Renal Health, Groundwater Contamination, and Water Policy in Sri Lanka

By

Shannon O’Hara

Masters in Environmental Management (Ecotoxicology and Environmental Health)

Nicholas School of the Environment

Juris Doctor

Duke University School of Law

Advisors:

Professor Nishad Jayasundara, Nicholas School of the Environment

Dr. Soumya Balasubramanya, The World Bank

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EXECUTIVE SUMMARY

Chronic Kidney Disease of unknown etiology (CKDu) is a global disease and Sri Lanka is one of the most affected countries. The disease predominantly affects low-income, male agricultural workers, many of whom live in the country's dry zone, particularly in the Northern Central Province, and thus poses an enormous burden to the region. Mortality associated with the disease is high, given that the disease requires expensive treatment not typically available in the communities most substantially impacted. No study has definitively identified a cause of the heightened prevalence of CKDu among these individuals, although the vast majority of research suggests that the disease is linked to groundwater contamination. Groundwater is the primary source of drinking water in many of the communities most severely impacted by CKDu.

This project utilizes samples taken from groundwater wells from districts across Sri Lanka where CKDu is known to be most prevalent. The samples were matched across CKD- and non-CKD households using relevant variables (such as proximity to agricultural fields, number of females in the household, etc.) as the matching characteristics. The samples were analyzed for many potential contaminants, including metals, minerals, and aggregate metrics, such as electrical conductivity. I conducted a series of statistical analyses to identify a clear association between a contaminant or set of contaminants and disease. A distinct link, however, was not identified, suggesting that any link may involve a contaminant that was not measured, such as agrochemicals, or may involve a complex synergism. This is seemingly consistent with much of the existing research that emphasizes the role of agrochemicals and heavy metals but is similarly unable to identify a singular association, leading many to presume multiple factors are simultaneously contributing to CKDu prevalence. This study also examined whether groundwater contamination can be related to latitude (CKDu is related to latitude in Sri Lanka), and the resulting correlations presented intriguing questions about the hydrogeological drivers of contamination.

This project also incorporated a policy component. There is considerable interest in Sri Lanka to shift resources toward using reverse osmosis (RO) units as an alternative source of drinking water, but there are no policies regulating these units. In this section of the project, a literature review was conducted to assess effective policies regarding alternative sources of drinking water, with a specific focus on RO units that are of increasing popularity in the country. In conducting this review, we determined that RO units have several pitfalls with respect to filtration quality, sustainability, and maintenance that must be addressed in order to render RO units a feasible future water source. Using the results of the literature review, a series of policy recommendations were promulgated, which can be used by the Sri Lankan government or other organizations operating in the region to ensure that citizens have access to safe, sanitary drinking water and that the incidence of CKDu is reduced. Many of these recommendations relate to advancements of filtration technology, improved recovery rates and wastewater disposal procedures, and educational campaigns designed to maintain the cultural importance of water in Sri Lanka and reduce the socioeconomic disparities in CKDu prevalence.

INTRODUCTION

CKDu and Sri Lanka: Preexisting Literature

Chronic Kidney Disease of unknown (or uncertain) etiology (CKDu) is a form of chronic kidney disease that is not associated with any of the factors typically associated with other forms of CKD, such as hypertension, diabetes, and glomerulonephritis (Balasubramanya et al. 2020). It is a disease with a global impact: in addition to cases reported in Sri Lanka, several Central American countries, as well as parts of India and Egypt, have been impacted (Weaver et al. 2015). It is often asymptomatic in early stages and there is little scientific consensus on the case definition, so it is not well-documented how many people around the world are impacted by CKDu, although estimates of prevalence range from 8-21% (Kafle et al. 2019). Mortality and morbidity related to CKDu is considerable, cutting short the lives of the disease's relatively young afflicted population (Weaver et al. 2015). Problems related to underdiagnosis and limited accessibility of expensive medical treatment only exacerbate the growing crisis (Elledge et al. 2014).

CKDu predominantly impacts agricultural communities in hot, dry zone regions, such as Sri Lanka. In Sri Lanka, young male farmers are among the most commonly affected in these communities, and so in addition to be critical for personal health outcomes, identifying preventative measures is of significant import to these local economies. Relatedly, CKDu patients place a considerable burden on the country's healthcare system, and therefore understanding CKDu should be a public health priority. (Nanayakkara et al. 2019).

The question remains, however, as to what preventative measures are practical, effective, and available. Numerous studies have attempted to link the prevalence of CKDu to one or more environmental toxins, principally those that are present in drinking water or found in rice grown in the affected regions. For example, Nanayakkara et al. (2019) examined exposures to arsenic and cadmium, which are known nephrotoxins and the subject of much CKDu-related discussion, in drinking water and rice in Sri Lanka to determine whether there was a relationship between these elements and CKDu prevalence in the region. These sources were identified based on preexisting knowledge about how the two elements are most likely to enter the body in Sri Lanka. The authors collected urine and hair samples from their study population, which included both CKDu patients and healthy individuals, and collected samples of drinking water and rice in both affected and unaffected areas. The authors also examined renal tissue via transmission electronic microscopic analysis. Ultimately, the study found that cadmium and arsenic were not present beyond trace amounts within recommended levels in areas with high prevalence of CKDu, ruling out a direct relationship between these two elements and CKDu in Sri Lanka.

Other suspected contributors include chloride and glyphosate, and particular attention has been given to agrochemicals and the iconicity of the groundwater. In the impacted agricultural regions, agrochemical use is high and there are minimal regulations preventing these chemicals from permeating groundwater supplies that are used for drinking and cooking. Nikogalla et al. (2020) pointed to an elevated concentration of silica in groundwater in certain wells, suggesting a further need to consider how agrochemicals degrade in the water and what impact these components may be having on the health of those who consume it. McDonough et al. (2020) considered the role of microbes in the water in contributing to CKD, and did find that certain bacterial phyla exist in both the groundwater and in CKD patients, and that these microbes are associated with specific geographical regions, water temperature, and fertilizer use. This lends further support to the necessity of understanding the role of agricultural toxins, and suggests that households should be wary of using stagnant water for drinking and cooking purposes.

No clear consensus has been reached as to the cause of CKDu, and the stakes only heighten as prevalence increases. The global nature of the disease has led to something of an ideological divide among researchers; systematic reviews have found that where studies on CKDu in South Asia focused on the link to agrochemicals and heavy metals as well as family history, studies out of Central America tended to focus on heat stress, dehydration, and altitude (Lunyera et al. 2016; Redmon et al. 2021). Without a clear picture of CKDu's drivers, populations all over the world are placed at risk for an assortment of renal health problems, including fatal renal failure, which is the predominant outcome in cases where there is no treatment (Gunasekara et al. 2020).

Study Area

Sri Lanka is a diverse nation home to over 21 million people. It is divided into 9 provinces and 25 districts. The island is relatively flat or rolling, with mountains in the south-central region. It has a tropical, warm climate and is influenced by monsoon patterns. Much of the east, southeast, and northern regions of the country are categorized as dry zones. A dry zone is characterized as one with little rainfall and harsh periods of drought. Consequently, many Sri Lankans are reliant upon groundwater, which contains high amounts of TDS. This hard water has been identified to contain high amounts of fluoride, magnesium, and phosphates in certain regions, as well as agrochemicals. There is little evidence showing an excessive amount of trace metals, such as lead, arsenic, etc.

Estimations of CKDu prevalence in Sri Lanka range from 2-3% to as high as 15-23%, and multiple studies have hypothesized that the incidence of CKDu doubles every 4-5 years in the country. 3% of the estimated 150,000 patients lose their lives annually. One study found a prevalence of 15.4% and that on average, a CKD affected household had more than one symptomatic adult. (Kafle et al. 2019).

CKD poses a particular problem for the Northern Central Province (NCP) of Sri Lanka, and of these patients, an estimated 15.1-22.9% of cases were of unknown etiology, according to a 2013 study. (Jayatilake et al. 2013). The NCP is primarily an agricultural region wherein communities are at a low socioeconomic status. Since the 2013 study, the number of CKDu patients has only increased dramatically, exacerbating the burden the disease places on the Sri Lankan economy and healthcare system.

Drinking Water Behavior in Sri Lanka

One study concluded that 98% of households in the NCP consumed groundwater as the primary source of drinking water for at least 5 years from 2000 to 2018. In the same study, the authors found that households affected by CKD used groundwater more consistently than nonaffected households. The relationship was stronger for households that pump groundwater from deep in the ground as opposed to retrieved with buckets from shallower wells, and it appeared that households that boil their water are less likely to be impacted by CKD (although this is also dependent on the depth from which the water was extracted). The authors of that study also found links to agrochemical use and socioeconomic status. (Kafle et al. 2019).

Researchers have not yet systematically mapped out the groundwater systems in Sri Lanka, rendering any plans to undertake an environmental remediation effort a long way off. Instead, much attention has been given to promoting alternative sources of drinking water. In particular, the Sri Lankan government has responded to the suspected role of groundwater contamination by expanding access to alternative sources of drinking water. The government, for example, has acquired and sent hundreds of reverse osmosis (RO) units to the most affected regions for public use. (Balasubramanya et al. 2020).

Since the 2018 study, there have been marked changes observed in drinking water patterns in Sri Lanka. In Horbulyk et al. (2021), a group of researchers interviewed 1500 households (both affected and unaffected by CKD) to understand the factors driving decision-making with respect to drinking water source. According to this study, the number of households that rely on untreated groundwater has dropped to a third of households, with half of households now relying on RO units. There is a growing perception that untreated groundwater is linked with kidney disease, but households do tend to trust the safety of government-provided RO. There remain barriers to total RO adoption, however, as it can be costly, time-consuming, or altogether unavailable. Alternatively, households express an interest in transferring to a piped water system.

Presently, RO is highly unregulated, and few standards have been set for the construction of adequate units. A considerable amount of research remains to create appropriate safety standards for RO units. Further studies are needed to confirm whether switching to RO actually presents the benefit of reducing CKD in a given region, or whether widescale investment and promotion is simply not worth the effort when compared to more affordable, potentially more effective alternatives.

Importantly, little is known about how the COVID-19 pandemic impacted drinking water access in Sri Lanka. The country’s lockdowns may have reduced access to government-issued RO units and it is possible that many households had to switch back to groundwater. Whether this would have had any impact on CKD prevalence is also unknown.

