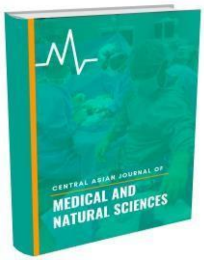

CENTRAL ASIAN JOURNAL OF
MEDICAL AND NATURAL SCIENCES
https://cajmns.centralasianstudies.org/index.php/CAJMNS
Volume: 06 Issue: 03 | July 2025 ISSN: 2660-4159

Article

Exploring the Geographical Distribution of Groundwater Sources and their Associations to Chronic Kidney Diseases: A Review

Ali Suleiman Arzek[1], Bilal Muayad Abdulrahem Alalosy*[2], Mohammed R. Al-Shaheen[3], Ayoob alqurqash[4]

1. Anbar Education Directorate, Ministry of Education, Iraq
2,4 Upper Euphrates Basin Developing Centre, University of Anbar, Iraq
3. Laboratory Department, Ramadi Teaching Hospital, Anbar Health Directorate, Ministry of Health, Iraq
* Correspondence: bilal.m.a@uoanbar.edu.iq

Abstract: This review explores the geographical distribution of groundwater sources and their potential link to chronic kidney diseases (CKD), with a focus on relevancy to Iraq. Groundwater is a crucial water source for many regions, including parts of Iraq, and its availability and quality vary significantly across geographical locations due to geological, hydrological and anthropogenic factors. The review examines studies and data from various locations including Sri Lanka, India, Bangladesh, Mauritania, Saudi Arabia and Iraq to identify patterns and associations between groundwater quality and CKD prevalence. These regions provide useful case studies due to widespread groundwater usage, available research, and diverse environmental settings. The findings highlight how groundwater mineral composition can impact CKD rates in different areas. In Iraq, chronic kidney disease has spread widely in recent years as some communities have increasingly relied on groundwater extraction for drinking and irrigation, due to declining flows in the Tigris and Euphrates rivers. The review investigates factors influencing groundwater quality and considers their potential influence on chronic kidney disease in Iraq and other regions. While an association between groundwater and CKD is evident, additional research is still needed to fully characterize this relationship and its public health implications when accounting for confounding variables and clarifying mechanisms. The review provides valuable insights for studying the spatial distribution of CKD in Iraq and surrounding areas.

Keywords: Chronic Kidney Disease, Renal Disease, Groundwater, Water End-stage

Citation: Arzek, A. S., Alalosy, B. M. A., Mohammed R. Al-Shaheen, M. R., Alqurqash, A. Exploring the Geographical Distribution of Groundwater Sources and their Associations to Chronic Kidney Diseases: A Review. Central Asian Journal of Medical and Natural Science 2025, 6(3), 890-903.

Received: 20th Mar 2025
Revised: 23th Mar 2025
Accepted: 1st Apr 2025
Published: 16th Apr 2025

1. Introduction

Groundwater plays a crucial role as a water source in various regions around the world. Groundwater is extensively used in Iraq for agricultural purposes and occasionally for drinking due to the recent scarcity of water in the Tigris and Euphrates Rivers. However, in this article, we have taken Sri Lanka, India and Bangladesh as examples due to the abundance of research in these regions, their distinctiveness in using groundwater, the diversity of their environments, and the rise in chronic kidney disease in these areas. Where, its importance is evident in areas Sri Lanka, where groundwater is the primary source of water for drinking and cooking. However, the geographical distribution of groundwater in certain regions has raised concerns regarding its quality and potential health risks [1]. One significant health issue that has been associated with poor groundwater quality is Chronic Kidney Disease of Unknown Etiology (CKDu).

CKDu is a prevalent public health problem observed in many parts of the world, including countries like the USA, Australia, and Japan. It has also been reported in Africa, Central America, Asia, and specifically in the rural dry zone regions of Sri Lanka for over two decades. The remarkable geographical distribution of CKDu in regions where groundwater is the main drinking water source suggests that long-term exposure to nephrotoxic elements through drinking groundwater may be a significant risk factor [2].

Groundwater quality is influenced by various factors such as lithology, land use, climatic conditions, and anthropogenic activities. For example, high concentrations of nitrate (NO3) have been found in districts with a higher percentage of agricultural lands, particularly in coastal zones. Additionally, higher levels of hardness and fluoride have been observed in the dry zone regions. These findings highlight the importance of understanding the geochemical status of groundwater to ensure its suitability for drinking [3].

The use of statistical analysis methods such as correlation matrix and principal component analysis helps to identify the controlling factors of groundwater quality. These analyses have revealed that agricultural activities contribute to elevated levels of NO3, hardness, arsenic (As), and chromium (Cr) in groundwater. Other components are primarily attributed to natural sources and processes [4].

Moreover, environmental factors such as precipitation, air temperature, presence of unconsolidated sediments, and agricultural lands have been found to affect groundwater quality. These factors can account for a significant portion of spatial variation in groundwater geochemistry [5].

It is important to note that the relationship between groundwater quality and CKDu has not been definitively established. However, the coupled controls of lithology, land use, and climate on groundwater quality in Sri Lanka highlight the need for further research. Future studies should focus on clarifying the synergistic effects of different chemical constituents on CKDu.

In conclusion, groundwater is an indispensable resource that plays a vital role in social and economic development worldwide. However, poor groundwater quality in certain regions, such as the rural dry zones of Sri Lanka, raises concerns about its suitability for drinking [6]. Understanding the factors influencing groundwater quality is crucial for effective planning and management of this valuable resource. By addressing these concerns and conducting further research, we can ensure the sustainable use of groundwater while minimizing potential health risks associated with CKDu.

