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Drinking water salinity is associated with hypertension and hyperdilute urine among Daasanach pastoralists in Northern Kenya

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CONFLICTS OF INTEREST

HJB has consulted for Novo Nordisk on a project unrelated to this one. There are no other conflicts of interest to declare.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Abstract

Water salinity is a growing global environmental health concern. However, little is known about the relation between water salinity and chronic health outcomes in non-coastal, lean populations. Daasanach pastoralists living in northern Kenya, traditionally rely on milk, yet are experiencing socioecological changes and have expressed concerns about the saltiness of their drinking water. Therefore, this cross-sectional study conducted water quality analyses to examine how water salinity, along with lifestyle factors like milk intake, was associated with hypertension (blood pressure BP ≥140mmHg systolic or ≥90mmHg diastolic) and hyperdilute urine (urine specific gravity <1.003 g/ml, indicative of altered kidney function). We collected health biomarkers and survey data from 226 non-pregnant adults (46.9% male) aged 18+ from 134 households in 2019 along with participant observations in 2020. The salinity (total concentration of all dissolved salts) of reported drinking water from hand-dug wells in dry river beds, boreholes, and a pond ranged from 120–520 mg/L. Water from Lake Turkana and standpipes, which was only periodically used for consumption when no other drinking sources are available, ranged from 1100–2300 mg/L. Multiple logistic regression models with standard errors clustered on households indicate that each additional 100 mg/L of drinking water salinity was associated with 45% (95% CI: 1.09–1.93, P=0.010) increased odds of hypertension and 33% (95% CI: 0.97–1.83, P=0.075) increased odds of hyperdilute urine adjusted for confounders. Results were robust to multiple specifications of the models and sensitivity analyses. Daily milk consumption was associated with 61–63% (P<0.01) lower odds of both outcomes. This considerable protective effect of milk intake may be due to the high potassium, magnesium, and calcium contents or the protective lifestyle considerations of moving with livestock. Our study results demonstrate that drinking water salinity may have critical health implications for blood pressure and kidney function even among lean, active pastoralists.

Keywords

Water salinity; chronic health; pastoralists; water quality; blood pressure; kidney

1. Introduction

Salt leaching into freshwater is a growing concern to global environmental health (Benneyworth et al. 2016; Khan et al. 2014; Scheelbeek Pauline et al. 2017). Many processes lead to groundwater salinity, including coastal water intrusion, climate change, enrichment of groundwater by mineral content via evaporation, natural dissolution of evaporite salts, membrane effects such as salt filtering, and anthropogenic effects such as groundwater abstraction for consumption or irrigation and salting roads (Damania et al. 2019; Kaushal et al. 2005; Nthunya et al. 2018; Rivett et al. 2019; Van Weert et al. 2009). Yet regardless of the cause, drinking water salinity affects acceptability and palatability of drinking water and contributes to water insecurity (Benneyworth et al. 2016). While the majority of research has examined the health implications of improved (e.g., public standpipe, borehole) vs unimproved (e.g., unprotected dug well, surface water) water sources on fecal contamination (Mackinnon et al. 2018; World Health Organization 2019a; World Health Organization 2019b), much less research has examined the negative health outcomes of water salinity, particularly outside the contexts of saltwater intrusion in coastal sites (Scheelbeek Pauline et al. 2017). A scarcity of data exist on how many people consume potentially health-harming, high-salinity drinking water or on the connection between salty drinking water and chronic health outcomes, especially in semi-arid African sites (Comte et al. 2016; Rivett et al. 2019; Rivett et al. 2020).

Salt in drinking water can have several negative effects on health and human biology (Rosinger and Young 2020; Shammi et al. 2019). Most notably, drinking water salinity has been linked with raised systolic and diastolic blood pressure (BP) as well as increased risk of hypertension (Khan et al. 2014; Naser et al. 2019; Scheelbeek Pauline et al. 2017; Shammi et al. 2019). Among women, increased consumption of saline water is associated with risk of pre-eclampsia, gestational hypertension, and fetal loss (Khan et al. 2014). Moreover, drinking water salinity might be related to cognitive performance, as it was found to be negatively associated with children's educational attainment (Akter 2019). However, recent data also showed that mild salinity was associated with lower BP and hypertension because of higher concentrations of potassium (K+), calcium (Ca), and magnesium (Mg) cations in the water, which are protective against hypertension (Naser et al. 2019). Therefore, while the body of literature demonstrates the negative health effects of water salinity on BP, these effects may be mitigated by the concentration of accompanying cations.