Purpose of Study

The purpose of this study is to further investigate the relationship between groundwater quality and CKDu prevalence. No study has successfully established the pathogenesis of a specific toxin causing CKDu. This study will endeavor to narrow the scope of the search by ruling out suspected toxins as well as identifying candidates for further study. If certain contaminants are perpetuating CKDu, this information can be used to create targeted plans for reducing exposures, which will have an overall positive benefit on Sri Lanka, its economy, and its healthcare system.

Moreover, this study aims to identify drivers of behaviors and decision-making with respect to available drinking water sources in Sri Lanka. In understanding how and why Sri Lankans choose to utilize drinking water or not, we aim to provide a framework by which policymakers can optimize for superior health outcomes and economic accessibility in their community. Reverse osmosis systems – and more specifically, their flaws – receive particular attention as the most viable drinking water alternative to groundwater in an effort to identify potential processes by which these systems may be improved and made both more efficient and safer. In doing so, we establish the need for greater regulatory oversight over reverse osmosis with an intent to minimize exposures to toxins via contaminated groundwater.

The above justifies the decision to present this project in two chapters. The first chapter is a quantitative analysis of water quality data to determine the relationship between groundwater contamination and CKDu, while the second chapter is a policy analysis evaluating the most effective strategies for implementing sustainable alternative drinking water sources in Sri Lanka. The marriage of the quantitative and policy approaches is fundamental. A quantitative examination establishing what drives disease is only rendered useful if researchers also consider socioeconomic factors in tandem when recommending a response. CKDu is a disease that predominantly effects poor agricultural laborers, and a study of the disease must view its eradication through this lens. If groundwater is not an acceptable source of drinking water, alternative sources must be cost-effective, sustainable, accessible, and regulatable.

METHODOLOGY

Data Collection

Data was collected by the International Water Management Institute, operating in Sri Lanka. Households with and without residing CKDu patients were selected for interviewing. 1,497 households were used in the study, from 40 administrative divisions (10 districts). In 824 of these households, there were no diagnosed CKD patients residing there, while the remaining 673 households were home to at least one CKD patient. This represents an oversampling of diseased households disproportionate to their representation in the actual population so that a sufficient number of diseased households were included.

Each household interviewed was assigned a propensity score. The scores were designed to incorporate relevant household characteristics so that households could be compared against each other. Such characteristics include:

- Number of years 2000-2017 that households drank from an agrowell (a well used for agricultural purposes)
- Number of years 2000-2017 that a household drank from a household well
- Whether the household had a secondary water source 2000-2017
- Whether the household's primary well was located inside agricultural land
- Whether households ever used protective gloves, masks, or boots while working in agriculture
- Whether the primary well was less than 10 meters deep
- Total number of people in household aged <30 years, 31-60 years, and >60 years
- Share of females in the household
- Whether household received income from abroad remittances

The characteristics above, when converted into a propensity score, allowed the International Water Management Institute to identify three matched pairs of disease and non-disease households in each of the 40 villages. Upon completion of this pairing process, the final data set included 240 households, with equal numbers of disease and non-disease households represented. A water sample was taken from the well that each household utilized for the longest amount of time in an 18-year period (2000-2017). The information on the variables that were measured from the well water samples is included below in Table 1.

Table 1: A Summary of Variables Measured in Groundwater Samples and Relevant Acceptable Threshold Values for Drinking Water

Metric	Unit	Mean Value	Acceptable Limit
Chemical Oxygen Demand (COD)	mg/l	17.00	250
Chloride	mg/l	69.08	250
Electrical Conductivity	µS/cm @ 25C	687.08	400
Fluoride	mg/l	0.69	4
Nitrate	mg/l	4.58	10
Sulfate	mg/l	36.41	500
Total Alkalinity	mg/l	263.35	180
Total Dissolved Solids (TDS)	mg/l	496.35	500
Total Hardness	mg/l	264.04	170
Phosphorous	mg/l	0.57	40
Biological Oxygen Demand (BOD)	LOD 5 mg/l after 5 days	11.71	30
pH	N/A	6.99	6.5-8.5
Calcium	mg/l	54.24	180
Iron	mg/l	0.64	.3
Magnesium	mg/l	32.40	50

Manganese	mg/l	0.16	.3
Potassium	mg/l	1.98	N/A
Sodium	mg/l	51.31	20

Statistical Analysis

Multiple statistical tools were utilized in analyzing the relationships between contaminants in the sample well water and households' disease status. The analysis was conducted in R version 4.0.2. First, based on WHO guidelines, I identified standard acceptable limits in the drinking water for each variable that was measured. Each data point was converted to a percent of each relevant limit and visually analyzed for instances wherein the majority of samples taken appeared to exceed the acceptable limit in drinking water using the ggplot2 package (v3.3.3; Wickham 2016). Subsequently, a principal component analysis was undertaken to determine whether there were any variables, including the district where the sample was taken, that would explain their role in disease status or if there were any location specific variables correlated to disease endemicity. Because previous studies hypothesized that disease prevalence may vary along a North-South gradient, a linear model was generated to examine whether any variables sampled in the study could be correlated to latitude, which could be indicative of a potential relationship between disease and that contaminant.

Policy Framework Design

While there are many alternative drinking water sources available and discussed in the literature, this project will focus on reverse osmosis units, which represent the most promising alternative in terms of cost and access. These units are already increasing in popularity in Sri Lanka, so they are the ideal alternative drinking water source for consideration in the context of the country.

Reverse osmosis is a filtering process that can remove a large number of contaminants from water by forcing the untreated water through a semipermeable membrane that traps dissolved solids while permitting water molecules to pass through. There are other filters attached to an RO unit in addition to the semipermeable membrane. First, there is a sediment filter, which catches larger sediment particles, such as dirt. Second, there is a carbon filter, which is effective at trapping chlorine and other contaminants. These filters are applied first, to catch trap sediment and larger molecules that may clog the semipermeable membrane. Because this process is rather slow, the treated water is stored in a storage tank. As previously discussed, these filtration processes and storage tanks are not standardized or regulated in Sri Lanka, so more information is needed to evaluate their efficacy.

A literature review was conducted, wherein studies were reviewed for their insights on the standardization of RO units, policy recommendations related to drinking water access, and relative value of RO unit implementation in reducing potential risk factors for CKDu. Studies were reviewed over a breadth of specific subjects, ranging from behavioral analyses in Sri Lanka related to sociocultural questions regarding drinking water to proposed projects addressing the problem of RO unit waste. The breadth was intended to assist in developing a maximally comprehensive set of policy recommendations and to account for any downstream problems potentially created by the introduction of RO units en masse.

A policy framework was designed. This framework accounts for the benefits and shortcomings of RO units, counterbalanced by those of groundwater wells. This framework was designed with the objective of reducing risk of CKDu and other adverse health outcomes, while maintaining accessibility and citizen trust in the available drinking water. The project concludes on a discussion of directions for further research that could additionally enhance these policy recommendations.

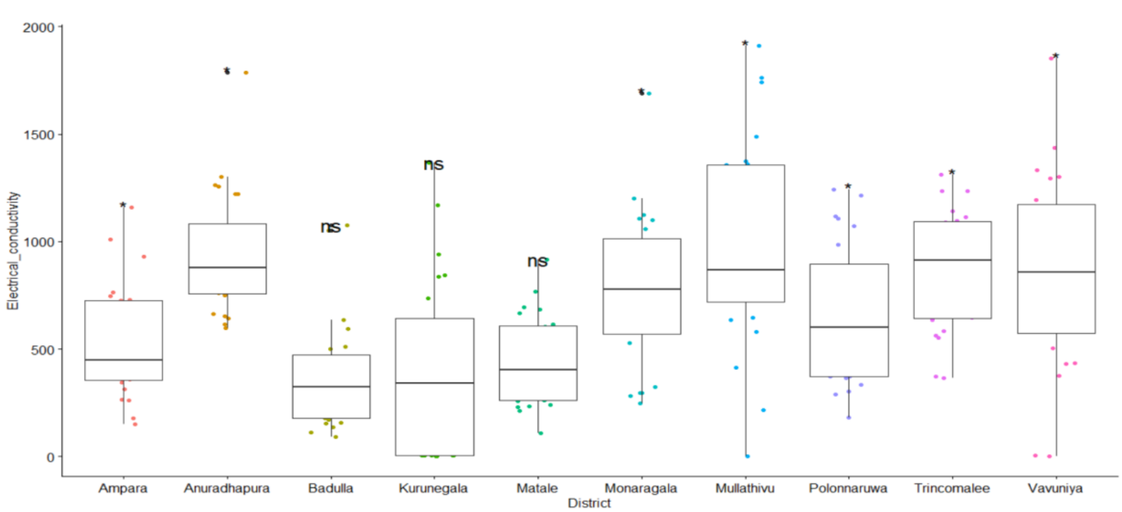
RESULTS AND DISCUSSION

Observations from Well Data

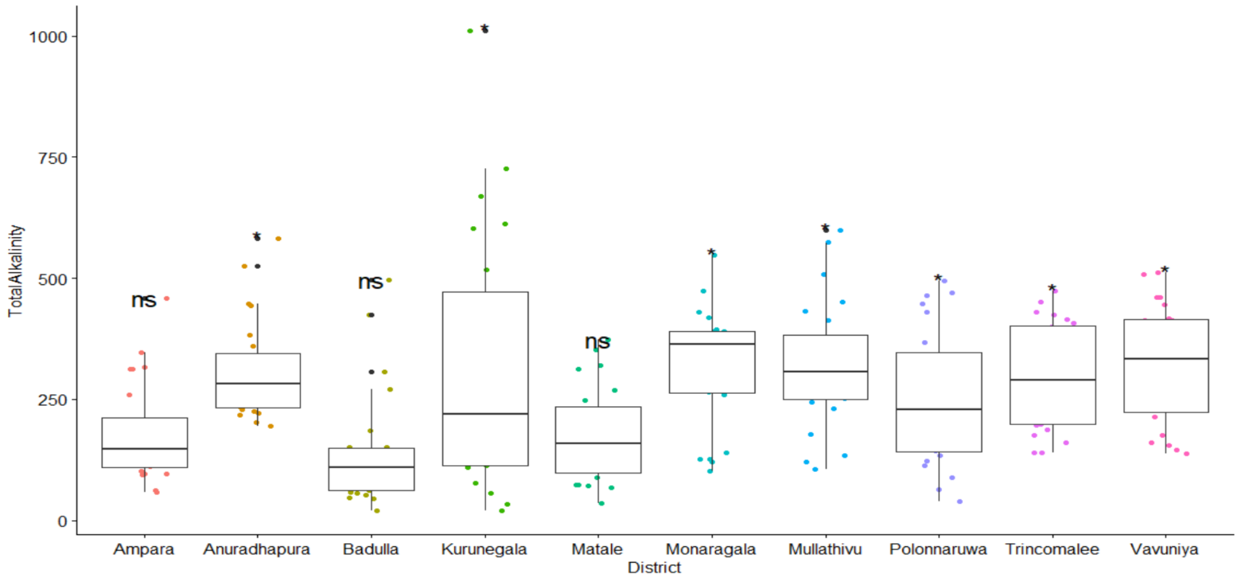
When comparing various contaminant metrics against their acceptable limits, five variables presented as significantly exceeding acceptable limits in at least half of the districts ($p < .05$): electrical conductivity, total alkalinity, total dissolved solids, total hardness, and sodium. Figure 1 summarizes the mean levels for each of the five metrics grouped by district, with an asterisk indicating a significant difference from the established acceptable limits. While the results indicate that certain groundwater sources contain levels of contamination above WHO thresholds, none of these effects could be linked to a significant relationship with disease (Figure 2).