Variation in availability and quality across regions

The availability and quality of groundwater vary across different regions, particularly in relation to chronic kidney disease of unknown etiology (CKDu). CKDu is a prevalent public health issue observed worldwide, with higher rates reported in countries such as the USA, Australia, and Japan [7]. In recent years, CKDu cases with unknown causes have emerged in various parts of Africa, Central America, and Asia [8]. One such region affected by CKDu is the rural dry zone of Sri Lanka, specifically the North Central Province and adjacent areas [9]. The remarkable geographical distribution of CKDu in these regions where groundwater serves as the primary drinking water source suggests a potential link between long-term exposure to nephrotoxic elements in groundwater and the disease [2], [6].

Groundwater plays a crucial role in social and economic development globally. However, in the rural dry zone regions of Sri Lanka, limited precipitation and high temperatures pose challenges for meeting daily water needs. Groundwater serves as the main source of water for drinking and cooking purposes in these areas, making poor groundwater quality a concern for CKDu. The depletion of water resources and deterioration of groundwater quality due to population growth and excessive use of pesticides and agrochemicals further threaten public health [6].

Previous studies have found that the prevalence of CKDu is associated with recharge sources and stagnated groundwater flow paths [10]. Therefore, factors such as source aquifer lithology, residence time of water, recharge mechanisms, flow patterns, and geological conditions can contribute to natural contamination of groundwater and potentially lead to CKDu [4].

Understanding the geochemistry of groundwater is essential for ensuring its suitability for drinking purposes. Factors such as rock-water interactions, evaporation and precipitation patterns, aquifer lithology, origin of groundwater, and flow directions influence groundwater geochemistry. Geochemical studies have shown that high concentrations of fluoride in groundwater can adversely affect dental and skeletal health in India, while arsenic contamination has been linked to serious health issues [11].

Although scientific evidence linking groundwater to CKDu is still lacking, distinctions in the geochemical characteristics of groundwater have been observed between CKDu-endemic and non-endemic areas in Sri Lanka. Investigating water quality and dominant geochemical processes in CKDu-endemic regions can help identify potential sources and routes of undesirable chemical constituents, shedding light on the causes of the disease. Additionally, this research can guide sustainable groundwater management and effective utilization to prevent further contamination [9], [10].

Further studies are needed to explore the synergistic effects of different chemical constituents on CKDu. Utilizing statistical analysis methods such as correlation matrices, bivariate analyses, and hierarchical component analyses can provide valuable insights into complex water quality systems. Geographic Information System (GIS) and Remote Sensing (RS) tools are also instrumental in analyzing spatial data associated with groundwater resources. These tools facilitate the understanding of hydrogeological conditions by examining geological structures, geomorphic features, and lithological characteristics [11].

In conclusion, understanding the variation in availability and quality of groundwater across regions is crucial for addressing the issue of CKDu. Poor groundwater quality in CKDu-endemic areas, particularly in the rural dry zones of Sri Lanka, has been identified as a potential risk factor for the disease. Factors such as lithology, land use practices, climate conditions, recharge sources, and flow patterns contribute to variations in groundwater geochemistry. Further research should focus on clarifying the relationship between different chemical constituents and CKDu while effectively managing groundwater resources to prevent contamination and promote public health.

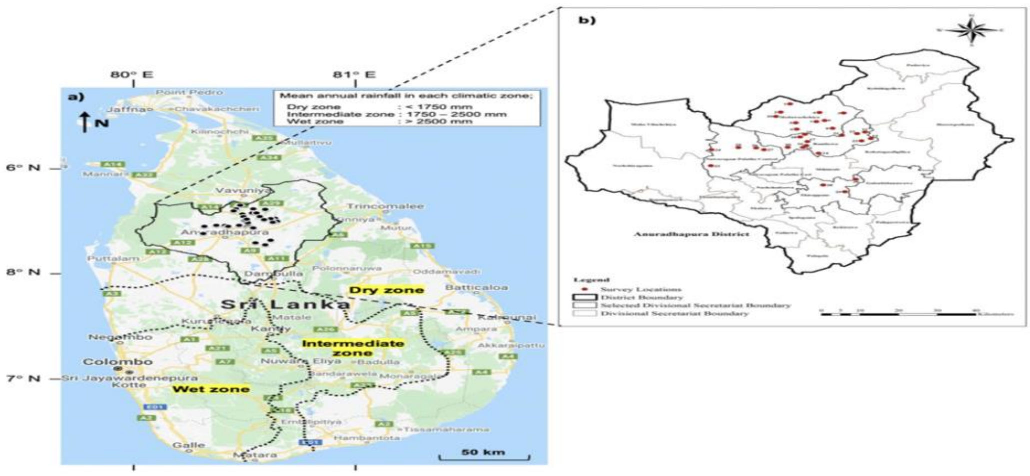

Figure 1. (a) Climatic zones of Sri Lanka areas [10], (b) Sampling locations in the study.

2. Materials and Methods

Exploring the geographical distribution of groundwater sources

2.1. Examination of studies and data from different locations

Examining studies and data from different locations is crucial for exploring the geographical distribution of groundwater sources and its potential implications for Chronic Kidney Disease of Unknown Etiology (CKDu). In Sri Lanka, poor groundwater quality in household wells is believed to contribute to CKDu, but national-scale investigations into the influencing factors of groundwater quality are limited [2]. Therefore, this essay aims to describe the spatial characteristics of groundwater geochemistry in Sri Lanka and examine the relationships between groundwater quality parameters and environmental factors.

The results of various studies reveal significant spatial heterogeneity in groundwater geochemistry in Sri Lanka. For instance, districts with a higher percentage of agricultural lands, particularly those in the coastal zone, exhibit high concentrations of NO3 [13]. On the other hand, higher levels of hardness and fluoride are predominantly observed in the dry zone(14). While trace elements such as Cd, Pb, Cu, and Cr are found to be within World Health Organization guideline values in most samples, some samples show elevated concentrations of As and Al beyond these limits [15].