Less is known about the relation between salinity in water and kidney function. Salt in drinking water may lead to kidney issues directly via excessive strain (i.e., increased workload for the sodium and other cellular pumps in the nephron) or indirectly via its hypertensive effects (Brenner et al. 1988; Choukroun et al. 1997; Lindeman et al. 1984). The kidneys play a critical role in body water and electrolyte balance (Schrier 2006). The number of nephrons, the functional units of the kidney, correspond to renal functional capacity. They remove excess solutes from blood before it becomes toxic, including electrolytes and protein, and waste products, like creatinine and urea. Nephrons also concentrate and dilute urine in response to water intake and concomitant changes in anti-diuretic and anti-natriuretic hormones such as arginine vasopressin and aldosterone (Sands 2009). Thus, nephrons are critical in concentrating urine to conserve body water (Sands and Layton 2014). Preliminary findings suggest that higher salt intake from water sources in Bangladesh are associated with higher sodium and protein excretion, which can indicate progressive kidney failure (Naser et al. 2020a; Naser et al. 2017). Moreover, water quality has been posited as potentially playing a direct or indirect role in chronic kidney disease (CKD) of unknown etiology (Imbulana et al. 2020). One of the signs of declining kidney function is the inability to concentrate urine to conserve body water, which typically occurs with aging and a variety of disease states (Bricker et al. 1959; Lindeman et al. 1985; Rosinger et al. 2019; Sands 2012). However, to date, a critical gap exists in the literature connecting the potential impacts of water salinity levels on kidney function.

The relation between water salinity and health is of growing concern in many parts of eastern Africa (Rivett et al. 2019), where a variety of socioecological changes are impacting environmental exposures, water security, lifestyle changes, and human health. Perception of water and its organoleptic properties often drives behavior and choice related to which water sources are used within an environment (Doria et al. 2009; Rowles et al. 2018; Wright et al. 2018). Lake Turkana is the world's largest desert lake. It is a moderately saline and alkaline endorheic lake, with more than 80% of its inflow coming from the Omo River in the north and no outflow, as it is a closed basin. Lake Turkana's salinity has been increasing slowly since the basin became closed hydrologically some 10,000 years ago (Avery and Tebbs 2018), and is prone to salinity due to evaporation and concentration of salts in the water (Yuretich and Cerling 1983). The principal ionic contributions of the lake's salinity are sodium ($Na+$), chloride ($Cl-$), and bicarbonate (HCO_3) (Avery 2013; Serem 2012; Yuretich and Cerling 1983). Similarly, the soil and groundwater in shallow dug wells in the Turkana basin are also dominated by Na, Cl, and HCO_3 as they constitute the majority of the water salinity with a minority due to K + Mg + Ca (Hopson 1982; Mugai 2004; Yuretich and Cerling 1983).

Daasanach semi-nomadic agro-pastoralists living in the area avoid using Lake Turkana as a source of drinking water unless no other options are available (Bethancourt et al. In Press). Instead, they dig wells in dry riverbeds as a primary water source, but even that water is known to be salty. In fact, the name given to one of their dug wells, "El Chuchumbi," literally translates to "the salty river." In informal interviews with our study team in 2017, Daasanach frequently expressed concerns about the saltiness of their drinking water and worry that it makes their cattle sick. The Gilgel Gibe III Dam completed in 2015 in southern Ethiopia has stopped flood pulses, causing shrinking of Lake Turkana in Northern Kenya and an ~1.5-meter drop in water levels, (Hodbod et al. 2019). The water salinity of Lake Turkana has been shown to be driven by lake levels as greater evaporation exacerbates this problem (Tebbs et al. 2020). Therefore, this socioecological change, coupled with increasing frequency of droughts due to climate change, has caused further concern of increased future salinization of the Lake and surrounding groundwater for Daasanach (Avery 2013; Avery and Eng 2012; Avery and Tebbs 2018).

