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A field study of the EmWat 4000

An evaluation of the performance of the emergency water treatment unit on the behalf of UNICEF, Ethiopia

Master Thesis
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1. The filter units of the EmWat 4000

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Summary

The subject for this thesis was based on a request to assist UNICEF, Ethiopia, in evaluating an emergency water treatment unit. Since June 2003 the purification system EmWat 4000 has been employed in different areas with water scarcity. An evaluation was needed to ensure that the system was effective and that the quality of the produced water was sufficient.

The goal for this master's work is therefore to evaluate the performance of the kit and identify shortcomings and possible adjustments for improvement. To achieve the goal the evaluation was divided into different parts: complementary tests of the water produced by three different EmWat 4000 units was conducted mainly to state the microbial quality; reports from the previous operations of the unit were summarised and evaluated for a wider understanding of the performance on different waters and under other circumstances; a full-scale test was conducted to measure the impact of the different adjustments available for controlling the process. Finally, an objective during the visit at the sites was to gather practical experiences and impressions to gain an understanding of how the system is operated as well as its shortcomings.

The EmWat 4000 kit is a compact water treatment system that is easy to transport and has the capacity to produce 4000 litres of potable water per hour from surface water. The system consists of four different purification processes: flocculation, sand filtration, activated carbon filtration, and chlorination. For the flocculation process different coagulation and flocculation tablets are included with the kit. Depending on the raw water quality the kind and number of tablets is chosen for best flocculation. The chlorine is dosed in a chamber where hypochlorite tablets are placed.

The removal of pathogenic organisms is the main concern when producing drinking water of high quality. The treatment process was therefore evaluated by measuring E-coli, in the purified water, because of its ability to indicate faecal contamination, which would suggest the possible presence of several other pathogens. The turbidity, level of free chlorine, and pH were measured to supplement the bacteria counts as their respective values indicate the conditions for disinfection. The results were then compared with the results from previous sites where the EmWat had been operated.

The objective of the full-scale test was to obtain knowledge about how and to which degree the amount of coagulant tablets influenced the purification efficiency. The filtering stage, where pathogens are removed, is considerably improved by successful flocculation. Furthermore, effective disinfection with chlorine is only possible for water with small amounts of particles and consequently dependent on the filtration. This underlines the importance of choosing the most effective coagulants for each type of water in order to achieve a high particle reduction in the filter. Tests with different combinations and number of coagulant tablets were conducted and the difference in turbidity, prior to and after the purification was measured. Additionally, each test was done for both 4000 l/h and 2000 l/h to measure the impact of the flow rate.

The results of the complementary tests, when compared with the results of previous EmWat 4000 operations revealed that the kit was capable of producing good quality potable water using very poor sources. Furthermore, the failure of the kit to produce water that guaranteed microbiological safety was a result of a dysfunctional purification process due to broken equipment. The equipment was broken as a result of purifying water above the design flow, and without the use of the provided safety valve. The full-scale test showed that the use of flocculants enhanced the filtration process when using the design flow rate, however they did not have a marked effect when using the halved flow. When keeping the tablet concentration constant, purifying water at the reduced flow rate gave improved results. Finally, a test conducted using the carbon filter showed that this filter is not suited to remove turbidity. Practical experiences on site gave the impression that the kit was easy to use. However, after

seeing damages on the equipment and that the quality of the produced water did not meet the WHO standard, its simplicity can be assumed to be misleading. Careful installation and operation is crucial in order to produce good drinking water. Furthermore, the manual was found to be incomplete, and in the case of the turbidity level for chlorination the information was misleading. The presentation of some important information in the manual was also found to be unclear. From talking with other operators it was found that people were grateful for having the kit, and it was implied that the kit functioned well.

These results lead to the conclusion that the EmWat 4000 has a capacity to produce potable water of an acceptable quality. However, the design flow must not be exceeded and it is emphasised that careful operation is required in order to gain good results and long-lasting use of the equipment. Moreover, the monitoring of water quality should be performed regularly to ensure that the WHO standards are met. Since the dissolution of the tablets has not been shown to be less for lower flow rates, it is advisable to use the design flow in order to produce as much water as possible per tablet. When improvements to the process are required the addition of flocculants should be the first choice in order to keep the high flow rate, and as a second choice the flow rate can be reduced. Maintaining a high flow rate would entail economic benefits as well as the possibility of producing a larger volume of water in a shorter time, which is crucial in emergencies. The manual needs to give more information in order to better enable the operators to assess the performance of the EmWat 4000 and adapt it to the conditions at hand. Since surface water will often be of a quality that an activated carbon filter cannot handle, directive values for the maximum turbidity allowed to pass through the carbon filter should be given. This will increase the life of the activated carbon filter and the EmWat 4000 kit. Finally, the monitoring of operations, with consistent recording of data, should be encouraged so as to allow for more efficient future operations.

Sammanfattning

Ämne för detta examensarbete valdes efter en förfrågan från UNICEF att bistå dem att utvärdera ett mobilt system för dricksvattenproduktion. Sedan juni 2003 har EmWat 4000-systemet använts i Etiopien i områden med vattenbrist. För att försäkra sig om att systemet fungerar effektivt och att det producerade vattnet är av tillräckligt hög kvalitet behövdes en utvärdering.

Målet med examensarbetet är att utföra utvärderingen av EmWat 4000 för UNICEF i Etiopien med avseende på hur vattenreningssystemet har fungerat, att identifiera begränsningar samt att undersöka hur anpassningsbart systemet är till olika förhållanden i Etiopien. För att uppnå målet har arbetet indelats i tre aktiviteter: tester av den mikrobiella kvaliteten på dricksvattnet som producerats på tre olika platser, utvärdering och summering av resultat från tidigare driftstillfällen och utförandet av två fullskaletest för att undersöka hur olika tänkbara åtgärder kan påverka reningsprocessen. Besöken på de olika platserna syftade även till att samla praktiska erfarenheter av systemet samt problemen som kan uppstå vid drift.

EmWat 4000 är ett komprimerat vattenreningssystem som är lätt att transportera och kan producera upp till 4000 liter dricksvatten per timme. Systemet är speciellt anpassat för katastrofhjälp där det finns ytvatten att tillgå. EmWat 4000 är uppbygg av fyra olika reningsprocesser: flockulering, sandfiltrering, aktivt kolfiltrering och klorering. I utrustningen ingår fyra olika kemikalier för flockuleringsprocessen. Av dessa är två koaguleringskemikalier och två flockuleringskemikalier. Typen av kemikalie för vattenreningen bestäms utifrån kvaliteten på råvattnet som skall användas. Klor doseras från en behållare där hypoklorittabletter har placerats.

Det huvudsakliga målet vid produktion av dricksvatten är att avlägsna patogena organismer. Därför bedömdes reningsgraden i systemet genom räkning av E-coli i det renade vattnet. Denna bakterie är en indikator på fekal förorening som medför en förhöjd risk att patogena organismer finns i vattnet. För att komplettera resultaten av bakterieräkningarna mättes turbiditet, fri klorhalt och pH för att bedöma disinfektionsförhållandena. Dessa uppmätta värden jämfördes sedan med rapporterade resultat från andra områden där EmWat 4000 tidigare använts.

En del av fullskaletestet var att undersöka hur och till vilken grad antalet koagulerings- och flockuleringstabletter påverkar reningsprocessen. Filtreringssteget, där patogena organismer samt partiklar avlägsnas, kan avsevärt förbättras med hjälp av en effektiv flockulering. Kloreringen som oskadliggör de organismer som passerat filtret är enbart slagkraftig då partikelhalten är låg. För att optimera flockuleringssteget är valet av kemikalier för varje enskilt vatten avgörande. Därför testades olika antal och kombinationer av tabletter och dess olika effekt på turbiditetsreduktion i sandfiltret mättes. Vidare bestod fullskaletestet i att analysera hur flödet påverkade reningsgraden. Turbiditetsreduktionen, över sandfiltret, vid användande av designflödet på 4000 l/h jämfördes med det halverade flödet. Slutligen undersöktes även turbiditetsreduktionen i filtret med aktivt kol.

Resultaten från de tidigare driftstillfällena bekräftade att EmWat 4000 kan producera dricksvatten av god kvalitet. Testresultaten från de platser som besöktes under detta arbete uppnådde dock inte WHO:s dricksvattenstandard. Den låga kvaliteten anses bero på att delar av utrustningen var skadad eller trasig samt att alla delar inte användes. Troligtvis hade filterenheterna gått sönder då vatten renats vid ett för högt flöde utan att säkerhetsventilen använts. Fullskaletestet visade att tillsatts av flockuleringsmedel medförde en markant förbättring av turbiditetsreduktionen då designflödet användes. Även sänkning av flödet visade förhöjd reningsgrad med avseende på turbiditet. Resultaten från fullskaletestet antydde även att kolfiltret inte har kapacitet att reducera höga halter av turbiditet. Praktiska erfarenheter av systemet var att det är lätthanterligt men kräver noggrannhet vid installering och drift för att erhålla acceptabel dricksvattenkvalitet. Dessutom visade sig manualen vara bristfällig i

information och presentationen av denna samt även missvisande vad gäller turbiditetsgränsvärdet för klorering. Samtalen med driftsteknikerna gav intrycket att många var nöjda med EmWat 4000.

Slutsatsen är att EmWat 4000 har kapacitet att producera dricksvatten av en acceptabel kvalitet, men, behovet av noggrann drift understryks. Designflödet skall ej överskridas för att förhindra att utrustningen skadas. Vidare skall mätning och kontrollering av vattenkvaliteten utföras regelbundet för att försäkra att WHO:s standard uppnås. Då snabb vattenproduktion är angeläget vid katastrofhjälp är det fördelaktigt att i första hand använda flockuleringskemikalier för att förbättra reningsgraden vid högturbida vatten. I andra hand kan flödet reduceras. Manualen bör förbättras och kompletteras med mer information för att möjliggöra bättre anpassningar till olika förhållanden i fält. För att förhindra att kolfiltret sätts igen bör det i manualen finnas ett gränsvärde för hur hög turbiditet som kan tillåtas passera. Slutligen, genom att uppmuntra att erfarenheter sammanställs och förs vidare kan effektiviteten vid framtida driftstillfällen förhöjas.

Preface

We would first of all like to thank the WES section at UNICEF, Addis Ababa, for giving us the opportunity to perform this thesis work and for supporting us during our stay in Ethiopia. We would specifically like to thank Haile Gashaw, Wossen Mulatu, Tensae Asrat, and Tesfay Mamo who have spent many hours helping us to organise trips, contact people, and driving us to different locations, making this thesis work possible.

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1 Introduction

To meet the demands of clean drinking water in emergency situations a mobile water treatment kit, EmWat 4000, has been used to purify surface water. This kit has been used in many different countries and under different circumstances and has saved lives in emergency situations when access to other potable water has been denied as a result of, for example, floods or droughts. The kit is designed to serve 3−4000 people with 10 litres per day after only 2−6 hours of set-up.

In June 2003 ten EmWat kits were donated to UNICEF Ethiopia by the Norwegian government through the Ethiopian Disaster Prevention and Preparedness Commission (DPPC). Five units have been sent out to the water bureaus in five regions, and five are kept in the capital city Addis Ababa, prepared for emergencies.

The EmWat 4000 kit is an emergency water purification system developed by a French company, LMS and sold by the Norwegian company Plastec.

To ensure that the purified water meets the criteria for drinking water it is crucial that testing and monitoring is carried out regularly. In cooperation with Lund Institute of Technology the evaluation of the EmWat 4000 was performed as a master thesis.

Field studies were carried out in Ethiopia from the 1st October to the middle of December, 2004. From January to the end of March 2005 the thesis work was completed at the Lund Institute of Technology in Sweden.

2 Goal

The overall goal of this paper is to assist UNICEF Ethiopia by doing an evaluation of the implementation of the EmWat 4000-kit. UNICEF Ethiopia expresses its commitments to the Ethiopian government in a Master Plan of Operation, further presented in chapter 3.1, and it is emphasised that this evaluation is designed to assist UNICEF in meeting these goals.

To achieve this overall goal the following objectives were set:

- To evaluate the performance of EmWat 4000 in Ethiopia, in terms of the microbiological saftey of the produced water and the unit's adaptability to the conditions in the country,
- To identify the shortcomings of the unit and to forward recommendations for improvements.

In order to achieve these objectives the following activities were performed:

- Conducting complementary tests to investigate the treatment efficiency and safety of the water produced,
- Summarising and evaluating the test results gathered from other sites where the EmWat 4000 had been operated on behalf of UNICEF in Ethiopia,
- Performing a full-scale test to evaluate the effects of flow rate and different combinations of coagulants and flocculants on the quality of the produced water,
- Gathering practical experiences and impressions gained from operations of the kit.

2.1 Limitations of the evaluation

The primary focus of this thesis is to investigate how well the EmWat 4000 is suited for the conditions in Ethiopia. Evaluation of the techniques employed in the purification system is not performed. Rather, possibilities of enhancing the effectiveness of the processes by means available in the field are explored. An economic comparison of the EmWat 4000 with other emergency water relief options is not made, as it was not possible to gather all the required information. Finally it should be noted that many of the circumstances in the field were difficult to foresee, making it difficult to plan tests so as to gain the best results. Therefore, the results in this thesis should not be extended beyond the limits set for them by the authors, as this could lead to false conclusions.

3 Background

3.1 UNICEF

The United Nations International Children’s Emergency Fund (UNICEF) was established 1946 with the expressed aim of caring for children in the wake of the Second World War. Initially their work involved the provision of food, health care, and clothing for children. However, with time their goals have expanded to include other aspects of child development as well as the situation for women. (unicef.org 2005 a and b)

UNICEF has been active in Ethiopia since 1952 (unicef.org 2005 c). The country program, Master Plan of Operation (MPO), adopted by both UNICEF and the Ethiopian government in 2002, expresses a goal to realise “… the rights of children to survival, development, protection and participation.” (MPO, article 5). UNICEF works in cooperation with the government as well as other non-government organisations to fulfil these goals.

The UNICEF work is divided in to different programs. The water programs in the country are headed by the Water and Environmental Sanitation (WES) section. The WES section works together with regional water bureaus that implement and operate the EmWat 4000 kits. The need to monitor the performance of the kit is supported by article 9, on monitoring and evaluation, in the MPO, which states that “To the extent possible, monitoring will rely upon existing Federal, Regional, UNICEF, and partner routine reporting system. These will however, need to be supplemented by surveys, studies and field operations.” Field operations have been conducted in different regions in the country and the reports need to be brought together for an evaluation of the kit’s general performance.

3.2 Ethiopia

Ethiopia covers an area of 1,127,127 km^2 at the horn of eastern Africa. The terrain is a high plateau divided into two parts by a rift valley that cuts through the country from north to south. The altitude varies from 125 metre, under sea level, to 4620 metre above sea level. (cia.gov 2005)

Figure 3.1 The Ethiopian map and the location of the visited sites (utexas.edu)

The country is inhabited by 70,678,000 people of whom 16 % live in urban areas (unicef.org 2005 d).

Recurring droughts have led to famines which are a liability to the survival of individuals, specifically that of children. Owing to conflicts and insecure life conditions there is a large population of internally displaced persons in the country with low access to potable water. Efforts are being made to secure water availability and relieve the consequences of these disasters.

The number of people having access to improved water sources is a measure of the water situation for the people. Improved water sources are defined as household connections, public standpipes, boreholes, protected dug wells, protected springs and rainwater collection (unicef.org 2005 e). During 2002 a total of 22 % of the population had access to improved water sources. However, the situation for the people in the rural areas differs greatly from the situation of people in the urban areas. The access to improved water sources for these two groups is 11% and 81%, respectively. The Millennium Development Goal is to provide 75% of the population with access to improved water sources by 2015. (unicef.org 2005 f)

3.3 Site descriptions

For this study three different sites were visited: Two sites where the EmWat was employed to produce drinking water, Dire Kiltu in Oromiya region and Konta Koysha in Southern Nations Nationalities Peoples Region, SNNPR, and one site in Sofi Lugo, in the Harari region to where the EmWat 4000 kit was brought to conduct a full-scale test. The surroundings, climate, water source as well as the purification procedures differed between the sites.

Dire Kiltu is a flat and dry area where water tankering previously was used to serve the people. When this study was performed the EmWat 4000 was used to produce drinking water from a dug pond in the middle of a crater-like hill. The pond contained harvested rainwater and was the water source for 291 families. To protect the pond from being polluted by cattle and other livestock, a thorny hedge surrounded the catchments area. However, it was not fully effective and the pond was shaded by large trees hosting an innumerable number of birds.

Konta Koysha is a resettlement area. Landless farmers from the Wolaita district had been given the opportunity to resettle and farm the uncultivated land in the Konta district. The district contains large areas with rain forest, broken ground and lush vegetation. Natural springs and small rivers are common in the area. At the point in time when the study was conducted only a few members from each family had moved to the resettlement site to begin the farming. The road was still being constructed so the area was difficult to access. The EmWat 4000 kit was employed to serve these first farmers with drinking water from a nearby stream until a sustainable water source would be constructed. The plan was to pipe water from a natural spring, and was supposed to be finished within a couple of months.

The full-scale test was planned to be carried out on river water. Upon arrival at the site, the river was dried out and another source had to be found. A retention dam for farm irrigation, next to a village called Sofi Lugo, was the best option. The dam was situated in the dry and hilly area north of the city Harar. It was filled by water from a natural spring 50 metres away, but since the water normally was not used for drinking the dam was not protected from the entrance of animals, on the contrary, cattle were often led there to drink.

4 EmWat 4000

This chapter is mainly based on the manual produced by Plastec (Plastec, 2004).

The EmWat 4000 is suited for producing water in emergency operations. For easy transport it is packed in pallets, each with a maximum weight of 100 kg, and is small enough to fit in the back of an ordinary pick-up truck. The procedure for assembling the kit is designed to be simple and fast. To further adjust the equipment for ruff conditions and poor availability of spare parts it is constructed as simple as possible. All the elements are motionless except for the engine, and the material is mainly plastic to avoid corrosion problems. Crucial for emergency situations is also the fast distribution of water. The tap station divides into several outlets and high pressure, ensured by gravity and guarantees fast fillings of several containers simultaneously.

The production capacity is 4000 litres per hour in ideal situations depending on the raw water quality. Simple adjustments make it possible to purify different kinds of water.

The EmWat 4000 kit consists of four different purification processes: flocculation, sand filtration, activated carbon filtration, and chlorination. A pump, powered by a diesel engine, drives the system, and the purified water is stored in plastic pillow tanks. After the chlorine has had a contact time of at least half an hour, the water can be fetched from the taps. Figure 4.1 displays the EmWat system set-up.

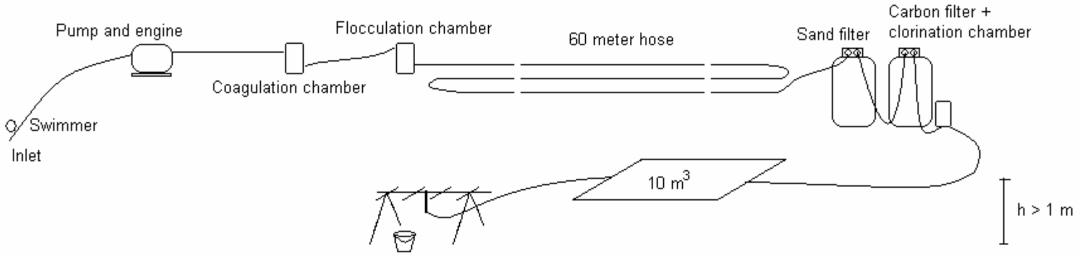

Figure 4.1 An overview of the set-up of EmWat 4000

The processes for coagulation, filtering and chlorination are explained further in the theory chapter.

Collection of surface water should preferably be done at a place where turbulence is at its minimum. To minimize the intake of large particles the inlet is protected by a strainer basket. For shallow water the inlet and the strainer can be connected to a swimmer to stop the inlet pipe from scraping the river or lake bottom.

The first step is the coagulation. Tablets of chemicals are placed to dissolve in a chamber constructed for mixing ensured by the turbulence created by small grooves, that cover the interior, see Figure 4.2

The following stage is the flocculation chamber, which has the same design as the coagulation chamber in order to produce turbulence and optimal mixing of flocculants.

Figure 4.2 The coagulation chamber

A static mixer is placed before each chamber to increase the turbulence of the water. Four different kinds of coagulant and flocculant chemicals, in tablet form, come with the kit. They are mineral ions and organic polymers: Alufloc, Ferufloc, Aniofloc and Catiofloc. The Alufloc contains 99 % aluminium sulphate and the Ferufloc 84% iron sulphate (Bray 2004). To choose the best chemical for each type of water a shake test is recommended in the manual. By scraping a little bit of each tablet into different bottles and comparing the flocculation and sedimentation the best-suited chemical can be determined. Also combinations of the flocculants can be used. The manual presents a table of guidelines for which tablet to be used for water characterized as muddy, clayish, tropical yellow to orange rivers and lakes, and organic rich waters. The numbers of tablets are to be adjusted depending on the purification result.

To allow the building of the flocs the water is then led through a 60−80 metre long PVC hose before reaching the sand filter. For the maximum purification capacity of 4000 litres this corresponds to a retention time of 1.8 minutes according to the manual.

The sand filter (Figure 4.3) is a closed downward filter of approximately 0.1 m^3 with granules. The characteristics of the grains have not been available for this thesis. The water is led into the filter on the top and passes through the sand to the bottom. In the middle of the filter there is a vertical tube, which the water enters at the bottom. The water exits the filter unit on top through the tube. According to the manual, the filter can be used until the pressure exceeds 3 bars or the pressure difference between sand and carbon filter is above one bar. Then the filter has to be cleaned by flushing it with water in the opposite direction.

Figure 4.3 Sand[1] and activated carbon[2] filter units and chlorination chamber[3]

After the sand filter the activated carbon filter (Figure 4.3) is applied. The filter has a design similar to the sand filter, but uses small grains of activated carbon. The characteristics of the carbon filter have not been available for this thesis.

The disinfection is done using a chlorination chamber (Figure 4.3) with hypochlorite tablets containing 70% chlorine. The size of the chamber is estimated to 3−4 litres. A dosing system, dependent on the hydraulic pressure, lets water into the chamber to dissolve the tablets. The chlorine solution is then added to the water depending on the dosage chosen. The free residual chlorine for tap water should be in the range of 0.2−0.5 mg/l.

To maintain a high quality of the purification process, it is essential to test and follow up the process. A turbidity tube and a kit for analysing residual chlorine and pH manually are provided with the kit.

If the testing reveals that the performance is inadequate, adjustments for improving are suggested in the manual. The dosages or the type of chemical might be modified, or a combination of different types might be needed. If the water is of extremely low quality the retention time for the flocculants can be prolonged. By allowing formations of flocs in a separate reservoir for some time before being transferred to the sand filter and succeeding processes, higher reduction may be possible. One of the pillow tanks included in the kit can be used as the supplement reservoir.

There are two manuals for the EmWat 4000, the Field manual and the Engineer’s Manual. The Field Manual includes instructions for the connection and maintaining process step by step in a foreseeable way. The Engineer’s Manual includes a more complete background for emergency water treatment, discusses different aspects and describes the process more in detail.

Along with the EmWat 4000 kit, training was included in the in-kind donation. Technicians from regional and zonal water bureaus attended the training and have in their turn trained local operators. (Wurzel 2003)

5 Theory

5.1 Water quality

Different organisations set standards or guidelines for substances present in drinking water. As the raw water quality differs for every source, the concerns in treatment vary.

A healthy drinking water is characterised by a combination of the absence of toxic and hazardous compounds as well as the presence of essential substances. The process to produce drinking water is mainly a matter of removing unwanted components.

