>c. 5,0b + 5,0v + 3,5p | a. 5.5b + 5.5v + 3.5p<br>b. 5.5b + 5.5v + 4.0p<br>c. 5.5b + 5.5v + 4.5p |
| > 10.000 persons connected | | 4.0b + 4.0v + 3.0p | 5.0b + 5.0v + 3.0p | a. 5,5b + 5,5v + 3,5p<br>b. 5,5b + 5,5v + 3,75p<br>c. 5,5b + 5,5v + 4,0p | a. 6.0b + 6.0v + 4.0p<br>b. 6.0b + 6.0v + 4.5p<br>c. 6.0b + 6.0v + 5.0p |

### 3.1.3 Catchment area and water source barriers

If there are barrier actions present, log-credits may be given. Barrier actions concerns the following (Ødegaard et al., 2014):

- *"Physical barrier actions*
- *Restrictions on the activity in the catchment area and water source*
- *Improved raw water quality actions"*

For the current study no barrier actions are assumed to be present, therefor no log credits are applied from this step.

### 3.1.4 Particle removal barriers

Different treatment processes vary in efficiency concerning particle removal or separation of microorganisms (Ødegaard et al., 2014). Table 4 shows the log-credits for each pathogen for each treatment alternative. In the current study conventional treatment with coagulation, flocculation, sedimentation, and filtration is used and are marked in green see Table 4.

*Table 4. Log-credit for particle separation* (Ødegaard et al., 2014).

| Particle separation method | Log-credit |
|---|---|
| Rapid sand filtration without coagulation (filtration rate < 7,5 m/h)[1)] | 0.5b + 0.25v +0.5p |
| Membrane (MF) filtration[2)] | 2.0b + 1.0v + 2.0p |
| Membrane (UF) filtration[3)] | 2.5b + 2.0v + 2.5p |
| Membrane (NF) filtration[4)] | 3.0b + 3.0v + 3.0p |
| Slow sand filtration (filtration rate < 0,5 m/h) | 2.0b + 2.0v + 2.0p |
| Coagulation/direct filtration (media-filter)[5)] | 2.25b + 1.5v + 2.25p |
| Coagulation/direct filtration (media-filter)[6)] | 2.5b + 2.0v + 2.5p |
| Coagulation + sedimentation (or flotation) + filtration[6] | 2.5b + 1.75v + 2.5p |
| Coagulation + sedimentation (or flotation) + filtration[6] | 2.75b + 2.25v + 2.75p |
| Coagulation/membrane MF filtration[6)] | 3.0b + 2.5v + 3.0p |
| Coagulation/membrane UF filtration[6)] | 3.0b + 3.0v + 3.0p |

### 3.1.5 Disinfection barriers

The $\log_{10}$-reduction from the chlorination process depend on the Ct-value. However, the maximum $\log_{10}$-reduction for final disinfection is limited to 4b + 4v +3p (Ødegaard et al., 2014). For calculations on Ct-value and final $\log_{10}$-reduction from the chlorination disinfection see Appendix 1.

### 3.1.6 Overall barrier status

The final step is to evaluate if the barrier status is sufficient or not, if the barriers levels in steps 3,4 and 5 are enough to disarm the pathogen levels.

## 3.2 QMRA – method

For the QMRA analysis the tool is built using the software Analytica. Firstly, the characterization of raw water and pathogen concentrations was inserted into the QMRA tool. Since this is a theoretical study no such pathogen data is available, therefore the pathogen concentrations were estimated using other methods.

The review article "*The use of quantitative microbial risk assessment to estimate the health risk from viral water exposures in sub-Saharn Africa: A review*" investigates the occurrence of viruses in sub-Saharan African countries, and Ghana was one of the countries studied (Van Abel & Taylor, 2018). The concentrations were investigated by data collection from several different studies that had perform microbial analysis. For Norovirus in Ghana in surface water in floods or drains the mean concentration was $5.30*10^4$ /100 ml and was used as input value in the QMRA (Van Abel & Taylor, 2018). However, only a small share of this concentration is infectious, for Norovirus, assuming 1 in 1000 being infectious (Odhiambo et al., 2023).

For bacteria and parasites, the data is more challenging, since very limited number of studies have been performed analysing these microorganisms in Ghana. In addition, as previously mentioned there is a weak correlation between indicator organisms and pathogens. Therefore, some assumptions were made to estimate the concentration of bacteria and parasites in the Tano River.

Upstream the suggested WTP at the Tano River 10 000 people are assumed to affect the river in the upstream catchment area. Of these people, 5 % are assumed to be

infected with E. coli O157 and 5 % by Cryptosporidium. This assumption is plausible since there is a lack of wastewater collection in the area. Only a fraction of faecally infected water is assumed to reach the Tano River untreated, and the remaining water is assumed to most likely infiltrate into the ground or be kept in temporary pits. Since there is a large uncertainty here, two scenarios were assumed: 20 % and 50 % respectively of faecally infected water reaching the river.

Each person is assumed to produce 300 g faeces per day. Further, according to Livsmedelsverket a typical concentration of E. coli in faeces is 10-100 million cells per gram faeces (Livsmedelsverket, 2022). For Cryptosporidium the concentration is about the same, $10^8$ for each gram om faeces (Livsmedelsverket et al., 2017). Only 8 % of the E. coli bacteria is considered pathogenic, i.e. E. coli O157 (Machdar et al., 2013). In addition, the decay rate of E. coli is quite rapid outside the human body, therefore only 1 % is assumed not being inactivated. Cryptosporidium on the other hand is more resistance and a larger fraction is pathogenic, for this reason 50 % is assumed to be pathogenic. A summary of the assumptions and calculations of pathogenic concentrations can be seen in Appendix 2. The pathogen concentrations used as input to the QMRA modelling can be seen below in Table 5 and Table 6.

The flow in the river also effects the concentration of pathogens. At low flow periods the concentration of pathogens will be higher due to less dilution compared to normal or high flow periods (Amisah & Nuamah, 2014). From the hydrological institute in Accra the flow in the Tano River is obtained, see the hydrograph in Figure 8 below (The hydrological Institute, 2022). The minimum flow was assumed to 3 $m^3$/s (used in the worst case scenario) and a medium flow of 6 $m^3$/s (used for the best case scenario) based on the hydrograph below.

