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Short Communication

Temporal dynamics of drinking water sodium levels in coastal areas, Cyprus 2009–2020

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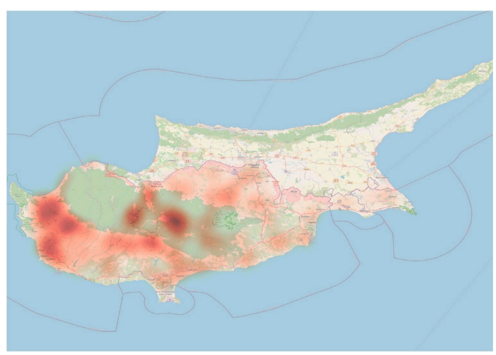
HIGHLIGHTS

- Groundwater quality of coastal areas may be perturbed under a changing climate.
- An annual change in drinking water salinity in coastal areas but not in non-coastal areas.
- Distance of each sampling point from coastline was negatively associated with water Na in coastal areas.

GRAPHICAL ABSTRACT



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ABSTRACT

Around the world, groundwater salinity levels are increasing in coastal areas, as a result of its systematic overexploitation for domestic, agricultural and industrial demand and potentially due to climate change manifestations (such as, sea level rise). We hypothesized that the groundwater quality of many Mediterranean coastal areas is already being perturbed, especially for water salinity, depending on the groundwater distance from the seafront. The objectives of this study were: i) to evaluate the magnitude and temporal variance of drinking water sodium (Na) as a metric of salt intake used for public health purposes using drinking water data in Cyprus; and ii) to examine the degree of Na enrichment in drinking water as defined by the seawater coastline distance of each sampling point. Open access governmental data of drinking water Na ($n = 3304$), daily max ambient air temperature and total rainfall were obtained for the period of 2009–2020 from governmental repositories. Linear mixed-effect regression models of drinking water Na with unsupervised covariance matrix were used. After adjusting for temperature and rainfall data, there was a significant annual increase in drinking water Na levels over time (beta = 0.01; 95 % CI: 0.00, 0.02; $p = 0.02$) for the coastal areas (<10 km from coastline, cutoff used

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by the EU Environment Agency), but this was not the case for non-coastal areas (>10 km distance from coastline). The distance of each sampling point from the coastline in Cyprus was negatively associated with drinking water Na in coastal areas (beta = −0.04, 95%CI: −0.06, −0.01; p = 0.002); this was not the case for non-coastal areas. More research is warranted to better understand the impacts of global environmental change on water quality in association with the burden of disease in coastal areas.

1. Introduction

Increasing ambient air temperatures, rising sea water level and persistent droughts are important manifestations of global climate change. Their impacts on environmental phenomena, such as increasing saltwater intrusion into coastal fresh groundwater are well demonstrated in various coastal areas of the globe (Zamrsky et al., 2024; Khan et al., 2011; Van Weert et al., 2009; Mazi et al., 2014; Li et al., 2020; Kaushal et al., 2021; RamyaPriya and Elango, 2018; Guimond, 2021). Globally, at least 750 million people already live in coastal areas with elevation <10 m above present sea level (Macmanus et al., 2021); and this number will likely increase under most shared socioeconomic pathways (Kulp and Strauss, 2019; Hauer et al., 2021). Especially in these coastal zones, groundwater salinity levels are often high given that the sea is close by (Siemon et al., 2015; Delsman et al., 2018; Sheng et al., 2023).

Although saltwater intrusion into the coastal groundwater system is a natural process caused by density differences between fresh and saline groundwater (Cooper et al., 1964) and topography-driven advective-dispersive salt transport from salty marine and brine deposits (Hanor, 1994a, 1994b), this process is often disturbed by human interferences, such as excessive overexploitation of fresh groundwater from the aquifers (Custodio, 2002), sometimes leading to severe land subsidence (Minderhoud et al., 2017). Saltwater intrusion can hinder the use of water for agriculture due to soil salinization and soil fertility reduction (Daliakopoulos et al., 2016; Negacz et al., 2022), causing salt damage to crops (FAO, 2021) and nature (Stofberg et al., 2015), leading to economic losses (Qadir et al., 2014).

In this paper, we focus on coastal communities that rely on fresh groundwater supplies for their livelihood. They are at risk of increasing water salinity levels over the coming years (Khan et al., 2011; WHO, 2003) due to both anthropogenic activities (e.g. documented groundwater overexploitation for agriculture, so-called sealing of urban areas reducing the capacity of precipitation to infiltrate into the groundwater systems) and climate change induced saltwater intrusion phenomena (e.g., sea level rise and saltwater over-wash during more intense storm surges (Xiao et al., 2019; Cantelon et al., 2023) Muis et al., 2016.

