Norwegian University
of Life Sciences

Master's Thesis 2016 30 ECTS
Department of Mathematical Sciences and Technology

Chronic Kidney Disease (CKD) in Sri Lanka – Evaluation of Status, Practices and Potential Pollutants

Mathias Espeland
Water and environmental engineering

2016

Title: Chronic Kidney Disease (CKD) in Sri Lanka – Evaluation of Status, Practices and Potential Pollutants

Mathias Espeland

http://brage.bibsys.no/nmbu

Print: Norsk Aero AS

Preface

This MSc thesis is a product of 5 years of education at the Norwegian University of Life Science (NMBU). The whole study was conducted from January to May 2016 while the field research was done from January to April in Sri Lanka.

The problem of Chronic Kidney Disease in Sri Lanka caught my attention due to the possibility of making a change in the lives of several persons. Professor H.C. Ratnaweera informed me of the possibility of helping a village which had an immediate problem, treating contaminated ground water, as well as contributing to find the cause of the bigger problem.

The thesis is targeted towards researchers and others studying and working with the CKDu issue in the dry zone of Sri Lanka.

This study would not have been possible without the kind assistance, advice and arrangements given by the following individuals.

Professor Harsha C. Ratnaweera, Department of Mathematical Sciences and Technology (IMT) at NMBU, worked as my main supervisor. Without him I would never have been able to conduct this study. I am forever grateful for his help and assistance during my work.

Dr. Zakhar Maletskyi, IMT at NMBU, worked as my co-supervisor. He has helped me with my technical and academic questions during the study and he has advised me on how to proceed.

My deepest gratitude goes to Professor S.B. Weerakoon and Dr. G.B.B. Herath, Department of Civil Engineering at University of Peradeniya. They were always ready to answer my questions, and helped me with my practical problems. They also set me up with fellow students at the University of Peradeniya who could be of assistance to me during my research.

Other academic staff at UoP also deserve to be thanked. Everyone was ready to help me with any inquiries, especially Mr. D.D. Dias, who was always available to help me with any practical concern during my stay at the university.

My fellow students, including S.G.C.L Subhawickrama and M.K.D.C.S. Meegoda deserve a thank you. They both helped me practically and in acquiring information I needed to complete my thesis. Special thanks goes to Meegoda who joined me for almost all my field trips, helping me to understand the local customs and translating the information obtained.

I would also like to thank all the technical staff at UoP and NMBU, including the lab staff. They helped me with practical and analytical work and things would have been much harder without them.

My gratitude goes to Dr. S.K. Weragoda and Mr. Jayasiri at the National Water Supply and Drainage Board (NWSDB). They helped me with every practical activity in the Anuradhapura district, as well giving me valuable feedback on the research. A thank you is also directed to all the workers who helped me with guiding, plumbing and general problem solving.

Thank you also to the local people in the Anuradhapura district who helped me do my examinations, especially our hosts at Medawachchiya, whose hospitality and help during the installation process was invaluable.

I would also like to thank George Ralak, my roommate in Sri Lanka, who kept me company, both at the university and at the house. He also helped me to keep my spirits up and gave me good advice and feedback during my research.

The Norwegian Water Association, the Erasmus+ programme of the European Union and the Norwegian University of Life Science all contributed with economical funding, thus making this project a viable option. A thank you is appropriate.

Last, but not least, I want to thank my wife, Linda, for being patient with me, persevering, staying home alone in Norway, and believing in me throughout the course of this education.

Mathias Espeland,

Ås, 18.05.2016

Abstract

A number of studies and comments have tried to find the cause of Chronic Kidney Disease of unknown etiology (CKDu) which has stricken the North Central Province (NCP) of Sri Lanka during the last two decades. The preliminary conclusion is that the main cause is water contaminated by agrochemicals, both organic (pesticides etc.) and inorganic (metals etc.).

There are studies that have attempted to find out if heavy metals have spread to the ground water from agrochemicals. Some studies have found arsenic and cadmium, while others did not find any trace of these elements.

One of the goals of this thesis is to contribute on this matter so that the research can progress. Ten different RO-units were examined, samples collected and these samples were analyzed for arsenic, cadmium, lead and other metals. In addition to these, fluoride levels were also checked. The results show the levels to be low, both in the raw water and the permeate from the units. The conclusion is that heavy metals in the ground water, at least in the area examined, are not the cause of CKDu.

The second goal was to set up and operate a research facility consisting of an RO-unit in the NCP. This research plant was installed and the initial start and optimization was conducted. Water samples were also collected from this plant so as to analyze for the above mentioned elements, whose concentration values were found to be below the limit set by the WHO.

This thesis suggests further research focus on organic compounds that come from agrochemicals since, based on this study, heavy metals can be disregarded as a cause of CKDu.

Furthermore, a pamphlet was developed to guide people in the installation and operation of new and existing RO-plants. The pamphlet demonstrates the procedure for installing, operating and disinfecting an RO-plant. This pamphlet will be available for everyone to use for non-commercial activity.

Further research on operating and optimization of the RO-unit are proposed.

The people of the NCP deserve good and safe water. To make sure this happens, the cause of CKDu must be found, and the operation of RO-units must be carried out in a proper and optimized manner.

Sammendrag (Norwegian Abstract)

En rekke studier har forsøkt å finne årsaken til kronisk nyresykdom av ukjent etiologi (CKDu) som har rammet den nordlige sentrale provinsen (NCP) av Sri Lanka de siste to tiårene. Den foreløpige konklusjonen er at hovedårsaken til sykdommen er drikkevann som er forurenset av plantevernmidler, både organiske forbindelser (pesticider) og anorganiske (metaller).

Flere studier har undersøkt om tungmetaller har spred seg til grunnvannet fra plantevernmidler. Noen studier har funnet arsenikk og kadmium, mens andre ikke finner spor av disse elementene i grunnvannet.

Ett av målene med denne avhandlingen er å bidra i denne saken, slik at forskningen kan utvikles. Ti forskjellige RO-enheter i NCP ble undersøkt, vannprøver ble tatt og disse prøvene ble analysert for arsenikk, kadmium, bly og andre metaller. I tillegg til dette ble det analysert for fluor. Resultatene viser at nivåene er lave både i råvannet og permeatet fra enhetene. Konklusjonen blir derfor at tungmetaller i grunnvannet, i det minste i det undersøkte området, ikke er årsaken til CKDu.

Det andre målet med oppgaven var å sette opp og drive et forskningsanlegg bestående av en RO-enhet i NCP. Dette forskningsanlegget ble installert, og oppstart, samt optimalisering gjennomført. Vannprøver ble samlet inn fra anlegget, slik at de kunne analyseres for de samme elementene som nevnt ovenfor. Resultatene viser også her konsentrasjonsverdier under WHOs grense for drikkevann.

Det er gitt forslag til videre forskning, som fokuserer på de organiske forbindelsene fra landbrukskjemikalier, basert på denne oppgaven kan tungmetaller ignoreres som årsak til CKD.

Videre ble en pamflett utviklet for å veilede i installasjon og drift av nye og eksisterende RO-anlegg. Brosjyren viser prosedyren for installasjon, drift og desinfisering en RO-anlegg. Dette heftet vil være tilgjengelig for alle til bruk og distribusjon.

Forslag til videre forskning på drift og optimalisering av RO-enheten er gitt.

Innbyggerne i NCP fortjener godt og trygt vann. For å sikre at dette skjer, må årsaken til CKDu bli funnet, og driften av RO-enheter må gjennomføres på en forsvarlig måte.

Table of Contents

Abbreviations

CKD	Chronic Kidney Disease
GRF	Glomerular Filtration Rate
IARC	International Agency for Research on Cancer
LKR	Sri Lankan Rupees
NCP	North Central Province of Sri Lanka
NMBU	Norwegian University of Life Science
NWSDB	National Water Supply and Drainage Board
ppm	Parts per million
RO	Reverse Osmosis
UoP	University of Peradeniya, Sri Lanka
UV	Ultraviolet light
WHO	World Health Organization

g	Gram
kg	Kilogram
mg	Milligram
µg	Microgram
L	Liter
m^3	Cubic meter
h	Hour

Chemical abbreviation

Al	Aluminium
As	Arsenic
B	Boron
Ca	Calcium
Cd	Cadmium
Cl	Chlorine
Co	Cobalt
Cr	Chromium
Cu	Cobber
F^-	Fluoride
H	Hydrogen
Inorg-C	Inorganic Carbon
Mn	Manganese
Na	Natrium
Ni	Nickel
NO	Nitrogen Monoxide
O	Oxygen
Pb	Lead
TOC	Total Organic Carbon
Tot-N	Total Nitrogen
Zn	Zinc

List of Figures

List of Tables

1 Introduction

During the last two decades, Sri Lanka has experienced an escalating incidents of Chronic Kidney Disease of unknown etiology (CKDu). Most incidents are in the dry zonal areas of the North Central Province (NCP), at the northeastern part of the island, as shown in Figure 1.1. This is where 45% of the country's paddy fields are located. Similar incidences have been reported in dry agricultural areas in other countries. The cause of this illness is heavily debated; however, mounting evidence implicates several active pollutants. Some have named it CKD of multifactorial origin (CKD-mfo). CKDu kills over 5000 individuals annually in Sri Lanka, mainly middle-aged male farmers (Wimalawansa 2014).

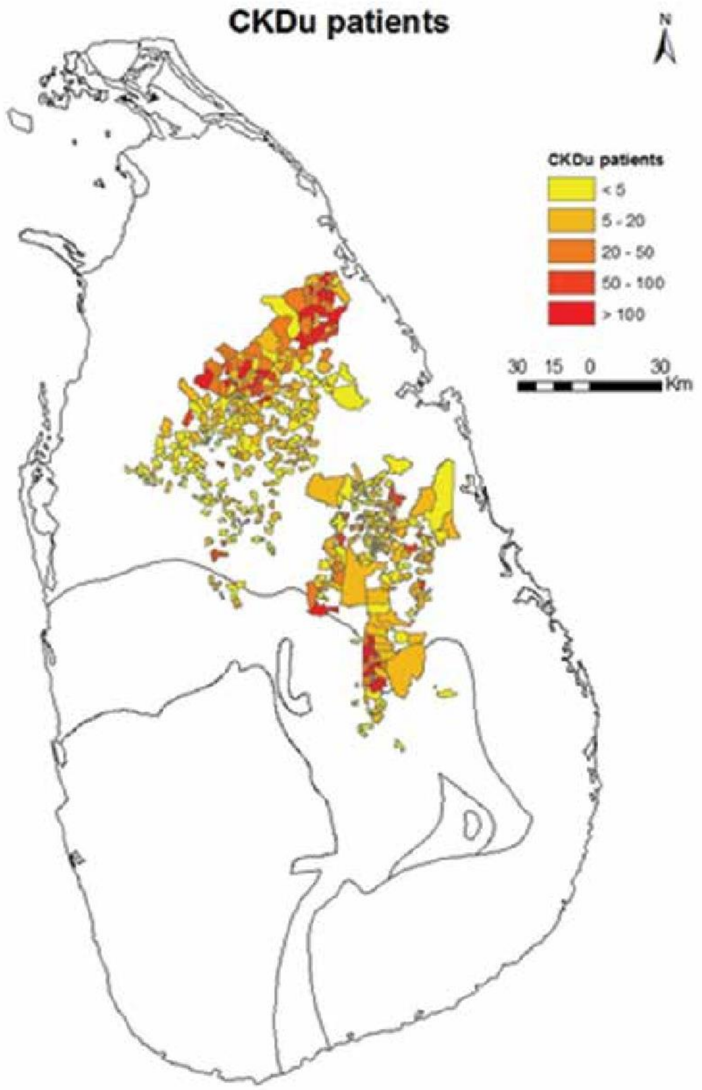


Figure 1.1: Distribution of CDK patients reported ((Noble et al. 2014) adapted from (Jayasekara et al. 2013))

Drinking water is claimed to be the main source of CKDu, a fear circulated by the media. The inhabitants are now too scared to drink the ground water. As a solution, people buy commercially bottled water or treat their water with a Reverse Osmosis (RO) unit. RO-units have, in addition to the privately bought ones, been installed by the government and NGOs. When water is treated with a good-working RO-unit, it is free of any harmful substances and safe to drink. However, many RO-units in Sri Lanka are distributed with no form of documentation, and the only assurance the consumer has for good treatment is the label "RO". This greatly jeopardizes the safety of the drinking water.

A submerging theory is that agrochemical compounds cause CKDu (Jayasinghe 2014; Wimalawansa 2014). There are mainly two kinds of agrochemical compounds: inorganic (metals etc.) and organic (pesticides etc.). It is hard to justify the true cause based on literature. This thesis will examine the inorganic part of the alleged agrochemical pollution. The contaminants in focus are Arsenic (As), Cadmium (Cd), Fluoride (F^-) and Lead (Pb). These substances have been pointed out as possible causes for CKDu, as they are harmful in large amounts. In addition, the substances are present in the agrochemicals used locally. A critical analysis on the water pollution will be carried out. Analyses of other substances will also be conducted to broaden the work done, regarding CKDu and possible contaminants.

This thesis compiles and analyzes the existing research on the potential role of water quality as a cause for CKDu in Sri Lanka, supplemented with additional analysis. It also analyses the need and impact of RO systems in selected areas. It will lay the foundation for future work, regarding CKDu, Reverse Osmosis, and safe drinking water. This will be done by evaluating the existing studies, analyzing water samples from wells within the region affected by CKDu and other drinking water sources, and assessing the current use and state of RO-plants in the North Central Province (NCP) of Sri Lanka

A project coordinated by NMBU has provided a new reverse osmosis plant. This plant, manufactured by Ecosoft, will be installed and operated in the Anuradhapura District. Water from this plant will be sampled and analyzed to compare it with the water from the older RO-plants and other sources. The installation and commissioning of the plant, training of operators and graduate students, and initiation of mechanisms for secure operation and maintenance of the RO-plant are focused on in this thesis.

2 Background

2.1 Chronic Kidney Disease of Unknown Etiology (CKDu)

Chronic Kidney Disease (CKD) is defined as kidney damage evidenced by structural or functional abnormalities of the kidney with or without decreased Glomerular Filtration Rate over a three month period (Wanigasuriya 2012). CKD patients are asymptomatic in the early stages of the illness; CKD is in most cases not detected until the last stage of the illness. This causes Chronic Renal Failure with many fatalities in areas where advanced treatment is not available. Treatment of CKD includes liver transplant and regular dialysis. Recognized causes of CKD are diabetes, hypertension, obstructive uropathy etc. The reason for CKD in Sri Lanka is unknown, thus the term Chronic Kidney Disease of unknown etiology (CKDu) is used (Bandara et al. 2010; Jayasumana et al. 2013b; Noble et al. 2014; Wanigasuriya 2012).

There have been several studies to find the etiology of CKD in Sri Lanka. The disease mainly affects male farmers over the age of 40 situated in the North Central Province (NCP) of Sri Lanka. These farmers work long days in the field, resulting in dehydration, which stresses the kidneys, and/or have a high consumption of groundwater, which is believed to contain the pollutants that affect the kidneys. Most of the studies agree that the substances in the ground water are part of the etiology, which substance is a whole other discussion. Studies go back and forth, word against word, in regards to what substance is the main cause of CKD in the NCP, Sri Lanka (Noble et al. 2014).

2.2 Arsenic

Several studies implicate Arsenic (As) as one of the main sources of CKDu. The World Health Organization (WHO) has, however, done a study of groundwater samples from the affected areas, where the As levels were found to be normal (Chandrajith et al. 2011b; Nanayakkara et al. 2014). On the other hand, other studies show that As exists and suggests that As in combination with hardness may be a factor (Jayasumana et al. 2014a; Jayasumana et al. 2013b). In another study, several water sources have been tested for As and Cadmium (Cd) (Jayatilake et al. 2013). This study analyzed samples to find raised As values. However, repeated testing of the same wells showed normal levels. Based on the studies, it seems that direct localization of high As levels is difficult to obtain in Sri Lanka, if not impossible. The CKDu affected areas do not have a centralized water supply system, which indicates that people get their water from several different sources. Analyses of water from a small area can therefore not be generalized to assume that As levels in all of the sources are normal.

2.2.1 Chemistry of Arsenic

Arsenic is considered a metalloid. It exists in the oxidation states of -3, 0, 3 and 5. It is widely distributed throughout the Earth's crust, most often as arsenic sulfide or as metal arsenates or arsenides. In oxygenated water, As is most likely to occur as arsenate, with an oxidation state of 5. This state is relatively instable and therefore has a tendency to form extended molecular structures. However, in reducing conditions, it will be present as arsenite, with an oxidation state of 3. The average concentration in the world's crust is 1.5 to 5 mg/kg. Through erosion, dissolution, and weathering, arsenic may be released to surface and groundwater (Ning 2002; Sun 2011; World Health Organization 2011a). This leads to high concentration levels around the world, exceeding the WHO and EPA's drinking water guideline value of 10 μg/L (Environmental Protection Agency 2001; Gomez-Caminero et al. 2001). Arsenic is occurring both colorless and tasteless, and in that way is difficult to detect in food, water and air. The most toxic form is considered Arsine, followed by arsenic(III), arsenic(V), and organic arsenic compounds (World Health Organization 2011a).

2.2.2 Health Impacts of Arsenic

Infrequent ingestion of water containing low levels of As can pass through the body without causing any harm. However, consuming water with elevated levels of inorganic As can hurt the body. The effects of arsenic exposure depend on many factors, with As concentration and duration of exposure as the most important factors. Acute poisoning occurs when water with concentration of 60 mg/L is congested, and this poisoning can cause death. The main problem with As in drinking water is not acute poisoning, but ingestion of low levels of arsenic over a relatively long time. This type of exposure is usually delayed, with years of exposure required to initiate the disease process. The signs of chronic As poisoning, also called arsenicosis, might be darkened skin (melanosis), skin lesions, cancer of the skin, gastrointestinal symptoms, anemia, neurological effects, liver and kidney disease (Dvorak et al. 2014; Lesikar et al. 2005; World Health Organization 2004; World Health Organization 2011a). There are four recognized stages of arsenicosis (Choong et al. 2007):

- *Preclinical:* Arsenic can be found in the patient's hair, nails and urine. Nevertheless, the patient is without any symptoms.
- *Clinical:* Melanosis is the most common symptom, as well as swelling of hands and feet. WHO estimates this stage to require 5-10 years of exposure to Arsenic.
- *Complications:* Clinical systems become more pronounced and internal organs are affected.

- *Malignancy:* Tumors or cancer to skin or other organs affects the patient.

Clinical findings suggest that almost all stages are found when examining arsenic poisoning through drinking water (Hotta 1989).

2.3 Cadmium

There are some studies looking into the role of Cadmium (Cd) in the development of CKDu in Sri Lanka. A study conducted in 2008 of five reservoirs in NCP measured high concentrations of Cd in water samples collected (Bandara et al. 2008). These values ranged from 30 – 60 µg/L. The maximum contamination level set by the WHO is 3 µg/L (World Health Organization 2011b), which shows how severe the contamination in these wells were. A large amount of Cd was also found in rice, roots of lotus and freshwater fish in the same area (Bandara et al. 2008), which is commonly consumed food. Combined, all this gives a rather high consumption of Cd in a regular day, a lot higher than the maximum contamination level of 7 µg/kg body weight. It was also found that the amount of Cd in urine samples from the CKDu patients in the area is relatively high, ranging from 5 – 14 µg Cd/g creatinine, while 2 µg Cd/g creatinine is considered normal. A study done by Chandrajith et al. (2011b) compared these results with asymptomatic individuals from the NCP showing values ranging from 0.39 – 0.79 µg Cd/g creatinine, which is notably lower than those observed by Bandara et al. (2008). There exists some confusion in the role of Cd as an agent for illness, as these studies show completely opposite results.

2.3.1 Chemistry of Cadmium

Cadmium is a metal with a usual oxidation state of +2, it also exists in the +1 state. Cd is rare in the Earth's crust, with a concentration rate of about 0.1 ppm in the crust (Wedepohl 1995) and 0.01 – 0.07 ppm in soil tested by Bowen (1966). It occurs naturally with zinc and lead. The Cd in soils seem to be tightly held and are not easily removed by leaching; as a bulk metal it is insoluble in water. In powder or manifested with other metals, it will be soluble (Agency for Toxic Substances and Disease Registry 2008; Hem 1972; World Health Organization 2011b).