It is currently unknown, however, if and how consumption of this notably salty water may be affecting the health of Daasanach people. It is important to investigate whether it might be having similar effects on BP and kidney health as observed in other populations exposed to saline water (Scheelbeek Pauline et al. 2017). As pastoralists, Daasanach are lean and relatively physically active, characteristics that are normally key protective factors against chronic diseases like hypertension (Chobanian et al. 2003; Pescatello et al. 2004) and chronic kidney disease (Stengel et al. 2003). East African pastoralists also have traditionally consumed high quantities of milk (Leslie and Little 1999), which may be protective of hypertension due to its high potassium levels (Houston and Harper 2008). Yet, even their activity levels may be changing as water shortages, increased demand for oil and energy resources in the area, and resulting food insecurity affect their traditionally semi-nomadic livelihood and ability to travel with their livestock to find pasture (Avery 2013; Serem 2012). These socioecological changes could have major consequences for Daasanach BP, kidney health, and related chronic disease risk.

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To fill these knowledge gaps and better understand how water salinity relates to BP and kidney function in a lean, active pastoralist population experiencing socioecological changes affecting their water security and livelihood, this study had three aims:

Aim 1: Describe the water salinity of the environmental water sources used both for drinking and primarily non-drinking purposes throughout a range of communities and environments used by Daasanach.

Aim 2: Test the association between water salinity and BP and the prevalence of hypertension (BP ≥140mmHg systolic or ≥90mmHg diastolic). We hypothesized that increased water salinity would be associated with higher systolic and diastolic BP and higher odds of hypertension.

Aim 3: Test the association between water salinity and urine concentration, a proxy of kidney function. We hypothesized that increased water salinity would be associated with higher odds of hyperdilute urine (urine specific gravity <1.003 g/ml), which is indicative of kidney tubular epithelial damage, deterioration in the kidneys' ability to concentrate urine, and below typical hydration levels.

2. Methods

2.1. Field site and environment

Daasanach agro-pastoralists inhabit a territory that surrounds the northeastern shore of Lake Turkana in northern Kenya with an estimated population of 12,000 across 26 communities. They also live along the Omo River in southern Ethiopia (Gebre 2012). In June and July 2019, we collected health biomarkers and survey data among seven Daasanach communities in Northern Kenya, which ranged from 110 meters to 32.9 kilometers from the Illeret Health Clinic (Figure 1). The variation in distance from the main town of Illeret, located near the shore of Lake Turkana at 4.314° N, 36.227° E and ~380 m above sea level, allowed us to capture variation in water source use and access, lifestyles, and environmental exposures. Six of the seven sampled communities were permanent settlements, while one community was nomadic, meaning they moved their shelters, belongings, and livestock every few days or weeks. Communities, especially in Illeret, frequently run together without formal cutoff points.

In addition to health and survey data, we also tested the quality of the drinking water used by the communities we surveyed and several additional water sources near Illeret and in the neighboring pasture lands. The primary source of drinking water used by Daasanach households are hand dug wells (locally referred to as lagas, laggas, or luggahs) within the dry riverbeds that drain into Lake Turkana. The depth of the wells varies by season but most vary from 1/3 of a meter to 1.5 meters in depth. Depending on the geology and water table, shallower wells are dug and can be re-dug a meter or two away if they get overused or destroyed by livestock or wild animals. In rockier riverbeds or with deeper groundwater, wells can be used for several days by many people and can take up to two-three days of digging. The water from these wells can be considerably turbid, so Daasanach use a variety of flocculants/natural coagulants as traditional water treatments to deal with the turbidity of water, including stirring it with the huluf branch (*Maerua Decumbens*) (Musyoki et al.

2016), adding a spoonful of milk, or adding a pinch of salt to get the sand or dirt to settle before drinking it.