In literature, data are scarce about the potential human health effects of water salinity (e.g., water Na salts) (WHO, 2003). To date, it is well established that diets high in Na may be associated with the risk of hypertension (He and MacGregor, 2009; Huang et al., 2020; Filippini et al., 2021). The U.S. Environmental Protection Agency (U.S. EPA) issued a drinking water guidance advisory for Na, motivated by consumer acceptability of taste and potential health effects from sodium chloride and other sodium salts (U.S. EPA, 2003). Although the U.S. EPA did not recommend a Na reference dose due to the limited availability of data for quantifying health risk, it did recommend reducing Na concentrations in drinking water to ~30–60 ppm to avoid problems with taste (U.S. EPA, 2003).

Drinking water has not been typically considered as a major Na human exposure source that would substantially contribute to the total body burden of salts and their downstream health effects. An earlier systematic review and meta-analysis found a small positive association between water Na and blood pressure in epidemiological studies (Talukder et al., 2017). Under a changing climate, the possible contribution of drinking water salinity to the risk of hypertension and other related health impacts (e.g. preeclampsia, a hypertensive disorder that occurs after 20 weeks of gestation during pregnancy or shortly after delivery) is unknown (Thompson et al., 2022; Xeni et al., 2023).

Recent evidence suggests that the global mean sea level rising might be particularly important for cities and settlements at low-lying islands and coastal zones (Oppenheimer et al., 2019). In effect, a combination of anthropogenic activities on ocean and land, together with sea level rise, pose a risk for the resilience of coastal areas and their ecosystems (Oppenheimer et al., 2019). Cyprus is a Mediterranean island, and it is considered a major climate change hotspot (Lelieveld et al., 2012). It was estimated that the largest warming phenomena for Europe are likely to be manifested over southern Europe and the Mediterranean region during warmer months (May–October) (Lelieveld et al., 2012).

In Cyprus, there are 66 (medium to small-scale) aquifers (viz. good permeable water-bearing porous media) divided into 20 (local) groundwater systems based on their lithology, hydraulic characteristics, pollution pressures, as well as their use and type (WDD, 2017b). In addition, there are 108 dams with a total water capacity of 331 million m^3 (WDD, 2017c). The total annual water demand of about 266 million m^3 in Cyprus is driven by the agricultural sector (irrigation) and the domestic usage with approximately 69 % and 20 % of total water use, respectively; other major consumers include tourism (5 %), industry (1 %) and amenities (5 %) (Park, 2020).

Currently, the water used for drinking purposes in Cyprus comes from surface water collected in the dams, from groundwater collected from extraction wells and natural springs (often sold in kiosks), and from sea water/brackish groundwater desalination (WDD, 2017a; MPHS, 2019). A water consumption survey in urban Cyprus (n = 326) reflected the frequency of usage of the above-mentioned major water sources (Charisiadis et al., 2014). Water treated at central drinking water treatment facilities typically meets regulatory requirements associated with the potable and household needs of people living in urban areas, but this may not always be the case in rural areas. It has been estimated that about 36 % of the general population of Cyprus resides in rural (non-urban) areas according to the degree of urbanization classification system of Europe (DEGURBA). Those living in rural communities or in peri-urban settings (EU DEGURBA 2 degree of urbanization) may be (solely) relying upon groundwater to satisfy their potable needs, using either untreated groundwater or treated (some form of chlorination) groundwater.

A better understanding of the manifestations of global environmental change in association with the burden of disease, particularly in coastal aquifers is an ongoing and important research area (Zamrsky et al., 2024; Cantelon et al., 2023; Micallef et al., 2021; Zamrsky et al., 2022; van Van Engelen et al., 2022). Climatic manifestations may adversely impact on the population health and economic systems of coastal populations, especially those living in coastal urban areas. Prospective epidemiological studies that monitor population health outcomes and associated exposures using holistic environmental and public health frameworks over time and space (e.g., the human exposome, Haddad et al., 2019; Andrianou and Makris, 2018) in coastal urban areas are warranted, if we were to better characterize the human health and other impacts of the global environmental change, including ways to mitigate and adapt to such global pressures.