2.3.2 Health Impacts of Cadmium

Cadmium is a chronic toxin. Cadmium is classified as a "carcinogenic to humans" by the International Agency for Research on Cancer (IARC). Studies show that Cd may trigger cancer in the lungs, prostate, and kidneys (IARC 2012). Studies indicate that skeletal damage is a critical effect of cadmium exposure. Long time exposure to Cd leads to renal failure characterized by proteinuria due to renal tubular dysfunction as a result of Cd affecting enzymes which reabsorbs proteins in kidney tubules (Gunatilake et al. 2014). It is shown that a general average of about 2.5 µg/g creatinine will increase the risk of renal failure, which will be a result of long-term intake of 50µg Cd per day. Renal tubular damage will develop in 5 % of the adult population in high-risk groups, with a consumption of 30 µg per day. (Järup et al. 1998)

2.4 Lead

Lead (Pb) is mentioned as a reason for CKD. A study conducted by Chandrajith et al. (2010) found Pb in paddy soils in several CKDu areas they examined. The study also tells us that many of the pesticides used in Sri Lanka today contain toxic heavy metals. There is no scientific data available on Pb concentration in drinking water wells in Sri Lanka. Lead, 0.01-0.03 mg/L, however, has been proven to exist in natural vegetation and grassland associated with the main reservoirs in NCP that are used for irrigation and drinking purposes (Gunatilake et al. 2014).

2.4.1 Chemistry of Lead

Lead is the most common heavy metal, accounting for 13 mg/kg of the earth's crust. Lead has a valance of +2 of +4. Several stable isotopes of lead exist in nature, including ^{208}Pb, ^{207}Pb, ^{206}Pb, and ^{204}Pb. There is also lead from human activity that leads to a majority of human poisoned. Lead from sources like paint, gasoline and pesticides often evolves into a variety of Pb^{2+}, which is very persistent in the environment (Godwin 2001; IARC 2006; World Health Organization 2003).

2.4.2 Health Impacts of Lead

Lead is a chronic toxin and therefore, blood lead (PbB) concentration is taken as a measure of the chronic exposure to assess health effects. Lead has an impact on human health in low levels. When a patient has PbB between 30 and 50, one may expect renal failure. Such as glomerular sclerosis, interstitial fibrosis and proximal tubular nephropathy, which have been commonly observed among patients with CKDu. Other health effects of chronic lead exposure include muscle weakness, disturbance in mood, gastrointestinal symptoms, and negative effects on reproduction. Children and pregnant women are the group with the highest risk of experiencing serious health effects (Gunatilake et al. 2014; World Health Organization 2003).

2.5 Fluoride

Fluoride (F^-) is an interesting element regarding CKDu. The areas affected by CKDu is also the areas of Sri Lanka with high levels of fluoride in the ground water. A study by Dissanayake (1996) suggested the link between F^- and CKDu. There have been several studies on fluoride levels. Most of the wells analyzed do not have F^- contents exceeding the WHOs recommended limit of 1.5 mg/L. For tropical countries, the WHO recommends a limit of 0.5 mg/L, a limit which most samples from the dry area of Sri Lanka exceeded. Some studies report values as high as 3.9 – 7.3 mg-F^-/L. High F^--content in groundwater paves the way to excess fluoride in local food crops, adding even more fluoride to the systems of the consumers. Chandrajith et al. (2011a) proposed that F^- in endemic areas has to interact with other elements to cause CKDu (Chandrajith et al. 2011b; Dharmaratne 2015; Noble et al. 2014).

2.5.1 Chemistry of Fluoride

Fluorine is the lightest member of the halogen group and is one of the most reactive of all chemical elements. Because of this, it is not found as fluorine in the environment. It is the most electronegative of all the elements and therefore it acquires negative charge, forming F^- ions. Fluoride ions have about the same radius and the same charge as hydroxide ions, and therefore they may replace each other in mineral structures. Fluorides are found in a wide variety of minerals, including fluorspar, rock phosphate, cryolite, apatite etc. When focusing on ground water, the F^- concentration depends deeply on the nature of the rocks and the occurrence of fluoride-bearing minerals (Ayoob & Gupta 2006; Bailey et al. 2006; Edmunds & Smedley 1996).

2.5.2 Health Impacts of Fluoride

Fluoride has beneficial effects on teeth at low concentrations, but excessive exposure can give rise to a number of adverse effects. Fluoride poisoning is called fluorosis. Fluorosis effects mainly the teeth and the skeleton by weakening them (Ayoob & Gupta 2006; Bailey et al. 2006). The effect on the kidney is not well documented, resulting in Schiffl (2007) writing an article with the statement: "Absence of evidence is not evidence of absence". A study from China suggests a correlation between F^- and damage to the tubular structure in children (Xiong et al. 2007). Because of lack of evidence, it is presumed that fluoride has to act together with another element to cause CKDu.

2.6 Hardness

Places with high ground water hardness and the geographical distribution of CKDu in Sri Lanka are well correlated. Hardness of water is caused by the presence of the polyvalent metallic cations calcium, magnesium, strontium and iron, together with carbonate, bicarbonate, sulphate, and chloride anions. The water is classified based on the amount of Ca and Mg in the water. Water in the CKDu area is mostly hard or very hard. In other words, above 121 mg/L. 96% of the CKDu patients had consumed hard or very hard water over a period of at least ten years, and so the correlation is in other words, probable. Other than these correlations, there is no scientific evidence that consumption of hard water can cause CKD. This suggests that hardness, combined with an unknown factor, is the cause of CKDu (Jayasumana et al. 2014b; Jayasumana et al. 2013a).

2.6.1 Effects and Sources of Hardness

Hardness is a characterization of water and not a chemical substance, a description of the chemistry of each substance that affects the hardness would not be feasible in this thesis. The main substances that affects the hardness is calcium (Ca) and magnesium (Mg). Hardness manifests by precipitation of Ca and Mg under boiling or by formation of compounds of low solubility when reacting with soap. Ca and Mg is absorbed from soil and rock as the water travels through the earth (Haraldsen 2009).

2.6.2 Health Impacts of Hard Water

The World Health Organization (1996a) has concluded that "there does not appear to be any convincing evidence that water hardness causes adverse health effects in humans". In fact, the United States National Research Council has found that hard water can serve as a dietary supplement for calcium and magnesium (Oram 2013).

2.7 Other Possible Metals

Other contaminants will also be analyzed for as a precaution, to ensure that no harmful metals are present in the water. The contaminants will not be described in the thesis and neither will the removal processes. However, most of the elements can be removed by the same processes as, Cd and Pb. The results of the analysis will be presented and discussed succinctly. The metals are Boron (B), Aluminium (Al), Chromium (Cr), Manganese (Mn), Cobalt (Co), Nickel (Ni), Cobber (Cu), and Zinc (Zn).

2.8 Removal of Arsenic, Cadmium and Lead

Removal of Arsenic has been heavily researched, as it is the most hazardous in small concentrations. Nevertheless, Cadmium and Lead may be removed by more or less the same processes. The most used processes are coagulation-precipitation, lime softening, nanofiltration, reverse osmosis, and ion exchange. In addition, activated alumina exchange may remove arsenic (Davis 2010).

2.8.1 Coagulation-precipitation

Coagulation is one of the most used methods for heavy metal removal. Both ferric- and aluminium salts can be used (for Cd only ferric salts). The process removes the metals through three steps (Ahmed 2001):

- Formation of insoluble compounds (precipitation)
- Soluble heavy metals are incorporated into growing metal hydroxide phase (co-precipitation)
- The electrostatic bonds formed between soluble arsenic and insoluble metal hydroxide (adsorption).

During this process, the salts are added to the water and mixed to ensure that flocks are formed. These flocks get larger and heavier after a few minutes of gently stirring. Negative particles will attach to the flocks by electrostatic bonds. This requires that the heavy metals are negative which is not always the case. If not, the particles need to be oxidized to form negative particles. For instance, converting As(III) to As(V) will ensure removal by this process. The flocks can be removed by either sedimentation or filtration.

Coagulation has other advantages, as it significantly improves the water quality by reducing turbidity, color, and odor.

2.8.2 Lime Softening

Lime softening is mainly connected with removal of hardness in the water. It is, however, well known that lime softening will remove substances other than hardness. Heavy metals, as As, Cd, and Pb, can be removed by lime softening. The heavy metal removing efficiency of the lime softening process is heavily affected by pH. The main problem is that the desired pH is affected by which element you want to remove. Arsenic requires $pH>11$, Cadmium requires $pH<8.5$ and Lead requires pH between 7 and 8.5 for the removal to be at its most effective (Davis 2010).

Regarding Arsenic, As(III) needs to be oxidized. This is easily done with chlorine. Chlorine will also have a positive impact on the removal efficiency of As. illustrates the arsenic removal efficiency for water containing 400 µg/L arsenic.

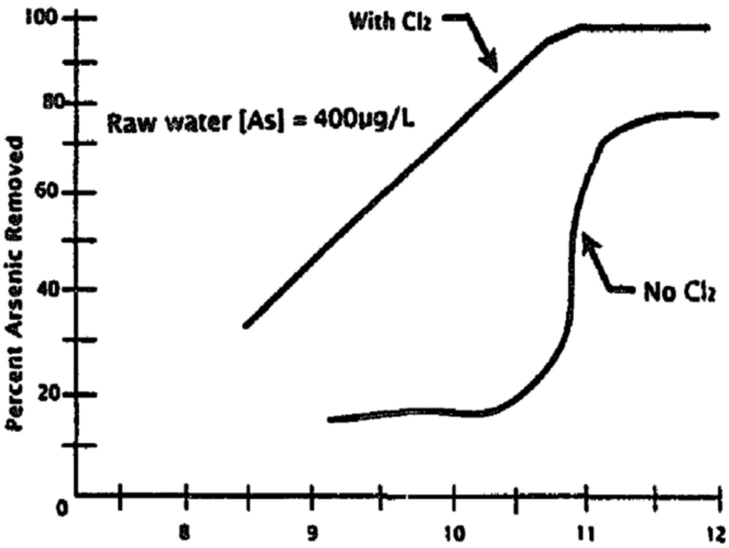


Figure 2.1: Removal of As with lime softening (Kartinen & Martin 1995).

In other words, lime softening is an effective way to remove over 90 % of the mentioned elements, but it is necessary to change the conditions to target the desired element.

2.8.3 Membrane Filtration

Membrane filtration is a collective term for filtration through membranes with different pore sizes. Microfiltration has pore sizes from 100 – 1000 nm, ultrafiltration from 10 – 100 nm, and nanofiltration from 1-10 nm. If the membrane has pore sizes smaller than 1 nm, the membrane is classified as reverse osmosis.

For removal of arsenic, cadmium and lead, which often is totally dissolved, simple restraining is not enough. Preferential diffusion, that is to say nanofiltration or reverse osmosis, is required. The membranes allow water to pass through and retain the impurities.

Reverse Osmosis (RO) is based on osmosis. When a semi-permeable membrane separates two solutions with different concentrations of dissolved chemicals, the concentration will equalize by pure water passing through the membrane from the diluted solution to the concentrated one. This is cause by a pressure difference, called the osmotic pressure. In RO, applied pressure to the most concentrated solution forces pure water to pass through the membrane to the diluted solution – which is potable water (Dvorak & Skipton 2008). Figure 2.2 shows the operating principle of RO, with the diluted solution on the left side of the membrane, and the concentrated solution on the right. Water passing though the membrane is called permeate, the clean and potable water. The remaining water called concentrate or reject water, is often recycled and in the end discarded.

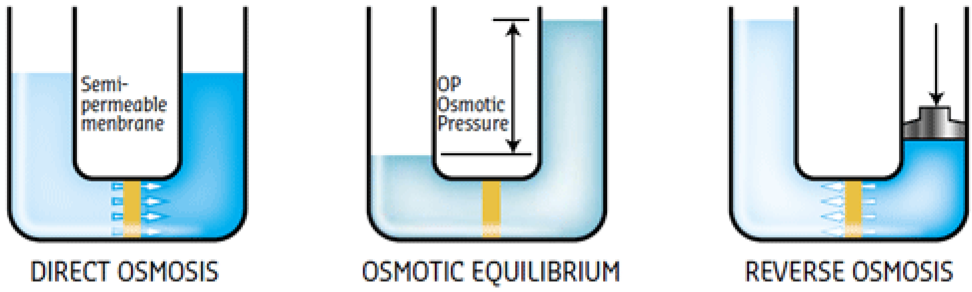


Figure 2.2: The operating principle of Reverse Osmosis(Degremont n.d.)

Due to the pressure needed to force the water from the concentrated side to the diluted site, the energy cost for RO-technology is quite high. New improvements on the technology, as well as the usage of renewable power sources, results in the energy costs rapidly declining from year to year. The latest RO desalination plant in Israel delivers potable water for as little as US$ 0.58 per m^3 (Gude 2011; Talbot 2015).

Reverse osmosis does not have definable pores, as the film used in other filtration technologies would have. RO has spaces between the fibers making up the semipermeable membranes. Semipermeable membrane is defined as a material that is permeable to some components in the feed stream and impermeable to others, and has an overall thickness of less than 1 mm. Separation of truly dissolved solutes from water is a result of solution-diffusion mechanisms through the membrane, not sieving as with other membrane technology. This means that the rejection efficiency is dependent on influent solute concentration, pressure, and water flux rate (Crittenden et al. 2012; Van der Bruggen et al. 2003).

Since the spaces between the fibers of the RO membrane are small, pre-treatment is required to prevent extensive fouling and clogging of the membrane. This includes pre-filtration to remove particles before they reach the membrane. As a minimum, a filter with 5 µm strainer opening is used. This depends however, on the water source used. When sparingly soluble salts, such as calcium carbonate, calcium sulfate, barium sulfate, and strontium sulfate, are present in the raw water, there must be some pre-treatment to prevent scaling on the membrane. This is done by pH adjustment, by adding acid, or by adding antiscalant, usually in the form of a polymeric compound. Antiscalant prevents carbonate precipitation on the membrane and in that way keeps the membrane clean. This happens by allowing super saturation without precipitation occurring by preventing crystal formation and growth. The degree of supersaturation allowed depends on the antiscalant's properties, which often are proprietary. For determining appropriate antiscalant and doses necessary for a specific feed water analysis and design, the recommendations from the antiscalant or equipment manufacturer are used (Crittenden et al. 2012). After pretreatment, the water is pressurized with a feed pump to penetrate the membrane, and force the water through the system. A backwash cycle of the membrane is needed. Without it, particles can clog the feed channels or accumulate on the membrane surface.

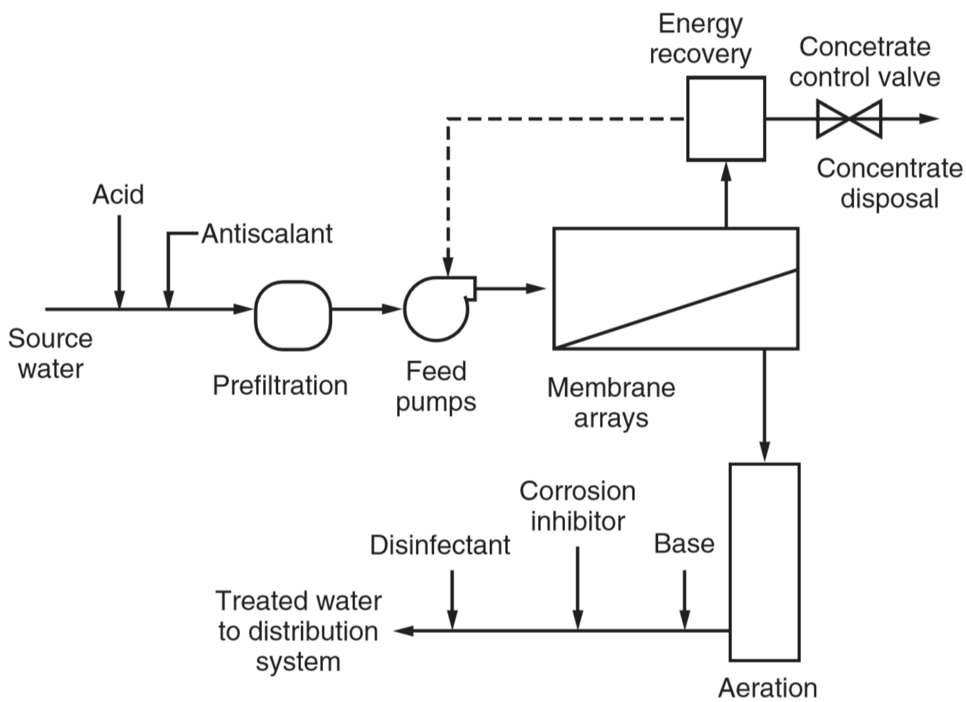


Figure 2.3: Schematic of typical reverse osmosis facility (Crittenden et al. 2012).

Some post treatments are required, depending on the quality of the raw water. Post-treatments consist of removal of dissolved gasses and alkalinity, and pH adjustment. Finally, before the water is provided to the distribution system a disinfectant may be added. If it is a small system, with a relatively small permeate tank, there is no need to add a disinfectant to the water. Instead the permeate tank should be disinfected regularly, and the water in the tank should be pumped through a loop where a UV lamp disinfects the water continuously.

The concentrate stream has to be discarded safely as it will contain large amounts of unwanted substances removed from the feed water. This is usually a big problem in the design of RO-plants, as the concentrate may require treatment before it is disposed. Methods for concentrate disposal includes discharge to municipal sewer, ocean, brackish river, evaporation ponds, and infiltration basins.

2.8.4 Ion Exchange

Ion exchange is normally used for removal of specific cations or anions in water. It utilizes adsorption, much like sorptive mediums, however the medium is synthetic with a defined capacity. The process exchanges a charged ion in the solution for a similarly charged ion from the medium. In common practice the water is passed through a bed of resin. Typical ion exchangers are zeolites, montmorillonite, clay, soil humus and ion exchange resins. The resin, which is the most used for removal of heavy metals, acts as a sponge and actively removes contaminants from the water. Ion exchange is a reversible process and the ion exchanger can be regenerated by washing with an excess of the desirable ions (Davis 2010).

The process for removing Arsenic is shown by this equation:

$$2RCl + HAsO_4^- = R_2HAsO_4 + 2Cl^- \quad (2.1)$$

Where R stands for ion exchange resin.

The arsenic removal is dependent on the sulfate and nitrate contents of raw water, sulfate and nitrate exchanges before arsenic. Similar conditions apply for the other heavy metals. The ion exchange process is less dependent on pH, which makes it advantageous when the raw water is too high or too low pH (Ahmed 2001).

2.8.5 Comparison of Technologies

Table 2.1: Comparison of technologies for Arsenic, Cadmium and Lead removal

Technology	Advantages	Disadvantages
Coagulation-precipitation	- Low capital cost - Simple in operation - Common chemical available	- Produces toxic sludge - Not ideal for anion rich water treatment - Efficiencies may be inadequate to meet strict standards
Lime softening	- Relatively well known and commercially available - Well-defined technology	- Heavily dependent on pH - Needs to be adjusted depending on the targeted metal
Membrane filtration	- Well-defined and high removal rates - Capable of removing other contaminants	- High-tech operation and maintenance - High capital- and running costs - Reject water has a high amount of unwanted substances
Ion exchange	- Not dependent on pH - Capable of removing other contaminants	- High sulfate and nitrate contents disturbs the process - Regeneration is required - Relatively high cost

2.9 Removal of Fluoride

Defluoridation of drinking water is the only practicable option to overcome the problem of excessive fluoride in drinking water. Fluoride removal is mainly done by four different methods. Adsorption, coagulation-precipitation, ion exchange and membrane filtration technology (Maheshwari 2006; Mohapatra et al. 2009).

2.9.1 Coagulation-precipitation

Coagulation-precipitation is mentioned in this thesis in a previous chapter. When dealing with fluoride, lime and aluminium are the most used coagulants. The addition of lime leads to precipitation of F as insoluble calcium fluoride and raises the pH value up to 12. Lime leaves about 8 mgF^-/L in the water. Therefore it is mostly used together with aluminium coagulants to ensure proper defluoridation and to lower the pH to practical levels (Mohapatra et al. 2009).

2.9.2 Membrane Filtration

Membrane filtration is described in a previous chapter in this thesis. In the case of fluoride, nanofiltration and reverse osmosis is used. The fundamentals are the same, so is the result.

2.9.3 Ion Exchange

The concept of ion exchange is already described in this thesis. The removal of fluoride takes place according to the following reaction:

$$[R^{+}]Cl^{-} + F^{-} = [R^{+}]F^{-} + Cl^{-} \tag{2.2}$$

Where R is the ionic group attached to the exchange resin (Crittenden et al. 2012).

The fluoride ions replace the chloride ions of the resin. When all the sites in the resin are occupied, backwashing is needed. This is done with water saturated with sodium chloride salts (Maheshwari 2006).

2.9.4 Adsorption

The most commonly used adsorption materials is activated carbon and activated alumina. For defluoridation, activated alumina is the best solution, and it is far superior to synthetic organic ion exchange resins (Clifford 1999). The fluoride removal efficiency of activated alumina is affected by hardness and surface loading, as well as the pH.

Adsorption works by particles in the media adsorbing pollutants in the water. Adsorption is a surface-based process where pollutants will be trapped and held back by the surface forces, unlike absorption, in which molecules are taken up by the volume of the absorbent. When the media is exhausted, backwash and a two-step regeneration process is required to make it usable once again (Crittenden et al. 2012).

