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RESEARCH ARTICLE

Groundwater mapping and locally engaged water governance in a small island terrain: Case study of Karainagar island, Northern Sri Lanka

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Abstract

Groundwater is a vital resource under threat in island communities. Karainagar, a 22 km^2 island, is one of seven islands off the coast of Jaffna in Northern Sri Lanka, with its population of just about 11,000 persons, experiences seasonal water shortage, and salinity in groundwater as twin threats impacting on their lives. This paper reports on a 3-year study (October 2019 to September 2022) to map groundwater dynamics of Karainagar island spatially and seasonally and discusses the patterns revealed in terms of community needs, policy implications, and governance ideas that could already be considered by relevant authorities and citizens jointly. Thirty-six dug wells used for drinking, domestic, agricultural, and public purposes were selected, and water level, salinity, and pH changes recorded along with daily rainfall. This paper offers a thorough description of the geography, land use, distribution of wells, and water bodies, followed by discussion of the current status of the groundwater in Karainagar island. Year-to-year differences in rainfall pattern resulted in different rates of change and range in water level with a corresponding reverse pattern seen in salinity with some exceptions across the island. Cumulative rainfall required to reach full capacity of wells ranged from 652 to 892 mm over the 3 years with an average figure of 739 mm of rain. This implies that any further rainfall during early phase of the main rainy season is potential surface water for storage and runoff. Practices such as unregulated pumping and construction of tube wells are argued to be contributing to increase in salinity levels with health implications for residents. A participatory governance approach that overcomes limitations of the existing institutional approach is proposed. Its success based on broad stakeholder engagement, improved equity, and transparency when supported by adequate policies and village level aquifer monitoring will enable sustainability of groundwater resources in Karainagar.

KEYWORDS

electrical conductivity, governance, groundwater, Karainagar Island, salinity, water security

1 | INTRODUCTION

As a consequence of population rise, economic growth, and technological advance worldwide, wide water use has risen by a factor of 6 over the past century, whereby the seasonal water availability is likely to change throughout the year due to climate phenomena (UN-Water, 2020). Groundwater resources are shrinking throughout the world due to overexploitation through the unsustainable level of abstraction of groundwater at levels exceeding recharge from precipitation (Asoka et al., 2017; de Graaf et al., 2019; Shah et al., 2001; Sikka et al., 2021). In general, water withdrawal from a surface source, from a ground source (aquifer) or from a tidal source, either permanently or temporarily, is used for municipal (direct use by the population), agricultural (irrigation, livestock, and aquaculture), or industrial purposes (FAO, 2023). In some countries, in order to protect both the water sources and the environment, water withdrawals from ground, surface, and tidal sources are regulated through a system of licenses (DEFRA, 2019; Rameshwaran et al., 2022; Santato et al., 2016).

Groundwater is a vital resource for island communities, as it is often the primary source of drinking water, irrigation, and industrial water supply. However, the unique geological and hydrological characteristics of island landscapes can make managing groundwater resources a complex task (Vlahović & Munda, 2012). The small and very small islands around the world like the small sand cays of the Caribbean Sea and the coral atolls of the Pacific and Indian Oceans are characterized by surface water that does not exist in an exploitable form, and fresh groundwater resources are limited. In addition, over-extraction and pollution of groundwater resources can lead to water scarcity and degradation of water quality, which can have severe consequences for island communities. On these islands, conventional options for freshwater supplies are limited to groundwater development and rainwater (UNESCO, 1991).

The Northern Province (NP) of Sri Lanka, including the Jaffna Peninsula and the adjoining islands, have no perennial rivers, and the geological and climatic conditions in many parts there are not favorable for surface water storage. Therefore, freshwater demand is often a critical matter in the Jaffna peninsula (Thushyanthy & de Silva, 2012) and its adjoining islands. Inhabitants of the peninsula and the islands are entirely dependent on groundwater sources for all their water needs. Due to the extensive movement of people during the war years and the rapid urbanization process now underway, traditional knowledge about water security and groundwater conservation is being eroded. Technological developments and social changes contribute to groundwater contamination from extraneous sources.

Ancient forms of water conservation, particularly through the construction of a wide variety of surface water bodies to capture rainwater, have been in existence in the islands, ranging in size, capacity and level of sophistication, and serving multiple needs of the community, including the recharging of ground water. These had been maintained through the ages in functional ways, almost entirely through collective community action until the 1970s. Such tanks and ponds in agricultural areas as well as the sacred temple ponds all over Jaffna and the islands, including in Karainagar, are now in a state of degradation through decades of neglect or have been filled for development purposes. Mikunthan et al. (2013) have commented on the same phenomenon of how a very large number of such ponds of varying sizes present in the mainland of Jaffna Peninsula in the past, serving the function of holding a high proportion of rainwater for recharge of groundwater resources, have dwindled in number to about 2000 in the recent decades, including those that belong to temples.

Small islands usually have thin lenses of freshwater in aquifers that are highly vulnerable to the pressure of external factors such as tidal effects, frequent storms, and increasing anthropogenic pressures including excessive pumping of groundwater (Singh & Gupta, 1999; Wu et al., 2022). Hence, small islands that have specific hydrological and water resources management practices, and their assessment and development, need to be studied separately from those of the larger islands (UNESCO, 1991). A "freshwater lens" is a layer of fresh groundwater effectively floating above the denser saline groundwater normally found in coastal or island settings (Bedekar et al., 2019; Underwood et al., 1992; Werner et al., 2013, 2017). Freshwater lenses in Karainagar display highly dynamic and spatial variability with temporal or seasonal fluctuations in volume. Due to the combined effects of a complex geology, seasonal and climatic variability, high impact weather events, and anthropogenic influences, fresh groundwater lenses within Karainagar are highly heterogeneous and remain a critical area for further research to address the water security concerns of island residents.

Aquifer monitoring with community engagement is a key element to ensure sustainable use of the groundwater resources in an island terrain (Masood et al., 2022). Aquifer monitoring implies the process of measuring, monitoring, and analyzing the physical, chemical, and biological characteristics of an aquifer. It plays an essential role in understanding the dynamics of the aquifer and detecting potential problems, such as contamination, saltwater intrusion, or over-extraction. Regular monitoring can also help to ensure the sustainability of groundwater resources, which is crucial in island landscapes.

Furthermore, climate change impacts are likely to exacerbate existing environmental stresses (Abobatta, 2023). Sea level rise combined with heavy precipitation and storm surge will intensify compound flood risks in future in the low-lying areas (IPCC, 2022; Sebastian, 2022). The risk posed by sea level rise and intrusion of saline water into coastal groundwater aquifers are considerable for low-lying deltas and islands (Lall et al., 2020; Lassiter, 2021; UN, 2022; Werner et al., 2013). Sea water intrusion depends on several factors including aquifer type, amount of freshwater recharge and withdrawal, and geologic structure (Chang et al., 2011; Luo et al., 2021). These issues can have severe consequences for social and economic development, as well as the ecological health of island communities. Thus, hydrogeology and hydrology of the islands need to be studied in order to develop a rational program of water management, but with the intent of going beyond the more descriptive studies attempted in other islands in the past while approaching the issues here from a governance perspective that incorporates the technical, social, economic, policy, and political dimensions for such management plans for Karainagar to be sustainable (Maheshwari et al., 2014).

The study took inspiration from the Australian funded MARVI project (Managing Aquifer Recharge and Sustaining Groundwater Use through Village-level Intervention) in operation at the time in Rajasthan and Gujarat States of India (www.marvi.org.in; Maheshwari, 2020; Maheshwari et al., 2014). Incorporation of this work as a graduate study into the larger, province-wide "Water Security through Participatory Action Research" project (WASPAR) took place in 2020.

This paper maps the spatiotemporal distribution of groundwater in Karainagar island and goes on to discuss what the maps revealed in terms of the present status of groundwater and its seasonal dynamics along with human usage. The implications of salinization to human health are discussed next, and we close by taking up the pathways for participatory governance available to the island community and the early steps taken towards this within our study. The paper is arranged in five sections: This introduction (Section 1) is followed by a thorough description of Karainagar island and its geography and land use and the key elements of the research methodology (Section 2). The results of groundwater monitoring and mapping over the three water years are given in Section 3. Section 4 is arranged in four parts as outlined earlier, and Section 5 offers some concluding remarks. A number of angles for further investigation in the hydrogeology portion of this study and several aspects of policy relevance for achieving locally engaged water governance have been identified throughout the discussion.

A part of this work covering water year 2020–2021 only has been presented at the National Conference of the National Water Supply and Drainage Board (NWSDB) of Sri Lanka held on December 14–16, 2022 (Karthiga et al., 2022).

2 | BACKGROUND TO THE STUDY

2.1 | Geography of Karainagar Island

The study area, Karainagar, also known as Karaitivu (*tivu* = island), is one of the seven islets located off Jaffna in Northern Sri Lanka, with three sides of this rectangular island bounded by the Palk Strait and the fourth facing the Jaffna lagoon with a causeway linking it to the mainland (Figure 1).