In this study, it was hypothesized that the drinking water quality of Mediterranean coastal areas would have been gradually perturbed, as a result of groundwater (over)exploitation phenomena coupled with droughts and other climatic manifestations (including sea level rise). The focus of this study was on public health metrics and less on hydrogeological or hydrogeochemical indices, albeit these are interrelated in a complex network of systems. This study focused on potable water, i.e. the specific portion of the actual domestic water use system that the general population in Cyprus comes in direct contact with after water treatment (the case for surface water or desalinated water) or no treatment (usually the case for direct groundwater use in rural areas). Nevertheless, the systematic temporal evolution of drinking water quality profile in Cyprus for selected parameters over the years has not been studied before.

The objectives of this study were: i) to evaluate the magnitude and temporal variance of sodium (Na) in finished drinking water of Cyprus during the 2009–2020 period; and ii) to examine the degree of Na enrichment in drinking water supplies of Cyprus' coastal areas, as defined by the seafront coastline distance of each sampling point during the same period (2009–2020), giving emphasis on the coastal areas with <10 km distance from seafront.

2. Methods

2.1. Design and setting

This is a retrospective study using time series data from secondary sources. Data about drinking water quality and meteorological measurements in the five districts of the government-controlled areas of the Republic of Cyprus (Limassol, Nicosia, Larnaca, Pafos, Famagusta), covering both urban, peri-urban and rural areas, were accessed. According to the European Environment Agency, coastal areas were defined as local administration units (LAU) that border the coastline or LAUs that have at least 50 % of their surface area within a distance of 10 km from the coastline (EEA, 2023; EUROSTAT, 2018); non-coastal areas were defined as those with distances from coastline being >10 km.

2.2. Data sources

Open access data about drinking water chemical quality, ambient air temperature and rainfall were obtained from governmental repositories or governmental websites (State General Laboratory, 2022; Public Health Services, 2018; Ministry of Finance, 2022). Data used in this study were obtained from the annual national control program for drinking water (~1400 sampling points). Water supply zone is defined as a geographically defined area in which water enters from one or more sources and its quality can be judged as uniform (Cyprus Ministry of Health Services, 2021). Drinking water chloride (Cl^-) data were also incorporated; Cl^- is used more often for hydrogeological purposes since it is a conservative tracer. Data about the daily maximum air temperature and the total rainfall per month for the years 2010–2020 were also obtained (Ministry of Finance, 2022; Department of Meteorology, 2022).

2.3. Data processing

The different datasets of this study covering the years 2009–2011 and 2017–2020 together with 2014–2016 were integrated; all sampling points/areas for each water supply zone were identified and geolocated (Fig. 1). The governmental datasets of years 2009–2011 and 2017–2020 contained information about both specific geographic sampling points and their specific sampling dates. The governmental datasets of drinking water quality for the years 2014–2016 reported the mean value of the drinking water measurements of each water supply zone; they did not provide information about the specific geographic coordinates of the sampling points or the specific sampling date.

Drinking water sampling for Na from the water supply zones in Cyprus for the years 2014–2016 was conducted either in the first half (January–June), or in the second half of each year (July–December), or in both periods for each year. For the 2014–2016 dataset, we identified

