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Groundwater quality in the endemic areas of chronic kidney disease of unknown etiology in Sri Lanka and its treatment by community-based reverse osmosis water treatment plants

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GROUNDWATER QUALITY IN THE ENDEMIC AREAS OF CHRONIC KIDNEY DISEASE OF UNKNOWN ETIOLOGY IN SRI LANKA AND ITS TREATMENT BY COMMUNITY-BASED REVERSE OSMOSIS WATER TREATMENT PLANTS

Sachithra Madhushani Imbulana

No. 1309 March 2022

Asian Development Bank Institute

Sachithra Madhushani Imbulana was studying for a master's degree in urban engineering at the University of Tokyo at the time of writing this thesis.

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Abstract

Community-based reverse osmosis (RO) water treatment plants provide an interim solution for producing safe drinking water for the endemic areas of chronic kidney disease of unknown etiology (CKDu) in the rural dry zone of Sri Lanka. RO-treated groundwater diminishes the progression of CKDu; thus, proper maintenance of these RO plants is indispensable to protect public health. This study investigated the quality characteristics of groundwater in the endemic areas of CKDu; the performance, operations, and maintenance (O&M) of the existing RO plants; and the socio-economic background of the RO plants. The study analyzed feedwater (i.e., groundwater) and treated water from 32 RO plants in Anuradhapura District, comprising 27 the CKDu hiah-risk (HR) reaion in and five in the low-risk (LR) region, to establish the major chemical and biological water quality parameters. The alkalinity, hardness, and microbiological parameters in groundwater exceeded the maximum allowable levels (MALs) for drinking in all the study areas. Additionally, the total dissolved solids (TDS) and magnesium exceeded the MALs exclusively in the HR areas. The quality and the chemical composition of groundwater did not indicate significant seasonal differences. The elevated occurrence of magnesium-predominant hardness and ionicity in groundwater showed a significant relationship with the incidence of CKDu. All the RO plants achieved high removal rates (>90%) for excessive chemical constituents in groundwater, but the recovery rates were slightly low (~46%). The current disinfection practices in the RO plants were insufficient to ensure the microbial safety of the product water. The low demand for product water, scarcity of groundwater, lack of technical capacity of the local communities, poor maintenance practices, and unplanned brine removal were the key issues concerning RO plant O&M. Unless properly handled, the lack of rules and regulations for RO water treatment in the CKDu-endemic region could lead to numerous environmental and public health issues in the future.

Keywords: chronic kidney disease of unknown etiology (CKDu), community-based water supply, groundwater, reverse osmosis, water quality

JEL Classification: |

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1. INTRODUCTION

1.1 Background

A unique form of deadly chronic kidney disease that has no association with any traditional risk factors of kidney ailments has emerged in Sri Lanka since the mid-1990s (Athuraliya et al. 2011; Elledge et al. 2014). This disease was named "chronic kidney disease of unknown etiology" (CKDu), because its actual cause is unknown. CKDu is largely observable in the rural dry zone of Sri Lanka, which experiences year-round high temperatures (25–30°C) and limited rainfall (<1,500 mm/year) (Department of Meteorology Sri Lanka 2000). The highest disease prevalence (4.7%) is reportedly in the North Central Province (NCP), where the primary victims are paddy farmers from low socio-economic backgrounds (Jayatilake et al. 2013; Senanayake et al. 2020). CKDu has created a serious public health crisis within the context of Sri Lanka due to its rising prevalence and associated mortality.

Multidisciplinary studies over nearly three decades have postulated a large number of potential risk factors to describe the genesis and development of CKDu. While none of these risk factors have provided clear scientific evidence indicating that they cause the disease, a strong suspect is the direct or indirect influence of the drinking of groundwater as a result of some irrefutable facts that support a hydrogeochemical etiology for CKDu, as the study explains below.

Groundwater from shallow and tube wells is the primary source of drinking water for nearly 90% of the inhabitants of the NCP (Chandrajith et al. 2011a). Extensive water quality studies have revealed that groundwater in this region is not fit for direct potable purposes as it contains elevated levels of fluoride, hardness, and other ions that exceed international and local drinking water quality standards (Dissanayake 1996; Herath and Ratnayake 2010; Chandrajith et al. 2011b; Wasana et al. 2016; Wickramarathna et al. 2017). Therefore, many researchers have attempted to draw links between the occurrence of CKDu and the elevated concentrations of these constituents in groundwater.

Studies have suggested a close relationship between the fluoride in groundwater and the occurrence of CKDu, as the CKDu-affected areas overlap with the zones with groundwater containing high fluoride levels (Dissanayake 1996; Chandrajith et al. 2011a). Additionally, research has found that more than 96% of CKDu subjects had consumed shallow well water containing high hardness levels (from 120 mg/L of CaCO₃ to levels exceeding 180 mg/L of CaCO₃) (Jayasumana, Gunatilake, and Senanayake 2014). Chandrajith et al. (2011b), Dharma-wardana et al. (2015), Thammitiyagodage et al. (2017), Wasana et al. (2017), and Dharma-wardana (2018) investigated the possible ways in which the above-mentioned dissolved ions in groundwater may act together to induce toxicity in human kidneys.

Despite the scarce scientific evidence, some research findings and anecdotal evidence have suggested that providing safe drinking water that complies with the drinking water quality guidelines/standards helps in reducing the occurrence of CKDu. For instance, a very low incidence of the disease was apparent among people who consumed natural spring water and treated water from large municipal water supply schemes while living within the hotspots of CKDu (Jayasumana, Gunatilake, and Senanayake 2014; Jayasekara et al. 2015; Wasana et al. 2016). This suggested supplying safe drinking water as a possible intervention in CKDu, even in the absence of knowledge about its real root cause. Moreover, researchers have considered reducing the excessive contents of fluoride, hardness, and other dissolved ions in groundwater to be effective not only in

mitigating the incidence of CKDu but also in protecting the residents from other health impacts of drinking high-fluoride water and/or hard water. Considering these facts, small communities facing CKDu while experiencing difficulties in finding alternative sources of safe drinking water have embraced community-based reverse osmosis (RO) water treatment as a holistic interim solution.

More than 600 RO plants are currently in operation within the endemic areas of CKDu in the NCP. The National Water Supply and Drainage Board (NWSDB) and the Sri Lanka Navy respectively initiated nearly 27% and 28% of these plants within several social welfare projects of the government. The community-based organizations (CBOs) now operate and maintain these plants. The remaining 45% largely comprises RO plants under the private ownership of CBOs and various social groups (information from the Regional Supporting Centre of NWSDB, Anuradhapura).

Nowadays, RO-treated water is the main source of potable water in CKDu-affected areas. Personal communications with the water supply authorities and residents of the endemic areas revealed that RO-treated water seems to have reduced the incidence of CKDu and issues concerning the urinary tract while increasing the intake of drinking water among the consumers. Nonetheless, the construction and the operations and maintenance (O&M) of RO plants involve high costs and require technical skills; thus, the adoption of RO plants to reduce the incidence of CKDu often encounters arguments, considering the difficulties that local people may face in operating and maintaining the RO plants in these rural settings. A limited number of publications to date have reported on the operation of these plants (Jayasumana et al. 2016) and their overall performance based on comprehensive water quality assessments.

1.2 Objectives

To provide insights to fill the above-mentioned gaps in the previous research, the objectives of the present study were the following:

- i. To determine the quality of groundwater in the endemic areas of CKDu (with respect to the drinking water standards) and its seasonal variations and to understand the differences in groundwater quality in CKDu between high-risk and low-risk areas;
- ii. To verify the effectiveness of the existing RO plants in reducing the excessive constituents in groundwater to meet the drinking water quality standards; and
- iii. To provide an overview of the current status and problems of the O&M of the RO plants.

2. LITERATURE REVIEW

2.1 What is CKDu?

Chronic kidney disease (CKD) is a global health problem of a "non-communicable" nature that causes nearly 700 million active cases and 1.2 million deaths annually (GBD–CKD Collaboration 2020). While research has recognized hypertension, diabetes, and chronic glomerulonephritis as common risk factors of CKD (Athuraliya et al. 2011), many parts of the world have reported a different form of the disease that is asymptomatic of any of these traditional risk factors. The general term for this condition is CKD of unknown etiology (CKDu), and its diagnosis involves exclusion criteria, whereby patients fulfill the CKD criteria of the Kidney Disease Improving Global Outcomes (KDIGO) yet fail to

present evidence of any of the commonly known risk factors (Gifford et al. 2017). CKDu progresses slowly, and the symptoms are often observable when the disease reaches the end stage, causing irreversible damage to the kidneys (Elledge et al. 2014; Noble et al. 2014).

CKDu is widely prevalent in certain developing countries of the tropical arid regions (mostly equatorial countries) of Central America, Eastern Europe, and South Asia (Lunyera et al. 2016). Balkan endemic nephropathy (BEN) in countries around the Danube River basin, such as Serbia, Bosnia, Croatia, Bulgaria, and Romania; Mesoamerican nephropathy (MeN) among sugar cane cutters, mainly from El Salvador and Nicaragua; Uddanam endemic nephropathy in Andra Pradesh, India; and CKDu in the rural dry zone of Sri Lanka provide the best examples of well-known CKDu cases across the world. A striking similarity of these nephropathies is their strong prevalence among rural agricultural communities that engage in strenuous labor under hot climatic conditions (Weaver, Fadrowski, and Jaar 2015; Levine et al. 2016; Gifford et al. 2017; Kumaresan and Seneviratne 2017; Johnson, Wesseling, and Newman 2019). Decades of research have revealed in the recent past that BEN results from chronic dietary exposure to aristolochic acid via *Aristolochia clematitis*, a weed that grows in the wheat fields of the endemic region (Stiborová, Arlt, and Schmeiser 2016). Nevertheless, the causes of CKDu elsewhere remain unidentified despite immense research efforts.

2.2 CKDu in Sri Lanka

The first report of CKDu in Sri Lanka occurred in the NCP in the rural dry zone (temperature: 25–30°C and mean annual rainfall: <1,500 mm) around the mid-1990s (Athuraliya et al. 2011; Elledge et al. 2014). Sri Lanka consists of nine provinces, of which the NCP is the largest, covering 15% of the total land area and 5.5% of the total population in Sri Lanka. Early socio-demographic studies identified 2–3% of the prevalence of CKDu in the NCP (Athuraliya et al. 2006), but recent studies have reported an increased incidence of around 15–23% (Rajapakse, Shivanthan, and Selvarajah 2016).

Of the two administrative districts of the NCP, Anuradhapura (with a population of 745,700 spread across an area of 6,664 sq. km) and Polonnaruwa (with a population of 359,000 spread across an area of 3,077 sq. km.), Anuradhapura reported the highest number of CKDu incidents, which was three times higher than the number of cases and death in Polonnaruwa (Poulter and Mendis 2009). Medical and clinical evidence has suggested an annual death rate of 1,400 due to CKDu, and, to date, the areas of the NCP with the highest prevalence have reported approximately 70,000 cases from CKDu (Kumaresan and Seneviratne 2017). In the meantime, research has found that the disease has propagated rapidly to other farming areas of the dry zone that are outside the NCP (the Northern, Eastern, North Western, Central, and Uva provinces) over the past 3 decades (Jayatilake et al. 2013; Noble et al. 2014; Jayasumana et al. 2015a).

The prevalence of CKDu in Sri Lanka is relatively high among female (17%) compared with male individuals (13%), but the more severe form of the disease that is, stages 3 and 4, is more significant among male (23%) than among female patients (7%) (Kumaresan and Seneviratne 2017). A majority of the male patients are farmers in the 30–60 year age group who have been continuously engaged in agricultural activities for more than a decade, and most of them are from a very low socio-economic background (Athuraliya et al. 2006; Jayatilake et al. 2013; Elledge et al. 2014). Nevertheless, a recent study elucidated early renal damage among children living in the endemic regions of Sri Lanka, suggesting propagation of the disease to early ages (Agampodi et al. 2018).

The most comprehensive research program in relation to CKDu in Sri Lanka to date has been the "Sri Lanka National Research Program for CKDu" (from 2009 to 2012), which was a collaborative project of the Ministry of Health Sri Lanka and the World Health Organization (WHO). This project developed a definition of CKDu in Sri Lanka, which included the following three main criteria (Jayasumana, Gunatilake, and Senanayake 2014):

- i. No history of, or current treatment for, diabetes mellitus or chronic and/or severe hypertension, snake bites, urological disease of known etiology, or glomerulonephritis;
- ii. Normal glycosylated hemoglobin levels (HbAiC <6.5%);
- iii. Blood pressure <160/100 mmHg untreated or <140/90 mmHg on up to two antihypertensive agents.

Research has found that CKDu mainly affects the proximal tubules and interstitium, leading to histopathological changes and the appearance of clinical features. There are four stages (stages 1 to 4) of the disease based on proteinuria and cut-off values of eGFR (in ml/min/1.73 m²). The principal abnormalities apparent in CKDu are proteinuria (albumin–creatinine ratio (ACR)) ≥30 mg/g and unbalanced renal function (Jayasumana, Gunatilake, and Senanayake 2014). The most noticeable symptoms of CKDu in Sri Lanka are fatigue, panting, a lack of appetite, nausea, anemia, and abnormal skin manifestations, like spotty pigmentation on the soles and palms.

CKDu is the normal diagnosis when the kidney function is largely dilapidated; therefore, the ultimate treatment solutions are either dialysis or kidney transplantation (Noble et al. 2014). Only specialized hospitals in Sri Lanka carry out such treatments, and they are not affordable to a majority of the rural communities; thus, the free public health care services of Sri Lanka strive hard to meet the escalating demand for renal treatments of CKDu patients (Kumaresan and Seneviratne 2017). Renal treatments account for nearly 4% of the public healthcare budget, yet the demand keeps growing with the escalating incidence of the disease (Elledge et al. 2014).

2.3 Suspected Risk Factors of CKDu in Sri Lanka

A large number of studies covering socio-economic, environmental, health, geoenvironmental, geo-chemical, and many more disciplines have taken place over the past 3 decades with the aim of revealing the cause of CKDu in Sri Lanka. While none of these studies have presented conclusive evidence on the origin of the disease, the confined nature of the geographical and socio-economic disease patterns has implied that toxicity associated with geo-environmental and occupational factors may be contributing to this epidemic (Wanigasuriya et al. 2007; Chandrajith et al. 2011a, 2011b; Jayasekara et al. 2015; Jayasumana et al. 2015a; Edirisinghe et al. 2017).

Some of the popular theories/hypotheses that are under debate are (Figure 1) chronic exposure to nephrotoxic elements, such as agrochemical residues and toxic heavy metals, mainly arsenic and cadmium, during farming activities; long-term consumption of untreated groundwater, which contains elevated hardness and dissolved ions and their dose-dependent interactions; and occupational exposure to hot climatic conditions and subsequent low water intake, which result in dehydration of the kidneys.

In addition, genetic predisposition, the nutritional status of individuals, a history of viral infections and snake bites, and lifestyle habits are under consideration because it is possible to find CKDu non-affected families/individuals even within an endemic village despite their common exposure to similar geo-environmental conditions as CKDu patients (Chandrajith et al. 2011a, 2011b).



Figure 1: Suspected Risk Factors of CKDu in Sri Lanka

Source: Author.

2.4 Identification of the Most Likely Risk Factors of CKDu

Several past studies have attempted to identify the cause of CKDu through case–controltype research. A part of the present study included an intensive literature review focusing on such case–control studies to identify the most likely risk factor/s of CKDu in Sri Lanka. Table 1 summarizes the findings of this review.

The 14 research areas in Table 1 were different from one another; therefore, making a comparison between them was quite difficult. However, it was possible to categorize them simply based on the sources and types of contaminants (Table 2). The studies investigated:

- The potential harmful effect of groundwater quality and its ionic interactions, or
- Heavy metal contamination through food/drinking water/agrochemicals; or
- Other risk factors, like viral infections.

	Area of Study	Authors	Potential Causes
1	Fluoride (F) and cadmium (Cd) in groundwater Cd in human urine	Chandrajith et al. (2011a)	Fluoride (F) in groundwater (exposure to Cd through any source is not a likely cause)
2	Interactions between ionic constituents in groundwater	Chandrajith et al. (2011b)	F ⁻ and Ca ²⁺ when present together in low Na ⁺ concentrations in groundwater
3	Heavy metals and pesticides in urine, blood, hair, and nails Heavy metals in water, food, tobacco, soil, and agrochemicals	Jayatilake et al. (2013)	Chronic exposure to low levels of Cd, probably through the food chain and pesticides <i>but not through drinking</i> <i>water</i>
4	Urinary β2 microglobulin (β2m) excretion and dietary pattern	Siriwardhana et al. (2014)	Potential exposure to heavy metals (the dietary pattern has no effect)
5	Occupational exposure to pesticides and fertilizers	Jayasumana et al. (2015a)	Exposure to agrochemicals in paddy cultivation
	Consumption of well water		Drinking well water, especially from wells abandoned for a long period
6	Nephrotoxic elements (As, Cd, Pb, and U) in drinking water and human urine	Rango et al. (2015)	Exposure to nephrotoxic elements through sources other than drinking water
7	F, Al, Cd, As, and hardness in drinking water	Wasana et al. (2016)	Synergic effect of fluoride, hardness, and Cd in drinking water
8	Nephrotoxic elements (mainly Cd and As) in hair and nails	Diyabalanage et al. (2016)	Exposure to As and Cd is not a likely cause
9	Viral infections	Gamage et al. (2017)	Subclinical hantavirus infections
10	Fluoride toxicity in rats fed with well water	Thammitiya-godage et al. (2017)	Fluoride in groundwater
11	Interactions among ions in drinking water	Paranagama, Bhuiyan, and Jayasuriya (2018)	Multiple interactions among F ⁻ , Cl ⁻ , Ca ²⁺ , Mg ²⁺ , and Na ⁺ in drinking water
12	Groundwater dynamics	Edirisinghe et al. (2017)	The quality of groundwater that is directly recharged by rain (agrochemicals mixed with groundwater are not a cause)
13	Nephrotoxic heavy metals in well water, rice, and urine	Herath et al. (2018)	Nephrotoxic heavy metals, including As, Cd, Pb, and Cr, are not likely causes
14	Characteristics of groundwater	Balasooriya et al. (2019)	Synergistic effect of fluoride and hardness in groundwater

Table 1: Summary of the Case Control Studies on the Etiology Determination of CKDu

Source: Author.

Eight studies in Table 2 concluded that groundwater is a potential source of contaminants, whereas most of the other studies suggested that the source is food/agrochemicals/viruses. Meanwhile, two studies (studies 3 and 6) rejected groundwater as the source but failed to confirm the other most likely source/s of contaminants.