Karainagar island covers an area of about 22 km^2 including inland water bodies and measures about 6 km North–South and about 4 km East–West. It is generally flat (Figure 2a) with much of the land below 4 m measured from mean sea level (MSL). A total population of 10,678 persons in 3,618 families live in the island under nine administrative divisions at present

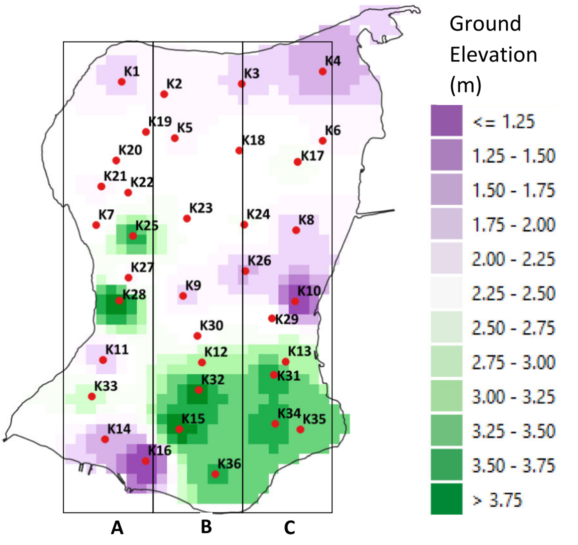
FIGURE 1 Karainagar Island and its location in Northern Sri Lanka (after Google Earth and OpenStreetMap).

(Statistical-Handbook, 2022), which is approximately half of the peak population seen in the island in the late 1980s. A small proportion of the families live in Jaffna and outside of the peninsula in NP while managing property and farming in the island with a strong sense of belonging to the community. A notable size of the original population immigrated overseas. Agriculture and fisheries are the major income source of the residents, supplemented by trade in other parts of Sri Lanka and to an extent also by foreign remittances.

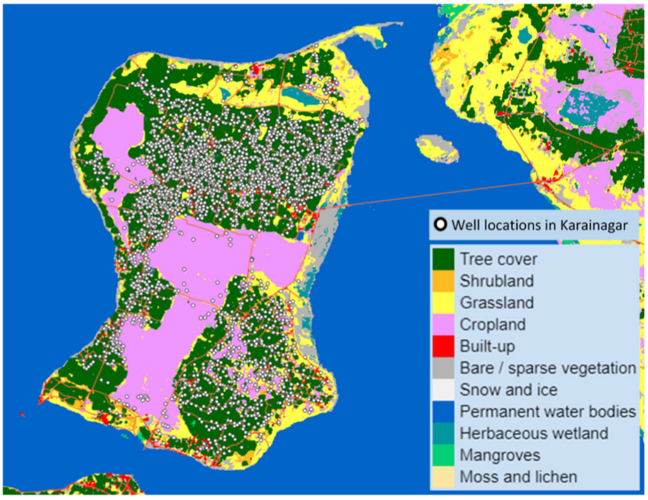
2.2 | Geology, land use, and well distribution

The soil and water resources of Karainagar are both related to the limestone geology of the land. Lagoonal and estuarine deposits and unconsolidated brown and gray coastal sand are the common soil type in this island (Statistical-Handbook, 2022). Much of the farmland on the island is used in the main growing (*Maha*) season for rainfed paddy cultivation and to a limited extent for other field crops. Unlike the rest of the NP, vegetable and subsidiary crop cultivation is generally not undertaken in the dry *Yala* months due to the low availability and poor quality of water.

Figure 2b shows the distribution of the 2,697 wells scattered across the island (Saravanan et al., 2013), which translates to a well density of approximately 123 wells per km^2. However, this figure masks the much higher density of wells for domestic use in the tree covered residential area (over 200 wells per km^2) than that in the cropped area (20 wells per km^2), which in Karainagar is primarily rainfed rice farming and not irrigated agriculture. The comparable figure for well density in the mainland Jaffna peninsula with its significant irrigated cultivation practices is reported to be ranging from 15 to 200 wells per km^2 (Sood & Smakhtin, 2015). The tree cover of the island is composed of a range of native tropical trees, Palmyra palms, and thorny bushes. Households rely on domestic wells for washing needs, while drinking water comes from a few freshwater sources existing as public wells, supplemented by water moved in



(a)



(b)

FIGURE 2 (a) Spatial ground elevation from mean sea level (MSL) with 36 wells in three equal slices of Karainagar Island. Spatial ground elevation created by spatial interpolation using ground-level data at well locations and (b) Karainagar land cover (ESA WorldCover 2021; Zanaga et al., 2022) and distribution of 2,697 wells (Saravanan et al., 2013).

from mainland sources by bowsers/tankers. Water withdrawn from most wells and the small ponds show high Electrical Conductivity (EC) and are of low quality for drinking and domestic purposes. EC is commonly used as the measure of saltiness or salinity in water.

2.3 | Indigenous water bodies and saltwater exclusion schemes

In addition to the ~2,700 dug and tube wells, 23 ponds, numerous smaller ponds, and a few ponds designed to be for livestock drinking purpose are found in Karainagar

(Saravanan et al., 2013; Statistical-Handbook, 2022). In among these mapped wells are a number of wells known to the villagers as reliable sources of drinking water. Figure 3a–h shows examples of these indigenous waterbodies and more recent saltwater exclusion schemes from the island.

Close to 99% are dug wells or *kiṇaṟu* (Figure 3a), which can range about 2 to 8 m in depth, with well diameter ranging from 1 to 3 m (Saravanan et al., 2013). Although these wells are mainly constructed to exploit an aquifer to provide water all year round, there are some wells that dry up during the peak of dry season. Almost all the wells have been lined with or without a kerb protection. Maintenance of domestic wells is done by households, and agro-wells located in the middle of the crop lands are maintained by the government Agrarian Service Centre. In recent times, drilled tube wells or *kuḻāy kiṇaṟu* have become the preferred type of well construction (Figure 3b).

The ponds or *kuḷam* in Tamil (Figure 3c) become silted over time (Statistical-Handbook, 2022) due to lack of maintenance, while most of the livestock drinking ponds or *tuṟavu* (Figure 3d) have disappeared through years of silting. On the other hand, some small ponds or temple *kerṉi* in Tamil (Figure 3e) are maintained regularly by local groups. Wetland or *taravai* (Figure 3f) is the main large body of seasonal wetland ecosystem in Karainagar, which in the dry season serves as commons for grazing.

Saltwater exclusion schemes from recent times exist in seven coastal locations around the island. These are named as Saambalodai Bund, Vernon Bund, Kiluvanai vaaikaal flood outlet, Periya mathavady vaaikaal, Sakkalavodai vaaikaal Bund, Thillai Bund, and Paravaikkadal (Provincial-Statistical-Information, 2022). Two of these, Saambalodai Bund and Vernon Bund, are kept functional by the Irrigation Department. The intended purpose of these saltwater exclusion schemes is not only prevention of sea water intrusion but also the retention of rainwater in the middle of the island, which influence groundwater recharge (Figure 3g,h).

In addition to the above, there are tracts of open land that become seasonal wetlands capable of providing pastures for livestock when not inundated, also carrying dry zone bushes and other vegetation that contribute directly to the enrichment of the ecosystem.

2.4 | Water supply schemes

The National Water Supply and Drainage Board (NWSDB), Jaffna, has implemented a piped water supply scheme to provide water for domestic purposes except drinking to limited residents in Karainagar to supplement their domestic water needs. About 117 families get benefitted from this scheme with average amount 225 m^3 monthly supply (District-Statistical-Hand-Book, 2022), which is withdrawn from a dug well located in the island (Figure 4a). This scheme has helped to improve access to good water for household use. In some parts of Karainagar, the household's main source of water for domestic use including drinking is from supply bowsers/tankers (Figure 4b), where water is abstracted from a local dug well or from a well in the mainland. The average daily supply amount is about 150 m^3.

2.5 | Climate

Karainagar falls into the low country dry zone region of Sri Lanka. Rainfall in Karainagar area is distinctly seasonal and follows the same bimodal precipitation pattern noted for other regions

(a) Dug well or *kiṇaṟu*

(b) Tube well or *kuḻāy kiṇaṟu*

(c) Pond or *kuḷam*

(d) Open pond accessible to livestock or *tuṟavu*

(e) Small pond or *kerṉi*

(f) Wetland or *taravai*

(g) Saltwater exclusion bund or *aṇai*

(h) Flood outlet from farmland or *vāykkāl*

FIGURE 3 Example of indigenous water bodies (a to f) and saltwater exclusion schemes (g and h). Equivalent Tamil names are given in italics.

(a) Piped water supply scheme source

(b) Drinking water supply from bowser/tanker

FIGURE 4 Water supply schemes.