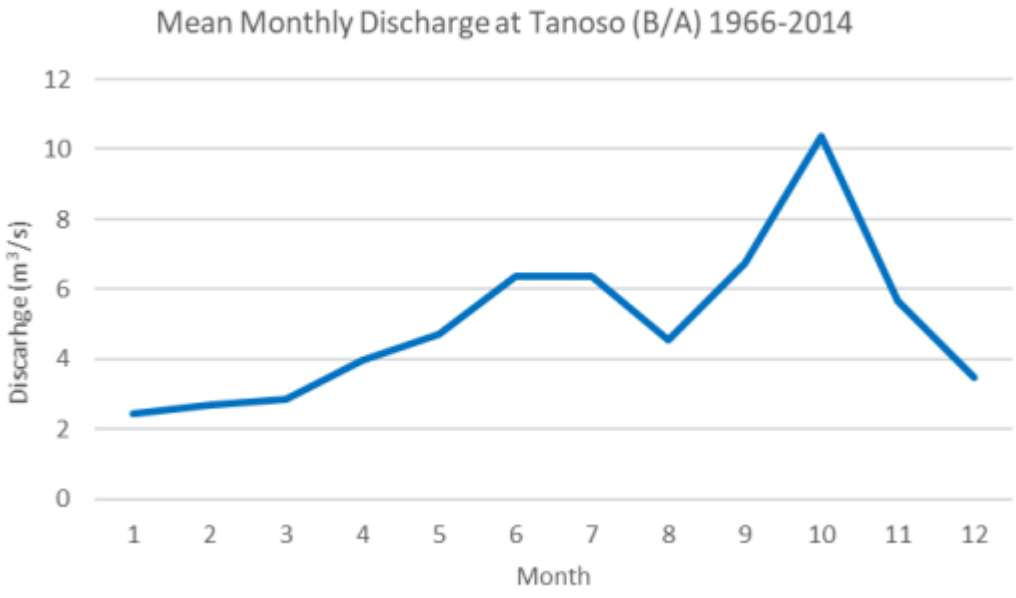


*Figure 8. Seasonal River Flow at Abeim Bridge in Tanoso (James & Otto, 2023).*

### 3.2.1 Water quality scenarios

As mentioned above two scenarios were made, described below:

*Worst case scenario:*

- 50 % of the wastewater reaches the river water.
- Minimum flow, set to 3 $m^3$/s.

This resulted in the following pathogen concentration see Table 5 (see Appendix 2 for detailed calculations):

*Table 5. Pathogen concentration for worst-case scenario.*

| Pathogen | E. coli O157 | Cryptosporidium | Norovirus |
|---|---|---|---|
| Infectious Pathogens/liter | 23 | 14 500 | 530 |

*Best case scenario:*

- 20 % of the wastewater reaches the river water.
- Medium flow, set to 6 $m^3$/s.

This resulted in the following pathogen concentrations see Table 6 (see Appendix 2 for detailed calculations):

*Table 6. Pathogen concentration for best-case scenario.*

| Pathogen | E. coli O157 | Cryptosporidium | Norovirus |
|---|---|---|---|
| Infectious Pathogens/liter | 5 | 2 890 | 530 |

The selected standard treatment process was applied into the QMRA tool, and the treatment processes of interest are: the conventional treatment (coagulation, sedimentation and filtration) and final disinfection using calcium hypochlorite (chlorination).

Lastly, the volume of drinking water consumed were inserted into the QMRA tool, the exposure of ingested water volume per person and day was set to 1.0 L, based on a study that concluded in general people drink 5 glasses of water in 24 hours and one glass contains 200 ml of water (Säve-Söderbergh et al., 2017).

# 4 Result

Firstly, the result and the procedure for the MBA will be presented, and thereafter for the QMRA.

## 4.1 MBA – result

The following steps are in accordance with the MBA guideline, and each step's $\log_{10}$-reduction, or log-credits are based on values that have been tabulated according to the MBA guideline (Ødegaard et al., 2014), see also 3.1 MBA - method.

### 4.1.1 Determination of the water quality level – the Tano River

Since there is an obvious risk of wastewater discharge to the Tano River, a worst-case scenario, of pathogen levels in the raw water, is chosen i.e. is class Dc in the raw water class table in MBA, see Figure 7. The WTP is planned to supply around 400 000 people, which resulted in the following barrier levels required, see also Table 3 (Ødegaard et al., 2014):

$$6.0b + 6.0v + 5.0p$$

This means that a 6 $\log_{10}$-reduction of bacteria and virus is needed, and 5 $\log_{10}$-reduction of parasites.

### 4.1.2 Particle separation measures

The particle separation process in the WTP is the conventional treatment processes (coagulation, flocculation, lamella sedimentation and rapid sand filtration) which corresponds to the category:

"*Coagulation + sedimentation (or flotation) + filtration*" (Provided turbidity in produced water < 0.2 NTU on-line monitored) (Ødegaard et al., 2014). This gives following $\log_{10}$-reduction:

$$2.5b + 1.75v + 2.5p$$

That $\log_{10}$-reduction can be deducted depending on lack of operation control monitoring actions. However, the on-line monitoring is assumed to be adequate, therefore no deduction will be necessary here.

### 4.1.3 Disinfection

The necessary $\log_{10}$-reduction that the final disinfection process need to manage is 3.5 for bacteria, 4.25 for viruses, and 2.5 for parasites, see Table 7.

*Table 7. Necessary $\log_{10}$-reduction for disinfection.*

| **Need of disinfection** | | | |
|---|---|---|---|
| | Bacteria | Viruses | Parasites |
| Barrier level required | 6 | 6 | 5 |
| Particle removal | -2.5 | -1.75 | -2.5 |
| Necessary $\log_{10}$-reduction | 3.5 | 4.25 | 2.5 |

For the disinfection treatment the pH will be below 7 (the same as after the coagulation and flocculation) and the temperature in the water around 26 degrees (Larbi et al., 2022). Calculations of Ct value, contact time in the tank, dosage of free chlorine and calculated $\log_{10}$-reduction can be seen in Appendix 1. The calculation of Ct-value resulted in the following $\log_{10}$-reduction:

$$4.0b + 4.0v + 0.28p$$

The result after adding disinfection, show that the $\log_{10}$-reduction for viruses and parasites are not satisfactory, see Table 8 (the results should be negative if the barrier effects were enough).