The limited water quality data describing the groundwater from dry river beds and springs indicate that sodium and chloride are the predominant anions (Hopson 1982). The salinity in soils and groundwater in this region is due to long-term mineral weathering due to extreme aridity and evaporation (Mugai 2004). Due to these conditions, soluble salts, primarily sodium and chlorides, are widely present in the region due to weathering of volcanic parent materials in these arid conditions (Mugai 2004). Far more data on the hydrology and geochemistry of Lake Turkana is available (Avery and Tebbs 2018; Hopson 1982; Ojwang et al. 2016; Tebbs et al. 2020; Yuretich and Cerling 1983). In brief, Lake Turkana is the largest (surface area: 6,750 km^2) closed-basin, desert, moderately saline (2500 TDS, conductivity 3500 ms/cm), alkaline (pH ~9.2) lake located in the Great Rift Valley (Ojwang et al. 2016). It's primary inflow (~88%) is from the Omo River, while the remaining inflow comes from the Turkwell and Kerio Rivers, and less than 5% from rainfall (Yuretich and Cerling 1983). Due to its closed-basin nature, it loses water primarily through evaporation and some to groundwater exchange (Ojwang et al. 2016). The salinity is dependent on lake level and season as conductivity is lowest during the rainy season when inflow from the Omo River is the highest; the conductivity increases farther south away from the Omo delta and is highest during the dry season (Hopson 1982). Detailed analyses by Hopson found that sodium contributed over 95% of the weight of the major ions, similar to other closed basin East African lakes with high salinities. The volcanic rocks of the Omo River catchment produce runoff waters rich in sodium (Hopson 1982).

The region of Kenya inhabited by Daasanach is hot and arid. According to weather data from the nearest weather station to our site, Lodwar located on the southwest side of Lake Turkana, average monthly temperatures over the last decade have ranged from 27°C to 34°C, with lows between 22°C and 27°C, and highs between 35°C and 37°C while real feel temperature often exceeds 40°C (World Weather Online 2020). Data spanning the years 1950 to 2012 suggest that annual rainfall ranged from 54 to 725 mm, with a mean of 217 mm (Opiyo 2014). Even during the rainy seasons, between March and May and again between October and December, peak monthly rainfall has not surpassed 110 mm over the last decade (World Weather Online 2020).

As a consequence of the heat and scarce rain, water, and irrigation, agricultural activity is more limited among Daasanach communities in northern Kenya relative to those in Ethiopia. Hence, the staple foods of Daasanach diet, maize, beans, and sorghum, often have to be purchased at small stores or larger trading depots in Ethiopia or from passing merchants or received via food aid. The limited water also means that livestock have to regularly move to new areas for grazing, so availability of milk may be substantially limited among those living in settled communities relative to those traveling with the livestock. Communities, both settled and nomadic, are typically constructed such that the living structure(s) and livestock enclosures are in very close proximity. The household unit, called a boma, often contains a large number of domestic animals, most typically goats and sheep, at any given time. This regular close contact and lack of delineation between human and livestock living spaces result in high levels of animal fecal material existing around the living spaces of community members, even for those living in more settled communities.

2.2. Participant Recruitment

Participating households were recruited with the help of Community Health Volunteers and community elders. A protocol of inviting every third house (or the neighboring house when a selected household was empty) to participate in the study allowed for a random selection of households and provided a sample 12–28 households per community. Further description of the study is available elsewhere (Bethancourt et al. In Press). For this study, we analyzed data from 226 non-pregnant adults aged 18 years or older living in 134 households; 225 had data collected on urine specific gravity and all covariates and 223 had data on BP and all covariates.

The research was conducted following the Declaration of Helsinki and was approved by the Institutional Review Board of Pennsylvania State University (STUDY00009589) and the Kenya Medical Research Institute (KEMRI/RES/7/3/1). Permission was also obtained from the Director of Health in the county government of Marsabit, Kenya and from community leaders in all of the communities sampled. All participants provided written and verbal informed consent.

2.3. Outcomes

2.3.1. Systolic and diastolic blood pressure and Hypertension: Systolic and diastolic BP was measured twice using an Omron (7 Series) upper-arm blood pressure monitor with a period of 3–5 minutes in between readings. Following protocols for field studies and using the appropriate cuff size to fit upper arm circumference (James and Gerber 2018), BP measurements were taken while participants were seated in a chair with their arm resting on an armrest or table following a period of inactivity of at least 5 minutes. In analyses, we used the second BP reading to reduce the chances of the white coat effect (James and Gerber 2018). Systolic and diastolic BP readings were, on average, 2.4 and 1.8 mmHg lower, respectively, in the second readings relative to the first. BP data were imputed for four adults lacking a second BP measurement by subtracting these values from their single BP measurements.