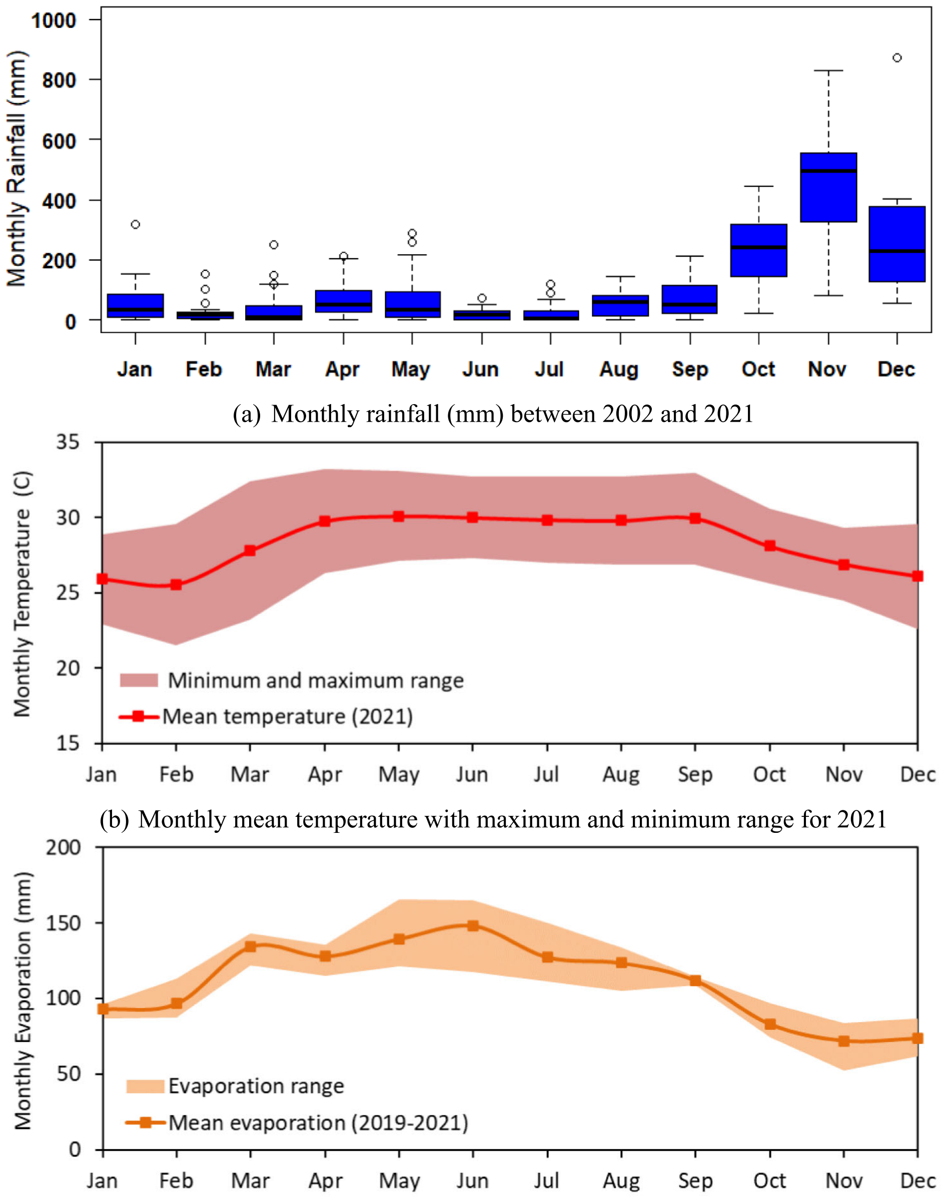
of Sri Lanka. Heavy rainfall is obtained during the Northeast (NE) monsoon season, nominally from August to December. A smaller amount of scattered rainfall is obtained in April to July through the Southeast (SE) monsoon. Annual average rainfall measured since 2012 at the Agrarian Service Centre, Karainagar, shows the lowest recording of 517 mm (in the calendar year 2016) and the highest recording of 1868 mm (in the calendar year 2021). These readings are on the whole lower than the annual average rainfall recorded in Jaffna in the mainland (Figure 5a). Piratheeparajah (2015) has studied the spatial and temporal variations of rainfall in the Northern Province from 1972 to 2014 and identified that number of rainy days decrease year by year while indicating that the intensity of rainfall events has increased. Manawadu and Fernando (2008) study found that although the number of rainy days has reduced, the total amount of annual rainfall has not declined.

The monthly mean temperature is lower during October to February period than during March to September period corresponding to the wet and dry seasons, and ranging from a low of 21.5°C to a high of 33.2°C in 2021 (Figure 5b). Annual average evaporation in Karainagar is expected to follow the same pattern as in the Jaffna Peninsula with 1,314 mm recorded for evaporation data in Jaffna in Meteorological Department for the years 2019–21(Figure 5c).

2.6 | Methodology

Thirty-six dug wells named K1 to K36 (Figure 2a) in use for drinking, domestic, agricultural, and public purposes were inventoried. This enabled the monitoring of water levels and respective physicochemical parameters: EC and pH on Karainagar island.

In the first pilot phase of this study that commenced in November 2019, there were only 20 wells included (Anojan et al., 2020), with 16 more wells added in April 2020 to make up 36 representative wells in all. The initial 20 wells were chosen with the help of local community leaders for the pilot phase. Later in April 2020, when it was decided to cover the entire island more systematically in the study, a grid with 36 cells was developed, which accommodated the initial 20 wells as well as the additional 16 wells chosen randomly to fall within the gaps. This resulted in eight wells that were either private wells currently not in use or those in public areas. All wells were assessed weekly during the main rainy season and monthly during the dry season.



(a) Monthly rainfall (mm) between 2002 and 2021

(b) Monthly mean temperature with maximum and minimum range for 2021

(c) Monthly Class A Pan evaporation (mm) between 2019 and 2021

FIGURE 5 Monthly rainfall (mm), mean temperature (°C), and Class A pan evaporation (mm) measured at regional Meteorological Station, Jaffna.

Owners of all private wells (17) in the initial group of 20 were provided with measuring equipment and notebooks and coached to measure the water level in their own wells. Sampling of all wells for water analysis was carried out by project staff who also maintained close contact with owners on a regular basis. A number of well owners (15) have participated in two different consultative workshops, which included the presentation of interim findings during this time.

Water levels and well dimensions (kerb height and bottom level) were measured using meter tape. Positioning wells and hydraulic heads with respect to MSL were then determined using Global Positioning System (GPS) and land surveys. EC and pH measurements were made using Multi parameter meter (Model: Hach HQ40D) at the Department of Chemistry, University of Jaffna. Daily rainfall was obtained from the record at the Agrarian Services Centre, Karainagar.

3 | RESULTS

The water year has been defined as a period of 12 months beginning in October and ending in September of the following year (e.g., October 1, 2021, to September 30, 2022, is water year 2021–2022). This coincides with the onset of the main or *Maha* season rains and, therefore, the main cropping season. All data on rainfall, water level, pH, and EC for the whole study period comprising three water years 2019–2022 have been included in this paper. Qualitative research findings around well owner engagement and community consultations are ongoing and will be reported in due course.

Figure 6a shows the daily rainfall (mm day^{-1}) variation across Karainagar for water years 2019–2022. Figure 6b,c portrays variation in water level above MSL (m) and EC (mS cm^{-1}) of sampled wells across the same period. The island has been sliced into three sections as shown in Figure 2a to enable the examination of a smaller number of wells in clusters in each section for their variability of water level and salinity rather than examine all 36 wells together.

The range of water level for each well for each of 3 years is presented in Figure 7a in their respective sections. Well bottom elevation and the ground elevation are marked for each well along the water level range. Figure 7b shows the range of EC for each well according to its sections. The EC level considered to mark acceptable drinking quality of water (2,500 μS cm^{-1} or 2.5 mS cm^{-1}) is indicated as a horizontal line. The maximum and minimum water levels of each well are shown in Figure 7c, where each level is made up of 3 points corresponding to the three water years. Figure 8 shows the cumulative rainfall for the island during each year.

A total of seven wells among the 36 study wells, recognized as reliable sources of drinking water today, are marked as circles in Figure 7b. Water level, EC, and pH fluctuations in four (K20, K30, K32, and K34) of these seven selected wells (i.e., with three water years of measured data) are presented in Figure 9a–c, where each line represents one water year.

The representative wells in Karainagar island will continue to be sampled for three more years to generate more data of the kind outlined above to fulfill the needs of the modeling part of this study. The spatiotemporal patterns revealed so far will be discussed in the section below, particularly in terms of policy needs and governance ideas that could already be considered by relevant authorities.

4 | DISCUSSION

4.1 | Current status of groundwater

Salinity in groundwater has been a permanent feature of the lived experience of communities in island landscapes and coastal areas of NP, which has had significant influence in many aspects of their livelihood including agriculture, employment, and demographics. The rising levels of salinization in recent times in the Jaffna islands have been recorded