	No. of Studies (Out of 14)				
Source	For	Against			
Groundwater	8	2			
Food	1	1			
Agrochemicals	2	1			
Other	1	-			

Table 2: Categorization of the Case–Control Studies Based on the Source of Contaminants

Source: Author.

The potential contaminants that are responsible for the disease (Table 3) could be either heavy metals and pesticide residues or geochemical contaminants in groundwater. It is rather clear that a higher number of studies supported the latter category, that is, groundwater. Interestingly, none of the studies supporting exposure to heavy metal as a cause claimed that the potential source is groundwater. This was due to the negligible concentrations of heavy metal residues that they found in groundwater. Instead, they identified agrochemicals, food, or tobacco as the potential sources.

Table 3: Categories of Case–Control Studies Based on Types of Contaminants

	No. of Studies (Out of 14)		
Contaminants	For	Against	
Elevated levels of fluoride, hardness, and other ionic constituents and their interactions in groundwater	6	_	
Nephrotoxic compounds, including heavy metals (Cd, As, Pb, etc.) and agrochemical residues	4	3	

Source: Author.

This review showed that groundwater contamination due to elevated levels of fluoride, hardness, and other dissolved ions and their harmful complexations seem to be the most-suspected risk factor of CKDu under investigation so far.

2.5 Water Resources in the Endemic Areas of CKDu

The dry zone of Sri Lanka, including the NCP, the geographic hotspot of CKDu in the country, suffers extremely dry weather conditions and limited rainfall. Therefore, supplying enough water to fulfill daily water needs is challenging. The NCP is the home to one of the ancient tank cascade systems in Asia that has supplied water for irrigation-based agriculture in the dry zone for nearly two millennia (Madduma Bandara 1985). "A 'cascade' is a connected series of tanks (more like man-made reservoirs) organized within a micro/meso-catchment of the dry zone landscape for storing, conveying and utilizing water from an ephemeral rivulet" (Geekiyanage and Pushpakumara 2013).

As the population kept growing, the subsequent expansion of agricultural activities started stressing the limited water resources of the dry zone. To meet this increased demand, the exploitation of groundwater commenced in the dry zone around the 1960s. The literature has reported rapid growth of bore hole excavations since then, resulting in about 50,000 agro-wells (~10 m deep) by the end of 2000. The concentration of the majority of these shallow wells along the minor irrigation schemes of the north central (NCP) and north western parts of the dry zone was apparent. They

were entirely dependent on the shallow regolith aquifers that are unique to this region. These aquifers hold groundwater in the form of pockets rather than a continuous body of water and hence are of a stagnant nature (Panabokka and Perera 2005).

Residents of the NCP rarely use irrigation canals and tanks as sources of potable water (Jayasumana et al. 2017), yet more than 80% of the total population depends solely on groundwater that it abstracts from dug wells and tube wells (Chandrajith et al. 2011a) connected with the above-mentioned tank cascade schemes. Meanwhile, the NWSDB has reported that only 32% of the total population in the NCP has access to regular piped-water supplies. Some people also use harvested rainwater and spring water based on the seasonal availability (NWSDB 2015).

2.6 Role of Groundwater in CKDu

It is rather clear that groundwater plays a key role in the day-to-day lives of the inhabitants of the CKDu-endemic region. One of the IWMI's very recent studies showed that groundwater has been the main source of drinking and cooking water for more than 98% of the population in the most-affected CKD/CKDu areas of Sri Lanka for at least 5 consecutive years during the last 2 decades (Kafle, Balasubramanya, and Horbulyk 2019). A substantial number of studies have shown that groundwater in this region is not suitable for direct potable purposes as the quality does not comply with the international and local drinking water standards (Dissanayake 1996; Herath and Ratnayake 2010; Chandrajith et al. 2011b; Wasana et al. 2016; Wickramarathna et al. 2017).

Surprisingly, studies have reported very low or zero prevalence of CKDu among those who consumed spring water continuously for more than 10 years while living amidst the affected communities (Jayasekara et al. 2015; Wasana et al. 2016). They have found that spring water is of high quality as it originates from deeper quartzite formations, unlike shallow wells (Jayasumana et al. 2017). Additionally, inhabitants who consumed treated water from large water supply schemes were free from the disease, although they lived within CKDu-endemic areas (Jayasumana, Gunatilake, and Senanayake 2014). Anecdotal evidence has suggested that the provision of safe drinking water improves the situation among early stage CKDu patients in several villages with high incidence of the disease (Noble et al. 2014).

The above findings highlight a close association between the quality of groundwater and the occurrence of CKDu in the dry zone. Therefore, a large number of water quality studies to date have investigated a range of harmful contaminants in groundwater in the endemic areas as potential causative agents of CKDu. As Section 2.4 explained, researchers have widely suspected the elevated presence of hardness, fluoride, major dissolved ions, and minute quantities of heavy metals, like cadmium, and their interactions in groundwater in the etiology of CKDu. Section 2.7 will present an elaborate discussion of these elements in groundwater and their possible implications for CKDu.

2.7 Potential Links between Groundwater Quality and CKDu

The groundwater in the endemic areas of CKDu is slightly alkaline, thus indicating moderately basic pH levels (pH ~7.5). The mean EC between 315 and 1,008 μ S/cm (the maximum levels exceed 3,000 μ S/cm) indicate high ionicity of the groundwater. Intensified weathering of mineral-bearing rocks under the extremely dry weather conditions and high evaporation rates that prevail in the dry zone is a likely reason for the high ion concentrations in the groundwater (Chandrajith et al. 2011b). Research has found that the groundwater has dominant Ca–Mg–HCO₃ ion combinations; therefore, a

high hardness level (>250 mg/L of $CaCO_3$) is a key characteristic of the groundwater in this region (Chandrajith et al. 2011b; Jayasumana et al. 2015a; Dissanayake and Chandrajith 2017; Wickramarathna et al. 2017).

2.7.1 Fluoride

The high level of fluoride in groundwater is one of the most popular topics under discussion in relation to CKDu in Sri Lanka. According to the *Hydro-geochemical Atlas of Sri Lanka*, the dry zone of Sri Lanka possesses relatively high groundwater–fluoride concentrations (>0.5 mg/L) compared with the wet zone (<0.5 mg/L) (Dissanayake and Weerasooriya 1985). Following this observation, Chandrajith et al. (2011a) recognized that the CKDu-affected areas overlap with the high-fluoride groundwater zones (1 mg/L to levels exceeding 3 mg/L), indicating a possible correlation between the exposure to high levels of fluoride through drinking water and the occurrence of CKDu. Research has asserted that the weathering of fluoride-bearing minerals under extremely hot climatic conditions and subsequent high evaporation is the main pathway via which fluoride reaches groundwater in the dry zone (Dissanayake 1991).

Apart from CKDu, the endemic areas have indicated a high incidence of dental fluorosis (community fluorosis index >1.66), especially among children (Dissanayake 1991; Wimalawansa 2020). Under the hot tropical climatic conditions prevailing in Sri Lanka, people tend to consume greater volumes of water on a daily basis; thus, they are presumably exposed to high fluoride intakes compared with those who are from non-tropical regions. Therefore, the national standards for drinking water, that is, the Sri Lanka Standards for Potable Water Quality (SLS 614: 2013), have set the MAL for fluoride at 1 mg/L (Wasana et al. 2016). Meanwhile, some scientists have suggested that there is a need to lower this maximum limit further in line with the recommendation of the WHO to maintain an MAL of 0.5 mg/L fluoride for tropical countries, similar to Hong Kong, China, and the Gulf countries (WHO 1994).

The literature has reported fluoride levels exceeding 1.5 mg/L (the WHO maximum guideline) and as high as 8 mg/L in groundwater that CKDu-affected communities use. Nevertheless, the concentrations vary widely even within close vicinities (Dissanayake and Weerasooriya 1985), and, most of the time, the mean concentrations (0.5–1.6 mg/L) are less than or comparable to 1.5 mg/L but exceed 0.5 mg/L (Herath et al. 2005; Chandrajith et al. 2011b; Wasana et al. 2016; Herath et al. 2017; Wickramarathna et al. 2017). Therefore, researchers have considered the levels not to be acceptable for inhabitants' daily intake in the temperate dry zone. Furthermore, the marked prevalence of dental fluorosis in these areas has implied the importance of considering the total intake of fluoride (mainly dietary intake) rather than the intake from drinking water only. Negligence of the dietary exposure to fluoride through secondary sources of fluoride, like "tea," is a limitation of past research (Chandrajith et al. 2011a).

To date, research has not documented environmental exposure to fluoride and its nephrotoxic effects well, and the global literature has presented very limited evidence on renal failure that doctors have attributed to chronic fluoride intoxication (Shashi, Singh, and Thapar 2002). The kidneys are the main pathway for fluoride elimination in the human body. Research has stated that the kidneys eliminate around 50–80% of the total fluoride that the body absorbs; thus, they are highly vulnerable to fluoride intoxications (Shashi, Singh, and Thapar 2002; Xiong et al. 2007). Dharma-Wardana et al. (2015) emphasized that fluoride might contribute to CKDu due to its high rank in the Hofmeister Series for denaturing proteins of the kidney membrane.

While it is impossible to explore all the possible exposure routes of fluoride, clinical observations provide more reliable and solid evidence on fluoride exposure. Researchers have considered serum fluoride levels as an appropriate indicator of fluoride exposure (Kono et al. 1984; Shashi, Singh, and Thapar 2002). In a recent study, Fernando et al. (2020) identified significantly high serum fluoride concentrations (1.39 \pm 1.1 mg/L) in CKDu subjects in the NCP compared with controls from the same endemic areas and subjects from foreign countries. They portrayed higher fluoride exposure in CKDu in Sri Lanka. Furthermore, several studies have reported dose–effect relationships between fluoride in drinking water and kidney failure (Reggabi et al. 1984; Lantz et al. 1987; Xiong et al. 2007).

Apart from real-world incidents, plenty of animal studies worldwide have revealed the possibility of kidney damage through chronic exposure to small quantities of fluoride. Several studies on mice that local research groups have conducted have also shown that chronic exposure to fluoride levels apparent in CKDu groundwater could lead to impaired renal functions in mice that have similar histopathological characteristics to CKDu (Thammitiyagodage et al. 2017; Wasana et al. 2017; Perera et al. 2018). Section 4.4 will explain this further.

Apparently, the biological evidence supported the possible involvement of fluoride in the origin or development of CKDu, yet the findings of environmental studies (basically water quality studies) so far have not provided sufficient evidence to confirm a relationship between the fluoride in groundwater and the occurrence of CKDu. Although many scientists have claimed that high groundwater-fluoride zones overlap with CKDuaffected areas, these two components do not have an ideal correlation due to the sporadic geographic distribution of both fluoride and CKDu cases. At the same time, fluoride as a sole causative factor cannot explain why CKDu is absent in certain neighboring settlements located within the same endemic region and in non-endemic areas of the dry zone with similar geographic and socio-economic conditions (e.g., the northern and southern sectors of Sri Lanka), where the groundwater contains similar fluoride concentrations. On the other hand, studies have observed CKDu even among people who have consumed low-fluoride drinking water (Chandrajith et al. 2011b; Wasana et al. 2016; Wimalawansa 2016). Therefore, researchers have presumed that fluoride does not act alone in causing CKDu. Instead, it may interact with other chemical constituents in groundwater or influence certain environmental conditions that the CKDu patients experience to create such a problem.

2.7.2 Hardness

Hardness in groundwater does not occur due to a single substance. It is basically a result of a variety of dissolved polyvalent metallic ions, mainly calcium (Ca²⁺) and magnesium (Mg²⁺) cations, present in rocks holding groundwater (WHO 2010). Due to the lack of apparent health concerns about consuming hardwater, the WHO guidelines do not suggest a maximum recommended value for hardness in drinking water (WHO 2011). However, according to the WHO classification of water hardness, most of the wells in the CKDu region fall within the "very hard" (>180 mg/L hardness) category. The Sri Lankan water quality standards suggest a non-health-based MAL of 250 mg/L for hardness. The hydrogeochemical map of Sri Lanka marks the CKDu endemic NCP region as having hardness levels exceeding this MAL value (up to 850 mg/L as CaCO₃) (Dissanayake and Weerasooriya 1985).

Past studies have reported a positive correlation between the hardness in groundwater and the geographic occurrence of CKDu cases (Paranagama 2013; Jayasumana, Gunatilake, and Senanayake 2014; Wasana et al. 2016). Jayasumana, Gunatilake, and Senanayake (2014) found that 96% of CKDu patients had consumed hard (121–180 mg/L of CaCO₃) to very hard (>180 mg/L of CaCO₃) water from shallow wells for nearly 5 years. Wasana et al. (2016) reported significantly high hardness concentrations (~230 mg/L of CaCO₃) in groundwater in CKDu high-risk areas in comparison with low-risk (~150 mg/L of CaCO₃) and control areas (~25 mg/L of CaCO₃). Studies have reported increased hardness in well water over time and the abandonment of wells due to high hardness levels as well as noting a high incidence of CKDu with such abandoned wells (Jayasumana, Gunatilake, and Senanayake 2014; Jayasumana et al. 2015a). Meanwhile, they have reported a low prevalence of the disease among those who have consumed water from springs containing very low hardness levels (6–9 mg/L) while living in the same endemic areas (Paranagama 2013; Jayasumana, Gunatilake, and Senanayake 2014; Wasana et al. 2016).

Many researchers have believed that it may not be the individual effect of hardness that matters in the occurrence of CKDu, considering the limited evidence available on the direct implications of water hardness for renal failure. Moreover, some other parts of the country that experience worse effects from high hardness levels in groundwater (such as the northern region of the country) show an absence of CKDu. Nevertheless, hardness cations (calcium and magnesium), which are essential minerals for human health, are likely to relate to kidney function.

Sufficient intakes of magnesium (10-30 mg/L in drinking water) and calcium are beneficial for vascular health and protection against oxidative stress. In healthy people, the kidneys effectively excrete excess intakes of these minerals (WHO 2010). However, this does not happen properly with impaired kidneys as renal insufficiency reduces the ability to excrete excessive amounts of calcium and magnesium and hence they accumulate within the kidney tissues. An overdose of magnesium, that is, hypermagnesemia, would result in renal failure with a significantly decreased ability to excrete magnesium. In addition, these cations interact with other elements in groundwater to form harmful complexes (WHO 2009). The literature has discussed such interactions between hardness cations and fluoride, organic matter, pesticide components, and other micro-contaminants in the onset of CKDu.

2.7.3 Heavy Metals and Agrochemicals

There are international reports of the potential nephrotoxic effects of environmental exposure to many heavy metals, including but not limited to mercury (Hg), chromium (Cr), uranium (U), lead (Pb), cadmium (Cd), arsenic (As), iron (Fe), gold (Au), antimony (Sb), platinum (Pt), thallium (TI), and silicon (Si). These heavy metals are non-essential for human health, toxic even at very low doses, and non-biodegradable due to a very long biological half-life. The kidney, as the first target organ in the human body to reabsorb and accumulate divalent metals, has an increased chance of damage due to heavy metal toxicity (Barbier, Arreola-Mendoza, and Del Razo 2010; Chandrajith et al. 2011a).

Owing to the widespread notion that cadmium is a nephrotoxin and considering the similarities to the farming background and the rice-based staple diet in the "*itai-itai* disease" that occurred in Toyama Prefecture of Japan, exploratory studies related to CKDu in Sri Lanka have focused on dietary exposure to cadmium. In agreement, several studies have identified minute quantities of Cd in biological samples (urine, nails, and hair) from CKDu patients (Jayatilake et al. 2013; Jayasumana et al. 2017). Arsenic was in the early attempts to identify the etiology of CKDu. Jayatilake et al. (2013) noted significantly higher arsenic levels in the hair and nails of CKDu cases compared with controls. The urinary arsenic concentrations exceeded the US reference range in CKDu patients in Jayasumana et al.'s (2015b) study, yet arsenic mostly appeared in a non-toxic form. More importantly, other parts of the world, where the population's exposure to

arsenic concentrations through drinking water is much higher, have not reported arsenicassociated CKD (Kulathunga et al. 2019). Additionally, studies have detected lead and mercury at concentrations exceeding the US reference values in biological samples from some CKDu patients (Levine et al. 2016). Therefore, there are strong suspicions that bioaccumulation of these toxic heavy metals in the human body over time are a possible cause of the disease.

Water samples from dug wells, tube wells, irrigation canals, reservoirs, and natural springs that CKDu patients used as their primary drinking water sources contained heavy metals (cadmium, arsenic, lead, copper, and urenium) at lower concentrations than the WHO guideline values. The cadmium concentration in groundwater from CKDu-affected areas that Wickramarathna et al. (2017) investigated had a mean of 0.21 (range < 0.02-6.28 µg/L). Meanwhile, Javatilake et al. (2013) observed arsenic concentrations of up to 22 ua/L in aroundwater and surface water. but the findinas of Wickramarathna et al. (2017) suggested tenfold lower arsenic concentrations (0.22 µg/L) in all their well water samples. Herath et al. (2018) performed an extensive island-wide investigation of well water quality and found that no wells from the CKDu-endemic region exceeded the guideline values for arsenic, cadmium, lead, and chromium in drinking water. At the same time, the concentrations in water samples from endemic areas were not significantly different from those from non-endemic areas (Bandara et al. 2011; Chandrajith et al. 2011b; Jayatilake et al. 2013; Jayasumana et al. 2015b; Divabalanage et al. 2016; Wasana et al. 2016).

The origin of heavy metals in CKDu endemic areas is likely to be "agrochemicals," which are in extensive use during agricultural activities. Jayatilake et al. (2013) spotted pesticide residues in CKDu-affected patients, and some pesticides exceeded the permissible levels that the WHO suggested. Bandara et al. (2011) suggested that the application of triple super phosphates (TSPs) and rock phosphates during agricultural activities artificially adds cadmium to soil. These phosphate fertilizers contain extremely high levels of a multitude of heavy metals, and some soil analyses in the disease-endemic areas have indicated that the copper, mercury, iron, manganese, nickel, and selenium concentrations exceed those in US soils (Jayasumana et al. 2015a; Levine et al. 2016). However, the idea that fertilizers/agrochemicals might be contributing to the CKDu issue in the dry zone is questionable since the wet zone of Sri Lanka as well as many other parts of the world where CKDu is completely absent widely apply these fertilizers at a similar rate.