2.9.5 Comparison of Technologies

Table 2.2: Comparison of technologies for Fluoride removal

Technology	Advantages	Disadvantages
Coagulation-precipitation	- Low capital cost - Simple in operation - Common chemical available	- Produces toxic sludge - Not ideal for anion rich water treatment
Membrane filtration	- Well-defined and high removal rates - Capable of removing other contaminants	- High-tech operation and maintenance - High capital- and running costs - Reject water has a high amount of fluoride
Ion exchange	- Not dependent on pH - Capable of removing other contaminants	- High sulfate and nitrate contents disturbs the process - Regeneration is required - Relatively high cost
Adsorption	- Well-known and commercially available - Well-defined technique - Many possibilities	- Not ideal for anion rich water treatment - Produces fluoride-rich liquid and solid waste - Regeneration is required - High tech operation and maintenance - Relatively high cost

2.10 Removal of hardness

Removal of hardness, or softening, does eventually come down to removing calcium and magnesium from the water. The most usual methods are lime softening, ion exchange and membrane filtration.

2.10.1 Lime Softening

The main goal when using lime-soda in conventional treatment plants is to soften the water.

The lime-soda reactions are a direct application of the law of mass action (Le Chatelier's principle), which states that a reaction at equilibrium will adjust itself to relieve any force or stress that disturbs the equilibrium. An ion is selected to react with calcium or magnesium, so that more precipitation is formed. This can be shown with the following reactions.

$$Ca^{2+} + CO_3^{2-} = CaCO_3(s) \quad (2.3)$$

$$Mg^{2+} + 2OH^{-} = Mg(OH)_2(s) \quad (2.4)$$

The chemicals provide CO_3^{2-} and $2OH^-$, and drives the reactions shown in the equations above. The chemicals usually used are $Ca(OH)_2$ and Na_2CO_3. There are six different reactions going on to remove all hardness. All the reactions occur simultaneously and together they remove both soluble and insoluble Ca and Mg (Davis 2010).

2.10.2 Ion Exchange

As described earlier, ion exchange is used to remove specific anions and cations in the water. Therefore, it is very usable when the main goal is to soften the water.

The stoichiometric reaction for Na-removal will be.

$$2[R^-]Na^+ + Ca^{2+} = [2R^-]Ca^{2+} + 2Na^+ \quad (2.5)$$

Where R^- is the ionic group attached to the ion exchange resin. The same reaction can be written for Ca-removal, though with different exchange ions (Crittenden et al. 2012).

2.10.3 Membrane Filtration

Membrane filtration in regards to water softening is widely used, as it removes multiple other unwanted parts of the water. Both nanofiltration (NF) and reverse osmosis (RO) is used. NF removes divalent ions, while RO removes monovalent ions. Hard water will cause scaling of the membranes; this requires antiscalant (scale threshold inhibitor) chemicals to be added to the raw water before being driven through the plant.

More information regarding membrane filtration is given in chapter 2.8.3.

2.10.4 Comparison of Technologies

Table 2.3: Comparison of technologies for hardness removal

Technology	Advantages	Disadvantages
Lime softening	- Relatively well known and commercially available - Well-defined technology	- Heavily dependent on pH - Chemicals need to be added
Ion exchange	- Not dependent on pH - Capable of removing other contaminants	- High sulfate and nitrate contents disturbs the process - Regeneration is required - Relatively high cost
Membrane filtration	- Well-defined and high removal rates - Capable of removing other contaminants	- High-tech operation and maintenance - High capital- and running costs - Reject water has a high amount of Ca and Mg - Antiscalant needs to be added if the hardness is high

2.11 Choosing a Process for Areas Affected by CKDu

Since research is yet to solve the cause of CKD in the dry zone of Sri Lanka, the matter of delivering good and safe drinking water for the patients is complicated. It is not known which substance needs to be removed, or if it is a mix of several substances that causes the illness. The safest approach is to choose a process that removes most of the potentially harmful substances. It should also be a process which is area effective, energy effective, easy to maintain, and durable. The only process matching this list is membrane filtration. Membrane filtration is area effective, scalable according to need, and operation is easy as long as installation and maintenance is done by a specialist. This conclusion is already committed by authorities in the NCP of Sri Lanka. Currently there are 86 operating RO-plants in the area, which delivers water to 156,787 people. These are rather new plants, with the oldest one starting up in November 2013. Because of the relatively short timeframe, it is not known if these plants will have any long term effect on the rate of CKDu patients, although the immediate effect is believed to be rather good with fewer CKDu patients diagnosed in the specific areas with a RO-unit (NWSDB Anuradhapura District 2015).

Figure 2.4: Example of a poster advertising for water treated with RO (Photo: Mathias Espeland)

As mentioned there are two groups of possible CKDu causes, inorganic (metals etc.) and organic (pesticides etc.). Since it is hard to justify the true cause based on literature, it is important to take preventive measures by using a method which is able to remove both organic and inorganic contaminants reliably. As discussed, Reverse Osmosis is good for removing inorganic pollutants. Clifford et al. (1986) certifies that all contaminant ions and most dissolved non-ions are removed by reverse osmosis. So in total all organic and inorganic pollutants will be removed by RO. Meanwhile this information leads to RO being the safest and most reliable choice for treating ground water in the NCP to prevent CKDu.

Reverse Osmosis in Anuradhapura District

The ground water in Anuradhapura is known to have high values of hardness, as well as high water temperature. The air temperature may reach as high as 40°C, which may give a water temperature in that range. These factors have a huge impact on the operation of an RO-plant. High hardness will cause scaling of the membrane, which in turn will cause fouling. To prevent this, an antiscalant has to be added before the pre-filtration, as shown in Figure 2.3.

As shown by Goosen et al. (2002), the temperature has a huge effect on permeate flux and salt rejection in reverse osmosis plants. As the water temperature increases, the permeate flux increases almost linearly, due to the higher diffusion rate of water through the membrane. High water temperature increases the viscosity of water, which results in lower pressure needed to force the same amount of water through the RO-membrane. The salt passage will also increase with higher temperatures. The temperature changes the membrane polymer, and makes it more permeable (DOW 1998). The correlation is shown in Figure 2.5.

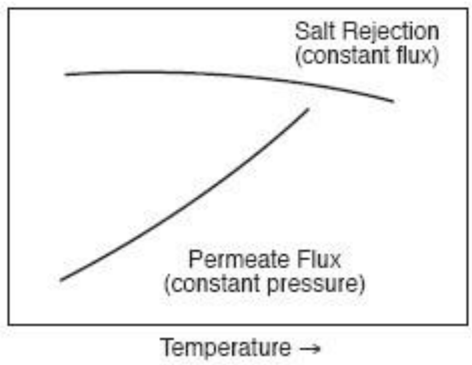


Figure 2.5: *Performance of the RO-membrane versus temperature* (DOW 1998)

An article written by Renuka Jeya Raj (2014) based on an interview with Harsha Kumar Suriyarachchi, former Vice Chairman, National Water Supply and Drainage board, has an interesting question as its title: “Is reverse osmosis (RO) treatment the answer to solving the CKDu riddle?” According to Suriyarachchi, RO technology is an important technology for removal of the unwanted chemicals in water. “The people who drink the water filtered by RO say their lives have improved, and that the impurities are less. The latest figures show that fewer or no new patients have been recorded with the disease in areas with RO machines”, he said during this interview.

In 2013, the president of Sri Lanka, Mahinda Rajapaksa, instructed the treasury to allocate 900 million LKR to purchase RO-units for the areas worst affected by CKDu. In 2014, RO units delivered water to over 15,000 families in the Anuradhapura district including Medawachchiya, which has the highest concentration of CKDu patients.

The initial cost for water production by these RO-units in Sri Lanka was between 3 and 4 rupees per liter. The goal of the water and drainage board was to lower this price to under 1 rupee per liter, which they achieved. Suriyarachchi says, “People suffering from CKDu are mainly from areas marginalized by the war, and they can’t afford to buy water at high prices. It was more or less a personal decision to bring down the price after a patient in Kidawarankulama told me that he had benefited from the water but couldn’t afford it. We have started supporting three Community-based Organizations (CBOs) at an all-inclusive cost of LRK 0.50 per liter. They keep up to LRK 0.50 as their profit and sell the water at LRK 1 or less per liter. A liter of commercial bottled water is about 30 times more expensive.”

There are some controversies regarding the use of RO-plants in the area. The Public Health Inspectors (PHI) claim that treated water should have higher TDS, and in that way contain more minerals. The problem with this is that higher TDS will not only give more minerals, but also more salts and water soluble metals. The lack of minerals is though a known problem with RO-treatment. This affects the taste of the water, and it may cause dietary deficiency causing risk of heart, brain and bone diseases (Joint & Organization 2005; World Health Organization 2009). In addition will people with liver disease notice an acidic taste from the water. To compete this, and in addition making the water more nutritious, a solution is to add minerals to the permeate. Many RO-units, including the pilot plant used in this study, has a dosing pump available to add this. WHO recommends 10 mg/L of Magnesium and 30 mg/L of Calcium in drinking water. Two solutions are widely used to remineralize water. Addition of CO_2, $CaCO_3$, MgO, and Na_2CO_3 or addition of $CaCl_2$ and $NaHCO_3$. This gives a mineral content of respectively 80 mg/L $CaCO_3$ and 100 mg/L $CaCO_3$, 100 mg/L Na, and 50 mg/L Cl (Lenntech BV n.d.).

Many RO-units and safer water for the community is initially a good thing, maintaining the RO-plants, and thus the water quality, has proven to be a challenge. Suriyarachchi continues, "Engineers were sent from India to train the people to operate the machines but, although they have become very competent, there is no mechanism to ensure that they continue to do it properly. Machine pressure and the monitoring meters must also be continuously monitored. Sri Lanka lacks the capacity to test water quality continuously. We should have online testing systems" (Raj 2014).

2.12 Analytical Methods

This study conducts analysis for several different substances and therefore this thesis is not the correct medium to go through all the different analytical methods that exist to determine the amount present in the water samples. The methods chosen for this thesis are the methods that were available at the University of Peradeniya. Because of the lack of facilities, As and Cd testing were conducted at Norwegian University of Life Science. This thesis will only include a description of the methods used during the research.

2.12.1 Method for As, Cd etc.

ICP-AES analysis for arsenic and cadmium was conducted at NMBU. ICP analysis is performed with computer-controlled spectrometers. The spectrometers use Charge Coupled Device (CCD) technology, which allows the instruments to measure a broad spectrum of elements.

Droplets are vaporized in the torch, where the aerosol is mixed with argon gas. A coupling coil is used to transmit radio frequency to the heated argon gas, producing an argon plasma located in the torch. The hot plasma dries any remaining solvent and causes sample atomization.

The ICP-AES spectrometer detects the atomic emissions produced as light. While ICP Mass Spectrometry uses ionization. The resulting mass of the ions gives the elements present in the sample. (Laboratory Testing Inc. n.d.)

Since ICP can measure a broad spectrum of elements. The samples were also analyzed for Boron (B), Magnesium (Mg), Aluminium (Al), Calcium (Ca), Chromium (Cr), Manganese (Mn), Iron (Fe), Cobalt (Co), Nickel (Ni), Cobber (Cu), Zinc (Zn), Arsenic (As), Cadmium (Cd), and Lead (Pb).

2.12.2 Method for Pb, Fe, Mn and Hardness

When analyzing for Lead, Iron, Manganese and hardness at UoP, the Shimadzu Atomic Absorption Spectrophotometer (AAS), AA-7000 Series was used. AAS can measure several different metals, from arsenic to gold to zinc. It is also capable of measuring magnesium and calcium (which was used to calculate hardness), iron, manganese and lead. There are two ways of using this system, by either flame method or furnace method. The AAS at the University of Peradeniya does not have the furnace available. So the flame method was used for all the tests. The flame method uses the fact that light with specific frequencies is absorbed by different metals when they vaporize in a flame. Lamps are used to emit light with the wanted frequency, which is then adsorbed by the sample containing the metal ion. The amount absorbed by the sample is compared to the amount of light adsorbed by a set of standards of known concentration. The amount of light absorbed is proportional to the concentration of the metal ion in the solution. This data is sent to a computer, where software analyses the results and gives a concentration in mg/L. The standards made with known concentrations are used to make a calibration curve. This absorbance of the unknown sample is then marked on the calibration curve and the concentration is found.

To find hardness, this method was used to find the concentration of Calcium and Magnesium. Then the following equation was used to calculate the hardness.

$$Hardness = 2.497[Ca] + 4.118[Mg] \tag{2.6}$$

2.12.3 Method for Fluoride

A Hach DR/2010 spectrophotometer was used for measuring fluoride in the samples. The procedure from the manual was followed. The main idea with this method is to add 2 ml of the chemical to the 10 ml sample; the chemical is red and will react with any available F^- and turn into a lighter red. The lighter color, the more Fluoride is present. The color is measured by the instrument; it is then compared to a blank sample made with the same chemical. The result is given as mg/L F^-.

2.12.4 Method for TOC, Inorganic Carbon, and Tot-N

The Total Organic Carbon (TOC), Inorganic Carbon (IC) and Total Nitrogen (Tot-N) analysis was done by a Shimadzu TOC-L instrument at UoP. It uses a 680°C combustion catalytic oxidation method. The TOC-L has a detection limit of 4 µg/L. It can even measure as high as 30,000 mg/L, through its automatic dilution function.

The process starts with the sample being delivered to the combustion furnace, which is supplied with purified air. Then it undergoes combustion through heating to 680°C with a platinum catalyst. It decomposes and is converted to carbon dioxide. The carbon dioxide is cooled and dehumidified, and finally detected by an infrared gas analyzer. The concentration of total carbon in the sample is found by comparing it with a calibration curve formula. Furthermore, by subjecting the oxidized sample to the sparging process, the Inorganic Carbon (IC) in the sample is converted to carbon dioxide, and the IC concentration is obtained by detecting this with the infrared gas analyzer. The TOC concentration is then calculated by subtracting the IC concentration from the obtained TC concentration. (Shimadzu n.d.-b)

Total Nitrogen is measured by the same machine, as long as a Tot-N unit is added. 720 °C catalytic thermal decomposition/chemiluminescence methods are used for Tot-N measurement (Shimadzu n.d.-a). First, Nitrogen compounds are oxidized by the thermal decomposition method to generate nitrogen monoxide (NO). The NO is reacted with ozone. Nitrogen Dioxide excited in metastable state generates chemiluminescence when it becomes stable nitrogen dioxide. The intensity of this chemiluminescence is proportional to the nitrogen concentration. The chemiluminescence is therefore detected to give the nitrogen concentration (Global Environment Centre Foundation n.d.).

3 Previous Studies

Over the past 12 years, a number of studies of CKDu have been conducted by a range of institutions. The studies range from hospital and community level studies, assessment of food sources, studies into possible genetic linkage and water resource studies. (Noble et al. 2014)

No study has been able to conclude, with evidence, which contaminants causes CKDu. However, several studies point to the possibility of contaminated water being the main distributor of the contaminants. Chandrajith et al. (2011b) concludes:

> "…that no single geochemical or biogeochemical parameter could be clearly and directly related to the etiology of CKD on the basis of the elements determined during this study. It should be stressed, however, that the hypothesis for a waterborne chemical being implicated in the disease is quite strong. As already pointed out, higher temperatures facilitate the ingestion of higher amounts of drinking water, and it is readily filtered by the kidney but not readily secreted by the renal tubules."

Most of the research available regarding etiology, in combination with water quality, is either a comment on another study or literature study. Just a handful of studies have been conducted with field and laboratory tests.

It is believed that the outburst of CKDu is a cause of the massive irrigation scheme, combined with excessive use of agrochemicals, which started in Sri Lanka two decades ago. Some agrochemicals contain heavy metals, which are believed to pollute the ground water. Heavy metals like Arsenic, Cadmium and Lead are all highly debated contaminants causing CKDu. There are several studies claiming that one of these has to be the cause, while other studies claims the opposite. None of the studies have any conclusive evidence for their view.

As mentioned earlier, the one element that all can agree has an effect is fluoride. It is easily shown that areas affected with CKDu are the same areas where the ground water has a high level of Fluoride shown in Figure 3.1 (Chandrajith et al. 2011a; Dissanayake 1996).

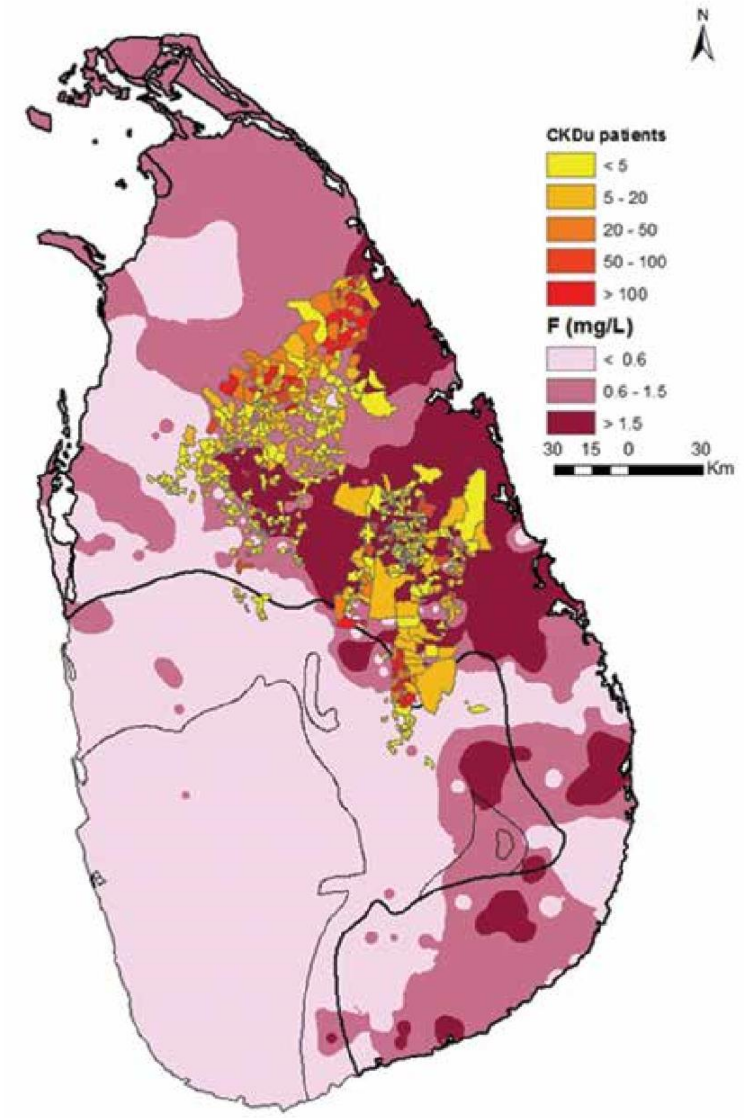


Figure 3.1: Map showing the correlation between CKDu and F^- in ground water (Noble et al. 2014)

There is also a strong correlation between CKDu cases and water hardness in Sri Lanka, shown in Figure 3.2. Although hard water has no proven negative health effects, it is proposed that hard water together with other unknown substances might cause CKD (Fonseka et al. 2012; Jayasumana et al. 2014b; Jayasumana et al. 2013a).

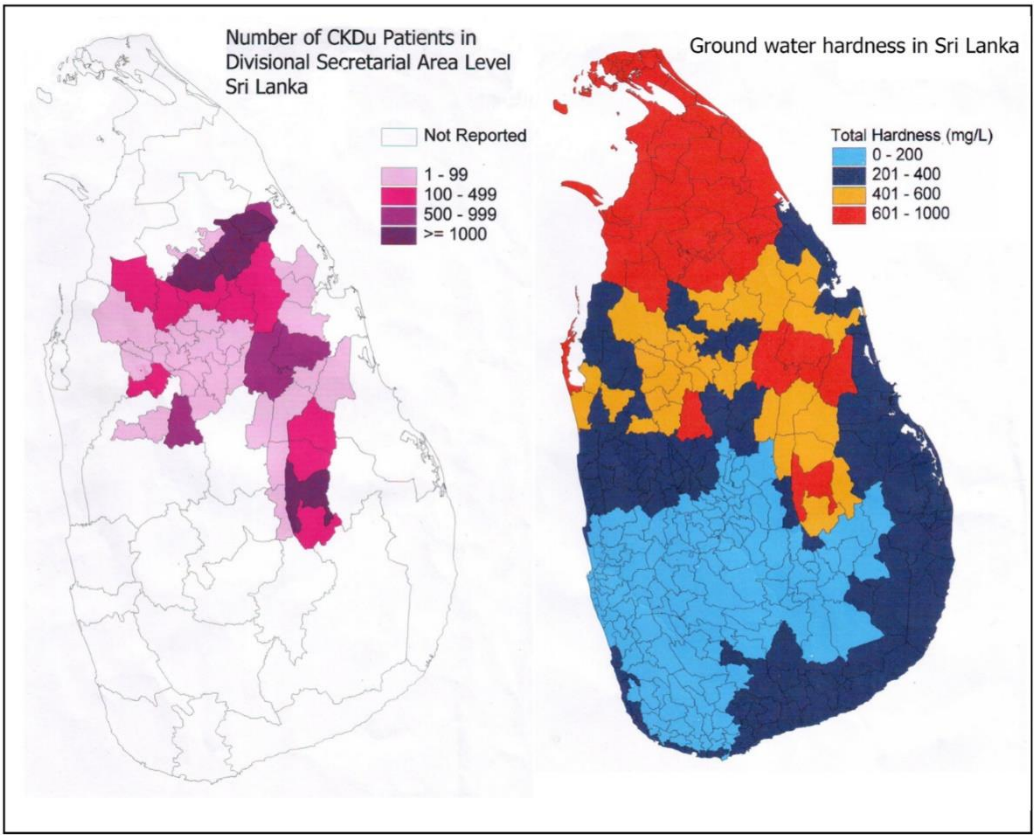


Figure 3.2: Map showing the correlation between hard water and CKDu in Sri Lanka (Jayasumana et al. 2014b)

Sri Lanka seems to lack both research facilities on RO and adequate analytical facilities for contaminants like Arsenic and Cadmium. Chandrajith et al. (2011b) used a laboratory at the University of Kyoto for their analysis of Cadmium presence. While Jayatilake et al. (2013) do not mention where the analysis for Cd and As were done. Nevertheless, very few analyses have been done, and there is definitely a need for more analytical work regarding As and Cd as a cause for CKDu.