Hypertension was our primary outcome and was defined following the World Health Organization and International Society of Hypertension (Unger et al. 2020) as either a systolic BP of ≥140 mm Hg or a diastolic BP of ≥90 mm Hg.

2.3.2. Hyperdilute urine—Participants provided a spot urine sample in standard urine container cups before being interviewed. Samples were covered and placed in the shade to cool. Within 30 minutes of sample collection, they were measured in triplicate for urine specific gravity (USG) using a hand-held digital refractometer (Atago; Tokyo, Japan). USG measures the ratio of the density of urine to the density of water and is a biomarker of hydration status that is highly correlated with other urinary biomarkers of hydration status, such as urine osmolality (r>0.9) (Wutich et al. 2020). For analyses, USG was averaged from the three readings. The normal range is defined clinically as 1.005–1.030 and hyperdilute urine, defined as <1.003, is considered highly unusual and is normally indicative of significant kidney tubular epithelial damage, or associated with either kidney failure, diabetes insipidus, polydipsia (excessive fluid intake) (Cook et al. 2000; Needleman et al. 1992).

2.4. Main predictor: Water salinity—During in-person surveys, we inquired about each household's primary source of drinking water. We traveled to each of the water sources guided by local research assistants and community members. Once there, water samples were collected following methods laid out by the USGS (Wilde et al. 1998). We tested the water quality of each named water source we were able to locate using a YSI ProDSS Multi-Parameter Water Quality Meter and accompanying sensors (Nthunya et al. 2018). We used the YSI calibration cup to collect water samples for immediate testing in the field. After ensuring all probes were completely submerged in the water sample, releasing any air bubbles, and waiting several seconds for the sensor to stabilize, three successive recordings were taken 1–2 seconds apart. We followed ProDSS protocols (YSI ProDSS 2017) for storage, cleaning, and calibration for each of the conductivity, pH, and turbidity probes. All probes were calibrated using their respective calibration standards, with the calibration verified each day the instrument was used.

Most households in each community shared the same one to three water sources. When respondents stated they used a hand-dug well in a dry riverbed but did not provide the specific name associated with the location, we imputed data from the average for the two nearest and most likely used hand-dug wells based on their location.

In addition to testing the primary drinking water sources, we also sampled several water sources, including Lake Turkana and standpipes that piped water from a shallow well in the flood plain beside Lake Turkana to communities near Illeret. The water from two normal standpipes was reportedly used for washing and cooking. These standpipes, which do not require any hand pumping but rather have a tap which is locked and flows freely when turned on, are described as salty and are likely to be infiltrated by lake water along with some exchange with the groundwater. This water was reportedly only consumed in small quantities if other water is not available. For example, during a follow-up visit in September-October, 2020, the water table in many of the dry riverbeds was too low for many hand-dug wells to be used. As a result, many community members reported drinking water from the tap standpipes, despite the salinity concerns. One standpipe near Illeret used de-salinization technology, but relative to the other standpipe water cost of 2 shillings per 20 liters, the de-salinated water was too costly (20 Kenyan shillings per 20 liters ~0.20 USD) for most households to use it as a primary drinking water source.

Our key predictor variable was the salinity content of drinking water sources used by Daasanach. The YSI ProDSS meter provided us with a direct measure of salinity, the total concentration of all dissolved salts in the water, in parts per thousand, the equivalent of 100 mg/L. This measure does not distinguish sodium chloride (NaCl), which is the most common salt composition contributing to water salinity overall (U.S. Geological Survey 2016). However, prior work has found that NaCl is the most common salt in the Lake Turkana basin groundwater (Hopson 1982; Yuretich and Cerling 1983). The YSI ProDSS also provided three additional proxies of water salinity through resistivity (ohm), specific conductivity (mS/cm) corrected to 25 °C, and total dissolved solids (TDS) (mg/L); these measures have been used in other studies as surrogates of water salinity (Akter 2019; Naser et al. 2019; Rivett et al. 2019). The same conductivity sensor provides the salinity, conductivity, resistivity, and TDS readings as they are based on calibrated equations. Additional measurements obtained from the water quality meter are water temperature (°C), pH, and turbidity (FNU). Coefficients of variation for triplicate samples of all water quality measures, with the exception of turbidity, were <0.3. Average coefficient of variation for all non-zero turbidity measurements was 1.51.