The elements in water can be either suspended or dissolved. The suspended particles are particulate elements and the size can range from sand grains to clay or even particles of less than one micrometre. The dissolved substances are even smaller and normally in form of ions. Also gases can be dissolved in water. (Degrémont 1991, 131) Particulate contaminants in water can be divided into two main groups: organic and inorganic. The organic particles are humus and microbiological substances. The inorganic constituents are salts, metal ions and minerals mostly comprised of sand and clay particles.

In most cases the microbiological pathogens are the major threat to the water quality. Some occur in all natural fresh waters whereas others may be found temporarily in specific areas causing outbreaks of epidemics. WHO's Guidelines for Drinking-water Quality state that test for pathogens should show complete absence if drinking water should be considered not being a threat to the health. The hazardous organisms are divided into four different groups: bacteria, viruses, protozoa and helminths. To determine the risk of presence and the treatment of the different pathogens, their characteristics have to be recognized. Human pathogens from each group that are transmitted mainly through drinking water and their differences in constituting a threat to the human body will be presented in the following tables. Table 5.1 to Table 5.4 give the health significance, persistence in water supply, resistance to chlorine, relative infectivity and whether animal contamination is an important source of pathogens. The tables and following explanations are adapted from the Guidelines (WHO 2004).

The *health significance* (of drinking water contaminated by the specific organism) indicates if the route of transmitting is primary through drinking water and thus if excluding the specific agent from the water would have high or low significance to a presumed user.

Pathogens and parasites gradually lose their ability to survive after leaving their host body. Temperature is the most important factor to the rate of decay, which usually is exponential as a function of time. The *persistence in water supplies* is defined as the period for infective stage in water at 20 °C; short: up to 1 week, moderate: 1 week to 1 month, long: over 1 month.

The pathogen's *resistance to chlorine* is measured for conventional doses and contact times when it is freely suspended in the water. Moderate resistance signifies that agents may not be completely destroyed.

The *relative infectivity* indicates the relative quantity of organism required to cause an infection. A pathogen with low relative infectivity must be present in larger amount than a pathogen with high relative infectivity, for which single units may cause infection. Relative infectivity is measured in experimental studies in which volunteers were exposed to a known number of pathogens. However, WHO states that as ”most studies are done with healthy adult volunteers, such data are applicable to only a part of the exposed population, and extrapolation to more sensitive groups is an issue that remains to be studied in more detail”.

Whether *animals are an important source* of contamination of the specific pathogens is stated in the last column in the tables. The information is useful for assessment of degree of improvement by preventing animals from reaching the water source. Pollution by animal faeces is a general problem stated by WHO: "The greatest microbial risks are associated with ingestion of water that is contaminated with human or animal faeces". (WHO 1993, 1)

Bacteria are single-celled prokaryotic (no nucleus) organisms of which there exist 20-30 million different species (ne.se 2005). There are species of bacteria that are benign (good) and essential for the human body, but others are harmful or fatal. Pathogenic bacteria are heterotrophic and consume organic material. As long as there are biodegradable organic compounds, and oxygen, and the temperature is favourable, persistence in water supplies will not be a problem for most species. Most bacteriological threats may be eliminated by chlorine. However their resistance to chlorine differs depending on the different thickness and material of their cell walls (Norton and LeChevallier, 2002).

Table 5.1 (WHO 2004 ch . 7.1.1)

Bacteria	**Health significance**	**Persistence in water supplies**	**Resistance to chlorine**	**Relative infectivity**	**Important animal source**
Burkholderia pseudomallei	Low	May multiply	Low	Low	No
Campylobacter jejuni, *C. coli*	High	Moderate	Low	Moderate	Yes
Escherichia coli – Pathogenicd	High	Moderate	Low	Low	Yes
E. coli – Enterohaemorrhagic	High	Moderate	Low	High	Yes
Legionella spp.	High	Multiply	Low	Moderate	No
Non-tuberculous mycobacteria	Low	Multiply	High	Low	No
Pseudomonas aeruginosa	Moderate	May multiply	Moderate	Low	No
Salmonella typhi	High	Moderate	Low	Low	No
Other salmonellae	High	May multiply	Low	Low	Yes
Shigella spp.	High	Short	Low	Moderate	No
Vibrio cholerae	High	Short	Low	Low	No
Yersinia enterocolitica	High	Long	Low	Low	Yes

Most of the bacteria presented in Table 5.1 cause enteric, or stomach, complications. Others such as Legionella spp. can cause respiratory diseases, as these organisms can be present in airborne water droplets. Some types of bacteria have been classified as having low or moderate health significance, even though some, like Pseudomonas aeruginosa, might cause skin infections. The classification, as low or moderate, is due to the fact that they seldom are infective in healthy hosts, but are opportunistic pathogens affecting people with suppressed immunity (WHO 1996, ch 2.1.2). Other kinds of bacteria that are not a direct health concern may affect the water quality. Iron and sulphur bacteria may cause corrosion of steal and iron in water systems as well as give the water undesirable colour and taste (WHO 2004, 6). Organisms such as Cyanobacteria (not presented in the table above), also known as blue-green algae, is an example of an organism that is not directly harmful. However, they can produce toxins that may cause deadly circulatory shock and liver collapse within 24 hours of ingestion.

Viruses are particles that cannot reproduce themselves without incorporating into and parasiting on living organisms and are therefore unable to multiply in water. The sizes of virus particles vary from one tenth to the approximate size of the smallest bacteria (Kemira 2003, 118). When existing outside, some are sheltered in membranes (NE 1996, 518). Their resistance to disinfection is generally higher than for bacteria. Furthermore, as seen in Table 5.2, a small number of viruses are sufficient for infection.

Table 5.2 (WHO 2004 ch. 7.1.1)

Viruses	**Health significance**	**Persistence in water supplies**	**Resistance to chlorine**	**Relative infectivity**	**Important animal source**
Adenoviruses	High	Long	Moderate	High	No
Enteroviruses	High	Long	Moderate	High	No
Hepatitis A	High	Long	Moderate	High	No
Hepatitis E	High	Long	Moderate	High	Potentially
Noroviruses and Sapoviruses	High	Long	Moderate	High	Potentially
Rotavirus	High	Long	Moderate	High	No

The consumption of the listed viruses can result in several diseases. Gastroenteritis normally involves nausea, vomiting and diarrhoea lasting for 1 to 3 days. The Hepatitis viruses attack the liver leading to several symptoms including fever, abdominal discomfort, and in extreme cases to death from liver failure. According to WHO, the transmission of viruses through water is difficult to prove, for several reasons. It has however been shown that contaminated water is a high risk factor. What is more, it has been proven that Hepatitis A and E viruses, and Rotaviruses can be transmitted by water and cause epidemics. (WHO 1996, ch 4.2.1)

Protozoa is a group of single-celled organisms to which, for example, amoebas belong. Some protozoa have different stages during their life cycle and their persistence and ability to infect vary. Cryptosporidium and Giardia are protozoa that have a resting stage in capsules named cysts and oocysts, respectively. The organisms in resting stages are unable to multiply in water but are extremely resistant to disinfection with chlorine as seen in Table 5.3. Consumed cysts or oocyst may develop and cause infections which often lead to diarrhoea in the host. (WHO 1996, ch 5.1) This is especially true of immuno-suppressed hosts (Endeshaw 2004).

Table 5.3 (WHO 2004, ch 7.1.1)

Protozoa	**Health significance**	**Persistence in water supplies**	**Resistance to chlorine**	**Relative infectivity**	**Important animal source**
Acanthamoeba spp.	High	Long	High	High	No
Cryptosporidium parvum	High	Long	High	High	Yes
Cyclospora cayetanensis	High	Long	High	High	No
Entamoeba histolytica	High	Moderate	High	High	No
Giardia intestinalis	High	Moderate	High	High	Yes
Naegleria fowleri	High	May multiply	High	High	No
Toxoplasma gondii	High	Long	High	High	Yes

Entamoeba Histolytica is one of the most common pathogens worldwide.

Helminths are also called parasitic worms. Two main worms are in focus when dealing with water. (Table 5.4)

Table 5.4 (WHO 3 micro.7.1.1)

Helminths	**Health significance**	**Persistence in water supplies**	**Resistance to chlorine**	**Relative infectivity**	**Important animal source**
Dracunculus medinensis	High	Moderate	Moderate	High	No
Schistosoma spp.	High	Short	Moderate	High	Yes

Guinea Worm, Dracunculus medinensis, is “the only human parasite that can be eradicated solely by the provision of safe drinking-water”. (WHO 1996, ch 6.1.2) When ingested, this worm begins to grow in the body, and can reach lengths of one metre. In time a blister will form, from which the worm can be hauled out after bursting. This worm does not usually cause long lasting effects. The removal is however extremely painful, and takes a long time. Schistosoma spp., also known as Bilharzias, is a worm transmitted by skin contact with water that causes severe sickness and has high health significance worldwide.

The removal of pathogens from water not only guarantees the health of the beneficiaries, it also disrupts their life cycle. This is advantageous as the proliferation of the organism and the concomitant diseases they cause will be reduced.

Apart form pathogens other organic content in the water is of concern. Even if it is not hazardous itself, its presence heightens the risk of pathogenic growth as it nourishes pathogens and prolongs their persistence. In addition, substances consume added disinfection chemicals inhibiting the inactivation of pathogens (see 5.3.4). Moreover, odour or colour, as a result of organic content, makes the water less attractive to consumers.

Dissolved inorganic substances in the drinking water are also of concern. If a major contamination occurs that leads to dangerous levels of toxins, the water in most cases becomes undrinkable in terms of taste, odour and appearance (WHO 2004, 6). However, even imperceptible substances may cause health effects when being consumed regularly over an extended period. This is due to the fact that they may accumulate in the body. Dissolved agents can be used to indicate contamination of the water if they are found in unusually high amounts in natural waters.

Water constituents are also important to the treatment process as they can affect the dose used in each treatment step as well as its effectiveness. Two such constituents, or parameters, are pH and bicarbonate concentration (alkalinity). pH is a measure of the free hydrogen ions in the water. This is one of the key factors governing both chemical pre-treatment (5.3.1) and disinfection with chlorine (5.3.4). The significance of alkalinity lies in the fact that it is a measure of the buffering capacity of the water, which is its ability to resist changes in pH upon addition of acidity. This is especially important in the chemical pre-treatment processes discussed in 5.3.1. In distribution systems, pH in the water needs to be regulated so that the pipes are not corroded. Furthermore, high bicarbonate concentrations, in combination with high levels of calcium, can cause clogging problems in pipe systems. Other chemical substances of interest to this thesis, are commented in Results, concerning the visited sites (7.2).

5.2 Monitoring water quality

Essential to both the treatment of water and management of the water source, is the consistent monitoring of quality. This is due to the often large variability in raw water quality as a result of factors difficult to predict, such as weather or anthropogenic activity in the area. Water treatment systems are not always able to cope with such changes, consequently ensuing in a deterioration of the quality of treated water.

The parameters to be tested vary depending on the type of water to be treated. Groundwater may carry with it certain elements that ought to be removed, the presence of which must therefore be investigated. Problems, such as Fluoridiosis[*], endemic to certain geographical areas, can influence the choice of test parameters. Factors, such as the pH, affect the water treatment process and needs to be taken into consideration when deciding which parameters are to be monitored. Finally, issues pertaining to infrastructure and economy are of great importance in deciding what is reasonable to monitor (WHO 1997, 51). Inadequate access to vehicles, poor roads, and long distances can for example, necessitate testing for certain water constituents on-site as the transport time for samples may exceed the allowed limit (see 5.2.1). These issues are especially significant in the monitoring of rural waters, as this may require access to remote sites.

Methods for testing in the field are more limited than laboratory methods, putting restrictions on the constituents that can be tested for, as well as the accuracy of the results (Degrémont 1991, 337).

The most basic parameters to be monitored, however, are those that will indicate the microbiological quality of the water, which has high health significance for consumers. WHO lists these as thermotolerant faecal coliforms, turbidity, chlorine residual, and pH. (WHO 1997, 51)

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[*] A disease caused by the drinking of water with high amounts fluoride, more than 1.5 mg/l, for an extended period of time.

5.2.1 Samples

The samples taken for analysis must give results that are representative of the situation at hand. This requires that sampling points are chosen with care so that the correct water is analysed. Samples must be taken at the source, the so-called “points of use”, such as faucets, and at the outlet from a treatment system. (WHO 1997, 52) WHO suggests that the points where the conditions are least favourable should be sampled.

When sampling water for microbiological testing at points of use, two types of samples may be taken. In order to be able to analyse the biological quality of the water without taking into account contamination from the tap, the tap has to be disinfected by burning with an alcohol-soaked swab. If the quality of the consumed water is to be analysed the sample is taken without flaming. Before disinfecting taps they should be wiped off with a cloth and the water should be allowed to run for one to two minutes at maximum flow. After disinfection, before sampling, the water should be allowed to run again for the same period of time. (WHO 1998, 183-5)

To limit physicochemical and bacteriological changes in the sampled water, the storage conditions are crucial. Hach’s method specification sheet (1999), states that samples should be stored in clean, sterile, heat-resistant glass bottles, or pre-sterilized sampling bags. Samples taken for physicochemical analysis should be stored in glass or plastic containers (Degrémont 1991, 335-6). All types of samples should be kept at a low temperature and in the dark (WHO 1997, 56). Different chemicals may be added to the sample to preserve the species that is to be analysed (Degrémont 1991, 335). For microbiological analysis of samples after a disinfection step, it is necessary to use containers with sodium thiosulfate to de-chlorinate the sample. The chlorine is inactivated in order to avoid decay of bacteria, which would otherwise give misrepresentative low results (WHO 1997, 53).

The time between sampling and testing should be kept as short as possible. Different maximum periods of evolution are given depending on the storage temperature and the parameters to be examined. Degrémont (1991, 335-6) states that testing of pH should be done at the latest 24 hours after sampling, and testing of chlorine can be carried out 48 hours after sampling provided the sample is kept at 4°C. Degrémont suggest that pH and chlorine residual generally are tested for on site (1991, 337). Hach (1999) indicates that potable water can be kept at refrigerator temperature (2−8°C) for a maximum of 30 hours before testing. However, non-potable water must be tested after 10 hours even though it is kept at less than 10°C. If the bacteriological sample is not refrigerated, it must be discarded after 2 hours (WHO 1997, 53).

5.2.2 Microbiological analysis

The microbe that is tested for will give an indication of the microbiological quality of the water, and is therefore called an index or indicator organism. An index organism is used to measure the degree of faecal contamination in water. An indicator organism is used to measure treatment efficiency of a water purification system. (Dufour 2003, 19)

To test for microbes, the most common tested for are bacteria, due to their ability to indicate possible presence of other pathogens. Additionally, the method to test for bacteria is relatively quick and uncomplicated. In the WHO guidelines (WHO 1993, 2.2.1) it is recommended that the indicator or index organism meets these criteria:

> They should be universally present in high numbers in the faeces of humans and warm-blooded animals, and readily detectable by simple methods, and they should not grow in natural water.… Their persistence in water and degree of

> removal in treatment of water [should be] similar to those of waterborne pathogens.

These guidelines then go on to conclude that Escherichia coli, or E-coli, is the bacterium that fulfils most of these criteria, and therefore should be the indicator of choice, if there is no possibility of testing for several indicators (WHO 1993, chapter 2.2.2). Although this family of bacteria contains harmful strains (WHO 1996, chapter 3.1.4), the strain that is tested for is not necessarily pathogenic itself.

E-coli is generally more sensitive than other bacteria to disinfection by chlorination (5.2.4). Consequently, the absence of E-coli does not guarantee the absence of pathogenic organisms. When tested water shows that this organism is present, recent faecal contamination is indicated. Furthermore, if this is found in treated water it shows that the water treatment is inadequate and therefore it is probable that pathogenic organisms are still active in the water.

Another group of indicators is total coliforms. This group includes bacteria from a vide variety of sources and, therefore, finding these organisms in water will not necessarily indicate faecal contamination. (Dufour 2003, 50) However, this group of organisms can be used as indicators of removal or disinfection efficiency. Their detected presence in potable water proves that the treatment is ineffective.

There are several methods of testing for bacteria. The most common ones are named in the WHO guidelines, (1997, 67): presence-absence tests, multiple-tube method, and membrane filtration. The use of presence-absence tests is recommended when testing water where there is a low probability of finding microorganisms (Dufour 2003, 249). This method does not allow enumeration of organisms and can not give an index of contamination. Therefore it is not recommended for testing on sources with a high probability of contamination. (WHO 1997, 62) For waters such as these, the multiple-tube and membrane filtration methods are better suited since they also allow the enumeration of organisms. Both methods involve the growing of bacteria in, or on, so-called culture media or substrate. This media is basically a selective substance that allows the growth of a specific organism. When using the multiple-tube method the sample is portioned into several tubes with culture media. After allowing the growth of bacteria for a period of time, usually 48 hours, the density of microorganisms in the tubes is compared to a statistical table, which gives the most probable number of the index or indicator organism. This method is more time consuming and involves the use of more consumables than membrane filtration. On the other hand, the multiple-tube method is viable when testing highly turbid waters. (WHO 1997, 61-2) The membrane filtration method involves the filtering of a water sample through a membrane with a pore size of between 0.22 μm to 0.45 μm (Dufour 2003,238). This filter is then moved to a Petri-dish containing culture medium and then incubated at the appropriate temperature, which is usually 35°C–37°C for E-coli and total coliforms (Dufour 2003, 49). After the incubation period, the formed colonies are counted. The use of membrane filtration is problematic when testing highly turbid waters. This problem can be counter-acted by dilution of the sample. Membrane filtration can also be carried out in the field, which is an advantage if it is not possible to transport samples to a laboratory within the required time or under the proper conditions. (WHO 1997, 61)

The use of selective culture media may give false results as the environment created to select a specific bacteria-type may hinder the growth of stressed organisms. Therefore, instead of using substrates with so-called “harsh selective agents”, chromogenic media-based methods may be used. These involve the use of culture media that identify a microorganism by reacting with an enzyme specific to it. For more information on this, see chapter 6.2.4. On the other hand, chromogenic methods allow the existence of other bacteria, which may cause interference. Another problem is the fact that the enzyme β-glucuronidase, produced by E-coli, also is present in some other bacteria strains, which can give false positive results. On the whole, however, these methods have proved to be better than other methods. (Dufour 2003, 252-3)

5.2.3 Turbidity analysis

The measuring of turbidity gives information on the amount of suspended solids in the water. The significance of this parameter to the treatment process is discussed in chapter 5.3.4. There are two main methods used to measure suspended solids: nephelometry and transparency. Both are relatively cheap, simple to use and can be performed on site (Dufour 2003, 71).

The nephelometric method for determining turbidity involves the measurement and comparison of transmitted light to scattered light (see figure 5.1). When a beam of light is shone through turbid water, the particles in suspension will scatter it so that only a portion will travel through to the other side along the same path. The amount of this transmitted light is contrasted to the amount of light received at a 90° angle to the original path. The ratio of these two parameters is then calibrated to reflect a certain degree of cloudiness, measured in Nephelometric Turbidity Units, NTU. (Degrémont 1991, 339)

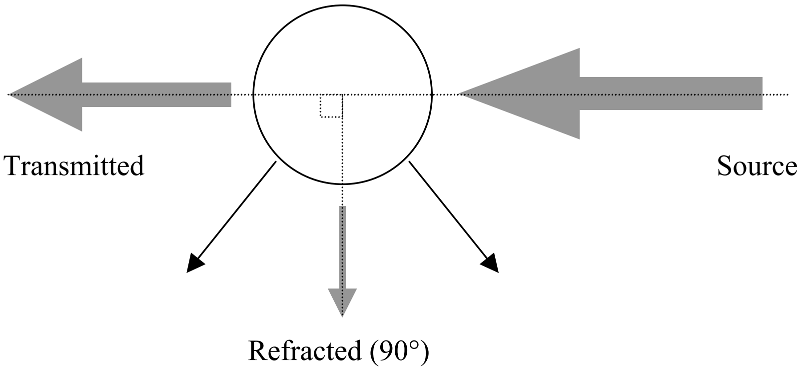

Figure 5.1 Basic principle of nephelometry (Adapted from Degrémont 1991,339)

Degrémont (1991, 339) recommends caution when using this method. Air bubbles as well as large particles can cause faulty results. Therefore it is recommended that comparative measurements be made, using the same apparatus to ensure accuracy. A value below 1 NTU indicates that there are few particles in the water, which is seen as completely transparent.
1000 NTU means that the visibility through the water is less than 1 cm. (Plastec 2004, 4). Nephelometric methods can measure down to 0.02 NTU (Dufour 2003, 68).

The difference of transparency, depending on turbidity, is used when measuring turbidity with a Turbidity tube. The principle is to fill water into a graduated cylinder with a mark on the bottom. The water is then poured out until the mark is visible through the water. The scale relates the height of the water column to the turbidity. This method can measure turbidities down to 5 NTU and also has the advantage of being the cheapest (Dufour 2003, 68). On the other hand, this method is not as accurate as nephelometry.

5.2.4 Residual chlorine analysis

In order to secure the microbiological quality of treated water, the chlorine residual should be monitored. It is also suggested that chlorine residual be monitored before and after the required disinfection or contact time. (Dufour 2003, 70) As chlorine is highly unstable in water, it should be measured on site (WHO 1997, 67).

Three types of chlorine can be measured: free chlorine, combined chlorine, and total chlorine. Free chlorine refers to the hypochlorous acid and hypochlorite, which are the reactive species of chlorine (5.3.4). Measuring the combined chlorine will give information about the amount of chlorine consumed due to reactions with other substances. Total chlorine is the sum of the concentration of both free and combined chlorine. (WHO 1997, 67)

Measuring chlorine can be done using photocolorimetry or colour-matching methods. This is done by adding a specific amount of reagent, as N,N-diethyl-p-phenylenediamine (DPD), to a specific volume of the water to be tested. This causes the water to turn pink, increasing in intensity with increasing chlorine concentration in the water. The colour is then compared to a standardised colour disc to find the concentration. Alternatively, the intensity of the coloured solution is measured using a photocolorimeter, which is calibrated to return the indicated chlorine concentration. The photocorimeter shines a ray of light with a specific wave-length through the sample, and measures the intensity of the light that comes through the coloured water. Different types of DPD-reagents are used to measure free, combined, or total chlorine in the water.

5.2.5 pH analysis

The pH of the water affects the coagulation-flocculation as well as the disinfection process in a water treatment system (5.3.1 and 5.3.2). Monitoring this parameter is a key to maintaining good potable water production.

This parameter can be measured using colour-matching methods involving the use of reagents equally to the method explained in chapter 5.2.4; electronic methods are however also available. Electronic, or potentiometric, methods make use the fact that an electric current is generated when a difference in electric potential is present. Using specialised electrodes that are sensitive to certain water constituents, in this case H_3O^+ (H^+), their concentration can be measured.

The pH electrode requires calibration through the use of so-called standard buffer solutions. Three solutions are used: pH 4.01, pH 7.00, and pH 10.00. This is called a three-point calibration where the pH-meter is submerged in each solution and the value is adjusted. WHO (1998, 233) suggests that calibration be carried out daily when the pH-meter is in use.

5.3 Water treatment

The ease with which pathogens and unwanted substances from water are removed depends on the raw water quality. The more polluted a source is, the more treatment steps or multiple barriers are required (Dufour 2004, 159). Coagulation with rapid mixing, flocculation during slow mixing, sedimentation and filtration is called a conventional treatment. If the sedimentation step is excluded it is called direct filtration, and if the flocculation step also is excluded the treatment is called in-line filtration. (LeChevallier 2004, 22)

For surface water, which is usually of relatively poor quality, direct filtration and disinfection are often employed to ensure good potable water quality.