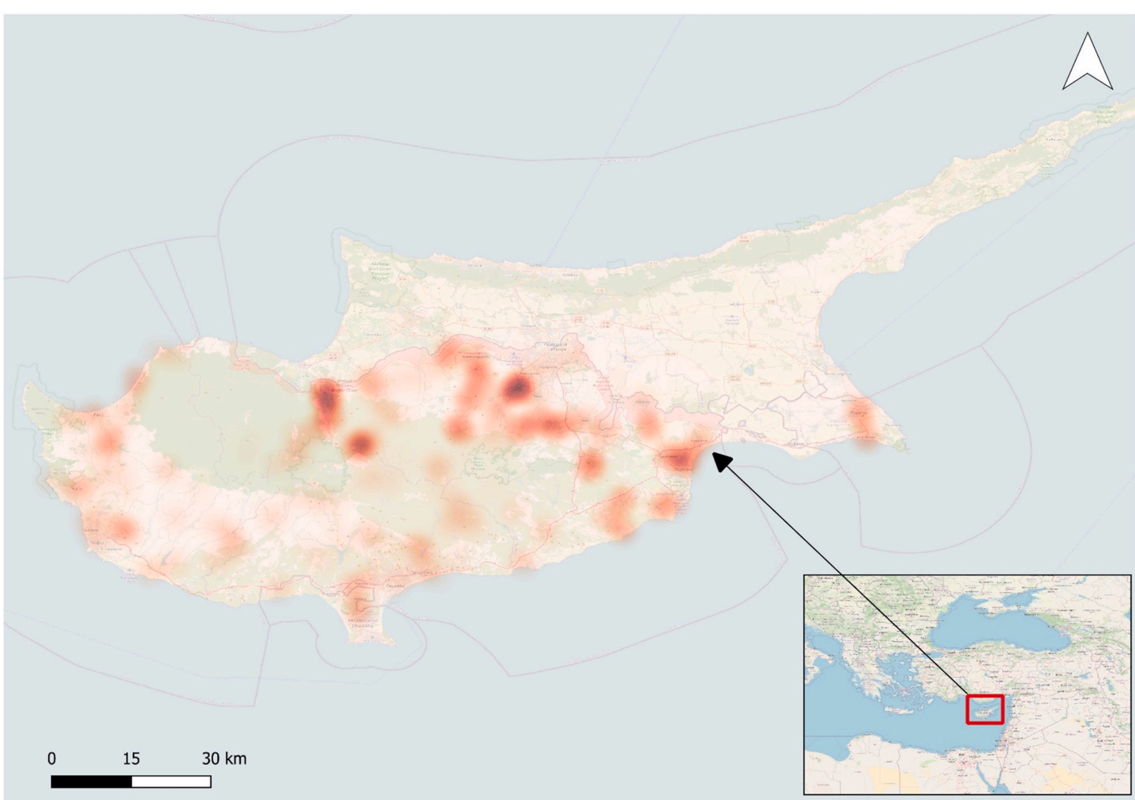

Fig. 1. Heat map (red denotes higher frequency of sampling points and lighter colors denote smaller sampling frequency) of the sampling points of drinking water for Na analysis that were employed in this study within the territories of the Republic of Cyprus (actual geolocation is intentionally missing).

the specific sampling points/areas within each water supply zone and then assigned the mean value of the water supply zone to each sampling point/area of it. Using the specific sampling dates of the datasets 2009–2011 and 2017–2020, a seasonal period variable was created (January–June, or July–December).

For a few sampling areas, more than a single Na measurement existed for a specific time period; the mean Na was calculated for these sampling points and used in the analysis. Areas for which no geographical coordinates could be found, were removed. Sodium concentrations reported as "zeros" in the governmental reports of the 2009–2011 datasets plus those Na levels reported as "not detected" in the 2017–2020 datasets were excluded from the analysis, because no information on the limits of detection/quantification could be located in those reports.

Using the R package 'nominatimlite', we located the coordinates of each sampling point/area for all study years 2009–2020. The use of OpenStreetMap© (Keßler, 2015) allowed us to identify the coordinates of Cyprus' coastline with which we were able to calculate the minimum distance of each sampling point/area from coastline.

Monthly rainfall data and the mean daily max ambient air temperature data for each of the six governmental meteorological stations spread throughout the Republic of Cyprus, covering both coastal and mountainous settings and urban or rural areas were made available from the open data portal data during the years 2010–2018 (State General Laboratory of the Cyprus, 2022) and from the Cyprus Department of Meteorology for the years 2019–2020 (Ministry of Finance, 2022). Geocoded sampling point/areas were assigned to one of the six governmental meteorological stations based on the shortest distance calculated.

2.4. Statistical analysis

Percentiles of drinking water Na, meteorological data by distance of all sampling points from the coastline were presented yearly for both coastal and non-coastal areas.

Linear mixed-effect regression models of drinking water Na with unsupervised covariance matrix were used (Brown, 2021). Mixed-effect models capture both participant and item variability while they offer more power and flexibility than other conventional statistical tools (Brown, 2021). To account for the repeated measures, models included sampling point/area)-level random intercepts. In all regression models, drinking water Na was log-transformed. Fixed effects were those of measurement year (either as categorical or continuous variable), sampling seasonal period (January–June vs July–December) and adjusted for the meteorological conditions (daily max ambient air temperature and total rainfall). Another set of linear mixed-effect regression models of drinking water Na were constructed as a function of the distance from the coastline (continuous variable), the measurement year, and the sampling seasonal period (January–June vs. July–December). These models were adjusted for total rainfall and the mean daily maximum air temperature for the corresponding period as these variables are associated with both Na and they present with temporal (seasonal) variations.

As a sensitivity analysis, we also ran mixed effect regression models for those drinking water samples across Cyprus whose distance from coastline were in the order of >10 km, <10 km, <15 km, <20 km, and <30 km from the coastline. All analyses were conducted in R (v.4.2.0) using RStudio (v. 2022.07.1 Build 554).