While there are no guidelines regarding the maximum salinity levels in water for health, the taste and acceptability of water are generally reported as unsatisfactory at levels above 200 mg/L (Benneyworth et al. 2016; World Health Organization 2008). Moreover, freshwater is defined as water with less than 0.5 or 1 ppt (500 or 1000 mg/L) salinity depending on the organization (Ohrel and Register 2006; U.S. Geological Survey 2016). However, we were interested in the health effects of incremental increase; therefore, we treated this variable as continuous, examining the relationship of each 100 mg/L in concentration of salt in water. We did not have a measure of total volume of water consumed and therefore we cannot account for volume or total salt consumed from water.

2.5. Covariates

Covariates for this study were chosen a priori based on the literature. Milk intake is a traditional hydration strategy for East African Pastoralists and historically the single largest source of calories (Galvin 1992; Leslie and Fry 1989). Milk availability can also serve as a proxy measure of access to livestock and a more traditional livelihood strategy, as the more distant communities (those outside of Illeret town) lived with their livestock, while those living in and around Illeret did not have immediate access to their full herd. Therefore, we asked participants about their usual intake of milk consumption from any of their animals in the previous week. We categorized this into no intake in the last 7 days, less than once per day (1–6 times per week), or daily intake (1 or more times per day).

Daasanach have a daily (often multiple times per day) tradition of drinking tea made with black tea leaves and/or coffee made with coffee husks (Sagawa 2006). We asked about the number of times each adult consumed coffee or tea in the previous day, as caffeinated beverages may affect blood pressure and urine concentration if consumed in high amounts (Killer et al. 2014; Nurminen et al. 1999).

We also controlled for time of day as it can influence BP (Koroboki et al. 2012) and urine concentration (Perrier et al. 2013). The time of urine samples was noted, and BP recordings were usually taken within the next 20 minutes. At this same time, ambient temperature, humidity, and heat index were measured with a Kestrel 3000 pocket digital weather meter (Kestrel; Boothwyn, PA) since ambient temperature and exposure to heat can affect BP (Scheelbeek Pauline et al. 2017), as well as water needs and the concentration of urine (Rosinger 2015).

Malnutrition either through high or low body mass index (BMI) is a risk factor for hypertension and chronic kidney disease (Hall et al. 2014). BMI is also associated with urine concentration (Yeh et al. 2015). Participants had their weight (nearest 0.1 kg) measured with a Tanita BF-680W bioelectronic impedance scale (Tanita; Arlington Heights, Illinois), and their height (nearest 0.1 cm) measured without shoes on a portable Seca standing stadiometer, which was placed on a hard, flat surface. BMI was calculated as kg/m^2 and treated as a continuous variable.

Since kidney problems and diabetes are both associated with hypertension (Atkins 2005; Jha et al. 2013), we asked participants if a doctor or nurse told them they had kidney problems or diabetes. We included in our analysis a binary variable indicating if they reported having either of those conditions. We note, however, that access to health care is limited in this population and undiagnosed kidney conditions may be present.

We controlled for age in years and sex (male/female) because of evidence suggesting men tend to have higher BP (Sandberg and Ji 2012) and USG (Perucca et al. 2007) than women.

Daasanach are traditionally nomadic, moving with their livestock. Therefore, we asked them about the number of times they have moved or traveled with their herd in the past year as an indicator of their mobility and lifestyle.

To account for distance to the water source and as a proxy of physical activity and time investment needed to get water, we asked participants to report the amount of time a single trip takes them to fetch water from their home, including wait time and return to their home. Participants reported total time, and for analysis this was treated as a continuous variable, broken into 10-minute increments.

Finally, we controlled for the value of their household's total livestock as a proxy for household wealth, as this is the primary livelihood strategy among East African pastoralists (McCabe 2010). We asked the male and female household heads about the total number of cattle, camels, sheep, goats, and other animals, and we obtained information on the approximate value of each species from our community assistants. We then multiplied livestock count for each species by the corresponding approximate Kenyan Shilling value (cattle=15000 KSH, camels=30,000, donkey=8,000, sheep/goat=3,750, chicken=1500) and summed these values across all species owned per household, then converted to US Dollars.