4 Method and Material

This research is divided in two. An examination of existing RO-plants and analysis of a new RO-plant. The experiments started in February 2016, and were completed in mid-April.

4.1 Examination of Existing RO-plants

The examination of the existing RO-plants was conducted on selected plants in the Anuradhapura district of Sri Lanka. These plants were chosen based on age, manufacturer, ground water aquifer and the number of affected CKDu patients in the area. Eleven plants were chosen. A detailed description of the plants and the area can be seen on the next page, Table 4.2.

The plants are manufactured by three different companies. Pure Aqua Inc., Hayles international, and Panda water. The former two are American, while Panda is an Indian company. The membranes are produced by Dow or Hydranautics, American membrane manufacturers. The membranes used are DOW FILMTEC LC LE-4040 and Hydranautics ESPA2-4040. The membranes are presented and compared in Table 4.1.

Table 4.1: Comparison of the two most used membranes in Anuradhapura District (DOW n.d.-c; Hydranautics n.d.)

	DOW LC LE-4040	**Hydranautics ESPA2-4040**
Membrane polymer	Polyamide Thin-film composite	Composite polyamide
Maximum operating temperature	45°C	45°C
Maximum operating pressure	41 bar	41 bar
Maximum pressure drop	1.0 bar	0.7 bar
Permeate flow	9.5 m^3/d	7.57 m^3/h
Salt rejection	99.2%	99.6%

The membranes are quite alike. With everyday use in NCP both of these membranes should behave rather similar and deliver equally good water.

Of all the plants, only one has exchanged its membranes since installation - the plant at Wewalkatiya/Thambalagollewa (GND 82). This plant has three membranes placed in series, and the first two of them were exchanged in March 2016.

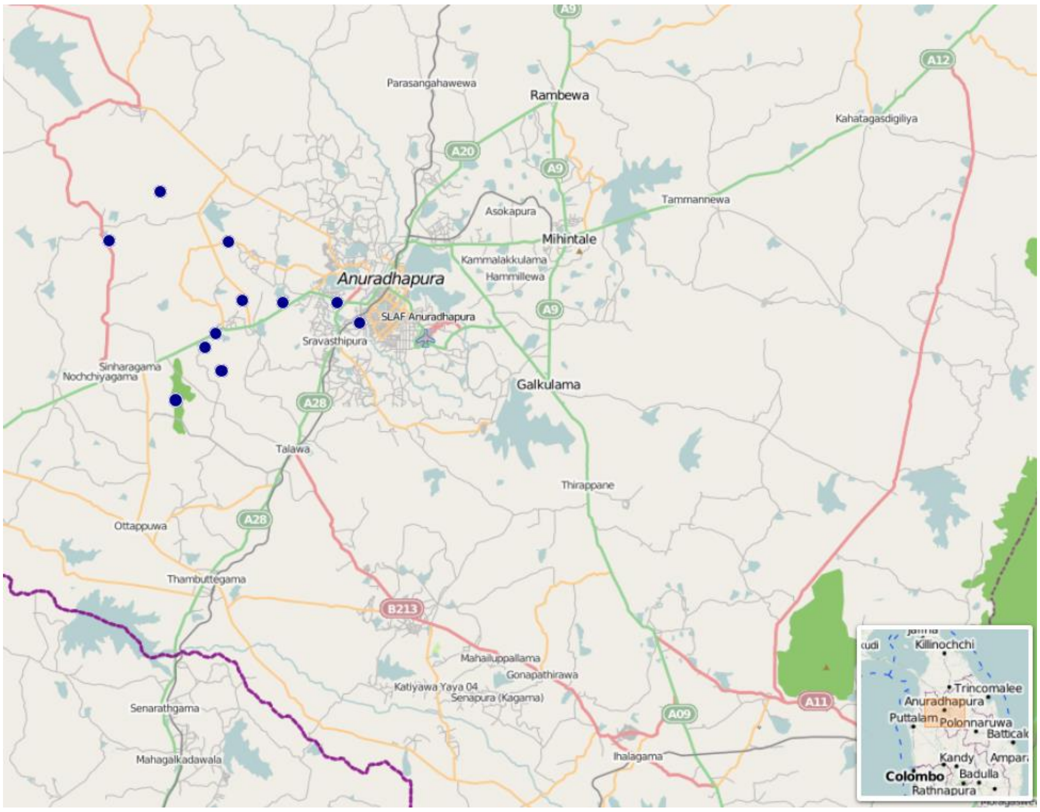


Figure 4.1: Locations of RO-plants where samples were taken (© OpenStreetMap contributors 2016)

Table 4.2: Overview of the chosen plants in the Anuradhapura district.

GND no.	Village(s)	Location		Population Covered	Affected		Manufacturer	Other treatment*	Commission date	Membrane
		N	E		No.	%				
42	Kidawarankulama	08°38.528'	080°27.285	1482	74	4.99	Panda Water Tech	AC, MF, UV	nov.13	DOW LC LE-4040
50	Yakawewa/ Periyakulama	08°35.679'	080°24.259'	1625	102	6.28	Panda Water Tech	AC, MF, UV	nov.13	DOW LC LE-4040
57	Mahadiulwewa	08°35.639	080°31.248'	1020	142	13.92	Panda Water Tech	AC, MF, UV	nov.13	DOW LC LE-4040
70	Halambugaswawe	08°32.255'	080°32.150'	Unknown	-	-	Pure Aqua Inc.	AC, UV	aug.15	Hydranautics ESPA2-LD-4040
72	Kirgalwewa	08°32.080'	080°34.406'	961	88	9.16	Pure Aqua Inc.	AC, MF, UV	sep.15	Hydranautics ESPA2-LD-4040
81	Pihimbiyagollewa	08°32.067'	080°37.673'	1144	29	2.53	Hayles Ind.	SD, AC, S, UV	nov.14	-
82	Wewalkatiya/ Thambalagollewa	08°30.943'	080°38.961'	1126	53	4.71	Pure Aqua Inc.	RSF, AC, UV	nov.13	-
102	Ikrigollewa	08°28.161'	080°30.877'	5562	11	0.2	Pure Aqua Inc.	AC, UV	jun.15	Hydranautics ESPA2-LD-4040
108	Wahamalgollewa	08°29.505'	080°29.884'	923	-	-	Pure Aqua Inc.	AC, UV	mai.14	Hydranautics ESPA2-LD-4040
111	Sangilikanadarawa	08°30.304'	080°30.529'	3474	46	1.32	Pure Aqua Inc.	AC, UV	apr.14	Hydranautics ESPA2-LD-4040
115	Pandakabhayapura	08°26.450'	080°28.169'	1206	17	1.41	Pure Aqua Inc.	AC, UV	sep.15	Hydranautics ESPA2-LD-4040

***AC**: Activated Carbon filter, **MF**: Multimedia filter, **RSF**: Rapid Sand Filter, **S**: Softener, **UV**: Ultraviolet light disinfection.

4.1.1 Sampling Process

The sampling was done in one day, 17 March 2016. The locations were visited and samples were taken from the raw water source and from the permeate tank. Four samples were collected from each location, two from the raw water and two from the permeate tank. The samples were collected in 750/500 ml plastic bottles. The bottles were bought locally, and rinsed before use.

To preserve the heavy metals in the sample nitric acid was added to one of the samples from each sampling point, to lower the pH to below 2. These samples were also placed in a Styrofoam box with ice to cool them down. The two remaining samples for Fluoride testing did not need any special treatment. The samples were transported to UoP where they were kept in suitable locations. The samples were then divided into several containers. About 100 ml of each sample were transported to NMBU for, among others, As and Cd testing while the remaining amount was used for the analyses at UoP.

4.1.2 Analyzing

The analyses were done as described in Chapter 2.12.

4.2 Research RO-plant

A part of this research is conducted with the use of an Ecosoft MO-1000 Reverse Osmosis plant. The plant was delivered to Sri Lanka as a part of an Erasmus+ project, coordinated by NMBU, to the University of Peradeniya.

Figure 4.2: Ecosoft MO10000 (Ecosoft n.d.-b)

The Ecosoft small commercial reverse osmosis systems are best suited for use in drinking, process, and deionized water applications. The machine is equipped with 4.5” pre-filter housing and 4.0x4.0” pressure vessels, and is used with normal cartridge and RO-membranes of the above size. Operation is completely automated, which makes it operable by most people (Ecosoft n.d.-b).

The operation manual describes the system operation this way:

> “First, raw water is fed through 5 μm polypropylene sediment filter in order to remove particulates. Then, high-pressure pump feeds the pre-filtered water into the membrane module, inside which feed stream undergoes reverse osmosis process and separates into

permeate and concentrate streams. Recycle flow control throttles flow of concentrate thereby maintaining working pressure in membrane module. Permeate exits the membrane module through permeate outlet and runs down the permeate line. Permeate flow rate depends on pressure in membrane module and numerous other conditions such as temperature and composition of water, type of membrane, and RO system recovery. Part of the concentrate stream is bled to drain; the rest is fed back to suction end of the high-pressure pump via recycle line. Flow rates in recycle line and drain line can be manually adjusted with respective flow controls." (Ecosoft n.d.-b)

Treated water is collected in a water tank. The float switch mounted in the tank stops the machine when the permeate tank is full. Two dosing pumps are mounted on the side of the plant. They lead chemicals to the raw water pipe and minerals to the permeate pipe. The raw-water dosing pump can be used to add antiscalant or biocides. The permeate dosing pump can be used to add minerals to the clean potable water, to avoid dead or flat water, so called remineralization. There is also a UV-lamp shipped with the unit, designed to be treat the water in the storage tank. The preferred way is to mount the UV-lamp on looped pipes, and have a pump force the water through the loop. The water will then be disinfected regularly, and no biological growth will occur.

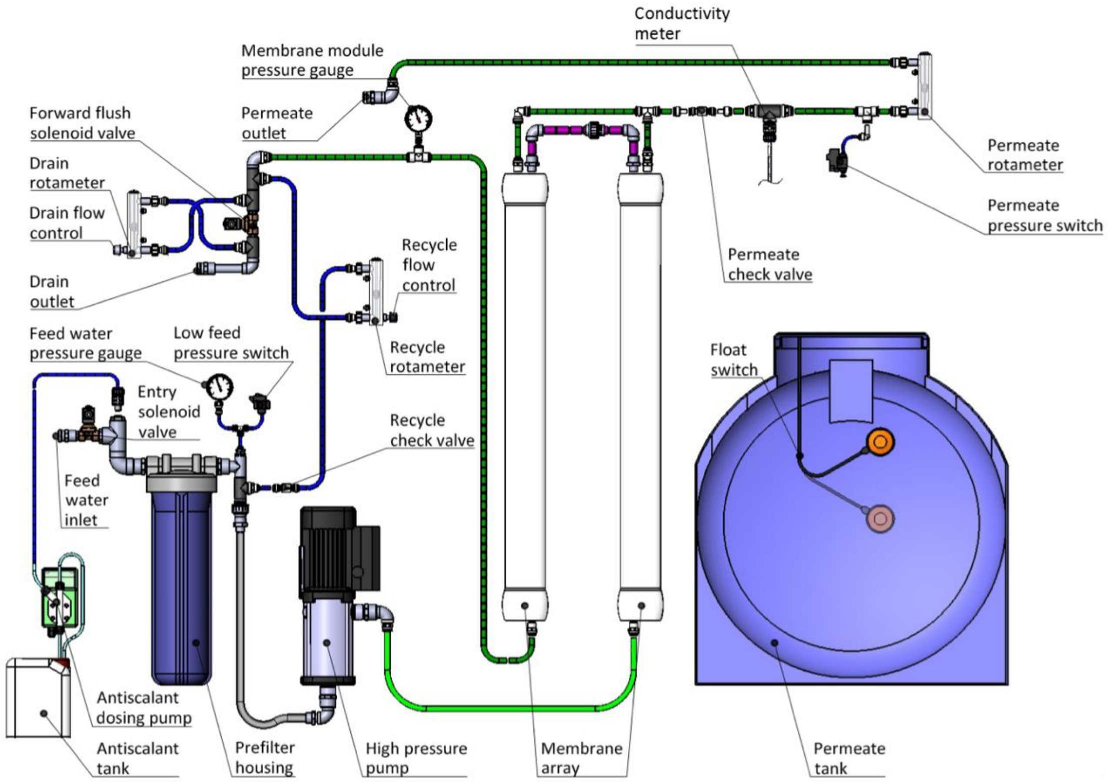


Figure 4.3: Layout of Ecosoft MO10000 RO system (Ecosoft n.d.-b)

4.2.1 Technical Information

Table 4.3: Physical details Ecosoft RO-plants (Ecosoft n.d.-b)

Model	MO6000	MO10000
Nominal capacity, L/day	6000±10%	10000±10%
Water use per forward flush, L	16	
Electrical rating	230V, 50Hz	
Power consumption, kW	0,67	
Dimensions of unit, mm (width × depth × height)	550×400×1400	
Dry mass of unit, kg	60	70
Operating specification[1]		
Recycle flow rate, LPM LPH	13-15 820-900	8,2-11,2 490-680
Drain flow rate, LPM LPH	1,2-1,7 70-100	2,2-3,0 130-180
Permeate flow rate, LPM LPH	3,5-4,5 200-270	6,5-9,0 390-540
Pressure in membrane module, MPa	0,8-1,0	0,8-1,0

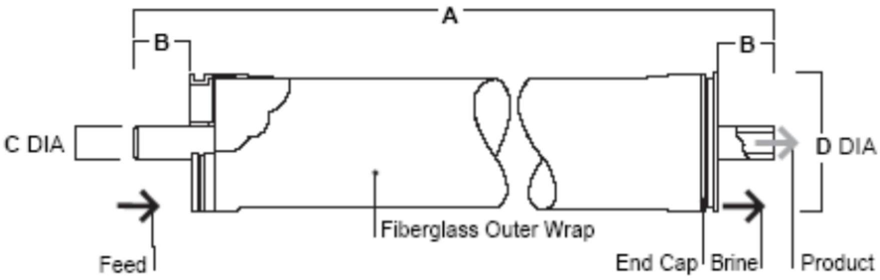
Table 4.4: Limitations Ecosoft RO-plants (Ecosoft n.d.-b)

Hardness	150 mg/L $CaCO_3$
	8,5 °dH
Iron	0,1 mg/L
Manganese	0,05 mg/L
Silicate	20 mg/L
Total dissolved solids	1500 mg/L
Chemical oxygen demand	4,0 mg/L O_2
Residual chlorine	0,1 mg/L
if using antiscalant/oxygen scavenger, above limitations can be exceeded	
Inlet pressure	0,2...0,4 MPa
Temperature of water	10...25 °C

Table 4.4 shows the limitations of the raw water quality. If these limitations are surpassed by the raw water, scaling will occur and fouling of the membrane is evitable.

4.2.2 Membrane

The membrane used for this RO-unit is DOW FILMTEC XLE-4040, an Extra Low Energy element. This element will operate at very low applied pressure. In that way the economics of the RO-plant will be the best possible due to low energy costs per liter permeate produced. XLE elements are available in a dry state for rapid start-up and easy operation.



Dimensions in mm	A	B	C	D
XLE-4040	1016	26.7	19	99

Figure 4.4: XLE-4040 dimensions (DOW n.d.-d)

The membrane is made of polyamide thin-film composite, with a maximum feed flow rate of 3.2 m3/h.

Table 4.5: XLE-4040 operating limitations (DOW n.d.-d)

Maximum operating temperature	45°C
Maximum operating pressure	41 bar
Maximum pressure drop	0.9 bar
pH range, continuous operation	2 – 11
pH range, short-term cleaning	1 – 13
Maximum feed silt density index	SDI 5
Free chlorine tolerance	< 0.1 ppm

Tests have been conducted by DOW to estimate the rejection rate by FT30 membranes. The results of these tests are shown in Table 4.6.

Table 4.6: Rejection rate with FILMTEC FT30 membrane (DOW n.d.-b)

Solute	MW	Rejection (%)
Sodium fluoride NaF[1]	42	99
Sodium cyanide NaCN (pH 11)	49	97
Sodium chloride NaCl	58	99
Silica SiO_2 (50 ppm)	60	98
Sodium bicarbonate $NaHCO_3$	84	99
Sodium nitrate $NaNO_3$	85	97
Magnesium chloride $MgCl_2$	95	99
Calcium chloride $CaCl_2$	111	99
Magnesium sulfate $MgSO_4$	120	> 99
Nickel sulfate $NiSO_4$	155	> 99
Copper sulfate $CuSO_4$	160	> 99
Formaldehyde	30	35
Methanol	32	25
Ethanol	46	70
Isopropanol	60	90
Urea	60	70
Lactic acid (pH 2)	90	94
Lactic acid (pH 5)	90	99
Glucose	180	98
Sucrose	342	99
Chlorinated pesticides (traces)	–	> 99

1. Solute rejection (approximate) 2,000 ppm solute, 225 psi (1.6 MPa), 77°F (25°C), pH 7 (unless otherwise noted).
2. Fluoride rejection is strongly pH dependent (about 75% at pH 5, 50% at pH 4, 30% at pH 3.5 and 0% below pH 3).
3. FT30 membrane is available in a wide variety of spiral-wound configurations.

4.3 Installation of RO-plant

After careful consideration, the decision was made to place the RO-plant at a location in NCP where there is a need for an RO-plant to treat the ground water. Table 4.4 shows several limitations need to be met for the RO-plant to operate perfectly. It was mandatory to consider several locations and find the most suitable one.

4.3.1 Choosing a Location

In total, five locations were considered in this phase. The location was chosen by personnel at the local National Water Supply and Drainage Board (NWSDB). The locations were spread out in the district and all of the locations needed some new water treatment. All locations also had people available to operate the plant on a daily basis, although the available facilities varied.

The analysis and assessment of the locations is shown in *Table 4.7*.

Table 4.7: Examination of possible locations for RO-plant.

GND	GPS Location		Water source	Existing facilities						Water quality parameters			
	E	N		Power supply	Water supply	Pipes	Tanks	Indoor Place	Security	H*	Fe	Mn	TDS
74	179765	374397	Shallow well	OK	OK	NO	NO	OK	OK	77.7	0.102	0.034	293.3
126	201229	364715	Tube Well	OK	OK	NO	OK	OK	OK	375.86	0.068	0.134	701.6
136	207231	369118	Tube well	OK	OK	NO	NO	NO	OK	262.83	0.042	0.052	661.7
219	164636	372435	Tube well	OK	OK	OK	OK	OK	OK	262.89	0.042	0.039	566.7
581	174143	346592	Dug well	OK	OK	OK	OK	OK	OK	317.05	0.697	0.074	745

GND: A number the local authorities give to every location with an RO-plant

Power: Secure and robust power supply available

Water: Water supply with good capacity available

Pipes/tanks: Pipes and tanks available at the location

Indoor place: Indoor place for the RO-unit

Security: Effective locks and security on the premises

Chlorine, Silicate and COD were not measured, since all the ground water measurements in the area showed no significant values.

The information in Table 4.7, matched with the limitations given in Table 4.4 and the wanted facilities at the location, gave a clear winner. Location 219. This location has every aspect in order; the plant could be installed right away. The one issue was the hardness of the water. This is a problem in all the deep wells in the area, so this needed to be addressed no matter what location was chosen. Location 219 is in the village of Medawachchiya and serves about 200 families and a school. There is an old aluminium sedimentation plant at the location, which was shut down when substantial aluminum levels were found in the treated water. The locals now use untreated well water for their daily needs. Drinking water is brought to them on a tractor from other treatment plants. The latest studies have shown that 1% of the people in the area have CKDu. The people operating the plant site claims this number is incorrect. The real numbers have to be much higher according to their experience, though exact figures are not available.