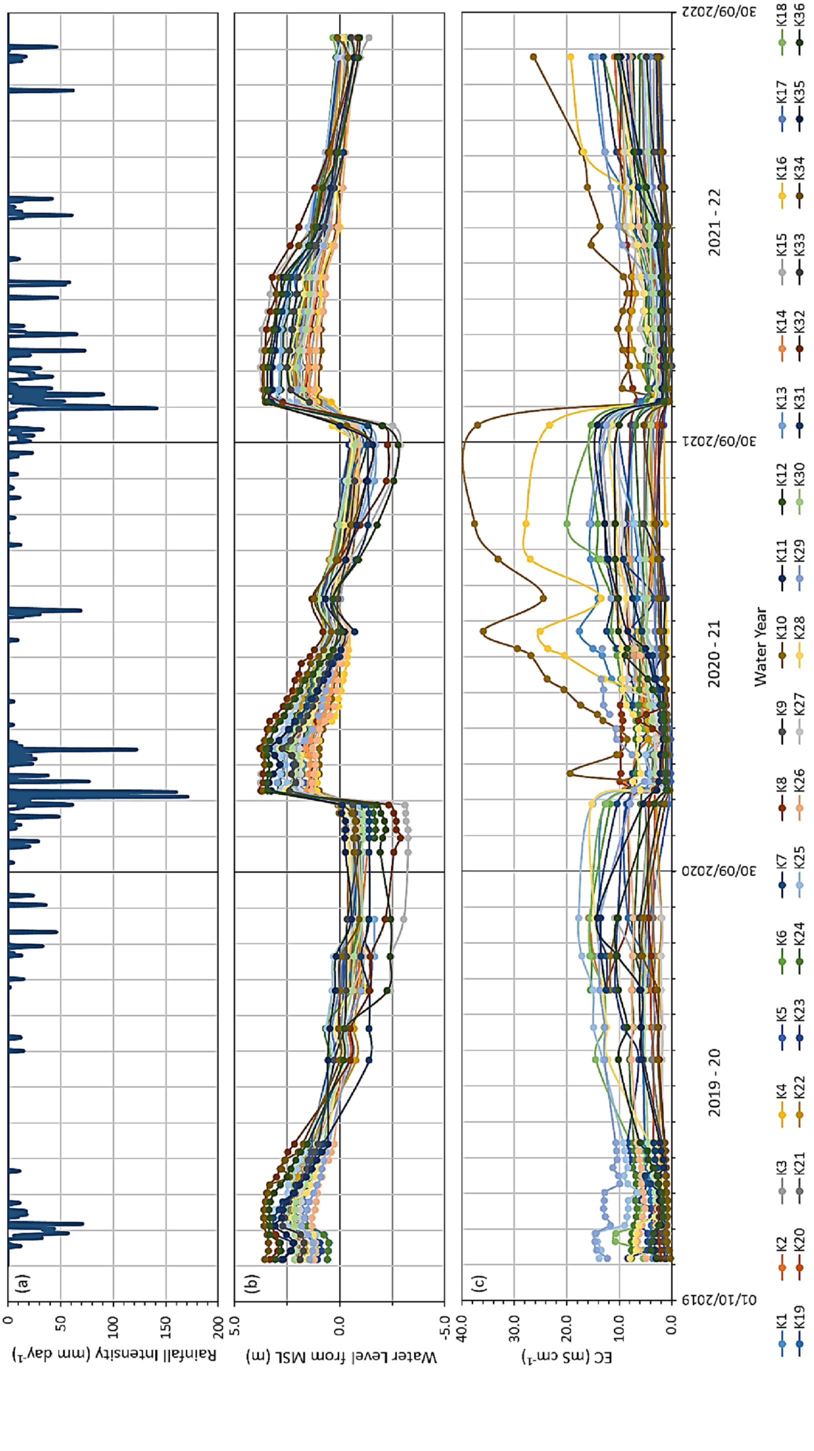


FIGURE 6 (a) Rainfall intensity (mm day^{-1}), (b) water level from MSL (m), and (c) EC (mS cm^{-1}) of 36 wells for water years 2019–2020, 2020–2021, and 2021–2022.

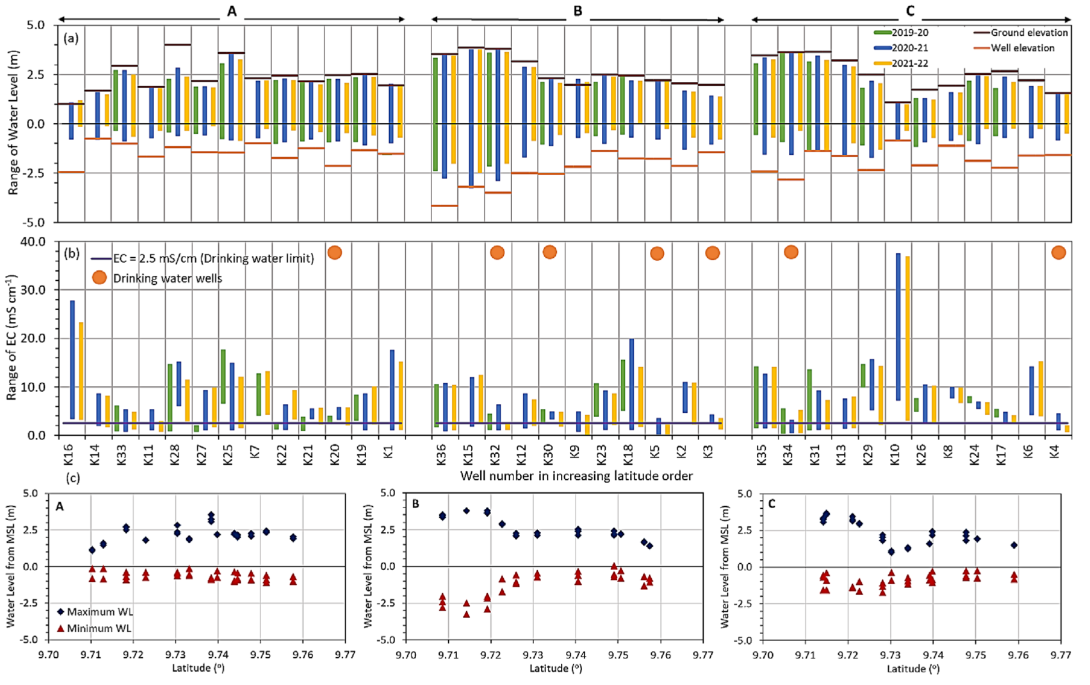


FIGURE 7 (a) Range of water level from MSL (m), ground elevation (m), and well bottom elevation (m); (b) range of EC (mS cm^{-1}) for 36 wells during water years 2019–2020, 2020–2021, and 2021–2022; and (c) maximum and minimum water levels for wells in Sections A–C wells.

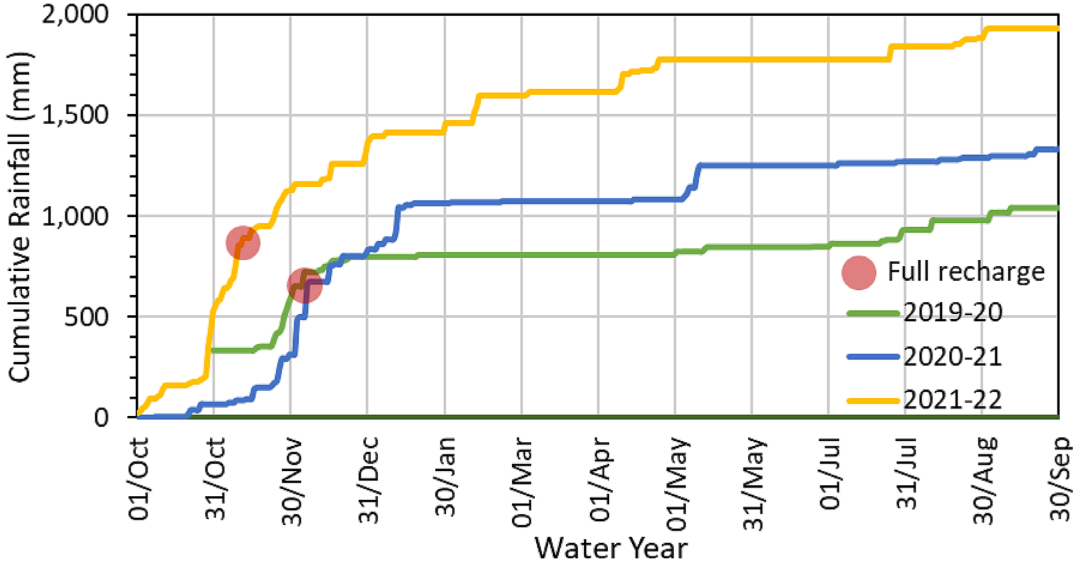


FIGURE 8 Cumulative rainfall (mm) for water years 2019–2020, 2020–2021, and 2021–2022.

(Pathmaja et al., 2019; Wu et al., 2022). This process and its impact in Karainagar have followed its own course due to the island's nearness to the mainland and the benefits of being connected to it via a causeway since early 1900s.

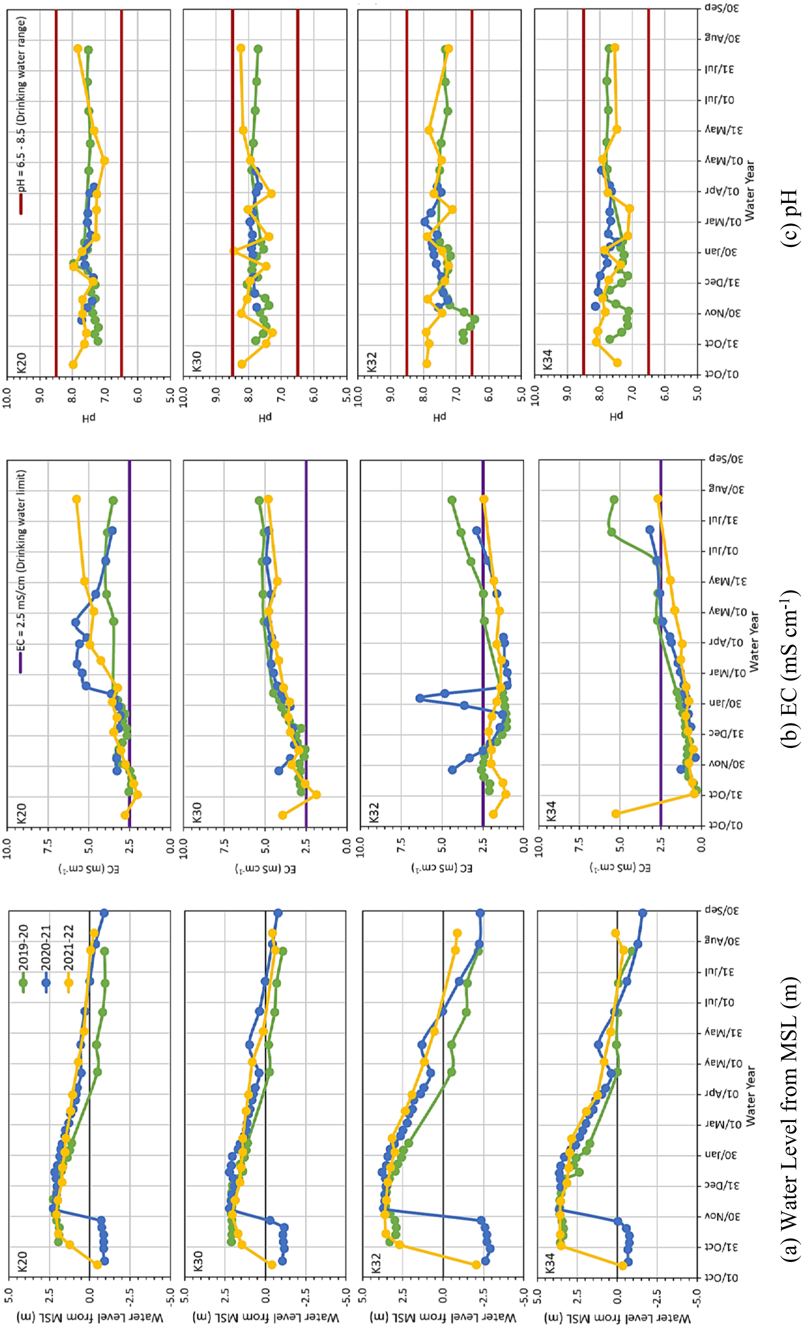


FIGURE 9 Four selected sources of drinking water wells K20, K30, K32, and K34 showing water level from MSL (m), EC (mS cm^{-1}), and pH for water years 2019–2020, 2020–2021, and 2021–2022.