Principal component analysis identifies four components that explain 73.2% of the total data variance. The first component, characterized by high loadings of NO3, hardness, As, and Cr, suggests the influence of agricultural activities on groundwater quality. Other components are primarily attributed to natural sources and processes. Further analysis reveals positive correlations between water hardness, fluoride, and As concentration with precipitation, while negative correlations with air temperature are observed [16]. Moreover, NO3 concentration and water hardness are positively correlated with agricultural lands, whereas As concentration is positively correlated with unconsolidated sediments [13], [3].

The overall spatial variation in groundwater geochemistry can be accounted for by environmental factors to a significant extent (58%), as indicated by redundancy analysis results. However, it should be noted that the groundwater quality data from these studies do not establish a direct relationship between groundwater quality and the occurrence of CKDu [2], [10].

Nevertheless, these findings highlight the intertwined influences of lithology, land use, and climate on groundwater quality in Sri Lanka. They emphasize the need for future research that effectively explores the synergistic effects of different chemical constituents on CKDu. Additionally, more comprehensive studies with higher spatial- temporal resolution sampling and multidisciplinary approaches are necessary to unravel the controlling factors of groundwater quality and identify the risk factors associated with CKDu in Sri Lanka.

This examination of studies and data from different locations provides valuable insights into the geographical distribution of groundwater sources and its potential implications for CKDu. Understanding the natural and anthropogenic controlling factors of groundwater quality is crucial for developing effective strategies to ensure safe drinking water sources and prevent CKDu in Sri Lanka. By conducting further research and investigating the relationships between groundwater quality, environmental factors, and CKDu occurrence, a better understanding of this complex disease can be achieved(17)(1).

2.2. Identification of patterns and associations with CKD prevalence

The geographical distribution of groundwater sources plays a significant role in the prevalence of chronic kidney diseases (CKD). In Sri Lanka, the distribution pattern of CKD is patchy and non-contiguous, with high prevalence in certain villages while neighboring villages remain unaffected. This highlights the potential link between geo-water contribution and CKD occurrence.

In villages with access to clean water springs or waterspouts, the disease prevalence is near zero. This suggests that contaminated water may be a key source causing CKD. Conversely, those who consume water from shallow or dug wells, especially those located between paddy fields, have a higher incidence of CKD. The quality of well water varies greatly within a small region, indicating the need for comprehensive testing rather than relying on limited samples.

Interestingly, the use of agrochemicals alone does not explain the discrepancies in CKD prevalence. While these chemicals are used across Sri Lanka, regions with higher usage do not necessarily have higher rates of CKD. For example, in Nuwara Eliya where agrochemical usage is significantly greater, CKD prevalence is low or non-existent. This suggests that other factors contribute to the occurrence of CKD.

Several studies have investigated the chemistry of groundwater in relation to CKD occurrence. While heavy metal pollutants were not found in groundwater samples, elevated concentrations of silica were identified and require further investigation. Isotopic analyses suggest different sources or origins for groundwater in endemic areas.

However, more research is needed to determine if groundwater chemistry directly correlates with CKD occurrence.

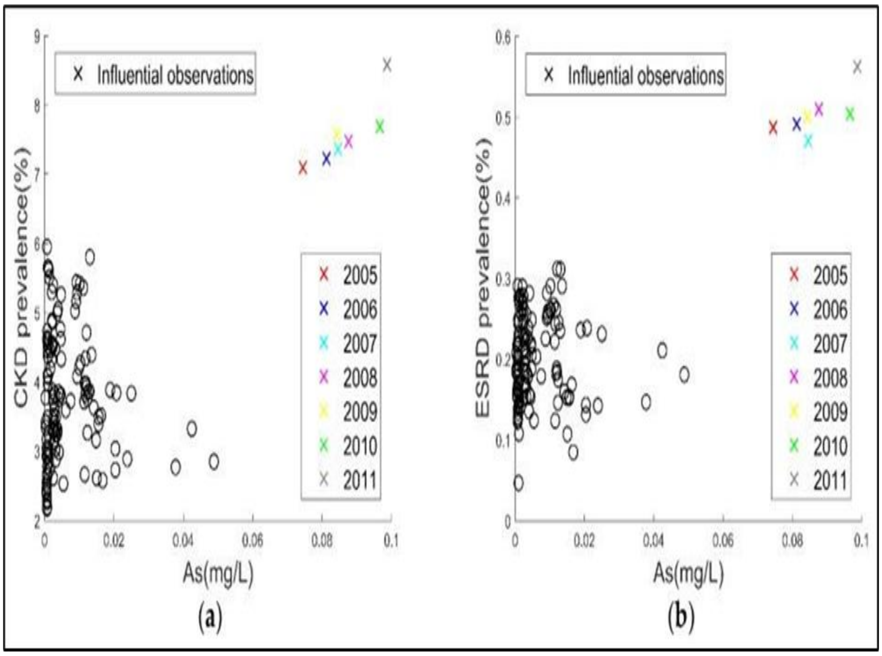

Figure 2. Illustrates the influential observations between arsenic in groundwater and CKD/ESRD

Seven highly influential observations that were far away from the other observations on the X axis were identified on the top right corner of Figure 2. We realized that all these high influencers came from the same region, Chiayi city. A clear trend was revealed in that the arsenic in the groundwater accompanying the CKD/ESRD prevalence in Chiayi city increased with time. The Z -score bar chart of all the monitored substances of Chiayi city.

Factors such as degradation products of agrochemicals and organic matter content may also play a role. Additionally, detailed investigation into elevated silica concentration is necessary.

Overall, it is clear that multiple factors are involved in precipitating CKD-mfo. A comprehensive and multi-focal approach is required to identify root causes and alleviate the problem. Narrowly designed studies are unlikely to yield conclusive results or preventive measures. Further research, including isotopic tracers and frequent sampling, is needed to capture potential pollutants and understand the relationship between groundwater quality and CKD occurrence. This knowledge will not only aid in identifying the causes of CKD but also guide sustainable management of groundwater resources [1], [4], [5], [6], [7], [8], [7], [9].