Due to the insignificant levels of heavy metals detectable in groundwater (and other drinking water sources) in the CKDu-endemic region, studies have largely rejected heavy metal contamination through drinking water in the etiology of CKDu. However, the chronic exposure to below-MAL concentrations of heavy metals via drinking water and food requires further examination considering the possibility of bioaccumulation within human body tissues. Wasana et al. (2017) and Dharma-wardana (2018) investigated the possible ways in which heavy metals, especially cadmium, could act along with water hardness and ionicity to cause damage to kidneys (refer Section 4.4 for further explanation).

2.7.4 Organic Matter

A very limited number of studies to date have discussed the potential implications of organic matter in drinking water for CKDu. As Makehelwala et al. (2019) observed, the concentrations of dissolved organic carbon (DOC) were not significantly different among CKDu-endemic (1.35–2.08 mg/L) and CKDu-non-endemic areas (1.37–1.62 mg/L). However, Cooray et al. (2019a) observed comparatively high DOC concentrations (up to 11 mg/L), but, once again, the concentrations were comparable among the endemic (3.9–6.4 mg/L) and the non-endemic (3.7–4.2 mg/L) regions. The concentrations that the latter group reported appeared to be unusually high because the DOC levels in natural groundwater typically fall below 4 mg/L, while concentrations exceeding this level generally indicated anthropogenic influences and/or contamination issues (Regan, Hynds, and Flynn 2017).

Research has not observed a dose–effect relationship between DOC and CKDu so far, but DOC is very complex in nature and it is necessary to consider the characteristics rather than the doses or concentrations in evaluating the harmful effects. For instance, the interactions between dissolved organic matter (DOM) and metals may influence the solubility and mobility of metals in aquatic and soil systems and thus could affect the toxicity and bioavailability of metals to living organisms (Vaughan, Lumsdon, and Linehan 1993). Makehelwala et al. (2019) characterized the DOC in CKDu-HR areas as the highly aromatic, non-biodegradable, or recalcitrant-type DOC of 900–1,800 Da weight fraction. They identified statistical correlations between DOC and magnesium, calcium, and sulfate in groundwater from the endemic region. Furthermore, this groundwater is likely to produce DOC–sulfone–calcium complexes that could act as a uremic toxicant, generating oxidative stress in kidneys and causing the CKDu condition (Makehelwala et al. 2020).

2.7.5 Synergistic Involvement of Major Chemical Constituents

Chandrajith et al. (2011b) and Dissanayake and Chandrajith (2017) described fluoride in drinking water as playing a dual role by exhibiting cytotoxic and cytoprotective properties, that are dose-dependent. The co-presence of major cations, Ca^{2+} , Mg^{2+} , and Na^+ , and the ratios at which they occur in the groundwater may govern the fine line between these two roles. Chandrajith et al. (2011b) characterized CKDu-endemic areas with lower Na^+/Ca^{2+} ratios (1.6–6.6) compared with non-endemic areas (34–469), portraying calcium-dominant geochemistry in the endemic areas but sodium-dominant chemistry in the non-endemic areas.

Dissanayake and Chandrajith (2017) observed higher total hardness concentrations but lower magnesium concentrations in groundwater from CKDu-endemic areas compared with non-endemic areas and thus explained that calcium hardness along with fluoride must cause CKDu in the endemic areas while magnesium hardness provides protection against such harmful effects in non-endemic areas. They reported the reason as being the calcium antagonistic properties of magnesium. However, none of the proceeding studies have discussed such a relationship between the concentrations/ratios of major cations in groundwater and the occurrence of CKDu.

Wasana et al. (2016), using multivariate scatterplot analysis, showed that the co-presence of elevated fluoride and hardness and cadmium in groundwater seems to have a relationship with the occurrence of CKDu. They later confirmed this hypothesis through experiments with mice in a follow-up study (Wasana et al. 2017). According to their observations, the simultaneous occurrence of the above elements at concentrations equal to/higher than the WHO maximum permissible levels for drinking would trigger histopathological changes similar to CKDu. Increasing doses aggravated

the damage. Interestingly, fluoride alone, even at 10 mg/L, did not show any toxic effects on the kidneys, thus indicating the enormity of fluoride toxicity when present with the right types and right amounts of counter-ions in drinking water.

Dharma-wardana (2018), using the Hofmeister concept and Gibbs free energy theory for ion pair formation, explained that fluoride along with magnesium hardness and cadmium (if present) could exert more nephrotoxic effects than fluoride ions alone. This coherently explained Wasana et al.'s (2017) observations in studies with mice. Cadmium, which is a well-known nephrotoxicant, reportedly appears in minute quantities (below MAL, i.e., 3 μ g/L) in groundwater in the CKDu region, but the co-presence of fluoride in the solution could intensify the toxicity of cadmium. Meanwhile, this study negated the idea that calcium hardness might combine with fluoride to cause toxicity, as Chandrajith et al. (2011b) and Dissanayake and Chandrajith (2017) explained.

Paranagama, Bhuiyan, and Jayasuriya (2018) conducted a broad statistical analysis to identify the most common ion combinations in CKDu groundwater. Interactions between sodium and fluoride (Na-F) were significantly prominent in the groundwater that CKDu patients consumed. Next, magnesium and fluoride ion combinations were observable to a greater extent.

Owing to the above evidence, the synergistic involvement of fluoride, hardness, and major dissolved ions in groundwater are strong suspects as a potential cause of CKDu. The findings of water quality studies have remained largely divided among different research groups, but, as far as the chronic exposure to contaminants though drinking water is concerned, many researchers hold the view that the critical doses of chemical constituents like fluoride must be based on their counter-ions in solution.

Besides, the extremely dry weather conditions in the dry zone demand that people consume large volumes of water, but the unpalatability of groundwater as a result of high hardness levels restricts their intake. The reduced water consumption is likely to cause dehydration of the kidneys, especially among farmers, who engage in strenuous labor under extreme weather conditions. A kidney that suffers initial damage in this manner (or some other unidentified manner) could experience further impairment due to its inability to excrete excess elements, such as fluoride, calcium, magnesium, and heavy metals. Chronic accumulation of these elements could subsequently impose toxicity on the kidneys (Wimalawansa 2016; Dissanayake and Chandrajith 2017).

It is arguable that groundwater with similar characteristics may occur in other parts of the world where CKDu is absent. Nevertheless, making such comparisons between different regions' groundwater quality may not be convenient or meaningful, ascribing CKDu to a large number of factors (Wimalawansa 2016). Despite similar groundwater characteristics, the geography and climate of the endemic areas, the socio-economic status of people, their health conditions, their genetic predisposition, and their lifestyle habits and so on can vary widely across different regions. CKDu is a health issue with a multifactorial origin; thus, it might occur due to a certain combination of various risk factors, including groundwater quality, that is unique to the endemic region.

2.8 Effects of Safe Drinking Water Interventions on CKDu

There is circumstantial evidence to suggest that the deleterious quality of groundwater, the main source of drinking water in CKDu-endemic areas, is involved with the cause of CKDu. Scientific research has not properly evaluated the beneficial health effects of safe drinking water on CKDu so far. Nevertheless, a very low prevalence of the disease is notable among certain communities living in the high-risk zones of CKDu that receive a

piped supply of drinking water. Moreover, the health condition of some patients with early stage CKDu has improved with safe drinking water (Wimalawansa 2016; Siriwardhana et al. 2018). Therefore, safe drinking water interventions are a potential measure for mitigating the disease in these areas. The Ministry of Health observed a reduction in CKD/CKDu cases in Sri Lanka after 2016, ascribing it to the safe drinking water interventions (Ranasinghe et al. 2019).

The Ministry of Water Supply and Drainage, together with the NWSDB and National Community Water Trust (NCWT), has developed a strategy and worked with short-term to long-term plans to provide CKDu-affected areas with safe drinking water. The target is to provide each person with a minimum of 5 liters/day of safe drinking water to fulfill their drinking and cooking water needs (Abeygunasekera and Wickremasinghe 2013). The short-term plans are as follows:

- Establishing small-scale RO water treatment plants to purify groundwater. CBOs will operate the plants at the community scale with the technical assistance of the NWSDB.
- Supplying treated water through bowsers to the affected areas that are in close proximity to the existing water supply schemes.
- Providing service extensions from existing water supply schemes.
- Promoting rainwater harvesting in areas that are difficult to cover with bowser supplies.

Regarding long-term plans, several large-scale water supply projects are on-going in the endemic region and more are in preparation. However, there is no master plan as such to extend the service area to the entire disease-prevalent areas of the dry zone or at least those in the NCP. Water supply authorities have estimated that it may take at least another 3 decades to attain 100% coverage of the centralized water supply in the endemic region (Wimalawansa 2019). Therefore, the above-mentioned temporary/short-term solutions are currently in use until the implementation of permanent water supply schemes.

Small-scale RO water treatment is the most prominent safe drinking water supply method in the CKDu-endemic region at present. Wimalawansa (2019) claimed an incidence reduction of the disease of ~45% with small-scale RO plants in this region (based on unpublished data).

2.9 Drinking Water Treatment using Reverse Osmosis

Nowadays, countries all over the world widely employ RO technology for the desalination of brackish water (TDS of 1,000–10,000 ppm) and sea water (TDS >10,000 ppm) as a solution to the water supply crisis. The use of membrane processes for desalination has been developing rapidly since the 1960s (Loeb and Sourirajan 1963), and more than 80% of desalination systems currently utilize RO technology (Greenlee et al. 2009). The application of centralized water treatment using RO technology for freshwater treatment is rare (TDS <100 ppm) due to the high capital and O&M costs involved in comparison with conventional methods (McCutcheon, McGinnis, and Elimelech 2005).

The water supply in rural areas less frequently uses small-scale RO systems due to the high costs and energy that they involve (Ayoub and Alward 1996). However, recent developments of renewable energy have paved the way for rural communities to benefit from RO technology for water treatment. As a result, RO water treatment coupled with photovoltaic technology, known as PV-RO systems, are undergoing extensive

investigation for community-scale seawater/brackish water desalination on the rural outskirts of Latin America, Africa, South Asia, the Middle East, Europe, Australia, and many other regions of the world. These systems operate at limited production capacities ranging from 0.1 to 60 m³/day (Joyce et al. 2000; Afonso, Jaber, and Mohsen 2004; de Carvalho et al. 2004; Greenlee et al. 2009).

The RO membrane is non-porous, and the nominal pore diameter varies between 1 and 10 Å. It can remove almost all dissolved solids, including mono-valent ions and microorganisms in feedwater, with very high efficiency (~99%) compared with other types of membranes with bigger pore sizes such as nanofiltration, ultrafiltration, and microfiltration membranes. During the RO process, water flows through a semipermeable membrane while applying high pressure (in the range of 2–10 MPa) to feedwater to overcome the natural osmotic pressure; hence, it is named "reverse osmosis." As pure water molecules pass through the membrane, the dissolved solids and other impurities remain on the membrane's surface, which rejects them as the concentrate (Malherbe 1993).

The process efficiency of RO is highly reliant on membrane properties, operational parameters, and feedwater characteristics. Membrane fouling is an inevitable phenomenon that occurs during RO treatment, mainly due to the accumulation of undesired deposits that the feedwater carries onto the membrane surface and/or inside the membrane pores (Malaeb and Ayoub 2011). It is possible to classify membrane fouling into biofouling, organic fouling, inorganic scaling, and colloidal fouling based on the nature of the fouling agents present in the feedwater (Jiang, Li, and Ladewig 2017).

Inorganic fouling can pose a significant threat to the operations of RO plants with feedwater containing high levels of hardness cations (calcium and magnesium) and iron (Tang et al. 2016). Meanwhile, calcium carbonate, calcium/magnesium sulfate, and barium/strontium sulfate are the commonly occurring membrane scalants in RO systems. These systems often use antiscalants and softeners for scale inhibition (Voutchkov 2017).

Dissolved organic matter in groundwater, which research has commonly measured as the DOC, could strongly influence the plant performance due to organic fouling. Because of its complexity and ability to interact with a multitude of contaminants, organic matter often brings a variety of foulants together to aggravate membrane fouling. For instance, organic matter forms insoluble complexes with metals like calcium and magnesium, which can easily accumulate on membranes. Biofouling results from the adhesion of microorganisms to the membrane surface, and they continue to grow on it, promoting biofilm formation. Since organic matter is an excellent carbon source, it enhances biofouling in RO systems in which the feedwater is rich in microorganisms. Typically, biofouling is highly likely to occur at TOC concentrations exceeding 2 mg/L in feedwater. Both organic fouling and biofouling are difficult to control compared with inorganic fouling and may involve large operational costs (Jiang, Li, and Ladewig 2017; Voutchkov 2017).

In addition, inorganic foulants, such as aluminum silicate minerals, silica, iron oxides/hydroxides, and organic macromolecules (e.g., polysaccharides and proteins) in feedwater may give rise to colloidal fouling (Tang et al. 2016). The deposition of colloids on the membrane surface causes cake layer formation and thus may reduce the permeate flux while increasing the operating pressure (Ang and Elimelech 2007). Silica fouling is very complex and has an inert nature. Alkaline environments favor the formation of silicate ions, which could react with hardness cations to form insoluble compounds. Therefore, silica fouling is difficult to inhibit using antiscalants or remove with chemical cleaning (Bergman 2007, p. 38).

It is vital to follow the necessary pre-treatment steps prior to RO treatment to overcome the fouling of the membrane. Basically, the characteristic of feedwater should form the foundation for the ideal pre-treatment steps, as Figure 2 shows.



Figure 2: Pre-treatment Measures to Control Membrane Fouling

Source: Author.

2.10 Reverse Osmosis (RO) Water Treatment in the CKDu-Endemic Region

The demand for groundwater purification using community-based RO plants is increasing in the CKDu-endemic region, and it has become a popular and viable business proposition in these areas (Jayaweera et al. 2014). Personal communications with the water supply authorities of the Regional Supporting Centre of NWSDB, Anuradhapura, revealed the following information (Table 4) regarding community-based RO plants in endemic areas. The NWSD, Sri Lanka Navy, and private entities are largely involved in establishing RO plants in the CKDu-endemic area of the NCP. Table 4 shows some of the basic differences between these three types of plants.

The NWSDB and the Sri Lanka Navy usually create plants with government funds. The NWSDB follows special criteria when designing its community RO plants:

- 1. Every person should be able to reach an RO plant within 20 mins; and
- 2. The per capita allocation of treated water should be at least 5 L/day, each family consisting of four persons on average.

Funding Entity	Source/s of Funding	O&M by	No. of Plants in the NCP	Price of RO Water per Liter
NWSDB	Government funds under NCKDPPa	CBOs	160	1 LKR*
Sri Lanka Navy	Government funds via the Special Presidential Task Force on CKDu	Sri Lanka Navy	170	Free of charge
Private parties	Personal/CBO funds or donations	CBOs	>270	3 LKR*

Table 4: Main Differences between RO Plants That Different Entities Have Established

^a National Chronic Kidney Disease Prevention Program.

* 1 LKR = 0.005 USD as of June 2020.

Source: Author.

After initiation, the NWSDB hands over the plants to CBOs for O&M. Despite free capital charges, the intention is that they will bear the O&M costs by themselves with income earned through sales of RO water. The NWDB provides the technical support for the O&M of the plants. Meanwhile, the Navy operates and maintains its plants by itself. It distributes water free of charge under certain volume restrictions.

The third type is the plants that non-governmental funds initiate. Local individuals or groups, such as CBOs, purchase plants by themselves (or with the support of various donors) from different private RO plant suppliers in the country. They can set the selling prices for the water that they produce as they wish and have the obligation to take care of the plant O&M by themselves. These plants are widely distributed across the NCP compared with the first two types of plants. In addition to direct sales of water at RO plants (Figure 3), bowser suppliers are largely involved in buying water in bulk from RO plants and supplying it to households at relatively high prices.



Figure 3: Production and Distribution of RO-Treated Water at RO Plant Premises

A great initiative to combat CKDu: The root-cause of the deadly chronic kidney disease of unknown etiology (CKDu) in the rural dry zone of Sri Lanka is still a mystery. Nevertheless, circumstantial evidence shows a reduction in the incidence of the disease with safe drinking water. As a result, local people now have access to clean water through the community-based reverse osmosis plants initiated by the National Water Supply and Drainage Board (Photos by Sachithra Imbulana).

Most of these community RO plants receive a supply of groundwater, and very few abstract water from surface water bodies. Studies have considered RO treatment as the ideal solution to treat groundwater in endemic areas in the absence of knowledge on the physicochemical characteristics of the contaminant that is likely to trigger CKDu. Nevertheless, operating and maintaining such a sophisticated water treatment method in these extremely rural settings is rather problematic and needs considerable investigation (Jayasumana et al. 2016; Wimalawansa 2019).

Jayasumana et al. (2016) investigated 10 random RO plants in the CKDu-affected areas of the NCP. They reported that each RO plant followed its own protocols with regard to operation, maintenance, and management. The plant operators had little technical knowledge about handling the O&M of the plants. They basically relied on TDS readings and the taste of the produced water to decide on requirements for cleaning or filter changing. Moreover, the plants hardly monitored the quality of the produced water. Cooray et al. (2019b) pointed out that existing RO plants are unsuitable for these rural areas due to the deficiency of minerals in permeate, consumer complaints about the unacceptable taste of the produced water, and the plants' maintenance and management issues.

3. MATERIALS AND METHODS

3.1 Study Areas and Selection of RO Plants

All the study areas belonged to the Anuradhapura District of the NCP, which has the highest reported occurrence of CKDu cases. The total land area of Anuradhapura is 7,179 km², with a total population of nearly 905,000 in 22 District Secretariat (DS) divisions (Department of Census and Statistics Sri Lanka 2019). It belongs to the dry zone of Sri Lanka, where the mean annual temperature varies between 25°C and 30°C and the mean annual rainfall is less than 1500 mm. The north-eastern monsoon brings the highest rainfall to this area from October to February, while a long dry spell lasts for the rest of the year (Department of Meteorology Sri Lanka 2000). An agriculture-based economy that is vastly dependent on the ancient tank cascade irrigation schemes is predominant in Anuradhapura. There are very limited water resources in these areas; hence, groundwater originating from shallow regolith aquifers is the main source of potable water for local people. Reddish brown earth and low humic gley soil are the commonly occurring soil types in these areas (Irrigation Department Sri Lanka 1988).