*Table 8. Result for standard treatment.*

| **Overall barrier status** | | | |
|---|---|---|---|
| | Bacteria | Viruses | Parasites |
| Barrier level required | 6 | 6 | 5 |
| Particle removal | -2.5 | -1.75 | -2.5 |
| Disinfection | -4 | -4 | -0.28 |
| Total $\log_{10}$-reduction | -0.5 | 0.25 | 2.22 |

### 4.1.4 Improvements

Since the barrier status is not satisfactory, with the suggested standard WTP, improvements are needed. For this purpose, UV-disinfection is added to the treatment train to improve the barrier status, since UV is efficient on parasites, as presented in Table 2. An UV dose of 40 mJ/cm$^2$ is added giving the following $\log_{10}$-reduction (Ødegaard et al., 2014):

$$4.0b + 1.25v + 4.0p$$

After the improvements of adding of UV-disinfection, the final log-credit for the treatment is approved, al values are negative which means that the barrier effect is sufficient, see result in Table 9.

*Table 9. Result with improved treatment.*

| **Adding UV, 40 mJ/cm2** | | | |
|---|---|---|---|
| | Bacteria | Viruses | Parasites |
| Barrier level required | 6 | 6 | 5 |
| Particle removal | -2.5 | -1.75 | -2.5 |
| Disinfection | -4 | -4 | -0.28 |
| *UV* | -4 | -1.25 | -4 |
| Final $\log_{10}$-reduction $\sum$ | -4.5 | -1 | -1.78 |

In conclusion the MBA analyse showed that standard (traditional) water treatment is not providing sufficient microbial barriers, see Table 8. However, if improvements are made, by adding UV-disinfection the treatment can reach sufficient levels, see Table 9.

## 4.2 QMRA – result

Firstly, the characterization of risk for the worst-case scenario will be presented, thereafter for the best-case scenario. In addition, the maximum load of pathogens/liter that the standard treatment can handle will be analysed. Lastly the $\log_{10}$-reduction for each treatment process in the QMRA tool will be presented.

### 4.2.1 Characterization of risk – Worst case scenario

With input data from Table 5 for each pathogen, the risk of daily infection at the 50 % percentile value was determined. Three different scenarios were tested,

(1) normal treatment operation

then two scenarios with suboptimal treatment:

(2) fail conventional treatment
(3) fail chlorination treatment, see Table 10 below.

*Table 10. Probability of daily infection, for the worst-case scenario.*

| $P_{daily}$ (50 % percentile) | E.coli O157 | Norovirus | Cryptosporidium |
|---|---|---|---|
| $P_{normal}$ (1) | 8.4E-08 | 1.3E-06 | 7.2E-01 |
| $P_{sub\_conventinal}$ (2) | 1.0E-05 | 1.3E-03 | 1.0E+00 |
| $P_{sub\_chlorination}$ (3) | 4.1E-04 | 3.1E-01 | 4.5E-01 |

Equation 1 (T, Pettersson, 24 May 2023) below was applied to determine the probability of annually infection rate. The assumption here was that during a year: 351 days of normal functioning treatment, and 7 days of conventional treatment failure and 7 days of chlorination treatment failure. The final row in Table 11 displays the outcome.

*Equation 1*

$$P_{Annual} = 1 - ((1 - P_{inf.normal)})^{t\,normal}(1 - P_{fial.conventional)})^{t\,fail}(1 - P_{fail.clorination)})^{t\,fail}$$

*Table 11. Probability of infection annually. Using Equation 1. Worst case scenario data. Standard treatment.*

| $P_{annual}$ | | | |
|---|---|---|---|
| Scenario | E. coli O157 | Norovirus | Cryptosporidium |
| Normal treatment, 365 days a year | 3.1E-05 | 4.8E-04 | 1.0E+00 |
| Fail conventional, 7 days, and normal treatment 358 days | 1.0E-04 | 9.3E-03 | 1.0E+00 |
| Fail chlorination, 7 days, and normal treatment 358 days | 2.9E-03 | 2.1E-02 | 1.0E+00 |
| Fail conventional, 7 days, fail chlorination 7 days, and normal treatment 351 days | 3.0E-03 | 9.2E-01 | 1.0E+00 |

In Ghana there is no acceptable health risk value available and therefore we use the US EPA's acceptable value of one infected consumer per 10 000 each year, i.e. $10^{-4}$ /year (Pettersson et al., 2017). In Table 11, red numbers indicate the health risk limit

was exceeded. As also can be seen, this limit is not reached for the standard treatment and the worst-case scenario data, even if there is normal treatment operation al year around. The treatment plant is specifically vulnerable for Cryptosporidium.

#### 4.2.1.1 Improvements of the WTP with additional microbial barrier for worst case scenario

To improve the microbial barrier at the WTP, UV was added, since UV is efficient on parasites, as presented in Table 2. Same UV dose as in the MBA, 40 mJ/cm$^2$, was used and resulted in the following probability of infection annually, see Table 12.

*Table 12. Probability of infection annually. Using Equation 1. Worst case scenario data and additional UV.*

| $P_{annual}$ | | | |
|---|---|---|---|
| Scenario | E. coli O157 | Norovirus | Cryptosporidium |
| Normal treatment, 365 days a year | 9.01E-11 | 2.83E-08 | 3.54E-01 |
| Fail conventional, 7 days, and normal treatment 358 days | 2.76E-10 | 5.43E-07 | 1.00E+00 |
| Fail chlorination, 7 days, and normal treatment 358 days | 1.31E-08 | 1.41E-04 | 3.52E-01 |
| Fail UV, 7 days, and normal treatment 358 days | 6.14E-07 | 9.17E-06 | 1.00E+00 |
| Fail conventional 7 days, fail chlorination 7 days, fail UV 7 days, and normal treatment 344 days | 6.27E-07 | 1.51E-04 | 1.00E+00 |

The risk of infection was reduced moderately by the addition of UV-disinfection. For E. coli O157 the risk is now below the tolerable limit of $10^{-4}$/year, and Norovirus is almost acceptable for all scenarios as well, but most sensitive for chlorination failure. However, Cryptosporidium is still very critical. Therefor an additional microbial barrier was added in the QMRA model, ultrafiltration (UF). Here UF with a pore size of 10-40 nm was chosen, and the calculated result is seen in Table 13. The pore size was chosen since it works efficiently on parasites and viruses (Svenskt Vatten, 2010a). However, acceptable levels of infection risk still aren't reached for Cryptosporidium.