(Figure S1) indicates that Chiayi city was like the other places in Taiwan except that it had an unusual high level of arsenic in the groundwater, with a Z -score was 3.85. In other words, the concentration of arsenic in the groundwater in Chiayi city was over 75 g/L, a value that was exceptionally higher than those of the other regions in Taiwan (source: reference [7]).

3. Results and Discussion

3. 1. Factors influencing groundwater quality and impact on CKD rates

3.1.1. Geological formations and their effect on water composition

The geological formations in a region have a significant effect on the composition of groundwater, which in turn can impact the prevalence of chronic kidney disease (CKD). In Sri Lanka, poor groundwater quality is believed to be a potential contributor to CKD. To understand the factors influencing groundwater quality in Sri Lanka, a study was conducted at a national scale. The study analyzed the spatial characteristics of groundwater geochemistry and its relationship with environmental factors such as lithology, land use, and climatic conditions.

The results revealed significant spatial heterogeneity in groundwater geochemistry across Sri Lanka. Districts with a higher percentage of agricultural lands, particularly those in coastal zones, showed elevated concentrations of nitrate (NO3). Groundwater in the dry zone exhibited higher levels of hardness and fluoride. While trace elements such as cadmium (Cd), lead (Pb), copper (Cu), and chromium (Cr) were within World Health Organization guideline values, some samples had higher concentrations of arsenic (As) and aluminum (Al) above these guidelines.

Principal component analysis identified four components that explained 73.2% of the total data variance. The first component, characterized by high loadings of NO3, hardness, As, and Cr, suggested the influence of agricultural activities on groundwater quality. Other components were primarily attributed to natural sources and processes.

Further analysis found positive correlations between water hardness, fluoride, and As concentration with precipitation, while negative correlations were observed with air temperature. Additionally, NO3 concentration and water hardness were positively correlated with agricultural lands, while As concentration was positively correlated with unconsolidated sediments.

Environmental factors accounted for 58% of the spatial variation in overall groundwater geochemistry based on redundancy analysis results. However, it is important to note that the study could not identify a direct link between groundwater quality and CKD occurrence.

Nonetheless, these findings highlight the interplay between lithology, land use practices, and climate in shaping groundwater quality in Sri Lanka. In order to fully understand the impact of different chemical constituents on CKD, future research should be designed to investigate their synergistic effects.

Overall, the geological formations in a region play a crucial role in determining groundwater composition. Understanding these geological controls is essential for managing and maintaining the quality of groundwater resources, particularly in areas where it is the main source of drinking water [1], [2], [3], [4], [5].

3.1.2. Hydrological processes affecting groundwater contamination

Hydrological processes impact groundwater contamination, which in turn affects the prevalence of Chronic Kidney Disease of multi-factorial origin (CKD-mfo) in Sri Lanka. The distribution of the disease is patchy and non-contiguous, suggesting contaminated water as a causal factor. Villages with clean water sources have low prevalence rates. CKD-mfo is higher among those consuming water from shallow wells between paddy fields. Groundwater quality varies within short distances, making it difficult to draw global conclusions. Agrochemical usage does not necessarily correlate with higher CKD-mfo rates. Fluctuations in groundwater tables during dry seasons contribute to the occurrence of CKD-mfo. Anthropogenic activities and environmental factors impact groundwater quality. Comprehensive studies are needed to understand the relationship between groundwater and CKD-mfo. A multi-focal approach is necessary to identify the root causes and develop prevention measures [1], [2], [4], [5], [6], [8].

3.1.3. Anthropogenic influences on groundwater quality

Anthropogenic influences have a significant impact on groundwater quality, which in turn affects the prevalence of Chronic Kidney Disease (CKD). Factors such as population growth, excessive use of pesticides and agrochemicals, and degradation of water resources contribute to the deterioration of groundwater quality. In Sri Lanka and Uddanam, India, CKD is a major public health concern, and groundwater contamination has been identified as a contributing factor. Geological factors like lithology and fault structures also play a role in groundwater contamination across Europe. To address CKD rates effectively, it is crucial to perform regional geo-hydrochemical analyses and implement preventive measures. By understanding the natural and anthropogenic factors that affect groundwater quality, public health risks associated with CKD can be mitigated through proper monitoring and assessment [1], [2], [3], [4], [5], [6], [8].

4. Findings and insights into the spatial distribution of CKD

4.1. Mapping the prevalence of CKD in relation to groundwater sources

Mapping the prevalence of chronic kidney disease (CKD) in relation to groundwater sources is crucial for understanding the spatial distribution of CKD and its potential causes. Several studies have examined the association between groundwater quality and CKD prevalence in different regions.

In Taiwan, a study investigated the relationship between arsenic in groundwater and age-standardized CKD prevalence rates. The results showed that there was a correlation between CKD prevalence and arsenic levels in groundwater. However, when the city of Chiayi, which had high levels of arsenic, was excluded from the analysis, similar associations were still observed. This suggests that although there may be some differences, the overall associations between groundwater quality and CKD prevalence remain stable.

In Sri Lanka, where groundwater plays an important role in water supply for rural communities, studies have also found a link between groundwater quality and the prevalence of CKDu (chronic kidney disease of unknown etiology). The deterioration of groundwater quality due to population growth and excessive use of pesticides and agrochemicals poses a threat to public health. It has been suggested that factors such as recharge sources, flow patterns, geological conditions, land use, lithology, and climatic conditions contribute to the occurrence of CKDu [13], [14], [15], [16], [17], [18], [19], [20].

Furthermore, research conducted in India's Srikakulam district revealed that groundwater contamination might be a contributing factor to the high prevalence of CKDu in Uddanam region. The study found elevated concentrations of silica during wet seasons and lead during dry seasons in groundwater samples. It is important to explore potential synergistic effects on kidney function resulting from exposure to lead, fluoride, silica, and water hardness in acidic water.