When looking at the treatment efficiency of a barrier, it is often interesting to investigate how much of the original amount of contaminants is removed. When dealing with particulate and microbial contaminants, which are often present in large numbers, it is not always practical to express removal rates in percent. Therefore these are sometimes expressed as logs removed, which is the logarithm of the ratio between original number present and the number remaining after treatment (la Cour Jansen, 2005).

5.3.1 Coagulation and flocculation

The purpose of coagulation and flocculation is the aggregation of particles to promote removal in the sedimentation and filtration steps. Coagulation is defined as “the process whereby charged particles are neutralised,” and flocculation as the aggregation of these particles. (Kemira 2003, 124) These steps in a water treatment process have a great influence on the effectiveness of subsequent steps. For example, according to LeChavallier and Au (2004, 23), “without proper chemical pre-treatment, rapid filtration … is not en effective barrier for microbial pathogens.” Inefficient coagulation and flocculation will also lead to a greater disinfectant consumption (Kemira 2003, 121).

Particles in water have a net negative charge, which keeps them from sticking together when they collide (Kemira 2003, 131). The reduction of this electrostatic charge allows the particles to come close enough to unite by means of van der Waal’s force (Kemira 2003, 132). This produces bundles of particles which are large enough to sediment or filter out.

Charge-neutralisation is achieved by the addition of a coagulant. This is usually done using metal salts, of which the most common are aluminium and ferrous sulphate. When the salt is added to water it dissolves, splitting the compound into a positive metal ion and a negative ion. The metal ion then reacts with water molecules to form polymeric hydroxide complexes (Kemira 2003, 125-7). The adsorption of these complexes to the negatively charged surfaces of the particles reduces electrostatic charge, making it possible for particles to aggregate (Kemira 2003, 131). Over-dosing a coagulant can lead to re-stabilisation of particles. This occurs when the cationic hydroxide complexes adsorb to the particle in such a great number, that the former net negative charge becomes positive. As a result the particles will become re-dispersed in the water and will not aggregate upon collision. (Kemira 2003, 135)

Flocculation, or aggregation, of particles involves several different mechanisms. One is by the action of van der Waal’s force after charge-neutralisation. There are, however, two other significant mechanisms: patch coagulation and sweep coagulation. In patch coagulation, the hydroxide complexes bind to a patch on a particle (Kemira 2003, 132). However, it can still bind to more particles meaning that the hydroxide acts as glue. By gluing together many particles a larger floc is formed and precipitated. Patch coagulation and charge neutralisation are most significant when particle concentrations are high (Kemira 2003, 136). Sweep coagulation also results from hydroxide complexes. The adsorption of a hydroxide onto a particle can cause other hydroxides to “grow” from this site. This growth will cause the particle to become heavier, allowing the force of gravity to pull it downwards out of suspension. As this particle moves past other particles, it will sweep them down with it. Thus the name: sweep coagulation. This mechanism can be utilised when the concentration of contaminants is low by using a high coagulant dose. (Kemira 2003, 132-133)

The pH of the raw water has a significant bearing on the coagulation and flocculation processes (Kemira 2003, 142). The surface charge of particles in the water becomes more negative as pH rises. Therefore a higher dose of coagulant or flocculant is required at a high pH than at a lower. The charge of hydroxides is also affected by pH (Kemira 2003, 148). Most hydroxides are positively charged at pHs lower than 7 and become increasingly negatively charged as the pH rises. Finally, the pH of the water affects both the rate of formation and the type of hydroxide that is formed when the metal salts polymerise (Kemira 2003, 150). It is therefore important to be aware of the particular pH range where a specific metal salt is most effective. The pH range for best coagulation with aluminium sulphate is 6.4 to 7.4. Meanwhile the limit for iron sulphate is above 5.

The coagulation process is not only affected by pH, the addition of coagulants may also influence it. An important parameter to be considered with respect to pH is relative basicity. The relative basicity of a salt is the ratio, expressed in percent, between the numbers of moles of hydroxide formed per three moles of aluminium or iron. (Kemira 2003,130) When a metal salt reacts with water, a metal hydroxide and a hydronium atom, H^+, is produced. This displaces the pH of the water in the acidic direction. If a metal salt is pre-polymerised, meaning the salt itself includes hydroxide complexes, there are less metal ions that will react with water to release H^+. The pH reduction will thus be less when using a pre-polymerised salt. It should be noted that the relative basicity of a non-polymerised metal salt is 0%. The significance of relative basicity is realised when treating water with a low buffering capacity (5.1). The addition of a metal salt will lower the pH to a certain degree depending on the relative basicity of the salt. As a rule, the use of high basicity salts is recommended for water with low alkalinity. However, the removal efficiency of different water constituents varies depending on the salt basicity. Relative basicity should also be taken into account when choosing the dose of a coagulant. The dosage range for neutralisation is smaller for a high basicity salt, and therefore the risk for re-stabilisation is higher.

The coagulation and flocculation of particles can be aided through the addition of polyelectrolytes. These are polymers comprised of charged monomers. Negatively and positively charged polymers are called anionic and cationic, respectively (Kemira 2003, 155). Anionic polymers are used as flocculation aids (Kemira 2003, 164). As they are negatively charged, they can bind to the positive metal hydroxides in the flocs connecting them together. This allows for a shorter flocculation time as well as stronger and denser flocs. The anionic polymer must not, however, be added to the water during the coagulation process, as the metal ions will react with the polymer instead of forming hydoxide complexes. Cationic polymers, on the other hand, can be added together with coagulants since they are positively charged and will not attract the metal ions that react with water. Cationic polymers are pH-sensitive due to their positive charged amine groups (Kemira 2003, 162). Four types of amines can be present at one time: primary, secondary, tertiary, and quaternary amines. Quaternary amines are always positive; the first three types of amines however loose their positive charge between pH 6 and pH 11. The loss of charge reduces the affinity of particles to the polymer, thus making it less effective. However, in some cases exposure to a high pH for a few minutes will allow it to be used as a flocculant as this will reduce the number of positive charges on the molecule, making it more negative. The addition of a positive polyelectrolyte will allow a reduction of coagulant dose, as well as allow for the treatment of water at higher pH levels (Kemira 2003, 160). At very high turbidity levels water can be treated solely with a cationic polymer. However, for water with less then 500 NTU a coagulant is required.

Rapid mixing plays an important role in the chemical pre-treatment process. Without adequate rapid mixing during coagulation there is a reduced contact between contaminants and the treatment chemicals, which slows down the reaction (Kemira 2003, 126). One previous study has shown that colloid bridging, when using polymers as coagulants, was significantly improved by rapid mixing. Another study stated that rapid mixing had considerable effects when patch coagulation and charge neutralisation were key mechanisms. Later, a study conducted by Kan et al. (2002) showed that the time for rapid mixing had significant effects on the final turbidity of the water. The coagulation was done using two types of aluminium salts on synthetic raw water (clay particle suspension). The mixing time was especially important when the aluminium salt dose was in the range where adsorption and charge neutralisation were the coagulation mechanisms. They also concluded that the exceeding of the optimal mixing time, when these same mechanisms were active, did not have significantly adverse effects on the turbidity reduction. However, when sweep coagulation was the main mechanism, excess mixing time lead to a final turbidity that was almost the same as that when no mixing was carried out. These poorer results were concluded to be a consequence of formed flocs being broken by the high shear forces caused by the rapid mixing. The optimal rapid mixing times varied between 20 to 180 seconds for adsorption and charge neutralisation, and between 10 to 50 seconds for sweep coagulation. (Kan et al. 2002, 9) For the formation of flocs, gentle mixing of the water is the key to accomplish the most effective flocculation (LeChevallier and Au 2004, 87). The mixing of the water encourages contact between particles to a greater extent than if the water were not stirred. It is important that this mixing is gentle, as a high shear (mixing) rate will destroy the forming flocs.

5.3.2 Sand filtration

Filtration is the step where particles are separated and removed from the water. The filter media can differ from delicate nets, such as micro- or nanofilters, to beds of grains of different sizes and shapes. In addition, the filters can be open or closed and the direction of the water can be downwards, upwards or both ways. Depending on the solids to be separated, desired quality of the treated water, economy, and facilities for washing different kinds of filters are chosen. Since the sand filter used in the EmWat 4000 is a closed downward filter with granules, this chapter is limited to only treat this type of filters.

By letting the water pass through the filter, solids will remain in the unit as a result of the mechanical straining, a consequence of the particles being larger than the mesh size of the filter media. The solids may also simply deposit on the filter material through settling, direct interception by rubbing, diffusion by Brownian movement or because of the inertia of the particle. However even solids smaller than the mesh size are retained and attached to the filter. The attachment mechanisms are physical forces, such as jamming and cohesion or adsorption forces like van der Waal. The active mechanism depends on the flow and on how close the particles come to the media. The attachment mechanisms are naturally favoured by low flow. As solids are being retained the flow through the filter will be inhibited and slowed down. The solids will also be forced to pass through narrow paths and the conditions for attachment will improve. For a new filter the first retained particles from the water will fill it up and help increase the reduction capacity of the filter. The period until the reduction rate stabilises is called the maturing period. However, uneven flow peaks, rubbing and the other mechanisms may lead to the detaching of already retained particles. This may cause the detached particles to be driven even further into the filter media or released back into the filtrate. (Degrémont, 1991, 179)

The removal capacity of the filter depends on the pore size of the filter media and on the type of solids retained. According to Degrémont (1991, 189), the possible volume of sludge that can be retained is on average one quarter of the filter pore volume. By using the density of the sludge the possible captured mass can be estimated. Thus, the amount of water to pass the filter before it becomes full can be calculated, if the density of the water to be treated and the removal degree is known.

Max removal (kg)/ solid (kg/l water) = water that can pass before filter becomes full (l)

For water passing through a porous media Darcy’s law is applicable.

$$v = \frac{k * \Delta p}{\eta * \Delta H}$$

v = filtration rate
k = permeability
Δp = head loss
η = dynamic viscosity of water
ΔH = depht of considered layer

If the velocity is known an assessment of the time, for the filter to become clogged, can be done. The capacity of bacterial removal in filters is completely depending on the coagulation process. Examples are given by reports from a study on low turbidity water, < 1 NTU. The reduction of Giardia increased from 69 % to 95% by using chemical pre-treatment. Varying the filter rate had little effect in comparison. Another study, conducted 1990, gave similar results. The reduction rate of Giardia cyst increased from 64% to 93.6% by added coagulators. Rapid filtration in combination with coagulation may remove between 2 and 3 logs of bacteria and parasites such as Cryptosporidium (Dufour 2003, 164). The removal potential for viruses is lower and range from 1 to 2 logs. (LeChevallier and Au 2004, 23 and 24)

As the particles fill up the pores and possible ways for the water to pass become limited, the pressure in the filter will rise. Before starting filtration the pressure in a granular media bed increases linearly through the filter. For a downward filter the top of the filter will treat the water first and therefore pressure will rise there first. During operation, a so-called filtration front, above which the head loss is raised, will move downward through the filter. When the front has moved through the whole filter the maximum capacity of the filter is reached. The process of filling up the pores is called clogging and when the capacity is reached the filter is said to be fully clogged. If the operation is continued after the filter has been clogged, a breakthrough will occur resulting in leakage of the untreated water to the subsequent process. Therefore cleaning the filter before this occurs is crucial. By rinsing the sand with water in the other direction, solids can be washed out. For an optimal backwashing with water, a current that can “lift” the sand is used so that a stable expansion of at least 15 % can be maintained during a period of time. If the flow is uneven, displacement of the sand due to convection currents may occur. The compacted filter media from the top of a downward filter may be transported down to the bottom where mud balls may be formed. The displacement of the sand also risks leading to a grading of the grains if different sizes are used. Air, or air and water in combination, can also be used for backwashing, diminishing the risk of formation of mud balls. (Degrémont 1991, 193) Another risk if the backwashing is done incorrectly is wash out of filter material.

It is essential to conduct back washing regularly to prevent permanent clogging. In a permanently clogged filter the packing of the retained particles might be dense and uneven. This might result in cracks (Dufour 2003, 164), and the water might find locally faster paths where filtering degree is reduced. The head loss will increase more rapidly and efficiency will decline. (Degrémont, 1991, 192)

Directly after cleaning, the capacity to retain small particles decreases as the pores are cleaned and pore-size increased. There is also a risk that particles detached by the back washing, but not washed out, might be released in the first flush of filtered water. Therefore, before starting the purification process it is good to rinse the filter with water in the normal direction for operation without using this water for drinking. A so-called slow start: rinsing for 30 minutes, alternatively limiting the flow initially is recommended (Dufour 2003, 164). Other techniques are delayed start and filter aid, which means leaving the filter inactive for a while before operation or using an additional filter during start up, respectively. (LeChevallier 2004, 22)

The water used for rinsing might very well be recycled and used for purification. However, as the backwash water may contain high levels of microorganisms it should not be recycled unless in the case of severe water scarcity. (LeChevailler 2004, 26)

Apart from the physical properties of the filter and grains the mode of operation is crucial for the filter maximum capacity. The first water after installation or filter cleaning, produced before the filter has matured completely, shall be used with caution not to deteriorate subsequent processes and the quality of the final produced water. It is also essential to determine when to stop operation to prevent breakthrough from occuring. If breakthrough occurs, the volume passed or the head loss at that moment can be used to estimate when backwashing should be performed next time. Keeping a steady flow also increases the capacity of the filter (LeChevallier 2004, 14). In conclusion, for optimised operation monitoring and process control is essential.

To improve the capacity of a sand filter, filter aids can be used. Filter aids are granules of a material with low bulk density and capacity of forming a porous filter. Diatomaceous Silica is a material that meets these criteria. If silica is added, the filter material chosen can be more permeable with remained retention capacity. The higher permeability allows higher flow rates to be treated with kept purification rate. (Perry and Green 1997, 18)

5.3.3 Activated carbon

Activated carbon is a material with extremely small pores and properties that attach selected molecules. The process can be used for polishing treatment of drinking water but also in processes of industrial wastewater and in the tertiary treatment of wastewater.

Activated carbon can be in the form of powder that is regularly added to the treated water or in a bed of grains that the water has to pass.

A material with high carbon content has to be activated to gain the specific properties of activated carbon. The material can range from the rock anthracite, containing over 90 % carbon, to soft wood or even coconut shells with a carbon content of 35%. The activation process can be either thermal or chemical. For thermal activation, variable application of heat removes different unwanted particles or molecules from the filter by burning. The filter is thus left with miniscule pores. A complication is that low quality carbon may leach ash (Huchler 2000). The chemical activation is a result of letting chemicals, mainly acids, hollow out the filter through different reactions (tifac.org).

The activated carbon filter works as an ordinary strainer filter for particles larger than the pores. For smaller particles and molecules the absorption mechanisms are Van der Waal's forces and Coulomb electrostatic forces, promoted by the significant large surface area due to the amount of pores. Under good conditions most organic molecules can bind to the surface of the filter media. The affinity is greater for slightly polar molecules such as heavy molecules and aromatic compounds. This is the reason why the activated carbon filter is used for reducing taste and smell of water. Most polar molecules, linear and with low molecular weight, are on the other hand more difficult to capture in the filter (Degrémont 1991, 223). Toxicity is difficult to remove in water by conventional methods, but activated carbon and oxidising are processes that have appeared to remove or reduce it but "knowledge is impeded by the lack of suitable analytical methods"(WHO 2004, ch 2.1.4). However, a study referred to by LeChevallier and Au (2004, 17) states that activated carbon have raised the removal level from 49% to 90 % or more, compared to conventional methods. The removal capacity is dependent on type of activated carbon and the dosage, and on toxin levels.

An additional property of the activated carbon is that it can also work as a catalyst in dechlorination to reduce chlorine and chloramines (Degrémont 1991, 223). The filter may also host biological activity. It can help to regenerate the filter by breaking down retained particles and releasing them. (Degrémont 1991, 226)

Decisive for the length of the life of the activated carbon is the hardness of the material. Sufficient hardness will limit the generation of fines and wash-out from the material (Huchler 2000). However, the capacity for the amount of water that can be purified depends on the water quality. According to Degrémont (1991, 226) experience has shown that, per hour, three volume of highly polluted water can be treated for every volume of carbon. However, if the particle density in the water is very low the volume of water to be treated can be 5 or 10 times the carbon volume per hour. These figures are only to be used as indicators. Another critical parameter for the treatment to be efficient is the suspended solids in the water, which should be less than 25 ppm (Huchler 2000). Since the value of suspended solids refers to the mass of suspended matter, conversions to turbidity is difficult. Using approximate conversion factors, 25 ppm would roughly correspond to 25‒35 NTU (duluthstreams.org 2005). The removal efficiency for the filter is measured by retained COD / kg activated carbon.

Like the sand filter, the activated carbon can be clogged, with a pressure rise and lowered capacity as a consequence. The capacity for retaining the molecules of low molar weight also decreases as the pore surfaces become covered. (Degrémont 1991, 226) Regeneration to a limited extent is possible by rinsing the filter, which will release molecules as a result of diffusion mechanisms. By reversing the conditions favouring adsorption, desorption and cleaning will be promoted. To remove all particles attached to the filter with chemical bonds, regeneration, by thermal or chemical methods is needed (Degrémont, 1991, 229). According to the journal “Carbon” the filter may very well be regenerated and reused. Comparisons had shown a higher degree of removal for activated carbon that had been thermally regenerated six times than for a completely new carbon filter. This was a result of the increasing size of the pore volume during regeneration. When the filter was put back into operation the particle attachment filled up the bigger pores and generated new small ones. Conversely, for the new filter the smallest pores were clogged (Moore et al, 2001). As mentioned, growth of bacteria is a part of the process in the activated carbon, and the bacteria might prolong the length of the filter life, but they can also be a risk. The bacteria might cause clogging and fermentation, which might release odours instead of decreasing them. The risk for growth of bacteria is even higher when the filter is not in use. Therefore washing the filter should be done with high doses of chlorine. Disinfection is essential before stand-by but can also be done regularly when the carbon is in use (Huchler 2000).

5.3.4 Chlorination

The previously mentioned water treatment steps cannot guarantee the complete absence of bacteria in the water. In order to ensure that the bacteria left after the treatment steps will not harm the consumer, the water has to be disinfected. Disinfection, or inactivation of microbiological activity, can be performed during the treatment process, or as a final step before the water is distributed. The former is termed primary, and the latter secondary disinfection.

Disinfection can be achieved by using several different methods. The use of ultra-violet light is an example of a non-chemical method. However, the most common are chemical methods where an oxidant is added to the water. Conventional disinfection is carried out through the use of chlorine-containing compounds, and is called chlorination.

Chlorination can involve the use of three kinds of oxidants: chlorine dioxide, chloramines, and chlorine. Chlorine dioxide is a stronger oxidant than chlorine. It is used to disinfect water that contains phenols, which cause bad taste when they react with chlorine. It can also remove dissolved iron and manganese under certain conditions, as well as water discoloration and odour. However, when reacting with water constituents it can produce unpalatable inorganic compounds (Dufour 2003, 168). The presence of these by-products may require additional water treatment before distribution. Chloramines are produced by reacting ammonia with chlorine. They are more stable than chlorine and chlorine dioxide, and are therefore suspected to have a longer residual effect. Chloramines are known to have a relatively slow rate of disinfection, which has lead to a lower proliferation in water treatment (Degrémont 1991, 911). In situations where a long-lasting residual effect is desired, disinfection is carried out using other agents before the application of chloramines (Dufour 2003, 168). The most common oxidant, chlorine, has been used in water treatment for over one hundred years. It has been considered an effective agent for the inactivation of most pathogens (LeChevallier and Au 2004, 45).

Chlorine can be introduced to water as a gas, as a solution in the form of Javel water, which is a sodium hypochlorite ($NaClO$) solution, or as a solid in the form of calcium hypochlorite ($Ca(ClO)_2$). In gaseous form chlorine is bubbled through water allowing it to react as follows (Degrémont 1991, 252):

$$Cl_2 + H_2O \leftrightarrow HClO + HCl \quad (1)$$

$$HClO \leftrightarrow ClO^- + H^+ \quad (2)$$

The reaction between chlorine and water produces hypochlorous acid ($HClO$), which will further dissociate into hypochlorite (ClO^-) and hydronium ions. If the chlorine is added in liquid or solid form, the hypochlorite will react directly with the water constituents as described in the previous equations. (Degrémont 1991, 878) According to the equilibrium equations present above, the amount of Cl_2, $HClO$, and ClO^- in the water is determined by the pH. This is due to the presence of the hydronium atom in equation 2, which means that an increase in the H^+ concentration will "push" the chemical processes towards the production of hypochlorous acid. This will in turn have effect in the equilibrium in equation 1, where an increase in HClO will cause the reaction to go "backwards", resulting in the production of molecular chlorine and water molecules. Therefore, when the pH is 2 or less, all chlorine is found in molecular form. At pHs between 2 and 5, both molecular and HClO chlorine is present. At pH 5 all chlorine is in the form of HClO. After the pH rises above 5, the chlorine is present as HClO and hypochlorite. The hypochlorite concentration rises with the pH until all chlorine is found as hypochlorite at pH 10 or above. Chlorine will be most effective at inactivating bacteria when the amount of hypochlorous acid is at a maximum. (Degrémont 1991, 252)

When chlorine is added to water the reactions with the constituents occur in different stages depending on the amount of chlorine added, as shown in Figure 5.2.

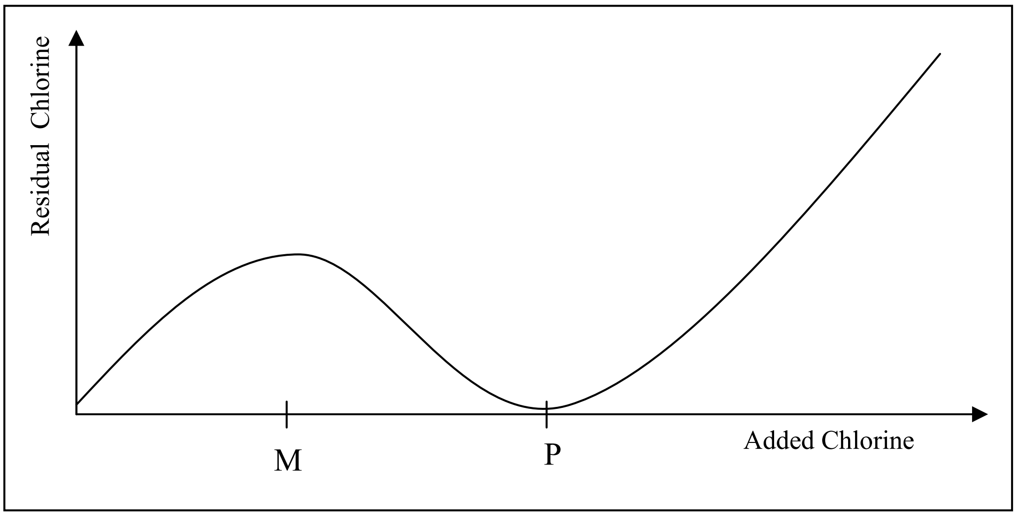

Figure 5.2 Change in free chlorine concentration (Adapted from Degrémont 1991, 253)

Initially, when chlorine is added to the water it reacts with ammonium in different water constituents. The compounds formed are residual chlorine, which is capable of disinfection. If more chlorine is added after point M, it reacts with and consumes these newly formed compounds, producing substances that are not disinfective. After the so-called breaking point (P), the amount of free chlorine (HClO and ClO^-) in the water will rise linearly with the added chlorine. (Degrémont 1991, 253)

It is not known exactly how chlorine interferes with normal cell activity and deactivates bacteria. The effects of free chlorine on bacteria have been studied, specifically that of hypochlorous acid. Studies have indicated that treatment with chlorine has resulted in a reduction of metabolism rate, glucose transport, and adenosine triphospate in bacteria, and changes in the structure of the cell membrane as well as disruption of protein synthesis. Chlorine has also been known to react with nucleic acids, leading to genetic defects (LeChevallier and Au 2004, 45). The effects of chlorine on microbes, as well as the reaction rate, depend on pH, chlorine concentration, contact time, and temperature. According to LeChevallier and Au (2004, 42) "… the rate of disinfection reactions [is affected by temperature] according to the Arrhenius equation, although this may not hold for certain disinfectants at low temperatures." The effects of pH with respect to the determination of the concentration of different chlorine-species have been discussed above. Furthermore, it has been noted that, "… the disinfection efficiency of free chlorine is increased at lower pH values…" (LeChevallier and Au 2004, 42). Chlorine concentration and contact time effects are studied as ct- values, which is the product of disinfectant concentration and contact time.