3. Results

3.1. Study descriptive characteristics

A total of 3304 samples corresponding to 421 unique sampling points within the government-controlled territories of the Republic of Cyprus with available drinking water Na levels during the 2009–2020 period were used (see the Cyprus map with the location of pseudo identified sampling points, Fig. 1). It appeared that about half of the sampling points had water Na levels >60 ppm in coastal areas of Cyprus, while a smaller number of sampling points had water Na higher than 60 ppm in non-coastal areas (>75th percentile) (Table 1). Coastal areas had overall higher drinking water Na levels reporting median and interquartile range (IQR) of 70.5 ppm (IQR: 58,112) in 2009 to 66 ppm (44,102) in 2020; non-coastal areas had median (IQR) water Na levels of 52 ppm (20,135) in 2009 to 40 ppm (22,69) in 2020 (Table 1). Higher water Na levels were observed during the July–December period than those observed in the period January–June period (Table 1).

3.2. Temporal trends of drinking water sodium

The temporal trends of drinking water Na during the 2009–2020 study period for both coastal areas and non-coastal areas of Cyprus is visualized in Fig. 2. There was a significant annual increase in drinking water Na levels over the years that this study took place (beta = 0.01; 95%CI: 0.00–0.02; $p = 0.023$) for the coastal areas, even after adjusting for daily max air temperature and rainfall data (Table 2). There was actually no significant ($p > 0.05$) effect of time during the study period of 2009–2020 on the drinking water Na levels of the non-coastal areas of Cyprus (beta = −0.00; 95%CI: −0.01, −0.01, $p = 0.71$) (Table 2). Similarly, the distance of each sampling point from the coastline was significantly negatively associated with drinking water Na levels in coastal areas (beta = −0.04, 95%CI: −0.06, −0.01; $p = 0.002$), but again this was not the case for the non-coastal areas of Cyprus, after adjusting for daily max air temperature and rainfall data.

A geospatial visualization of changes in drinking water Na content for the sampling points within the 10 km distance from the sea coastline was attempted (Fig. S1). The linear mixed-effect regression model for those sampling points geospatially located within the 0–10 km distance range from the sea coastline reaffirmed the significant association between the distance from the Cyprus' coastline and the drinking water Na levels (see Table S14).

4. Discussion

This study relied on open access secondary governmental data sources to better understand the temporal dynamics of drinking-water Na concentrations in coastal areas of a Mediterranean country (Republic of Cyprus) during an 11-year period (2009–2020). To the best of our knowledge, this study demonstrated for the first time, a gradually increasing in time trend of drinking water Na levels for the coastal areas of this Mediterranean island (being <10 km in distance from coastline); this upward temporal trend for water Na was not observed in the non-coastal areas (>10 km distance from coastline). The selected cutoff distance from coastline of 10 km is widely used by EUROSTAT and by the European Environment Agency (EEA, 2023), but this has not been in common use. It is anticipated that this distance cutoff from coastline would widely vary in different regions of the globe, depending on a suite of geohydrological, geochemical or urban use factors. It follows that this 10 km distance cutoff does not necessarily carry a mechanistic knowledge to rigorously explain saltwater intrusion phenomena. Indeed, saltwater intrusion might impact on coastal groundwater salinity in >10 km distances from the coastline (e.g., in Mekong delta, Gunnink et al., 2021; The Netherlands, Delsman et al., 2023; Nile delta, Mabrouk et al., 2019).

This study's findings indicate a temporal trend of gradually increasing water salinity (higher water Na) that support the established view of over-exploitation of coastal groundwater sources where groundwater is already naturally a mixture of fresh, brackish to saline groundwater. Persistent droughts negatively affecting groundwater recharge and the associated increase of groundwater extraction causing saline groundwater upconing would partially explain some of this study trends.

Cyprus, a Mediterranean island, often experiences droughts and high air temperatures associated with increased evapotranspiration processes

Table 1
Percentiles of the drinking water sodium concentrations (ppm) in coastal and non-coastal areas of Cyprus per year (January–December) and by 6-month period.