The dramatic increase in the numbers of dug wells (Figure 2b) in inhabited areas of Karainagar island in the decades until 1990, an almost complete evacuation of the island in early 1990s due to war, and partial return of the population gradually over the past 20 years, combined with access to electrical pumps and tube well technology have all had influence on the new dimension to the salinity experience in the island.

The presence of a remarkable number of public wells as reliable sources of fresh water among a preponderance of wells with unacceptable quality of water is also a puzzling feature of this landscape. Anecdotal evidence of some such wells having declined in quality through over extraction exist in the community. Wells K3, K20, and K32 fall in that category among the seven wells with drinkable water quality acknowledged by us among the 36 wells selected (Figure 9b).

The pattern of daily rainfall as measured in Karainagar and its relationship to water level and salinity in the study wells are presented in Figure 6a–c. The daily rainfall data presented in Figure 6a clearly indicate the year-to-year variation in number of rainy days, intensity of rain events, and the length of rain period in different seasons.

Differences observed in rainfall pattern resulted in different rates of change in the water level in the three water years. In 2020–2021, a minor peak was noted in the water level not seen in the other 2 years. This corresponds with the SW monsoon (*Yala*) period, which is recorded as a minor peak also in the past 20-year rainfall pattern observed in the mainland (Figure 5a). If such *Yala* rainfall occurs as a regular phenomenon in April–May in all years, it would show the potential that exists for groundwater recharging and the retention of EC level in the lower range. An abnormal rise in EC noted in certain wells (i.e., K10 and K16) during 2020–2021 period (Figure 6c) raises the question of sea water intrusion because of their locations too close to the sea in lower lying ground. This aspect along with the choice of those wells needs further investigation.

When comparing the three water years, 2019–2020 appears to be drier than the other 2 years when some wells, that is, K13 and K31, dried out in few months after the NE monsoon rain, while 2021–2022 was wetter than other years, and water was available throughout the year in most wells. Due to the variation in rainfall, water level range in each well differed from year to year (Figure 7a). Most of the wells filled up to ground level, with some wells such as K9 and K16, located in the agricultural area, reached levels slightly higher than the ground surface.

The pattern expressed in Figure 7a shows that wells nearer to each other that one would expect to behave similarly were in fact showing differences in the water level changes, for example, K15 and K32. Similarly, wells with the same water level range were showing variation in their EC values, for example, K5 and K18 (Figure 7b). These observations are somewhat unexpected and raise interesting new questions. At the same time, many wells with low figures for EC and, therefore, expected to hold drinkable water are either not drinkable due to no well maintenance or the well having been abandoned for a long time (e.g., K11 and K17). Figure 7c shows the maximum and minimum water levels in each well for three water years. Some of these location-specific observations need to be addressed in the next phase of research.

4.2 | Rainfall recharge relations

Rate of groundwater recharge depends on factors such as rainfall intensity, infiltration capacity, past hydrological conditions, and climate factors. The cumulative rainfall curves over three water years (Figure 8) show considerable differences across the 3 years in intensity. These curves demonstrate the total amount of rainfall needed to reach full capacity of each well marked with red circles in Figure 8, implying that any surplus rainfall becomes surface runoff. It is also clear that the amount of rainfall needed to fill the aquifer, in other words, reach full recharge (i.e., achieving maximum water level) of wells (Figure 6b), would differ from year to year, the estimates of which for the study period are presented in Table 1. This is clearly a function of rainfall intensity seen each year and further influenced by factors such as occurrence of the SW monsoon rain or water discharge rate connected to large scale abstraction including in agriculture.

The case of well K20, one of four drinking water sources mapped in detail in Figure 9, requires mention here. This is a well adjoining a banana field, and it has been a well with public access and serving as a source of drinking water for decades to the local community. The private portion of this public well and the recent intensification of banana production through adoption of electric pump for irrigation of the field since electrification of the village and therefore the increased extraction as reported, leading to the rise in EC. The apparent over extraction of groundwater for intensive banana production by one family in connection to K20 appears to be common knowledge in the area. Similar high extraction rate from well K32 for supplying drinking water to sections of the community (Figure 4b), carried out by the local authority, and even higher levels noted in K3 for supplying water to a military institution are prominent indicators of what might come to pass in terms of unacceptable level or even permanent salinization. Modest increases in salinity level of water used for domestic purposes, exacerbated by climate driven sea level rise in these areas, will have health implications for residents as discussed below. What depth each well has been dug up to in the first place also seems to be a factor to be considered in understanding the pattern of salinity in the wells highlighted above.

Unregulated pumping out from other wells not covered in our study is known to take place. The practice of individual homeowners drilling new deep tube wells, sometimes next to an existing dug well, such policies continue to prevail in spite of the knowledge that drilling of such wells is controlled by the local authority. It is also well known among coastal communities that such wells would most likely yield saline water. These practices point to the urgent need for not only drawing strict local level policy for governance of the water resource in Karainagar but also for enforcement of such policies, while taking cognizance of health impacts of large scale salinization of the island's aquifer(s).

4.3 | Health implications

The quality of potable drinking water sources is an influential factor that affects the health of the population. The various country or regional agencies and World Health Organization (WHO) have developed and introduced standards for potable water that specify the permissible

TABLE 1 Summary of rainfall amount and groundwater full recharge requirement for water years 2019–2020, 2020–2021, and 2021–2022.

Water year	Total cumulative rainfall (mm)	Cumulative rainfall required to achieve full recharge (mm)	Estimated date for full recharge
2019–2020	1,041	652	December 3, 2019
2020–2021	1,335	674	December 9, 2020
2021–2022	1929	892	November 13, 2021

level of chemical, radiological, and microbiological water quality parameters of safe drinking water. Table 2 lists the Sri Lanka (SLS-614, 2013), EU (EU, 2020), and WHO (WHO, 2022) current standards for pH range and EC along with the values from WHO global overview of national regulations and standards for drinking water quality (WHO, 2021). All standards have a specified range for pH. Standards for EC are not specified in Sri Lanka nor by the WHO. A WHO (2021) overview found that 52 countries and territories among the 125 surveyed have a standard for conductivity. Among them, they found that 29 countries and territories specified a value of 2,500 μS cm^{-1} as their standard and that the specified values for other countries ranged from 170 to 2,700 μS cm^{-1}.

The recommended standard for pH is often in the range 6.5–8.5 (Table 2), but it has no direct effect on water consumers. The control of pH is one of the most important operational factors during water treatment to ensure effectiveness and efficiency and to maintain supply systems away from corrosion (WHO, 2007). Figure 9c shows that the drinking water wells within the recommended pH range. Drinking water with EC of up to 2,500 μS cm^{-1} can be consumed by humans (Table 2) with anything above that value not generally being recommended for human consumption. However, it can be seen from Figures 7b and 9b that most of the drinking water wells failed to meet the recommended criteria of below 2,500 μS cm^{-1} (2.5 mS cm^{-1}) for the whole or the drier portion of the water year, indicating that the groundwater in these wells was non-drinkable and generally contained above recommended criteria of EC (i.e., increased salinity).

Vineis et al. (2011) indicate that increasing salinity of natural drinking water sources can have serious public health implications including hypertension. Recent study by Chakraborty et al. (2019) in the coastal areas of Bangladesh found that there is an association between raised drinking water salinity and hospital visits for cardiovascular diseases (CVD), diarrhea, and abdominal pain. In the same region, a study by Nahian et al. (2018) found an association between high blood pressure (prehypertension and hypertension) and the drinking water salinity. They also found that women tend to have a higher chance of being hypertensive than men. A systematic review by Talukder et al. (2017) tentatively indicates an association between saline drinking water and human blood pressure. There are also other studies linking the association between drinking water salinity and health risk including (pre)eclampsia and gestational hypertension (Khan et al., 2014), blood pressure (Scheelbeek et al., 2016; Talukder et al., 2016), and hypertension and hyper dilute urine (Rosinger et al., 2021). In the case of Karainagar, if it is presumed that existing levels of salt consumption derived from everyday cooked food is high, further consumption of saline water in all probability will create a salt burden injurious to health and a likely risk factor for cardiovascular disease. This aspect warrants a closer investigation along with health impacts of hardness of water as well as the chemical and microbiological contaminants in the water.

TABLE 2 pH and electrical conductivity standards for drinking water.