Two field surveys, from 23 to 30 August 2019 (targeting the dry season) and from 23 to 30 December 2019 (targeting the wet season), aimed to investigate 32 communitybased RO plants located in four DS divisions in Anuradhapura District. Considering the accessibility of their detailed information and the small disparities between plant models, this study selected only the plants that the NWSDB initiated and that CBOs are now operating and maintaining. Of the 32 plants, 27 were in CKDu high-risk (HR) areas, namely Rambewa/RAM (12 plants), Medawachchiya/MED (10 plants), and Nuwaragampalatha Central/NGP (five plants). The remaining five plants were in CKDu low-risk (LR) areas: Galnewa and Thirappane. The study based the definition of the CKDu risk category on CKDu prevalence data from the renal registry, Ministry of Health Sri Lanka. All the RO plants that the study investigated (Figure 4 and Figure 5) had existed since around 2014–2017. Of the 32 plants, 14 were located on public premises, whereas the other 18 were on private land. The feedwater sources for all the plants were dug wells and/or tube wells, and they had the same arrangement of unit treatment processes (Figure 6). The most common type of RO membrane that the plants used was Pure Aqua's Hydranautics ESPA2-LD-4040 membrane. The treatment capacities of the plants varied between 6 and 17 m³/day, and they usually served 100–500 families.



Figure 4: Appearance of a Typical Community RO Plant Facility

RO plant premises: Most of the community-type RO plants are in public premises, like schools and temples, or in private lands owned by the villagers. Some villagers are even generous enough to donate pieces of their own lands to construct the RO plant facilities, considering the financial difficulties of their respective communities (Photos by Sachithra Imbulana).

Figure 5: Inner and Outer Views of an RO Plant: a) RO Water Treatment System; b) Storage and Distribution Point of Treated Water



A national responsibility: The National Chronic Kidney Disease Prevention Program (NCKDPP) of the National Water Supply and Drainage Board has introduced hundreds of RO plants in the areas affected with CKDu, considering it a national responsibility to eradicate the disease from the country (Photos by Sachithra Imbulana).



Figure 6: Water Treatment Process in a Typical RO Plant under Investigation

Source: Author.

3.2 Questionnaire Surveys

The study conducted two types of questionnaire surveys for RO plant operators and RO-treated water consumers to gather information about the O&M of the RO plants and the socio-demographic factors associated with the RO plants, respectively (Figure 7).

The surveys obtained the following information on RO plants from the plant operators:

- Background information on the plants (year of establishment, plant premises, type of wells that they used for the abstraction of source water, number of people served, and treatment capacity);
- Their daily operations (duration of operation, average daily demand for treated water, and selling price of treated water); and
- The protocols that the O&M follows, including, but not limited to, water distribution, filter cleaning and replacement, chemical dosage, water quality assessment, and plant performance monitoring.

We interviewed one customer/consumer from each RO plant regarding the following aspects:

- Household profile, education, occupation, level of income, and expenditures;
- Water use behavior (with special emphasis on drinking water);
- Factors associated with purchasing RO-treated water;
- Perception of RO-treated water and level of service of the RO plants.



Figure 7: Interviews with a) RO Plant Operators and b) RO-Treated Water Consumers

Community involvement in RO water treatment: Usually, the community-based organizations (CBOs) take the responsibility of constructing, operating, and maintaining RO plants. A member of the CBO typically handles the O&M aspects of the plant, but he/she possesses very little technical capacity for this. On the other hand, the consumers also have little knowledge of RO water treatment, but they are very keen on plant operations (Photos by Sachithra Imbulana).

3.3 Water Quality Analysis

We tested the feedwater and treated water from the RO plants on site and off site using a predefined set of water quality parameters. Table 5 presents a summary of the water quality test methods and procedures that we followed. The on-site water quality measurements included pH, electrical conductivity (EC), total dissolved solids (TDS), alkalinity, total iron (Fe), ferrous iron (Fe²⁺), reactive silica, *E. coli*, and total coliform. We measured the parameters of pH, EC, and TDS with a portable water quality meter (LAQUAtwin, Horiba Corp., Japan) and the alkalinity using a digital titrator (Digital Titrator—model 16900, HACH, US). A portable colorimeter (DR/900, HACH, US) quantified the total iron, ferrous iron, and reactive silica, and m-Water test kits (mWater, US) determined the *E. coli* and total coliform counts.

The off-site measurements namely, cation-anion analysis and dissolved organic carbon (DOC) analysis required two separate sets of water samples collected from each location and preserved at 4°C. We analyzed the cations (Na⁺, K⁺, Ca²⁺, Mg²⁺, NH₄⁺) and anions (Cl⁻, F⁻, Br⁻, NO₂⁻, NO₃⁻, SO₄²⁻, PO₄³⁻) with ion chromatography using an Advanced IC-861 (TSKgel SuperIC-Cation HS column, Compact Japan) and Chromatogram IC-2010 (TSKgel SuperIC-Anion HS column, Japan), respectively. in the laboratory at the University of Tokyo, Japan. We analyzed DOC with a Total Organic Carbon Analyzer (TOC-L CSH/ CSN, Shimadzu, Japan), based on the difference between total carbon and inorganic carbon, in the same laboratory. For the IC analysis, we filtered the samples through 0.45 µm polyethersulfone (PES) membrane filters, collected them into 50 mL polypropylene (PP) bottles, and stored them at 4°C until analysis. In addition, in the same procedure, we added concentrated HCI immediately after filtration (till pH <2) to preserve the samples for DOC analysis. Finally, we calculated the bicarbonate (HCO₃⁻) based on alkalinity and the total hardness based on Ca²⁺ and Mg²⁺ concentrations using Equation (1) and Equation (2), respectively.

$$[HCO_3^{-}] = 1.22 \times \text{total alkalinity (in mg/L of CaCO_3)}$$
(1)

Total hardness (in mg/L of CaCO₃) =
$$2.5 \times [Ca^{2+}] + 4.1 \times [Mg^{2+}]$$
 (2)

We then compared the water quality data with the Sri Lankan standards for potable water quality (Sri Lanka Standards Institute 2013) to establish whether the untreated groundwater and treated water comply with the standards. We also considered the drinking water quality guidelines of the World Health Organization (WHO) when the permissible levels for drinking were different from the national standards (WHO 2011).

Parameter	Method/Instrument	Method of Sample Preservation
рН	Portable pH meter]
Electrical conductivity	Conductivity meter (LAQUAtwin)	
Alkalinity	Digital titrator (HACH)	-On-site testing
Total iron and ferrous	DR-900 portable colorimeter	
Reactive silica	(HACH)	
E. coli and total coliform	m-Water test kit -	
Cations (Na⁺, K⁺, Ca²⁺, Mg²⁺, NH₄⁺)	lon chromatography	Samples were filtered through 0.45 µm polyethersulfone (PES) membrane filters and
Anions (Cl⁻, F⁻, Br⁻, SO₄²- , NO₂⁻, NO₃⁻, PO₄³-)	Ion chromatography	collected in 50 mL polypropylene (PP) bottles. The samples were stored below 4°C until analysis (analyzed in the laboratory of the University of Tokyo)
Dissolved organic carbon (DOC)	Total Organic Carbon Analyzer (TOC-L, SHIMADZU) Method: NPOC method	Samples were filtered through 0.45 µm PES membrane filters and collected in 50 mL PP bottles. Concentrated HCI was added to make the pH <2 and, thereafter, the samples were stored below 4°C until analysis (analyzed in the laboratory of the University of Tokyo)

Table 5: Water Quality Para	meters and Test Methods
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Source: Author.

3.4 Statistical Analysis

We performed all the statistical analyses with the "R" statistical software (R Core Team 2018). Box–whisker plots provided a clear comparison of the groundwater quality with the standards. We conducted the Welch two-sample *t*-test, analysis of variance (ANOVA), and the subsequent Tukey honest significant differences (Tukey's HSD) tests for a statistical comparison of groundwater quality data. The tests identified significant differences based on the *p* values.

4. GROUNDWATER QUALITY IN THE CKDU REGION

4.1 Objectives for Section 4

This section provides a detailed discussion of Objective 1 of the study, that is, to determine the quality of groundwater in the endemic areas of CKDu (with respect to the drinking water standards) and its seasonal variations and to understand the differences in groundwater quality between CKDu high-risk and CKDu low-risk areas.

The quality of feedwater in RO plants (well water) varied with the quality of groundwater in the CKDu-endemic areas. In 26 plants, there were only dug wells, whereas five plants used only tube wells. Only one plant took water from both types of wells. In total, this study investigated 33 wells (27 dug wells and 6 tube wells).

The sampling took place during both dry (temperature: $24-33^{\circ}$ C; average monthly rainfall: 44 mm) and wet (temperature: $21-28^{\circ}$ C; average monthly rainfall: 230 mm) seasons in the study areas (Department of Meteorology Sri Lanka 2000). We confirmed the accuracy of the experimental results by calculating the ion balance of groundwater samples, which indicated a $\pm 8\%$ ion balance for all the groundwater samples that we collected during the two seasons.

We analyzed the groundwater quality data in three ways:

- Comparison of the groundwater quality with the drinking water quality standards;
- Comparison of the groundwater quality between dry and wet seasons;
- Comparison of the groundwater quality between CKDu-HR areas (MED, RAM, and NGP) and CKDu-LR areas.

The analysis took into account both mean and median values of water quality. Since most of the water quality parameters showed outliers, it would be more accurate to consider median values than to consider mean values in the comparison of groundwater quality.

4.2 Groundwater Quality with Respect to the Drinking Water Standards

The summary of the water quality data that Tables 6a and 6b present form the basis for this discussion. The temperature of the groundwater in the study areas varied between 28°C and 31°C, with the dry season having a slightly higher temperature than the wet season. The pH values in all the groundwater samples satisfied the permissible value for drinking water (6.5–8.5) during both seasons. Nevertheless, the pH in the dry season was slightly acidic (6.5–6.7) and significantly lower (p < 0.05) than the levels in the wet season (7.1–7.4) (Figure 8a).

When the pH lies within the range 6.3–10.3 (the present groundwater pH condition), alkalinity mainly appears in the form of bicarbonate (Suthersan and Payne 2005, pp. 24–25). The total alkalinity (Figure 8b) in the groundwater from all four areas was extremely high and far exceeded the MAL for drinking (200 mg/L of CaCO₃) in both dry and wet seasons (median 300–430 mg/L of CaCO₃). The TDS levels in the groundwater (Figure 8c) from CKDu-HR areas exceeded the MAL for drinking (500 ppm), particularly in the dry season (median 530–803 ppm), but the reported levels in LR areas complied with the MAL in both seasons (median 287–364 ppm). The high TDS (or high EC) levels in this groundwater may originate from accelerated rock–water interactions occurring under temperate climatic conditions in the CKDu-endemic region (Chandrajith et al. 2011b; Wickramarathna et al. 2017).

The reported total hardness levels (Figure 8d) in all four areas were extremely high and far exceeded the non-health-based MAL for drinking in both dry and wet seasons (median 260-521 mg/L of $CaCO_3 > MAL 250 \text{ mg/L}$ of $CaCO_3$). Similarly, the hydrogeochemical map of Sri Lanka indicated that the study areas fall within the 250-850 mg/L of $CaCO_3$ category of total hardness (Dissanayake and Weerasooriya 1985). Additionally, Herath and Ratnayake (2010), Chandrajith et al. (2011b), Jayasumana, Gunatilake, and Senanayake (2014), Wasana et al. (2016), and Wickramarathna et al. (2017) identified comparable hardness concentrations in groundwater from the same region.

Table 6a: Groundwater Quality of the Study Areas in the Dry Season

	Drinking		HR-ME	D (n = 10))		HR-RA	M (n = 13	3)
Water Quality Parameter	Water Standard	Min.	Max.	Mean	Median	Min.	Max.	Mean	Median
Temperature (°C)	-	29	33	31	31	27	32	30	29
рН	6.5-8.5	6.1	7.2	6.6	6.5	6.1	7.1	6.7	6.7
Alkalinity*	200	275	482	383	396	210	614	378	398
TDS (ppm)	500	394	788	540	530	333	1,580	674	584
Hardness*	250	258	517	378	386	202	741	399	395
Sodium (mg/L)	200	36	125	75	73	36	331	105	70
Potassium (mg/L)	-	0.8	18.7	3.2	1.3	0.4	15.4	2.8	1.8
Calcium (mg/L)	100	27	106	85	92	40	124	83	80
Magnesium (mg/L)	30	19	71	40	39	24	116	47	36
Total iron (mg/L)	0.30	0.00	0.10	0.00	0.00	0.00	0.03	0.01	0.00
Ammonium (mg/L)	0.06	0.00	0.08	0.00	0.00	0.00	0.42	0.03	0.00
Fluoride (mg/L)	1.0	0.4	1.2	0.7	0.7	0.4	2.0	0.9	0.8
Chloride (mg/L)	250	34	227	93	84	26	766	149	107
Sulfate (mg/L)	250	17	45	29	30	7	61	27	21
Nitrate (mg/L)	50	0.0	19.2	3.3	1.9	0.2	13.1	3.8	2.6
Bromide (mg/L)	_	0.0	6.3	0.7	0.0	0.0	3.8	0.5	0.0
DOC (mg/L)	_	0.0	5.4	1.9	1.6	0.6	5.6	2.3	2.1
E. coli (CFU/mL)	0	0	4	1	1	0	6	1	0
Total coliform (CFU/mL)	3 CFU/100 mL	5	52	27	23	2	493	70	18
	Drinking	HR-NGP (n = 5)				LR	LR (n = 5)		
Water Quality Parameter	Water Standard	Min.	Max.	Mean	Median	Min.	Max.	Mean	Median
Temperature (°C)	_	30	33	31	31	29	30	29	29
рН	6.5–8.5	6.6	6.8	6.7	6.7	6.2	6.9	6.5	6.6
Alkalinity*	200	342	508	428	430	119	329	256	300
TDS (ppm)	500	440	971	775	803	178	326	274	287
Hardness [*]	250	265	791	539	521	178	394	265	260
Sodium (mg/L)	200	19	250	121	104	41	91	58	49
Potassium (mg/L)	_	1.7	5.3	3.2	2.1	0.8	2.5	1.6	1.7
Calcium (mg/L)	100	33	189	116	140	36	76	61	64
Magnesium (mg/L)	30	42	78	61	69	17	50	27	23
Total iron (mg/L)	0.30	0.00	0.06	0.01	0.00	0.00	0.08	0.03	0.02
Ammonium (mg/L)	0.06	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00
Fluoride (mg/L)	4.0	03	2.6	1.0	0.5	0.2	1.0	0.8	0.9
Chloride (mg/L)	1.0	0.0							
ee. (g, _)	1.0 250	52	418	232	249	28	120	61	62
Sulfate (mg/L)	250 250	52 14	418 110	232 47	249 46	28 8	120 24	61 16	62 14
Sulfate (mg/L) Nitrate (mg/L)	250 250 50	52 14 0.0	418 110 1.8	232 47 0.4	249 46 0.1	28 8 0.1	120 24 6.3	61 16 1.6	62 14 0.3
Sulfate (mg/L) Nitrate (mg/L) Bromide (mg/L)	1.0 250 250 50	52 14 0.0 0.2	418 110 1.8 0.4	232 47 0.4 0.3	249 46 0.1 0.4	28 8 0.1 0.1	120 24 6.3 0.3	61 16 1.6 0.2	62 14 0.3 0.2
Sulfate (mg/L) Nitrate (mg/L) Bromide (mg/L) DOC (mg/L)	1.0 250 250 50 -	52 14 0.0 0.2 0.8	418 110 1.8 0.4 9.6	232 47 0.4 0.3 5.5	249 46 0.1 0.4 5.4	28 8 0.1 0.1 3.9	120 24 6.3 0.3 7.2	61 16 1.6 0.2 5.3	62 14 0.3 0.2 4.9
Sulfate (mg/L) Nitrate (mg/L) Bromide (mg/L) DOC (mg/L) <i>E. coli</i> (CFU/mL)	1.0 250 250 50 - - 0	52 14 0.0 0.2 0.8 0	418 110 1.8 0.4 9.6 2	232 47 0.4 0.3 5.5 1	249 46 0.1 0.4 5.4 1	28 8 0.1 0.1 3.9 0	120 24 6.3 0.3 7.2 10	61 16 1.6 0.2 5.3 3	62 14 0.3 0.2 4.9 1

* Measured in mg/L of CaCO₃. xxx – The mean and median values exceeded the drinking water standard. Source: Author.