2.6. Statistical methods

All analyses were conducted in Stata version 15.1 (College Station, TX). Two-tailed t-tests were used to assess mean differences in sample characteristics. For our first aim, we describe the water quality results of the drinking and non-drinking water sources available to Daasanach in the area around Illeret and in the more remote, communal land set aside for grazing purposes–known as the "Fora" on which one of the research communities and other nomadic Daasanach communities move with their herds in search of pasture and water. We provide the mean and range of variation of the water quality results.

For our second aim, we analyzed the association of water salinity on systolic and diastolic BP with linear regression models. We tested the odds of hypertension in relation to water salinity using logistic regression models. We clustered robust standard errors on the 134 households, similar to work done with other data from this study (Bethancourt et al. In Press). We also tested for a potential mediation effect of hyperdilute urine on hypertension, as impaired kidney function may increase risk of hypertension (Brenner et al. 1988). Next, we computed the predicted probability of hypertension using the results from the fully adjusted logistic regression model by water salinity levels using marginal standardization adjusting for the distribution of covariates (Muller and MacLehose 2014).

For our final aim, we analyzed the association of water salinity on the odds of hyperdilute urine (USG<1.003) using logistic regression models with robust standard errors clustered on the household. Similar to our approach to aim 2, we next estimated the predicted probability of hyperdilute urine using marginal standardization. We also tested for a potential mediation effect of hypertension on hyperdilute urine, as hypertension is known to affect kidney function (Lindeman et al. 1984).

We analyzed three models for each outcome following the same sequence: 1) unadjusted, 2) adjusted by sex, age, BMI, time of day of the measure, and heat index, and 3) fully adjusted for the aforementioned covariates in addition to milk consumption, tea and coffee consumption, kidney and diabetes, wealth, mobility, and time needed for a single water collection trip. This sequence of modeling is similar to other analyses (Naser et al. 2019). We examined the variance inflation factor (VIF) for the BP results of the fully adjusted model; all independent variables had VIFs<2, indicating multicollinearity was not affecting the results.

Finally, we conducted three sensitivity analyses. First, we excluded women with missing data on pregnancy status. Second, we excluded the two most remote communities (n=51) that live more traditional and mobile lifestyles, as this may confound the relationship between water salinity and BP and kidney function. Our final check re-estimated the regression models excluding adults who reported having any kidney problems or diabetes (n=14) from the restricted sample rather than control for these conditions.

3. Results

3.1. Water quality results of drinking and non-drinking water

Unprotected hand-dug wells in dry riverbeds (lagas) were the most commonly used water source for drinking purposes, reported by 91% of our sample (Figure 1). Other water sources reported for drinking purposes were a pond used by the most nomadic community in our sample. There was also a protected borehole near where the nomadic community had temporarily set up camp; households had not reported using the borehole in surveys, though individuals were seen traveling to the borehole the day following the surveys.

The water sampled in the dug wells in or near Illeret town had an average total salinity concentration of 340 mg/L ±110 standard deviation (SD) and ranged from 220–520 mg/L (Table 1; Figure 2). The salinity concentration of the water sampled in the dug wells used by our sample communities was slightly lower than the salinity in more remote dug wells used by other nomadic communities outside of Illeret [450 mg/L ±180]. The remote boreholes also had higher salinity levels [475 mg/L ±7]. The pond used by the nomadic community had the lowest salinity level at 120 mg/L of the reported drinking water sources used by our study sample. The other mean physical characteristics of dug wells were a water temperature of 30°C ±1.0, specific conductivity of 0.70±0.23 mS/cm, resistivity of 1,424 ±439 ohms, total dissolved solids (TDS) of 455±148 mg/L, pH of 8.2 ±0.2, and turbidity of 99.6±94.0 FNU. Salinity, TDS, and conductivity were all highly correlated (r>0.99) as they are measured by the same sensor. Therefore, we focus on the salinity measurements throughout the results.

Water sampled from Lake Turkana off the shore of Illeret was 1630 mg/L, while the two improved sources, i.e., the public standpipes that pumped water up from a well in the floodplain beside the lake had salinity concentrations of 1100 and 2300 mg/L. Lake Turkana had slightly higher salinity (1730 mg/L) farther south in Sibiloi National Park. The one improved de-salinated standpipe in Illeret was completely effective at removing salt (10 mg/L) at the time.