Standards	pH range	Electrical conductivity
SLS-614 (2013)	6.5–8.5	-
EU (2020)	6.5–9.5	2,500 μS cm^{-1}
WHO (2022)	6.5–8.5	-
WHO (2021)—Overview	(5 to 7)–(8 to 10.5) Median range: 6.5–8.5	170–2,700 μS cm^{-1} Median value: 2,500 μS cm^{-1}

4.4 | Governance pathways

This case study has brought to the forefront the issue of local collaborative actions in the governance of groundwater resources that take into account the community needs for water, the bio-physical constraints to the groundwater resource, and some location specific socio-cultural demands. The influx of a significant quantity of drinking water motored in and the steady increase of that volume in recent years to a current volume of 150 m^3 per day are also factors that have to be counted in when water governance for the whole island is considered. This study has already provided the basis for establishing groundwater balance at the level of the whole island. When the present study reaches its natural conclusive stages, the hydrogeological information about the groundwater resources derived from it would have been taken in, along with appropriate policy and regulatory mechanisms at the island level in order to "ensure the sustainability of aquifers and participatory groundwater management" as envisaged by Suhag (2016) in India.

The genesis of this study 4 years ago was drawing on experiences from India on local level management of aquifer recharge and was seeking to link this to planning, policy making, and regulatory options not just at the island level in Karainagar but at the village and community levels below that. While research to date has focused on clarifying the ground water balance at these levels, parallel efforts must be made in participatory planning and policy making engaging well owning residents as well as all other key players. Such a facilitated adaptive management process to allocate water to meet as many interests as possible would constitute an adequate governance approach to enhancing water security (Pahl-Wostl et al., 2013; Susskind, 2013). Summarizing the Indian experience on planning for groundwater management, Suhag (2016) emphasized the identification of ground water recharge areas, maintenance of ground water balance at the level of the village and creation of regulatory options at the community level. Suhag cited drilling depth and distance between wells and agreements over cropping patterns compatible with water balance in aquifers as examples of such regulatory activities at the local level. These are indeed the outcomes of the MARVI project (Maheshwari et al., 2014), which we believe are entirely compatible with the needs at a setting like Karainagar and constitute the elements of governance for there.

Water governance was described in simple terms as the political, social, economic, and administrative systems that influence the water use and management at different levels of society by Rogers and Hall (2003). But the general idea of shifting away from "government" towards the notion of "governance" has been advanced very much in recent decades, guided by the general governance discourse, so much so that water governance has replaced water management in discourse as well as in practical term (Dobner & Frede, 2016).

Armstrong (1994) described "weak governance" as being constituted by "arbitrary policy making, unaccountable bureaucracies, unenforced or unjust legal systems, the abuse of executive power, a civil society unengaged in public life, and widespread corruption". It could be argued that many of the above features of weak governance applied to water management as experienced today in the NP including in Karainagar, and indeed in many other regions of Sri Lanka. Working with a case of groundwater crisis in Morocco, Faysse et al. (2014)offered what they called a more explicit definition of weak governance with a system of dysfunctional institutions and the relations between actors that characterized them. These authors focused on the "actors" who use the natural resources and water in this instance and said that there were weak interactions between the user-actors and the actors-in-charge of the management of these resources, with sustainable management of the resource system rarely discussed. Besides, the actors themselves had limited capacity and limited interest in being involved in interacting with others involved in the management, and there was indeed limited trust between the actors concerned (Faysse et al., 2014).

How to go about creating the basis of an effective governance pathway that would transcend inappropriate institutional provisions, inactions and bureaucratic inefficiencies, and therefore, poor resource management, prevalent in layers of government throughout Sri Lanka? If water security at the island level is taken in the widest sense, yet with the most integrated perspective of water security, then it should extend beyond quantitative measures of water quantity and quality and taken more explicitly in a community context (Gerlak et al., 2018). Such an understanding of water security would not only be more conducive of good governance but also be mutually beneficial. In other words, as Cook and Bakker (2012) stated water security sets goals for good water governance and good water governance is necessary to move towards water security at an operational level.

4.5 | Lesson from the past

Water security in Karainagar when considered through the prism of a total and permanent degradation through salinization of groundwater of the island as a scenario alluded to in this study highlights why a governance approach can go hand in hand with consideration of water security. A not-so-distant example that was in desperate need of such an approach was the 2013 incident in Jaffna Peninsula, described as the Chunnakam Case, a case of suspected fossil fuel residues contaminating the most prominent of the three aquifers in the peninsula (Saravanan, 2018). The way the case was handled at the time of the incident and how it was left untouched later, probably because it was seen as a "wicked problem," that is, not a simple relationship between cause and effect but with many inter-related factors at play (Rittel & Webber, 1973), resulted in a role for the Sri Lankan Supreme Court to finally bring a form of closure to the case. The court ordered the power station operator as the polluter to pay residents of the area for the environmental damages caused to them in view of the violation of their fundamental rights, the court claimed (Konasinghe & Edirisinghe, 2020; Sarveswaran, 2022). This case brought to light not only the negligence and incapability on the part of the State authorities to prevent acute groundwater pollution but also the lack of institutions with the capacity and responsibility for immediate actions including remediation measures. A logical alternate approach in these instances could be the approach of good governance—emphasizing broad stakeholder participation and improved equity and transparency as its key features.

5 | CONCLUSION

This study has established the need for and the significance of continuous aquifer monitoring and the possibilities of developing a groundwater model for a specified area such as Karainagar island. The seasonal fluctuation in water level among the wells studied and its negative correlation with the level of salinity in groundwater is among the conclusive findings of this study, along with the potential and limits that exist for recharging the aquifer. Individual wells that maintain water of drinkable quality, some in regular use and others that have been abandoned for many years, have been established by this study. Closer monitoring of such wells and their locational contexts demand further investigation. Risks associated with new practices of unregulated pumping and drilling of deep tube wells in terms of salinization have been highlighted by this study.

In the long run, it is hoped that the knowledge derived from the present study, combined with increased citizen engagement and government agency involvement, would improve the island community's quality of life, reducing the possibility of further out-migration. The blending of research methods and participatory approach adopted here has relevance to other neighboring islands and to work in progress in the mainland to reach smarter strategies for water security in the whole NP under the larger WASPAR.

Whatever progress that has been made in the past 3 years under the WASPAR framework at the provincial level, in promoting a governance approach and a spirit of systemic co-inquiry among multiple actors (Foster et al., 2016), could easily be tested here at the very local level in Karainagar island. Also, the emergence of the Northern Water Dialogue Forum at the provincial level, facilitated by the WASPAR project, is a promising outcome of the past 3 years of work, through structured stakeholder interactions. The elements of such a forum for Karainagar island could be the "permanent consultation mechanism" called for by Foster et al. (2016). It would clearly include the well-owner network already involved in this research, as well as the farmer associations, elected representatives of the local government authority, and other supporting national state agencies who have all been close to our research.

Experiences from Sweden where an Action Research process similar to the one being followed in the WASPAR project are pertinent here (Nielsen et al., 2016). Such a democratic and participatory research resulted not only in the creation of *free spaces* for dialog, but it also enabled citizens to transcend power differences and institutional barriers to realize the change-oriented potential they had. Even there, without the existence of some form of local interest and engagement to begin with, no citizen-driven dialog could have been possible, despite the presence of a very favorable policy environment in the form of the European Water Framework Directive for achieving the changes continuing to be accomplished there (Nielsen et al., 2016).

Groundwater as a local resource is receiving so much global attention (Foster et al., 2013) because it is such a physically connected yet institutionally fragmented resource (Alaerts, 2022). This is as true of the small island of Karainagar as any other location at the brink of a crisis. In recognition of this, the imperative for the present research is to complement the work at hand monitoring the aquifer, with an array of parallel efforts as outlined by Foster et al. (2013). This would entail an effective public information campaign, capacity building program that prepares local champions who will be "groundwater informed" volunteers of the kind invented by the MARVI project and effective coordination of all relevant authorities, agencies, and administrations, who are engaged in ongoing conversations with local citizens. Finally, the list of new efforts needed, according to Foster et al. (2013), also includes policy processes that allow raising of the required amount of capital as investment to undertake the physical measures needed to protect recharge zones close to public wells, including payment of financial compensation, if necessary, to farmers of the designated catchment areas of land.

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CONFLICT OF INTEREST

There is no real or perceived financial conflict of interest for any author.