According to WHO's Guidelines for Drinking-Water Quality (1996, 11.2.9) disinfection kinetics follow Chick's law. This means that the ratio of the population at time t and initial population varies according to the following equation:

$$\frac{x_t}{x_0} = e^{-kt}$$

x_t, population at time t
x_0, initial population
k, specific death rate
t, time

Watson's empirical dilution law states that the specific death rate is proportional to the disinfectant concentration and contact time,

$k = C^n t$

k, specific death rate
C, disinfectant concentration
t, contact time

For disinfection it has been found that $n \approx 1$, therefore k is directly proportional to the product of concentration and time. (WHO 1996) In the light of this, it is practical to give CT-values that correspond to a specific removal rate (Table 5.5).

Table 5.5 CT values for 99% inactivation of various agents, 5°C (WHO 1993, table 11.1)

Agent	CT, mg min/l (using free chlorine, pH 6−7)
E. Coli	0.034 − 0.05
Poliovirus type 1	1.1 − 2.5
Hepatitis A virus	1.8
Rotavirus	0.01 − 0.05
Giardia lamblia cysts	47 − >150
Giardia muris cysts	30 − 630
Cryptosporidium parvum oocysts	−

Note that the values given in Table 5.5 were obtained at 5°C and a pH between six and seven. It is therefore imperative that all four factors that affect the disinfection kinetics are taken into account when reviewing CT data.

Other factors that affect disinfection efficiency are surface attachment, certain defensive mechanisms of specific organisms, aggregation, growth rate under nutrient limitations, and the type of organism to be inactivated. A study conducted by Steward and Olson (1986) showed that the aggregation of a certain strain of Acinetobacter lead to an extensive increase in the bacterias' resistance to hypochlorous acid. Reilly and Kippin (1983) as well as Clark (1984) were able to isolate bacteria that had produced an extra-cellular capsule, which protected it from the disinfectant. The limitation of nutrients, which results in a bacterial growth rate that is below maximum, can produce bacteria with a high resistance to disinfection. (LeChevallier and Au 2004, 42) The presence of turbidity in water increases the resistance of microbes to disinfection, by disallowing contact between organisms and the oxidant, effectively shielding pathogens (Dufour, A. et al. 2003, 166). Apart from factors in the environment, the target organism and its resistance to chlorine needs to be taken into account. A study conducted by Norton and LeChevallier (2000) suggested that bacteria with thicker cell walls were more resistant to chlorine. Likewise, Table 5.5 shows much higher CT values for Giardia Lamblia and Giardia Muris cysts than those for Escheria Coli and Poliovirus type 1. One study found that for the inactivation of 90 % of Cryptosporidium oocysts a free chlorine residual of 80 mg/l was required for a period of 90 minutes at a temperature of 25°C and pH 7 (LeChevallier and Au 2004, 50). The difference in chlorine resistance regarding more organisms is found in the chapter on Water quality (5.1)

As mentioned before, chlorine can react with other water constituents. Reducing agents consume a large amount of the disinfectant and result in higher required doses to ensure that organisms are inactivated. The oxidation of natural organic material can also produce chlorination by-products (CBPs), which may be toxic. Studies have suggested that the presence of chlorination CBPs increases cancer risks. The main group of by-products is trihaloromethanes (THMs), which include chloroform, bromodichloromethane, chlorordibromomethanes, and bromoform. All these substances are potential animal and human carcinogens, and have adverse effects on unborn children if mothers are exposed during pregnancy (Rodrigues et al. 2001, 2). Finally, the oxidation of organic matter by chlorine can make it more ready available to microorganisms. Measuring the nutritional content of water as assimilable organic carbon (AOC) or biodegradable dissolved organic carbon (BDOC) can give an indication of the potential for regrowth of bacterial in a water system. LeChevallier and Au (2004, 63) cited several studies that indicated an increase in AOC and BDOC as a result of chlorination. Organic compounds should therefore also be reduced as much as possible from water before disinfection, which is a reason to use activated carbon filter (5.3.3).

For effective chlorination to occur it is imperative that the right conditions are present. WHO (1993, 90) states that "…[to ensure] successful disinfection, turbidity should always be less than 5 NTU and preferably less than 1 NTU." This is due to the high frequency of failure at turbidity levels higher than 5. LeChevallier and Au (2004, 46) state that for the effective removal of viruses 1 NTU, 1 mg chlorine/l, 30 minutes contact time, and pH less than 8.0 is required. The difficulty of inactivating protozoan cysts and oocysts requires that they be removed at an earlier stage in the treatment process. In this respect the most significant part of the treatment process is coagulation and flocculation (LeChevallier and Au 2004, 16).

6 Method

6.1 Summarising results from previous EmWat operations

Since the EmWat 4000-kits were received in Ethiopia five units have been in operation. Reports were prepared by UNICEF personnel or staff at the local or regional water bureaus. To gain a better understanding of the performance of the kit, reports from these previous experiences have been studied.

More specifically, the three reports from the operations at Erebti in Zone 2, Afar; Amuta-Gasala, Oromiya; and Selamago in South Omo, SNNPR[*] were studied as they contained operational data or a summary of the kits' performance.

6.2 Testing *water quality after EmWat 4000 purification*

Three sites were visited where the EmWat 4000 was employed. Testing of the source and treated water was done in order to supplement the evaluation of the performance of the kit. Due to economic and practical restraints the four most basic parameters for monitoring water quality were tested (5.3.2). These are turbidity, pH, residual chlorine, and microbiological analysis. The results from measuring these parameters were used to assess the treatment efficiency of the EmWat 4000 and the safety of the water produced. The method for each test is explained below.

6.2.1 Turbidity

The turbidity measurements were conducted using 2100P ISO Turbidimeter. The water to be tested was gathered in a bucket, and two sample bottles, 20 ml each, were filled up after being rinsed. The same water that was tested was also used to rinse the bottles. Before inserting the bottles in the turbidimeter they were dried and polished. Two samples were taken from each sample point in order to reduce the risk of scratches or dirt on the bottles affecting the results. The two bottles were filled simultaneously and one was put aside while the first was being measured.

The precision and accuracy of the instrument is ±1% and ±2%, respectively, of the displayed value. It measures between 0 NTU to 1000 NTU in three ranges that can be either automatically or manually chosen. The resolution at the three ranges are shown in Table 6.1. (Hach 2004)

Table 6.1 Resolutions at different measurement ranges (Hach 2004).

	Range		
	0.00–9.99 (NTU)	0–99.9 (NTU)	0–1000 (NTU)
Resolution	0.01	0.1	1

During the tests, the instrument was set to automatically choose the appropriate range for resolution. The option of automatically taking several consecutive measurements and then returning the average value was used to ensure reliability of the results.

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[*] SNNPR: Southern Nations Nationality Peoples Region

6.2.2 Residual chlorine

The chlorine analyses were made using the Pocket Colorimeter II, provided by Hach, following the procedure described in the instruction manual. A test cell was filled with 10 ml of sample water and placed in the photocolorimeter without the addition of DPD reagent. The photocolorimeter was then calibrated. Afterwards, one powder pillow of DPD reagent was added to the cell, which was then shaken gently for 20 seconds. When measuring the free chlorine in the water, the "free chlorine" DPD reagent was used. Two samples were taken from each sample point to ensure reliability. The measurements were taken within 1 minute after the addition of the reagent. When measuring the total chlorine only one sample was taken. 3 to 6 minutes were allowed to pass after the addition of total chlorine DPD before the measurement was made.

The measuring equipment used in this thesis work employed a photocolorimeter to measure the chlorine content in disinfected water. Two types of DPD were provided, one for the measure of free and one for the measure of total chlorine. There are two different measurement ranges for this instrument that have to be set manually. In the lower range mode (LR) chlorine concentration between 0.02 mg/l to 2.00 mg/l can be measured. In the higher range mode (HR) between 1.00 mg/l and 8.00 mg/l Cl_2 can be measured. In LR-mode the precision of the instrument around 1.00 mg/l is ± 0.05. HR-mode has a precision of ± 0.2 at 5.0 mg/l. This manual also lists some water constituents or conditions that interfere with the chlorine measurement. Acidity or alkalinity greater than 150 mg/l $CaCO_3$ and 250 mg/l $CaCO_3$, respectively, will not allow the sample to develop full colour, or the colour will appear and fade instantly. The presence of oxidised manganese and chromium will give heightened concentration values. Similarly, monochloramine will cause a continuous increase in the values read within one minute after the addition of DPD.

6.2.3 pH

The hand held pH-meter, Pocket Pal Tester, was submerged 2–3 cm in the water and the value was read on the digital display. This instrument can measure the pH from 0 to 14, and has an accuracy of ±0.2. (Hach 1998)

6.2.4 Microbiological analysis

To monitor efficiency with regards to the presence of microorganisms, the membrane filtration method was used. Membrane filtration was chosen since it is a method that can be performed without a laboratory. Apart from E-coli the method used also showed total coliforms. The false positive error is 2.3% for detection of E coli, and 26.8% for total coliforms. Undetected target error was given as 0 % and 1.6% for E coli and total coliforms, respectively. (Hach 1999)

The sampling procedure was done to meet the standards from the Guidelines for Drinking as much as the practical conditions permitted (5.2.1). The Guidelines from WHO suggest that samples are taken from every branch and tap, to cover the whole system. However, this was not done, due to limited time and equipment. Four sample points were tested at each test site. The water in the source, the purified water at two different taps and lastly, one disinfected tap. All the taps seemed to be used with the same frequency so the test taps were chosen randomly. Two samples were taken at each sample point to ensure the reliability of the results. Before sampling, the taps were wiped with a clean cloth and water was allowed to flow for 30 s[*]. The disinfection

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[*] WHO suggest rinsing for 1–2 minute but that was impossible due to water shortage.

was done by cleaning the taps with alcohol-soaked cotton pads. Since the taps were made of plastic, sterilization with a flame as the standard suggests was impossible. The samples were taken in 100 ml sampling bags. For the purified water, thiosulfate tablets were used to inactivate the residual chlorine.

The membrane filtration method was conducted as soon after sampling as possible. Testing at the sites was not an option, as contamination would almost certainly occur during preparation. The samples from Dire Kiltu and Sofi Logo were transported during 4 to 5 hours before the filtration process. The samples from Dire Kiltu were kept at a low temperature using ice and isolating them with newspaper. After the sampling in Konta Koysha the samples were not tested until after 24 hours. During this period they were stored in a refrigerator for approximately 12 hours but for the rest of the time no cooling was available. This was a clear deviation from both the procedure presented by the Hach and the WHO standards.

The membrane filtering was conducted as close to the ISO 7704 standard, presented in Millipore Corporation (2000, 6−10), as possible. The microfilter support was wiped with alcohol and flamed. After this a membrane with a pore-size of 45 μm was placed on the microfilter support, and a funnel was placed on top of the filtering unit. The funnel was filled to the 100 ml line with sample water, which was then sucked through the filter by a vacuum pump. When the sample had passed, distilled water was used to rinse the funnel. For waters with high NTU or high expected amount of bacteria the sample was diluted with distilled water to achieve a countable number of colonies. The filter was then removed with sterile forceps and placed in a Petri dish prepared with a nutritive medium. The forceps and the microfilter support unit were sterilized using alcohol and a flame, and the funnels were changed for every sample. Each time a set of samples from a site was processed, two blanks were prepared by filtering only distilled water. This was done to check whether a contamination of the samples had occurred during the membrane filtration process. One blank was processed before and one after the series of tests.

For incubation the nutritive medium m-ColiBlue24 Broth by Hach was used. This media is a selective growth media, which inhibits non-coliforms, and will allow the enumeration of both E-coli and total coliforms. For the detection of colonies the medium includes a colorimetric indicator, a selective blue colour and a red colour for E-coli or total coliforms, respectively. Incubation was done for 24 hours at a temperature of 35°C, using an incubator purchased from Hach. For the samples from Konta Koysha, however, the incubator at the laboratory of water bureau in Awassa was used. After the incubation the number of E-coli and the total coliform colonies were counted. The Petri dishes that had an uncountable number of colonies were noted as such. For the diluted samples the number of coliforms per 100 ml was calculated using the dilution factor.

6.2.5 Laboratory tests

To supplement the bacteriological tests 20 litre-samples of source water and treated water from the sites at Dire Kiltu and Sofi Lugo were taken to the Ethiopian Health and Nutrition Research Institute in Addis Ababa. Microscope tests were performed to detect parasites, specifically Cryptosporidium and Giardia.

For the water species analysis, water samples from the three visited sites were taken to the Oromiya Water Laboratory in Addis Ababa. The water samples from Konta Koysha where taken to both the laboratory at the water bureau in Awassa, as well as to the Oromiya Water Laboratory.

In Dire Kiltu locally produced aluminium sulfate powder was used. In order to compare the coagulation and flocculation processes, the powder was sent together with the metal salts provided with the kit to Kemira for laboratory analysis of the active ingredients.

6.3 Full-scale test

A full-scale test was performed on the EmWat 4000 at the sites in Sofi Lugo and Dire Kiltu. The aim was to see to what degree changes in flow rate and different combinations of coagulants and flocculants had on the quality of the produced water. Initially, the method of performing the full-scale test will be presented. However, the outcome of this needed processing before interpretation was possible. The method for processing will be presented in this chapter and will contain results of the measurements. This should not be confused with the actual results from the processing, the impact of flow rates and chemical combinations, which will be presented in Results (7).

6.3.1 Performing the tests

The test was done so that the effects of dose and type of tablet could be studied. Five sets of tests were done, each at two different flows. The first test was conducted without the use of chemicals. The next three sets of tests varied the amount of coagulants used. They were performed using 3 coagulant tablets (3C), 6 coagulant tablets (6C), and 9 coagulant tablets (9C). The final two sets of tests were performed using 4 coagulant tablets with 2 flocculant tablets (4C+2F), and 6 coagulant tablets with 3 flocculant tablets (6C+3F). In order to be able to compare the results of the tests using flocculants with the rest of the tests, the total number of tablets was kept constant. The reason for using less flocculants than coagulants is that the amount of floc aids needed in a water treatment process is usually less than the coagulant dose. For each set of tests two flow rates were used: first 1 l/s and then 0.5 l/s. The treatment efficiency was monitored by measuring turbidity of the raw water at the inlet turbidity sample point and the filtered water at the outlet turbidity sample point (Figure 6.1). The turbidity from the inlet was measured three minutes before the turbidity of the outlet since rough estimations showed that the water would take approximately three minutes to travel through the system at 1 l/s. Sampling from these two points was repeated every five minutes.

The coagulants used in the full-scale test are called Ferufloc, which contains ferrous sulphate, and Aniofloc, which contains anionic polymers. These were chosen based on the results of a shake test. Four bottles were filled with 1 litre of untreated water from the source. Alufloc was added to two of the bottles, and Ferufloc was added to the two remaining bottles. The dose added was approximately one eighth of a tablet to a litre of water. After the addition of coagulant, the bottles were closed and shaken rapidly for a few seconds. The bottles were opened and quickly cationic flocculants were added to one bottle containing aluminium sulphate and one bottle containing ferrous sulphate. The same was done with the anionic flocculants. Approximately one eighth of the flocculant tablets was added. After the addition of flocculants, the bottles were again shaken, and particles were allowed to settle. The combination which produced the clearest water the fastest was chosen for the full-scale test.

The EmWat kit in Sofi Lugo was set up as depicted in the manual, with a few modifications (Figure 6.1). Before arriving at the site the pond was emptied for irrigation purposes. During the whole day the pond was filled up slowly with water from a spring. Due to the initial shortage all water that was pumped up was piped back close to the system inlet. The inlet pipe was fitted with a floater provided in the kit, without the use of a basket strainer. The pump was connected to the coagulant chamber with a two-metre pipe, a by-pass valve, and another two-metre pipe. A by-pass valve was connected for flow adjustments. The pipe between the coagulation and the flocculation chambers was chosen to be five metres long in order to allow for charge neutralization before the addition of the flocculants. Three 20-metre long flat-hoses were connected to make a 60-metre long flocculation pipe. This was then connected to a three-metre long pipe joining the sand filter. A 20-metre flat-hose was used to lead the filtered water back to the pond, emitting it close to the inlet. The recycling of this water was needed due to the shortage of water in the pond. As seen in Figure 6.1 the carbon filter was not connected. This was partly due to the lack of a sampling point between the sand and activated carbon filter, and partly due to the fact that the sand filter would not remove a sufficient amount of particles, which might lead to premature clogging of the new carbon filter.

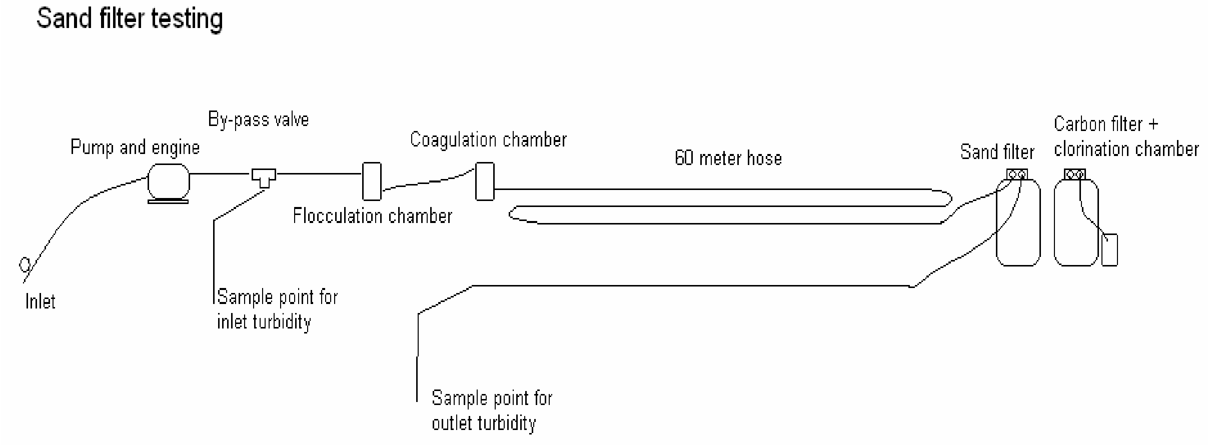

Figure 6.1 Set-up for full-scale test

The pump was primed by filling the suction pipe and pump chamber with water and then started. Using the accelerator and the by-pass valve, the flow through the system was adjusted to approximately one litre per second. The discharge was monitored using a 20-litre bucket and a timer, measured at the sample point for outlet turbidity (Figure 6.1). After the flow was adjusted to one litre per second, the monitoring of turbidity was started by taking a raw water sample. Each test set had a duration of 30 to 50 minutes. When the test was finished, the flow was completely diverted, so that the amount of tablets remaining in the coagulation and flocculation chambers could be checked. After adding the required amount of tablets, the rate was adjusted to 0.5 litres per second. The water at inlet and outlet was sampled and flow rate monitored, as explained above. After the completion of the measurements at 0.5 l/s, the water in the system was once again diverted and the system was prepared for the next test set.

The set-up for the full-scale test in Dire Kiltu was similar to the one in Sofi Lugo. However, at this point in time it had been discovered that the safety valve could be used to make sampling possible between the sand and the carbon filter. In this test the set-up (Figure 6.1) was modified by adding the carbon filter to the system and using the safety valve to sample the water after the sand filter. A new shake test was conducted in the same way as before, and the results yielded that ferrous sulphate and anionic polymers were to be used in Dire Kiltu as well. Due to time constraints only two sets of tests were performed at the site: 6C and 4C+2F. These two test sets were conducted almost in the same way as in Sofi Lugo, with the exception that the sampling from the carbon filter was also done. This was done 2 minutes later than the samples after the sand filter.

6.3.2 Processing measurement results

The two full-scale tests resulted in values for inlet turbidity and outlet turbidity. Initially the procedure to remove unreliable measurement values are presented and thereafter the method for estimating the reduction.

The accuracy of the turbidimeter is, according to Hach Lange, ±2%. Since the additional errors from taking measurements in the field were difficult to estimate, the correlation between the two sample pairs was used to determine the reliability of the measurements. The difference between the two sample values, the second subtracted from the first, was taken for each test pair. This difference was divided by the average value of the pair to calculate the difference in percentage. The arithmetic mean of the percentages from all the sample pairs was found to be 0.5 % and the standard deviation 5.8 %. The limits for a 95%-confidence interval for the differences were found to be -9.05 % and 10.3 %. (Appendix 12.1)

For three days, and at two different locations, 231 double samples were taken. Out of these, 9 pairs had a difference that did not lie within the 95 % confidence interval and were thus excluded from the results.

From a comparison of the remaining 222 sample pairs it was seen that the first of each pair had higher NTU value than the second in 114 samples. The second value was higher in the case of 63 samples. From a statistical analysis it was seen that the first value with a 95 % probability, statistically, is between 0.54 and 2.09 NTU higher than the second (Appendix 12.1). This indicates that there was a systematic error during sampling. The time between the samples normally did not exceed 30 seconds. One reason for the lower second value is that some particles may have managed to sediment out of suspension during this time. This supposition was confirmed by an analysis of the time required for particles to sediment the length of the sample bottle (Appendix 12.3). For this reason the first sample is assessed to correspond to the real value to a higher degree than the second, and for the analysis of the results only the first values will be used.

Suspicions about inaccuracy due to dirty flasks have been investigated. The bottles were rinsed and filled with tap water and the turbidity measured. The results were less than or equal to 1.44 NTU. When compared to the disparity between different turbidity pair samples, this amount is deemed relatively insignificant. Furthermore, during testing, the bottles were always rinsed with the sample water before a sample was taken. This makes it unlikely that particles from a previous sample will contaminate the latter.

The turbidimeter was also checked to see if it needed calibrating. This was done partly by using the formazine standards provided with the kit. The turbidimeter was also tested on a formazine solution prepared at the laboratory of the Department of Water and Environmental Engineering, and measurements were compared with apparatus in the laboratory. Tests showed that the turbidimeter was accurate, and consequently the results from the field studies were considered reliable.

In order to estimate the reduction rate, some assumptions had to be made. The raw water had declining turbidity during the whole first day of testing in Sofi Lugo, which is assumed to be due to sedimentation in the pond (Figure 6.2). Agitation in the pond on three occasions disturbed the smooth decline.