Figure 1: (a) Electrical Conductivity, (b) Total Alkalinity, (c) Total Dissolved Solids (TDS), (d) Total Hardness, and (e) Sodium as a percentage of acceptable threshold value in drinking water grouped by district where groundwater well was located. Significance values were calculated based on differences between data in each district and the threshold value ('ns' = not significant; '*' = p < 0.05; '**' = p < 0.01; '***' = p < 0.001).

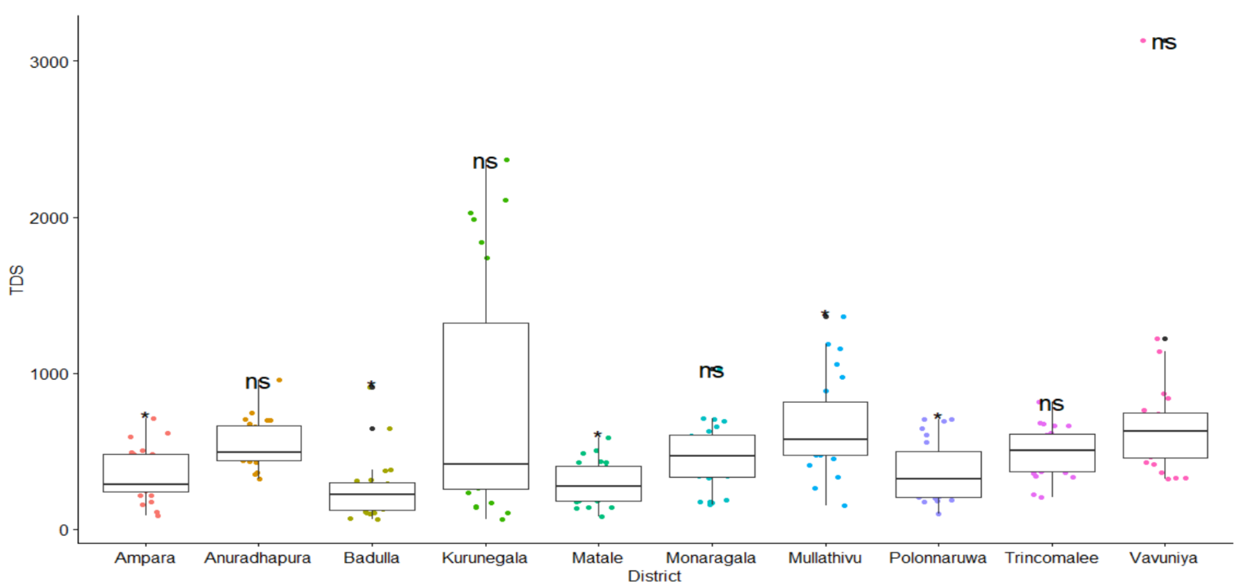
(a) Electrical conductivity



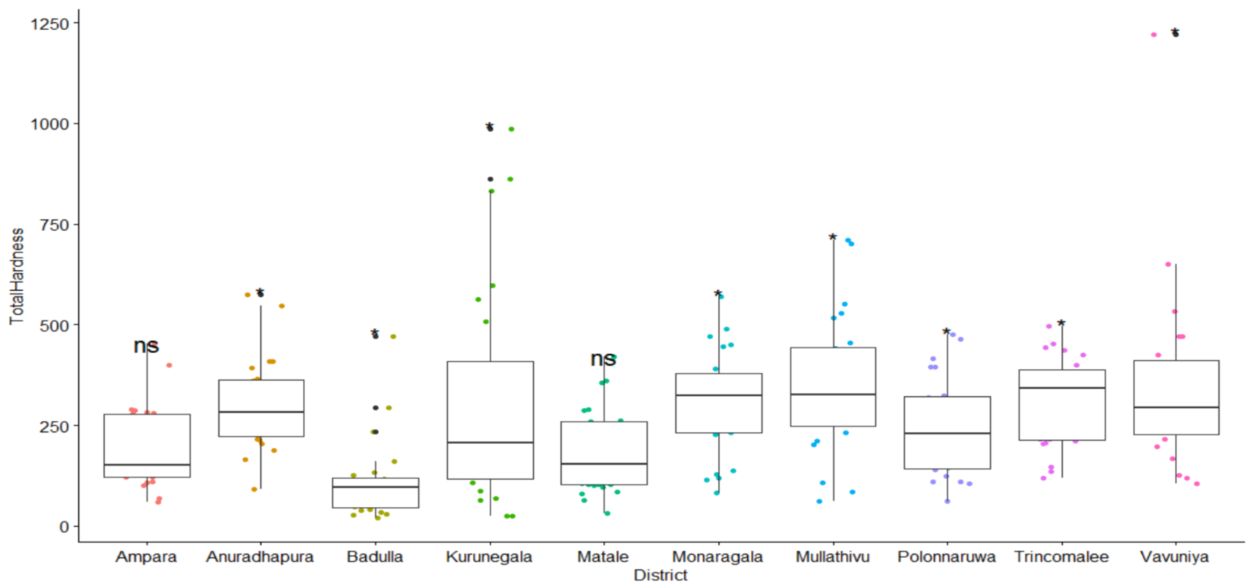
(b) Total Alkalinity



(c) Total Dissolved Solids (TDS)



(d) Total Hardness



(e) Sodium

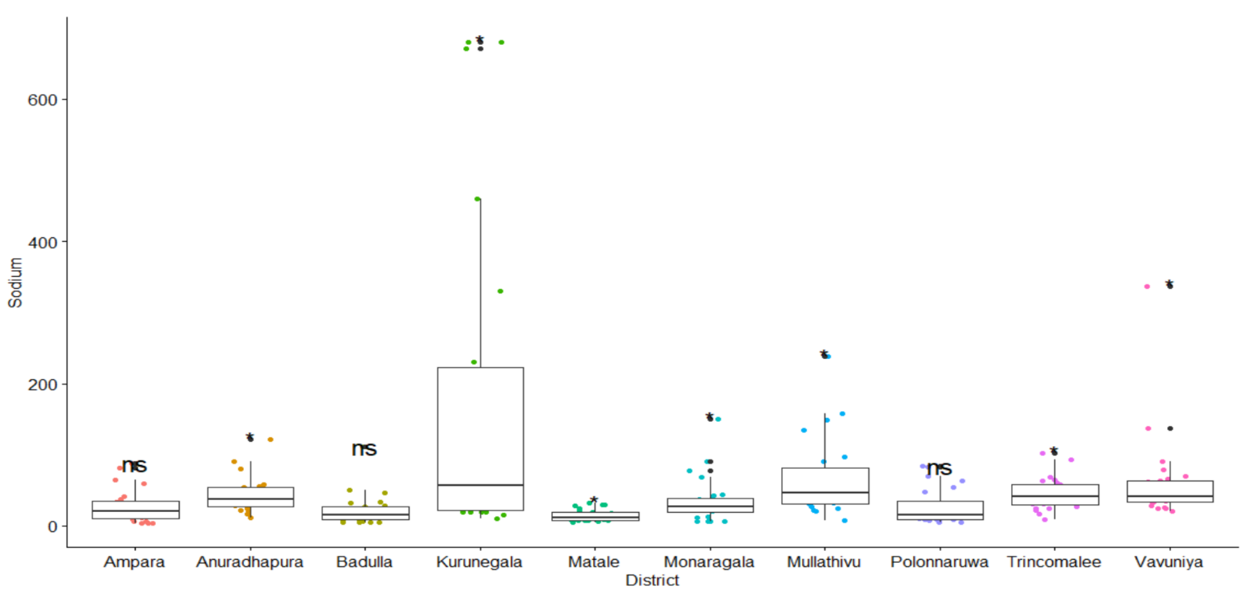
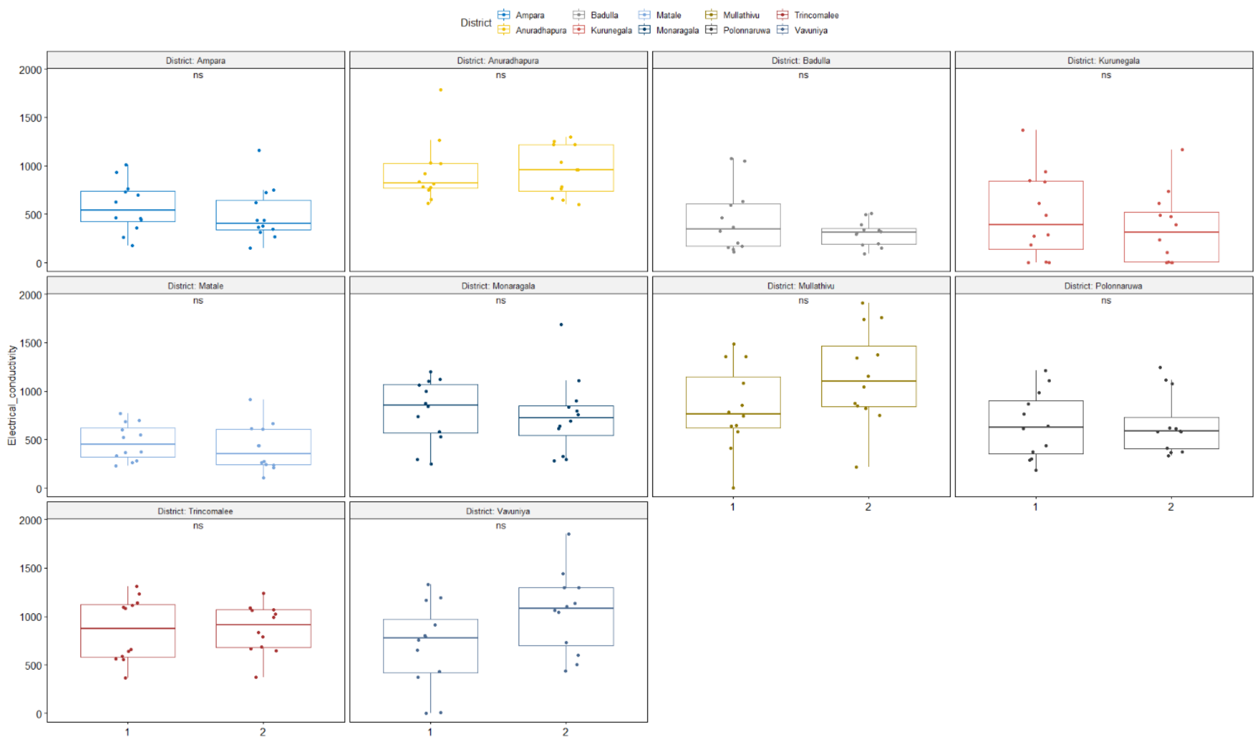
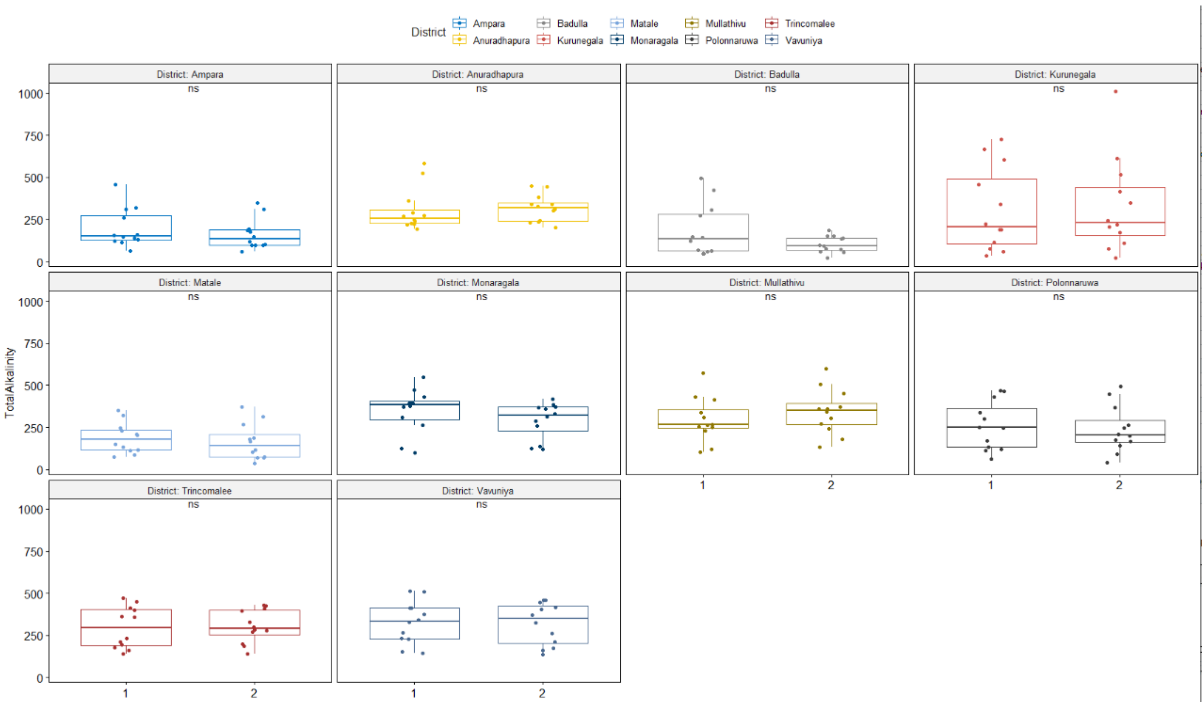