*Table 13. Probability of infection annually. Using Equation 1. Worst case scenario data and additional UV and ultrafiltration.*

| $P_{annual}$ | | | |
|---|---|---|---|
| Scenario | E.coli O157 | Norovirus | Cryptosporidium |
| Normal treatment, 365 days a year | 0.00E+00 | 2.71E-10 | 3.11E-05 |
| Fail conventional, 7 days, and normal treatment 358 days | 2.02E-14 | 2.59E-07 | 5.65E-02 |
| Fail chlorination, 7 days, and normal treatment 358 days | 1.29E-12 | 1.72E-06 | 5.55E-02 |
| Fail UV, 7 days, and normal treatment 358 days | 5.18E-11 | 3.45E-07 | 5.63E-02 |
| Fail UF, 7 days, and normal treatment 358 days | 1.78E-12 | 2.55E-07 | 6.29E-02 |
| Fail conventional 7 days, fail chlorination 7 days, fail UV 7 days, fail UF 7 days, and normal treatment 337 days | 5.49E-11 | 1.56E-06 | 9.95E-03 |

### 4.2.2 Characterization of risk – Best-case scenario

For the best-case scenario, with input data from Table 6, with medium flow and smaller share of faeces reaching the water (20 %) the result was improved. The probability of daily infection was calculated in the same way as for the worst scenario, but in this sub-chapter only the calculated probability of infection annually will be presented. Firstly, a simulation of the health risk of a standard WTP was done in QMRA tool, see result in Table 14 below. For E. coli O157 the risk of infection result is almost acceptable, close to the limit of $10^{-4}$/year, for Norovirus the risk is higher and for Cryptosporidium it is very critical. Wort mentioning is that even for normal functioning treatment all year around, Cryptosporidium is posing high risk.

*Table 14. Probability of infection annually. Using Equation 1. Best case scenario. Standard treatment.*

| $P_{annual}$ | | | |
|---|---|---|---|
| Scenario | E.coli O157 | Norovirus | Cryptosporidium |
| Normal treatment, 365 days a year | 5.6E-06 | 4.9E-04 | 1.0E+00 |
| Fail conventional, 7 days, and normal treatment 358 days | 2.1E-05 | 9.7E-03 | 1.0E+00 |
| Fail chlorination, 7 days, and normal treatment 358 days | 6.7E-04 | 5.2E-03 | 1.0E+00 |
| Fail conventional, 7 days, fail chlorination 7 days, and normal treatment 351 days | 6.9E-04 | 9.2E-01 | 1.0E+00 |

#### 4.2.2.1 Improvements of the WTP with additional microbial barrier for best - case scenario

In the next simulation, UV-disinfection (40 mJ/cm$^2$) was added in the treatment train which resulted in much lower risk for E. coli O157 and Norovirus, however for Cryptosporidium the risk is still very high see Table 15. Indicating that the UV is not enough to reduce the risk below the acceptable limit.

*Table 15. Probability of infection annually. Using Equation 1. Best case scenario. Standard treatment plus UV disinfection.*

| $P_{annual}$ | | | |
|---|---|---|---|
| Scenario | E.coli O157 | Norovirus | Cryptosporidium |
| Normal treatment, 365 days a year | 1.88E-11 | 2.61E-08 | 5.57E-02 |
| Fail conventional, 7 days, and normal treatment 358 days | 5.78E-11 | 5.48E-07 | 8.99E-01 |
| Fail chlorination, 7 days, and normal treatment 358 days | 2.27E-09 | 1.44E-04 | 5.65E-02 |
| Fail UV, 7 days, and normal treatment 358 days | 9.21E-08 | 8.76E-06 | 8.59E-01 |
| Fail conventional 7 days, fail chlorination 7 days, fail UV 7 days, and normal treatment 344 days | 9.44E-08 | 1.53E-04 | 9.85E-01 |

The last simulation included both UV-disinfection (40 mJ/cm$^2$) and ultrafiltration (pore size of 10-40 nm), which reduced the risk and improved the DW quality see Table 16. For normal treatment operation all year around the risk level is below the tolerable risk limit of infection, $10^{-4}$/year. However, Cryptosporidium is sensitive to failure regarding conventional treatment (including chemical precipitation), failing of UV and ultrafiltration. Although, the risk levels are considerably lower than for the worst-case scenario see Table 13.

*Table 16. Probability of infection annually. Using Equation 1. Best case scenario. Standard treatment plus UV disinfection and ultrafiltration.*

| $P_{annual}$ | | | |
|---|---|---|---|
| Scenario | E.coli O157 | Norovirus | Cryptosporidium |
| Normal treatment, 365 days a year | 0.00E+00 | 2.79E-10 | 8.29E-06 |
| Fail conventional, 7 days and normal treatment 358 days | 3.11E-15 | 5.54E-09 | 2.87E-04 |
| Fail chlorination, 7 days, and normal treatment 358 days | 2.48E-13 | 1.44E-06 | 8.31E-06 |
| Fail UV, 7 days, and normal treatment 358 days | 1.12E-11 | 9.28E-08 | 1.45E-04 |
| Fail UF, 7 days, and normal treatment 358 days | 3.82E-13 | 7.74E-10 | 1.37E-03 |
| Fail conventional 7 days, fail chlorination 7 days, fail UV 7 days, fail UF 7 days, and normal treatment 337 days a year | 1.19E-11 | 1.54E-06 | 1.78E-03 |

### 4.2.3 Maximum load that the standard treatment can handle

It was also investigated how many pathogens/liter the standard treatment could handle in the raw water and still result in acceptable risk. Possibly the water quality could be better than what is assumed in the previous scenarios (see chapter Water quality scenarios), or in addition the water quality could be improved in the future, e.g. implementing improved sanitation upstream the raw water intake. If the pathogen concentrations were decreased as presented in Table 17 (compare this with Table 5 and Table 6), tolerable risk levels ($10^{-4}$/year) were reached if no failure happens during the year see Table 18 (normal treatment). Furthermore, almost tolerable risk levels were reached even if the conventional treatment fail for one week, but the risk for Cryptosporidium is slightly over the limit. If the chlorination would fail for a week the risk is worst for Norovirus and also E.coli O157 as presented in the red numbers in Table 18.