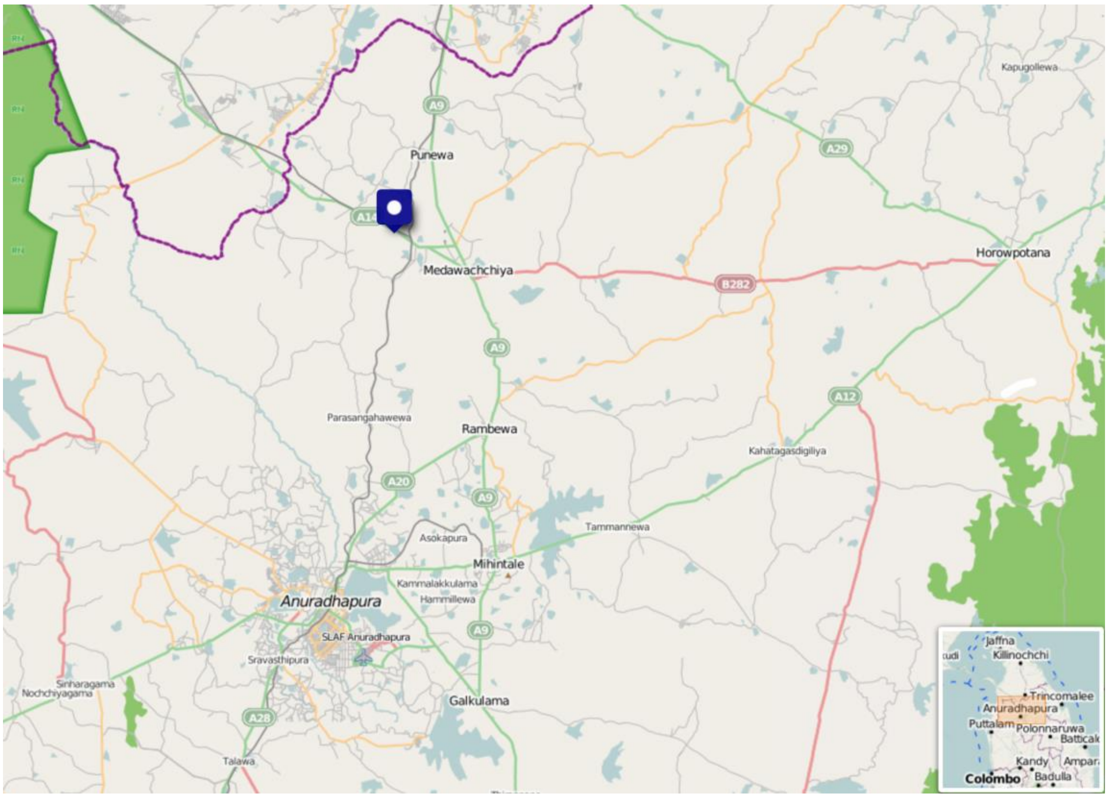


Figure 4.5: Map of location of RO-unit (© OpenStreetMap contributors 2016)

4.3.2 Plant Installation and Optimization

Figure 4.6 shows the intended layout of the RO-plant. This layout would work at any location. At the chosen location in Medawachchiya, the local water distribution network was used, this distribution system complies of a big tank and pipes. This delivers large enough amount of water with pressure measured to be in range of the unit. The pressure delivered to the site was measured to be 0.2 MPa. The rest of the desired amenities were available on site.

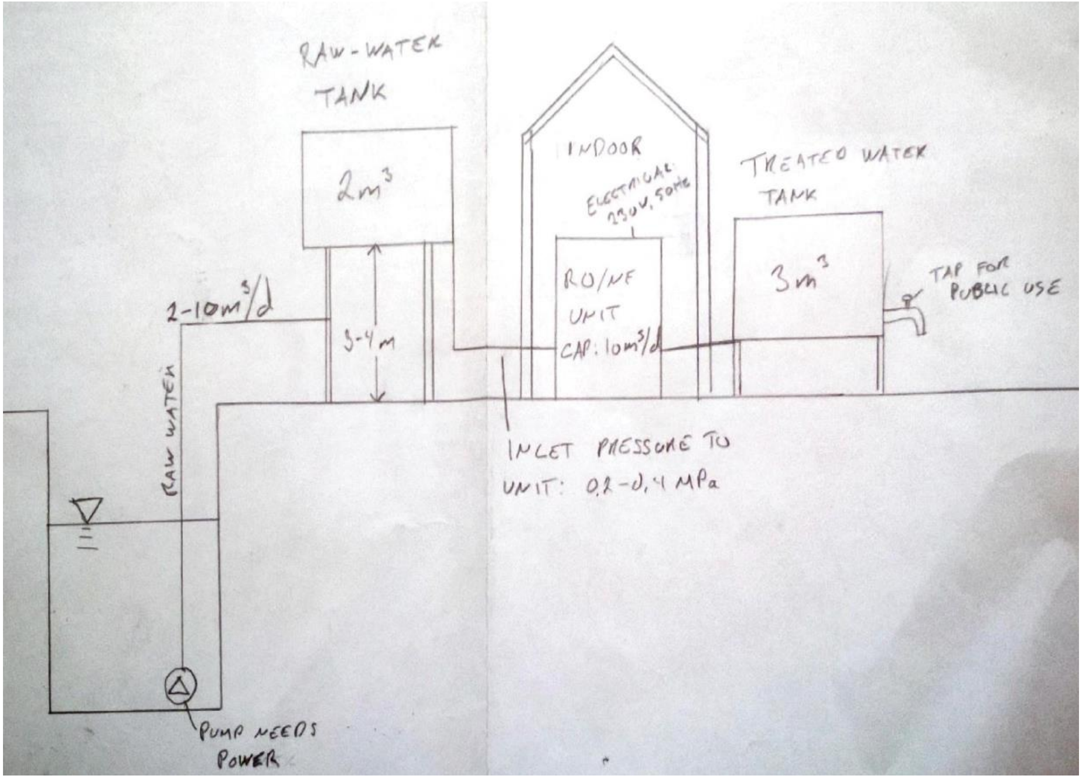


Figure 4.6: Intended layout of the RO-plant

The plant was installed with the help of the local representatives of the NWSDB, local persons, students from UoP, and Dr. Zakhar Maletskyi from NMBU. The installation and optimization took 5 days in total, during a three-week period. The installation was done as described in the manual by Ecosoft (n.d.-b).

The plant was transported from the UoP to the installation location in Medawachchiya. At the location, the position of the plant was decided. The plumbing was done the next day by the workers from the NWSDB in Anuradhapura. The next week, installation of the membranes was on the agenda. The two FILMTEC XLE-4040 membranes were installed carefully. Lab gloves were used when handling the membrane. Before placing the membrane in the housing, glycerol was applied on the end with the rubber edge to ensure a tight fit. During the membrane-installation, there was some confusion and the process had to be conducted three times to get the direction of the membranes right. After correct membrane installation, the unit was put together and was ready to start operating.

To prevent scaling of the membrane, due to the hardness, antiscalant dosing was installed. The antiscalant used is PA0100 from Pure Aqua Inc., bought locally. The antiscalant was added to the raw water through the dosing pump pre-mounted on the unit. The dilution and dose was calculated by using the method described in the FILMTEC Technical Manual Chapter 2 (DOW 2004) and the document Dosing Pump Calibration (Ecosoft n.d.-a)

Dilution of antiscalant

Fill in the cells with required data to calculate the dilution of antiscalant in the table (to edit the data use "Object Worksheet → Edit» in Microsoft Word application).

Please input the data into the squared cells			
Time to dose 100 mL os water	***t***		seconds
	OR		
Dosing pump flow rate by the diagram		1,2	L/hour
Antiscalant dosage (contact Ecosoft)		4	ppm
Permeate flow rate		5,0	LPM
Drain flow rate		5,0	LPM
Antiscalant should be diluted into		**200**	**times**

Dilute antiscalant with permeate using the calculated ration from the table. Fill the dosing station tank with obtained solution and put the foot filter into the tank.

Adjusting and start-up

Set the dosing pump stroke speed:

Dosing rate by pump knob	**40**	**%**

Turn the RO system on and ensure dosing pump starts and operates properly.

Figure 4.7: Screen-shot from the "Dosing Pump Calibration" (Ecosoft n.d.-a)

The antiscalant was diluted 200 times and the dosing rate was initially set to 40%. As the water temperature was high, resulting in high flow, the dosing rate had to be jacked up to 60% to ensure a high enough antiscalant dosing.

Previous examinations of the pressure indicated a high enough pressure. However, this was not the case with the installed plant. When starting up the plant, examinations of the process showed that there was a need for a pressure accumulator to ensure a high enough pressure from the feed water, if not there would be a risk of dry running of the high-pressure pump and fouling of the membrane due to no flushing. The initial pressure ensured a semi-stable run of the plant, and the process of flushing would not run. Because of the short time frame, it was necessary to choose a pump that was in stock locally and met the requirements. The result was a pump from Italy, manufactured by Pedrollo, together with a pressure accumulator tank of 24 L, a set called “HYDROFRESH” with the model name: JSWm 12H – 24 SF. The pressure settings advised were 2.5 – 4.0 bar. When matched with Table 4.4, this is within the limitations. The pressure settings were narrowed to 2.5 – 3.5 bar to ensure more stable operation of the plant. After the pressure alteration, the plant worked as intended.

The UV-lamp should ideally be installed in a loop where the permeate is pumped continuously to ensure absolute disinfection. This was not possible at Medawachchiya due to financial and operational aspects. To ensure disinfection the UV-lamp was mounted on the outlet pipe of the permeate tank. This results to all water sold being exposed to ultraviolet radiation.

Additional problems did occur. These included leakage, power outages, and tripping of the electrical grounding. These problems were fixed as they occurred and in the end, things worked out. In the end the plant was ready to start operating.

Several operation regimes were tested to find what kind of regime fit the location best. The drain flow and the recycle flow was edited, which resulted in differing permeate flow, operation pressure and water quality. The results were then evaluated.

Due to the high water temperature, it was not possible to follow the operation specifications given in Table 4.3. The operation specifications are based on a water temperature of 25°C. As the water temperature in this case varied between 33°C and 36°C, a huge impact was expected.

A temperature correction factor was needed to find the membrane permeate rate at the local temperature. This factor was found by using one of these two equations.

$$TCF = EXP\left[2640\left(\frac{1}{298} - \frac{1}{273+T}\right)\right]; T \geq 25°C \tag{4.1}$$

$$TCF = EXP\left[3020\left(\frac{1}{298} - \frac{1}{273+T}\right)\right]; T \leq 25°C \tag{4.2}$$

There are tables available to make the process of finding the factor faster and easier.

The average feed temperature in Medawachchiya during the tests was 34.7°C. This gives a temperature correction factor of 1.32, using Equation (4.1). The permeate flow in this temperature is found by multiplying the flow rate given in the manual by the correction factor.

$$6.5 \times 1.32 = 8.58$$

$$9.0 \times 1.32 = 11.88$$

The permeate flow should then be 8.58 – 11.88 LPM.

The same procedure is carried out for the drain and recycle flow. The flow rate at the local temperature should then be 10.82 – 14.78 LPM for the recycle flow, and 1.90 – 3.96 LPM for the drain flow.

The maximum readable drain flow on the Ecosoft unit is 4.25 LPM on the unit. To apply as low pressure as possible to the membrane, to prolong its life, the drain flow was kept at 4.25 LPM. The recycle flow was kept fully open. This gave the following operation parameters.

Table 4.8: Operation parameters for RO-plant at Medawachchiya

Parameter	**Value**
Permeate Flow	10 LPM
Drain Flow	4.25 LPM
Recycle Flow	12 LPM
Operating pressure	0.45 – 0.55 MPa
Pressure after pre-filter	0.25 – 0.35 MPa
Conductivity	35 µS/cm
Temperature	35°C

To find the recovery rate the following equation was used:

$$Recovery = \frac{Permeate\ Flow\ Rate}{Drain\ Flow\ Rate + Permeate\ Flow\ Rate} \times 100 \tag{4.3}$$

Which gives us the following recovery rate:

$$Recovery = \frac{10}{4.25 + 10} \times 100 = 70.2\ \%$$

The optimal recovery rate given by the manufacturer is 75 %. This would be possible to achieve, and even more so because of the high raw water temperature, by choking the drain flow to suggested values. Since this unit is located in a developing country, one of the goals is to keep the membrane in good shape for as long as possible. Low operation pressure is a huge factor for the lifespan, therefore the membrane pressure is kept low, which results in lower recovery rate.

To further see what operation parameters would give the best treatment result, several different operation modes were conducted and samples collected for analyzing. The operation modes and the results are shown in Chapter 5.2.

4.3.3 Operation Regimes

To test the plants' capacity and operation possibilities, different settings were applied. Whereupon water samples were collected and analyzed. Seven different regimes were conducted over a course of two days. The first day without the pump and pressure accumulator on the feed water, the second day with it. The main alliterations were conducted on the drain flow, as this had the wanted effect.

Seven different regimes were carried out, each with different flows and recovery rates.

4.3.4 Sampling Process

The same sampling process as described in Chapter 4.1.1 was used for the samples taken from the research plant at Medawachchiya. During each tested operation regime, samples were taken from the permeate stream, and the drain. Two samples were also taken of the raw water, one at the start of the process and one at the end of the process. This was done based on the presumption that groundwater does not change characteristics frequently.

One difference was that the acid added to the samples was changed for the two last sets of samples, operation regime 6 and 7, as well as the last raw water sample. Sulfuric acid was used to lower the pH for conservation of the sample.

4.3.5 Normalizing the Plant

To ensure optimal operation of the plant normalization is required. Normalization is done under normal operation of the plant. In this process all available data is recorded, including flows, pressure, conductivity, and temperature. This is done to track performance system trends, to decide when to clean and replace the membrane, and to account for feed water pressure, temperature concentration and recovery. The data collected from the plant is presented in Table 4.9.

Table 4.9: Data recorded from research plant in Medawachchiya

Date	Permeate Flow	Concentrate Flow	Feed pressure	Concentrate pressure	Feed TDS	Permeate TDS	Feed Temp
6/4/2016	0.63	0.255	5.3	5	3500	16.5	32°C
18/4/2016	0.63	0.255	5.3	5	3500	16.5	32°C
27/4/2016	0.63	0.255	5.3	5	3500	16.5	31°C
1/5/2016	0.66	0.255	5.3	5	3500	16.5	34°C
7/5/2016	0.63	0.255	5.3	5	3500	16.5	32°C

This data is then normalized to eliminate effects of fluctuating operating conditions, and to allow monitoring of the membrane properties. For normalization “Normalization of Membrane Systems (FTNORM) Software” from DOW is used.

4.4 Bottled Water

As the knowledge of CKDu and its alleged causes has spread throughout the Sri Lankan districts, the companies selling bottled water have seen their chance to market bottled water as a safe alternative to the ground water in the region affected by CKDu. Most of the bottled water in Sri Lanka is taken from springs or wells in different areas of Sri Lanka without any excessive treatment. To examine if that the bottled drinking water contain heavy metals or pesticides. Ten different commercial water bottles was purchased in Sri Lanka and brought to Norway for testing. Information regarding location and type of source is given in Table 4.10. The data has been anonymized.

Table 4.10: Label information from commercial bottled water analyzed.

No.	Location of source	Type of source
B1	Punchi Mandawala	Tube well
B2	Miyanavila, Deraniyagala	Spring
B3	Dagonna	Tube well
B4	Nirella, Ratnapura	Shallow well
B5	Yabaraluwa, Malwana	Tube well
B6	Unnaruwa, Minuwangoda	Tube well
B7	Namunukula Forest Range, Hali-ela	Tube well
B8	Embulgama, Ranala	Tube well
B9	Kateoloya Estate, Kandy	Spring
B10	Ehala lunugama, Mandawala	Dug well

The locations of the sources are mapped out in Figure 4.8. None of the locations are in areas affected by CKDu, and therefore it is safe to assume that this water will not contribute to CKD in the same way as ground water from the affected area.

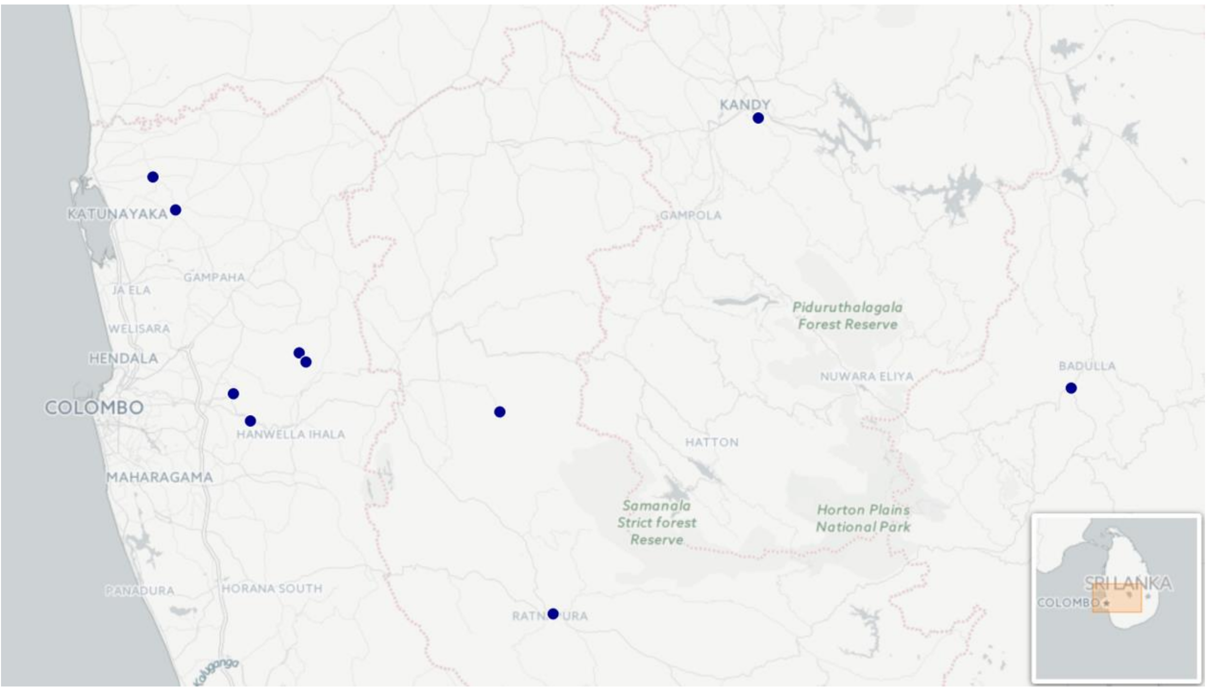


Figure 4.8: Approximate location of the bottled water sources (© OpenStreetMap contributors 2016)

The commercial bottled water has been analyzed using the same method as the well water, using ICP at NMBU.

5 Results

5.1 Examining Existing RO-plants

Information on the existing RO-plants is presented in Chapter 4.1. Analysis was carried out at NMBU and UoP. When results were obtained from both laboratories, the results were compared and possible sources of uncertainty evaluated. The results on Fluoride concentration are from UoP, the rest of the results are from NMBU.

The tables show the concentration in the influent to the RO-unit, which is the same as well water, untreated water. Effluent from the RO-unit, which is the permeate, the purified water. Then it shows the removal percentage of the current element at the RO-plant.

There were some problems with some of the samples brought to Norway. This has resulted in testing from locations with GND number 70 and 82, being incomplete.

The results show that none of the elements analyzed passes the membranes in harmful doses. When only the tested elements are taken into account, a safe conclusion is that all of the 10 tested plants have a good and safe product.

Table 5.1: Analysis results for As, Cd, Pb and F^- from existing plants in NCP.