Examining historical reliance on groundwater consumption can provide valuable insights into CKD prevalence. A study in Sri Lanka considered households' reliance on groundwater for drinking or cooking purposes over a period of several years. By linking this information with self-reported clinical diagnoses of CKD or CKDu among household members, the study aimed to identify potential associations between chronic exposure to water-borne contaminants and CKD prevalence [21], [22], [23], [24].

The fluctuation of groundwater tables and changing water quality during dry seasons have been observed in Sri Lanka's North Central Province (NCP). This fluctuation may affect human health, as indicated by a higher incidence of kidney stone formation during the dry season. However, there is still a need for more research to determine the precise impact of these changes in water quality on CKD prevalence.

It is worth noting that while several studies have identified potential associations between groundwater quality and CKD prevalence, no single factor has been found to be the sole cause of CKD or CKDu. The complex nature of this disease suggests the involvement of multiple factors, including environmental, geochemical, and other unknown causes. Therefore, future research should focus on comprehensive and multidisciplinary studies to unravel the risk factors and causal mechanisms behind CKD.

Similar concerns about groundwater quality have been observed in other regions, such as Bahir Dar City in Ethiopia and the Wadi Fatimah region in Saudi Arabia.

In Bahir Dar City, poor waste management practices and inadequate sanitation have led to contamination of groundwater from artificial sources. Geographic information system (GIS) studies have identified parameters that exceed World Health Organization limits, emphasizing the need for improved groundwater quality [26], [27], [28], [29] [30].

Saudi Arabia's Wadi Fatimah region relies heavily on groundwater, making groundwater quality evaluation crucial for public health. Physiochemical indicators and geospatial mapping techniques are used to assess groundwater quality and determine its suitability for different purposes.

India also faces challenges related to declining groundwater quality due to anthropogenic activities and climate change. Understanding the link between groundwater availability, anthropogenic activities, and the climate system is essential for sustainable management [31], [32].

In conclusion, mapping the prevalence of CKD in relation to groundwater sources provides valuable insights into the spatial distribution of this disease. Studies conducted in Taiwan, Sri Lanka, and India have highlighted associations between groundwater quality and CKD prevalence rates. However, further research is needed to fully understand the complex interplay between environmental factors, groundwater quality, and the occurrence of CKD [4], [5], [7], [8], [10], [11], [12].

4.2. Highlighting the importance of considering geographic factors

The geographical distribution of groundwater plays a crucial role in understanding the prevalence and spatial distribution of chronic kidney disease (CKD). Several studies conducted in Sri Lanka have focused on the relationship between groundwater quality and the occurrence of CKD, particularly CKDu.

In Sri Lanka, CKDu has become a significant public health concern, with a high incidence rate in certain regions. Studies have shown that the quality of drinking groundwater is a determining factor in the occurrence of CKDu. Areas with high groundwater salinity have been found to have a comparatively higher proportion of CKD cases than areas with lower salinity levels. This suggests that groundwater salinity may be an indirect factor contributing to CKD development.

Furthermore, research has identified various environmental factors that affect groundwater quality and subsequently influence the occurrence of CKDu. Land use and lithology have been found to have positive correlations with nitrate concentration, water hardness, and arsenic concentration in groundwater. These findings highlight the importance of considering geographic factors when investigating the spatial distribution of CKD.

A study conducted in the Uva Province of Sri Lanka utilized binary logistic regression modeling to identify geochemical risk factors associated with CKDu. The study found that fluoride (F) and phosphate (PO4) levels in groundwater were significantly associated with the progression of CKDu. Geochemical processes such as dissolution of bedrocks were identified as potential mechanisms leading to elevated F levels, while intensive application of agrochemicals contributed to increased PO4 concentrations.

To gain further insights into the relationship between groundwater quality and CKDu, multidisciplinary studies are needed. These studies should consider factors such as hydrochemical compounds, dietary salt intake, and climate patterns that may potentially interfere with research outcomes.

It is worth noting that while these studies provide valuable insights into the spatial distribution of CKD, they also have some limitations. For instance, measuring actual concentrations of groundwater salinity can be challenging due to financial constraints. Additionally, other confounding factors, such as dietary salt intake and hydrochemical compounds, may influence research outcomes.

Despite these limitations, the studies discussed lay the foundation for future epidemiological investigations into CKD. By understanding the geochemical risk factors associated with CKDu, policymakers and government authorities can develop effective strategies for groundwater management and public health interventions. Providing safe drinking water to communities in CKDu-prevalent areas is crucial for achieving sustainable development goals.

In conclusion, the geographical distribution of groundwater plays a significant role in understanding the prevalence and spatial distribution of CKD. Studies conducted in Sri Lanka have highlighted the importance of considering geographic factors when investigating the relationship between groundwater quality and CKDu. By identifying geochemical risk factors associated with CKDu, policymakers can prioritize interventions aimed at ensuring access to safe drinking water in affected areas. Multidisciplinary research efforts are needed to further explore the complex relationships between groundwater quality and CKD occurrence [33], [34], [35], [36], [37], [38], [39], [40], [41].

4. Conclusion

Summary of key findings from the review

In conclusion, the investigation of groundwater quality and its geographical distribution in various regions has provided valuable insights into the link between groundwater sources and chronic kidney diseases (CKDs). The studies conducted in Saudi Arabia, Sri Lanka, and Bangladesh have shed light on the factors contributing to the prevalence and progression of CKDs.

The study in Western Saudi Arabia highlighted the significant role of rainfall chemistry in providing various components of general water chemistry. It identified chemical weathering reactions as a long-term neutralizing process that affects the composition of groundwater. Groundwater was found to be a crucial source of freshwater for irrigation and other human uses. However, the contamination of groundwater due to human activities has worsened over time, leading to detrimental socioeconomic and health effects. The use of Geographic Information Systems (GIS) proved effective in visualizing the spatial distribution of water quality parameters, providing valuable information for policymakers.