	Drinking	HR-MED (n = 10)				HR-RAM (n = 13)				
Water Quality Parameter	Water Standard	Min.	Max.	Mean	Median	Min.	Max.	Mean	Median	
Temperature (°C)	_	27	34	29	29	26	30	28	29	
рН	6.5-8.5	6.9	7.6	7.2	7.2	6.1	7.8	7.3	7.4	
Alkalinity*	200	256	476	351	357	46	578	343	341	
TDS (ppm)	500	370	850	504	472	97	997	472	439	
Hardness*	250	256	547	364	344	62	630	360	363	
Sodium (mg/L)	200	29	163	74	70	14	241	99	67	
Potassium (mg/L)	-	0.8	44.6	6.9	2.5	0.3	19.6	3.4	1.7	
Calcium (mg/L)	100	27	116	83	89	12	158	79	73	
Magnesium (mg/L)	30	20	62	38	35	8	86	40	33	
Total iron (mg/L)	0.30	0.00	0.24	0.04	0.02	0.00	0.70	0.11	0.00	
Ammonium (mg/L)	0.06	0.00	0.01	0.00	0.00	0.00	0.17	0.01	0.00	
Fluoride (mg/L)	1.0	0.1	1.4	0.7	0.6	0.2	2.3	0.9	0.7	
Chloride (mg/L)	250	23	227	90	88	10	570	140	93	
Sulfate (mg/L)	250	10	81	33	26	6	51	30	31	
Nitrate (mg/L)	50	0.00	0.43	0.25	0.27	0.06	1.58	0.45	0.31	
Bromide (mg/L)	_	0.04	1.82	0.41	0.20	0.09	1.79	0.58	0.42	
DOC (mg/L)	-	0.4	4.9	1.8	1.3	0.4	2.8	1.4	1.4	
E. coli (CFU/mL)	0	0	40	4	0	0	384	30	0	
Total coliform (CFU/mL)	3 CFU/100 mL	0	197	50	20	0	648	90	24	
	Drinking	Drinking HR-NGP (n =			° (n = 5)			LR (n = 5)		
Water Quality Parameter	Water Standard	Min.	Max.	Mean	Median	Min.	Max.	Mean	Median	
Temperature (°C)	_	27	32	30	30	27	29	28	28	
pH	6.5-8.5	7.2	7.6	74	74	6.8	7.7	7 2	73	
Alkalinity*	200			1.4	1.4	0.0		1.5	1.0	
-	200	402	460	431	426	113	477	7.5 315	325	
TDS (ppm)	500	402 428	460 1410	431 793	426 742	113 196	477 592	315 376	325 364	
TDS (ppm) Hardness [*]	500 250	402 428 309	460 1410 1005	431 793 555	426 742 458	113 196 130	477 592 447	7.3 315 376 276	325 364 271	
TDS (ppm) Hardness [*] Sodium (mg/L)	500 250 200	402 428 309 27	460 1410 1005 234	431 793 555 132	426 742 458 108	0.0 113 196 130 33	477 592 447 90	7.3 315 376 276 61	325 364 271 59	
TDS (ppm) Hardness [*] Sodium (mg/L) Potassium (mg/L)	500 250 200 -	402 428 309 27 3.0	460 1410 1005 234 42.8	431 793 555 132 13.2	426 742 458 108 6.3	0.0 113 196 130 33 0.8	477 592 447 90 2.2	7.5 315 376 276 61 1.5	325 364 271 59 1.4	
TDS (ppm) Hardness [*] Sodium (mg/L) Potassium (mg/L) Calcium (mg/L)	500 250 200 - 100	402 428 309 27 3.0 38	460 1410 1005 234 42.8 252	431 793 555 132 13.2 120	426 742 458 108 6.3 103	0.8 113 196 130 33 0.8 37	477 592 447 90 2.2 77	7.3 315 376 276 61 1.5 62	325 364 271 59 1.4 63	
TDS (ppm) Hardness [*] Sodium (mg/L) Potassium (mg/L) Calcium (mg/L) Magnesium (mg/L)	500 250 200 - 100 30	402 428 309 27 3.0 38 46	460 1410 1005 234 42.8 252 92	431 793 555 132 13.2 120 62	426 742 458 108 6.3 103 52	0.8 113 196 130 33 0.8 37 9	477 592 447 90 2.2 77 62	315 376 276 61 1.5 62 30	325 364 271 59 1.4 63 24	
TDS (ppm) Hardness [*] Sodium (mg/L) Potassium (mg/L) Calcium (mg/L) Magnesium (mg/L) Total iron (mg/L)	500 250 200 - 100 30 0.30	402 428 309 27 3.0 38 46 0.00	460 1410 1005 234 42.8 252 92 0.36	431 793 555 132 13.2 120 62 0.09	426 742 458 108 6.3 103 52 0.03	0.8 113 196 130 33 0.8 37 9 0.04	477 592 447 90 2.2 77 62 0.46	315 376 276 61 1.5 62 30 0.14	325 364 271 59 1.4 63 24 0.04	
TDS (ppm) Hardness [*] Sodium (mg/L) Potassium (mg/L) Calcium (mg/L) Magnesium (mg/L) Total iron (mg/L) Ammonium (mg/L)	500 250 200 - 100 30 0.30 0.06	402 428 309 27 3.0 38 46 0.00 0.00	460 1410 1005 234 42.8 252 92 0.36 0.00	431 793 555 132 13.2 120 62 0.09 0.00	426 742 458 108 6.3 103 52 0.03 0.00	0.8 113 196 130 33 0.8 37 9 0.04 0.00	477 592 447 90 2.2 77 62 0.46 0.00	7.3 315 376 276 61 1.5 62 30 0.14 0.00	325 364 271 59 1.4 63 24 0.04 0.00	
TDS (ppm) Hardness [*] Sodium (mg/L) Potassium (mg/L) Calcium (mg/L) Magnesium (mg/L) Total iron (mg/L) Ammonium (mg/L) Fluoride (mg/L)	500 250 200 - 100 30 0.30 0.06 1.0	402 428 309 27 3.0 38 46 0.00 0.00 0.3	460 1410 1005 234 42.8 252 92 0.36 0.00 2.9	431 793 555 132 13.2 120 62 0.09 0.00 1.1	426 742 458 108 6.3 103 52 0.03 0.00 0.8	0.0 113 196 130 33 0.8 37 9 0.04 0.00 0.2	477 592 447 90 2.2 77 62 0.46 0.00 1.0	7.3 315 376 276 61 1.5 62 30 0.14 0.00 0.7	325 364 271 59 1.4 63 24 0.04 0.00 0.9	
TDS (ppm) Hardness [*] Sodium (mg/L) Potassium (mg/L) Calcium (mg/L) Magnesium (mg/L) Total iron (mg/L) Ammonium (mg/L) Fluoride (mg/L) Chloride (mg/L)	500 250 200 - 100 30 0.30 0.06 1.0 250	402 428 309 27 3.0 38 46 0.00 0.00 0.3 49	460 1410 1005 234 42.8 252 92 0.36 0.00 2.9 660	431 793 555 132 13.2 120 62 0.09 0.00 1.1 250	426 742 458 108 6.3 103 52 0.03 0.00 0.8 197	0.0 113 196 130 33 0.8 37 9 0.04 0.00 0.2 26	477 592 447 90 2.2 77 62 0.46 0.00 1.0 73	7.3 315 376 276 61 1.5 62 30 0.14 0.00 0.7 49	325 364 271 59 1.4 63 24 0.04 0.00 0.9 43	
TDS (ppm) Hardness [*] Sodium (mg/L) Potassium (mg/L) Calcium (mg/L) Magnesium (mg/L) Total iron (mg/L) Ammonium (mg/L) Fluoride (mg/L) Sulfate (mg/L)	500 250 200 - 100 30 0.30 0.06 1.0 250 250	402 428 309 27 3.0 38 46 0.00 0.00 0.3 49 22	460 1410 1005 234 42.8 252 92 0.36 0.00 2.9 660 125	431 793 555 132 13.2 120 62 0.09 0.00 1.1 250 56	426 742 458 108 6.3 103 52 0.03 0.00 0.8 197 54	0.0 113 196 130 33 0.8 37 9 0.04 0.00 0.2 26 6	477 592 447 90 2.2 77 62 0.46 0.00 1.0 73 46	7.3 315 376 276 61 1.5 62 30 0.14 0.00 0.7 49 21	325 364 271 59 1.4 63 24 0.04 0.00 0.9 43 17	
TDS (ppm) Hardness [*] Sodium (mg/L) Potassium (mg/L) Calcium (mg/L) Magnesium (mg/L) Total iron (mg/L) Ammonium (mg/L) Fluoride (mg/L) Sulfate (mg/L) Nitrate (mg/L)	500 250 200 - 100 30 0.30 0.06 1.0 250 250 50	402 428 309 27 3.0 38 46 0.00 0.3 49 22 0.15	460 1410 1005 234 42.8 252 92 0.36 0.00 2.9 660 125 1.50	431 793 555 132 13.2 120 62 0.09 0.00 1.1 250 56 0.67	426 742 458 108 6.3 103 52 0.03 0.00 0.8 197 54 0.58	0.0 113 196 130 33 0.8 37 9 0.04 0.00 0.2 26 6 0.10	477 592 447 90 2.2 77 62 0.46 0.00 1.0 73 46 0.38	7.3 315 376 276 61 1.5 62 30 0.14 0.00 0.7 49 21 0.20	325 364 271 59 1.4 63 24 0.04 0.00 0.9 43 17 0.17	
TDS (ppm) Hardness [*] Sodium (mg/L) Potassium (mg/L) Calcium (mg/L) Magnesium (mg/L) Total iron (mg/L) Ammonium (mg/L) Fluoride (mg/L) Sulfate (mg/L) Bromide (mg/L)	500 250 200 - 100 30 0.30 0.30 0.06 1.0 250 250 50 -	402 428 309 27 3.0 38 46 0.00 0.3 49 22 0.15 0.02	460 1410 1005 234 42.8 252 92 0.36 0.00 2.9 660 125 1.50 1.73	431 793 555 132 13.2 120 62 0.09 0.00 1.1 250 56 0.67 0.52	426 742 458 108 6.3 103 52 0.03 0.00 0.8 197 54 0.58 0.12	0.0 113 196 130 33 0.8 37 9 0.04 0.00 0.2 26 6 0.10 0.01	477 592 447 90 2.2 77 62 0.46 0.00 1.0 73 46 0.38 0.28	7.3 315 376 276 61 1.5 62 30 0.14 0.00 0.7 49 21 0.20 0.14	325 364 271 59 1.4 63 24 0.04 0.00 0.9 43 17 0.17 0.08	
TDS (ppm) Hardness [*] Sodium (mg/L) Potassium (mg/L) Calcium (mg/L) Magnesium (mg/L) Total iron (mg/L) Ammonium (mg/L) Fluoride (mg/L) Chloride (mg/L) Sulfate (mg/L) Bromide (mg/L) DOC (mg/L)	500 250 200 - 100 30 0.30 0.06 1.0 250 250 250 50 - -	402 428 309 27 3.0 38 46 0.00 0.3 49 22 0.15 0.02 1.2	460 1410 1005 234 42.8 252 92 0.36 0.00 2.9 660 125 1.50 1.73 2.9	431 793 555 132 13.2 120 62 0.09 0.00 1.1 250 56 0.67 0.52 1.8	426 742 458 108 6.3 103 52 0.03 0.00 0.8 197 54 0.58 0.12 1.4	0.0 113 196 130 33 0.8 37 9 0.04 0.00 0.2 26 6 0.10 0.01 0.6	477 592 447 90 2.2 77 62 0.46 0.00 1.0 73 46 0.38 0.28 1.8	7.3 315 376 276 61 1.5 62 30 0.14 0.00 0.7 49 21 0.20 0.14 1.2	325 364 271 59 1.4 63 24 0.04 0.00 0.9 43 17 0.17 0.08 1.2	
TDS (ppm) Hardness [*] Sodium (mg/L) Potassium (mg/L) Calcium (mg/L) Magnesium (mg/L) Total iron (mg/L) Ammonium (mg/L) Fluoride (mg/L) Sulfate (mg/L) Sulfate (mg/L) Bromide (mg/L) DOC (mg/L) <i>E. coli</i> (CFU/mL)	500 250 200 - 100 30 0.30 0.06 1.0 250 250 250 50 - - 0	402 428 309 27 3.0 38 46 0.00 0.3 49 22 0.15 0.02 1.2 0	460 1410 1005 234 42.8 252 92 0.36 0.00 2.9 660 125 1.50 1.73 2.9 5	431 793 555 132 13.2 120 62 0.09 0.00 1.1 250 56 0.67 0.52 1.8 2	426 742 458 108 6.3 103 52 0.03 0.00 0.8 197 54 0.58 0.12 1.4 1	0.0 113 196 130 33 0.8 37 9 0.04 0.00 0.2 26 6 0.10 0.01 0.6 0	477 592 447 90 2.2 77 62 0.46 0.00 1.0 73 46 0.38 0.28 1.8 7	7.3 315 376 276 61 1.5 62 30 0.14 0.00 0.7 49 21 0.20 0.14 1.2 1	325 364 271 59 1.4 63 24 0.04 0.00 0.9 43 17 0.17 0.08 1.2 0	

* Measured in mg/L of CaCO₃. xxx – The mean and median values exceeded the drinking water standard. Source: Author.

The reported sodium concentrations from all the study areas (Figure 8e) were lower than the MAL in both seasons (median 49–108 mg/L < MAL 200 mg/L). Neither the SLS nor the WHO has suggested standards/guidelines for potassium in drinking water. However, the maximum concentrations that the present study found (dry season 19 mg/L; wet season 45 mg/L) were lower than the levels that previous researchers have observed (up to 60 mg/L) (Chandrajith et al. 2011b; Wickramarathna et al. 2017).



Figure 8: a) pH; b) Alkalinity; c) TDS; d) Hardness; and e) Na⁺ in Groundwater from the Study Areas

Source: Author.

The calcium concentration in the HR-NGP area surpassed the MAL for drinking water, that is, 100 mg/L in both dry and wet seasons, whereas the other three areas always reported concentrations below the MAL (median 63–93 mg/L) (Figure 9a). The entire HR region clearly indicated magnesium levels exceeding the MAL of 30 mg/L during both seasons (median 33–69 mg/L), but the concentrations in the LR region were moderately lower than or comparable to the MAL (Figure 9b). The water quality data that the literature has reported also indicated that the magnesium levels exceeded the MAL (up to 98 mg/L) in certain CKDu-endemic areas while the calcium concentrations were below the MAL in almost all the surveyed locations (Chandrajith et al. 2011b; Wickramarathna et al. 2017). These findings suggested that, rather than calcium, magnesium might be contributing to the water quality problems and possibly the public health problems, such as CKDu, in the endemic regions. Section 4.3 will discuss this result further.

The measured concentrations of total iron and ammonium (measured as ammonia) were fairly low in both seasons. All the water samples complied with the MAL for total iron (0.3 mg/L) during the dry season, but four wells had higher concentrations (up to 0.7 mg/L) in the wet season. Cooray et al. (2019a) also observed tenfold higher dissolved iron concentrations in the wet season than in the dry season. The increased activity of iron-reducing bacteria (in the presence of labile organic matter) during the rainy season is a possible reason for this (Mladenov et al. 2010). The study did not detect ammonia in most of the wells during both seasons. However, two wells from MED and RAM did not meet the MAL (0.06 mg/L) during the dry season, probably due to sewage infiltration or the presence of organic matter.

The endemic areas of CKDu overlapped with the high groundwater fluoride zones (from 1 mg/L to levels exceeding 3 mg/L) of Sri Lanka (Dissanayake and Weerasooriya 1985; Chandrajith et al. 2011a). Apart from CKDu, the endemic areas indicated high incidence of dental fluorosis (Dissanayake 1996). Under the hot tropical climatic conditions prevailing in Sri Lanka, people tend to drink high volumes of water on a daily basis and thereby face exposure to high fluoride intakes (Chandrajith et al. 2011a). Therefore, the national standard for fluoride in drinking water is 1 mg/L. Additionally, the WHO has recommended maintaining an MAL of 0.5 mg/L for tropical countries (WHO 1994). The literature has reported fluoride levels exceeding 1.5 mg/L (WHO maximum guideline value) and as high as 8 mg/L in the groundwater of the endemic region, but the mean concentrations have mostly fallen within the 0.5-1.5 mg/L range (Chandrajith et al. 2011b; Wasana et al. 2016; Dissanavake and Chandrajith 2017; Herath et al. 2017; Wickramarathna et al. 2017). The present water quality analysis revealed relatively low fluoride concentrations (Figure 9c), which were less than or comparable with the MAL of 1 mg/L. The levels in all four areas varied between 0.5 and 1.0 mg/L during both seasons and hence were comparable with the fluoride levels reported in the past studies.

The reported chloride concentrations in all four areas were less than or comparable with the MAL (250 mg/L) in both dry and wet seasons (median 43–249 mg/L) (Figure 9d). The sulfate (median 14-54 mg/L) and nitrate (median 0.13-2.63 mg/L) concentrations in all the study areas were also mostly lower than the MALs (250 mg/L and 50 mg/L, respectively) during both seasons. Additionally, the reported nitrite (NO_{2⁻}) and phosphate (PO_4^{3-}) levels in both seasons were negligibly small in all 33 wells. This indicated that agrochemicals had not contaminated the wells. Some past studies have recognized high nitrate (up to 131 mg/L) and phosphate (up to 1.95 mg/L) concentrations in the groundwater in the study region, which they have attributed to frequent application of fertilizers and pesticides during agricultural practices (Young, Pitawala, and Gunatilake 2009; Herath et al. 2017). Nevertheless, the average concentrations hardly exceeded the drinking water standards.

Although no guidelines/standards are applicable to bromide in drinking water, potable groundwater with low salinity typically indicates bromide concentrations of less than 0.4 mg/L (Neal et al. 2007). The present study found much higher bromide levels in six wells in the dry season (up to 6.3 mg/L, mainly in MED and RAM) and in 11 wells in the wet season (up to 1.8 mg/L, mainly in RAM and NGP). Generally, Br/Cl ratios are useful for identifying the source of bromide in surface or groundwater sources. The average Br/Cl molar ratios were 0.8×10^{-3} in the dry season, whereas they were 2.1 \times 10⁻³ in the wet season. The calculated ratios for the wet season exceeded the typical ratio for seawater, that is, 1.542×10^{-3} , but it was less likely that bromide originated from seawater intrusion as the study areas were located far away from the coastal belt. Nevertheless, precipitation originating over the ocean might have affected the bromide Additionally, concentrations. sewage contamination (Br/Cl ratios up to 3×10^{-3}) and/or derivation from geological sources are possible sources of bromide in this groundwater (Koglin 1984; Schoonen, Devoe, and Brown n.d.).

Neither the SLS nor the WHO has suggested standards/guidelines for the DOC in drinking water. Nevertheless, DOC levels exceeding 4 mg/L in groundwater imply a polluted condition (Regan, Hynds, and Flynn 2017); thus, the present results indicated abnormally high DOC levels that surpassed 5 mg/L in the HR-NGP area and LR areas, particularly during the dry season (Figure 9e). The concentrations in the wet season were relatively low and comparable among the study areas (1.2–1.4 mg/L). One of the major sources of DOC in these groundwaters could be sewage. Although Cooray et al. (2019a) measured DOC levels ranging up to 11 mg/L and ascribed the excessive concentrations to agricultural activities, the present findings suggested a limited influence of agricultural activities on groundwater pollution due to the negligible amounts of nitrate and phosphate detected in the water samples.

Previous studies related to the groundwater quality in the CKDu region have often neglected microbial quality. The present results displayed very high *E. coli* and total coliform counts that exceeded the drinking water standards. The national drinking water standards require *E. coli* to remain at zero and total coliform to be <3 CFU/100 mL, whereas the WHO has recommended that both *E. coli* and total coliform are negative. Almost all the wells showed total coliform during both seasons (Figure 10a). *E. coli* was apparent in 17 wells in the dry season but only in 10 wells during the wet season (Figure 10b), probably due to increased dilution with the rise of the water table in the rainy season. Dug wells contained significantly higher (p < 0.05) *E. coli* and total coliform counts than tube wells. Most of the source water wells of RO plants were located within residential areas with poor sanitation facilities; thus, groundwater contamination with sewage was possible. Sewage pollution of groundwater due to improper construction of on-site toilet disposal systems is a common problem associated with groundwater in many parts of Sri Lanka (Herath and Ratnayake 2010).


Figure 9: a) Ca²⁺; b) Mg²⁺; c) F[−]; d) Cl[−]; and e) DOC in Groundwater from the Study Areas

Source: Author.



Figure 10: Seasonal Differences in a) Total Coliform and b) *E. coli* Counts in Wells

Source: Author.

4.3 Seasonal Variations in Groundwater Quality

4.3.1 Chemical Composition and Geochemical Processes

We plotted two piper diagrams (Figure 11a and Figure 11b) to understand the geochemical behavior of groundwater in the endemic areas of CKDu during the dry and wet seasons. The composition of ions was not particularly different between dry and wet seasons. The cation triangle depicted no dominant cation type but a mixed nature of Ca²⁺, Mg²⁺, and Na⁺, whereas the dominant anion type was HCO₃⁻. Generally, the groundwater from all the study areas was abundant in Ca–Mg–HCO₃ ion combinations. Furthermore, the composition of anions and cations in groundwater (based on milliequivalent (meq) weight per L) was HCO₃⁻ > Cl⁻ > SO₄²⁻ > F⁻ > NO₃⁻ > PO₄³⁻ and Ca²⁺ > Na⁺ > Mg²⁺ > K⁺, respectively. Chandrajith et al. (2011b) and Wickramarathna et al. (2017) observed similar behavior.