Figure 2: (a) Electrical Conductivity, (b) Total Alkalinity, (c) Total Dissolved Solids (TDS), (d) Total Hardness, and (e) Sodium levels in drinking water grouped by district where groundwater well was located and stratified by disease status (1 = Household with a CKD patient; 2 = Household without a CKD patient). Significance values were calculated based on differences between data on CKD households and non-CKD households (‘ns’ = not significant; ‘*’ = $p < 0.05$; ‘**’ = $p < 0.01$; ‘***’ = $p < 0.001$).

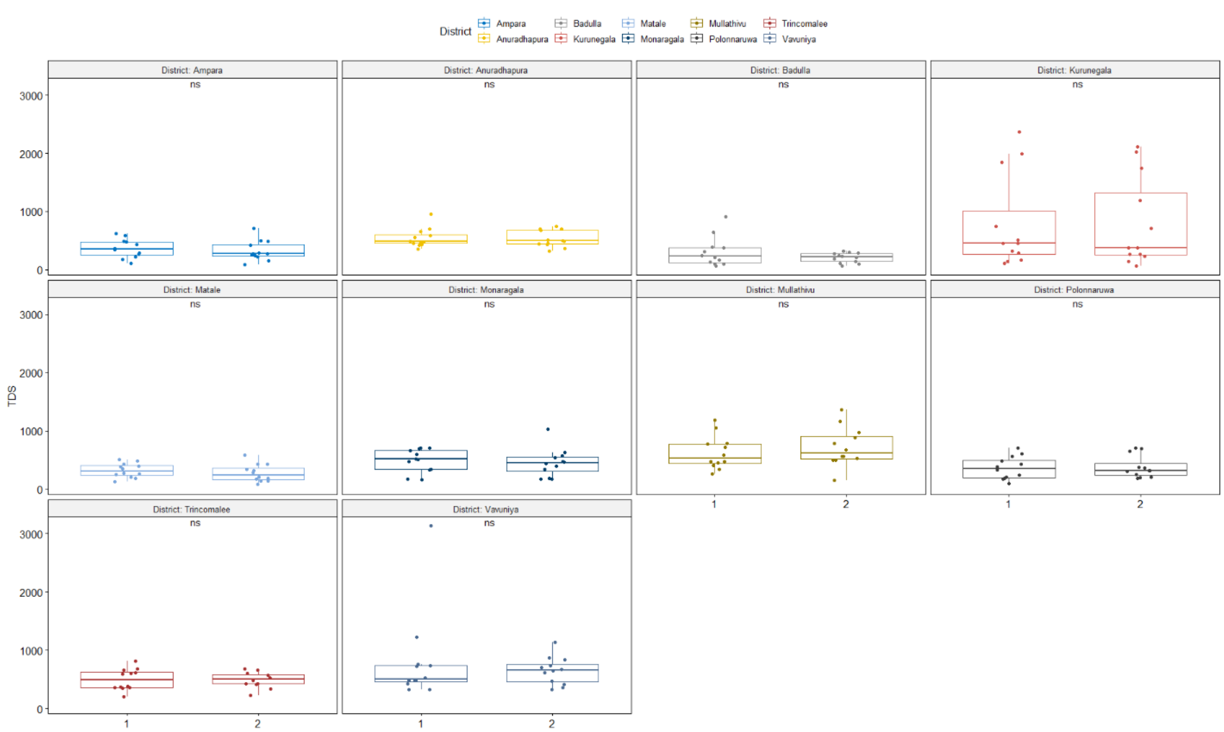
(a) Electrical Conductivity



(b) Total Alkalinity

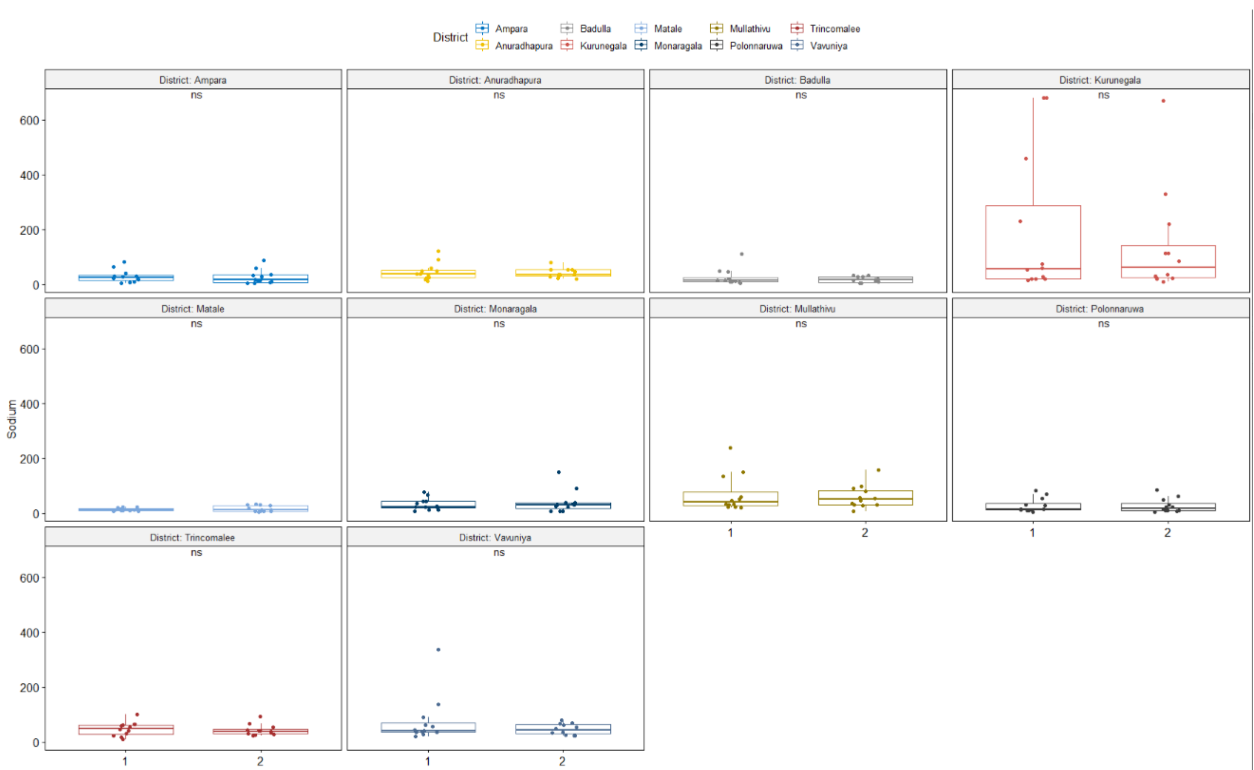


(c) Total Dissolved Solids (TDS)