*Table 17. Hypothetical decreased pathogen concentrations.*

| Pathogen | E. coli O157 | Norovirus | Cryptosporidium |
|---|---|---|---|
| Infectious pathogens/liter | 1 | 1 | $5*10^{-4}$ |

*Table 18. Probability of infection annually. Using Equation 1. Standard treatment. Load from Table 17.*

| $P_{annual}$ | | | |
|---|---|---|---|
| Scenario | E. coli O157 | Norovirus | Cryptosporidium |
| Normal treatment 365 days a year | 1.3E-06 | 8.9E-07 | 1.1E-05 |
| Fail conventional, 7 days, and normal treatment 358 days | 4.0E-06 | 1.7E-05 | 4.0E-04 |
| Fail chlorination, 7 days, and normal treatment 358 days | 1.8E-04 | 4.9E-03 | 1.1E-05 |
| Fail conventional, 7 days, fail chlorination 7 days, and normal treatment 351 days | 1.8E-04 | 4.9E-03 | 4.0E-04 |

### 4.2.4 $Log_{10}$-reduction for each treatment step in the QMRA tool

The result gained from QMRA model, is dependent on the $log_{10}$-reduction of pathogens in each treatment step, which is presented in Table 19.

*Table 19. $Log_{10}$-reduction for each treatment process used in the QMRA tool.*

mid — Mid Value of Log-reduktion av ingående beredningsprocesser

Referenspatogener i modellen — Totals

Valda beredningsprocesser — Totals

| | Kemisk fällning | Membranfilter | UV-desinfektion | Desinfektion med fritt klor | Totals |
|---|---|---|---|---|---|
| E. coli O157:H7 | 2.1 | 4 | 5.5 | 3.8 | 15 |
| Norovirus | 3 | 2 | 4.2 | 5.5 | 15 |
| Cryptosporidium | 3.2 | 4 | 3 | -8.9e-016 | 10 |

# 5 Discussion

Interpretation of the result and different aspects that may have affected the result will be discussed in this chapter. Additionally, the result of the MBA and the QMRA analysis are different; the possible reasons for this will also be examined.

## 5.1 MBA procedure

The MBA guideline is unfortunately only designed for Nordic countries conditions, this is important to reflect on while using the guideline for other countries. However, the guideline is still relevant to use if differences are taken into consideration. Things that can have affected the MBA for the WTP will here be discussed.

Since there is a high risk that wastewater is being washed into the river (Ghana statistical service, 2022) the microbial quality must be assumed to be the worst-case scenario when performing the MBA. Therefor the highest barrier level required was chosen for the raw water (6b+6v+5p), however this might still be an underestimation. In Nordic countries the water quality is in generally good, and the worst-case water in Nordic countries might still be better than the water quality for the Tano River.

In Nordic countries the temperature for chlorination is assumed to be between 0.5 and 4 degrees (Svenskt Vatten, 2015). However, the water temperature in the Tano River is around 26 degrees (Larbi et al., 2022). The water temperature affects the chlorination treatment (García-Ávila et al., 2020). It has been proven that if the temperature increases, the reaction rate of chlorine with water also will increase. A study performed in Ecuador showed this correlation, as can be seen in Figure 9 below (García-Ávila et al., 2020). Therefore, the temperature of 26 degrees in the water is not a disadvantage when it comes to chlorination.

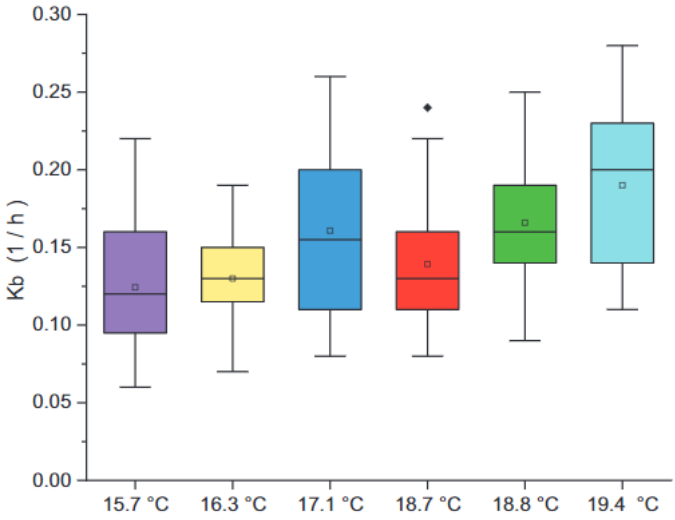


*Figure 9 The graph shows the variation of the decay of chlorination, the constant Kb as a function of the monthly average temperature* (García-Ávila et al., 2020).

For the standard WTP two microbial barriers are utilised, conventional treatment using chemical precipitation and chlorination. However, even if a combination of separation barrier and inactivation barrier are applied, the MBA result showed that these barriers are not enough to reduce the microbial load in the Tano River. More

barriers/measures were needed to reach an approved barrier level, for virus and parasites, see Table 9. Therefor UV-disinfection was added to the treatment.

The $log_{10}$-reduction caused by UV-disinfection depends on the UV-dose as well as whether adenovirus is taken into account or not (Ødegaard et al., 2014). In Norway and the Nordic countries the risk of being infected by Adenovirus is seen as small, and that the population have good immunity to such virus, therefor it is not motivated to design UV-facilities to inactivate Adenovirus in Norway (Ødegaard et al., 2014). However, the conditions cannot be assumed to be the same in Ghana, and there is limited information on adenovirus, however WHO states *"… adenoviruses is a major cause of gastroenteritis worldwide, notably in developing communities*" (WHO, 2017). Therefore, the $log_{10}$-reduction for Adenovirus was chosen, to be on the safe side, see Table 20 below.