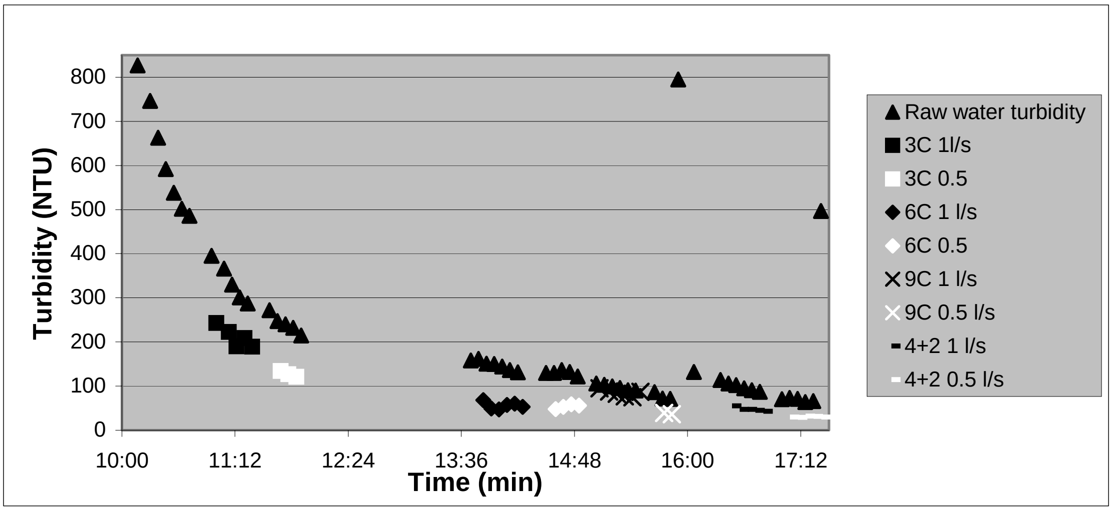

Figure 6.2 Turbidity decline in the raw water during the first test day in Sofi Lugo.

Each test was performed for roughly 30 minutes. A closer look at the turbidity measurements for a test period reveals that the change is approximately linear for small intervals of time. This was used for the procedure to calculate the reduction rates. The reduction rate was calculated as the decrease in NTU as a percentage of the raw water value. For the reduction rates, comparisons had to be made on corresponding water samples, before and after the purification process. Due to the short time series the travel time between the raw water and the purified water was difficult to perceive graphically. Therefore, the delay in the system was calculated (Appendix 12.2), and the retention time for the flow of 1 l/s in the pipe was 2.5 minutes and in the filter chamber approximately 30 seconds. The corresponding values for 0.5 l/s were 5 minutes and 1 minute for the pipe and the sand filter, respectively. To obtain the outlet turbidity 3 or 6 minutes delayed from the corresponding raw water value, interpolation between two sample points was used (Figure 6.3).

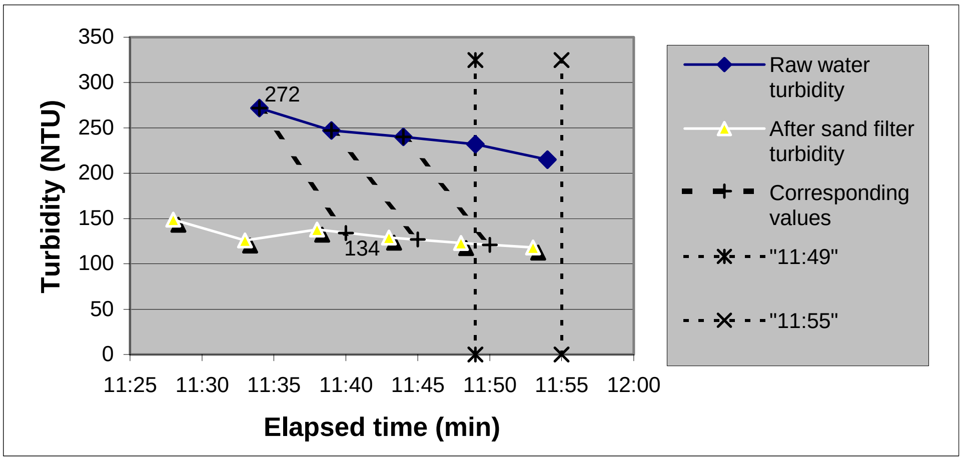

Figure 6.3 Interpolation between sample values. Extrapolation was not conducted.

In Figure 6.3 the flow is 0.5 l/s and the delay in the system 6 minutes. The reduction rate for the first value is (272-134)/ 272*100 = 50.7 %. In the same figure there are no turbidity values for the purified water that correspond to the two last raw water measurements. These two have therefore been excluded from the reduction rate analysis. Likewise, extraordinary results caused by disturbances in the water during measuring have been excluded in the reduction rate analysis. Figure 6.4 shows an example of the turbidity measurements after agitation of the pond.

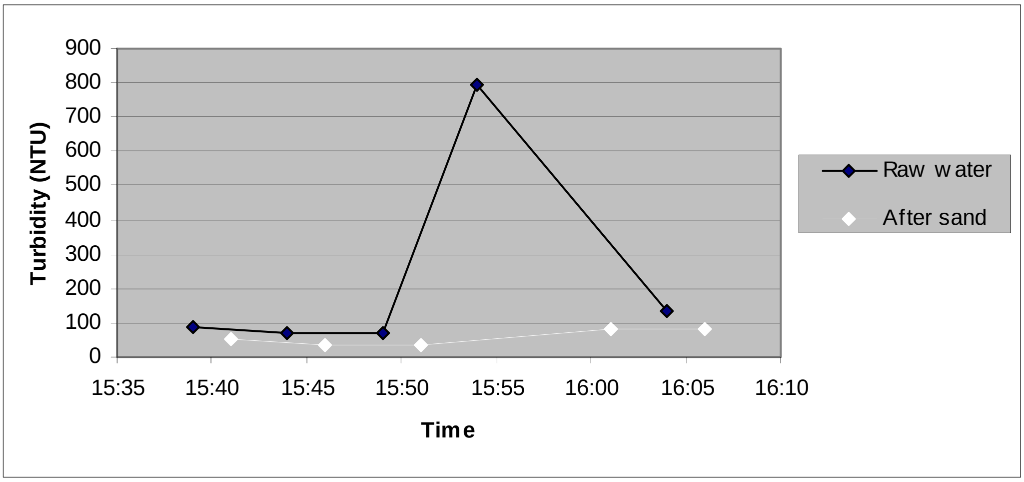

Figure 6.4 Change in turbidity due to agitation in the water

The method to interpolate is assessed to be reliable due to the consistently declining raw water turbidity. Even though differences in the behaviour of the filtered water as compared to the raw water have been seen, it is reasonable to assume that these two have similar patterns. Furthermore, the methods used to estimate the retention time in the system are seen as relatively reliable with respect to the task at hand. By interpolation, two data points are used and ought to give higher accuracy than using one point.

The turbidity measurements from Dire Kiltu (Figure 6.5) for both the raw water and filtered water varied much more than in Sofi Lugo. The assumption of linearity is therefore not valid to the same extent. The same method has however been used since the treated water turbidities vary so as to produce smoother curves than the raw water, which makes it possible for some consecutive points to be seen as lying on a line. What is more, the turbidity after filtration seems to follow the patterns of the raw water turbidities, suggesting that there is some correlation. The one data point that radically stood out from the rest of the filter-water data was excluded from the calculations (Figure 6.5).

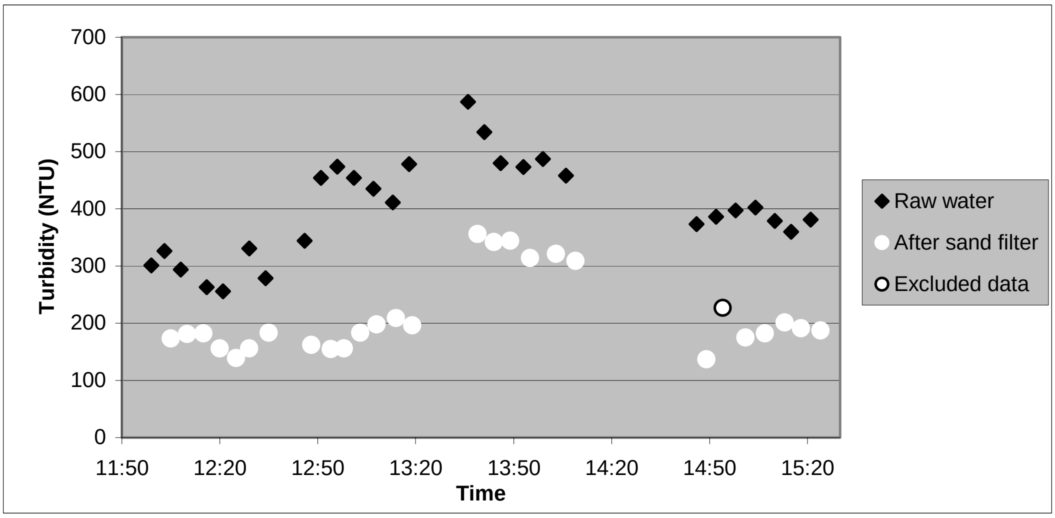

Figure 6.5 Fluctuations of the turbidity during the test in Dire Kiltu

The full-scale test in Dire Kiltu gave additional data on the performance of the carbon filter. Since information enabling the calculation of retention time and the reduction rate was unavailable, the effects of the carbon filter will be examined graphically to see if there are any trends in the data. (Figure 6.6)

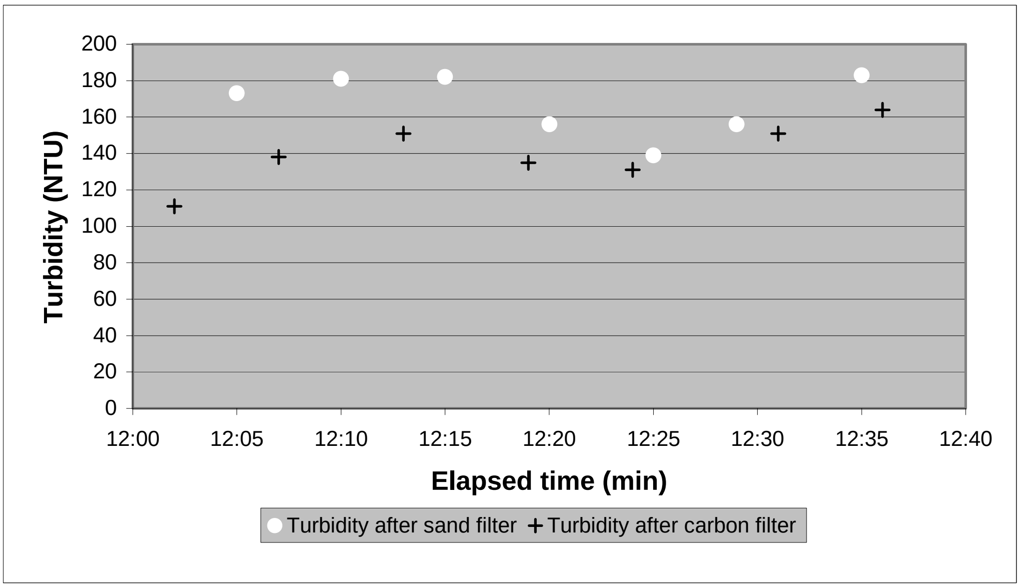

Figure 6.6 Residual turbidity at two different sampling points using 6 coagulants and 1 l/s

In addition, the average values of the residual turbidities from after and before the activated carbon filter will be taken and compared.

6.4 Gathering practical experiences

During the field-trips and operations one of the aims was to gather as much practical experiences as possible. Observations have been related and compared to descriptions in the manuals. The comprehensibility and correctness of the manual is considered extremely important and will therefore be studied closely. The instructions were evaluated simultaneously as they were followed practically during a full-scale test and discrepancies were observed.

7 Results

7.1 Previous EmWat operations

The reports referred to in this chapter are, Water Production and Consumable Usage Record Sheet for Erebti in Afar April 2004 (Hassem 2004), Test report and cost comparison of the EmWat 4000 with emergency water tankering for Amuta-Gasala in Oromia (Kebede 2003) and Report on Emergency Water Treatment Kit for Selamago in SNNPR (Reshid 2004).

The results from the previous EmWat 4000 experiences show high turbidity reduction capacity.

Table 7.1 Average values of results of previous EmWat 4000 operations

		Erebti	Amuta-Gasala	Selamago
Turbidity (NTU)	**Raw water**	5 −15	100	100
	Purified water	5 or < 5	5 or < 5	5 or < 5
Coliforms faecal + total	**Raw water**	−	Present	−
	Purified water	−	Absent	−
Chlorine residual (mg/l)		0.3−0.4	0.2−0.3	0.2 −0.5
pH		7.4	7.3	−
Average flow rate (m^3/h)		3.8	2	2
Coagulant/flocculants tablets		5 Cations (reduced to 3)	7 Alufloc +222 g $AlSO_4$ (powder)	−
Treated water/coagulants (m^3)		40−50	−	−
Hypochlorite tablets		3	2	−
Treated water/ hypochlorite (m^3)		180	20	−
Volume of water treated before backwashing (m^3)		30−40	70	−
Average fuel consumption (l/h)		0.3	0.3	0.19

The results from Erebti in Zone 2, Afar, were produced during a period of 28 days. 10 m^3 of river water were purified for 2 to 3 hours each day. Initially, five cationic polymer tablets were used to purify the water but were reduced to three for the last ten days of operation.

The report concerning the operation of the EmWat 4000 in Amuta-Gasala, Oromiya, gave data from 9 operation days during a period of 20 days. On average, 10 m^3 of potable water were produced each day. For an improved coagulation aluminium sulphate was added. For this purpose locally produced powder was used.

The report from Selamago in South Omo, SNNPR, was a summary of the performance during operation, and no detailed values per day were given.

All reports of EmWat 4000 operations expressed positive opinions of the kit and its importance for the work on water scarcity relief. However, in a report following a training session comments on the performance said that the flow rate of 4 m^3/h was misleading as this flow rate was practically only useful for very low turbid waters. Furthermore, it was expressed that suggestions on the appropriate flow rate within different turbidity ranges would be valuable. Other remarks include observations such as labels on pallet not corresponding to the content and unsatisfactory manuals. (Wurzel 2003)

7.2 Testing water quality after EmWat 4000 Purification

The results from the tested parameters at the three different sites are presented in Table 7.2 to Table 7.34. For the E-coli presence the column for purified water is divided into non-sterilised and sterilised. The former displays the result from the two taps that were only wiped off with a cloth. The result from the tap that was sterilised with alcohol is displayed in the following column. Information on the circumstances at each site is given after the tables.

Table 7.2 Results from water monitoring in Dire Kiltu

Dire Kiltu, Arsi, Oromiya	**Pond Water**	**Purified Water**	
Turbidity (NTU)	70, 76	16, 16	
Residual Chlorine (mg/l)	-	0.02, 0.07	
Total Chlorine (mg/l)	-	0.25	
pH	9.1, 9.4	7.5, 7.6	
E-coli per 100 ml	20, 0, 360*, 158*	Non-sterilized	Sterilized
		0,0,3,0	2,0
Parasitological results (organisms found)	Entamoeba/dispar cysts E-coli Blastocystist hominis	No parasites found	

***Results from diluted samples**

The purification procedure in Dire Kiltu had been modified. In order to reduce the turbidity of the purified water to the NTU recorded in Table 7.2, a pillow tank was used as a flocculation tank. Water was filled into the tank and aluminium sulphate in powder form was added. Analysis of the locally produced coagulant and the aluminium sulphate provided with the kit showed that the metal content was similar (Appendix 12.9). After at least 10 hours of settling, the water was pumped through the filters and chlorination chamber. The flow for processing the water was higher than the design flow. An additional complication was that the sand filter leaked due to a crack in the ceramic seal. Furthermore, the water level in the pond was declining, and the pH was rising. It can be seen from the table that the pH of the raw water was above the optimal range for coagulation with aluminium sulphate.

Table 7.3 Results from water monitoring in Konta Koysha

Konta Koysha, Konta, SNNPR	**Raw Water**	**Purified Water**	
Turbidity (NTU)	8	3	
Residual Chlorine (mg/l)	-	0.05	
Total Chlorine (mg/l)	-	0.3	
pH	-	-	
E-coli per 100 ml	tests uncountable	Non-sterilized	Sterilized
		13, 17	2

The activated carbon filter in the EmWat 4000 kit used in Konta Koysha had a leak due to a crack in the ceramic seal. As a result of this defect and the low raw water turbidity the unit was not used in the purification process. Consequently the chlorination chamber was not in use either, since it was not possible to disconnect if from the activated carbon filter. Instead chlorine powder was added directly to the purified water in the pillow tank. Due to time shortage no double samples were taken in Konta Koysha.

Table 7.4 Results from water monitoring in Sofi Lugo

Sofi Lugo, Harar	Raw Water	Purified Water	
Turbidity (NTU)	194	14, 25	
Residual Chlorine (mg/l)	-	0.03, 0.06	
Total Chlorine (mg/l)	-	-	
pH	7.6, 7.8	7.5, 7.5	
E-coli per 100 ml	tests uncountable	Non-sterilized	Sterilized
		Uncountable	Uncountable
Parasitology results (organisms found)	E-coli cysts Entamoeba coli cyst Entamoeba hystolitica Strongyloides stercoralis larvae	E-coli cysts Entamoeba hystolitica	

The results from Sofi Lugo should be studied in the light of the fact that the aim of the purification was not to produce drinking water. The water was produced after that the full-scale test at the site was finished, mainly to give the local technicians a demonstration of the complete purification process.

The laboratory examinations on the chemical content show that the source waters from the different sites have similar levels for most substances. Values that differ remarkably or exceed guideline limits are presented in the next table. For a comparison to other source water, the minimum and maximum values for natural ranges and the world median are also presented. The values are based on 75 watersheds with global average constituents from different countries (UN 1992, ch 6). The reports on chemical content received from the laboratories are presented in full in Appendix 12.4.

Laboratories in both Awassa and Oromiya have investigated the water from Konta Koysha. The dates for this investigation are seen in Table 7.5. It is notable that it is one week between the test dates. However the sample was handed in to the laboratory in Awassa first and is assumed to be stored properly. Some values are confirmed by the double testing and others differ, possibly owing to different measuring procedures or insecure methods. The water from the other sites is only investigated in the laboratory in Oromiya. WHO´s Guideline values for drinking water are presented to give an idea of acceptable values. The values represent the amount that would risk adverse health effects from a lifetime of consumption.

Table 7.5 Chemical content in water from the test sites with comparable numbers

	WHO[1]	Konta Koysha	Konta Koysha	Sofi Lugo	Dire Kiltu	Natural ranges of dissolved constituents Streams (1−100 km^2) [2]		Most common natural concentration [2]
		Awassa 10/11	Oromiya 3/11			Minimum	Maximum	(median)
	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
HCO_3^-	-	244	208	500.2	210	0	350	30,5
T. alkalinity		200	187	410	187			
Bicarbonate		200	171	410	172			
Cl^-	250[a]	17.5	0	90	4	0.09	530	3,9
PO_4^{-3}	0.621	0.67	4.06	0.67	0.67			
SO_4^{2-}	250[a]	0.9	1	24	1	0.14	720	4,8
Mn^{+2}	0.4	0.024	0.1	0	0.9			0,010 (average)
Cr^{+6}	0.05[b]	0.006	0.1	0.15	0.08			0,0001 (average)
NH_4^+	1.5[a]	0.14	0.3225	1.638	1.2126			

a, No health-based guidelines
b, Preliminary value due to limited knowledge about health effects
-, not analysed
1, WHO 2004, ch 12
2, UN 1992 ch 6

The results shown in the table above are those that were exceptionally high. The phosphate and chromium values, for all the sites, exceed the WHO guideline value. Furthermore, the manganese value in Dire Kiltu, and the ammonia concentration at Sofi Lugo is in excess of the WHO limits as well.

A comparison between the values from the different sites shows that Konta Koysha and Dire Kiltu have similar alkalinity values (HCO_3^-, Total alkalinity, and Bicarbonate). However, at Sofi Lugo these values were extremely high. Sofi Lugo also has the highest ammonium, sulphate, and chloride concentrations in the water.

7.3 Full-scale test

All the raw data from the measurements on the test sites are listed in Appendix 12.9. The reduction rates obtained after they were processed, as described in (6.3.2), are presented here in graphs.

Initially the effect of the different flow rates will be presented. Afterwards the influence of the different doses and combinations of chemicals are shown.

Figure 7.1 shows reduction of NTU, in percent, as a function of raw water turbidity. The data points depict the results at different flow rates irrespective of the pre-treatment chemicals used.

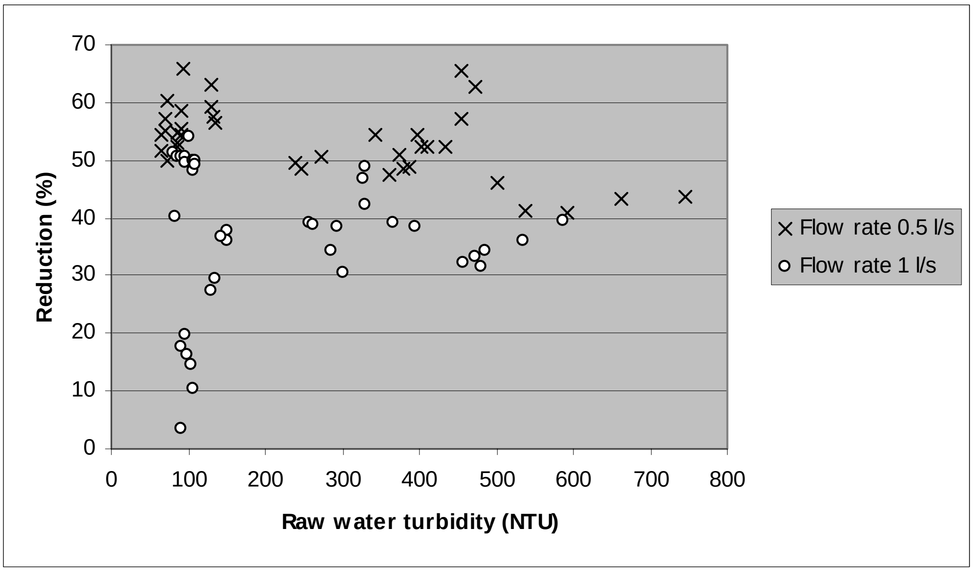

Figure 7.1 Effects of flow rate on turbidity reduction.

The graph shows that in spite of varying chemical dose and type, the lower flow rate in general leads to a higher turbidity reduction. This observation was confirmed using a rank test (Appendix 12.7). To see how the flow rate influences the turbidity reduction for the same chemical combinations, Figure 7.2 gives a more detailed presentation of the data, dividing it into two groups based on test-site.

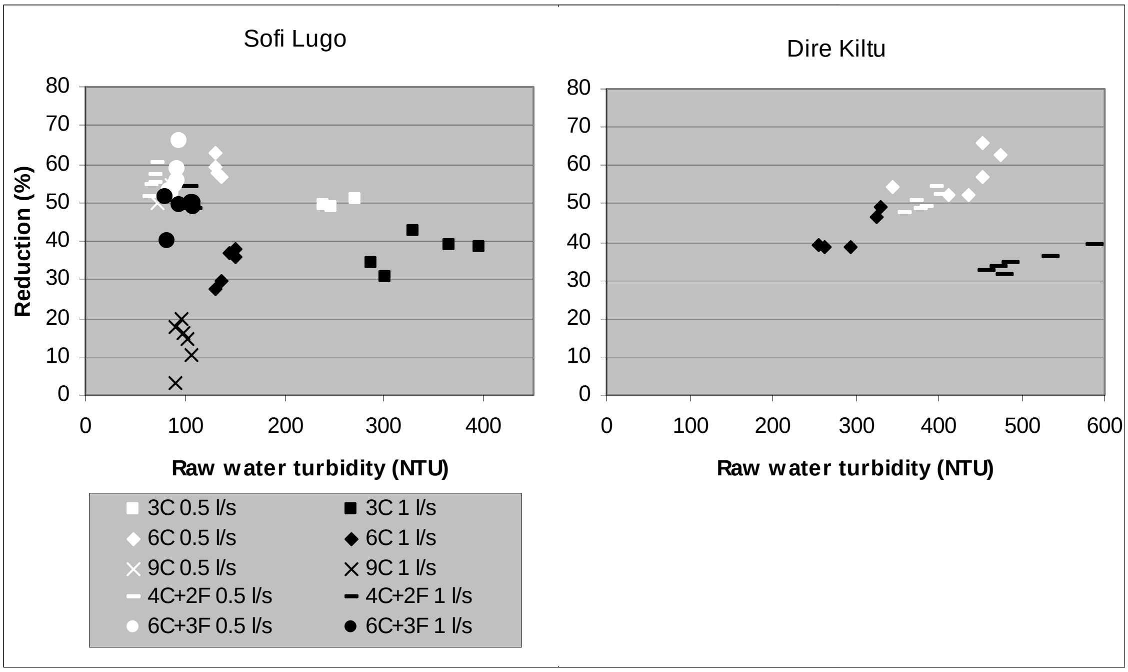

Figure 7.2 The percent reduction in turbidity as a function of raw water turbidity.