(d) Total Alkalinity

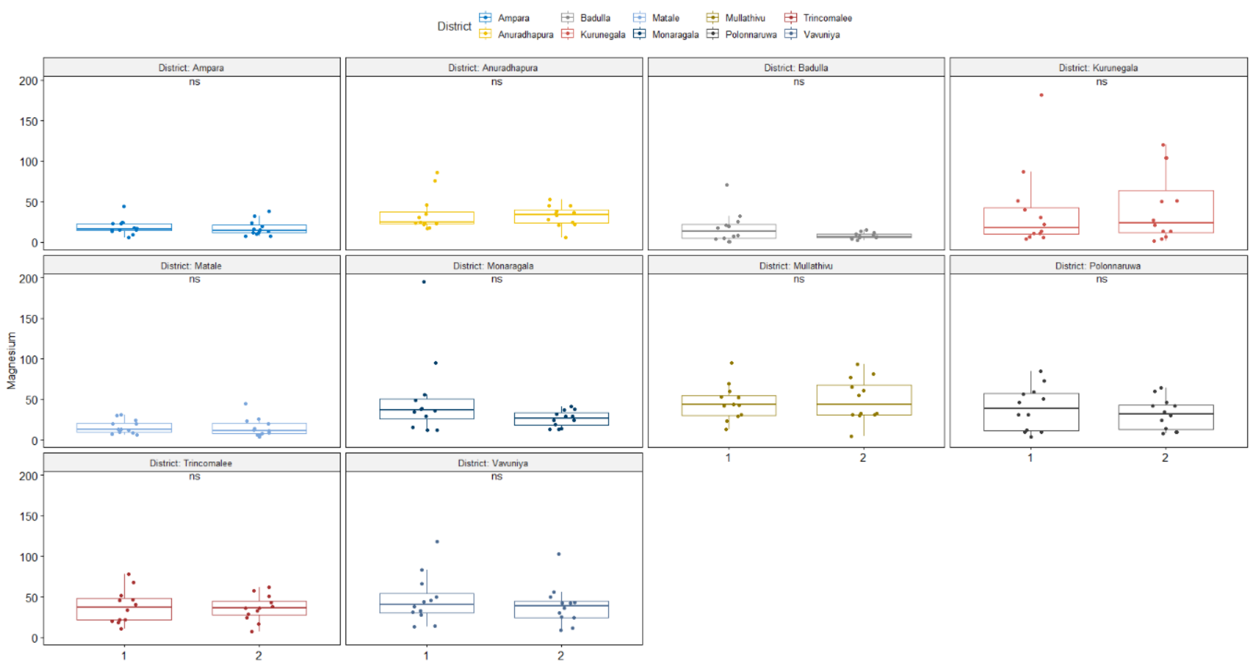
(e) Sodium



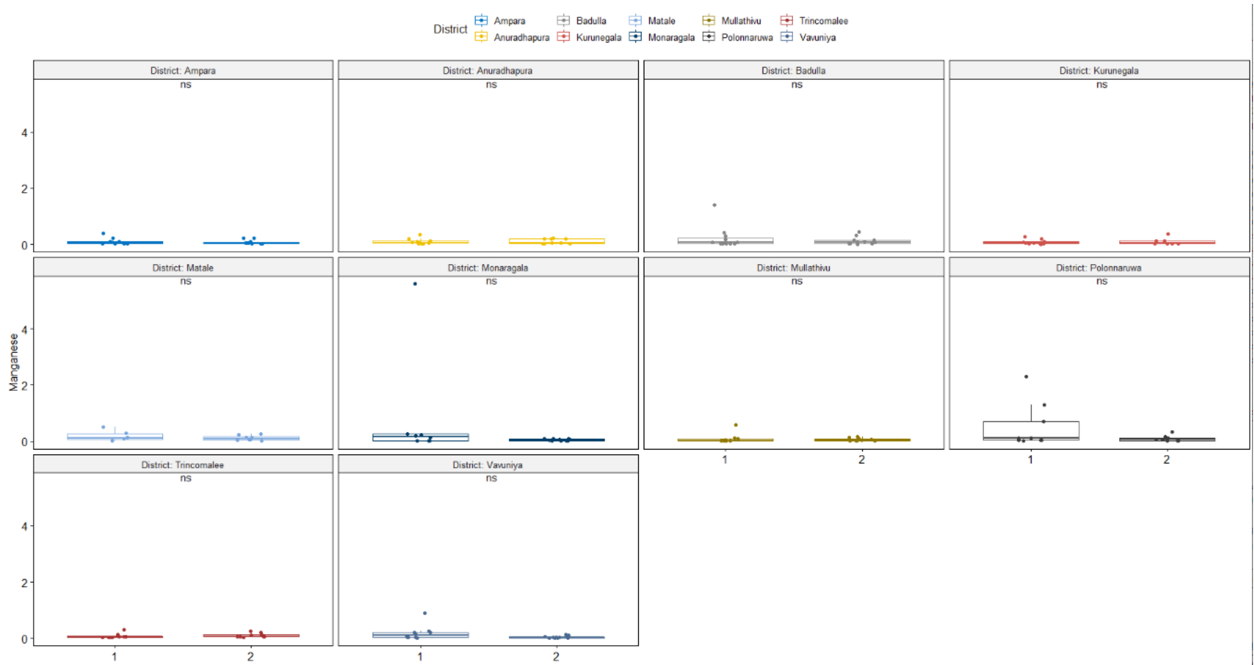
Metals were also examined, despite not registering as being present at significantly excessive concentrations. The three metals measured were magnesium, iron, and manganese. Metals were analyzed by district and separated by disease status. A visual inspection suggested that metal concentrations were slightly higher on average in wells associated with disease than with non-disease, but this effect was not found to be statistically significant using the Wilcoxon Signed-Rank Test for any of the three metals (Figure 3).

Figure 3: (a) Magnesium, (b) Manganese, and (c) Iron levels in drinking water grouped by district where groundwater well was located and stratified by disease status (1 = Household with a CKD patient; 2 = Household without a CKD patient). Significance values were calculated based on differences between data on CKD households and non-CKD households (‘ns’ = not significant; ‘*’ = $p < 0.05$; ‘**’ = $p < 0.01$; ‘***’ = $p < 0.001$).

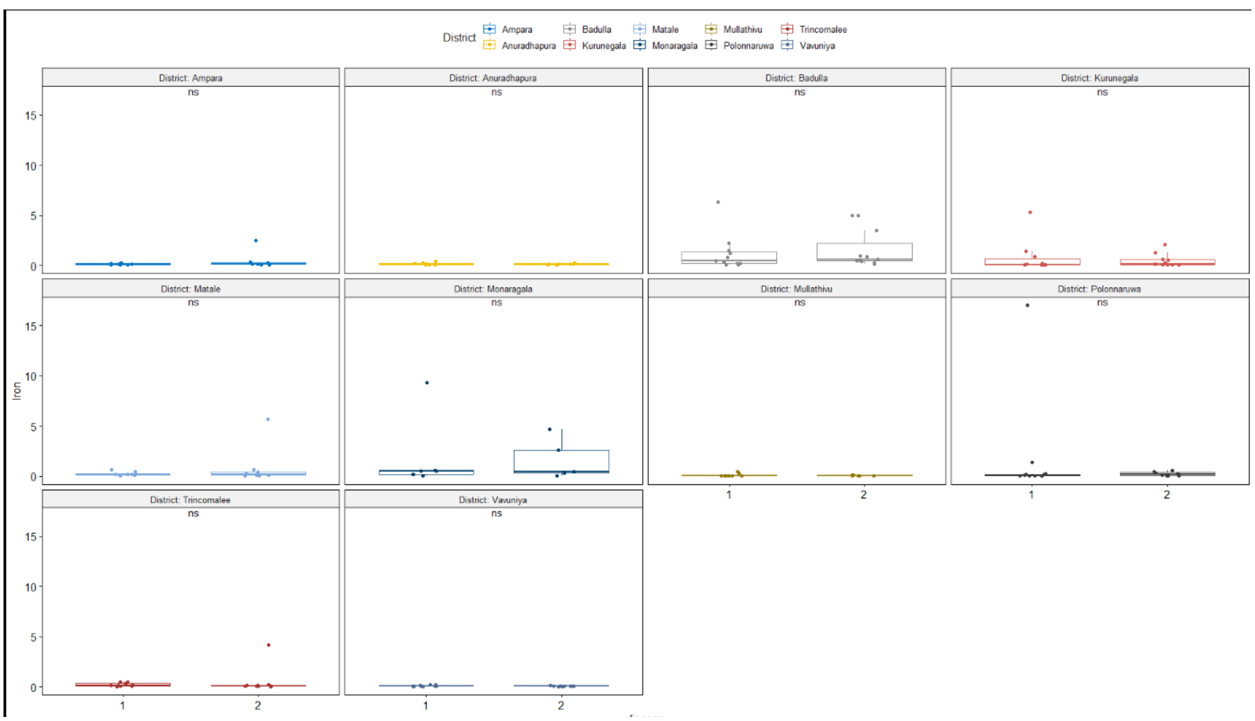
(a) Magnesium



(b) Manganese



(c) Iron



In the plots included above, multiple outliers can be observed. At least six wells were identified as being an outlier for three or more contaminant metrics measured. When we focused on the outliers on metal wells, 9 of the 12 wells that were identified as outliers for having high magnesium levels were linked to disease status.

The principal component analysis captured 83.26% of the variation based on the first two principal components. Notably, no clear patterns emerged along disease-status or geographic lines, except for distinctive behavior of the wells sampled in Kurunegala and, to a lesser extent, Mullathivu (Figure 4). The finding in Kurunegala is of particular interest given the district’s status as nearly CKDu-free (it is often considered a control site for CKDu studies). Here, we observe that in Kurunegala and Mullathivu, the wells display higher levels of sodium, chloride, and total dissolved solids. There do not appear to be any clustering effects related to disease (Figure 5). When wells from Kurunegala are removed from the analysis, Mullathivu appears more distinct from other districts than before. The effect is still driven by sodium, chloride, and total dissolved solids, although calcium and total hardness may play a more significant role (Figure 6).

Figure 4: Principal Component Analysis color-coded by district, with measured groundwater contaminants overlain. Note that the light blue dots represent Kurunegela, the yellow represent Mullathivu.