*Table 20. Maximum $log_{10}$-reduction for UV, at varying UV-dose* (Ødegaard et al., 2014).

| Biodosimetric dose | Virus excl. Adenovirus | Virus based on Adenovirus |
|---|---|---|
| 40 mJ/cm² | 4.0b + 3.5v + 4.0p | 4.0b + 1.25v + 4.0p |
| 30 mJ/cm² | 3.5b + 3.0v + 3.5p | 3.5b + 1.0v + 3.5p |
| 25 mJ/cm² | 3.0b + 2.5v + 3.0p | 3.0b + 0.75v + 3.0p |

1) Provided that the UV-doses are biodosimetrically determined
2) When analyzing existing systems that have been approved with an average dose of 30 mJ/cm², the maximum log-reduction is 3,0b + 2,5v + 3,0p (3b + 0,75v + 3p when virus requirement is based on Adenovirus).

In section 4.1.2 *Particle separation measures*, it is assumed that no deduction is needed for the WTP since the operation control monitoring is assumed to be adequate. This means that there is "*On-line monitoring of the treated water quality with follow up actions to comply with set limit values*" and that there is *"…an automatic closing of raw water supply until the cause of abnormality is found and normal operation is restored*", *"Continuous monitoring of the electricity supply with follow-up actions at lapse of electricity supply"* and that *"…activating automatic start-up of emergency el-supply generator and/or UPS at failure of electricity supply"*(Ødegaard et al., 2014 ). However, due to periods of electricity shortage in Ghana (Dye, 2023) these measures might not be possible to fulfil, in that case, a specific portion of the permissible $log_{10}$-reduction must be subtracted.

## 5.2 QMRA

The result differs between the MBA and the QMRA. For the MBA the result reach acceptable levels if UV-disinfection is added to the treatment train. However, for the QMRA both UV-disinfection and ultrafiltration are needed to reach almost acceptable risk levels for the *best-case scenario*. The reason why the result differs between the two analyses may depend on several things. In comparison the QMRA is more complex and take more aspects into consideration than the MBA. In the MBA the raw water quality is assumed to be the worst type that possibly can be chosen, but no specific pathogen data is needed for this analysis. For QMRA on the other hand, specific pathogen concentration on the raw water must be used.

QMRA and MBA distinguish when it comes to $log_{10}$-reduction for each treatment step, Table 19 show the log reduction used in the QMRA tool and Table 9 shows the log reduction in the MBA. Below in Table 21, a summary of these reductions are presented in order to make it easier to compare. The $log_{10}$-reduction for

Cryptosporidium in the MBA is 6.78 and for the QMRA it is 6.2. Even if the $log_{10}$-reduction is quite similar, the MBA result shows that this $log_{10}$-reduction is enough to reach acceptable levels see Table 9. While for the QMRA the $log_{10}$-reduction for these treatment steps is not enough, ultrafiltration is also needed to reach almost acceptable risk levels. The reason for this could possibly be that even if the worst water quality and highest barrier level required was chosen in the MBA, it still doesn't match the raw water quality in Ghana. The MBA might underestimate the number of pathogens in the river and therefore less treatment is needed compared to the QMRA.

*Table 21. $Log_{10}$- reduction for MBA and QMRA for each treatment step and pathogen.*

| | E.coli O157 | | Norovirus | | Cryptosporidium | |
|---|---|---|---|---|---|---|
| | MBA | QMRA | MBA | QMRA | MBA | QMRA |
| Conventional treatment, chemical precipitation | 2.5 | 2.1 | 1.75 | 3 | 2.5 | 3.2 |
| Chlorination | 4 | 3.8 | 4 | 5.5 | 0.28 | 0 |
| UV-disinfection | 4 | 5.5 | 1.25 | 4.2 | 4 | 3 |
| **Total $log_{10}$-reduction** | **10.5** | **11.4** | **7** | **12.7** | **6.78** | **6.2** |

The pathogen concentrations used in the QMRA are, however, uncertain. If pathogen sampling would have been a common practice in Ghana, Africa, more data would have been available, and the result could be presented with more accuracy and certainty. However, not enough pathogen sampling was found on the Tano River and the QMRA analysis had to be adapted for the current circumstances. Therefore, some estimations and assumptions had to be done for the input data. In further studies, it would of course be preferably if pathogen sampling could be performed. Otherwise, the assumptions also could be more closely considered, for example investigate the runoff area to the river more closely.

In Table 17 the pathogen concentrations that the standard treatment can handle are presented, requiring that normal treatment works all year around. Important to observe is that these concentrations are considerably lower than the concentrations estimated in worst and best-case scenario (Table 5 and Table 6). If comparing with the worst-case scenario pathogen concentration, E. coli need to decrease 96 %, and Norovirus and Cryptosporidium must decline significantly. So, the pathogen concentration needs to be considerably lower if the standard treatment containing conventional treatment with chemical precipitation and chlorination should be enough see Table 18. As a result, the water quality needs to be significantly improved for the standard treatment process to reduce the microbial risks to acceptable levels. Therefore, even if there is an uncertainty in the pathogen concentrations, it is quite certain that additional microbial barriers apart from the conventional treatment and chlorination are needed to guarantee safe drinking water quality.

For E.coli O157 and for Cryptosporidium, the number of pathogens/liter are reduced with 80 % between the worst and best-case scenario (see Table 5 and Table 6). However, the number of Norovirus stays the same, it would of course be preferably if Norovirus also was lowered with 80 % for the good-case scenario. Although this does not affect the result very much, if looking at the result from the QMRA for the bets-

case scenario in Table 16, the risk level for Norovirus is below the tolerable risk limit of infection, $10^{-4}$/year, while Cryptosporidium is still critical. Additionally, the concentration of Norovirus must go from 530 pathogens/liter to 1 pathogens/liter if the standard treatment containing conventional treatment with chemical precipitation and chlorination, would be enough as can be seen in Table 17 and Table 18.

From Table 18 it can also be concluded that E. coli O157 and Norovirus are most sensitive to chlorination, and if this treatment step fails the health risk levels for theses pathogens increases. For Cryptosporidium the conventional treatment is critical.