		Non-coastal areas						Coastal areas					
	Year	Min	25th	50th	75th	95th	Max	Min	25th	50th	75th	95th	Max
Jan–Dec	2009	4	20	52	135	208.4	436	12	57.9	70.5	112	191	266
	2010	4	20	40	99.8	204.1	395	4	50	70	106.5	186.5	321
	2011	5	16.3	33.5	64.3	172.9	280	16	50	65	99	133.7	199
	2014	6	32.5	44	62	157.4	357	19	51.8	65	98	142.8	270
	2015	5	28	38	63	130.8	419	13	48	63.8	98.6	139	264
	2016	6	34	48	83.5	140.1	414	19	51.8	80	98.5	137.9	249
	2017	5	22.5	43	87.5	181	466	21	60.5	85	112	178.4	274
	2018	5	24.5	42	95.5	175	372.7	21	56.8	86.5	118.5	190	357
	2019	5	19	38	82	149.9	333.3	15	56	80	115.5	168.7	250.5
	2020	5	22	40	69	153	334	20	44	66	102	161	205
Jan–Jun	2010	4	20	43	92	201	265	4	46.5	64.5	98.8	184.8	321
	2011	5	15.75	31	62.8	174.7	280	16	50	63.5	97.3	133.8	199
	2014	6	28	41	61.8	160.1	357	19	59.3	73	83.8	135.5	202
	2015	5	26	33	59.3	137.5	382	20	41	69.5	99.5	139	264
	2016	6	34	48	81.5	147	414	21	51	79	91.3	137.8	249
	2017	5	28.1	44	78	181.7	466	22	63.4	78.5	104.3	146.8	274
	2018	5	29	45	92	169.2	372.7	21	55	78	102	164	357
	2019	5	16.5	34	72	141.3	333.3	27	57.5	83.5	102.8	153.2	250.5
	2020	5	21.5	38	60.5	102.5	267	25	46.5	69.5	100	164.5	198
Jul–Dec	2009	4	20	52	135	208.4	436	12	57.9	70.5	112	191	266
	2010	4	20.5	37	104	205.9	395	20	60.8	72	113	180.1	219
	2011	41	47	56	86	129.3	141	119	119	119	119	119	119
	2014	6	34	44	72	152.2	288	22	48	65	105	154	270
	2015	8	32.3	42	71.5	125.4	419	13	50	59.5	98.5	143.8	236
	2016	8	29	47.5	89	120	392	19	61	89	110	137.1	231
	2017	5	20	42	92	163.6	429	21	56.4	90	138	218	252
	2018	6	21.3	41	101	173.7	249.5	21	60.5	109	143.3	209.8	242
	2019	5	20	40	89.5	157.4	218	15	54	80	125	213	243
	2020	5	21.5	46.5	75.5	160.6	334	20	40.4	64.5	102	156.3	205

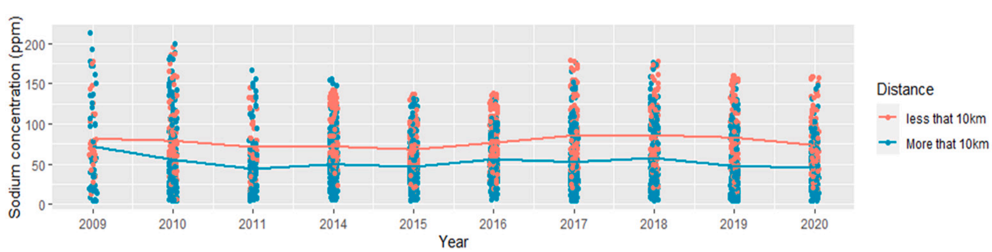

Fig. 2. Visualization of the temporal trend of drinking water log-transformed sodium levels in the coastal areas of Cyprus (<10 km) and the non-coastal areas of Cyprus (>10 km) (Lowess smoothing and removing >95th percentile data for aesthetic purposes only).

Table 2
Linear mixed-effect regression models of log-transformed sodium (Na) concentration (ppm) in coastal and non-coastal areas as a function of year of sampling date, distance from coastline adjusted for mean daily maximum air temperature and total rainfall (mm).

	Non-coastal areas			Coastal areas		
	Estimate	95%CI	*p*-Value	Estimate	95%CI	p-Value
Intercept	6.02	−8.19–20.22	0.406	−12.89	−27.45–1.68	0.083
Year	−0.00	−0.01–0.01	0.710	0.01	0.00–0.02	0.023
Period (JUL–DEC)	−0.12	−0.21 to −0.03	0.009	0.01	−0.10–0.11	0.863
Distance from coastline	0.00	−0.01–0.02	0.580	−0.04	−0.06 to −0.01	0.002
Temperature	0.02	0.01–0.04	0.001	0.01	−0.00–0.03	0.124
Rainfall	−0.00	−0.00 to −0.00	<0.001	0.00	−0.00–0.00	0.095
Random Effects						
σ^2	0.17			0.11		
$\tau_{00\ \text{sampling points/areas}}$	0.41			0.17		
ICC	0.71			0.62		
Observations	1870			1261		