In Sri Lanka's Uva Province, studies focused on identifying geochemical risk factors associated with Chronic Kidney Disease of Uncertain Origin (CKDu). High levels of contaminants in drinking water were considered a potential causative factor for CKDu.

Through binary logistic regression modeling, it was found that fluoride (F) and phosphate (PO4 3-) levels in groundwater were significantly associated with the progression of CKDu. Geochemical processes such as bedrock dissolution and intensive application of agrochemicals were identified as contributors to elevated F and PO4 3- concentrations. These findings can guide groundwater management strategies to mitigate CKDu prevalence and contribute to providing safe drinking water.

In southern Bangladesh, a study investigated the association between groundwater salinity and CKD. Although direct causation was not established, an indirect association was observed between hypertension and groundwater salinity. Further large-scale studies are needed to clarify this relationship more clearly.

A comprehensive review conducted in Sri Lanka explored multiple potential contaminants present in groundwaters that may contribute to CKD. While several substances showed positive or negative attributes towards triggering the disease, no definitive conclusions could be drawn regarding their direct involvement. The lack of consistency between clinical evidence and groundwater quality studies highlighted the need for localized and continuous monitoring of water pollutants and disease prevalence.

The study focused on the North Central Province (NCP) of Sri Lanka, where groundwater is the main source of drinking water for the rural population. A total of 334 groundwater samples were collected from two aquifers in the NCP during the wet season.

The analysis of these samples revealed that there were two main hydrochemical types of groundwater in the NCP: Ca-HCO3 and NaCa-HCO3. The dominant ions in both types were HCO3, Na+, and Ca2+, which originated from silicate and evaporite salt dissolution. The presence of NO3 was found to be primarily anthropogenic.

The geographical distribution of CKD-U in the North Central Region of Sri Lanka was studied using GIS and GPS technologies. High prevalence areas were identified, with communities consuming water from natural springs showing a lower prevalence of the disease. GPS mapping revealed that affected villages were often located below reservoirs and canals with stagnant irrigated water. This suggests a possible link between draining irrigated water into shallow wells used for drinking water and the prevalence of CKD-U.

In conclusion, these studies emphasize the importance of understanding groundwater quality and its geographical distribution in relation to chronic kidney diseases. They provide insights into potential risk factors, such as contamination from human activities, geochemical processes, and exposure to specific elements in drinking water. The findings can guide policymakers and water system operators in implementing effective groundwater management strategies to mitigate diseases like CKD. Further research is needed to validate these findings, enhance data collection methods, and establish definitive causative relationships between groundwater quality and chronic kidney diseases. See references: [10], [37], [38], [39], [40], [41].

Table 1. CKD and historical household reliance on groundwater (source: reference [10]).

Household's primary source of water for drinking or cooking was groundwater for at least 5 years between 1999 and 2018	**At least one adult residing in the household between 2009 and 2018 has had CKD**		**Total (%)**
	Yes (%)	**No (%)**	
Yes	15.22	83.11	98.33
Yes	(0.74)	(0.75)	(0.18)
No	0.16	1.51	1.67
No	(0.08)	(0.16)	(0.18)
Total	15.38	84.62	100
Total	(0.74)	(0.74)	

Number of households	1071	6978	8049

5.2. Implications for future research on groundwater sources and CKD

The geographical distribution of groundwater and its relationship to Chronic Kidney Disease of Unknown Etiology (CKDu) has significant implications for future research. Several studies have highlighted the effects of environmental factors on groundwater quality in Sri Lanka, particularly at a national scale. Land use and lithology have been identified as key factors influencing groundwater geochemistry, with positive correlations observed between cropland and nitrate concentration, as well as between unconsolidated sediments and arsenic concentration.

However, there is still a need for further research to unravel the controlling factors of groundwater quality and identify the risk factors associated with CKDu in Sri Lanka. This includes conducting high spatial-temporal resolution sampling to better understand the variations in groundwater quality over time and space. Multidisciplinary studies are also necessary to gain a comprehensive understanding of the complex relationships between groundwater quality and the occurrence of CKDu.

Monitoring and assessing groundwater quality on a regular basis is crucial, particularly in areas heavily reliant on groundwater as their primary source of drinking water, such as the North Central Province (NCP) in Sri Lanka. This can help identify potential contaminants and develop management plans to protect groundwater from contamination.

It is important to note that the chemical composition of groundwater is influenced by various factors, including aquifer rock type, residence time, flow path, and recharge source. These factors should be considered in future research efforts to understand the role of groundwater in CKDu development.

Furthermore, past research has highlighted inconsistencies between clinical evidence on CKDu and findings from groundwater quality studies. To address this issue, future studies should involve localized data on water pollutants and disease prevalence over time to better understand the trends between disease propagation and variations in groundwater quality.

To enhance the reliability and accuracy of results, future research should involve larger sample sizes, repetition of experimental trials under similar conditions, validation of results through multiple approaches (such as case-control studies), and collaboration among multidisciplinary experts.

Lastly, it is essential to determine the beneficial effects of providing safe drinking water in mitigating the progression of CKDu. This can be achieved through well-designed scientific approaches that take into account the gaps in previous research and utilize available resources effectively.

In conclusion, future research on groundwater sources and CKDu should focus on understanding the controlling factors of groundwater quality, identifying risk factors associated with CKDu, and verifying the beneficial effects of safe drinking water. Collaboration among experts from various disciplines is crucial to address the complexities of this issue and develop effective strategies for disease prevention and management [4], [7], [10], [36], [37], [38].

REFERENCES

[1] S. Indika, Y. Wei, T. Cooray, T. Ritigala, K. B. S. N. Jinadasa, S. K. Weragoda, and R. Weerasooriya, "Groundwater-based drinking water supply in Sri Lanka: Status and perspectives," *Water*, vol. 14, no. 9, p. 1428, 2022.