 Ca^{2+} and HCO_3^{-} in groundwater usually originate from either carbonate weathering or silicate weathering or from both processes. Equation (3) and Equation (4) show the chemical reactions that take place during the two processes (Colbourn, Ridgwell, and Lenton 2015).

$$CO_{2(aq)} + H_2O_{(l)} + CaCO_{3(s)} \rightarrow Ca^{2+}_{(aq)} + 2HCO_{3^{-}(aq)}$$
 (3)

$$2 \operatorname{CO}_{2(aq)} + \operatorname{H}_2 O_{(l)} + \operatorname{CaSiO}_{3(s)} \to \operatorname{Ca}^{2+}_{(aq)} + 2\operatorname{HCO}_3^{-}_{(aq)} + \operatorname{SiO}_{2(aq)}$$
(4)





Source: Author.

The scatter points above the 1:1 equiline in the (Ca + Mg) vs (HCO3 + SO4) diagram (Figure 12a) indicate that the Ca²⁺ in groundwater mainly derived from carbonate weathering. During rainy periods, the infiltrated rainwater may carry/dissolve the available carbonate minerals along the flow paths and later release Ca²⁺ and HCO₃⁻ into groundwater during the recharge process. Therefore, the wet season results also suggested carbonate weathering as a source of Ca²⁺ (Figure 12b). Meanwhile, the points fell along the 1:1 equiline, and the few points below the line in both graphs implied the contribution of silicate weathering to a limited extent (Elango and Kannan 2007).



Figure 12: (Ca + Mg) vs (HCO₃ + SO₄) Scatter Plot for a) the Dry Season and b) the Wet Season

Source: Author.

In the Na⁺ vs Cl⁻ scatter plot (Figure 13a and Figure 13b), the points mostly lie below the equiline. The distribution along the equiline, that is, the 1:1 relationship, usually implies that Na⁺ derives from the dissolution of halites (mainly Cl⁻). Nevertheless, Figure 13 depicts increased concentrations of Na⁺ with respect to Cl⁻ or the points mostly positioned below the equiline. This infers that silicate weathering is the most likely source of Na⁺ in this groundwater rather than halite dissolution.

Generally, an Na⁺ vs HCO₃⁻ scatter plot (Figure 14a and Figure 14b) is useful for clarifying whether HCO₃⁻ derives from carbonate weathering or silicate weathering. Given that the Na⁺ probably derived from silicate weathering, the Na⁺ vs HCO₃⁻ scatter diagram indicates that the HCO₃⁻ probably originated from carbonate weathering.



Figure 13: Na⁺ vs Cl⁻ Scatter Plot for a) the Dry Season and b) the Wet Season

Source: Author.





Source: Author.

Therefore, the carbonate weathering process could be the primary reason for the $Ca-Mg-HCO_3$ predominant geochemistry in the CKDu region. In addition to the weathering processes, ion exchange, oxidation/reduction, and hydrolysis processes may control the composition of ions in this area's groundwater (Elango and Kannan 2007).

4.3.2 Comparison of Water Quality

A similar geochemical composition of groundwater during dry and wet seasons is evident from Figure 11 to Figure 14. In terms of the measured levels/concentrations in groundwater, only pH and nitrate and DOC indicated significant seasonal differences (Table 7).

Water Quality				
Parameter	MED	NGP	RAM	LR
рН	0.000**	0.000**	0.000**	0.004**
TDS	0.518	0.928	0.085	0.202
Hardness	0.669	0.921	0.483	0.865
Alkalinity	0.280	0.942	0.517	0.441
Calcium	0.855	0.927	0.738	0.970
Magnesium	0.701	0.933	0.481	0.814
Sodium	0.944	0.845	0.838	0.843
Potassium	0.431	0.257	0.718	0.642
Chloride	0.909	0.888	0.893	0.537
Sulfate	0.634	0.731	0.619	0.538
Fluoride	0.613	0.843	0.899	0.884
Nitrate	0.124	0.564	0.007**	0.291
DOC	0.942	0.012*	0.052	0.001**
E. coli	0.503	0.705	0.809	0.561
Total coliform	0.307	0.054	0.743	0.980

Table 7: p Values for the Statistical Comparison of Groundwater Quality
between the Dry and the Wet Season

* Significant difference at p < 0.05. ** Significant difference at p < 0.01.

Source: Author.

Despite slightly higher alkalinity levels in the dry season than in the wet season, the pH levels were significantly low and acidic in the dry season in all four study areas (refer to Table 6a). A warmer solution can possess high buffering capacity (indicated by high alkalinity) despite having a lower pH (Jim 2020). Therefore, the relatively high temperature of groundwater in the dry season compared with the wet season is a possible reason for the significant seasonal differences between the pH levels.

The reported DOC levels in the HR-NGP and LR areas were significantly higher in the dry season than in the wet season. Additionally, the nitrate levels showed a significant difference between dry and wet seasons only in the HR-RAM area. The reported concentrations of all the other elements, including the excessive chemical constituents (alkalinity, hardness, TDS, and magnesium), in all the study areas (as Section 4.2 explains) were rather comparable between the two seasons (refer Table 6) and hence did not indicate any statistically significant seasonal variations (in Table 7).

Considering the increased mixing of groundwater with infiltrated rainwater, the expectation is that the concentrations of chemical parameters will be lower in the wet season than in the dry season. Meanwhile, the compositions of major ions are likely to differ between the two seasons, unlike the situation in the present case. These facts superficially inferred that rainwater infiltration had not affected the groundwater in the study areas by the time of the sampling during the wet season. The shallow groundwater in the CKDu-endemic region mostly originates from the regolith aquifers (refer to Section 2.5), which are mostly of a stagnant nature, and direct rain or surface water sources hardly recharge them (Edirisinghe et al. 2017). Therefore, it is possible that recharging of the aquifers did not occur soon after the rainfall.

On the contrary, personal communications with the local people and the evidence from past studies (Kumari et al. 2016) suggested that the groundwater table in these areas rises significantly during the month of December, when the sampling for the rainy season took place (water levels in August (dry season): <2 m; December (wet season): 5–10 m). Then, the possible explanation for comparable ion concentrations in dry and wet seasons would be as follows. When rain recharges regolith aquifers, the dissolved ion concentration in groundwater could increase despite the dilution that the rise of the water table causes. This is because the percolated rainwater carries available free ions from the overburdened soil as it reaches the aquifer (Subba Rao 2005). Kumari et al. (2016) observed similar EC levels in CKDu groundwaters during both dry and wet seasons despite a significant rise in the water table in the rainy/wet season.

The DOC in the HR-NGP and LR areas was significantly higher in the dry season than in the wet season (p < 0.05). Though the difference was not significant, the total coliform levels were comparatively higher in the wet season than in the dry season. As Section 4.2 explained, the potential source of DOC and coliforms in groundwater in the study region could be sewage. Groundwater contamination with sewage is typically high in the rainy season due to increased mixing resulting from the elevated water table (Arnade 1999). Therefore, both DOC and coliform levels are likely to be higher in the wet season than in the dry season. While this was true for the measured levels of total coliform, the DOC indicated the opposite behavior. The dissolved component of organic matter in domestic sewage accounts for only 21.5%, while the rest comprises colloidal (21.5%) and suspended (57%) fraction (Huang, Li, and Gu 2010). Therefore, it is possible to assume that the non-dissolved/particulate organic matter fraction reflected the increase in the organic matter content of groundwater.

4.4 Comparison of Groundwater Quality between HR and LR Areas

Many researchers have attempted to interpret possible correlations between the quality of groundwater and the occurrence of CKDu by identifying the water quality parameters that indicated significantly higher concentrations in the areas with high prevalence of CKDu compared with areas with low or zero prevalence. In the present study, the p values derived from the statistical comparison of groundwater quality between HR and LR areas (Table 8) indicated such kinds of positive correlations for some water quality parameters.

The mean and median concentrations, alkalinity, hardness, TDS, and major ions (calcium, magnesium, sodium, potassium, chloride, and sulfate) always showed higher concentrations in the HR areas than in the LR areas (refer to Table 6). These differences between HR and LR areas were significant at the p < 0.05 level, especially during the dry season (Table 8). Meanwhile, the groundwater in the HR areas deteriorated more due to the co-presence of elevated levels of alkalinity, hardness, TDS, and magnesium exceeding the MALs for drinking water (as Section 4.2 explained) and thus indicated a positive correlation with the geographic occurrence of CKDu. On the other hand, the fluoride, DOC, and coliforms levels in the LR areas were higher than or comparable with the concentrations in the HR areas and thus hardly suggested any positive correlation with the occurrence of CKDu.

	Dry Season				Wet Season				
Water Quality	ANOVA + Tukey's HSD Test			t-Test	ANOVA + Tukey's HSD Test			t-Test	
Parameter	MED-LR	NGP-LR	RAM-LR	HR-LR	MED-LR	NGP-LR	RAM-LR	HR-LR	
рН	0.971	0.586	0.708	0.427	0.897	0.967	0.992	0.975	
TDS	0.138	0.005**	0.008**	0.000**	0.766	0.048*	0.870	0.074	
Hardness	0.344	0.009**	0.208	0.009**	0.704	0.029*	0.711	0.080	
Alkalinity	0.091	0.034*	0.088	0.025*	0.935	0.380	0.965	0.499	
Calcium	0.508	0.054	0.588	0.013*	0.793	0.152	0.867	0.035*	
Magnesium	0.636	0.076	0.305	0.022*	0.073	0.790	0.144	0.227	
Sodium	0.374	0.480	0.513	0.019*	0.978	0.246	0.626	0.055	
Potassium	0.895	0.929	0.948	0.012*	0.766	0.294	0.983	0.012*	
Chloride	0.965	0.198	0.597	0.046*	0.953	0.140	0.628	0.006**	
Sulfate	0.605	0.054	0.669	0.004**	0.770	0.085	0.865	0.119	
Fluoride	0.999	0.883	0.981	0.698	0.993	0.730	0.987	0.669	
Nitrate	0.882	0.965	0.751	0.366	0.991	0.152	0.498	0.018*	
DOC	0.051	0.999	0.039*	0.007**	0.694	0.820	0.978	0.182	
<i>E.</i> coli	0.538	0.602	0.170	0.365	0.903	0.999	0.998	0.645	
Total coliform	0.974	0.996	0.817	0.495	0.883	0.723	0.621	0.061	

Table 8: p Values Resulting from the Statistical Comparison of Water Quality between CKDu-HR and CKDu-LR Areas

* Significant difference at p < 0.05. ** Significant difference at p < 0.01.

Source: Author.

Based on these correlations, it is reasonable to postulate that **high hardness due to elevated magnesium** and **high ionicity due to major dissolved ions** (which the high TDS reflects) might have an association with the incidence of CKDu. These results are in line with the findings of several past studies, as follows.

Wasana et al. (2016) reported significantly high hardness levels in the HR areas compared with the LR areas. Additionally, Balasooriya et al. (2019) found significantly high TDS and ion (magnesium, sodium, fluoride, sulphate, and phosphate) contents in groundwater that CKDu patients consumed compared with groundwater that non-patients from the same endemic areas consumed. Although a relationship between fluoride and the geological occurrence of CKDu was not notable in the present case, a substantial number of past studies have suggested fluoride as a potential risk factor of CKDu (as Section 4.2 explained). Studies have observed significant differences between the average reported fluoride levels from the endemic (0.5–1.5 mg/L) and non-endemic (<0.5 mg/L) regions but not always between the HR and the LR group within the same endemic region (Chandrajith et al. 2011a; Rango et al. 2015; Wasana et al. 2016). This was in agreement with the observations of the present study.

Among a large number of water quality parameters that studies have tested so far with respect to the onset of CKDu, fluoride has displayed a better possibility of triggering renal issues. Nevertheless, the failure to trace a straightforward relationship between fluoride and CKDu has suggested that it does not act alone to trigger the disease. Instead, researchers have suspected the synergistic involvement of elevated fluoride, hardness, and other dissolved ions (Chandrajith et al. 2011b; Dharma-wardana et al. 2015; Dissanayake and Chandrajith 2017; Wasana et al. 2017; Dharma-wardana 2018).

Wasana et al.'s (2017) study on mice indicated renal damage in mice ingesting synthetic water samples containing above-MAL levels of fluoride (1.5 mg/L) and hardness (CaCO₃ 200 mg/L or Ca²⁺ 80 mg/L; MgCO₃ 185 mg/L or Mg²⁺ 53 mg/L). They did not test for below-MAL fluoride and hardness concentrations, but, interestingly, fluoride alone, even at 10 mg/L, did not cause such histo-pathological changes in mice. In another study,

Thammitiyagodage et al. (2017) observed kidney failure among mice that they had fed with groundwater from endemic areas containing very high fluoride (4.8–13 mg/L) and rather low calcium (21–46 mg/L) concentrations. Through a deep theoretical analysis, Dharma-wardana (2018) explained that fluoride along with water hardness due to magnesium but not calcium would exert more nephrotoxic effects than fluoride ions alone. This hypothesis coherently explained the results of the above studies with mice in which both cases supposedly involved low calcium but high magnesium. Additionally, a few other studies have implied that fluoride tends to interact better with magnesium than calcium in the groundwater that CKDu patients used (Paranagama, Bhuiyan, and Jayasuriya 2018; Balasooriya et al. 2019). These pieces of evidence indicate that high hardness associated with high magnesium levels seems to play a role in CKDu. The present results compliment this idea well, showcasing significantly higher hardness levels in the HR areas than in the LR areas. Both parameters in the LR areas were below the MAL values.

There was no clear difference between the ionic composition of groundwater in the HR and LR regions (as Figure 11–Figure 14 portrayed), but it was rather obvious that the concentrations of major ions in the groundwater of the HR region were markedly higher than those in the LR region. Despite significant differences between the concentrations of major ions in the HR region and the LR region, no clear differences were apparent between the ionic compositions in the HR and LR regions. This implied that, despite the similar geological settings of the HR and LR regions, the ionic concentrations in groundwater are different, possibly due to different groundwater recharge, flow, and usage patterns. With the support of geochemical and isotopic evidence, Edirisinghe et al. (2017) suggested that the prevalence of CKDu is significantly high for groundwater that only direct rain and regional flow paths recharges but not for surface water sources. This groundwater consists of stagnant water bodies and thus contains high concentrations of major ions (high ionicity). On the contrary, the incidence of CKDu is significantly low in groundwater that surface water recharges, diluting the ions (low ionicity).

In addition to the ionic parameters, the characterization of the DOC in CKDu-endemic areas exposed the possibility that the complexations between DOC and pesticide residues/major ions like calcium and sulphate could have a link with CKDu (Makehelwala et al. 2020). The DOC concentrations that they measured in HR and LR areas were comparable and were lower than the levels that the present study reports. Our results did not support such a direct link between CKDu and DOC. Nevertheless, the DOC is a complex water quality parameter; hence, arriving at conclusions based on concentrations alone would not be meaningful.

4.5 Summary of Section 4

The groundwater quality differed substantially between the four study areas, but, generally, the LR areas showed better water quality with respect to the drinking water standards than the HR areas. The alkalinity, hardness, and microbiological parameters exceeded the drinking water quality standards/MALs in all the study areas, whereas the TDS and magnesium particularly exceeded the standards in the HR areas. Within the HR areas, NGP groundwater deteriorated more than in the other two areas, even though all three areas were in close vicinity. Although no drinking water standards are applicable, the DOC and bromide concentrations in the groundwater were unusually high (DOC >4 mg/L; bromide >0.4 mg/L) in certain locations of both the HR and the LR area. Sewage contamination could be the key reason for the high contents of coliform bacteria,

DOC, and bromide that the study detected in the groundwater in these areas. Negligibly small contents of nitrate, nitrite, and phosphate suggested that agrochemicals had not contaminated the groundwater.

Except for pH, DOC, and nitrate, none of the water quality parameters indicated significant seasonal differences in terms of the measured concentrations. All the groundwater was abundant in Ca–Mg–HCO₃ ion combinations, which could have derived from carbonate weathering of aquifer minerals. The composition of ions and major chemical parameters was not significantly different between the dry and the wet season. These observations suggested that either precipitation had not recharged the groundwater by the time of the sampling in the wet season or the rainwater had washed out a substantial amount of dissolved solids from the overburdened soil as it percolated through the soil to recharge the aquifer.

The groundwater from the HR areas indicated significantly higher concentrations of alkalinity, TDS, hardness, and almost all major ions than that from the LR areas, especially during the dry season. Considering the reported elevated concentrations of hardness, magnesium, and TDS from groundwater, and their significantly high presence in the HR groundwater compared with the LR groundwater, it is possible to postulate that hardness due to higher magnesium (than calcium) and ionicity associated with major dissolved ions might relate to the occurrence of CKDu. As far as the present survey data were concerned, no relationships with CKDu were notable for fluoride and DOC.

5. PERFORMANCE OF THE RO PLANTS

5.1 Objectives for Section 5

This section provides a detailed discussion of Objective 2 of the study, that is, to verify the effectiveness of the existing RO plants in reducing the excessive constituents in groundwater to meet the drinking water quality standards.

The study assessed the performance of the RO plants during the dry and wet seasons separately to determine the attained removal efficiency for each water quality parameter and the overall permeate recovery rates of the plants.

5.2 RO Plants' Removal of Excessive Contaminants

Figure 15 shows the water treatment process in a typical investigated RO plant. The calculated recovery rates of RO plants (dividing the permeate flow by the feed flow) varied between 36% and 55% (mean 46%) during the dry season and between 35% and 87% (mean 47%) during the wet season. The typical rates are about 35–45% for seawater desalination and about 75–90% for brackish water treatment (Greenlee et al. 2009). With relatively low TDS levels in feedwater (<1,000 ppm), the supposition is that these RO plants will achieve higher recover rates than seawater (TDS >10,000 ppm) or brackish water (TDS 1,000–10,000 ppm) RO plants. Low recovery rates are normally due to the design and operational conditions. For instance, these types of small-scale RO plants operate at low pressure to reduce the energy costs and the price of high-pressure pumps. In addition, the low recovery rates in these plants were possibly due to poor cleaning of RO membranes. Section 6.3 will explain this further.

The study calculated the contaminant removal rates of the RO plants by dividing the difference between the raw water quality and the treated water quality with the raw water quality (Table 9). The calculated rates for all the parameters of the plants from the HR and LR areas were comparable.