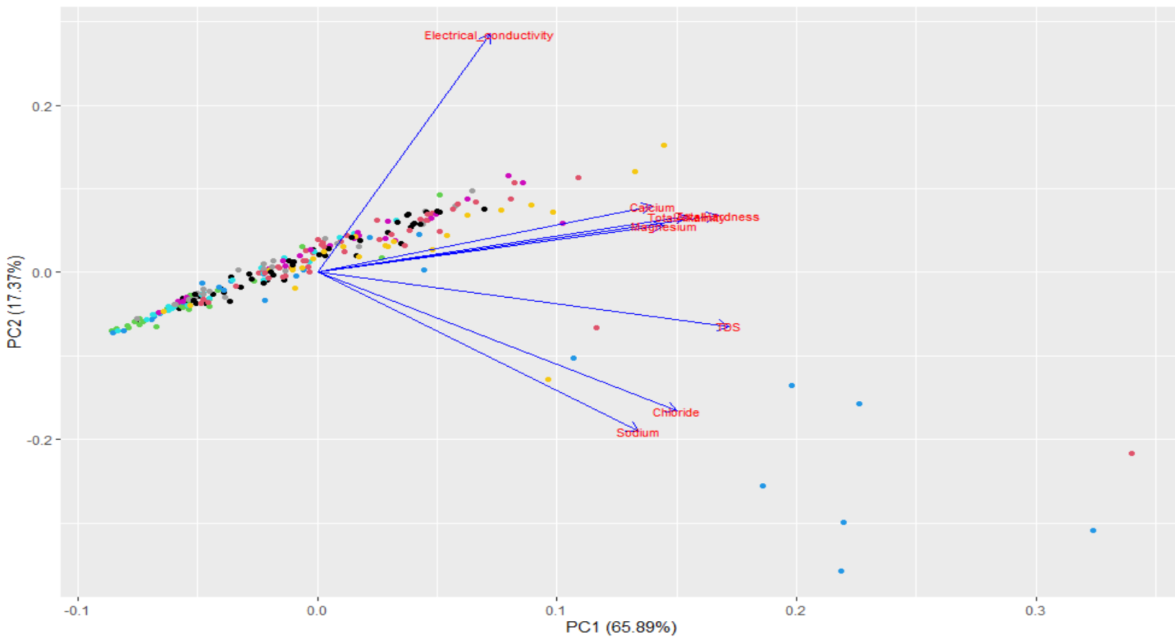


Figure 5: Principal Component Analysis color-coded by disease, with measured groundwater contaminants overlain. Black = CKD household, Red = non-CKD household.

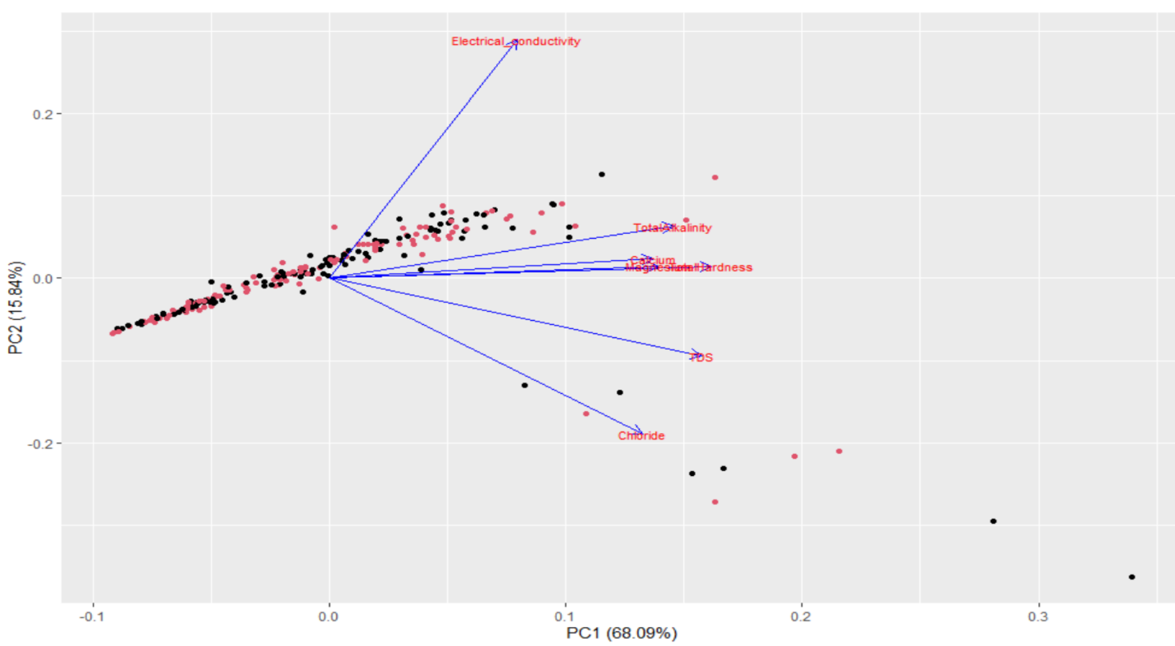
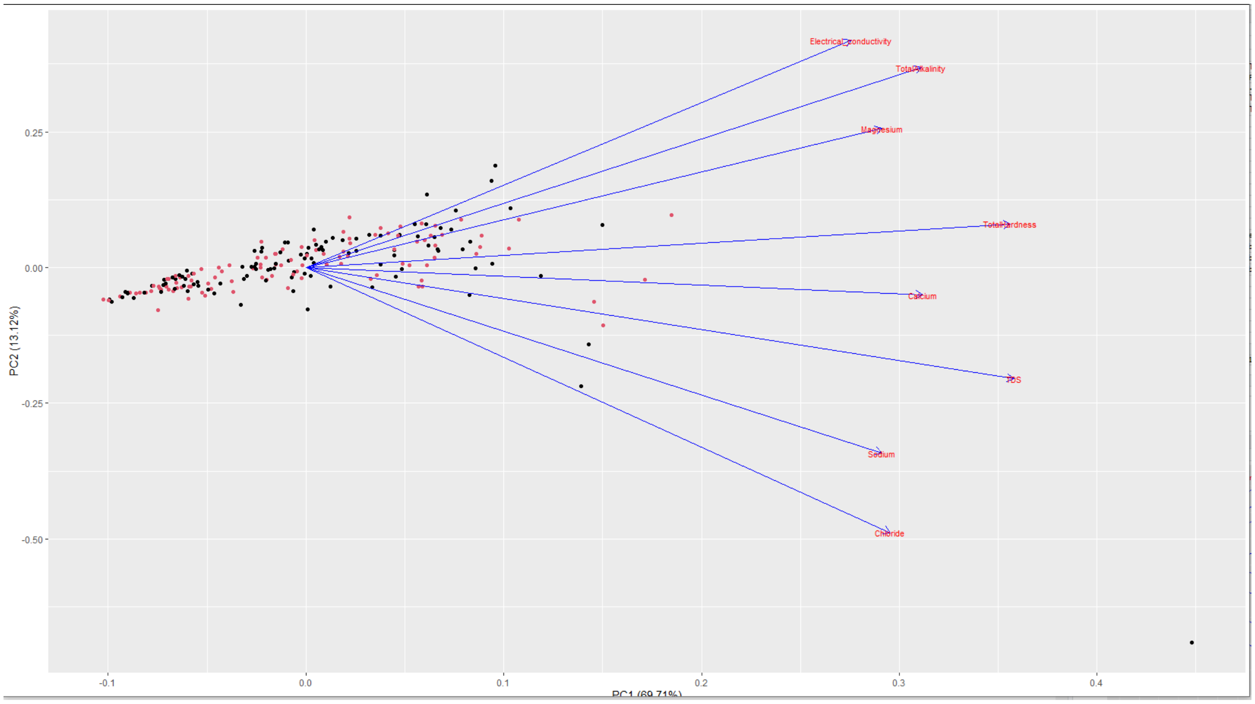


Figure 6: Principal Component Analysis color-coded by disease, with measured groundwater contaminants overlain. Black = CKD household, Red = non-CKD household.



Finally, we analyzed the contaminant patterns that could be observed along a latitude gradient. The two metrics most closely correlated to latitude were electrical conductivity (.65) and iron (-.73). Correlations are listed in Table 2.

Table 2: Pearson's Correlation Coefficients for the mean value of each measured contaminant by district to the mean latitude of respective district.

Metric (mean value by district)	**Correlation to Mean Latitude of District**
Electrical Conductivity	0.65
Sulfate	0.60
Total Hardness	0.52
Magnesium	0.49
Total Dissolved Solids (TDS)	0.45
Chemical Oxygen Demand (COD)	0.42
Total Alkalinity	0.40
Phosphorous	0.38
Calcium	0.31
Chloride	0.29
pH	0.29
Nitrate	0.08
Sodium	0.05
Potassium	-0.16
Fluoride	-0.37
Manganese	-0.52
Iron	-0.73

Limitations on the Statistical Analysis

Disease status was determined during interviews with the 1,497 households when interview subjects were asked if anyone in the household had CKD. This method for obtaining information about disease prevalence is inherently less stringent than acquiring and analyzing hospital data. Based on the symptoms of CKD, we can be relatively confident that individuals identifying as CKD patients are correct in their assessment of disease status. But nonpatients present a different concern: cases that have not presented symptoms or individuals who are concerned about revealing their health status are two biases which may drive overrepresentation of nonpatient households. One way to address this in a future study would be to corroborate any statistical information about CKD prevalence with any available hospital data on the subject.

GPS locations were only taken on a village-level, such that GPS coordinate data is not available for specific individual wells. This limits our ability to determine where specifically wells are located in a given village. Further study with more specific geographic data could be used to determine where clusters of patient wells exist, and whether these clusters can be linked to topographical features, agricultural activity, etc.

Contaminant levels and links to CKDu

All but one of the metrics significantly in excess of the relevant acceptable limit represent aggregate metrics, which would suggest that groundwater contamination in Sri Lanka cannot be attributed to a single measured contaminant or set of measured contaminants, but rather that contamination (and the suspected associated health problems) could be a result of synergism of multiple contaminants, including those not measured by this study.

The overarching conclusion is that even where groundwater presents problematic contamination levels, there is not enough evidence to demonstrate that the contamination from the measured contaminants is significantly contributing to disease. This effect is observed both on the individual contaminant level and in contaminants in aggregate – that is, individual measured contaminants do not contribute to disease, and the principal component analysis also does not show any clustering effect by disease being driven by one or multiple measured contaminants.

Slight, albeit not significant increases in disease should still be taken note of, however. This is particularly true in the case of metals, where visual inspection seems to suggest that metal concentrations are slightly higher in wells associated with disease. Future studies should expand upon this finding by expanding the number of metals measured and analyzing for synergistic effects involving multiple metals.