GND no.	Village(s)	Analysis results											
		Arsenic [µg/L]			**Cadmium [µg/L]**			**Lead [µg/L]**			**Fluoride [mg/L]**		
		Influent	***Effluent***	***%***	***Influent***	***Effluent***	***%***	***Influent***	***Effluent***	***%***	***Influent***	***Effluent***	***%***
42	Kidawarankulama	0.79	0.12	85 %	0.0250	0.0093	63 %	3.20	2.40	25 %	0.48	0.04	92 %
50	Yakawewa/ Periyakulama	1.10	0.14	87 %	0.0120	0.0210	-75 %	2.80	3.50	-25 %	0.72	0.00	100 %
57	Mahadiulwewa	0.51	0.25	51 %	0.0240	0.1200	-400 %	3.60	2.90	19 %	0.78	0.00	100 %
70	Halambugaswawe	No data	0.13	No data	-	0.0097	No data	No data	3.00	-	1.02	0.04	96 %
72	Kirgalwewa	0.28	0.17	39 %	0.0340	0.0810	-138 %	2.50	4.50	-80 %	0.85	0.00	100 %
81	Pihimbiyagollewa	0.60	0.16	73 %	0.0220	0.0110	50 %	2.30	4.20	-83 %	0.87	0.23	74 %
82	Wewalkatiya/ Thambalagollewa	No data	No data	-	No data	No data	-	-	-	-	0.85	0.10	88 %
102	Ikrigollewa	0.20	0.12	40 %	0.0190	0.0068	64 %	3.00	2.10	30 %	0.86	0.02	98 %
108	Wahamalgollewa	0.23	0.13	43 %	0.0110	0.0036	67 %	1.50	2.20	-47 %	0.83	0.00	100 %
111	Sangilikanadarawa	0.26	0.16	38 %	0.0086	0.0067	22 %	2.40	2.90	-21 %	0.61	0.00	100 %
115	Pandakabhayapura	0.22	0.16	27 %	0.0180	0.0710	-294 %	5.70	4.60	19 %	0.50	0.00	100 %
	AVERAGE	*0.47*	*0.15*	67 %	*0.0193*	*0.0340*	-76 %	*2.70*	*2.94*	-9 %	*0.76*	*0.04*	95 %

Table 5.2: Analysis results for Ca, Mg, H and Fe from existing plants in NCP.*

GND no.	Village(s)	Analysis results											
		Calcium [mg/L]			**Magnesium [mg/L]**			**Hardness***			**Ferrous [mg/L]**		
		Influent	***Effluent***	***%***	***Influent***	***Effluent***	***%***	***Influent***	***Effluent***	***%***	***Influent***	***Effluent***	***%***
42	Kidawarankulama	63.00	0.77	99 %	43.00	0.24	99 %	334.39	2.91	99 %	0.0280	0.0110	61 %
50	Yakawewa/ Periyakulama	92.00	0.35	100 %	44.00	0.18	100 %	410.92	1.62	100 %	0.0190	0.0110	42 %
57	Mahadiulwewa	78.00	120.00	-54 %	49.00	25.00	49 %	396.55	402.59	-2 %	0.0210	0.0300	-43 %
70	Halambugaswawe	No data	0.44	-	No data	0.17	-	No data	1.80	-	No data	0.0097	-
72	Kirgalwewa	81.00	0.32	100 %	31.00	0.11	100 %	329.92	1.25	100 %	0.0240	0.0130	46 %
81	Pihimbiyagollewa	86.00	0.62	99 %	70.00	0.39	99 %	503.00	3.15	99 %	0.0190	0.0120	37 %
102	Ikrigollewa	96	0.54	99 %	22	0.15	99 %	330.31	1.97	99 %	0.0220	0.0087	60 %
108	Wahamalgollewa	100	1.8	98 %	24	0.24	99 %	348.53	5.48	98 %	0.0130	0.0120	8 %
111	Sangilikanadarawa	93	1.2	99 %	34	0.26	99 %	372.23	4.07	99 %	0.0250	0.0130	48 %
115	Pandakabhayapura	0.35	2.3	-557 %	0.21	0.35	-67 %	1.74	7.18	-313 %	0.0220	0.0170	23 %
	AVERAGE	*76.59*	*12.83*	83 %	*35.25*	*2.71*	92 %	*336.40*	*43.20*	87 %	*0.0214*	*0.0137*	36 %

*Hardness is calculated using Ca and Mg concentrations: $Hardness = 2.497[Ca] + 4.118[Mg]$

Table 5.3: Analysis results for B, Al, Cr and Mn from existing plants in NCP.

GND no.	Village(s)	Analysis results											
		Boron [µg/L]			**Aluminum [mg/L]**			**Chromium [µg/L]**			**Manganese [µg/L]**		
		Influent	***Effluent***	***%***	***Influent***	***Effluent***	***%***	***Influent***	***Effluent***	***%***	***Influent***	***Effluent***	***%***
42	Kidawarankulama	66.00	41.00	38 %	0.0200	0.0110	45 %	0.120	0.160	-33 %	340.00	0.88	100 %
50	Yakawewa/ Periyakulama	61.00	70.00	-15 %	0.0130	0.0110	15 %	0.100	0.083	17 %	160.00	0.93	99 %
57	Mahadiulwewa	92.00	96.00	-4 %	0.0210	0.0380	-81 %	0.190	0.220	-16 %	3.40	11.00	-224 %
70	Halambugaswawe	No data	54.00	-	No data	0.0097	-	No data	0.077	-	No data	0.64	-
72	Kirgalwewa	58.00	44.00	24 %	0.0210	0.0130	38 %	0.400	0.077	81 %	380.00	0.68	100 %
81	Pihimbiyagollewa	130.00	41.00	68 %	0.0140	0.0110	21 %	0.280	0.140	50 %	120.00	0.58	100 %
102	Ikrigollewa	48.00	36.00	25 %	0.0120	0.0080	33 %	0.210	0.077	63 %	13.00	0.55	96 %
108	Wahamalgollewa	47.00	37.00	21 %	0.0082	0.0094	-15 %	0.077	0.100	-30 %	6.50	0.56	91 %
111	Sangilikanadarawa	61.00	44.00	28 %	0.0110	0.0100	9 %	0.130	0.120	8 %	0.73	0.62	15 %
115	Pandakabhayapura	56.00	77.00	-38 %	0.0180	0.0220	-22 %	0.091	0.110	-21 %	0.82	3.50	-327 %
	AVERAGE	*68.78*	*54.00*	21 %	*0.0154*	*0.0143*	7 %	*0.178*	*0.116*	34 %	*113.83*	*1.99*	98 %

Chromium: The value 0.077 is actually <0.078. It is converted to 0.077 for calculation purposes.

Table 5.4: Analysis results for Co, Ni, Cu and Zn from existing plants in NCP.

GND no.	Village(s)	Analysis results											
		Cobalt [µg/L]			**Nickel [mg/L]**			**Cobber [mg/L]**			**Zinc [mg/L]**		
		Influent	***Effluent***	***%***	***Influent***	***Effluent***	***%***	***Influent***	***Effluent***	***%***	***Influent***	***Effluent***	***%***
42	Kidawarankulama	6.70	3.70	45 %	2.30	1.40	39 %	0.53	0.32	40 %	0.0089	0.0240	-170 %
50	Yakawewa/ Periyakulama	6.50	4.70	28 %	2.40	1.80	25 %	0.56	0.44	21 %	0.0160	0.0410	-156 %
57	Mahadiulwewa	7.20	2.70	63 %	2.60	0.94	64 %	7.20	0.19	97 %	0.0120	0.0390	-225 %
70	Halambugaswawe	No data	4.40	-	No data	1.70	-	No data	0.39	-	No data	0.0260	-
72	Kirgalwewa	5.30	6.10	-15 %	1.80	2.30	-28 %	0.40	0.55	-38 %	0.0110	0.0180	-64 %
81	Pihimbiyagollewa	4.90	5.80	-18 %	1.80	2.10	-17 %	0.41	0.50	-22 %	0.0120	0.0360	-200 %
102	Ikrigollewa	3.70	4.00	-8 %	1.30	1.50	-15 %	0.28	0.33	-18 %	0.0086	0.0140	-63 %
108	Wahamalgollewa	2.50	4.40	-76 %	0.88	1.60	-82 %	0.19	0.36	-89 %	0.0038	0.0075	-97 %
111	Sangilikanadarawa	5.00	5.20	-4 %	1.90	2.00	-5 %	0.40	0.43	-7 %	0.0075	0.0120	-60 %
115	Pandakabhayapura	7.90	4.70	41 %	3.00	1.80	40 %	0.73	0.39	47 %	0.0690	0.0320	54 %
	AVERAGE	*5.52*	*4.57*	17 %	*2.00*	*1.71*	14 %	*1.19*	*0.39*	67 %	*0.0165*	*0.0250*	-51 %

5.2 Testing Ecosoft RO-plant

5.2.1 Operation Regimes

Several operation regimes were tested out to ensure good operation, some of the results are shown in Table 5.5.

The average temperature correction factor was used to calculate the expected flow, the result showing that the permeate flow should be between 8.58 and 11.88 LPM (0.51-0.71 m^3/h). The flow rate 10.82 – 14.78 LPM (0.65 – 0.89 m^3/h) recycle flow, and drain flow from 1.90 to 3.96 LPM (0.11 – 0.24 m^3/h) as described in chapter 4.3.2.

Table 5.5: Overview of the operation regimes for RO-plant testing at Medawachchiya

No.	Date	Time	Permeate Flow	Concentrate flow	Feed pressure	Calculated Perm TDS	Perm Conductivity	Feed temp (°C)	Feed flow	Recovery (%)	Differential pressure	Temperature correction factor
1	5-Apr-16	10:30:00	0.54	0.26	1.80	18	39	33	0.80	68%	0.30	1.260
2	5-Apr-16	11:00:00	0.54	0.21	1.80	20	43	34	0.75	72%	0.30	1.296
3	5-Apr-16	11:30:00	0.54	0.18	1.90	23	48	35	0.72	75%	0.30	1.333
4	5-Apr-16	12:00:00	0.54	0.15	1.80	25	53	35	0.69	78%	0.30	1.333
5	5-Apr-16	12:30:00	0.61	0.18	1.50	21	44	35	0.79	77%	0.30	1.333
6	6-Apr-16	13:30:00	0.66	0.12	3.00	26	55	36	0.78	85%	0.10	1.370
7	6-Apr-16	14:00:00	0.60	0.26	3.00	16	35	35	0.86	70%	0.30	1.333

Flow in m^3/h, Pressure in bar

5.2.2 Analytical Results

Due to the good results from the analysis from the existing plants, it was decided to test only the samples from the last and final operating regime, number 7, and the raw water samples taken at the same time.

The results from this analysis are shown in Table 5.6. Fluoride, TOC, Inorganic C and Tot-N results are all from UoP. The rest of the results are from NMBU.

Table 5.6: Results from analysis of water from research plant at Medawachchiya

	Raw water	Permeate	Removal	Drain	Recommended limit (WHO)
Arsenic [µg/L]	1.70	0.015	99 %	1.2	5.00
Cadmium [µg/L]	0.0054	<0.0031	> 43%	0.01	3.00
Lead [µg/L]	1.10	0.69	37 %	1.70	10.00
Fluoride [mg/L]	1.13	0.28	75 %	5.10	0.50
Calcium [mg/L]	85.00	0.50	99 %	260.00	-
Magnesium [mg/L]	44.00	0.23	99 %	130.00	-
Hardness* [mg/L]	393.44	2.20	99 %	1184.56	-
Ferrous [mg/L]	0.49	0.11	78 %	0.27	2.00
Boron [µg/L]	64.00	53.00	17 %	82.00	500.00
Aluminium [mg/L]	0.0065	0.0037	43 %	0.0044	0.10
Chromium [µg/L]	17.00	16.00	6 %	16.00	5.00
Manganese [µg/L]	3.50	1.60	54 %	2.40	30.00
Cobalt [µg/L]	0.42	0.37	12 %	0.54	100.00
Nickel [mg/L]	0.049	0.058	-18 %	0.062	0.07
Cobber [mg/L]	0.14	0.16	-14 %	0.15	2.00
Zinc [mg/L]	0.016	0.0019	88 %	0.063	3.00
TOC [mg/L]	29.48	7.87	73 %	168.60	-
Inorg. C [mg/L]	28.60	11.81	59 %	126.20	-
Tot-N [mg/L]	8.16	3.41	58 %	1.98	-

*Equation (2.6) is used for calculation

5.2.3 Normalized Data

The data collected from the research plant in Medawachchiya is presented in Table 4.9. These data are normalized and gives the result presented in Table 5.7.

Table 5.7: Overview of normalized data from RO-plant at Medawachchiya

Date	Days of operation	Recovery	Temperature correction facture	Calculated Feed/Brine Avg Conc	Net driving pressure	Normalized Permeate Salt Passage	Normalized Permeate Salt Rejection
6/4/2016	0	71%	1.225	6118	0.18	0.5%	99.5%
18/4/2016	12	71%	1.225	6118	0.18	0.5%	99.5%
27/4/2016	21	71%	1.191	6118	0.19	0.5%	99.5%
1/5/2016	25	72%	1.296	6200	0.08	0.5%	99.5%
7/5/2016	31	71%	1.225	6118	0.18	0.5%	99.5%

To show the significance of the results a diagram of normalized permeate salt passage and normalized permeate salt rejection is presented in Figure 5.1.

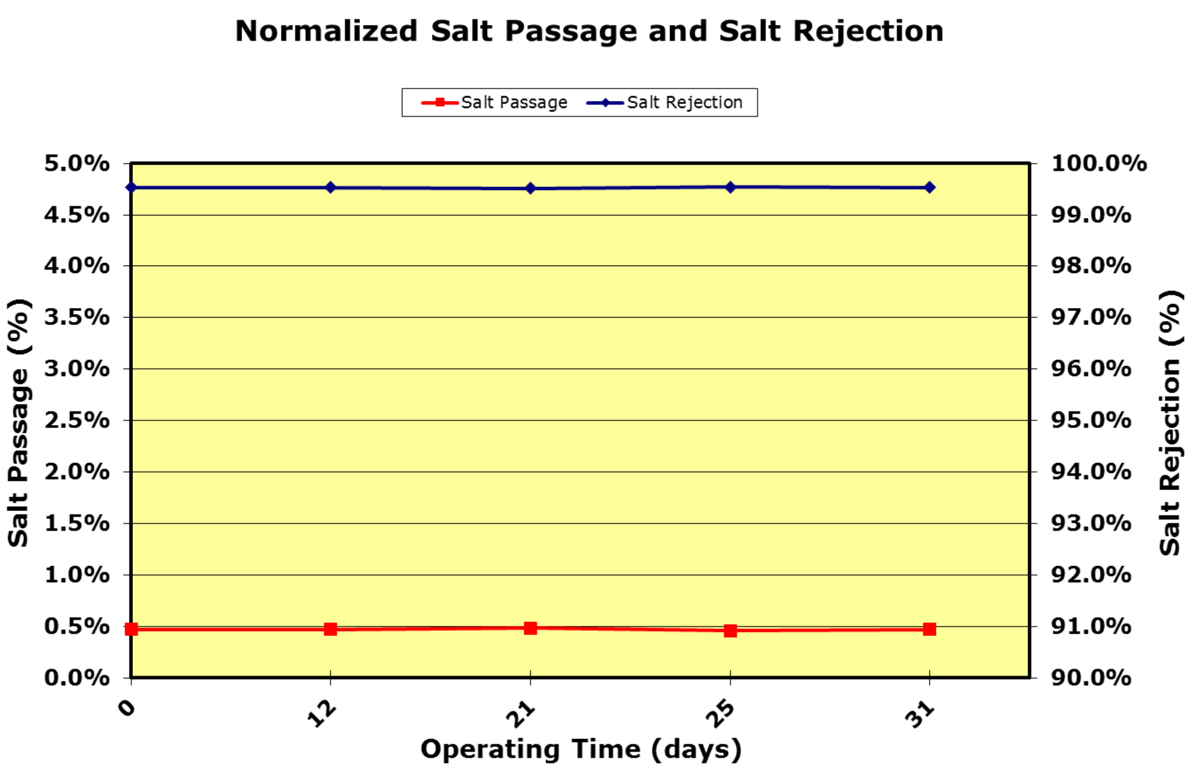


Figure 5.1: Diagram of Salt Passage and Salt Rejection at the research plant.

This diagram shows a very good trend, with stable rejection rates. This proves that the operation is good, with right amount of antiscalant and feed flow.

5.3 Bottled Water

The commercial bottled water was analyzed for the same pollutants in the same batch as the existing RO-plants. The bottled water was duplicated into several samples, and tested separately, the results of all of these analyses are given in “Appendix IV”.

The average concentration in the samples are shown in *Table 5.8*.

Table 5.8: Analysis result of commercially bottled drinking water.

No.	B µg/L	Mg mg/L	Al mg/L	Ca mg/L	Cr µg/L	Mn µg/L	Fe mg/L	Co µg/L	Ni mg/L	Cu mg/L	Zn mg/L	As µg/L	Cd µg/L	Pb µg/L
B1	6.533	4.267	0.00105	8.03	0.0780	0.3267	0.00420	0.012	0.00104	0.00070	0.00180	0.00790	<0.0021	0.3433
B2	4.833	0.960	0.01367	1.60	<0.078	13.6667	<LD	0.477	0.00171	0.00116	0.00240	<0.054	0.0079	0.1150
B3	2.950	0.945	0.00130	2.60	<0.078	11.0000	<LD	0.250	0.00130	0.00145	0.00320	<0.0054	0.0049	0.0860
B4	4.550	1.600	0.01200	3.45	1.4500	8.5000	<LD	0.145	0.00280	0.00105	0.00535	<0.0054	0.0107	0.0715
B5	2.567	1.000	0.00052	1.60	0.1113	0.0443	<0.0042	0.010	0.00077	0.00084	0.00177	0.00627	0.0023	0.1320
B6	14.000	1.300	0.03100	2.77	0.0840	23.3333	<0.0042	0.450	0.00151	0.00890	0.01300	0.01500	0.0130	1.3000
B7	3.567	2.200	<0.0003	3.83	<0.078	0.0327	<LD	0.010	0.00049	0.00167	0.00120	0.01087	<0.0021	0.0903
B8	15.667	0.039	0.00073	0.13	0.1433	0.0600	<LD	0.010	0.00660	0.00034	0.00097	0.00727	<0.0021	0.1380
B9	4.067	2.400	0.00121	5.17	0.0960	0.2367	0.00520	0.017	0.00126	0.00071	0.00088	0.00577	0.0045	0.2390
B10	5.667	1.333	0.00517	3.80	0.5200	4.6000	<0.0042	0.019	0.00144	0.00077	0.00102	0.01103	0.0025	0.1057

5.4 Guideline for Operation and Maintenance of RO-plants

During this study some critical methods of operating an RO-plant was discovered. Some plants operate with pressure on the membrane set too high, which shortens the lifespan of the membrane. Others have the UV-lamp right after the RO-unit, where it is of no use as the water is disinfected after a RO-process. Additionally, several small glitches in operation routines where uncovered.

A guideline of operation and maintenance of RO-plants has been developed to educate the RO-operators and owners. It is intended to be used during training and as a work of reference during operation and maintenance. The goal is to spread important information regarding RO-plant operation and maintenance. And through this make sure that RO-plants in the area have high operation-standards so that consumers can be safe when using the water produced by these plants.

The pamphlet is double-sided and can be seen in an unfolded state on the next page. It will be free to use and distribute.

GLOSSARY

RO	Reverse Osmosis
CKDu	Chronic Kidney Disease of uncertain etiology
Pressure	A given pressure is needed to ensure good operation of the plant – check manual
UV	Ultra Violet light for disinfection
HTH	High Test Hypochlorite
Chlorine	Used for disinfection
Permeate	The purified product from the RO.
1 m^3	1,000 liters
E.coli	A bacteria indicating fecal pollution
Turbidity	Cloudiness of the water, caused by particles
Color	Color of the water, caused by organic material and some inorganic components

REFERENCES

"Waterdrop" – shot by Davide Restivo.

Photo of M.K.D.C.S Meegoda and the RO-plant, shot by Mathias Espeland.

"Cleaning and disinfecting water storage tanks" – WHO. Available at: http://www.who.int/water_sanitation_health/hygiene/envsan/tn03/en

RO OPERATION

This pamphlet is produced and designed by Mathias Espeland, 2016.

REVERSE OSMOSIS PLANT

Good practices on operation and maintenance for Reverse Osmosis plants in Sri Lanka.

This pamphlet gives an introduction on how to operate, do maintenance on, and disinfect a Reverse Osmosis plant in CKDu affected areas of Sri Lanka.

INSTALLATION

During the installation, it is important strictly to follow the RO-manual. Power source, water source, piping and adequate pressure should all be in place before the membranes are installed. When installing the membrane gloves should be used, and glycerin should be applied on the rubber edge to ensure a tight fit.

DISINFECTION OF TREATED WATER

Most RO-plants are accompanied with a UV lamp for the purpose of disinfection. As the membrane disinfects the water from the plant, there is no need to have the UV-lamp right after the RO-plant. Instead permeate should be pumped through a pipe-loop, passing the UV-lamp. This is to ensure no biological growth occurs in the permeate tank, thus clean and safe water at all times. If this is not possible the UV-lamps should be mounted on the outlet pipe of the permeate tank.

PERMEATE TANK

The size of the permeate tank should be assed against the production rate of the RO-unit. A bigger tank would be needed if the production rate is low. The operation should be such as stagnation of water is avoided. Overnight storage of water should be avoided. It is preferable to have fresh water in the morning.

PREPARATION OF TANK

Before the tank is used for the first time, cleaning and disinfection is mandatory. The tank should be disinfected by following these easy instructions:

1. Completely empty the tank.
2. Clean/scrub all internal surfaces.
3. Wash all internal surfaces to remove all traces of detergent.
4. Fill the tank up a quarter way with purified water from RO-unit.
5. Disinfect the tank with chlorine
    a. HTH is the best. If unavailable use either bleach or chlorine tablets. Check label for chlorine concentration.
    b. Add 25 g chlorine per cubic meter water.
6. Rinse the tank a couple of times until the chlorine smell/taste is gone

This should be done every other week during operation of RO-plant.
(Unless a loop with the UV-lamp is installed)

OPERATION

The operation process may differ slightly from unit to unit, but the main ideas are the same. Start the unit when water is needed, stop it when there is no more need for water. There should also be a float switch in the permeate tank to stop the production when the tank is full.