that are usually combined with groundwater overexploitation practices in agriculture (WDD, 2020). As such, it was estimated that about 33 % of the groundwater systems in Cyprus have been recently contaminated via saltwater intrusion; and about 26 % of them are not in good chemical condition (violating maximum permissible values for salts such as chlorides, sulphates, or arsenic etc.) (WDD, 2020). Indeed, there have been localized cases of saltwater intrusion observed in coastal area wells of Cyprus due to over-exploitation; this phenomenon was associated with higher chloride and sulfate levels in groundwater (WDD, 2020; Milnes and Renard, 2004). Chloride is typically used in hydrogeological studies as it is more conservative than Na in the sense that Na easily reacts with other components, making the connection to sea water at the lower ranges of concentration less obvious (Goes et al., 2009).

In our study, drinking water chloride (Cl^-) data came from the same samples that Na was measured in order to provide an indication regarding the Na—Cl co-existence as a result of saltwater intrusion. A high correlation between Na and Cl (correlation coefficient = 0.8) on a molar basis (to provide the necessary stoichiometry) was indeed shown (Fig. S19); this correlation is usually the case for sea water, but this may not be always the case for groundwater systems, especially for karst systems (Chen et al., 2017). The maximum permissible levels of chloride ions in groundwater systems of Cyprus range between 250 and 400 mg/L (WDD, 2020).

This study's findings have important ramifications for coastal populations and their (partial) reliance on local groundwater sources used directly for satisfying potable needs, or being mixed with other water sources (surface water, sea water, etc.) before consumption. The scenario of groundwater mixing with seawater during seawater intrusion into freshwater bodies of coastal areas or the often intentional mixing of desalinated water with a small percent of groundwater/surface water would potentially increase bromide and iodide ions by osmosis phenomena to the water medium having lower salt concentration (e.g., groundwater) (Ioannou et al., 2016). These are important precursors for the water formation potential of toxic disinfection byproducts, posing an additional human health risk factor (Evlampidou et al., 2020). A simulation of saltwater intrusion experimental study showed the elevated disinfection byproducts, such as, trihalomethanes (THMs) and haloacetic acids (HAAs) formation potential upon mixing groundwater with up to 2.0 % seawater (by volume) and with liquid chlorine as disinfectant (Chowdhury, 2022).

The (ground)water salination processes is of relevance to estimates of the drinking water contribution to the total body burden of sodium and other salts, This water-based Na contribution has been underestimated or received little attention, when compared with the influence of dietary Na on a suite of cardiovascular diseases. In Europe and North America, the estimated overall consumption of dietary sodium chloride is 5–20 g/day (2–8 g of Na per day), with the average being 10 g/day (4 g of Na) (WHO, 2003). The U.S. Environmental Protection Agency (EPA) issued a drinking water guidance advisory for Na, motivated by consumer acceptability of taste and potential health effects from sodium chloride and other sodium salts (U.S. EPA, 2003). Although the Advisory did not recommend a Na reference dose due to the limited availability of data for quantifying health risk, it did recommend reducing Na concentrations in drinking water to between 30 and 60 ppm to avoid problems with taste. For individuals on a restricted sodium diet, the U.S. EPA provided a guidance level of 20 ppm (U.S. Institute of Medicine, 2004). In Cyprus, coastal areas consistently had about half of the sampling points with water Na levels >60 ppm, suggesting issues with taste and potentially associated with health risks, albeit not assessed yet.

All data sources of water Na came from the official governmental datasets of the drinking water quality monitoring network program that operates in Cyprus per the requirements of the European Directive 98/83. Indeed, the population that directly uses groundwater with minimal treatment for potable purposes and household use may be those directly exposed to sodium. About one third (36.6 %) of the Cypriot population resides in rural areas, where most of them rely upon original groundwater sources for their potable needs with minimal, or no treatment at all (CYSTAT, Statistical Service, 2021). For those subpopulation groups with less direct exposure or no exposure to groundwater, this study's model results would less accurately depict their sodium body burden providing biased estimates, such as those receiving drinking water that has been centrally treated, as in urban areas. However, this bias would likely lead to null associations and provide underestimated effect sizes when such a Na exposure misclassification occurs.