The most obvious difference in reduction between the two flow rates is seen in the 3, 6, and 9 coagulant tablet tests in Sofi Lugo and in both tests performed in Dire Kiltu. The 9 coagulant tablet test shows the greatest disparity of turbidity reduction for the different flow rates. The large variation in the turbidity of the raw water makes it difficult to compare the results. On the other hand, the cluster of data points around 100 NTU in the Sofi Lugo test allows for good comparisons. Figure 7.3 shows the data points for tests with raw water turbidity from 70 to 110 NTU.

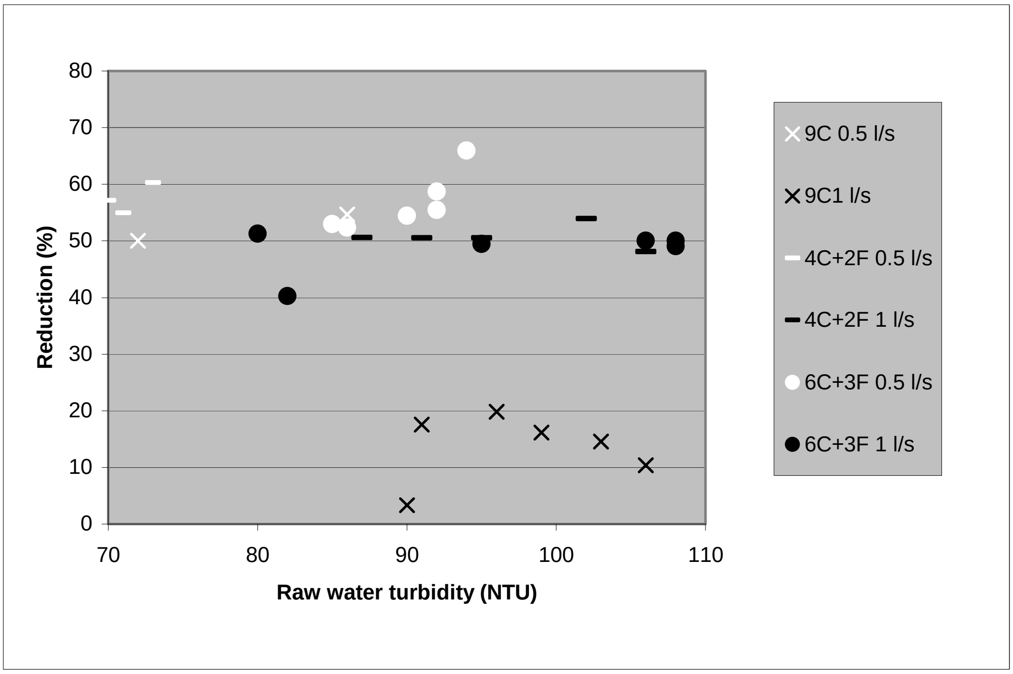

Figure 7.3 Percentage reduction of turbidity using different chemical combinations and flows.

From the previous graph it is seen that for every combination the halved flow rate has a higher reduction rate.

To be able to compare the impact of the different chemical combinations the results for the different flows are separated. All the results from both sites are displayed in the same figures. The results from the two test sites are not comparable since the waters were different. Most tests were conducted in Sofi Lugo and are therefore not labelled. The two tests conducted in Dire Kiltu are indicated in the graph keys.

The figures below show the reduction in NTU (Figure 7.4) and the percent reduction (Figure 7.5) of turbidity as a function of raw water turbidity.

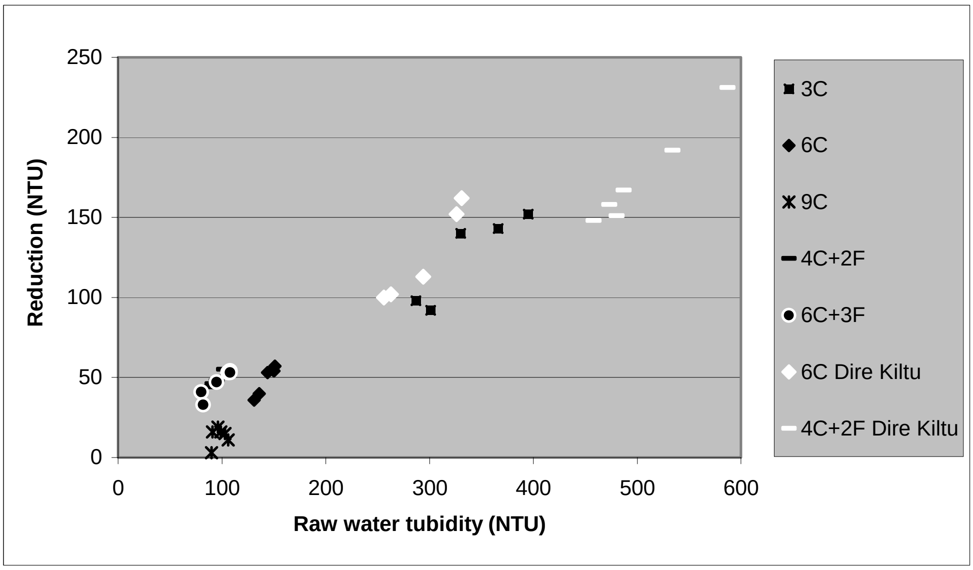

Figure 7.4 Effects on chemical combinations on reduction (NTU) of turbidity at 1 l/s.

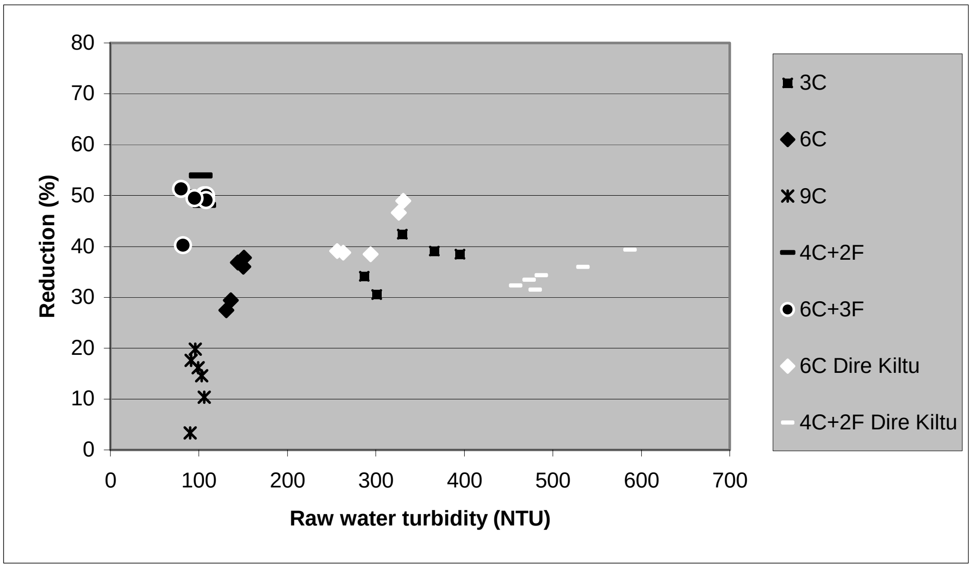

Figure 7.5 Effects of chemical combinations on reduction (%) of turbidity at 1 l/s

The best reduction results in the Sofi Lugo test were obtained using the combinations with coagulants and flocculants. However, in Dire Kiltu the 6C test was better in precentage reduction than the combination test. The results for the 3C and 6C tests show almost no differences in Figure 7.5. The poorest results came from the 9C-test, showing reduction rates of less than 20%, which is far below the percentages for the other tests.

To investigate the effect of chemicals at the lower flow rate the data is plotted in Figure 7.6 and Figure 7.7, where the reduction rate is shown as NTU removed and percentage removed, respectively.

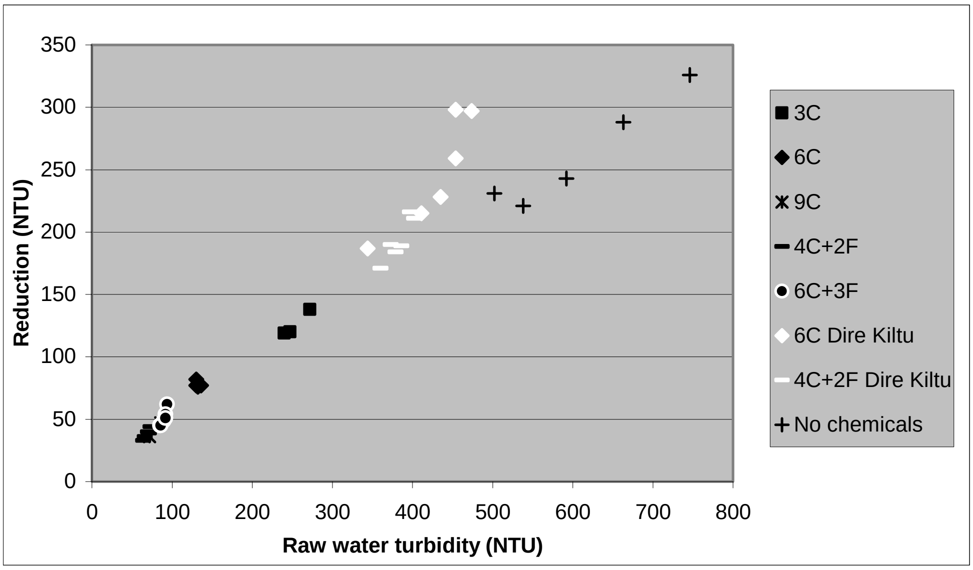

Figure 7.6 Effects of chemical combinations on reduction (NTU) of turbidity at 0.5 l/s

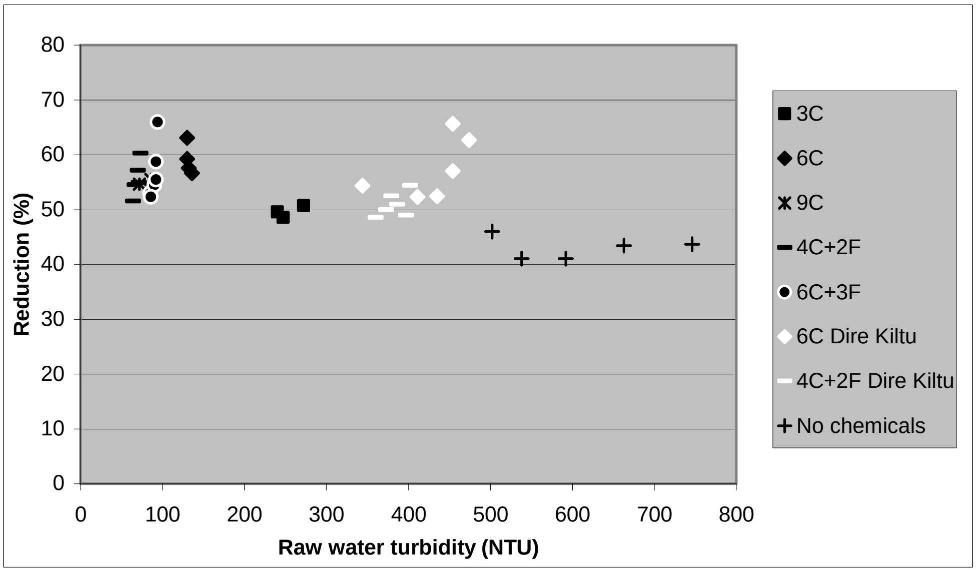

Figure 7.7 Effects of chemical combinations on reduction (%) of turbidity at 0.5 l/s

In Figure 7.7 the data points from the Sofi Lugo tests seem to lie on a straight line. The reduction in NTU is thus linear to the raw water turbidity.

The last five points in Figure 7.7, where raw water turbidity progressed from 502 NTU to 746 NTU, are results from the test where water was simply passed through the sand filter. All the other reduction rates in this series, which come from tests where chemical pre-treatment was performed, were above these last five reduction values. The tests with flocculants show similar results as the tests with only coagulants.

In most cases the remaining tablets in the coagulation chamber were counted or estimated after each test. The consumption of coagulant tablets is found in Table 7.6. The table shows the concentration of coagulant in the water as well as the reduction and the remaining alkalinity. It is seen here that the addition of coagulants does not significantly reduce the bicarbonate concentration in the water. It also shows that the coagulant dose varies between 1 mg Fe^{3+}/l and 7,02 mg Fe^{3+}/l. The calculations are found in Appendix 12.5. The consumption of flocculants was too small for ocular observation and is therefore excluded.

Table 7.6 Coagulant tablet consumption and alkalinity reduction

Test	Flow rate (l/s)	Number of tablets added	Number of tablets remaining	Number of tablets dissolved	Concentration (mg Fe^{3+}/l)	Amount of alkalinity reduced (mg HCO$_3^-$/l)	Alkalinity after treatment (mg HCO$_3^-$/l)
3C	1.0	3.0	1.0	2.0	1.1	1.2	498.8
3C	0.5	3.0	0.5	2.5	2.9	3.1	496.9
6C	1.0	6.0	0.0	6.0	2.9	3.1	496.9
6C	0.5	6.0	2.0	4.0	4.8	5.3	494.7
9C	1.0	9.0	2.0	7.0	4.4	4.8	495.2
4C+2F	1.0	4.0	0.5	3.5	1.7	1.9	498.1
4C+2F	0.5	4.0	0.0	4.0	1.7	1.9	498.1
6C+3F	0.5	6.0	1.0	5.0	3.2	3.5	496.5
Dire Kiltu 6C	1.0	6.0	1.5	4.5	6.4	7.0	202.0

Figure 7.8 illustrates the tablet consumption as percentages of the original number of tablets. The minutes displayed in the parentheses are the times between start-up of each test and checking of remaining tablets.

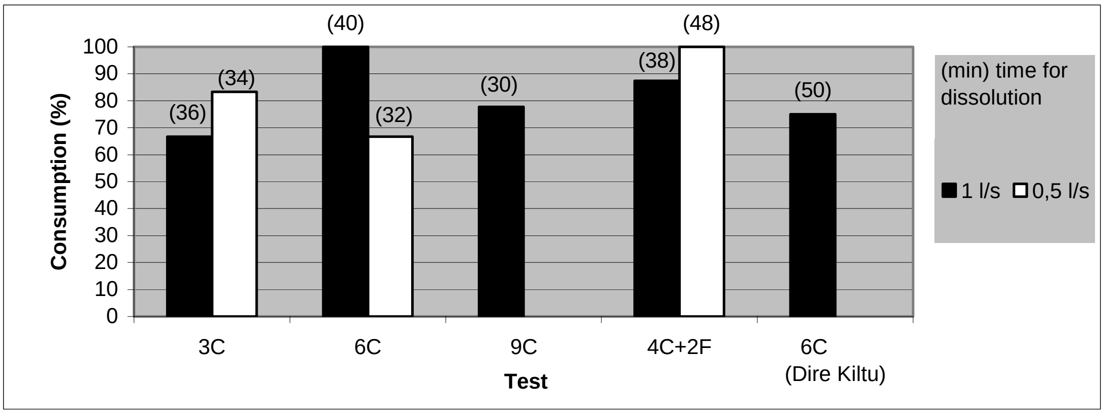

Figure 7.8 Consumption of tablets at different doses and flow rates.

From the graph it can be seen that more than 60% of the tablets were consumed regardless of the flow rate and amount of tablets added. The consumption of the tablets took place within a time span of 30 to 50 minutes.

According to the gauge, the pressure in the sand filter did not change during the first day of testing in Sofi Lugo. The second day showed that the pressure in the filter was at a maximum of 0.5 bar, when using a flow rate of 1 l/s, and a maximum of 0.2 bar when treating water at 0.5 l/s. The pressure in the sand filter in Dire Kiltu was between 0.7 and 0.9 bars for the 1l/s test.

The effects on turbidity removal of the carbon filter in comparison with the sand filter are presented below (Figure 7.9).

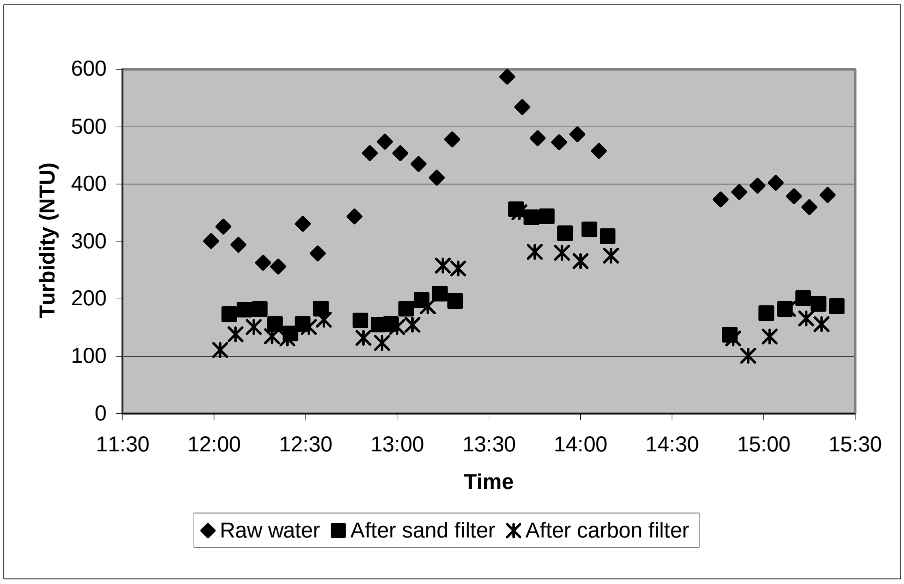

Figure 7.9 The effects of activated carbon on the treatment of water.

A look at the results shows that the carbon filter can not be expected to reduce the turbidity levels over 100 to the limit of 5 NTU, recommended by WHO. Furthermore, the residual turbidity after the carbon filter seems to follow the trends in the residual turbidity after the sand filter.

Table 7.7 Average reduction after carbon filtration.

	6C 1 l/s	6C 0.5 l/s	4C+2F 1 l/s	4C+2F 0.5 l/s
Average turbidity after sand filter (NTU)	167	180	325	179
Average turbidity after carbon filter (NTU)	141	150	275	145
Reduced turbidity (NTU)	26	30	50	34
As a portion of average sand filter turbidity	16 %	17 %	15 %	19 %

Looking at the number of turbidity units removed after carbon filtration (Table 7.7), a pattern can be seen suggesting that the higher the turbidity, the more turbidity is removed. The average reduction in percent does not show any trends.

7.4 Observations of practical operations

During the operation of the EmWat 4000-kit the following observations were made:

- No flow-meter is included in the kit. A by-pass valve between the pipe and sand filter is shown in the set-up picture in the manual and could possibly be used for manual measuring. However, no advice or instructions concerning this are found.
- The adjusting of the flow to 1 or 0.5 l/s was found to be very difficult.
- The suggestion on how to adjust the flow rate by closing or opening the valve before the sand filter is only found in the Engineer's Manual.
- The security valve was not used at the visited sites.
- Chlorine addition was not possible at 0.5 l/s because hydraulic pressure in the chlorination chamber was too low.
- The Ferufloc tablets dissolved at a surprisingly fast rate.
- The required length of connection pipe between the coagulation and flocculation chamber is only given in the Engineer's Manual.
- The instructions for set-up of the kit for backwashing were unclear. It was not expressed whether to use raw or purified water. The connections were marked with different colours for simplifying set-up, but the instructions did not use this fact to clarify the connection set-up.
- The static mixers were not found at the test site in Sofi Lugo.
- One operator expressed worries about the non-durable material of the filter units.
- There were no instructions or information concerning acceptable turbidity levels for the activated carbon filter in the manual.
- Daily monitoring of the residual chlorine was not possible for practical reasons.
- The manuals are not available in any native language.

From the experiences gained during the field trips and discussions with operators it was found that following additions are useful in the manuals:

- The importance of not exceeding the maximum capacity of 4 m^3/h.
- Attention should be given to the fact that the maximum capacity is only valid for waters with low turbidity.
- A list containing the possible adjustments to improve the performance of the kit, many of which are found throughout the Engineer's Manual. Furthermore the list should contain levels of turbidity where different adjustments are recommended.
- A checklist before starting the purification in the Field Manual. Several important instructions are given throughout the Engineer's Manual, which need to be applied in the field.
- Operators said that problems with rats eating the flat-hoses had been experienced. It might be advised in the manual to protect the hoses at night, bringing attention to this dilemma.
- The importance of monitoring turbidity and residual chlorine regularly.

Some additional issues worth commenting were found after reading the manual. The target value for turbidity after treatment is, according to the manual, 15 NTU. The value is recommended to ensure the effectiveness of chlorination. It is noted that the WHO guidelines recommend 5 NTU or less (5.3.4). Another aspect is the use of the chemicals provided with the kit. According to the theory presented in the previous chapters of this thesis, polymers must be used in combination with coagulants for effective turbidity reduction at levels below 500 NTU (5.3.1). The manual does not discuss this. Instructions in the manuals on backwashing the carbon filter were vague: backwashing was to be performed "after a long time of operation", and the instructions for the procedure, the flow rate, and pressure, are not given with any directive values. Finally, the Engineer's Manual has insufficient technical details on the kit.

8 Discussion

8.1 The performance of the EmWat 4000

The main objective of gathering site data was to supplement the evaluation of the EmWat 4000 kit's performance. Towards the end of this chapter the data will be compared to the results of the reports from previous EmWat 4000 operations in Ethiopia and discussed. To begin with, the data will be interpreted based on the WHO guidelines for drinking water quality.

The pH values measured after treatment at the Dire Kiltu, Konta Koysha, and Sofi Lugo sites were in the acceptable range for chlorination, as recommended by WHO. The pH measured in the raw water at Dire Kiltu and Sofi Lugo was, however, above the optimum range for treatment with aluminium and ferrous sulphate. This could have lead to less than optimal chemical pre-treatment. In the case of Dire Kiltu, a jar test was conducted to find the right dose of aluminium sulphate. This was when there was more water in the pond, and the pH was higher. As mentioned in the chapter on coagulation and flocculation (5.3.1), the higher the pH, the more coagulant is required. Thus, for better potable water, a new jar test may have been required in order to adjust the coagulant dose.

Turbidity values from Dire Kiltu and Sofi Lugo showed higher values than the WHO guidelines. This is unfortunate since a high amount of particles in the water will shield pathogens during chlorination (5.2.4). A likely explanation for the heightened turbidity can be found in the circumstances on the sites. At the Dire Kiltu site the sand filter had cracked during treatment. Furthermore, the water at this site was pumped through the filter above design flow, which is likely to be part of the reason for the reduced efficiency (5.3.2). The poor results at Sofi Lugo may be due to dysfunctional chemical pre-treatment. After approximately 45 minutes of treating water at a flow of 0.5 l/s, it was found that the coagulants were completely consumed.