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REFERENCES

Abobatta, W. F. (2023). Chapter 25—The influence of climate change on interactions between environmental stresses and plants. In *Plant stress mitigators* (pp. 425–434). Elsevier. https://doi.org/10.1016/B978-0-323-89871-3.00021-5

Alaerts, G. J. (2022). Chapter 2—Water, physically connected yet institutionally fragmented—Investing in its strategies, asset classes, and organizations. In X. Leflaive, K. Dominique, & G. J. Alaerts (Eds.), *Financing investment in water security* (pp. 17–55). Elsevier. https://doi.org/10.1016/B978-0-12-822847-0.00012-0

Anojan, S.R., Wijetunga, S., & Sriskandarajah, N. (2020). Community participation in village scale groundwater monitoring and management: A Case sudy in Karainagar Island of Jaffna. *Proceedings of the undergraduate research symposium on agricultural engineering & green technology 2020* (p. 22). Department of Agricultural Engineering, Faculty of Agriculture, University of Ruhuna, Sri Lanka. https://ageng.agri.ruh.ac.lk/wp-content/uploads/2021/05/final-all.pdf

Armstrong, P. (1994). Human rights and multilateral development banks: Governance concerns in decision making. *Proceedings of the ASIL Annual Meeting*, *88*, 277–282. https://doi.org/10.1017/S0272503700082203

Asoka, A., Gleeson, T., Wada, Y., & Mishra, V. (2017). Relative contribution of monsoon precipitation and pumping to changes in groundwater storage in India. *Nature Geoscience*, *10*(2), 109–117. https://doi.org/10.1038/ngeo2869

Bedekar, V. S., Memari, S. S., & Clement, T. P. (2019). Investigation of transient freshwater storage in island aquifers. *Journal of Contaminant Hydrology*, *221*, 98–107. https://doi.org/10.1016/j.jconhyd.2019.02.004

Chakraborty, R., Khan, K. M., Dibaba, D. T., Khan, M. A., Ahmed, A., & Islam, M. Z. (2019). Health implications of drinking water salinity in coastal areas of Bangladesh. *International Journal of Environmental Research and Public Health*, *16*(19), 3746. https://doi.org/10.3390/ijerph16193746

Chang, S. W., Clement, T. P., Simpson, M. J., & Lee, K.-K. (2011). Does sea-level rise have an impact on saltwater intrusion? *Advances in Water Resources*, *34*(10), 1283–1291. https://doi.org/10.1016/j.advwatres.2011.06.006

Cook, C., & Bakker, K. (2012). Water security: Debating an emerging paradigm. *Global Environmental Change*, *22*(1), 94–102. https://doi.org/10.1016/j.gloenvcha.2011.10.011

de Graaf, I. E. M., Gleeson, T., van Beek, L. P. H., Sutanudjaja, E. H., & Bierkens, M. F. P. (2019). Environmental flow limits to global groundwater pumping. *Nature*, *574*(7776), 90–94. https://doi.org/10.1038/s41586-019-1594-4

DEFRA. (2019). Abstraction reform report: Progress made in reforming the arrangements for managing water abstraction in England. Department for Environment, Food and Rural Affairs. https://www.gov.uk/government/publications/abstraction-reform-report-2019

District-Statistical-Hand-Book. (2022). District-statistical-hand-book 2022, District Planning Unit, District Secretariat, Jaffna.

Dobner, P., & Frede, H.-G. (2016). Water governance: A systemic approach. In R. F. Hüttl, O. Bens, C. Bismuth, & S. Hoechstetter (Eds.), *Society–water–technology: A critical appraisal of major water engineering projects* (pp. 79–87). Springer International Publishing. https://doi.org/10.1007/978-3-319-18971-0_6

EU. (2020). Directive (EU) 2020/2184 of the European Parliament and of the Council of 16 December 2020 on the quality of water intended for human consumption. https://eur-lex.europa.eu/eli/dir/2020/2184/oj

FAO. (2023). AQUASTAT Core Database. Food and Agriculture Organization of the United Nations. https://www.fao.org/aquastat/en/databases/

Faysse, N., Errahj, M., Imache, A., Kemmoun, H., & Labbaci, T. (2014). Paving the way for social learning when governance is weak: Supporting dialogue between stakeholders to face a groundwater crisis in Morocco. *Society & Natural Resources*, *27*(3), 249–264. https://doi.org/10.1080/08941920.2013.847998

Foster, N., Collins, K., Ison, R., & Blackmore, C. (2016). Water governance in England: Improving understandings and practices through systemic co-inquiry. *Water*, *8*(11), 540. https://doi.org/10.3390/w8110540

Foster, S., Chilton, J., Nijsten, G.-J., & Richts, A. (2013). Groundwater—A global focus on the 'local resource'. *Current Opinion in Environmental Sustainability*, *5*(6), 685–695. https://doi.org/10.1016/j.cosust.2013.10.010

Gerlak, A. K., House-Peters, L., Varady, R. G., Albrecht, T., Zúñiga-Terán, A., de Grenade, R. R., Cook, C., & Scott, C. A. (2018). Water security: A review of place-based research. *Environmental Science & Policy*, *82*, 79–89. https://doi.org/10.1016/j.envsci.2018.01.009

IPCC. (2022). *Climate change 2022: Impacts, adaptation and vulnerability. Contribution of working group II to the sixth assessment report of the intergovernmental panel on climate change*. Cambridge University Press. 3056 pp. https://www.ipcc.ch/report/ar6/wg2/

Karthiga, I., Rameshwaran, P., Ketheesan, B., & Sriskandarajah, N. (2022). Aquifer monitoring and community engagement in groundwater management for water security in northern Sri Lanka. *7th Annual Research Symposium, The International Water Conference 2022, 14–16 of December 2022. National Water Supply and Drainage Board, Sri Lanka*, 256–263. https://www.researchgate.net/publication/369542685_Aquifer_Monitoring_and_Community_Engagement_in_Groundwater_Management_for_Water_Security_in_Northern_Sri_Lanka#fullTextFileContent

Khan, A. E., Scheelbeek, P. F., Shilpi, A. B., Chan, Q., Mojumder, S. K., Rahman, A., Haines, A., & Vineis, P. (2014). Salinity in drinking water and the risk of (pre)eclampsia and gestational hypertension in coastal Bangladesh: A case-control study. *PLoS ONE*, *9*(9), e108715. https://doi.org/10.1371/journal.pone.0108715

Konasinghe, K. L., & Edirisinghe, A. A. (2020). Protecting human rights in the light of industrial water pollution: Sri Lankan law and obligations under international law. *University of Colombo Review (Series III)*, *1*(1), 60–80. https://ucr.cmb.ac.lk/protecting-human-rights-in-the-light-of-industrial-water-pollution-sri-lankan-law-and-obligations-under-international-law/. https://doi.org/10.4038/ucr.v1i1.29

Lall, U., Josset, L., & Russo, T. (2020). A snapshot of the world's groundwater challenges. *Annual Review of Environment and Resources*, *45*(1), 171–194. https://doi.org/10.1146/annurev-environ-102017-025800

Lassiter, A. (2021). Rising seas, changing salt lines, and drinking water salinization. *Current Opinion in Environmental Sustainability*, *50*, 208–214. https://doi.org/10.1016/j.cosust.2021.04.009

Luo, Z., Kong, J., Shen, C., Xin, P., Lu, C., Li, L., & Barry, D. A. (2021). Effects of aquifer geometry on seawater intrusion in annulus segment island aquifers. *Hydrology and Earth System Sciences*, *25*(12), 6591–6602. https://hess.copernicus.org/articles/25/6591/2021/. https://doi.org/10.5194/hess-25-6591-2021

Maheshwari, B., Varua, M., Ward, J., Packham, R., Chinnasamy, P., Dashora, Y., Dave, S., Soni, P., Dillon, P., Purohit, R., Hakimuddin, S., Shah, T., Oza, S., Singh, P., Prathapar, S., Patel, A., Jadeja, Y., Thaker, B., Kookana, R., … Rao, P. (2014). The role of transdisciplinary approach and community participation in village scale groundwater management: Insights from Gujarat and Rajasthan, India. *Water*, *6*(11), 3386–3408. https://doi.org/10.3390/w6113386

Maheshwari, B. L. (2020). Participatory groundwater management: Making the invisible resource visible and giving ownership of its sustainability to villagers. In E. W. Christen (Ed.), *Success stories in agricultural water management research for development* (pp. 27–34). Australian Centre for International Agricultural Research. https://www.researchgate.net/profile/Evan-Christen/publication/344731964_Success_stories_in_agricultural_water_management_research_for_development/links/5f8cf163299bf1b53e324b3a/Success-stories-in-agricultural-water-management-research-for-development.pdf#page=38

Manawadu, L., & Fernando, N. (2008). Climate change in Sri Lanka. *Colombo Review*, *1*(2), 1–26. http://192.248.16.117:8080/research/bitstream/70130/1100/1/Manawadu_CLIMATE%20CHANGES%20IN%20SRI%20LANKA.pdf

Masood, A., Tariq, M. A. U. R., Hashmi, M. Z. U. R., Waseem, M., Sarwar, M. K., Ali, W., Farooq, R., Almazroui, M., & Ng, A. W. M. (2022). An overview of groundwater monitoring through point-to satellite-based techniques. *Water*, *14*(4), 565. https://doi.org/10.3390/w14040565

Mikunthan, T., Vithanage, M., Pathmarajah, S., Arasalingam, S., Ariyaratne, R., & Manthrithilake, H. (2013). Hydrogeochemical characterization of Jaffna's aquifer systems in Sri Lanka. I. W. M. I. (IWMI). https://doi.org/10.5337/2014.001

Nahian, M. A., Ahmed, A., Lázár, A. N., Hutton, C. W., Salehin, M., & Streatfield, P. K. (2018). Drinking water salinity associated health crisis in coastal Bangladesh. *Elementa: Science of the Anthropocene*, *6*, 1–14. https://doi.org/10.1525/elementa.143

Nielsen, H., Hansen, H. P., & Sriskandarajah, N. (2016). Recovering multiple rationalities for public deliberation within the EU water framework directive. https://doi.org/10.4324/9781315647951-19

Pahl-Wostl, C., Palmer, M., & Richards, K. (2013). Enhancing water security for the benefits of humans and nature—The role of governance. *Current Opinion in Environmental Sustainability*, *5*(6), 676–684. https://doi.org/10.1016/j.cosust.2013.10.018

Pathmaja, S., Dharmagunawardhane, H. A., Senthilnanthanan, M., Mikunthan, T., & Rajasooriyar, L. D. (2019). Risk of groundwater pollution in open dug wells in the Pungudutivu Island of the Jaffna Peninsula, Sri Lanka. *Journal of the Geological Society of Sri Lanka*, *20*(2), 31–36. https://doi.org/10.4038/jgssl.v20i2.30