## 5.3 Choice of additional treatment

The MBA result showed that additional treatment processes was needed to inactivate viruses but especially parasites, since the standard treatment was not providing enough $\log_{10}$-reduction for these microorganisms. UV-disinfection was then chosen since it effectively inactivates parasites, presented in Table 2 (Ødegaard et al., 2014). The parasites Giardia and Cryptosporidium is for instance very resistant against chlorination, therefore UV-disinfection is a good compliment to reach sufficient $\log_{10}$-reduction (Svenskt Vatten, 2011b).

Unfortunately, the standard water treatment in combination with UV-disinfection was not enough to reach acceptable risk levels in the QMRA analyses. For the parasite Cryptosporidium more treatment was needed, therefore ultrafiltration with the pore size 10-40 nm was suggested. Ultrafilter is also efficient in removing parasites, as can be seen in Table 1 (Ødegaard et al., 2014).

Another possible option is to extend the contact time for the chlorination, however since Cryptosporidium is almost resistant to chlorination it would not have improved the result. Chlorination only have an impact on Cryptosporidium with doses that would be so high that the water would not be safe to drink (Ministry of Water Resources, 2015). The effectiveness for chlorination can also be seen in Table 2. Commonly used disinfection methods and their efficiency regarding microorganism inactivation (Ødegaard et al., 2014).

If UV-disinfection or ultrafiltration would not function or if these barrier improvements are not made the risk of infection of parasites would increase. Cryptosporidium infection causes diarrhoea, nausea, fever and vomiting but are in generally self-limiting (WHO, 2017). However, the severity depends on immune status and age. For people that are immunocompromised, Cryptosporidium infection may be life-threatening. Giardia infection is similar, causing diarrhoea and abdominal cramps, but are in most cases self-limiting. However, for some people, otherwise healthy, it can be chronic and last over a year. In addition, severe cases can led to malabsorption deficiencie, especially among young children (WHO, 2017).

## 5.4 Future

Better protection of the watershed's areas along the Tano River is important if the water quality is going to be improved (Nyantakyi et al., 2013). Reduce the discharge of untreated wastewater is crucial for the microbial water quality (Amisah & Nuamah, 2014). A better water quality would reduce the need for complicated water treatment processes for the WTP and lower the risk for drinking water consumers.

Future climate change will have a negative impact on the Tano River's water availability. Unfortunately, higher temperatures will increase the evaporation, increase the frequency of droughts, and reduce the streamflow (Larbi et al., 2022). The climate scenario RCP4.5 indicate a streamflow decrease of 19.9 % and RCP8.5 scenario indicate a 37.5 % decrease. The capacity of the water infrastructure will possibly be hampered and the capacity lowered (Larbi et al., 2022). As mentioning in the background, lower river flow led to less dilution and higher concentration of solid waste (Amisah & Nuamah, 2014), and this will also have a negative impact on the microbial water quality and therefore better upstream control will be even more important in the future.

Even if the result in this study indicates that more treatment than suggested is recommended to lower the risk of infection, other aspects need to be considered as well. Limited finances need to be taken into consideration, decisions about improvements cannot be isolated from the practicability aspect (Ministry of Water Resources, 2015). The treatment might not be sufficient from a microbial point of view; however, the water might be much safer after treatment concerning chemical quality, regarding for example heavy metals. Therefore, further work should include a more comprehensive evaluation considering a wider perspective, including benefits, risks, and costs. With the primary goal of producing a safer drinking water for the people in Ghana and reduce the vulnerability to water related diseases.

# 6 Conclusions

The main purpose of the current study was to evaluate a standard WTP in Ghana with the Tano River as raw water source, from a microbial water quality perspective. This was investigated by performing an MBA and a QMRA analysis. The standard WTP included two microbial barriers, conventional treatment with chemical precipitation, and chlorination as disinfection. Due to lack of proper pathogen data, existing research in combination with carefully considered assumptions led to the final pathogen level used in the QMRA analysis.

The main result showed that the standard treatment was not sufficient, the risk of infection of viruses and parasites was too high. The result from the MBA showed that if UV-disinfection was added, the result would be tolerable. Then the microbial barriers would be sufficient for the current water quality that was assumed to be the worst possibly chosen. However, for the QMRA both UV-disinfection and ultrafiltration was needed to gain an almost acceptable result, although Cryptosporidium still is critical during suboptimal treatment, for the best-case scenario data. The reasons for the differences in the result between the MBA and the QMRA, are most likely dependent on how the raw water quality is characterised for the two methods. In the MBA the raw water quality is more roughly estimated, while for the QMRA the actual pathogen concentrations must be used.

The QMRA result also showed that Cryptosporidium is sensitive to process failure concerning the conventional treatment, UV-disinfection, and ultrafiltration. E.coli O157 and Norovirus are sensitive for chlorination failure.

The main uncertainty in the result is the raw water quality data, the concentrations of pathogens. To improve the QMRA, measurements on Cryptosporidium would be very beneficial since this pathogen is the most critical one. Additionally, if a specific location for this hypothetical standard WTP were decided, a more detailed investigation of the upstream area conditions could be performed, and then for example examine how much untreated wastewater that reaches the river. Also, in further studies, a wider risk assessment for the standard WTP could be performed, concerning the chemical quality, distribution network, and costs. With the purpose to direct the resources where they benefit the most.

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# Appendix

In appendix 1 the calculation for $\log_{10}$- reduction for the chlorination in the MBA is presented, and in appendix 2 the pathogen concentrations for the worst- and best-case scenario are calculated, for the QMRA analyses.

# Appendix 1

The $\log_{10}$-reduction from disinfection depend mainly on tree factors, the water flow, the organic matter content (TOC) and the Ct value. Calculations below is preformed according to the MBA-guideline.