For the three visited sites, the measured chlorine residuals after disinfection were too low, according to the WHO guidelines, to guarantee microbiological safety (5.3.4). A reason for this deviation from the recommended values could be the unreliability of the measurement method used. The chlorine measurements at Sofi Lugo showed a slight increase in value after consecutive measurements, which indicate the presence of chloramines. Additionally, the water analysis of the three waters, presented in Appendix 12.4, shows that bromide and oxidized chromium are present, which also can interfere with chlorine measurements. These two substances and chloramines will give results that show higher concentrations than what is present in the water. If the measurement values are reduced in order to correct the error caused by these water species, the measured values are nonetheless below the WHO standard. If the uncertainty concerning the instrument is dismissed, low residual chlorine concentrations can be attributed to inadequate chlorine dose. For chlorination Plastec has recommended that between 0.2−0.5 mg/l residual chlorine be retained in the water after half an hour of disinfection. The total chlorine measured in the water at Konta Koysha and Dire Kiltu shows that by the time the samples were taken, the residual was consumed, therefore it may be advisable that a higher chlorine dose is used. A second viable explanation for the low residual chlorine is the presence of a high amount of turbidity in the water that consumes the chlorine (chapter 5.3.4). This can be seen in Sofi Lugo where an initial free chlorine concentration was measured directly after the chlorination chamber at 0.88 mg/l, which was after half an hour of contact reduced to 0.06 mg/l. The turbidity directly after the chlorination chamber was 24 NTU.

The WHO guidelines state that coliform bacteria should not be found in drinking water. This criterion was not met at any of the visited sites. As explained in chapter 5.2.2 E-coli and total coliform organisms are the easiest to remove. Their presence therefore points towards a high probability of the existence of other possibly pathogenic organisms in the water. However, the results show large enough disparities between raw and treated water to indicate a reduction of bacteria after water treatment. The difference in the bacterial counts of the water from the sterilized and non-sterilized taps from Konta Koysha additionally suggests bacterial contamination of the water from the taps. In Dire Kiltu this difference is too low to make it possible to say with any certainty whether contamination of the water occurs at the taps. As mentioned in the chapter 6.2.3, deviations were made from the WHO recommendations on sampling. The shortest time for transporting the samples was 4 hours, which was from Dire Kiltu. It can also be noted that these samples were the only ones transported on ice. Samples from the Sofi Lugo and Konta Koysha sites were transported during 5 and 24 hours, respectively, before the opportunity for testing arose. The reason for this is that the membrane filtration procedure requires an environment that minimizes the risk of contamination. Apart from the issues of transport time and transport conditions, the possibility for contamination during preparation of the Petri dishes was always imminent. The results are nonetheless kept for two reasons: they are the only available microbiological indicators, and they are supported by the physicochemical or parasitological test results. However, there is due cause to interpret the bacteriological results cautiously.

The reasons for finding bacteria in the water at the visited sites are several, and shall be investigated by site. In Konta Koysha the produced water had a low disinfectant dose, which would account for the finding of bacteria. Furthermore, the possibility of a high concentration of organic matter in the water would also allow bacteria to survive the chlorination step (chapter 5.3.4). The stream from which raw water was taken passed through a forested area, which would make it possible for the water to accumulate organic compounds. It can be noted that the purification of the water at the Konta Koysha site was done without the activated carbon filter as it was cracked. It is reasonable to assume that in the absence of this filter not enough organic compounds were removed, which leads to a large consumption of free chlorine, hindering disinfection (5.3.4). The finding of E-coli at the Sofi Lugo and Dire Kiltu sites could be due to failure of disinfection as a result of high turbidity in the water. Furthermore, at the Sofi Lugo site there was a failure in the chemical pre-treatment as indicated by the presence of parasites in the treated water (5.2.2).

In the following discussion the results from Sofi Lugo are disregarded as the water produced was not intended for drinking. Comparisons of the results obtained from the site visits and the results found in the reports from previous operations of the kit show wide discrepancies in residual turbidity, residual chlorine, and bacteria counts. The reports of previous operations of the EmWat 4000 show that the kit has been able to produce water that meets the basic recommendations set by WHO. Since this was not the case in Konta Koysha and Dire Kiltu several reasons for the discrepancies are discussed. The first two possible reasons discussed are whether the difference in measurements is a result of using different techniques, or if the water after treatment at the two visited sites actually was of the poor quality shown in the results. The reliability of the turbidimeter used (6.3.2) waylays any suspicions that the turbidity measurements on-site were faulty. The turbidity tube that was used for monitoring during the previous operation of the kit is less accurate than the turbidimeter. However, it is more likely to give false results showing too high turbidity rather than too low. The measurements made with this instrument can thus be assumed to be on the safe side. The accuracy of the chlorine measurements performed on site has already been discussed. The measuring equipment provided by Plastec involves the use of DPD-reagent and colour matching, as explained in chapter 5.2.2. This technique, which was used during the previous tests, is relatively robust and is also recommended by WHO. Therefore, there is no reason to doubt that the results is reliable, even if they are less exact when compared to the colorimetric method used at the two visited sites. The reliability of the bacteriological results from Dire Kiltu and Konta Koysha has already been discussed. Bacteriological tests from the previous operations of the kit were given only in the report from Amuta Gasala. The assessment of the microbial quality of the water at the other sites can therefore be solely based on the physicochemical parameters, which show that bacteria is unlikely to have been found in the water. The reported absence of the microbes in the tests from Amuta Gasala does not in itself guarantee the safety of the produced water. However, review of the physicochemical results attests to the probable safety of the water after treatment.

If the difference in results cannot be attributed to faulty measurements, then the question of the difference in water quality remains. The main factors that would lead to the production of poor quality potable water are the quality of the raw water source, and purification of water using a sub-optimal process. Firstly, it can be noted that the quality of the raw water used in previous operations was as varied as quality of the water used at the two visited sites. Unfortunately no data is provided on the chemical composition of the water at these previously used sources. As far as the turbidity of the water is concerned, good results were obtained irrespective of the initial turbidity of the water. The report from the Selamago mentioned that the turbidity of treated water with initially 500 NTU was reduced to 0 NTU. Since the source water quality seems to be irrelevant for the final quality of the treated water, attention must be given to the purification process itself. It is assumed that the previous operations of the EmWat 4000 were performed using fully functional equipment, as there is no mention of broken equipment in the reports received. As noted before, the equipment at Konta Koysha and Dire Kiltu was damaged, the effects of which also have been discussed. Furthermore, during the previous operation of the kit, water was generally produced at the design flow of 4 m^3/l or below. In contrast to this, at Dire Kiltu filtration was consistently performed above design flow. The effects of this have also been previously discussed. At Dire Kiltu, and previously at Amuta Gasala, a locally produced aluminium sulphate was used as coagulant. In Amuta Gasala the powder was used in combination with the AluFloc tablets provided with the kit. The better results obtained at the Amuta Gasala could be attributed to the possibility that AluFloc has a higher percent of aluminium than the locally produced powder, which would enhance the chemical pre-treatment. However, chemical composition tests performed on the tablet and the powder (Appendix 12.10) revealed that the metal content in these two agents is approximately the same. Therefore, it can be assumed that identical doses of aluminium sulphate, whether in tablet or powder form, will have the same effect on the water treatment process at a specific site. Both at the Amuta Gasala and the Dire Kiltu sites the coagulant dose was decided using a jar test. Furthermore, the same EmWat 4000 kit was used. It can therefore be assumed that the correct dose is being applied at both sites, and the discrepancies in purification results would more likely be due to the broken equipment and high surface load applied to the filter in Dire Kiltu.

In conclusion, the discrepancy between the previous performances of the EmWat 4000 kit is not due to poor measurements or raw water quality. The key factor is the optimisation of the treatment process. Damaged filtering equipment and the application of too much pressure during filtration, by using a high flow rate, are the likely reasons for the insufficient purification of water. The replacing of broken filters and the measuring of flow rate during operations are two ways to resolve these issues.

8.2 The full-scale test

The first notation to be made is that following comparisons of effects of changed dosages are only valid for the Ferufloc and Aniofloc used in this full-scale test and that the outcome of different flow rates may differ under other circumstances. It is underlined that no matter which type and amount of chemical pre-treatment was used, the target of achieving a reduction to 15 NTU was never met.

Interfering circumstances that have made interpretation of the results of the full-scale test difficult are the continuously changing raw water turbidity and a possible maturation of the filter (5.3.2). If the turbidity reduction were more easily achieved at higher NTUs the reduction rate would decline during the first day at the Sofi Lugo test site. On the other hand, filter maturation would progressively increase the efficiency. Taken together, the impact of these events might cancel out each other, and their respective influence would not be noticeable. Theoretically, the turbidity of the water ought to affect coagulation and consequently the reduction. The nature of charge neutralization is such that the amount of required charges is dependant on the amount of particles. However, several factors negate any considerable impact of turbidity level on the results. The tight clusters of data points for the respective test and their distinct location give reason to believe that the main influence on the reduction rates is the differences of dose. In addition, the results for the 0.5 l/s tests (Figure 7.6) reveal a linear relationship between the reduced NTU and the raw water turbidity. This would indicate that the raw water turbidity does not influence the percentage turbidity removal significantly. The percent reduction from the Dire Kiltu test, where the raw water turbidity was altering irregularly, shows no tendencies to be influenced by the magnitude of the raw water turbidity (Figure 6.5). After having dismissed the potential influence of the raw water turbidity, a possible influence of filter maturation is considered negligible since there are no discernable time-dependent changes in reduction rate during the day.

The 1 l/s tests for each coagulant case were always performed before the 0.5 l/s tests, and thus used more turbid water. Due to the fact that the impact of raw water turbidity was neglected, comparisons between the different flow rates are possible.

An effect of the irregular dissolution of tablets as shown in the result chapter (7) is that the dose of iron (mg/l) has not been steady and comparable during the tests. Comparing the calculated dosages is problematic as they are based on an assumption that the tablets dissolve continuously at the same rate. For the calculations of dosage the amount of dissolved tablets has been divided by the volume of water that passed the chamber during each test. Due to the differences in duration of the tests this volume varied considerably and was given disproportional weight in the dosage calculations. Since the only means for the operators of the EmWat 4000 to adjust the dosage is by manipulating the number of tablets the analysis has also been done in this way. The choice of this analysis method is reasonable since the dosage will always increase if the number of tablets is increased.

The hypothesis that a flow rate of 0.5 l/s would increase the efficiency of the turbidity reduction was confirmed by all the tests (Figure 7.3). The difference of purification degree when the flow is reduced, and the chemicals are the same, can be attributed to the fact that sand filters function better at lower flow rates (5.3.2). The surface load for rapid filters should vary between 5−10 m/h (CTH 2001). For the high flow in these tests the surface load was approximately 22 m/h. The filter seems to be under dimensioned for the design flow. However, through LMS (Bray 2005) it was found out that the filter in a similar emergency kit, produced by the same company that developed the EmWat, contains filter-aids in the form of activated silica. It is therefore reasonable to assume that also the EmWat 4000 contains filter-aids which would allow for higher flow rates (5.3.2). Doubled retention time in the pipe and improved conditions for floc building are additional consequences of halved flow rate. The concomitant reduction in turbulence is not seen as having any affect on the coagulation process. Reynolds number indicates definite turbulence in both cases (Appendix 12.6) and the velocity gradient for the 1 l/s flow is still within the range of good floc building.

In the case of 9 coagulant tablets the difference was so large that an alternative explanation was explored. The 9C test has the highest coagulant dose of all the performed trials, meaning that it is possible to have reached the dose range where Sweep flocculation may occur (5.3.3). This flocculation mechanism requires an environment of less turbulence for it to function well. Therefore, increasing flow in the water will adversely affect the treatment. The results showed that the removal of turbidity was between 2% and 20% at 1 l/s, while it was 50% and higher when operating at the lower flow rate (5.3.2), suggesting a failure in the chemical step of the treatment process. However, this supposition is negated by the fact that sweep flocculation also requires low contaminant levels, which is not the case when water has 100 NTU of suspended solids.

The over all poor turbidity reduction that never met the target of 15 NTU leads to suspicions that the chosen coagulant was not the best one suited for the type of water used for the tests. Overdosing in the shake test could have caused decreased pH and favourable conditions for the Ferufloc in comparison to the Alufloc. However, from calculations it is seen that the high alkalinity in raw waters was not consumed even after the high dosages for the shake tests. The alternative that the doses were too low is discredited by the fact that the efficiency decreased when the number of tablets was increased from 6 to 9 coagulants. The different number of tablets produced doses of 1 to 6.5 mg Fe/l water, which is a reasonable magnitude (5.3.1).

The degree of reduction was higher for all chemical variations of tablets than with no pre-treatment at all. The dosages of 6 tablets had higher turbidity removal than 3 coagulant tablets when the flow rate was set to 0.5 l/s. However, when running the system with 1 l/s the result for 3 and 6 coagulant tablets showed similar results. That is the expected result and it is assumed that the cause is that more and larger flocs were produced and captured in the filter.

While the coagulant dissolved relatively quickly, there was hardly any visible dissolution of the flocculants. Added to the water the flocculants swelled and became sticky. Between the tests the flocculants were found glued to the bottom of the flocculation chamber, therefore the contribution to the floc-building process was doubted. However, the complementary effect of the flocculants was confirmed by the reduction rates in Sofi Lugo for the 1l/s case, displayed in Figure 7.2. The reduction rate increased by approximately 15% when 3 flocculant tablets were added to the 6 coagulants. The tests were designed to detect whether a change was due to addition of another kind of chemical tablet or just to modified number of tablets. By comparing the result for 6 coagulants and 4C+2F, the addition of flocculants is shown to be the main influence on the improved reduction. The effects of flocculants were not seen when using 0.5 l/s. In Figure 7.7 it can be seen that the reduction rate for 6C, 6C+3F and 4C+2F were similar. That the improvement as a result of added flocculants was negligible for the lower flow rate might be attributed to the fact that the prolonged retention time in the hoses allowed for sufficient floc-building also without floc-aids. For the higher flow rate, on the other hand, the shorter retention time required floc-aids. In Dire Kiltu the addition of flocculants only seemed to deteriorate the reduction rates. Several reasons that would explain the poor contribution of the floc-aids will be discussed. Firstly, the pH of the water was higher than the recommended value for coagulation. If the degree of coagulation is low the addition of flocculants will be ineffective. Secondly, the pipe between the coagulation and flocculation chambers may have been shorter than the one used in Sofi Lugo. If the coagulation process is not given enough time the addition of flocculants would have a negative effect by reacting with the hydroxide ions that should be used for charge neutralisation (5.3.1). Lastly, if the floc-aids are assumed not to work on this water, the number of coagulants used was less for the 4C+2F test compared to the 6C test, which could be a reason for the poor result.

If the poor turbidity reduction was due to dysfunctional coagulation, one reason for this may be the absence of static mixers in the set-up. The importance of rapid mixing, just after coagulant addition, for the charge neutralization and patch coagulation has been discussed in chapter 5.3.1. Without this step, the neutralization of charged particles may have been insufficient, consequently affecting the rest of the purification process. This may also have had an effect on the flocculation process, as the anionic polymer is designed to aggregate flocs by attaching to the positively charged hydroxides. If these hydroxides have not been able to attach to a sufficient number of particles, the anionic polymer will not be effective.

The results of the tests on the activated carbon filter, in Dire Kiltu, show that the turbidity after the use of this unit is not low enough for chlorination. The methods used to analyse turbidity removal in the carbon filter are very rough and useful only for finding very obvious trends. In the results it is noted that there is a pattern that indicates that the turbidity removal after the carbon filter increases with increasing turbidity. However, when looking at the percentage removal, no trends are discernable. This would suggest that, although more turbidity is removed at higher turbidities, this removal is not increased sufficiently to compensate for the poorer water quality. These results are in agreement with the theory that the main purpose of the activated carbon filter is not the removal of large amounts of turbidity. On the other hand, using highly turbid water may have adverse effects on the activated carbon filter in the long run as it could result in clogging. Another aspect is the dimensions of the carbon filter. If the theory on treatment capacity of the carbon filer, saying that water 3 times the carbon volume can be purified per hour, is applicable for this type of carbon, the filter capacity would not be more than 0.27 m^3/h. Even for low turbid waters the filter capacity would have a maximum of 1 m^3/h. (5.3.3)

It is important to note that the system did not show any remarkable ability to dampen sudden and high turbidity rises. Therefore, if agitation of source water occurs during purification, attention ought to be given to the risk of polluting the purified water with high turbidity flushes. If a by-pass valve is connected the water from such flushes might be diverted. On the other hand, sharp changes in flow might deteriorate the filter performance. Therefore it is crucial to prevent agitation of the source water.

The fast dissolution of the tablets is unfortunate. Over 60 % of the tablets were dissolved per 30 minutes on average of all the tests. Using the dose that gave the best results, the 6 coagulant-case, 8 tablets would be required for an hour, producing 3.6 m^3. The cost of $1.53 per tablet (Supply Requisition 2004) would lead to a cost of $ 3.4 per m^3 for the chemicals only. The results of this full-scale test have shown that the purification degree rises when the flow is reduced from 1 l/s to 0.5 l/s. However, the improvement is still small and the halved flow doubles the cost for the chemicals as the dissolution rates have not been shown to differ when the flow rate was changed. For further investigations, it is advisable to assess the advantages of the prolonged retention time. If simply longer pipes lead to more effective purification at high flows it is cost-efficient and advantageous.

As discussed, the reduction rates in percentage are approximated to be constant, regardless of changes in raw water turbidity. To achieve water with less turbidity than 15 or 5 NTU, using the highest reduction rate in these tests, the maximum permitted raw water turbidity would be 37.5 or 12.5 NTU, respectively. This illustrates the remarkably low results but it cannot be assumed that the same reduction rate would be valid for water with less turbidity than 100 NTU.

8.3 The manual

Precise instructions are crucial for the maintenance of the EmWat 4000-kit and the quality of the produced water. Training sessions have been carried out, but the manuals are decisive for the operation in field, as the varied circumstances often give rise to unforeseeable complications. The methods used for instruction in the manual are pedagogical, making it easy to get a quick overview of how to operate the kit. However, some shortcomings have been experienced (7.4) and need to be drawn attention to. The difficulties in adjusting and measuring flow rate in combination with the absence of the safety valve present a high risk for a sub optimal purification process and damaging of the equipment (7.1). In order to guarantee the correct use of the kit, information in the manual should stress the importance of not exceeding the design flow and using a lower flow rate when treating highly turbid water. Furthermore, it is recommended that the manual emphasises the importance of monitoring flow rate and water quality to ensure good quality potable water and longer use of the equipment.

No limit on the turbidity levels of the water lead into the carbon filter was stated in the manual. It would be advantageous to reduce the turbidity after sand filtration to a certain turbidity value before connecting the carbon filter. This would lengthen the life of the unit as well as allow it to maintain a high removal capacity for a longer time.

The Engineer's Manual (Plastec 2004, 16) is quoted as stating that "Disinfection, meaning *guaranteed removal* of any pathogenic organisms is usually a process only working with ´clear´ (<15 NTU) water" (Emphasis ours). It is true that chlorination has little effect when the water has a higher turbidity than 15 NTU. It should, however, be noted that the WHO states that there is a high frequency of failure of disinfection when the turbidity is above 5 NTU. The production of potable water with turbidities higher than 5 NTU can thus lead to false security, as the absence of pathogens cannot be guaranteed. This is especially significant when using the EmWat 4000 kit in emergency situations such as epidemics, where the microbiological safety of the water is the sole purpose of the water treatment. As shown by the results in chapter 7.1, it is possible to reduce the turbidity in polluted waters to less than 5 NTU using the EmWat 4000, and is therefore a goal worth striving for. Thus it is recommended that in the Engineer's Manual it be stressed that turbidity must be reduced as much as possible. It is also recommended that the risks associated with chlorinating water with turbidities higher than 5 NTU be commented.

Recommendations on sampling points and methods for evaluation of the coagulation process and the efficiency of the filters are needed. The kit is operated not only in emergencies but also during longer periods where analyses in order to improve the efficiency are possible. To further this process, more technical details on the kit should be provided. This would allow for better assessments of the performance and the development of improvements and adaptive methods, which could lead to possibly better water quality and more cost-effective operations.

9 Conclusion

9.1 Performance

Gathered experiences from previous operations with EmWat 4000 show that satisfactory water quality is achievable. It has been possible to reduce turbidity to levels where chlorination is effective, using source water with turbidities up to 500 NTU. Therefore, it can be concluded that the EmWat 4000 is adaptable to Ethiopian conditions and can be used effectively.

The water quality test performed at the test sites in Dire Kiltu and Konta Koysha showed that the inadequate water treatment was due to the poor performance of the purification process. The low efficiency is likely caused by exceeded surface loads, broken and missing equipment, and inadequate monitoring of turbidity and residual chlorine. These problems, however, do not show that the EmWat 4000 is unsuitable for use in Ethiopia but rather emphasise the necessity of careful operation.

The EmWat 4000 is designed to be simple in terms of connections and operation, but it is not a low-tech device. Its simplicity might be misleading and give the impression that the kit does not need careful surveillance. To avoid damaging equipment it is crucial that the flow rate and the pressure in the filtering units are kept under observation. Furthermore, the instructions concerning connection of the kit need to be followed precisely. Emphasis is given to the importance of the use of the safety valve.

In order to ensure that the water quality guidelines set by WHO are met, monitoring needs to be made consistently during water production. Of the utmost importance for the microbiological quality are sufficiently low turbidity for chlorination and the residual chlorine concentration. By observing these parameters it is possible to make adjustments to the process to maintain a high water quality. Therefore, monitoring should be made a requirement for the operation of the kit. The monitoring sheets provided with the kit could be used for this purpose.

Monitoring makes possible the gathering of experience from treatment of different kinds of water. This may lead to improvements of the purification process in terms of shortened start-up times after arriving at the sites, higher water quality, and more cost effective operations.

Two adjustments that can be made in the field to improve the process are the use of floc-aids and reducing the flow rate. Since the dissolution of the tablets has not been shown to be less for lower flow rates, it is advisable to use the design flow in order to produce as much water as possible per tablet. This would entail economic benefits as well as the possibility of producing a larger volume of water in a shorter time, which is crucial in emergencies.

9.2 Shortcomings and recommendations

It has been concluded that in the cases where produced water quality has been unsatisfactory the causes are shortcomings in operations. This can be partly attributed to divergence from the instructions in the manual, and partly to lack of information and emphasis on key factors in the manuals for securing good results.

To avoid divergence from instructions, an understanding of the processes in the kit is required as well as awareness of the risks of damaging equipment. By training operators and providing the information necessary in the field the purification process can be made more reliable. Especially important is the use of the safety valve, since it guarantees the longevity of the kit, and the static mixers which ensure efficient coagulation and flocculation. If the emphasis of the use of these in the manual is not sufficient, it should be considered whether these parts should be permanently built into the kit.

Due to the importance of the correctness of the manual, several amendments and additions have to be made. The following improvements in the Field Manual are suggested:

- a checklist concerning the connection of the kit that should be completed before starting the pump;
- specification of the length of the pipe between the coagulation and flocculation chambers;
- directives not to connect the carbon filter until the turbidity after the sand filter has been reduced as much as possible;
- clear instructions on how to set up the kit for backwashing, using the colour coded connections. These instructions should include suggestions on when to use purified water for backwash, if ever, and when to use raw water for backwash.

Furthermore, the following improvements are suggested for the Engineer's Manual:

- a discussion warning of the risk for insufficient disinfection when chlorinating water with turbidities higher than 5 NTU;
- a table containing the WHO guideline values for turbidity, pH, and residual chlorine;
- giving suggestions of adaptations to be made when purifying water within specific turbidity ranges;
- a warning concerning the risk of compromising chlorination when the flow rate is too low;
- more technical information on the different parts of the EmWat 4000, specifically the filter units, and information on the metal content in the coagulants.

Finally, since not all operators are English speaking it is strongly recommended that the Field Manual is translated into Amharic.