There should be no more production at the end of the day's sale. To prevent water being stored in the tank during the night.

The RO-plant needs to be in operation at least one hour every 24 hour to prevent biological growth on the membrane.

EXAMPLE OF OPERATION

A location has a RO-plant that produces 10 m^3/day, and a 2 m^3 tank. The sale of water takes place between 9 AM and 11 AM, then 2 PM to 5 PM every day, at an average rate of 1 m^3 per hour.

Production should start at 7 am to fill the tanks. During the day the plant should remain on, the float switch will turn it on and off as needed. At about 3:30 PM the plant should be switched off, and when the remaining water is sold out the locations should be closed.

Repeat the same the next day.

QUALITY CONTROL AND MAINTANENCE

The permeate should be closely monitored. The best solution is to have online measurements of turbidity and color to ensure that the quality is satisfactory. If not possible, this should be checked manually. Analysis for coliform bacteria and hardness should be done regularly.

PRE-FILTER AND MEMBRANE

The membrane and pre-filter will after some time need to be replaced. A number of things that may indicate this:

- Low pressure after the pre-filter
- Low permeate flow, despite high enough pressure
- High turbidity/color in the permeate

If this is discovered a new membrane/pre-filter should be purchased to replace the old one.

6 Discussion

6.1 Sources of Errors and Uncertainty

The uncertainties in this study are mostly connected to sampling and conservation of samples.

The sampling process was done with non-standardized bottles, due to no availability. Sorption, desorption and leaching from material in the bottle may be a problem.

The sample preservation is another field of uncertainty. The samples were preserved with nitric acid and sulfuric acid of unknown quality. There was not a portable pH meter available, so there was no definite way to know that the pH was lowered below 2 in the samples. This may have caused changes in hydrochemistry during transportation and storage.

The acid in itself is another source of error due to the unknown quality. External conditions made sure the blank acid sample never reached Norway and the laboratory. This means that any heavy metals found in the samples might have come from the acid used for conservation.

Transportation and storage is on its own a source of error. Samples planed for heavy metals analysis should be kept at below 4°C from the moment of extraction. As described, the samples were placed in a Styrofoam box with ice inside to cool them down. Because of the warm weather, there is a remote chance that the samples were cooled to 4°C. When arriving at the UoP, the lab was closed and therefore the samples were not put in a fridge before the morning after the sampling was done. Chemical reactions may have taken place during the storage.

The samples were kept for 3 weeks before transported to Norway for analyzing. When transporting the samples to Norway, the amount of sample brought was quite low, only 100 ml of each sample. This resulted in few replicas and another source of error as there is no analysis to which the results can be compared. During transportation, there is also a small chance that the samples had been contaminated each other by leakage.

Laboratory analysis is always a source of error, as the results may deviate from true concentrations. In this case, the source of error is considered very small as the analysis was done with modern and calibrated equipment, by highly trained staff.

6.2 Examining Existing RO-plants

The results for As, Cd, Pb and F^- are presented in *Table 5.1*.

The average concentration of As in the ground water tested is 0.47 µg/L, way below the recommended limit of 5 µg/L. The average removal efficiency of the RO-plants is 67% which gives an average As concentration of the permeate at 0.15 µg/L. In the area where these examinations have been conducted, there is therefore more or less zero possibility for arsenic being the cause of CKDu. Neither before or after the installation of RO-units.

The average concentration of Cd in the ground water tested is 0.0193 µg/L, while the limit recommended for drinking water is 3 µg/L. The removal efficiency of the RO-plants gives an assorted picture. Some plants removed almost 70% of Cd, but some added 400%. Anyhow the average removal rate was -76%. This is probably caused by contamination during sampling, storage, transport or analysis. In any case, the average concentration in the effluent is 0.034 µg/L, still very low compared to the recommended limit. Thus, there is no possibility of cadmium being the cause of CKDu in these areas.

The same ground water has an average Lead concentration of 2.45 µg/L. In the case of Lead, as it was with cadmium, the plants add to the concentration so that it becomes 2.94 µg/L, up 20%. Although the percentage is rater high, the value is too close to the detection limit of 1 µg/L to be a true quantitative analyses. The “addition” may be contamination or just a wrongful lab report. The recommended limit, by WHO, is however 10 µg/L, and therefore there is no problem with the lead concentration, neither in the ground water nor in the permeate from the RO-plants.

Several studies agree that fluoride has been characterized as one of the elements that has something to do with CKDu. The results from this study shows F^- concentration to be 0.76 mg/L in average. Considering the recommended limit in tropical areas being 0.50 mg/L, the ground water in the area has a slightly raised value of Fluoride. The RO-units, however, remove 95% of the F^- in average, leaving only 0.04 mg/L. The result is a concentration so low that the drinking water from the RO-plants can be considered fluoride free. There is still a good reason for considering F^-, in correlation with some other contaminant, to cause CKDu in areas where there were no RO-plants when the illness was developed. Since the RO-plants are rather new, this goes for most incidents.

The results for Ca, Mg, hardness and Fe are shown in *Table 5.2*.

Ca and Mg concentrations are used to calculate hardness. The comments on hardness will be true for Ca and Mg as well. Hardness in the area is, as mentioned before, rather high. However, the results show that the RO-units remove most of the hardness in the water. There are some exceptions to this in the results in *Table 5.2*. The outlet at GND 57 shows high hardness, and the inlet at GND 115 shows a very low hardness, mainly caused by the Ca concentration. These results are contradicted by results from analysis at UoP. These results show that the calcium concentration in the outlet at GND 57 is 0.62 mg/L and the calcium concentration in the inlet at GND 115 is 41.32. There is a considerably amount of uncertainty for these results. When taken into consideration, the conclusion would be that the hardness in all the area is high, and all the RO-units examined will remove substantial amounts of hardness.

The amount of ferrous in the area is quite low. The World Health Organization (1996b) advices a limit of 2 mg/L of iron in drinking water. The raw water and the purified water in these cases are so low that ferrous will not be a health risk.

As shown in *Table 5.3* and *Table 5.4* there are interesting results regarding the other elements included in the analysis. *Table 6.1* gives a summary of these results.

Table 6.1: Summary of analysis results for B, Al, Cr, Mn, Co, Ni, Cu, and Zn from existing plants in NCP.

Element	**Average cons. raw water**	**Average removal rate**	**Average cons. permeate**	**Recommended limit (WHO)**
Boron	68.78 µg/L	21%	54 µg/L	500 µg/L
Aluminium	0.0154 mg/L	7%	0.0143 mg/L	0.1 mg/L
Chromium	0.178 µg/L	34%	0.116 µg/L	5 µg/L
Manganese	113.83 µg/L	98%	1.99 µg/L	30 µg/L
Cobalt	5.52 µg/L	17%	4.57 µg/L	100 µg/L
Nickel	2.00 mg/L	14%	1.71 mg/L	0.07 mg/L
Cobber	1.19 mg/L	67%	0.39 mg/L	2 mg/L
Zinc	0.0165 mg/L	- 51%	0.0250 mg/L	3 mg/L

As the results show, all the values are below the recommended limit, except for Nickel. It is however likely that the nickel is added to the water samples through the nitric acid used for conservation. This suspicion is verified by the analysis done on the sample from the research plant in Medawachchiya, Table 5.6. In this sample, sulfuric acid was added, and the analysis shows low levels of nickel. There is a very small chance that all these ten examined plants have high amounts of nickel, and the one at Medawachchiya has rather low concentrations. Therefore, it is safe to assume that the nitric acid contains a substantial amount of nickel. In conclusion it can be assumed that all the examined locations have low concentration of nickel.

There is a notable amount of Zinc “added” by the RO-units. This is not a surprise as contamination of some elements are rather common. Zinc, for instance, is present everywhere, especially in air dust. This means that the samples may have been contaminated during sampling, storage, transport and analysis. There is no foundation to conclude that the RO-units affect the Zinc concentrations in the water, when concentrations are this low. With a limit in drinking water set to 3 mg/L by WHO, the concentration in these waters are too low to be of any risk to human health.

It is not possible to find a tendency in treatment effect based on the age of the plant or the manufacturer. All the plants have satisfactory permeate quality. Other factors, like maintenance and raw water quality seem to make the biggest impact on the treatment effect although this impact this far is rather small.

Other than the role of these elements relating to CKDu, we can make some general assumptions of the effect of Reverse Osmosis on removal of some elements. There is a clear tendency in the results, that the process has below average removal of certain elements. As mentioned before, the concentration of the elements is way below levels injurious to health, and the observations are just a general assessment on the effect of RO. A general uncertainty must be taken into consideration with concentrations this low.

6.3 Ecosoft RO-plant

The results show that the permeate flow is within the limit in all the conducted regimes. The drain flow is a bit high in some of the operation regimes, deliberately chosen to prolong the life of the membrane by lowering the pressure.

By staying inside the given operation limits, it is possible to get a recovery rate of at least 85%. This is possible because of the high temperature, but not advisable since the membrane will have a shorter life span due to the higher pressure. Although the pressure is not above the operation limit.

Operation regime number 7, the final one, is the settings on which the unit is operating on a daily basis. This gives a recovery rate of 70%, and a feed flow rate 14.33 LPM. TDS of 16 g/L in the permeate is measured through conductivity. The raw water TDS at Medawachchiya is measured to be 3.45 g/L.

The analytical results show that the research plant at Medawachchiya is treating the water to a satisfying level. This goes for all the elements except for chromium. Here we have elevated levels hazardous for people. However, it looks like this is a faulty reading as raw water, permeate and drains have almost equal values. This suggests that it is the sulfuric acid added for conservation that has contained some chromium. All the other values are below the limits recommended by the WHO. This also goes for the raw water; the concentration is not above the limits. This indicates that heavy metals in water are also not a cause of CKDu in this area.

6.4 Bottled Water

Table 5.8 shows the average concentration of selected elements for the bottled water. While Appendix IV shows the results of all the analysis conducted.

None of the commercial bottled water bottles have harmful amounts of the elements checked. Based on these examinations, the bottled water in Sri Lanka is safe and free of harmful heavy metals. The assumption that bottled drinking water does contribute to CKDu is therefore, as far as this study shows, falsified.

6.5 Suggested Further Research

As this study has contained an installation of a pilot plant, and a review of the existing studies done on the matter of CKDu in Sri Lanka. Further research, both on the pilot plant and the role of water in CKDu is suggested using this research as a foundation.

6.5.1 Studies Using the RO-unit in Medawachchiya

Several possible studies can and should be conducted by using the RO-unit in Medawachchiya to achieve higher knowledge of the operation of RO-units in the area. These studies would build on the results achieved by this research, and therefore broaden the impact of this thesis.

Exploration of Membrane Types

A study of treatment effect with different membranes should be conducted. As of now, the membrane installed is a FILMTEC XLE-4040. This membrane needs low pressure to operate, which will result in fewer pollutants held back by the membrane at a given pressure. Further studies could use the following membranes. These membranes can be used in an Ecosoft RO-unit without any modifications.

FILMTEC LP-4040 and FILMTEC TW30-4040 are the same range of products as XLE-4040 with the same physical dimensions and operating limits. LP-4040 delivers high quality water at low pressure, but still requires higher pressure than the XLE-4040. TW30-4040 is the industry standard for reliable operation and production of the highest quality water. These elements are built with the same high quality membranes and construction materials as industrial elements and are more economical for small commercial systems.

Table 6.2: Operating limits for FILMTEC LP-4040 and TW30-4040 elements (DOW n.d.-a)

Membrane type	Polyamide Thin-Film Composite
Maximum operating temperature	45°C
Maximum operating pressure	41 bar
Maximum feed flow rate	3.2 m^3/h
Maximum pressure drop	0.9 bar
pH range, continuous operation	2 – 11
pH range, short term cleaning (30 min.)	1 – 13
Maximum feed silt density index	SDI 5

FILMTEC NF-4040 membranes is nanofiltration membranes from Dow. These NF membrane elements are designed for process applications where a separation of solutes is desired. It is designed to reject organics with a molecular weight above 200 while passing monovalent salts.

Table 6.3: Operating limits for FILMTEC NF-4040 (DOW n.d.-e)

Membrane type	Polypiperazine amide thin-film composite
Maximum operating temperature	45°C
Maximum operating pressure	41 bar
Maximum pressure drop	1.0 bar
pH range, continuous operation	3 – 10
pH range, short-term cleaning	1 – 12
Free chlorine concentration	< 0.1 ppm
Hydrogen peroxide, continuous operation	20 ppm

FILMTEC SW30-4040 membranes is a seawater reverse osmosis element which offer high productivity and an excellent salt rejection. These elements are specialized in desalination. They need a rather high operation pressure to produce water. They can be operated in lower pressure, the consequence being low permeate flow.

Table 6.4: Operating limits for FILMTEC SW30-4040 (DOW n.d.-f)

Membrane type	Polyamide Thin-Film Composite
Maximum operating temperature	45°C
Maximum operating pressure	69 bar
Maximum pressure drop	1.0 bar
pH range, continuous operation	2 – 11
pH range, short-term cleaning	1 – 13
Maximum feed silt density index	SDI 5
Free chlorine Tolerance	< 0.1 ppm

Treatment effect for the different membranes should be evaluated conjointly with permeate flow and energy usage.

Operation and its influence on drain quality

How to discard the drain from a RO-plant has long been an issue, especially when the drain has a high concentration of pollutants. The RO-units in Anuradhapura district discards the drain on the earth. Some will evaporate, but most of the water will infiltrate through the ground and into the ground water. With a small number of RO-units and a big aquifer, this is usually not a problem. In the North Central Province, there are a number of RO-units and the number just keeps growing to keep up with the increasing water demand.

A study using the RO-plant in Medawachchiya should research the change in drain water quality during different operation modes. Theoretically, the concentration of pollutants in the drain water should increase with higher permeate flow compared to drain flow. The impact this has on the local environment in Anuradhapura District is unknown.

The broader impact of the infiltrated drain on the ground water has not been looked into in Sri Lanka. A study looking for negative impact on the soil and ground water in a larger scale should be conducted. Analyses of drain flow, the soil where the infiltration has occurred, and local ground water should be analyzed. If the analyses indicate that the drain flow is having a negative effect on the ground water or the soil in the area, solutions should be proposed. It may be as easy as building an evaporation pond, as the weather is warm and sunny. Evaporation should occur fast; consequently, the pond should not need to be a large structure.

6.5.2 Questionnaire for People in CKDu Area

To get the full overview of the impact of CKDu, and especially RO-units as a solution, a questionnaire should be conducted in the area. The questionnaire should target CKDu affected persons and people living in the CKDu endangered areas, RO-plant operators, officials at the NWSDB and others that can shed light on CKDu and the role of RO-plants. This will help the Sri Lankan community to establish that pollutants in the ground water is the cause of CKDu and ensure that RO is the best solution for treating the ground water.

A tentative questionnaire to CKDu affected persons and people living in the CKDu area is shown on the next page. It is based on the assumption that the quality and quantity of drinking water may be a cause of CKDu.

Questionnaire for persons affected by CKDu or people living in affected areas

1. Gender
2. Age
3. Residence time in current area
4. Occupation
    - This part should clarify what kind of occupation the interviewee has, and of what nature it is.
        i. Outdoor or indoor?
        ii. Labor intensive?
        iii. How long they have been doing that particular work?
    - It is important to know if the interviewee is working in the agricultural sector:
        i. What kind of pesticide and fertilizer is used in that particular field?
        ii. What kind of crops are cultivated?
5. Family history with respect to CKDu

Family Member	Gender	Age	Health Condition

6. The water quantity should be examined.
    - Water intake per day
    - Time of consumption, how spread out is the intake
7. The water source should be examined
    - Water source.
        i. Ground water or surface water?
        ii. Water distributed through pipes?
        iii. Water treated before consumption?
        iv. How is the water stored?
        v. Is water always brought from home? Or is it a source where the interviewee works.

A separate questionnaire for the RO-operators should also be conducted. That questionnaire should include the following questions.

Questionnaire for RO-plant operators

1. General information
    - Manufacturer of plant, membrane and chemicals
    - Time of installation
    - Time of last membrane exchange
2. Training
    - Who gave the necessary training to the operator?
    - Is this knowledge updated in any way?
3. Operation
    - Operation procedure.
    - Operation interval
    - Disinfection of water
4. Maintenance
    - Maintenance procedure
    - Maintenance interval
    - Maintenance personnel
5. Quality
    - Is the quality controlled?
    - Who controls it?
6. Quantity
    - Quantity produced
    - Quantity sold
7. Impact
    - The operators' impression of the plants impact on the community
    - The plants impact on the operators' life

Other questionnaires could also be necessary to gather the information of interest.

6.5.3 Agrochemicals

This hypothesis of this thesis was greatly falsified when there were no heavy metals to be found in the water samples. This result clears the way for a new hypothesis. The most probable one being, “Organic compounds infiltrated into the ground water causes CKDu”, and these organic compounds are believed to come from pesticides and fertilizers.

There have been some studies checking this hypothesis. However, no conclusions have been made.

Dharma-Wardana et al. (2015) noted a correlation of incidences of CKDu and the ecological consequences of excess fertilizer use, often as much as 10 times the recommended amounts. The excess fertilizer is distributed through the region by the irrigation systems in the region, which adds to the ionicity of the water. It has been suggested that prolonged use of ionic water causes CKDu by a Hofmeister-type protein-denaturing mechanism in the kidney.

There are several studies doing a systematic literature search to find out what has been researched. Many of these include agrochemicals as one possible cause, for instance Wanigasuriya (2014), Wimalawansa (2014), and Weeraratna (2009).

Jayasinghe (2014) goes the furthest by concluding that “Chronic Kidney Disease of Unknown Etiology Should Be Renamed Chronic Agrochemical Nephropathy” after going through the recent evidence.

Noble et al. (2014) and Wimalawansa (2014) has also done a study of previous research on the matter, and the possibilities that pesticides and fertilizers are causing CKDu. Both of these studies do focus on heavy metals in combination with agrochemicals.

The problem with all of the mentioned studies is that there are no clinical investigations of the problem. There is a need of an in-depth inspection of the problem of agrochemicals. A laboratorial analysis for other agrochemicals than heavy metals in water, body-tissue and food needs to be done. There are strong implications that there is a need to confirm the implications so that the problem is found and the process of solving the problem can begin.

6.6 Recommended Treatment of Drinking Water

As mentioned there is mainly two groups of possible CKDu causes. Inorganic (metals etc.) and organic (pesticides etc.). Inorganic pollutants are more or less invalidated through this study, left is the organic pollutants.

Since agriculture is the alleged reason for the spread of the pollutants. The raw water quality will have seasonal fluctuations. Instead of adjusting treatment, if using chemical methods or ion exchange, based on raw water quality. It is a better solution to have a secure barrier which removes pollutants independently of raw water quality. RO is one such barrier.

Reverse Osmosis will continue to be the recommended technology of treating ground water in the North Central Province of Sri Lanka, if evaluated necessary a re-mineralization unit should be installed.

7 Conclusion

Several studies have pointed to heavy metals, originated from agrochemicals, as a probable cause of CKDu in Sri Lanka. This thesis has studied the hypothesis of heavy metals as the main cause of CKDu.

The hypothesis has been falsified during the analytical work in this thesis. The concentration of heavy metals in ground water, purified water, and bottled water are low and way below the concentration limits considered safe by WHO. There are no reasons to blame heavy metals in water for CKDu in the examined area.

Although the RO-units in all the examined cases have an adequate removal rate on heavy metals, critical methods of operating plants were found. It does not sacrifice the security of the water, regarding heavy metals, as far as this study know, but it shortens the lifespan of the membrane and allows biological growth in the permeate tank. To compete this, a pamphlet with correct installation and operation has been developed. This pamphlet should be distributed to all RO-plants in the area.

The research plant installed at Medawachchiya has been used for preliminary tests and examinations. The initial start-up and calibration showed good results. And the plant is operating and delivering water every day. Most research using this plant will be done following the completion of this thesis. Based on the analytical results in this thesis it is suggested that further research be conducted on the research plant to complete examinations with different membranes and the quality of the drain water. A questionnaire to people and operators in the area should also be conducted.

There is still a big need for RO-plants in NCP. The results show that the RO-plants already installed have good rejection rates. It is not possible to distinguish them from the results from the new plant installed during this research. Since the etiology of CKD is yet to be found, the best way to treat the water is with a total barrier for all the suspected pollutants. This results in safer water for the population in the North Central Province.

The research in this thesis points at organic compounds in agrochemicals as the probable cause of CKDu, when heavy metals are ruled out. Further studies regarding this issue are essential.

8 References

© OpenStreetMap contributors. (2016).

Agency for Toxic Substances and Disease Registry. (2008). Case Studies in Environmental Medicine (CSEM), Cadmium Toxicity.