Figure 15: Water Treatment Process in the RO Plants

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Table 9: RU P	Plants' Remova	ai of Maior C		trom the	reedwater
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	Γ	Dry Season	Wet Season					
	Compliance	% Removal Rates			Compliance	% Removal Rates		
Parameter	with Standards	Range	Mean	SD	with Standards	Range	Mean	SD
рН	All 32 plants	_	-	_	16 plants failed	-	_	-
Alkalinity	complied	61–100	95	7	All 32 plants	85–99	96	3
Hardness		98–100	99	1	complied	97–100	99	1
TDS		93–99	96	1		60–98	90	9
Mg ²⁺		98–100	99	1		97–100	99	1
Ca ²⁺		98–100	99	1		97–100	99	1
Na⁺		81–97	92	4		79–99	92	5
K ⁺	N/A	56–100	90	10	N/A	56–100	91	9
Cl	All 32 plants	93–99	97	2	All 32 plants	92–100	97	2
F ⁻	complied	34–92	74	12	complied	40–94	80	14
SO4 ²⁻		94–99	98	1		98–100	99	1
NO ₃ -		8–96	71	25		84–100	94	5
DOC	N/A	9–93	55	23	N/A	35–100	94	15
Total coliform	10 plants failed	0–100	88	23	6 plants failed	22–100	95	16
E. coli	2 plants failed	80–100	99	4	1 plant failed	100% rem other 32 p	oval for th ants	e

Source: Author.

The pH levels of treated water in the dry season (mean 7.6) were relatively higher than those in the wet season (mean 6.6), probably due to the significant seasonal differences that the study observed in the feedwater pH (dry season: 6.6; wet season: 7.3). Usually, RO membrane treatment involves a critical feed pH, below which the permeate shows a higher pH than the feed but above which the permeate pH is lower than the feed pH (Qin, Conialio 2005). Therefore. Oo. and it is possible to assume that the feed pH in the dry season was lower than the critical feed pH, while it was higher than the critical pH in the wet season. Furthermore, the permeate pH in the dry season was acceptable for drinking, but, in the wet season, nearly 50% of the plants (5.75-6.44) did not comply with the minimum standard for drinking, that is, 6.5. The RO plants did not adopt any measures to fix the pH levels of permeate.

All 32 RO plants showed an excellent performance (90–99% removal) in terms of the removal of high TDS, hardness, alkalinity, reactive silica (up to 81 mg/L in feedwater), and major ions: calcium, magnesium, sodium, potassium, chloride, and sulfate. Meanwhile, the permeate that all the RO plants produced complied with the relevant MALs for these parameters during both seasons. The removal of fluoride (dry: 74%; wet: 80%) was not as efficient as the removal of other major anions (chloride and sulfate), probably due to the low fluoride contents in the feedwater. However, the permeate always satisfied the MAL for drinking (1.0 mg/L). As Section 4.4 explained, researchers have suspected that the high hardness associated with high magnesium and the high ionicity that high TDS and fluoride reflect have a link with the incidence of CKDu. Therefore, the satisfactory removal of these components could reduce the propagation of CKDu, as local people and water supply authorities have speculated (personal communications).

On the other hand, the excessive removal of major ions implied continuous exposure to low mineral contents through drinking water. Since RO treated water is the main source of drinking and cooking water in the endemic areas, it would be advisable to maintain adequate levels of essential minerals, especially calcium, in treated water to ensure the health benefits for the consumers in the long run. The recommendation is to maintain a minimum level of 30 mg/L of calcium, along with a minimum of 100 mg/L of dissolved salts, in demineralized water, considering the long-term health benefits for children and adults (Kozisek 2004). Remineralization of product water with calcium/magnesium may not be the best solution in the present case as it will encourage biofilm growth in the produced water, further increasing the DOC and coliform contents (Wang and Hu 2018). Therefore, a more sensible way of increasing the mineral contents would be to adopt loose pore/low-rejection RO membranes or nano-filter (NF) membranes instead of the currently used tight pore membranes. In this way, the production volume of treated water and the permeate pH could also increase. Another potential solution would be to allow a bypass flow from the permeate of the micro-filter (MF) membrane to combine with the RO permeate to maintain a desirable concentration of ions in the treated water.

The average removal of DOC by RO plants was rather low during the dry season (mean 55%, SD 23%) compared with the wet season (mean 94%, SD 15%), probably due to relatively high feed DOC concentrations (>4 mg/L) during the dry season. In addition, nine plants showed comparatively higher DOC levels in permeate than in feed. The release of pre-deposited particles that had become trapped and accumulated within pre-filtration units, the membrane itself, and treated-water storage tanks over time, the leaching of DOC into product water from HDPE-treated water tanks, and other components like piping materials could be some of the potential ways in which DOC increases in permeate. Nevertheless, further investigations should involve periodic monitoring of DOC levels at different locations of the treatment process. Frequent

backwashing of activated carbon filter (ACF) and periodic cleaning of MF are vital to improve the RO plants' DOC removal.

Next, the performance of the RO plants was not satisfactory in terms of the removal of *E. coli* and total coliform as a substantial number of plants still indicated coliforms in the produced water during both seasons (Table 9; Figure 16). The only disinfection measure was UV disinfection, which took place immediately after RO membrane treatment and before treating the water storage tanks. The testing of water samples just before and after storage tanks revealed that the contamination is likely to have occurred within the tanks without frequent cleaning. The lack of cleaning might have promoted biofilm formation and the release of *E. coli* and total coliform into the product water (Zhang et al. 2013). To overcome this issue, a suitable disinfection measure, such as chlorination before the storage tank and/or another UV disinfection unit at the outlet of the storage tanks, is recommendable.

Figure 16: Microbiology Test for Feedwater and Treated Water: a) Sufficient Disinfection of Permeate; b) Insufficient Disinfection of Permeate



Microbiological safety of drinking water: Safe drinking water should be free of microbiological contaminants. Before the spread of CKDu, the local people in the north central region used to consume raw groundwater abstracted from the wells. Some of these wells now supply feedwater to the RO plants, and most of the times report high coliform levels, indicating microbial contamination of the well water. Unfortunately, some RO plants fail to eliminate such contaminants in feedwater due to the lack of disinfection measures (Photos by Sachithra Imbulana).

Furthermore, it was observable during the field investigation that the distribution of treated water is not safe. The distribution pipes and outlets and the water containers that consumers use did not appear to be clean enough (Figure 17). These components can further enhance biofilm formation in treated water during its storage inside the containers for several days before consumption. Therefore, CBOs should clean the tanks and distribution pipes frequently while educating the consumers to follow safe water collection and storage practices.



Figure 17: Unsafe Water Distribution and Collection

Effective water purification is not always sufficient: The quality of treated water produced by the RO plants relies highly not only on the effectiveness of the treatment process, but also on post-treatment water distribution practices. Some of the existing RO plants in the CKDu-affected areas adopted unsafe water distribution and collection methods such as ill-suited treated-water outlets and unclean water containers. Such practices could impair the quality of the treated water produced by the plants, and thus waste the efforts put into the exhaustive treatment process (Photos by Sachithra Imbulana).

These RO plants employed the Hydranautics ESPA2-LD-4040 type of membrane, which is a low-fouling composite polyamide membrane. Therefore, the study considered that these RO plants maintained organic fouling due to the minimum level of DOC and biofouling due to microorganisms. However, high DOC concentrations in the feedwater appeared to affect the performance of the MF. The two RO plants that reported the highest feedwater DOC levels during the dry season (6.23 mg/L and 9.63 mg/L) required more frequent changing of the MF (once a month) than other plants (Figure 18).

Figure 18: Wasted Micro-filter (MF)



Costly pre-treatment: The pre-treatment units of RO plants, including the micro-filters are costly and require periodic replacement due to clogging after prolonged use. The period of replacement may vary among plants depending on a number of factors, including the quality of feedwater, operational conditions, and maintenance practices. The micro-filters shown in these pictures clogged rapidly and frequently due to bad quality of feedwater, causing high expenses to the operators (Photos by Sachithra Imbulana).

The study also calculated the removal efficiency for reactive silica (in the dissolved form) as it could contribute significantly to membrane fouling in RO systems. The feedwater contained reactive silica up to 81 mg/L (mean 55 mg/L), which is quite normal for groundwater (Khan, Umar, and Khan 2015). These levels fell to less than 1.5 mg/L in most of the plants to achieve silica removal rates >90%. The intervention of PA0100 antiscalant presumably effectively controlled inorganic scaling due to silica as well as high hardness levels (Jiang, Li, and Ladewig 2017). However, controlling the scale formation in ACF and Multimedia filter (MMF) units that appeared prior to the injection of antiscalant was problematic in some plants (Figure 19). Frequent replacement of the filter media of these two filters was necessary with high hardness levels in the feedwater. A few plants experienced operational issues when they did not use antiscalant for 5 days in a row.

Figure 19: White Stains on Plant Equipment (a) MMF and ACF and b) Water Tanks Indicate High Hardness Levels in the Source Water



Site-specific challenges of operating RO plants: The poor quality of feedwater (i.e., groundwater) itself can be deleterious to the performance of the RO plants. In this particular plant from the Thambalagollewa area, the feedwater contains high hardness levels leading to scaling of the pre-treatment units. The operators have to clean those units regularly and even replace them frequently, in order to maintain the continuous operation of the plant (Photos by Sachithra Imbulana).

5.3 Summary of Section 5

Seasonal changes affected the feedwater pH levels of treated water, and the wet season showed rather low pH levels (5.7–6.4). All the RO plants achieved excellent removal rates (>90%) for excessive chemical contaminants in the groundwater (alkalinity, hardness, TDS, and magnesium) during both seasons. The study noted excessive removal of essential minerals, like calcium, and it is necessary to solve this problem considering the health issues of long-term exposure to low mineral contents in drinking

water. The removal rates for DOC were rather low during the dry season (55%) when the feed DOC exceeded 4 mg/L.

The recovery rates of RO plants were rather low (mean 46%) and quite comparable between the two seasons. Additionally, high DOC and hardness levels in the feedwater affected the operations of the pre-filtration units. Periodic chemical cleaning and backwashing of filters is necessary to overcome the fouling resulting from a range of membrane foulants present in the feedwater and the clogging issues of filters and to achieve high recovery rates. Recontamination of the treated water occurred during storage in treated water tanks; therefore, plants should employ additional disinfection measures between the treated water storage tanks and the distribution outlets. Furthermore, periodic maintenance is vital to ensure the optimum performance of the plants as well as the good health of the local people.

6. OPERATION AND MAINTENANCE OF RO PLANTS

6.1 Objectives of Section 6

This section provides a detailed discussion of Objective 3 of the study, that is, **to provide** an overview of the current status and problems regarding the O&M of the RO plants. The discussion mainly concerns the findings of the interviews that we conducted with RO plant operators about plant O&M and with RO-treated water consumers in relation to consumer behavior and satisfaction.

6.2 Socio-economic Background of the Study Areas and Consumer Behavior Regarding RO Water

The interviews with consumers of RO-treated water (32 people) in CKDu-endemic areas revealed the following information about their household profiles and water usage behavior. In total, these interviews gathered information from 129 inhabitants.

A typical family had four persons, with a 1:1 male to female ratio. Nearly 62% of the inhabitants belonged to the working population, that is, the 18–60 years age group. Only 31% of the adults (>18 years group) had received proper school education (beyond Ordinary Level or Grade 11) to be sufficiently qualified to secure a decent job (Figure 20). Regarding the employment status of the community (Figure 21), 25% of individuals were unemployed, and these were mostly women (Figure 21); cultivation was the main source of income (Figure 22) for 35%; 29% were involved in either government or private sector jobs; and the rest were self-employed (e.g., trishaw drivers, dairy farmers, or carpenters) or engaged in higher education. Even if cultivation was not the main source of income for many, it was a secondary source of income for almost all the families. The monthly income of a family ranged between 1,000 and 80,000 LKR or 5–400 USD (1 LKR = 0.005 USD as of June 2020), with an average of 33,000 LKR (165 USD). This was considerably lower than the national average in Sri Lanka, which is 62,237 LKR (311 USD) (Central Bank of Sri Lanka 2018). According to the respondents, day-to-day expenses accounted for almost all the household income, leaving no money as savings.



Figure 20: Level of Education of the Local People in the Study Areas

Source: Author.

Figure 21: Main Types of Employment of the Local People in the Study Areas



Source: Author.

Figure 22: Irrigation-Based Paddy Cultivation is the Main Source of Income in CKDu-Endemic Areas: a) an Irrigation Tank; b) a Paddy Field



Tank-based irrigation: The north central dry zone of Sri Lanka was home to a unique hydraulic civilization comprising a cascade of irrigation tanks. The purpose of these tanks was to store rainwater for irrigating paddy cultivations of the locality. This agricultural tradition is still in practice in the dry zone and is the main source of income for many local people. The tank-based irrigation plays a significant role not just in the economy of these areas, but also in its culture and traditions (Photos by Sachithra Imbulana).

The queries about water usage behavior revealed that most of the local people had been solely reliant on dug wells or tube wells (75%) to fulfill their drinking and cooking water needs before the inception of the RO plants. Additionally, water from springs/streams/irrigational canals and piped-water schemes were common. Nearly one-third of the villages or GNDs under investigation had access to piped-water supply schemes that CBOs operated. These groundwater-based schemes adopted only chlorination as a treatment step. After the establishment of the RO plants, almost everyone moved to RO-treated water to meet their drinking (100%) and cooking (88%) water needs. Nevertheless, 12% continued to use well water or piped water for cooking purposes due to a lack of knowledge on the potential ingestion of contaminants through cooking water. In addition, 16% used harvested rainwater as an alternative source of potable water during the wet season.

As the reason for shifting to RO-treated water, most of the respondents (72%) mentioned that they believe that it helps them to avoid CKDu. Additionally, the poor quality of past drinking water sources (28%), the advice of health authorities (25%), and the practices of neighbors (22%) motivated them to choose RO-treated water over other sources of drinking water. The survey elucidated that the local people have scant knowledge about the importance and health benefits of consuming safe drinking water. Nevertheless, they have experienced a reduction in urinary tract diseases and gastro-intestinal diseases with RO-treated water. A few respondents had observed a reduction of the progression of CKDu in their village after the inception of the RO plants.

The treated water that the RO plants produced was distributed to the community at the plant premises (Figure 23). The residents carried their containers to the plants and collected water after paying money. The NWSDB has recommended that all CBOs maintain the price of treated water at a very low level, like 1 LKR/L (0.005 USD/L), considering the low income levels of the consumers. On average, RO-treated water accounted for 2% of the monthly household income (660 LKR = 3.3 USD). About 90% of the interviewees were satisfied with the current price of treated water, while a few expected lower prices. The average consumption of RO-treated water was approximately 21 L/day/household (5–50 L/day/household), meaning about 5 L/day/person (for a family with four members), thus meeting the target of the NWSDB to provide at least 5 L/person/day of RO-treated water.

It usually took 15 minutes at most (average 5 minutes) for the consumers to reach the RO plants. The study observed equal participation of men and women in visiting the RO plants to purchase water. Motorcycles and bicycles were the most common ways of transporting water (Figure 23). Of 32 villages, 20 had multiple (two to five) RO plants which different entities had established, whereas the other 12 had only the NWSDB plant. Those who could access multiple options tended to choose a suitable RO plant based on the proximity to their house (55%), a better quality of produced water (45%), and the preference of a majority of the villagers (25%). Additionally, a lower price than other RO plants and acquaintance with CBOs influenced a few consumers (15%). Truck delivery services or bowser suppliers of RO-treated water were also available in half of the villages. They maintained two- to threefold higher prices per liter of treated water. Despite the higher prices, nearly 50% of the consumers preferred to buy water from those vendors due to their wide accessibility. The poor quality of the water that such vendors delivered was a concern for the other 50%.

The perception of all the respondents about the quality of treated water that the RO plants produced (with respect to their old source of water), the quantity and price of RO-treated water, and the operating hours and levels of O&M of the RO plants were highly positive. A few of them mentioned that the plants were unable to meet the demand during extremely dry periods; hence, the quantity of water available for the consumers was

limited. Moreover, respondents highlighted the necessity to carry out frequent cleaning of the plants, considering the changes that occurred in the taste of the produced water over time.



Figure 23: Distribution of Treated Water to the Local People at the RO Plants

New alternative to village wells: RO plants have become a place where the community gathers on a daily basis for chitchats, as they did at the village wells in the past, before the spread of CKDu. They normally visit the plant by their bicycles, trishaws or by foot, along with their empty water containers, pay money and purchase enough RO-treated water to fulfill their daily potable water needs (Photos by Sachithra Imbulana).

6.3 Current Status and Problems of O&M of the RO Plants

All the RO plants operated for 8 hours daily, and the treatment capacities varied between 6 and 17 m³/day. They usually served 100–500 families, depending on the treatment capacities. The daily demand of a plant varied between 1 and 5 m³/day (average 2 m³/day) in the absence of bulk supplying (Figure 24). As Table 10 shows, the monthly income sufficiently covered the basic O&M expenses for most of the CBOs.

	Amount*		
Cost Item	LKR	USD	
Income			
Sales of treated water (2,000 L/day × 1 LKR/L × 30 days)	60,000	300	
Expenses			
Wage for the plant operator	15,000	75	
Electricity bill	8,000	40	
Miscellaneous expenses	2,000	10	
Savings	35,000	175	

Table 10: An Example of the Average Monthly Balance of a Typical RO Plant

* 1 LKR = 0.005 USD as of June 2020.

Source: Author.

However, a few plants experienced a low demand for RO-treated water and hence earned a low income. This was mainly due to the availability of multiple RO plants, including privately owned and charity-based RO plants, and truck delivery services of RO-treated water for a certain community. As Section 6.2 explained, the private vendors set higher unit prices for treated water than the NWSDB, but they distributed the plants/services widely in the areas, offering customers easier access. Meanwhile, charity-based plants offered water for free. Thus, some people opted for such alternatives considering the lower price and easy accessibility.



Figure 24: The Daily Demand for RO-Treated Water in the RO Plants

Source: Author.

Seasonal variations strongly affected the operations of the RO plants and the demand for treated water. During the wet season, 28 plants experienced a substantial drop in demand due to the usage of harvested rainwater and spring water. Meanwhile, 12 RO plants found it difficult to carry out their normal operations during prolonged dry periods due to the scarcity of well water. To deal with this issue, some plants investigated alternative wells, whereas others reduced the operational duration of the plants or temporarily terminated the plant operations during the dry season. It would be convenient for the government to outsource the supply of safe drinking water (probably to some bottled water companies) to these areas during such difficult times. On the other hand, this issue highlighted that an increasing number of RO plants may further deplete the scarce groundwater resources of the CKDu-endemic areas (Jaber and Ahmed 2004; Panabokka and Perera 2005).