[2] S. Imbulana and K. Oguma, "Groundwater as a potential cause of Chronic Kidney Disease of unknown etiology (CKDu) in Sri Lanka: a review," *Journal of Water and Health*, vol. 19, no. 3, pp. 393–410, 2021.

[3] R. R. Weil, R. A. Weismiller, and R. S. Turner, "Nitrate contamination of groundwater under irrigated coastal plain soils," *Am. Soc. Agron., Crop Sci. Soc. Am., Soil Sci. Soc. Am.*, vol. 19, no. 3, pp. 441–448, 1990.

[4] A. E. Marín Celestino, D. A. Martínez Cruz, E. M. Otazo Sánchez, F. Gavi Reyes, and D. Vásquez Soto, "Groundwater quality assessment: An improved approach to K-means clustering, principal component analysis and spatial analysis: A case study," *Water*, vol. 10, no. 4, p. 437, 2018.

[5] M. J. Nematollahi, P. Ebrahimi, and M. Ebrahimi, "Evaluating hydrogeochemical processes regulating groundwater quality in an unconfined aquifer," *Environ. Process.*, vol. 3, pp. 1021–1043, 2016.

[6] C. B. Dissanayake, "Water quality in the dry zone of Sri Lanka—some interesting health aspects," 2005.

[7] J. Lunyera, D. Mohottige, M. Von Isenburg, M. Jeuland, U. D. Patel, and J. W. Stanifer, "CKD of uncertain etiology: a systematic review," *Clin. J. Am. Soc. Nephrol.*, vol. 11, no. 3, pp. 379–389, 2016.

[8] W. V. D. Priyadarshani, A. F. D. de Namor, and S. R. P. Silva, "Rising of a global silent killer: critical analysis of chronic kidney disease of uncertain aetiology (CKDu) worldwide and mitigation steps," *Environ. Geochem. Health*, vol. 45, no. 6, pp. 2647–2662, 2023.

[9] S. Wickramarathna, S. Balasooriya, S. Diyabalanage, and R. Chandrajith, "Tracing environmental aetiological factors of chronic kidney diseases in the dry zone of Sri Lanka—A hydrogeochemical and isotope approach," *J. Trace Elem. Med. Biol.*, vol. 44, pp. 298–306, 2017.

[10] S. Imbulana, K. Oguma, and S. Takizawa, "Seasonal variations in groundwater quality and hydrogeochemistry in the endemic areas of Chronic Kidney Disease of Unknown Etiology (CKDu) in Sri Lanka," *Water*, vol. 13, no. 23, p. 3356, 2021.

[11] P. K. Jha and P. Tripathi, "Arsenic and fluoride contamination in groundwater: a review of global scenarios with special reference to India," *Groundwater for Sustainable Development*, vol. 13, p. 100576, 2021.

[12] G. S. Bhunia, P. K. Shit, P. P. Adhikary, and D. Sengupta, "Groundwater research and societal development: integration with remote sensing and geographical information system," in *Groundwater and Society: Applications of Geospatial Technology*, 2021, pp. 29–52.

[13] M. A. Hashim, S. Mukhopadhyay, J. N. Sahu, and B. Sengupta, "Remediation technologies for heavy metal contaminated groundwater," *J. Environ. Manag.*, vol. 92, no. 10, pp. 2355–2388, 2011.

[14] V. Elumalai, K. Brindha, and E. Lakshmanan, "Human exposure risk assessment due to heavy metals in groundwater by pollution index and multivariate statistical methods: a case study from South Africa," *Water*, vol. 9, no. 4, p. 234, 2017.

[15] X. Zeng, W. He, H. Guo, C. He, Q. Shi, Q. Shi, and M. Vithanage, "Molecular linkage of dissolved organic matter in groundwater with prevalence of chronic kidney disease with unknown etiology," *Exposure Health*, vol. 15, no. 3, pp. 489–503, 2023.

[16] K. Y. Chang, I. W. Wu, B. R. Huang, J. G. Juang, J. C. Wu, S. W. Chang, and C. C. Chang, "Associations between water quality measures and chronic kidney disease prevalence in Taiwan," *Int. J. Environ. Res. Public Health*, vol. 15, no. 12, p. 2726, 2018.

[17] M. Vithanage, T. Mikunthan, S. Pathmarajah, S. Arasalingam, and H. Manthrithilake, "Assessment of nitrate-N contamination in the Chunnakam aquifer system, Jaffna Peninsula, Sri Lanka," *SpringerPlus*, vol. 3, p. 1–8, 2014.

[18] R. Chandrajith, S. Diyabalanage, and C. B. Dissanayake, "Geogenic fluoride and arsenic in groundwater of Sri Lanka and its implications to community health," *Groundwater for Sustainable Development*, vol. 10, p. 100359, 2020.

[19] K. E. Levine, J. H. Redmon, M. F. Elledge, K. P. Wanigasuriya, K. Smith, B. Munoz, et al., "Quest to identify geochemical risk factors associated with chronic kidney disease of unknown etiology (CKDu) in an endemic region of Sri Lanka—a multimedia laboratory analysis of biological, food, and environmental samples," *Environ. Monit. Assess.*, vol. 188, pp. 1–16, 2016.

[20] S. Xu, S. L. Li, F. Yue, C. Udeshani, and R. Chandrajith, "Natural and anthropogenic controls of groundwater quality in Sri Lanka: Implications for chronic kidney disease of unknown etiology (CKDU)," *Water*, vol. 13, no. 19, p. 2724, 2021.

[21] D. T. Jayawardana, H. M. T. G. A. Pitawala, and H. Ishiga, "Groundwater quality in different climatic zones of Sri Lanka: focus on the occurrence of fluoride," *Int. J. Environ. Sci. Dev.*, vol. 1, no. 3, pp. 244–250, 2010.