It is not immediately clear why wells in Kurunegala, and to a lesser extent in Mullathivu, behave differently than wells in other districts. Higher levels of sodium and chloride (and thus higher salinity and TDS) may suggest that proximity to coastal waters plays a role, but Kurunegala is a land-locked district. Mullathivu does possess a substantial coastline, but other coastal districts sampled, such as Trincomalee and Ampara, do not show a clustering effect related to salinity (Figure 4). Additionally, there do not appear to be many commonalities between Kurunegala and Mullathivu that would suggest this effect is driven by the same set of factors in both districts: Mullathivu is a poorer region of Sri Lanka, located in the northern portion of the country and predominantly occupied by Tamil Sri Lankans. Kurunegala, a wealthier district, is located in the northwest and boasts the city of Kurunegala and numerous coconut plantations.

Salinity and dissolved solids levels in groundwater are two key variables that differ in these two districts compared to other regions. For example, salinity and dissolved solids tend to be higher in regions with older aquifers that are eroded by the water. The effect is exacerbated in arid regions (an effect unlikely to play a role here – Kurunegala is a tropical rainforest; Mullathivu is a tropical savanna). Irrigation activity can also lead to increased dissolved solids.

The latitude correlation matrix poses further questions. The fact that electrical conductivity has a strong positive correlation to latitude means that there may be a higher concentration of particulates, especially salts, in the water in districts that are further north. This could be potentially linked to greater prevalence of CKDu in the Northern Central Province of Sri Lanka, although this project did not identify such a link. Electrical conductivity of water also increases with temperature (Southard 2006), and as the warmest parts of Sri Lanka are in the northern regions, it is also possible that this effect is contributing to the correlation.

There is no existing research that sheds light on potential reasons for iron to be strongly negatively correlated to latitude in Sri Lanka. Iron can enter groundwater through a number of ways, including being released from natural iron deposits in the earth's crust, industrial waste, or corrosion of metal structures, such as pipes or wells. Better well maintenance is the primary means by which one can limit the concentrations of iron in groundwater supplies. While it is unclear why iron concentrations are higher in the southern regions of Sri Lanka, it is important to remember that none of the iron levels measured were higher than the acceptable limits for metals in water. So, while this relationship is certainly peculiar, it's role in CKDu prevalence remain unclear.

A Regulatory Scheme for RO Units: Literature Review

Optimistically, the Sri Lanka government has committed to meeting the UN's sustainable development goals, which involve supplying safe, sanitary drinking water to Sri Lankans, including those who do not rely on the national water supply grid. (Cooray et al. 2019). Although this project did not find a clear association between groundwater contamination and CKDu, other studies have found that access to alternative sources of drinking water, such as natural spring water, are associated with lower incidence of CKDu. This, in part, has contributed to the proliferation of RO units in Sri Lanka. (Imbulana et al. 2020).

A 2015 study identified 600 RO units in the Northern Central Province. 27% and 28% of these units were established by the National Water Supply and Drainage Board and the Sri Lanka Navy, respectively. Once introduced, the government delegates maintenance of the unit to community-based organizations. Other RO units are privately owned. Each unit serves 100-500 families from typically low-income communities. While some units are operated by charity-based organizations that do not charge for their services, other units charged a price, with an average family spending 2% of their monthly income on RO-treated water. Sri Lankans interviewed by the researchers in this study were satisfied with this price, although some relied on free options, like charity-based units and truck delivery. The units are less popular in the wet season, when rainwater harvesting is possible, but struggle to keep up with demand in the dry season, when groundwater supplies are depleted. (Imbulana et al. 2020). Notably, this study was published in 2020, and it is unclear how COVID-19 and mandated isolations impacted Sri Lankans' access to alternative drinking water.

Researchers have repeatedly demonstrated the effectiveness of RO units in reducing drinking water contamination. Imbulana et al. (2020) found that in the 600 RO units studied, there was 91-98% removal of TDS, hardness, alkalinity, silica, calcium, magnesium, sodium, chloride, and sulfate. Studies focusing specifically on arsenic contamination have showed especially promising results, with 80-99% of arsenic removed under laboratory conditions. (George et al. 2006). Finally, there appears to be a negative association between frequent use of filtration systems like RO units and harmful bacteria in the water, leading to a reduction in gastrointestinal illnesses. (Payment et al. 1991). The ability to remove salinity, heavy metals, and fluoride from water distinguishes RO units from other filtration methods that are unable to remove these ions. (Wimalawansa 2013).

The units are imperfect, however. For example, multiple studies found that the units were not able to suitably reduce the amount of fluoride present in the groundwater. In one study, fluoride was only reduced in water by 59-67%. (Schneiter et al. 1983). This is potentially due to fluoride's relatively small particle size, its low ionic charge, and/or interference from heavy ions present at much higher concentrations. The researchers recommended that any standards set for the quality of untreated water suitable for use in the RO unit have adjusted standards for fluoride levels. Pre-treatment of the water may also be advisable, as this would reduce the fluoride levels in water prior to reverse osmosis treatment and benefit the overall effectiveness of the unit (Imbulana et al. 2015). There is also insufficient data on the effectiveness of removal of pesticide residues, heavy metals, and biological contaminants. (Jayasumana et al. 2016). Overall, effectiveness is influenced by pressure of the water inlet, temperature, and the amount of contaminants present in the water. (Wimalawansa 2013).

As previously discussed, many Sri Lankans, especially those who are impacted by CKDu, reside in rural areas, which do not have access to a centralized water source. For this reason, researchers suggest that the Sri Lankan government rely on a decentralized approach, which should prove more sustainable in rural areas. This is already the case in most regions where RO units are common; the community-based organizations who maintain the units set their own protocols and training, and they rely on the units' manufacturers for repairs. (Jayasumana et al. 2016). Where decentralization is synonymous with minimal maintenance, however, researchers have uncovered problems. Filters on RO units must typically be replaced annually, while membranes must be replaced 2-3 years, adding a cumbersome burden to the maintenance of RO units. (George et al. 2006). In studies of other countries, over 50% of RO units are abandoned after one year, primarily due to the unsustainability of maintenance. More specifically, maintenance requires skilled laborers, access to specific chemicals, and spare parts that are often not available in rural regions of developing countries. (Cooray et al. 2019). Additionally, in a study on arsenic contamination, researchers found that purification levels achieved in the laboratory could not even be nearly replicated in real-life conditions. This was due to poor set-up of the RO unit, the varying quality of different filters provided by different manufacturers, and the variability of water chemistry. (George et al. 2006). With that in mind, even where decentralization is practical, some researchers have argued that the Health Ministry of Sri Lanka should assume some authority in regulation, oversight, and education, so that community-based organizations may operate with some consistency. (Jayasumana et al. 2016). The Health Ministry could regulate the quality of parts used to limit leakage and pressure problems, pore sizes, filter types, and frequency of cleaning and replacement. (Wimalawansa 2013).

Sustainability is a critical concern of many researchers examining the future of RO units in developing countries. Researchers seek to ensure that RO units are operating with the smallest possible carbon footprints and generate a minimal amount of waste. Some studies have discussed that RO units, particularly those that rely on electricity, are energy intensive (Dissanayake 2020; Wimalawansa 2013). Those researchers have proposed zero-emission alternatives that rely on hand-pumping or other energy sources, which would reduce the carbon footprint drastically and reduce overall government expenses by 50%. These alternatives, however, may be difficult to scale up for largescale production (as opposed to personal use) and still boast a recovery rate of only 50%. This relatively low output exacerbates the burden on families who must then draw from multiple water sources, requiring them to walk long distances. (Dissanayake 2020). In response, there has been a semi-successful effort to design units with an increased recovery ratio. (Dissanayake et al. 2021). Even so, there remains the question of how best to deal with the generated wastewater, which goes presently untreated and is used for irrigation or dumped into the soil, harming the environment. Some countries have responded to this problem by discharging the water into sewage treatment plants, deep wells, evaporation ponds, etc., but these are beyond the capacity of rural communities in Sri Lanka. One study found that there could be potential in Sri Lanka to utilize constructed or engineered wetlands, which were shown to reduce contaminants in the wastewater by 20-85%. This would be a much more cost-effective option, with each wetland costing only $400 USD and requiring only locally available materials. (Attapathu et al. 2017).

Many researchers have advocated for a related alternative to RO units: nanofiltration. These researchers argue that nanofiltration is far more sustainable, both because it is easier to maintain and because it produces a smaller carbon footprint. Additionally, nanofiltration has been shown to be more effective at removing salts without disrupting the ionic balance. This means that those using the RO units do not have to retroactively add more salts back into the treated water to avoid an unnatural, unpleasant taste. (Cooray et al. 2019). Because the current tight-pore filters remove valuable minerals from the water (such as calcium), and remineralization can contribute to the growth of biofilms, nanofiltration, in conjunction with disinfection methods, presents desirable benefits. (Imbulana et al. 2020).

Finally, we must consider the cultural implications of how RO units may change Sri Lankans' relationship to water. de Silva et al. (2021) examined this specifically in Anuradhapura, where the researchers considered the district's 2,500-year history and found deeply embedded values and practices related to water. Water sharing was a collaborative affair, one that relied on systems of labor exchange and collective management. To have access to well water signaled prosperity, and it was frequently used in religious rituals or offered as a goodwill gesture. Water supplies, however, became increasingly polluted, and people who traditionally used the water to bathe, wash clothes, bathe livestock, harvest vegetables and fish, were no longer able to do so. This fundamentally altered the community's relationship to the water. What was once a communal resource transitioned to commercialized property, a phenomenon perhaps best evinced by the fact that CKDu incidence is lower in higher-income communities than it is in poorer communities. The presence of CKDu and other diseases, including alcoholism, exacerbate socially discriminatory practices against agricultural laborers. (Amarasiri de Silva et al. 2021).

In this context, RO units have the potential to be culturally transformative. Access to affordable treated water from RO units may lead to better health outcomes. In the Amarasiri de Silva et al. (2021) study, those who acquired access to RO unit-treated water noticed significant improvement in their health, allowing some to return to work and increase their quality of life and standard of living. Sri Lankans interviewed in the study reported that they value the water they receive much more and take great care not to waste it. (Amarasiri de Silva et al. 2021). If such shifts are significant, they may assist in narrowing socioeconomic gaps and restore many of the cultural values previously associated with water.