This study's focus on drinking water samples was intentional in order to reflect the most relevant sodium doses to humans. Obviously, some of these sampling points over the multi-annual study period may have originated from the same geocoded location, but others may have not. As far as the exposure source of water is concerned, this is a bit complicated and there is a risk of bias, because the study accessed and used data from all government-controlled territories of the Republic of Cyprus. Most rural areas used groundwater for potable purposes, but urban areas mostly use desalinated water from sea or brackish groundwater, or surface water from dams. During the warmer months, a mix of water sources may be concurrently used to cover increased demand for tap water due to varying waves of tourism.

4.1. Limitations

First, we assumed a single source of drinking water for those consuming water from the study's sampling sites. It is not uncommon for the general population to rely less on municipal water and/or to employ points of use filters and other water treatment technologies. For example, home water softeners typically remove hardness-causing minerals (i.e., Ca^{2+} and Mg^{2+}) through ion exchange, but this process could potentially serve as another Na source, because it replaces these minerals in drinking-water with an equivalent amount of sodium being unintentionally added to drinking-water during ion exchange (Thompson et al., 2022). The highest Na levels in drinking water were found in households using either point of use softening or in those households receiving water subject to ion exchange softening by the municipality during treatment (Thompson et al., 2022). A limitation was the fact that we did not use Cl^- in the main analysis, since it is more widely used by hydrogeologists for describing saltwater intrusion than presenting Na alone; however, the hydrogeological mechanisms of saltwater intrusion was not the focus of this work. Another limitation was that the calculated distance of each sampling point to the coastline did not account for its main raw water source distance to coastline; for instance, there were sampling points that received drinking water directly from groundwater being in close distance from this groundwater source; while other sampling points, (such as those in a city) might have different distances from coastline than their original water source (e.g., in a dam, or in the case of a seawater/groundwater mix source). Novel geostatistical analyses coupled with enhanced understanding of hydrogeological processes in karst systems may be warranted to better understand the complexity of spatial and temporal salinization patterns of subsurface systems, such as those encountered in Cyprus (Mazi et al., 2014; Panagiotou et al., 2022).

Also, it is often the case that Water Boards may mix two water sources, i.e., surface water from dam with groundwater, thus, affecting the finished water quality with respect to its salinity content (and its Na levels). Nevertheless, the fact that this dataset is based on drinking water Na levels rather than source water Na is a strength of this study for better understanding population exposure dynamics related to various salts in drinking water and their associated burden of disease in future epidemiological studies. Summarizing patterns in household finished drinking water consumption rates is a reasonable empirical approach to characterizing patterns in population exposure to salinity from drinking water, recognizing the existence of other sources, as well (e.g., drinking water at work, bottled water) (Rhonda et al., 2011).

5. Conclusions

This study demonstrated for the first time a gradually upward in time trend of drinking water Na levels for the coastal areas of Cyprus (being <10 km in distance from coastline). This upward trend for water Na was not documented for the non-coastal (>10 km distance from coastline) sampling points.

The implications of this work are important, as ongoing climate change manifestations via e.g., sea level rise or precipitation pattern changes continue to threaten the resilience of groundwater bodies near coastal zones in the Mediterranean region and beyond. This is not just a coastal (island) phenomenon; increase in freshwater salinity has been evidently observed in water quality data from e.g., U.S. rivers and streams (Stets et al., 2020; Thorslund et al., 2021). Groundwater depletion threatens water security in semi-arid or arid areas, like those areas in the Mediterranean region but recent data suggest an overall greater role of groundwater in supplying streamflow and evapotranspiration due to larger groundwater recharge (Berghuijs et al., 2022). The coastline and its cities located in the Mediterranean region and in Southeastern Asia, including islands all over the globe will be especially vulnerable to climate-driven environmental pressures, such as salinization of groundwater, erosional patterns and overall water resources deterioration, both in quantity and quality, including public health impacts.

Globally, the salinity of drinking water associated with coastal groundwater aquifers is anticipated to significantly increase in the next decades (Zamrsky et al., 2024). This is particularly important for coastal areas as they usually host cities and mega-cities. This study's findings have important ramifications for the burden of disease for such coastal populations around the globe under a changing climate prism, and their reliance on local groundwater sources used directly for satisfying potable needs, or being mixed with other water sources (surface water, desalinized sea water, etc.) before consumption.

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CRediT authorship contribution statement

Christina Xeni: Writing – original draft, Validation, Formal analysis, Data curation. **Matthew O. Gribble:** Writing – review & editing, Writing – original draft, Validation, Resources, Investigation. **Gualbert H.P. Oude Essink:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Lora E. Fleming:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation. **Konstantinos C. Makris:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

No conflict of interest for all co-authors.

Data availability

The datasets used and analyzed during the current study will be made available online upon acceptance of the article.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.173332.

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