Ahmed, M. F. (2001). *An overview of arsenic removal technologies in Bangladesh and India*. Proceedings of BUET-UNU International Workshop on Technologies for Arsenic Removal from Drinking Water, Dhaka. 5-7 pp.

Ayoob, S. & Gupta, A. K. (2006). Fluoride in drinking water: a review on the status and stress effects. *Critical Reviews in Environmental Science and Technology*, 36 (6): 433-487.

Bailey, J., Chilton, J., Dahi, E., Fawell, J. & Fewtrell, L. (2006). Fluoride in drinking-water (World Health Organization Drinking Water). *Geneva: World Health Organization*.

Bandara, J., Senevirathna, D., Dasanayake, D., Herath, V., Bandara, J., Abeysekara, T. & Rajapaksha, K. (2008). Chronic renal failure among farm families in cascade irrigation systems in Sri Lanka associated with elevated dietary cadmium levels in rice and freshwater fish (Tilapia). *Environmental Geochemistry and Health*, 30 (5): 465-478.

Bandara, J., Wijewardena, H., Liyanege, J., Upul, M. & Bandara, J. (2010). Chronic renal failure in Sri Lanka caused by elevated dietary cadmium: Trojan horse of the green revolution. *Toxicology Letters*, 198 (1): 33-39.

Bowen, H. J. M. (1966). Trace elements in biochemistry. *Trace Elements in Biochemistry.*

Chandrajith, R., Seneviratna, S., Wickramaarachchi, K., Attanayake, T., Aturaliya, T. & Dissanayake, C. (2010). Natural radionuclides and trace elements in rice field soils in relation to fertilizer application: study of a chronic kidney disease area in Sri Lanka. *Environmental Earth Sciences*, 60 (1): 193-201.

Chandrajith, R., Dissanayake, C., Ariyarathna, T., Herath, H. & Padmasiri, J. (2011a). Dose-dependent Na and Ca in fluoride-rich drinking water—another major cause of chronic renal failure in tropical arid regions. *Science of the Total Environment*, 409 (4): 671-675.

Chandrajith, R., Nanayakkara, S., Itai, K., Aturaliya, T., Dissanayake, C., Abeysekera, T., Harada, K., Watanabe, T. & Koizumi, A. (2011b). Chronic kidney diseases of uncertain etiology (CKDue) in Sri Lanka: geographic distribution and environmental implications. *Environmental Geochemistry and Health*, 33 (3): 267-278.

Choong, T. S., Chuah, T., Robiah, Y., Koay, F. G. & Azni, I. (2007). Arsenic toxicity, health hazards and removal techniques from water: an overview. *Desalination*, 217 (1): 139-166.

Clifford, D., Subramonian, S. & Sorg, T. J. (1986). Water treatment processes. III. Removing dissolved inorganic contaminants from water. *Environmental science & technology*, 20 (11): 1072-1080.

Clifford, D. A. (1999). Ion exchange and inorganic adsorption. *Water quality and treatment*, 4: 561-564.

Crittenden, J. C., Trussell, R. R., Hand, D. W., Howe, K. J. & Tchobanoglous, G. (2012). *MWH's Water Treatment: Principles and Design*: John Wiley & Sons.

Davis, M. L. (2010). *Water and wastewater engineering*: McGraw-Hill.

Degremont. (n.d.). *Reverse Osmosis Operating Principles*. Available at: http://www.degremont.com/cms/degremont_7_refonte/upload/savoir-faire/en/reverse_osmosis.png (accessed: 19/03).

Dharma-Wardana, M. W., Amarasiri, S. L., Dharmawardene, N. & Panabokke, C. R. (2015). Chronic kidney disease of unknown aetiology and ground-water ionicity: study based on Sri Lanka. *Environ Geochem Health*, 37 (2): 221-31.

Dharmaratne, R. W. (2015). Fluoride in drinking water and diet: the causative factor of chronic kidney diseases in the North Central Province of Sri Lanka. *Environ Health Prev Med*, 20 (4): 237-42.

Dissanayake, C. (1996). Water quality and dental health in the Dry Zone of Sri Lanka. *Geological Society, London, Special Publications*, 113 (1): 131-140.

DOW. (1998). *FILMTEC membranes - Factors Affecting RO Membrane Performance*

DOW. (2004). *FILMTEC, Reverse Osmosis Membranes, Technical Manual*.

DOW. (n.d.-a). *FILMTEC LP-4040 membranes*. 609-00364-0408.

DOW. (n.d.-b). *FILMTEC membranes FT30 Reverse Osmosis Membrane Specifications*. 609-01020-0406.

DOW. (n.d.-c). *Product information - Large Commercial 4040 Reverse Osmosis elements*. 609-02216-0811.

DOW. (n.d.-d). *Product Information DOW FILMTEC Membranes*. 609-00349-0512.

DOW. (n.d.-e). *Product Information, FILMTEC NF-4040 Membranes*. 609-00341-1008.

DOW. (n.d.-f). *Product information, FILMTEC SW30 membranes*. 609-00377-0406.

Dvorak, B. I. & Skipton, S. O. (2008). Drinking water treatment: Reverse osmosis. *University of Nebraska–Lincoln Extension, Institute of Agriculture and Natural Resources*.

Dvorak, B. I., Skipton, S., Woldt, W. & Kahle, A. (2014). Drinking Water: Arsenic. *University of Nebraska–Lincoln Extension, Institute of Agriculture and Natural Resources*.

Ecosoft. (n.d.-a). *Dosing Pump Calibration*.

Ecosoft. (n.d.-b). *Instruction Manual, Ecosoft RO-systems*.

Edmunds, W. & Smedley, P. (1996). Groundwater geochemistry and health: an overview. *Geological Society, London, Special Publications*, 113 (1): 91-105.

Environmental Protection Agency. (2001). Drinking water standard for Arsenic.

Fonseka, S., Jayasumana, C., Jayalath, K., Amarasinghe, M., Senanayake, K., Wijewardhane, C., Samarasinghe, D., Dahanayake, K., Mahamithawa, P. & Paranagama, P. (2012). Arsenic and hardness in ground water from Chronic Kidney Disease of Unknown Etiology (CKDU) prevalent areas and non-CKDU prevalent areas in Sri Lanka.

Global Environment Centre Foundation. (n.d.). *Total Nitrogen Analyzer*. Available at: http://nett21.gec.jp/CTT_DATA/WMON/CHAP_4/html/Wmon-087.html (accessed: 04/05).

Godwin, H. A. (2001). The biological chemistry of lead. *Current opinion in chemical biology*, 5 (2): 223-227.

Gomez-Caminero, A., Howe, P., Hughes, M., Kenyon, E., Lewis, D., Moore, M., Ng, J., Aitio, A. & Becking, G. (2001). *Environmental health criteria 224 arsenic and arsenic compounds*, vol. 13: World Health Organization.

Goosen, M. F., Sablani, S. S., Al-Maskari, S. S., Al-Belushi, R. H. & Wilf, M. (2002). Effect of feed temperature on permeate flux and mass transfer coefficient in spiral-wound reverse osmosis systems. *Desalination*, 144 (1): 367-372.

Gude, V. G. (2011). Energy consumption and recovery in reverse osmosis. *Desalination and water treatment*, 36 (1-3): 239-260.

Gunatilake, S. K., Samaratunga, S. S. & Rubasinghe, R. T. (2014). Chronic Kidney Disease (CKD) in Sri Lanka - Current Research Evidence Justification: A Review. *Sabaragamuwa University Journal*, 13 (2): 31-58.

Haraldsen, H. (2009). *Hardt Vann*: Store Norske Leksikon. Available at: https://snl.no/hardt_vann (accessed: 15/03).

Hem, J. D. (1972). Chemistry and occurrence of cadmium and zinc in surface water and groundwater. *Water Resources Research*, 8 (3): 661-679.

Hotta, N. (1989). Clinical aspects of chronic arsenic poisoning due to environmental and occupational pollution in and around a small refining spot. *日本体質学雑誌*, 53 (1): p49-70.

Hydranautics. (n.d.). *Membrane element - ESPA2-4040*.

IARC. (2006). Inorganic and Organic Lead Compounds. *IARC MONOGRAPHS*, 87.

IARC. (2012). Arsenic, metals, fibres, and dusts. *IARC MONOGRAPHS*, 100C.

Järup, L., Berglund, M., Elinder, C. G., Nordberg, G. & Vanter, M. (1998). Health effects of cadmium exposure–a review of the literature and a risk estimate. *Scandinavian journal of work, environment & health*: 1-51.

Jayasekara, J., Dissanayake, D., Adhikari, S. & Bandara, P. (2013). Geographical distribution of chronic kidney disease of unknown origin in North Central Region of Sri Lanka. *Ceylon Med J*, 58 (1): 6-10.

Jayasinghe, S. M. M. F. (2014). Chronic kidney disease of unknown etiology should be renamed chronic agrochemical nephropathy. *MEDICC review*, 16: 72-74.

Jayasumana, C., Gajanayake, R. & Siribaddana, S. (2014a). Importance of Arsenic and pesticides in epidemic chronic kidney disease in Sri Lanka. *BMC nephrology*, 15 (1): 124.

Jayasumana, C., Gunatilake, S. & Senanayake, P. (2014b). Glyphosate, hard water and nephrotoxic metals: are they the culprits behind the epidemic of chronic kidney disease of unknown etiology in Sri Lanka? *International journal of environmental research and public health*, 11 (2): 2125-2147.

Jayasumana, M., Paranagama, P., Amarasinghe, M. & Fonseka, S. (2013a). *Is hard water an etiological factor for CKDu*. Mesoamerican Nephropathy: Report From the First International Research Workshop on MeN, SALTRA/IRET-UNA, Heredia, Costa Rica. 91-94 pp.

Jayasumana, M., Paranagama, P., Amarasinghe, M., Wijewardane, K., Dahanayake, K., Fonseka, S., Rajakaruna, K., Mahamithawa, A., Samarasinghe, U. & Senanayake, V. (2013b). Possible link of chronic arsenic toxicity with chronic kidney disease of unknown etiology in Sri Lanka. *Journal of Natural Sciences Research*, 3 (1): 64-73.

Jayatilake, N., Mendis, S., Maheepala, P. & Mehta, F. R. (2013). Chronic kidney disease of uncertain aetiology: prevalence and causative factors in a developing country. *BMC nephrology*, 14 (1): 180.

Joint, F. & Organization, W. H. (2005). Vitamin and mineral requirements in human nutrition.

Kartinen, E. O. & Martin, C. J. (1995). An overview of arsenic removal processes. *Desalination*, 103 (1): 79-88.

Laboratory Testing Inc. (n.d.). *ICP Analysis*. Available at: https://www.labtesting.com/services/materials-testing/chemical-analysis/icp-analysis/ (accessed: 27/04).

Lenntech BV. (n.d.). *Remineralisation*. Available at: http://www.lenntech.com/processes/remineralisation/remineralisation.htm (accessed: 09/05).

Lesikar, B. J., Melton, R., Hare, M., Hopkins, J. & Dozier, M. (2005). Drinking water problems: Arsenic.

Maheshwari, R. (2006). Fluoride in drinking water and its removal. *Journal of Hazardous materials*, 137 (1): 456-463.

Mohapatra, M., Anand, S., Mishra, B., Giles, D. E. & Singh, P. (2009). Review of fluoride removal from drinking water. *Journal of Environmental Management*, 91 (1): 67-77.

Nanayakkara, S., Senevirathna, S., Abeysekera, T., Chandrajith, R., Ratnatunga, N., Gunarathne, E., Yan, J., Hitomi, T., Muso, E. & Komiya, T. (2014). An integrative study of the genetic, social and environmental determinants of chronic kidney disease characterized by tubulointerstitial damages in the North Central Region of Sri Lanka. *Journal of Occupational Health*, 56 (1): 28-38.

Ning, R. Y. (2002). Arsenic removal by reverse osmosis. *Desalination*, 143 (3): 237-241.

Noble, A., Amerasinghe, P., Manthrithilake, H. & Arasalingam, S. (2014). Review of Literature on Chronic Kidney Disease of Unknown Etiology (CKDu) in Sri Lanka. *International Water Management Institute*: 41.

NWSDB Anuradhapura District. (2015). *Progress related to CKDu/CKD*. Unpublished manuscript.

Oram, B. (2013). *Hard Water*. Water Research Center. Available at: http://www.water-research.net/index.php/water-treatment/tools/hard-water-hardness (accessed: 15/03).

Raj, R. J. (2014). Is reverse osmosis (RO) treatment the answer to solving the CKDu riddle? *Lindha Langa (ළිඳ ළඟ).*

Schiffl, H. (2007). Fluoridation of drinking water and chronic kidney disease: absence of evidence is not evidence of absence. *Nephrology Dialysis Transplantation*.

Shimadzu. (n.d.-a). *TNM-L*. Available at: http://www.shimadzu.com/an/toc/lab/tnm-l.html (accessed: 03/05).

Shimadzu. (n.d.-b). *TOC-L*. Available at: http://www.shimadzu.com/an/toc/lab/toc-l4.html (accessed: 03/05).

Sun, H. (2011). *Biological chemistry of arsenic, antimony and bismuth*: Wiley Online Library.

Talbot, D. (2015). *Megascale Desalination*. MIT Technology Review. Available at: https://www.technologyreview.com/s/534996/megascale-desalination/ (accessed: 19/03).

Van der Bruggen, B., Vandecasteele, C., Van Gestel, T., Doyen, W. & Leysen, R. (2003). A review of pressure-driven membrane processes in wastewater treatment and drinking water production. *Environmental progress*, 22 (1): 46-56.

Wanigasuriya, K. (2012). Aetiological factors of Chronic Kidney Disease in the North Central Province of Sri Lanka: A review of evidence to-date. *Journal of the College of Community Physicians of Sri Lanka*, 17 (1).

Wanigasuriya, K. (2014). Update on uncertain etiology of chronic kidney disease in Sri Lanka's north-central dry zone. *MEDICC review*, 16 (2): 61-65.

Wedepohl, K. H. (1995). The composition of the continental crust. *Geochimica et cosmochimica Acta*, 59 (7): 1217-1232.

Weeraratna, C. (2009). Fertilizer use in Sri Lanka with special reference to Chronic Kidney Disease of unidentified etiology (CKDu). *TSP*, 2010: 2011.

Wimalawansa, S. J. (2014). Escalating chronic kidney diseases of multi-factorial origin in Sri Lanka: causes, solutions, and recommendations. *Environ Health Prev Med*, 19 (6): 375-94.

World Health Organization. (1996a). Hardness in Drinking-water.

World Health Organization. (1996b). Iron in Drinking-water.

World Health Organization. (2003). Lead in drinking-water: background document for development of WHO guidelines for drinking-water quality.

World Health Organization. (2004). *Guidelines for drinking-water quality: recommendations*, vol. 1: World Health Organization.

World Health Organization. (2009). *Calcium and Magnesium in Drinking-water: Public health significance*: World Health Organization.

World Health Organization. (2011a). *Arsenic in Drinking-water*. Background document for development of WHO Guidelines for Drinking-water Quality.

World Health Organization. (2011b). *Cadmium in Drinking-water*. Background document for development of WHO Guidelines for Drinking-water Quality.

Xiong, X., Liu, J., He, W., Xia, T., He, P., Chen, X., Yang, K. & Wang, A. (2007). Dose–effect relationship between drinking water fluoride levels and damage to liver and kidney functions in children. *Environmental Research*, 103 (1): 112-116.

Appendix I – Existing RO-plants

Pictures from the four different kinds of RO-units examined. Photos shot on the day of sampling.

GND 57 – Panda Water Tech

GND 81 – Hayles Ind. (Puritas Private LTD.)

GND 102 – Pure Aqua Inc. TW-3.0K-240

GND108 – Pure Aqua Inc. TW-4.5K-340

Appendix II – Sampling Process

Example of sample points, and how the samples were taken

GND 72 – sampling of raw water

GND 108 – sampling of permeate

GND 115 – sampling of raw water

Appendix III – Installation of Research Plant

Pictures of the pilot plant during installation, calibration and finalization

Appendix IV – Results, Commercially Bottled Water

Full results from water analyses of commercially bottled water.

	B	Mg	Al	Ca	Cr	Mn	Fe	Co	Ni	Cu	Zn	As	Cd	Pb
	µg/L	mg/L	mg/L	mg/L	µg/L	µg/L	mg/L	µg/L	mg/L	mg/L	mg/L	µg/L	µg/L	µg/L
B1	6.5	4.3	0.0011	8	0.08	0.34	0.005	0.011	0.00083	0.00071	0.0018	0.0073	<0.0021	0.34
B1	6.3	4.2	0.00085	8.2	<0,078	0.31	<0.0042	0.011	0.0008	0.0006	0.0018	<0.0054	<0.0021	0.33
B1	6.8	4.3	0.0012	7.9	<0,078	0.33	0.0046	0.013	0.0015	0.00078	0.0018	0.011	<0.0021	0.36
B2	5.1	0.95	0.013	1.6	<0,078	13	<LD	0.48	0.0023	0.0014	0.0024	<0.0054	0.0086	0.079
B2	5.1	0.98	0.014	1.6	<0,078	14	<LD	0.48	0.0021	0.0012	0.0024	<LD	0.0065	0.17
B2	4.3	0.95	0.014	1.6	<0,078	14	<LD	0.47	0.00073	0.00089	0.0024	<0.0054	0.0085	0.096
B3	2.9	0.92	0.0016	2.6	<0,078	11	<LD	0.25	0.0015	0.0016	0.0032	<0.0054	0.0045	0.087
B3	3	0.97	0.001	2.6	<LD	11	<LD	0.25	0.0011	0.0013	0.0032	<0.0054	0.0052	0.085
B4	4.9	1.6	0.012	3.5	1.5	8.7	<LD	0.15	0.0032	0.0012	0.0055	<0.0054	0.013	0.1
B4	4.2	1.6	0.012	3.4	1.4	8.3	<LD	0.14	0.0024	0.00089	0.0052	<LD	0.0083	0.043
B5	2.5	1	0.00052	1.6	0.12	0.057	<0.0042	0.0087	<0.00029	0.00073	0.0027	<0.0054	0.0023	0.17
B5	2.6	1	<0.0003	1.6	0.094	0.03	<LD	0.012	0.0017	0.001	0.0013	0.0067	<0.0021	0.076
B5	2.6	1	0.00075	1.6	0.12	0.046	<LD	0.0091	0.00033	0.0008	0.0013	0.0067	0.0025	0.15
B6	14	1.3	0.031	2.8	<0.078	24	<0.0042	0.46	0.0025	0.0091	0.013	0.017	0.014	1.3
B6	14	1.3	0.03	2.7	<0.078	23	<0.0042	0.44	0.0011	0.0087	0.013	0.014	0.014	1.3
B6	14	1.3	0.032	2.8	0.097	23	<0.0042	0.45	0.00094	0.0089	0.013	0.014	0.011	1.3
B7	3.4	2.2	<LD	3.8	<0.078	0.019	<LD	0.012	<0.00029	0.0016	0.0012	0.0076	<LD	0.093
B7	3.7	2.2	<0,0003	3.9	<0.078	0.029	<LD	0.0079	0.0006	0.0017	0.0012	0.013	<0.0021	0.094
B7	3.6	2.2	<LD	3.8	<0.078	0.05	<LD	0.0099	0.00059	0.0017	0.0012	0.012	<0.0021	0.084
B8	16	0.031	0.00038	0.091	0.11	0.043	<LD	0.0063	<0.00029	0.00024	0.00096	0.011	<0.0021	0.069
B8	15	0.036	<0.0003	0.099	0.16	0.044	<LD	0.0095	<0.00029	0.00027	0.00086	<LD	<0.0021	0.055
B8	16	0.05	0.0015	0.19	0.16	0.093	<LD	0.013	0.0014	0.0005	0.0011	<0.0054	<0.0021	0.29
B9	4	2.4	0.00075	5.2	0.11	0.3	0.0072	0.016	0.00089	0.00064	0.00082	<0.0054	0.0043	0.077
B9	4.2	2.4	0.00097	5.2	0.1	0.22	<0.0042	0.019	0.0015	0.00074	0.00085	0.0065	0.005	0.44
B9	4	2.4	0.0019	5.1	<0.078	0.19	<0.0042	0.015	0.0014	0.00076	0.00096	<0.0054	0.0042	0.2
B10	5.6	1.3	0.005	3.8	0.51	4.5	<0.0042	0.018	0.00068	0.00059	0.00096	0.01	0.0022	0.1
B10	5.4	1.3	0.005	3.8	0.5	4.6	<LD	0.017	0.00053	0.00063	0.001	0.0091	0.0029	0.067
B10	6	1.4	0.0055	3.8	0.55	4.7	<LD	0.023	0.0031	0.0011	0.0011	0.014	0.0024	0.15

Norges miljø- og biovitenskapelig universitet
Noregs miljø- og biovitskapelege universitet
Norwegian University of Life Sciences

Postboks 5003
NO-1432 Ås
Norway