Policy Recommendations

Based on the above literature review, we can develop a set of policy recommendations for the Sri Lankan government that can serve as a framework for sustainable access to alternative drinking water. The strongest policies will not only be ideal for community members, but feasible to execute for relevant government agencies. Additionally, policies should bear in mind long-term goals of sustainability and improved health outcomes so as to avoid creating further problems down the line. Practical policies cannot be evaluated through solely an economic lens, but must also take into account the sociocultural elements that influence individuals' relationship to the water they drink. Because RO units are already familiar to many Sri Lankans living in rural areas and previous studies have found that these units are viewed as generally trustworthy and affordable, these policy recommendations will focus specifically on their effective implementation, rather than on more costly and likely inaccessible alternatives, like piped water or bottled water from natural springs.

A decentralized approach is best-suited to rural communities. This approach is suitable because it combines already established trust in government-supplied water with the customizability and small-scale capabilities that are most feasible in low-income, rural areas. Delegating maintenance of RO units to community-based organizations has proven effective, although more training should be required to ensure competency when cleaning and replacing filters or other parts. Community-based organizations should be registered, accountable organizations. While studies do not currently identify problematic pricing of RO unit-treated water, it is possible that COVID-19 and the effects of climate change will intensify issues of scarcity and lead to inflated prices. For this reason, the price charged by community-based organizations should be regulated or subsidized if possible. Sri Lanka would benefit from a governmental effort to attract more charitable organizations to the area that can provide treated water at no cost to communities, or to attract organizations that operate as truck-delivery systems, thereby reducing the need for families to travel long distances on foot to acquire water.

Community-based organizations should adhere to government-promulgated maintenance standards based on comprehensive data. As previous studies have suggested, the effectiveness of RO units can vary widely with proper maintenance, as well as with local water chemistry. Manufacturers of RO units should operate with a manner of consistency insofar as they are all head to a standard of similar quality; this will avoid disparities in filtration effectiveness based on which manufacturer the unit is purchased from. Before making use of the RO unit, community-based organizations should take samples of local groundwater supplies in order to analyze the particular contamination profile of the water. This may determine if pre-treatment is necessary, such as in the case of excess fluoride or biological contamination. Where water is remineralized to restore taste and health benefits, clear standards should govern this process in order to prevent the growth of biofilms. Filters should be replaced by competent persons on a regular basis, and community-based organizations should maintain relationships with manufacturers in order to ensure that spare parts or more sophisticated repairs are accessible when needed.

If RO units are designed both for largescale as well as personal use, this will expand accessibility by increasing the flexibility of options. Largescale RO units that can serve several hundred families are enormously valuable and can be highly cost-effective, as previously demonstrated by several studies, but they cannot be everywhere. Even with their proliferation, many families still have to travel great distances on foot to access water from a largescale RO unit. If largescale RO units are not properly maintained, the negative consequences can also be significantly more impactful. Many largescale units, according to some studies, also demonstrated lower effectiveness and boasted a much higher carbon footprint due to their reliance on electricity. Thus, although the value of largescale units is clear, alternatives should be available as well. The most viable small-scale RO units involve hand-pumps, which are sustainable and cost-effective. The availability of domestic RO units would reduce the burden on many families who cannot access largescale RO units with great frequency.

It is incredibly important to prioritize sustainability when promulgated water policies. RO units that require enormous amounts of electricity or are too expensive or complicated to maintain pose a threat to the long-term viability of safe drinking water. Fortunately, many studies have identified ways in which RO units can become more sustainable. First, advances in RO units should ideally focus on increasing the recovery rate in order to reduce the amount of harmful wastewater produced. Where wastewater is produced, however, disposal procedures should be established to avoid the water contaminating food or other water supplies. Some studies have suggested constructed wetlands as a low-cost remediation option where higher cost solutions (such as evaporation ponds) would be wholly impractical. Further research should also focus on how wastewater can be treated in a low-cost manner before being applied to agricultural fields so that the harmful contaminants in the wastewater are not harming the soil or contaminating food supplies. Second, RO units should be continually improved to reduce maintenance and cleaning requirements where possible, as the inability to maintain the unit is one of the most-cited reasons why RO unit-treated water had to be abandoned in a given community. Parts that do not need to be replaced as often or filters that do not require so frequent of cleaning would be enormously helpful in increasing the sustainability of the unit where skilled labor or available parts are not always going to be consistently available when they are needed most.

An underlying goal of any water policy should be to maintain local cultural values and restore trust in water supplies in order to promote healthy living. Access to healthy water brings many benefits beyond protection from waterborne health problems. Clean water enables individuals to be more productive and improve their standard of living, reducing many inequities that are driven by underlying health disparities between populations. In restoring faith in the water, RO units may also restore many of the cultural values of collective management of water that were of previous prominence, and water may once again be a fundamental part of religious rites and community-building that promote safer, better-connected communities. A reduction of CKDu would reduce the enormous burden placed on families who have to care for patients in their household and allow many agricultural laborers to return to work. These goals should guide policymakers in their effort, so that any promulgated policies present well-rounded solutions that involve the community and allow it to move forward into a healthier world. Policymakers can leverage preexisting attitudes toward water and the Sri Lankan government to engender trust in the sustainability and practicality of RO unit-treated water. Educational campaigns can be enormously helpful in this regard; many undertaken in Sri Lanka already have informed communities about the dangers of CKDu and other diseases potentially related to contaminated groundwater, thereby motivating individuals to seek alternatives.

Future Directions

There are numerous opportunities for expansion both with respect to groundwater contamination and water policy. Such research was beyond the scope of this project but would nonetheless be highly complementary to it as well as to the existing research landscape.

First, numerous researchers over the last two decades have collected water samples in Sri Lanka from groundwater wells and other sources. Consolidation of these water quality data would be enormously beneficial to the scientific community. A meta-analytical approach that aggregates the various water quality data and highlights both where this data is internally consistent and where there appear to be contradictory findings would limit the duplication of research effort and allow for the community to identify findings in need of reconciliation. It would allow for a single access point to numerous research studies and limit the possibility that relevant research is overlooked while conducting a new study.

While this project highlighted some findings related to dissolved solids and their geographic distribution, little is understood about the underlying hydrogeology driving the distribution of these dissolved solids. A study examining the various hydrogeological features at the district level, overlain with the locations of the country's groundwater wells is needed. Such a study would allow the community to assess drainage patterns as well as the general pathway water takes from rain to well. How the water moves through the landscape and into the groundwater is influential on the amount of dissolved solids in the water (Wickramasinghe et al. 2021), and findings may allow for more effective planning with regard to well location and aquifer construction so as to avoid particularly hazardous areas prone to high total dissolved solids that may contribute to health problems. An ideal study would taken into account the relevant industrial, agricultural, or other anthropogenic activity taking place in the region that might be contributing to increased contamination of the water as it passes through these regions.

This project concluded that while no individual metal's contamination levels were cause for concern or otherwise associated with disease prevalence, it did suggest that a synergism was possible. More sophisticated analysis of potential synergistic effects would be highly valuable.

The data collected for this project examined three different metals (magnesium, manganese, and iron), but sampling could be expanded to include cadmium, lead, mercury, chromium, and any other potential metals of concern that are known to contaminate water supplies (Kulathunga et al. 2019 summarizes the dozens of studies which have focused on heavy metals). A study would be even more effective if it could potentially trace the sources of these metals so as to make better remediation recommendations and potentially relate the findings to previously observed geographic patterns. It is possible that all the metals together contribute to disease prevalence, a particular combination of some of them, or no combination at all.

Relatedly, this project did not specifically examine the concentrations of particular agrochemicals in the water. Much existing research has suggested that agrochemical contamination is a relevant contributor to CKDu prevalence (Jayatilake et al. 2013; Wimalawansa 2016), but definitive conclusions have not yet been identified in this regard. This project did take into account some metrics related to agrochemicals, such as elemental species that may be broken down components of these chemicals as well as metrics indicating aggregate contamination levels, but further direct study of agrochemicals may be beneficial to the research community as it may identify patterns previously missed.

Further research can also be performed with respect to reverse osmosis and drinking water policy. As at least one study suggested nanofiltration may be a superior alternative to reverse osmosis as it filters more effectively without sacrificing the taste of water due to lost electrolytes. Further research could be helpful to evaluate the effectiveness of nanofiltration, which in turn could spurn discoveries related to optimizing cost effectiveness, minimal carbon footprint, accessibility, etc. Alternatively, if reverse osmosis is already widely accepted and more popular in Sri Lanka as a form of alternative drinking water, research could be conducted to determine further possibilities regarding taste improvement. These could include alternative filters, new additives improving flavor, etc. The goal of such research would be to encourage the use of RO units by preserving the desired taste of water without perpetuating new burdens, costs, or harms.

Given the unknown, but potentially significant role metals play in contributing to CKDu prevalence, maximizing the effectiveness of metal filtration should be a priority for those seeking to build superior RO units. Studies may be needed to understand how effective existing filtration methods are in the field, and how this effect plays out across the different metals present in Sri Lanka's groundwater. It is possible that an improved RO unit that is more highly capable of metal filtration may increase the cost of water derived from these units, which presents difficult policy implications that also warrant further research and discussion. While the health and safety of the water provided is paramount, the proliferation of RO units in low-income regions of Sri Lanka necessitates their minimal costliness, both for the initial installation of the unit in the community as well as ongoing maintenance, repair, and replacement.

CONCLUSION

This project represents two analyses: one quantitative and one based on policy. The quantitative analysis utilized water samples taken from wells from several Sri Lankan districts. The samples were analyzed for various contaminants. These samples were matched to data on households hosting at least one individual diagnosed with CKDu. We identified potential signs of harmful contamination levels and attempted to identify associations between contaminants and disease. Although certain wells in certain districts were identified as being contaminated beyond an acceptable level for a given metric, no clear association emerged between a given contaminant or set of contaminants and the incidence of CKDu. This would suggest that contaminants not measured by this study, such as agrochemicals, may be contributing to CKDu incidence more than any contaminant measured in this study. Alternatively, we propose that there is potential for a synergistic effect due to slight contamination from multiple heavy metals that is contributing to the disease (examined by Babich et al. 2020).

Studies have shown that access to clean, treated water is associated with a reduction in CKDu diagnoses. A literature review was conducted to evaluate the effective ways in which alternative drinking water may be supplied, particularly in low-income, rural communities. More specifically, this project focused on reverse osmosis units, which are of increasing popularity in Sri Lanka and present a cost-effective opportunity for accessing clean water. These units, however, require laborious maintenance and cleaning, and Sri Lanka currently lacks clear standards by which community-based organizations can safely and effectively operate RO units to deliver high-quality water without compromising on expense or on the water's taste. Several recommendations, including utilizing a decentralized process for water distribution, were proposed.

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