Piratheeparajah, N. (2015). Spatial and temporal variations of rainfall in the Northern Province of Sri Lanka. *Journal of Environment and Earth Science*, *5*(15), 179–189. https://core.ac.uk/download/pdf/234664351.pdf

Provincial-Statistical-Information. (2022). Provincial statistical information 2022. Office of the Deputy Chief Secretary—Planning, Northern Province, 265pp. https://np.gov.lk/statistical-information-2021/

Rameshwaran, P., Bell, V. A., Brown, M. J., Davies, H. N., Kay, A. L., Rudd, A. C., & Sefton, C. (2022). Use of abstraction and discharge data to improve the performance of a national-scale hydrological model. *Water Resources Research*, *58*(1), e2021WR029787. https://doi.org/10.1029/2021WR029787

Rittel, H. W. J., & Webber, M. M. (1973). Dilemmas in a general theory of planning. *Policy Sciences*, *4*(2), 155–169. https://doi.org/10.1007/BF01405730

Rogers, P., & Hall, A. H. (2003). Effective water governance. Global Water Partnership (GWP), TEC Background Papers No. 7. https://www.gwp.org/globalassets/global/toolbox/publications/background-papers/07-effective-water-governance-2003-english.pdf

Rosinger, A. Y., Bethancourt, H., Swanson, Z. S., Nzunza, R., Saunders, J., Dhanasekar, S., Kenney, W. L., Hu, K., Douglass, M. J., Ndiema, E., Braun, D. R., & Pontzer, H. (2021). Drinking water salinity is associated with hypertension and hyperdilute urine among Daasanach pastoralists in Northern Kenya. *Science of the Total Environment*, *770*, 144667. https://doi.org/10.1016/j.scitotenv.2020.144667

Santato, S., Mysiak, J., & Pérez-Blanco, C. D. (2016). The water abstraction license regime in Italy: A case for reform? *Water*, *8*(3), 103. https://doi.org/10.3390/w8030103

Saravanan, S. (2018). Oil spill contamination of ground water in Chunnakam aquifer, Jaffna, Srilanka. *Open Water Journal*, *5*(2), 3. https://scholarsarchive.byu.edu/openwater/vol5/iss2/3

Saravanan, S., Thushyanthy, M., Gunalan, K., & Gunawartana, D. (2013). Spatial Distribution of Ground water salinity at coastal region in Jaffna Peninsula: A case study at Karainagar. *Ministry of Water Supply & Drainage, National Water Supply & Drainagfe Board, Srilanka Water Convention 2013, The National Conference to mark the World Water Day, 21st March 2013*, 99–103. https://www.researchgate.net/publication/303814245_Spatial_Distribution_of_Ground_water_salinity_at_coastal_region_in_Jaffna_Peninsula_A_case_study_at_Karainagar

Sarveswaran, A. (2022). Judicial activism in environmental jurisprudence of Sri Lanka: A reflection in light of the Chunnakam Power Station case. *South Asian Journal of Environmental Law and Policy*, *1*(1), 61–73. https://sajelp.org/south-asian-journal-of-environmental-law-and-policy/

Scheelbeek, P. F. D., Khan, A. E., Mojumder, S., Elliott, P., & Vineis, P. (2016). Drinking water sodium and elevated blood pressure of healthy pregnant women in salinity-affected coastal areas. *Hypertension*, *68*(2), 464–470. https://doi.org/10.1161/HYPERTENSIONAHA.116.07743

Sebastian, A. (2022). Chapter 7—Compound flooding. In S. Brody, Y. Lee, & B. B. Kothuis (Eds.), *Coastal flood risk reduction* (pp. 77–88). Elsevier. https://doi.org/10.1016/B978-0-323-85251-7.00007-X

Shah, T., David, M., Sakthivadivel, R., & Seckler, D. (2001). Global groundwater situation: Opportunities and challenges. *Economic and Political Weekly*, *36*(43), 4142–4150. http://www.jstor.org/stable/4411304

Sikka, A. K., Alam, M. F., & Pavelic, P. (2021). Managing groundwater for building resilience for sustainable agriculture in South Asia. *Irrigation and Drainage*, *70*(3), 560–573. https://doi.org/10.1002/ird.2558

Singh, V. S., & Gupta, C. P. (1999). Feasibility of groundwater withdrawal in a coral island. *Hydrological Sciences Journal*, *44*(2), 173–182. https://doi.org/10.1080/02626669909492216

SLS-614. (2013). Specification for potable water (First revision). Sri Lanks Standard Institutuion 614: 2013. https://www.slsi.lk/index.php?option=com_slstandards&view=search_standards&Itemid=436&lang=en

Sood, A., & Smakhtin, V. (2015). Global hydrological models: A review. *Hydrological Sciences Journal*, *60*(4), 549–565. https://doi.org/10.1080/02626667.2014.950580

Statistical-Handbook. (2022). *Statistical handbook 2022*. Divisional Secretariat.

Suhag, R. (2016). Overview of ground water in India. https://prsindia.org/files/policy/policy_analytical_reports/1455682937–Overview%20of%20Ground%20Water%20in%20India_0.pdf

Susskind, L. (2013). Water and democracy: New roles for civil society in water governance. *International Journal of Water Resources Development*, *29*(4), 666–677. https://doi.org/10.1080/07900627.2013.781914

Talukder, M. R. R., Rutherford, S., Huang, C., Phung, D., Islam, M. Z., & Chu, C. (2017). Drinking water salinity and risk of hypertension: A systematic review and meta-analysis. *Archives of Environmental & Occupational Health*, *72*(3), 126–138. https://doi.org/10.1080/19338244.2016.1175413

Talukder, M. R. R., Rutherford, S., Phung, D., Islam, M. Z., & Chu, C. (2016). The effect of drinking water salinity on blood pressure in young adults of coastal Bangladesh. *Environmental Pollution*, *214*, 248–254. https://doi.org/10.1016/j.envpol.2016.03.074

Thushyanthy, M., & de Silva, C. S. (2012). Assessment of groundwater resources in Jaffna limestone aquifer. *Tropical Agricultural Research*, *23*, 177–185. https://doi.org/10.4038/tar.v23i2.4649

UN. (2022). The United Nations world water development report 2022: Groundwater: Making the invisible visible. UNESCO, Paris. https://unesdoc.unesco.org/ark:/48223/pf0000380721

Underwood, M. R., Peterson, F. L., & Voss, C. I. (1992). Groundwater lens dynamics of Atoll Islands. *Water Resources Research*, *28*(11), 2889–2902. https://doi.org/10.1029/92WR01723

UNESCO. (1991). Hydrology and water resources of small islands: A practical guide. A contribution to the International HydrologicalProgramme, IHP-111, PRO 4.6, 435. https://unesdoc.unesco.org/ark:/48223/pf0000090426

UN-Water. (2020). United Nations world water development report 2020: Water and climate change. UNESCO. https://www.unwater.org/publications/world-water-development-report-2020/

Vineis, P., Chan, Q., & Khan, A. (2011). Climate change impacts on water salinity and health. *Journal of Epidemiology and Global Health*, *1*(1), 5–10. https://doi.org/10.1016/j.jegh.2011.09.001

Vlahović, T., & Munda, B. (2012). Karst aquifers on small islands—The island of Olib, Croatia. *Environmental Monitoring and Assessment*, *184*(10), 6211–6228. https://doi.org/10.1007/s10661-011-2414-y

Werner, A. D., Bakker, M., Post, V. E. A., Vandenbohede, A., Lu, C., Ataie-Ashtiani, B., Simmons, C. T., & Barry, D. A. (2013). Seawater intrusion processes, investigation and management: Recent advances and future challenges. *Advances in Water Resources*, *51*, 3–26. https://doi.org/10.1016/j.advwatres.2012.03.004

Werner, A. D., Sharp, H. K., Galvis, S. C., Post, V. E. A., & Sinclair, P. (2017). Hydrogeology and management of freshwater lenses on atoll islands: Review of current knowledge and research needs. *Journal of Hydrology*, *551*, 819–844. https://doi.org/10.1016/j.jhydrol.2017.02.047

WHO. (2007). pH in drinking-water. Revised background document for development of WHO Guidelines for Drinking-water Quality, WHO/SDE/WSH/07.01/1. https://cdn.who.int/media/docs/default-source/wash-documents/wash-chemicals/ph.pdf?sfvrsn=16b10656_4#:~:text=The%20pH%20of%20most%20drinking,within%20the%20range%206.5%E2%80%938.5

WHO. (2021). *A global overview of national regulations and standards for drinkingwater quality* (second ed., Vol. 2021). World Health Organization. https://www.who.int/publications/i/item/9789240023642

WHO. (2022). *Guidelines for drinking-water quality: Fourth edition incorporating the first and second addenda* (Vol. 2022). World Health Organization. https://www.who.int/publications/i/item/9789241549950

Wu, C. L. R., Stigter, T. Y., & Craig, S. G. (2022). Assessing the quantity and quality controls of the freshwater lens on a semi-arid coral-Limestone Island in Sri Lanka. *Frontiers in Water*, *4*, 1–18. https://doi.org/10.3389/frwa.2022.832227

Zanaga, D., van de Kerchove, R., Daems, D., de Keersmaecker, W., Brockmann, C., Kirches, G., Wevers, J., Cartus, O., Santoro, M., Fritz, S., Lesiv, M., Herold, M., Tsendbazar, N. E., Xu, P., Ramoino, F., & Arino, O. (2022). ESA WorldCover 10 m 2021 v200. https://doi.org/10.5281/zenodo.7254221

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