[22] S. A. Wimalawansa and S. J. Wimalawansa, "Environmentally induced, occupational diseases with emphasis on chronic kidney disease of multifactorial origin affecting tropical countries," *Ann. Occup. Environ. Med.*, vol. 28, p. 1–13, 2016.

[23] K. Lal, M. Sehgal, V. Gupta, A. Sharma, O. John, B. Gummidi, et al., "Assessment of groundwater quality of CKDu affected Uddanam region in Srikakulam district and across Andhra Pradesh, India," *Groundwater for Sustainable Development*, vol. 11, p. 100432, 2020.

[24] N. O. Kitterød, J. Kværner, P. Aagaard, J. Arustienė, J. Bikše, A. Dagestad, et al., "Hydrogeology and groundwater quality in the Nordic and Baltic countries," *Hydrol. Res.*, vol. 53, no. 7, pp. 958–982, 2022.

[25] S. Indika, D. Hu, Y. Wei, I. Yapabandara, T. Cooray, M. Makehelwala, et al., "Spatiotemporal variation of groundwater quality in North Central Province, Sri Lanka," *ACS ES&T Water*, vol. 3, no. 6, pp. 1687–1698, 2023.

[26] F. Alshehri and K. Abdelrahman, "Groundwater potentiality of Wadi Fatimah, Western Saudi Arabia: Geophysical and remote sensing integrated approach," *Water*, vol. 15, no. 10, p. 1828, 2023.

[27] M. Asmamaw and E. Debie, "Characterizing groundwater quality for a safe supply of water using WQI and GIS in Bahir Dar city, northwest Ethiopia," *Water Pract. Technol.*, vol. 18, no. 4, pp. 859–883, 2023.

[28] A. I. A. S. S. Andrade and T. Y. Stigter, "Multi-method assessment of nitrate and pesticide contamination in shallow alluvial groundwater as a function of hydrogeological setting and land use," *Agric. Water Manag.*, vol. 96, no. 12, pp. 1751–1765, 2009.

[29] I. D. U. H. Piyathilake, W. A. C. Udeshani, H. A. C. S. Hapuarachchi, L. V. Ranaweera, E. P. N. Udayakumara, S. K. Gunatilake, and C. B. Dissanayake, "Geochemistry of groundwater in the Uva province, Sri Lanka—implications for chronic kidney disease of uncertain origin," *Front. Water*, vol. 3, p. 771501, 2021.

[30] R. Mondal, P. C. Banik, M. Faruque, S. R. Mashreky, and L. Ali, "Association of exposure to salinity in groundwater with chronic kidney disease among diabetic population in Bangladesh," *PLoS One*, vol. 18, no. 4, p. e0284126, 2023.

[31] M. Makehelwala, Y. Wei, S. K. Weragoda, R. Weerasooriya, and L. Zheng, "Characterization of dissolved organic carbon in shallow groundwater of chronic kidney disease affected regions in Sri Lanka," *Sci. Total Environ.*, vol. 660, pp. 865–875, 2019.

[32] J. M. Jayasekara, D. M. Dissanayake, S. B. Adhikari, and P. Bandara, "Geographical distribution of chronic kidney disease of unknown origin in North Central Region of Sri Lanka," *Ceylon Med. J.*, vol. 58, no. 1, pp. 6–10, 2013.

[33] K. Kafle, S. Balasubramanya, and T. Horbulyk, "Prevalence of chronic kidney disease in Sri Lanka: a profile of affected districts reliant on groundwater," *Sci. Total Environ.*, vol. 694, p. 133767, 2019.

[34] D. L. Jayasekera, J. J. Kaluarachchi, and K. G. Villholth, "Groundwater stress and vulnerability in rural coastal aquifers under competing demands: a case study from Sri Lanka," *Environ. Monit. Assess.*, vol. 176, pp. 13–30, 2011.

[35] R. Rubasinghe, S. K. Gunatilake, and R. Chandrajith, "Geochemical characteristics of groundwater in different climatic zones of Sri Lanka," *Environ. Earth Sci.*, vol. 74, pp. 3067–3076, 2015.

[36] S. Premarathne, R. Chandrajith, N. Nanayakkara, C. D. Gamage, N. Ratnatunga, S. Wijetunge, et al., "Could consumption of trace element–contaminated rice Be a risk factor for acute interstitial nephritis with uncertain etiology in the dry zone of Sri Lanka?," *Biol. Trace Element Res.*, pp. 1–9, 2022.

[37] C. B. Dissanayake, "The fluoride problem in the ground water of Sri Lanka—environmental management and health," *Int. J. Environ. Stud.*, vol. 38, no. 2–3, pp. 137–155, 1991.

[38] T. Cooray, Y. Wei, H. Zhong, L. Zheng, S. K. Weragoda, and R. Weerasooriya, "Assessment of groundwater quality in CKDu affected areas of Sri Lanka: implications for drinking water treatment," *Int. J. Environ. Res. Public Health*, vol. 16, no. 10, p. 1698, 2019.

[39] R. Chandrajith, S. Nanayakkara, K. Itai, T. N. C. Aturaliya, C. B. Dissanayake, T. Abeysekera, et al., "Chronic kidney diseases of uncertain etiology (CKDue) in Sri Lanka: geographic distribution and environmental implications," *Environ. Geochem. Health*, vol. 33, pp. 267–278, 2011.

[40] S. J. Wimalawansa, "Escalating chronic kidney diseases of multi-factorial origin in Sri Lanka: causes, solutions, and recommendations," *Environ. Health Prev. Med.*, vol. 19, no. 6, pp. 375–394, 2014.

[41] S. A. Wimalawansa and S. J. Wimalawansa, "Impact of changing agricultural practices on human health: Chronic kidney disease of multi-factorial origin in Sri Lanka," *Wudpecker J. Agric. Res.*, vol. 3, no. 5, pp. 110–124, 2014.