10 Further studies

Due to the limited time in the field not all aspects of the kit were able to be studied. Some suggestions for further studies include:

- studying the cost effectiveness of using the EmWat and comparing it to other emergency options;
- studying the effectiveness of modifications, such as using locally produced aluminium sulphate powder, their economic impact, and how these can be optimised;
- studying the consumption of coagulant tablets when using aluminium or ferric sulphate;
- studying the impact of the static mixers and their locations
- studying the minimum achievable turbidity after sand filtration with the expressed aim of using it as a guideline value for when the carbon filter should be connected to the unit.

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12 Appendix

12.1 Pair sample analysis

The sample pairs were examined to exclude the pairs with a difference, as percentage of the mean value, which would not be in the 95 % confidence interval. By using the function “NORMINV” in Microsoft Excel the limits for a 95 % confidence interval were found.

T1= Turbidity measurement 1
T2= Turbidity measurement 2

$$\Delta T = T1 - T2$$

$$\Delta T_{\%} = \frac{\Delta T}{(T1 + T2)/2}$$

$\bar{z}(\Delta T_{\%})$	0.5 %
$s\ (\Delta T_{\%})$	5.8 %
$I_{0,025}$	-9.05 %
$I_{0.975}$	10.3 %

During the investigation of the reliability of the turbidity measurements, the first sample of every pair was suspected, on average, to be higher than the second. To evaluate this, a mean of the difference of every pair, the second subtracted from the first, was calculated. Furthermore the interval of 95 % confidence within which the difference of the values would statistically vary was determined. The function for average and standard deviation in Microsoft Excel was used. The value for $t_{0.0025}(n-1)$ was found in table 3 in Blom (1999, 317).

$$I\Delta = \bar{z} \pm t_{0.025}(n) * \frac{s}{\sqrt{n}}$$

$I\Delta$ = The interval within which the values would statistically vary
$\bar{z}$ = The average of the difference of the two samples
n = The number of sample pairs
$t_{0.025}(n)$ = The value that with 95 % probability the difference of the two samples exceeds
s = Standard deviation

Results:

$\bar{z}(\Delta T)$	1.315
$s\ (\Delta T)$	5.935
n	222
$t_{0.025}(n-1)$	1.96
$I\Delta$	0.54-2.09

This indicates that the first value with a 95 % probability, statistically, is between 0.54 and 2.09 NTU higher than the second.

12.2 Retention time in pipe and sand filter

Pipe:
Ø: diameter = 52 mm → A: Area = $2.12 \cdot 10^{-3}\text{m}^2$

Q: The flow through the pipe is

a, 1 l/s = $1 \cdot 10^{-3}\ \text{m}^3/\text{s}$ and b, 0.5 l/s = $0.5 \cdot 10^{-3}\ \text{m}^3/\text{s}$

The retention times for the both cases are calculated below:

$$v_{1\,\text{l/s}} = \frac{\text{Q}}{\text{A}} = \frac{1 * 10^{-3}}{2.12 * 10^{-3}} = 0.47\ \text{m/s} \qquad \text{v}_{0.5\ \text{l/s}} = \frac{\text{Q}}{\text{A}} = \frac{0.5 * 10^{-3}}{2.12 * 10^{-3}} = 0.24\ \text{m/s}$$

The actual flocculation pipe is 60 metres long. Together with all connection pipes the whole length of pipe is approximately 70 metre.

$$t_{70m} = \frac{x}{v} = \frac{70}{0.47} = 148\, s \qquad t_{70m} = \frac{x}{v} = \frac{70}{0.24} = 297\, s$$

Sand filter:
The time through the sand filter had to be estimated since no information was known about the granules or the exact construction. Since the water is uncompressible the retention time is equal to the time for filling up the filter.

Ø: diameter = 450 mm→ A = 0.159 m^2 → V(h:0.56m) = 0.089 m^3

Since the sand filter is supposed to be backwashed, there must be space enough for expansions for the sand of about 15 %. Furthermore, from the remaining 85 % of sand, it is reasonable to estimate the effective pore volume for the sand to be 30 %. The volume for the water would consequently be 40.5 %. The estimation is done by assuming that the grain size is similar to other rapid filter grains. According to Degrémont(1991) it is between 0.5 and 1 mm. Since the EmWat 4000 is an all round filter, it is estimated that the size is in the upper range. The effective porosity is given in a graph, porosity verses grain size (Knutsson, Morfeldt 1993).

30 % of 85% = 85*0.3 = 25.5 %

25.5 %+15 % = 40.5 %

$\text{V}_{(\text{fill able volume})} = 0.089 * 0.405 = 0.036\ \text{m}^3$

The time to fill up the volume with the two different flows would be:

$$t_{sandfilter} = \frac{V_{fillable}}{Q} = \frac{0.036}{1 * 10^{-3}} = 36\, s \qquad t_{sandfilter} = \frac{V_{fillable}}{Q} = \frac{0.036}{0.5 * 10^{-3}} = 72\, s$$

The total retention time in the system is the retention time for the pipe added to the time through the sand filter:

$$t_{1 l/s} = 148 + 36 = 184\,\mathrm{s} \approx 3\,\mathrm{min} \qquad t_{0.5\, l/s} = 297 + 72 = 369\,\mathrm{s} \approx 6\,\mathrm{min}$$

12.3 Sedimentation estimation

To see whether the hypothesis of marginal sedimentation during 30 seconds is reasonable, Stokes law will be used. The bottles for turbidity measurement are approximately 45 mm. For particles to settle that length during 30 seconds a speed of 0.15 cm/s is needed. To verify the hypothesis the size of particles that settle with that speed will be calculated. The size will thus be compared to the particles that were seen in the water. In order to use Stoke´s law the particle concentration must be less than 1%. This criteria is not valid but will be disregarded for this estimation.

Stoke´s law:

$$v = \frac{2*(d_s - d_f)*g*r^2}{9\mu} = \frac{2*(2{,}65 - 0{,}997)*980*r^2}{9*0.008904} = 36385*r^2$$

v = velocity cm/s

d_s = density of the particle g/cm ^{3}

d_f = density of the fluid g/cm $^3 (25^\circ)$

g = acceleration due to gravity cm/s ^{2}

r = radius of the sphere cm

μ = Dynamic viscosity N *

The formula and constants are found in the Handbook of Chemistry and Physics (Weast 1976).

$$r = \sqrt{\frac{0.15}{36385}} = 2.03*10^{-3}\,cm$$

$$d = 2*r = 2*2.01*10^{-3} = 4.06*10^{-3}\,cm = 0.04\,mm = 40\mu m$$

The particles that manage to settle 45 mm or less during 30 seconds are thus particles of size 40 µm. That is the size of particles that can be discerned by the naked eye (Kemira 2003, 118). Water was of the quality that particles could be discerned and therefor it was stated that the particle sizes varied within the range of possible marginal sedimentation within 30 seconds.

12.4 Water content

The water content from the laboratory analyses is presented in the tables below. Laboratories in both Awassa and Oromiya have investigated the water from Konta Koysha. The dates for this investigation are seen in the table. The water from the other sites was only investigated in the laboratory in Oromiya.

WHO´s guideline values for drinking water are presented to give an idea of acceptable values. The values represent the amount that would risk adverse health effects from a lifetime of consumption. For a comparison with other source water, the minimum and maximum values for natural ranges and the world median are also presented. The values are based on 75 watersheds from all countries with global average constituents. (UN 1992, Chapter 6)

The results are divided into two tables due to lack of space. The contents of the substances in the second table are without comparable values.

Table 12.1 Results of chemical constituent analyses

	WHO[1]	Konta Koysha Awassa 10/11	Konta Koysha Oromiya 3/11	Sofi Lugo	Dire Kiltu	Natural ranges of dissolved constituents[2]. (Streams: 1−100 km^2		Most common natural concentration [2] (median)^x (average)^{xx}
						Min	Max	
	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
Ca^{2+}		36	35.6	64	50	0.06	210	8.0^x
Mg^{2+}		26.4	3.12	14.4	2.88	0.05	80	2.4^x
Na^+		8.5928	-	-	-	0.06	350	3.7^x
HCO_3^-		244	208	500.2	210	0	350	30,5^x
K^+		8.000		-	-	0.1	6.3	1.0^x
Cl^-	250^a	17.5	0	90	4	0.09	530	3,9^x
SO_4^{2-}	250^a	0.9	1	24	1	0.14	720	4,8^x
Fe^{+2}	0.3^a	0.133	0.05	0.02	0.17			0,05^x
Cu^{+2}	2	0.096	0.05	0.53	0.37			0,0014^{xx}
Mn^{+2}	0.4	0.024	0.1	0	0.9			0,010^{xx}
Cr^{+6}	0.05^b	0.006	0.1	0.15	0.08			0,0001^{xx}
F^-	1.5	0.38	1.2	0.02	0.81			0,100^x
NH_3	35^a	-	0.302	1.536	1.1374			
NH_4^+	1.5^a	0.14	0.3225	1.638	1.2126			
TDS	1000^a	158	-	-	-			
Total free Cl_2	5^a	0.08	0.05	0.04	0.08			
NO_3^{-1}	50	2.64	5.72	8.36	4.48			
NO_2^{-1}	0.2 /3	0.0099	-	-	-			

a, No health-based guidelines
b, Preliminary value due to limited knowledge about health effects
-, not analysed
1, WHO (2004) chapter 12.
2, UN (1992) Chapter 6

	Konta Koysha Awassa 10/11	Konta Koysha Oromiya 3/11	Sofi Logo	Dire Kiltu
	mg/l	mg/l	mg/l	mg/l
Total hardness	200 mg/l ($CaCO_3$)	102 mg/l ($CaCO_3$)	220	137
Calcium	90	89	160	125
Magnesium	110	13	60	12
T. alkalinity	200	187	410	187
Bicarbonate	200	171	410	172
Hydroxide	0	0	0	0
Carbonate	0	16	0	30
Conductivity	263	-	-	-
Br^{-1}	0.1	-	-	-
CO_3^{-2}	0	9.6	0	18
PO_4^{-3}	0.621	0.67	4.06	0.67
Dissolved NH_3	0.1281			

12.5 Calculations of remaining alkalinity

When a coagulant is added to water the metal ions, Me^{3+}, react with the water molecules producing acidity, H^+. This production of H^+ will cause a drop in pH if it is not buffered by the alkalinity. This process is described by the equilibrium equations below.

$$Me^{3+} + H_2O \leftrightarrow Me(OH)_3 + 3H^+$$

$$H^+ + HCO_3^- \leftrightarrow H_2CO_3$$

As can be seen from the equations, the alkalinity (HCO_3^-) is consumed when the acidity increases. When the alkalinity is consumed, the pH will begin to drop. The consumed alkalinity when using a known concentration, *X*, of iron sulphate can be calculated as follows:

$$\left[\frac{X\ g\,Fe_2(SO_4)_3}{l}\right]\cdot\frac{1\,mol\,Fe_2(SO_4)_3}{399.9\,g\,Fe_2(SO_4)_3}\cdot\frac{2\,mol\,Fe^{3+}}{1\,mol\,Fe_2(SO_4)_3}\cdot\frac{1\,mol\,H^+}{1\,mol\,Fe^{3+}}\cdot\frac{1\,mol\,HCO_3^-}{1\,mol\,H^+}\cdot\frac{61\,g\,HCO_3^-}{1\,mol\,HCO_3^-}=$$

$$=\left[\frac{X\ g\,Fe_2(SO_4)_3}{l}\right]\cdot\left[\frac{0.305\,g\,HCO_3^-}{g\,Fe_2(SO_4)_3}\right]=$$

$$\frac{0.305X\,g\,HCO_3^-}{l}.$$

12.6 Turbulence check

Reynolds number determines whether the type of flow is turbulent or laminar. The criterion for laminar flow in circular pipes is that Reynolds number, for normal cases, does not exceed 2000. The circumstances for the flow during the EmWat 4000 purification are not extraordinary; the pipes have several connections, have not a negligible roughness and are not straight.

R = Reynolds number

V_d = velocity m/s

ν = Kinematic viscosity m^2/s

$$R_{1l/s} = \frac{D * V_d}{\nu} = \frac{52 * 10^{-3} * 0.47}{0.893 * 10^{-6}} \approx 28000$$

$$R_{0.5l/s} = \frac{D * V_d}{\nu} = \frac{52 * 10^{-3} * 0.24}{0.893 * 10^{-6}} \approx 14000$$

The criterion, the formula, and the constants are found in Fluid Mechanics with Engineering Applications (1997). The speeds are calculated in Appendix 10.3 Retention time in pipe and sand filter.

The hypothesis of turbulent flow is confirmed.

12.7 Rank test of flow rate influence

In order to test whether the difference in reduction rates at the two different flows is statistically significant a rank test was performed. This test was chosen since the distribution of the two data groups was unknown. The rank tests were divided by site into two groups.

First all the data in each group was sorted and ranked. Afterwards the sum of the ranks for each flow rate was taken, as is shown below:

Test	Flow Rate (l/s)	Reduction (%)	Rank
O4C+2F 0.5	0,5	47,5	11
O4C+2F 0.5	0,5	48,5	12
O4C+2F 0.5	0,5	49,0	14
O4C+2F 0.5	0,5	50,9	15
O6C 0.5	0,5	52,3	16
O6C 0.5	0,5	52,4	17
O4C+2F 0.5	0,5	52,5	18
O6C 0.5	0,5	54,4	19,5
O4C+2F 0.5	0,5	54,4	19,5
O6C 0.5	0,5	57,0	21
O6C 0.5	0,5	62,7	22
O6C 0.5	0,5	65,6	23
		Sum	208

Test	Flow Rate (l/s)	Reduction (%)	Rank
O4C+2F 1	1	31,5	1
O4C+2F 1	1	32,3	2
O4C+2F 1	1	33,4	3
O4C+2F 1	1	34,3	4
O4C+2F 1	1	36,0	5
O6C 1	1	38,4	6
O6C 1	1	38,8	7
O6C 1	1	39,1	8
O4C+2F 1	1	39,4	9
O6C 1	1	46,6	10
O6C 1	1	48,9	13
		Sum	68

After this, the hypothesis was made that the reduction at a flow rate of 0.5 l/s is greater than that at 1 l/s. From this hypothesis a critical value, $c_{0.975}$, was found, such that the rank sum of 0.5 l/s, $\mathrm{Sum}_{0.5\ \mathrm{l/s}}$ is greater than $c_{0.975}$ with a certainty of 95%. For the values obtained in Dire Kiltu, Oromiya, $c_{0.975}$ was found using tables found in Conradsen (1973, 27), and subsequently it was seen that

$$c_{0.975} = 165$$
$$Sum_{0.5l/s} = 208$$
$$c_{0.975} < Sum_{0.5l/s}$$

As the number of amount of data from Sofi Lugo, Harar, was large, an alternative method was used.

First the mean, *E*, and variance, *V*, were calculated as directed in Conradsen (1975, 3.74):

$$E = \frac{1}{2} \cdot n(m+n+1) = \frac{1}{2} \cdot 20(28+20+1) = 490$$
$$V = \frac{1}{12} \cdot m \cdot n(m+n+1) = \frac{1}{12} \cdot 25 \cdot 20(28+20+1) = 2147$$

$n =$ number of values obtained at 0.5 l/s
$m =$ number of values obtained at 1 l/s

Using Microsoft Excel, $c_{0.975}$ was obtained as the value where 97.5% of the data would statistically lie below. A normal distribution with the mean, *E*, and standard deviation, $\sqrt{V}$, was used for this. The results are as follows:

$$c_{0.975} = 581$$
$$Sum_{0.5l/s} = 723$$
$$c_{0.975} < Sum_{0.5l/s}$$

The Rank test has shown that the reduction rate at a flow rate of 0.5 l/s is greater than reduction at 1 l/s at both Sofi Lugo and Dire Kiltu.

12.8 Rank test of flocculant influence

In order to test whether the addition of flocculants had a significant effect, a rank test was performed. The reduction rates for 6C and 9C were compared with the reduction rates for 4C+2F and 6C+3F. The values were sorted and ranked as described in the previous chapter and critical value was found in Conradsen (1973, 27). The following results were found:

$$c_{0.975} = 132$$
$$Sum_{flocculants} = 187$$
$$c_{0.975} < Sum_{flocculants}$$

It is thus confirmed that in this test the addition of flocculants resulted in higher reduction rates than merely increasing the coagulant dose.

12.9 Turbidity result measurement

The following are the unprocessed values that were obtained in the full-scale tests. For the test in Sofi Lugo, the purified water indicates the water treated by the various coagulant combinations and the sand filter. The results from Dire Kiltu also give the results from after that the carbon filter had been used.

	Raw water			Purified Water		
Sand fil	**Time**	**Tubidity 1**	**Turbidity 2**	**Time**	**Tubidity 1**	**Turbidity 2**
1 l/s				09:27	179	177
				09:32	251	253
				09:37	284	282
				09:42	264	262
				09:47	249	254
				09:52	197	197
				09:57	490	497
0.5 l/s	10:10	827	815	10:15	460	446
	10:18	746	739	10:20	462	466
	10:23	663	657	10:25	410	399
	10:28	592	597	10:30	366	359
	10:33	538	533	10:35	345	344
	10:38	502	500	10:40	310	305
	10:43	486	483	10:45	261	258

3 C	**Time**	**Tubidity 1**	**Turbidity 2**	**Time**	**Tubidity 1**	**Turbidity 2**
1 l/s	10:57	395	398	10:58	254	249
	11:05	366	372	11:03	227	228
	11:10	330	332	11:08	223	222
	11:15	301	304	11:13	190	187
	11:20	287	281	11:18	209	205
				11:23	189	191
0.5 l/s	11:34	272	271	11:28	149	143
	11:39	247	248	11:33	126	123
	11:44	240	240	11:38	138	138
	11:49	232	226	11:43	129	129
	11:54	215	211	11:48	123	124
				11:53	118	120

6 C	**Time**	**Tubidity 1**	**Turbidity 2**	**Time**	**Tubidity 1**	**Turbidity 2**
1 l/s	13:42	158	160	13:50	137	137
	13:47	162	162	13:55	94	89
	13:52	151	151	14:00	96	93
	13:57	150	151	14:05	91	89
	14:02	144	142	14:10	96	96
	14:07	136	136	14:15	95	95
	14:12	131	133			
0.5 l/s	14:30	130	127	14:29	68	66
	14:35	130	129	14:33	49	47
	14:40	136	135	14:38	47	47
	14:45	132	133	14:43	57	56
	14:50	122	123	14:48	60	60
				14:53	53	53

9 C	Time	Tubidity 1	Turbidity 2	Time	Tubidity 1	Turbidity 2
1 l/s	15:02	106	105	15:05	95	94
	15:07	103	103	15:10	88	89
	15:12	99	98	15:15	83	81
	15:17	96	93	15:20	77	79
	15:22	91	92	15:25	75	77
	15:27	90	89	15:30	87	85
0.5 l/s	15:39	86	86	15:41	54	51
	15:44	72	72	15:46	36	36
	15:49	71	71	15:51	36	36
	15:54	795	732	16:01	83	79
	16:04	132	134	16:06	84	81

4C+2F	Time	Tubidity 1	Turbidity 2	Time	Tubidity 1	Turbidity 2
1 l/s	16:21	114	113	16:29	55	52
	16:26	106	107	16:34	47	44
	16:31	102	100	16:39	47	47
	16:36	95	95	16:44	45	44
	16:41	91	92	16:49	43	40
	16:46	87	86			
0.5 l/s	17:00	70	70	17:03	40	39
	17:05	73	73	17:08	24	24
	17:10	71	69	17:13	32	31
	17:15	64	64	17:18	32	32
	17:20	66	66	17:23	31	30
		30	497	17:28	30	30

6C+3F	Time	Tubidity 1	Turbidity 2	Time	Tubidity 1	Turbidity 2
1 l/s	09:16	99	99	09:25	47	44
	09:21	107	103	09:28	63	59
	09:26	106	101	09:34	53	52
	09:31	108	108	09:39	54	53
	09:36	108	106	09:44	55	52
	09:41	95	91	09:49	48	45
	09:46	80	79	09:55	39	41
	09:52	82	81	10:00	49	48
	09:57	46	84			
0.5 l/s	10:17	94	93	10:20	30	29
	10:22	92	92	10:25	34	33
	10:27	85	86	10:30	41	41
	10:32	90	92	10:35	40	38
	10:37	86	86	10:40	41	39
	10:42	92	93	10:45	41	40
	10:47	108	107	10:50	41	40

Dire Kiltu	**Raw water**			**After sand filter**			**Afton carbonfilter**		
6 C	**Time**	**Tubidity 1**	**Turbidity 2**	**Time**	**Tubidity 1**	**Turbidity 2**	**Time**	**Tubidity 1**	**Turbidity 2**
1 l/s	11:59	301	291	12:05	173	181	12:02	111	106
	12:03	326	316	12:10	181	185	12:07	138	147
	12:08	294	293	12:15	182	178	12:13	151	144
	12:16	263	263	12:20	156	147	12:19	135	136
	12:21	256	256	12:29	156	155	12:24	131	126
	12:29	331	329	12:35	183	173	12:31	151	148
	12:34	279	282				12:36	164	164
0,5 l/s	12:46	344	360	12:48	162	151	12:49	132	130
	12:51	454	445	12:54	155	149	12:55	123	124
	12:56	474	475	12:58	156	152	13:00	151	152
	13:01	454	454	13:03	183	185	13:05	155	158
	13:07	435	441	13:08	198	194	13:10	187	189
	13:13	411	413	13:14	209	210	13:15	258	258
	13:18	478	477	13:19	196	193	13:20	253	264

4C+2F	**Time**	**Tubidity 1**	**Turbidity 2**	**Time**	**Tubidity 1**	**Turbidity 2**	**Time**	**Tubidity 1**	**Turbidity 2**
1 l/s	13:36	587	568	13:39	356	346	13:40	351	348
	13:41	534	534	13:44	342	341	13:45	282	285
	13:46	480	483	13:55	314	319	13:50	505	507
	13:53	473	478	14:03	321	321	13:54	280	274
	13:59	487	465	14:09	309	310	14:00	266	270
	14:06	458	455				14:05	380	386
							14:10	275	276
0,5 l/s	14:46	373	373	14:49	137	135	14:50	131	131
	14:52	386	386	14:54	227	232	14:55	101	104
	14:58	397	397	15:01	175	174	15:02	134	135
	15:04	402	399	15:07	182	186	15:08	183	189
	15:10	379	372	15:13	201	197	15:14	166	161
	15:15	360	354	15:18	191	193	15:19	156	156
	15:21	381	389	15:24	187	188			

12.10 Laboratory analyses on the coagulants

		Aluminium sulphate Ethiopia	**Alufloc**	**Ferufloc**
Al	%	8.60	8.80	
Fe	%			18.5
Cl	%	<0.1	<0.1	<0.1
OH/Al		0.03	0.06	
Free H_2SO_4	%	-0.4	-0.9	0.65
Al	mg/kg			140
B	mg/kg	2	1	<0.5
C tot	%	<0.1	0.7	10
Ca	mg/kg	170	40	40
Cr	mg/kg	<0.5	<0.5	40
Cu	mg/kg	9.3	<0.5	8.2
Mg	mg/kg	130	370	410
Mn	mg/kg	90	<0.5	480
Na	mg/kg	82	530	52
Ni	mg/kg	6.5	<0.5	30
P	mg/kg	16	<5	<5
S	mg/kg	130000	182000	130000
Si	mg/kg	62	7.6	5
Ti	mg/kg	40	3.7	5.7
Zn	mg/kg	8.8	0.9	25
$Al_2(SO_4)_3$ calculated from				
Al	%	54.4	55.7	
S	%	46.3	65.0	
$Fe_2(SO_4)_3$ calculated from				
Fe	%			66.2
S	%			54.2