The CBOs appointed a member as the "plant operator," who possessed very low technical knowledge and awareness of plant operations; therefore, the NWSDB provided them with the relevant technical support. A lack of human resources in place to operate desalination plants is a key issue that people face in rural India, where plants remain shut down for longer periods until the authorities fix them (Kelkar et al. 2003). Some of the RO plants that this study investigated had experienced similar situations. Furthermore, low technical knowledge of operators could lead to wrong and inadequate maintenance practices, which may cause unnecessary costs for the CBOs (Figure 25).

The plant operator was responsible for taking care of the daily O&M activities of the plant. The cleaning of filters supposedly followed the instructions from the authorities. However, two consumers from the survey mentioned that the plants required more frequent cleaning as they sometimes experienced a musty taste in treated water. In most of the plants, backwashing of the MMF and ACF took place every 3 days using the automated backwashing system (Figure 26), and cleaning of the MF occurred once every 3 to 4 weeks. However, the cleaning frequency varied with the feedwater quality and duration of operation of the plants.

Figure 25: A Poorly Maintained Plant That Was Out of Service at the Time of the Survey: a) the Plant Facility in Use as a Storage Place; b) a Notice Informing the Community That the Plant Is Temporarily Closed Due to a Technical Issue



Technical challenges of RO water treatment: Operation and maintenance of RO plants require skills and knowledge to diagnose and troubleshoot technical faults. In the existing RO plants, a member of the community who does not possess such capabilities is handling all plant operations. As a result, some communities tend to shut down their plant operations until receiving technical expertise to solve the problems (Photos by Sachithra Imbulana).



Figure 26: Automated Backwashing System in the MMF and ACF

Proper maintenance is the key to sustenance: Periodic cleaning is vital to ensure continuous operation and efficient performance of the RO plants. This includes manual as well as automated cleaning of the plant units. Generally, the technical experts from NWSDB advise the plant operators on cleaning and other maintenance aspects of the RO plants (Photos by Sachithra Imbulana).

Despite high concentrations of membrane foulants (hardness, silica, DOC, and coliforms) in feedwater, none of these RO plants engaged in chemical cleaning to regenerate the RO membranes. They did not clean the membrane unless the NWSDB identified such a requirement during the performance monitoring, which it usually conducted two to three times/year. The useful life of an RO membrane in these plants (Figure 27 shows a Hydranautics ESPA2-LD-4040 membrane) varied between 1 and 5 years, with an average of 3 years. It costs around 1,000 USD to replace the membranes (two membranes of 500 USD), and the savings of a typical RO plant can easily cover this (175 USD/month \times 36 months = 6,300 USD), but the situation can be different for the plants earning a low income. Periodic chemical cleaning would probably extend the useful life of a membrane, and this may in turn save a considerable amount of money for the CBOs in the long run.

Figure 27: Hydranautics ESPA2-LD-4040 Membrane That RO Plants Used



Quality comes at a price: The reverse osmosis water treatment technology utilizes a semi-permeable membrane to remove almost all dissolved contaminants, even microorganisms in feedwater, at a very high efficiency (~99%). While it promises excellent quality of product-water, the installation, operation and maintenance of RO plants, especially the membranes, require a considerable sum of money (Photos by Sachithra Imbulana).

The CBOs were responsible for submitting quarter-yearly treated water samples to the NWSDB for water quality testing, and the NWSDB issued a certificate confirming the water quality's compliance with the national drinking water standards. This had been happening effectively in most of the RO plants, yet a few CBOs were less motivated to perform the test on time. Meanwhile, a delay was apparent on the part of the NWSDB as well with regard to delivering the test reports to the CBOs. Section 5.2 revealed the

importance of monitoring the microbiological quality of the treated water, but the above water quality assessment did not include this test. The water supply authorities need to design more robust criteria to assess the quality of RO-treated water. Besides, CBOs should consider it a responsibility to keep up to date with the quality of the produced water that they deliver.

This study focused on the RO plants that the NWSDB initiated with government funds. However, other types of RO plants and truck delivery services of RO-treated water also play significant roles in this business. These operators and vendors can set the prices of produced water for sale, while they do not necessarily guarantee the water quality in an authorized way. They are rapidly increasing in number, yet there are no adequate rules and regulations regarding the instigation or operation of the businesses. For instance, there is no requirement either to conduct an environmental impact assessment before the inception of RO plants or to obtain an environmental protection license to operate them. Moreover, there is no obligation for RO plants to meet any standards when it comes to discharging brine onto land or using it for irrigational purposes. These are some serious concerns that the authorities need to address regarding the long-term operations of these community-based RO plants.

The absence of rules and regulations for this type of community-based RO treatment schemes has created many issues, such as unnecessary rivalry among vendors, a lack of attention to maintaining the quality of produced water, poor maintenance of RO plants, and overexploitation of aquifers, in other parts of the world (El Sheikh 2004; Jaber and Ahmed 2004). Learning lessons from such cases, the Government of Sri Lanka needs to regulate these different types of RO-treated water vendors to operate a sustainable business. In addition to a stringent licensing procedure, it should impose regulations on setting the price of treated water, the O&M of the RO plants and treated water distribution facilities, quality control of treated water, discharging of brine, and abstracting of groundwater. Moreover, it should implement a surveillance system to provide an overview of vendors' compliance with the regulations.

6.4 Summary of Section 6

A very low socio-economic status marks the endemic areas of CKDu. Despite low knowledge of safe drinking water, the residents preferred RO-treated water to other unsafe drinking water sources (especially well water) and were quite certain that RO-treated water reduces the progression of CKDu and improves their overall health condition. Additionally, they were satisfied with the level of service that the RO plants provided and the price of treated water.

The income that RO plants earned was sufficient to cover their daily/monthly O&M expenses, and the savings were able to cover the major expenses of filtration units. The study identified the rivalry stemming from different RO water suppliers in the same locality, the scarcity of groundwater during the dry season, and the lack of technical knowledge and awareness of plant operations as the key challenges relating to the O&M of the RO plants. Additionally, a lack of protocols for chemical cleaning, water quality monitoring, and brine management was problematic for the sustainable operations of RO plants in the long run. Although the authority of the NWSDB supervised the plants under investigation, no rules/regulations bound other types of RO water treatment businesses, and they did not receive any technical assistance for O&M. The government needs to regulate these different types of RO-treated water vendors to safeguard the environment and the good health of the local people in the CKDu-endemic region.

7. CONCLUSIONS

7.1 Conclusions of Section 4—Objective 1

The first objective was to determine the quality of groundwater in the endemic areas of CKDu (with respect to the drinking water standards) and its seasonal variations and to understand the differences in groundwater quality between CKDu high-risk and CKDu low-risk areas.

The study investigated the quality of groundwater in the CKDu-HR and CKDu-LR areas located within the endemic region during dry and wet seasons. The quality of groundwater varied widely even within the close vicinity of a certain locality. Nevertheless, it was possible to characterize all the groundwater primarily as having a Ca-Mg-HCO₃ predominant geochemistry, possibly due to carbonate weathering, and undesirable contents of alkalinity, hardness, and microbiological parameters (E. coli and total coliform) that exceeded the proposed MAL values for drinking water. In general, the groundwater in the LR areas was of better guality than that in the HR areas, and beyond-MAL TDS and magnesium concentrations were the key characteristics of the groundwater in the HR region. Although many researchers have recognized high fluoride as a key characteristic of groundwater in the CKDu-endemic region, the present study revealed acceptable fluoride levels for drinking (0.5-1 mg/L). It seems that the intensive agricultural activities in the endemic regions of CKDu have less impact on the quality of groundwater. Groundwater at certain locations in the CKDu region could be high in DOC (>4 mg/L) and bromide (>0.4 mg/L), probably due to sewage contamination.

As far as the survey data were concerned, significant seasonal variations were not apparent in the quality and the chemical composition of groundwater, probably due to 1) late recharge of stagnant regolith aquifers, on which most of the shallow wells in the CKDu-endemic region rely; or 2) increased mixing of chemical constituents from overburdened soil that are washed along with infiltrated rain water, in parallel to the replenishment of the aquifers. It would be useful to analyze the post-monsoon water quality of the wells to clarify further the seasonal impacts on the groundwater quality.

The findings of this study were in good agreement with those that previous research groups have reported regarding the observation that the geographic distribution of CKDu relates to the water hardness due to high magnesium and ionicity associated with major dissolved ions. It may be worthwhile exploring further the synergistic involvement of hardness and other dissolved ions in the onset of CKDu through laboratory and field experiments. As far as the survey data were concerned, no relationships with CKDu were apparent for fluoride and DOC, which are among the suspected risk factors of CKDu. However, these parameters remain possible causes of CKDu until any concrete evidence denies the possibility.

7.2 Conclusions of Section 5—Objective 2

The second objective was to verify the effectiveness of the existing RO plants in reducing the excessive constituents in groundwater to meet the drinking water quality standards.

The study evaluated the performance of the community-based RO plants in removing the excessive concentrations of alkalinity, hardness, TDS, major ions, coliforms, and DOC in groundwater. All the RO plants achieved high removal rates (>90%) for the excessive chemical constituents existing in groundwater (TDS, alkalinity, hardness, and

magnesium) during the dry and wet seasons. Utilizing low-rejection membranes like NF would be preferable to eliminate excessive removal of essential minerals like calcium, to fix the low pH of permeate, and to achieve higher permeate recovery than at present (~46%). The removal rates for DOC were significantly low during the dry season (55% against 94% in the wet season) when the feed DOC exceeded 4 mg/L. A considerable number of RO plants failed to secure the microbiological safety of the product water; therefore, the study recommends a suitable disinfection method between the treated water storage tanks and the distribution outlets. Moreover, the RO plants as well as the consumers must adopt safe water distribution, collection, and storage practices, and the plants must undergo regular cleaning to minimize the microbiological contamination of the produced water.

The co-existence of a variety of membrane foulants (hardness, DOC, microbes, and silica) in groundwater, which themselves should be the target contaminants for water treatment, would question the applicability of RO treatment for CKDu groundwater. Additionally, high DOC and hardness levels indicated some obvious impacts on the performance of the pre-filtration units. Proper maintenance practices, including periodic chemical treatment of membranes and cleaning and backwashing filter units, as well as periodic water quality monitoring including testing for microbiological quality, are vital not only to ensure the optimum performance of the RO plants but also to ensure the good health of the local people.

7.3 Conclusions of Section 6—Objective 3

The third objective was to provide an overview of the current status and problems of O&M of the RO plants.

The endemic areas of CKDu have a very low socio-economic status, which the low income and educational levels of the inhabitants and the high unemployment rates reflect. The local people possessed little knowledge of the importance of consuming safe drinking water and RO water treatment. Nevertheless, they preferred RO-treated water to other unsafe drinking water sources and were satisfied with the level of O&M of the RO plants and the price of RO-treated water. With the initiative of local governments, the health and water supply authorities should conduct social awareness programs to educate local people on safe drinking water and build their capacity to manage their own RO plants.

The monthly income sufficiently covered the basic O&M expenses for most of the CBOs, leaving some savings at hand for the beneficial use of the respective communities. A low demand for RO-treated water due to the availability of multiple RO water vendors in the same locality, the scarcity of groundwater during the dry season, the low technical knowledge and lack of training of the RO plant operators to handle O&M aspects, and the lack of filter cleaning and water quality monitoring were the identified key challenges related to the O&M of the RO plants. Therefore, CBOs may require further assistance from the water supply authorities regarding chemical cleaning of the RO plants, water quality testing, and technical training for plant operators. It would be convenient for the government to outsource the supply of safe drinking water to these areas during severe drought periods when groundwater becomes scarce to operate the RO plants.

This study mainly focused on the RO plants that the government initiated with the involvement of the NWSDB, but personal observations revealed that the privately owned RO plants and the ones targeting charity purposes are not receiving any technical advice or guidance on O&M. While the government considers it a social responsibility to provide safe drinking water to the areas affected with CKDu, producing and delivering RO-treated water has become a viable business opportunity for some local people and private

parties who are involved in RO water treatment. The long-term operations of such businesses could lead to a multitude of environmental and social issues in the CKDustricken areas without proper counteractions. Therefore, the government needs to regulate these different types of RO water suppliers by introducing a proper licensing procedure for the instigation of RO plants that includes an environmental assessment, regulations on the price setting of the treated water, protocols for the O&M of the RO plants (including protocols for brine management), and quality control of treated water and promoting them to operate a sustainable business while providing the rural communities in the endemic areas of CKDu with a high-quality service.

7.4 Overall Conclusions

The aim of this study was to evaluate the quality of groundwater in the CKDu-endemic areas of Sri Lanka and the performance and O&M of the community-based RO water treatment plants that purified this groundwater to fulfill the potable water needs of the rural communities in the endemic region. As necessary as it is to understand the root cause of CKDu, it is equally important to verify the effective implementation of the mitigatory measures that are in place to alleviate the disease. One such interim mitigatory solution for CKDu is small-scale RO treatment, and, for the first time, this study carried out a comprehensive evaluation of the performance and O&M of these RO plants in the CKDu-endemic areas based on a broad groundwater quality survey and questionnaire surveys for RO plant operators and consumers.

It is possible to classify the groundwater in the CKDu-endemic region generally as the Ca–Mg–HCO₃ type, and chemical processes rather than precipitation primarily appear to control its geochemistry. Elevated concentrations of hardness, alkalinity, TDS, magnesium, and coliforms that exceeded the drinking water standards made this groundwater highly unfit for drinking. The groundwater appeared to have extensive contamination from sewage, yet the contamination from agrochemicals was minimal. Meanwhile, hardness due to high magnesium concentrations and high ionicity (represented by high TDS) indicated a significant relationship with the geographic occurrence of CKDu. Fluoride, which researchers have considered as one of the top risk factors of CKDu, showed rather low concentrations in groundwater in the present analysis and did not indicate any correlation with the occurrence of the disease. Nevertheless, it is important not to overlook its possible involvement in the etiology of CKDu in the absence of concrete evidence.

All the RO plants satisfactorily removed (>90% removal) the excessive chemical constituents of groundwater. RO plants' excellent removal (90-99%) of hardness, magnesium, and ionicity is a possible reason for anecdotal evidence suggesting a reduction of the incidence of CKDu with RO-treated water. The low permeate recovery (~46%) of the existing RO plants implied the necessity to perform periodic chemical cleaning of the membranes. Meanwhile, the study recommends loose-pore RO membranes to achieve high recovery, to eliminate excessive demineralization of produced water, and to maintain high pH in permeate. No seasonal variations were notable in the groundwater quality as far as the survey data were concerned; hence, the removal rates and recovery of RO plants did not differ significantly between the two seasons. However, the scarcity of water during the dry season was problematic for the operations of the RO plants. They should implement strong disinfection measures, probably an additional UV disinfection unit, just before distributing treated water to the community. Care is necessary if they adopt chlorination for disinfection as the RO plants were not always effective in removing high concentrations (>4 mg/L) of DOC, which forms disinfection by-products. Furthermore, plants should adopt a robust water quality assessment criterion that involves microbiological quality to assess the quality of the treated water that they produce in a periodic manner.

The water supply authorities seemed to play a satisfactory role in assisting CBOs with the O&M of the RO plants that they had initiated under their jurisdiction. Nonetheless, further support in the areas of chemical cleaning, technical training for RO plant operators, and water quality monitoring would be helpful to improve the operations of the plants. The local authorities should take the initiative and gradually build the capacity of the respective communities to operate and maintain the RO plants by themselves. Meanwhile, the government needs to regulate the different types of RO-treated water producers and suppliers in the CKDu-endemic region with regard to the instigation, operation, and maintenance of the businesses. This would help in eliminating unnecessary rivalry and business interests among the different vendors and ultimately in safeguarding the environment and consumers' health in the long run.

The vast spatial variations in groundwater quality within a certain locality indicated that plants should adopt water treatment methods based on the quality characteristic of the groundwater rather than embracing RO treatment as a universal solution. Meanwhile, the characteristics of the common target elements in groundwater that required treatment for drinking; the presence of high membrane foulants (hardness, DOC, microorganisms, and silica) in groundwater; the scarcity of groundwater during the dry season; the lack of technical capacity of the rural communities to operate and maintain the RO plants; the low permeate recovery; and the lack of regulations on environmental and consumer safety hardly suggested RO plants as a sustainable water treatment solution for these rural areas.

All in all, the existing RO plants have appreciably addressed the pressing water crisis that rural communities are facing in the CKDu-endemic regions. Moreover, the consumption of RO water seems to have upgraded the health conditions of the local people. Therefore, these systems are already deeply rooted as a perfect water treatment solution among the rural communities and the water supply authorities. Although the introduction of the concept of small-scale RO plants was initially an interim solution for producing safe drinking water, for the above reasons, they will continue to operate for another two to three decades until the inauguration of centralized schemes. In such a scenario, the authorities should regulate, empower, and promote these small-scale RO-water treatment businesses to provide the rural communities in the endemic areas of CKDu with a sustainable and reliable service.

8. SUGGESTIONS FOR FUTURE RESEARCH

8.1 Limitations of the Present Study

The present study simply derived correlations between the groundwater quality and the occurrence of CKDu through a comparison of water quality between CKDu-HR and CKDu-LR areas. It was unable to obtain CKDu prevalence data regarding the investigated wells due to technical difficulties and the absence of proper registries to report the prevalence of CKDu in these rural areas. Such data would have been useful in reaching strong conclusions regarding the relationships between water quality parameters and CKDu.

Since the present study aimed to investigate RO plant operations in the CKDu-endemic areas, the groundwater survey involved sampling in the endemic region only. However, samples from the areas without CKDu are also necessary for a proper case–control study

to identify relationships between the groundwater quality and the occurrence of CKDu.

8.2 Recommendations for Future Research

Observing the trends between the groundwater quality and the prevalence of CKDu over time would be useful to understand the correlations between water quality and CKDu. Moreover, it is vital to investigate the impacts of RO-treated water on the health of CKDu patients.

Sampling after the monsoon rain period (post-monsoon sampling) would be helpful in obtaining more representative water quality data for the wet season. An analysis of the quality and composition of brine that the RO plants produce would be useful for speculating about the potential harmful impacts of discharging brine onto the land.

It is worth investigating other types of vendors of RO-treated water from the CKDu-endemic region regarding the O&M status of their businesses. Meanwhile, a broad sociological survey that involves random villagers, rather than the ones visiting certain RO plants, would be useful to understand the real situation of RO water treatment businesses in the CKDu-endemic region.

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