$$IC_{chlorine} = 0.06 * TOC + 0.36 * C_{dose} + 0.08 * \left(\frac{C_{dose}}{TOC}\right) - 0.12 \qquad (A)$$

$$k_{chlorine} = 0.013 * TOC - 0.040 * C_i - 0.010 * \left(\frac{C_i}{TOC}\right) + 0.022 \qquad (B)$$

$$Ct = \left(\frac{C_i}{k}\right) * (1 - e^{-k*t}) \qquad (C)$$

$$t_{eff} = \left(\frac{V}{Q}\right) * F_h * F_s \qquad (D)$$

| | | |
|---|---|---|
| | Input data | |
| | Calculated values | |
| | Assumed values | |
| Cdose (Swedish maximum dos) | 1.0 | mg/l |
| TOC (After conventional treatment, TOC usually lays around 2 mg/l) | 2.0 | mg/l |
| | | |
| IC (calculated using equation A) | 0.4 | mg/l |
| | | |
| Ci=Cdose-IC | 0.6 | mg/l |
| Kchlorine (calculated using equation B) | 0.0 | |
| | | |
| C.t calculated (calculated using equation C) | 10.6 | mg/min/L |
| | | |
| | | |
| | | |
| Number of chambers in series | 1.0 | |
| Volume of tank, V | 600.0 | m3 |
| Flow (2 parallel tanks), Q | 19 | m3/min |
| Hydraulic factor, Fh (t10/T), Quite good PF | 0.7 | |
| Serial factor, Fs | 1.0 | |
| | | |
| Teff (calculated using equation D) | 22.0 | min |

To calculate the final $\log_{10}$-reduction the following equation was used:

$$log_{10}\text{reduction} = (n * \text{Ct. calculated})/\text{Ct. required} \quad \text{(E)}$$

The values for n and Ct.required are from tabulated values in the MBA guideline, and theses depends on the pH and the temperature. The pH is assumed to be below 7, and the temperature 4 degrees.

| | Assume pH<7, 4 degrees | | |
|---|---|---|---|
| | | | |
| | Bacteria | Virus | Parasite |
| n | 3.00 | 3.00 | 2.00 |
| Ct.required | 1.00 | 4.00 | 75.00 |
| Ct.calculated (from table above) | 10.6 | 10.6 | 10.6 |
| $\log_{10}$-reduction (calculated using equation E) | 31.70 | 7.93 | 0.28 |

The $\log_{10}$-reduction for the disinfection using chlorination was then determined to

$$31.7b + 7.93v + 0.28p$$

However according to the MBA guidelines there is a maximum $\log_{10}$-reduction for chemical disinfection: 4b+4v+3p, therefore the following $\log_{10}$-reduction was used:

$$4b + 4v + 0.28p$$

# Appendix 2

The pathogen concentrations for worst- and best-case scenario are here calculated, for the QMRA analyses.

Worst-case scenario, minimum flow 3 $m^3/s$ and 50 % of the wastewater reaches the river water.

| | | unit | |
|---|---|---|---|
| Flow (min) | **3** | $m^3/s$ | Input |
| Flow (medium) | | $m^3/s$ | Estimated/suggested |
| People upstream | 10 000 | pe | Calculated |
| Number of people infected | 0.05 | 5%. | |
| Faecal per person/day | 300 | g | |
| Number of pathogens/gram faeces | 100000000=1.0E+08 | E. coli or Cryptosporidium | (Livsmedelsverket, 2022) (Livsmedelsverket et al., 2017) |
| Share of faeces reaching the water | **0.5** | 50 %. | |
| Number of pathogen/day | 10 000*0.05*300*1.0E+08*0.5= =7.5E+12 | pathogen/day | |
| | | | |
| Flow | 3*60*60*24*1000=2.59E+08 | liter/day | |
| Pathogen/liter | 7.5E+12 /2.59E+08= 2.89E+04 | pathogen/liter | |

*Pathogen concentration calculation for the worst-case scenario. The numbers in bold were used as input data in the QMRA tool.*

| Pathogen | Pathogen/litter water |
|---|---|
| E. coli (from Table above) | 2.89E+04 |
| E. coli O157[1] | 2.89E+04 * 0.08*0.01= **23.1** |
| Cryptosporidium (from Table above) | 2.89E+04 |
| Infectious Cryptosporidium[2] | 2.89E+04*0.5= **1.45E+04** |
| Norovirus (from literature) | 530 000 |
| Infectious Norovirus[3] | 530 000*0.001=**530** |

[1] Explanation: Only 8 % of E.coli is considered pathogenic (Machdar et al., 2013), and due to rapidly decay outside the human body only 1 % is assumed to stay active.
[2] Explanation: 50 % of Cryptosporidium is assumed to be pathogenic, since they are more resistance, and a larger fraction is pathogenic.
[3] Explanation: For Norovirus, assuming 1 in 1000 can being infectious (Odhiambo et al., 2023).

Best-case scenario, medium flow 6 $m^3/s$ and 20 % of the wastewater reaches the river water.

| | | unit | |
|---|---|---|---|
| Flow (min) | | $m^3/s$ | Input from literature |
| Flow (medium) | **6** | $m^3/s$ | Estimated/suggested |
| People upstream | 10000 | pe | Calculated |
| Number of people infected | 0.05 | 5%. | |
| Faecal per person/day | 300 | g | |
| Number of pathogens/gram faeces | 100000000 | E. coli or Cryptosporidium | (Livsmedelsverket, 2022) (Livsmedelsverket et al., 2017) |
| Share of faeces reaching the water | **0.2** | 20%. | |
| Number of pathogen/day | 10000*0.05*300*1E+8*0.2= =3E+12 | pathogen/day | |
| | | | |
| Flow (medium) | 6*60*60*24*1000=5.18E+08 | l/day | |
| Pathogen/litter | 3E+12 / 5.18E+08= =5.79E+03 | pathogen/liter | |

*Pathogen concentration calculation for the best-case scenario. The numbers in bold were used as input data in the QMRA tool.*

| Pathogen | Pathogen/litter water |
|---|---|
| E. coli (from **Error! Reference source not found.**) | 5.79E+03 |
| E. coli O157[4] | 5.79E+03* 0.08*0.01=**4.63** |
| Cryptosporidium (from **Error! Reference source not found.**) | 5.79E+03 |
| Infectious Cryptosporidium [5] | 2.89E+04*0.5= **2.89E+03** |
| Norovirus, from literature: (Van Abel & Taylor, 2018). | 530 000 |
| Infectious Norovirus [6] | 530 000*0.001=**530** |

[4] Explanation: Only 8 % of E.coli is considered pathogenic (Machdar et al., 2013), and due to rapidly decay outside the human body only 1 % is assumed to stay active.
[5] Explanation: 50 % of Cryptosporidium is assumed to be pathogenic, since they are more resistance, and a larger fraction is pathogenic.
[6] Explanation: For Norovirus, assuming 1 in 1000 can being infectious (Odhiambo et al., 2023).

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