3.2. Drinking water salinity and blood pressure and hypertension

The mean systolic and diastolic BP values for adults were 116 and 83 mmHg, respectively. Systolic, but not diastolic pressure, was significantly higher for men (119/84 mmHg) than for women (114/82 mmHg) (t=2.71; P=0.007). Overall, 26% of adults had hypertension, with no sex differences (25.4% men vs 26.7% women). The average age of the sample was 40.7 years, with men older than women (46.5 vs 35.2 years, t=6.1, P<0.001). Those with hypertension were significantly older than normotensive adults (45.1 vs 38.9 years, t=2.73, P=0.007). The mean BMI of adults was 18.2 kg/m^2 which is classified as underweight, with no significant sex differences (17.9 for men vs 18.6 for women) and no differences by BP (Table 2). The average drinking water salinity consumed by those with hypertension was significantly higher (393 mg/L) than the water consumed by normotensive adults (348 mg/L) (t=2.53; P=0.012).

In examining the bivariate relationships for men and women, we see a trend toward increasing systolic and diastolic BP with increasing water salinity levels up until the highest level of water salinity (Supplemental Figure A.1a/b). However, it is important to note that the water source with the highest salinity levels was the main water source of a community relatively far outside of Illeret town. Households in that community were more mobile (4.6 moves in the last year) than communities in and around Illeret (1–2 moves), which is indicative of a more traditional lifestyle. These households were also able to keep their livestock nearby, allowing for more regular milk consumption relative to households near Illeret where pasture land was scarce. In contrast, the pond used as a drinking water source by the nomadic community had the lowest measured salinity level at 120 mg/L, but their active and traditional lifestyle (11.1 moves in the last year) may help account for their low BP.

We next examined the relationship using multiple linear regressions. In these analyses, each 100 mg/L increase in drinking water salinity was significantly associated with higher diastolic (β=1.58 mm Hg, SE=0.59, P=0.008), but not systolic (β=1.04 mm Hg, SE=0.87, P=0.23), BP in the models adjusted for sex, age, BMI, time of measurement, and heat index

(Table 3, **models 2 & 5**). The associations were slightly attenuated for both systolic BP (β=0.81 mm Hg, SE=0.88, *P*=0.36) and diastolic BP (β=1.15 mm Hg, SE=0.60, *P*=0.055) in the fully adjusted model that further controlled for milk intake, tea and coffee consumption, kidney problems or diabetes, wealth, mobility, and water fetching time.

Finally, we used logistic regression models to examine the association of drinking water salinity with the odds of hypertension. These analyses produced results consistent across the unadjusted, adjusted, and fully-adjusted models (Table 4, **models 1–3**). In the fully adjusted model, each additional 100 mg/L of salt in drinking water was associated with 45% (Odds ratio [OR]=1.45, 95% confidence interval [CI]: 1.09–1.94, *P*=0.010) higher odds of hypertension. Notably, consuming milk one or more times per day was associated with significantly lower odds of hypertension (OR=0.39, 95% CI=0.18–0.84, *P*=0.016) compared to not consuming any milk in the previous week. Using data from this analysis to model the predicted probability of hypertension over the range of water salinity for drinking sources measured, the predicted probability of hypertension increased from 13.0% at the low end of 120 mg/L up to 36.2% at the high end of 520 mg/L (Figure 3).

To examine whether hyperdilute urine mediated the relationship between water salinity and hypertension, we added it as a predictor. We did not find evidence of mediation as hyperdilute urine was not significantly associated with hypertension (OR=0.74, 95% CI: 0.37–1.46, *P*=0.39), and the association between water salinity and hypertension was consistent with the main analyses (Supplemental Table A.1, **Model 1**).

3.3. Water salinity and kidney function/hyperdilute urine

The average USG for adults in our sample was 1.010 g/ml ±0.008, and there were no sex differences. Overall, 30.7% had hyperdilute urine, and the proportions were not significantly different by sex, BMI, or age. The average water salinity was significantly higher (386 mg/L) for those with hyperdilute urine than those with USG≥1.003 (349 mg/L) (t=2.18, *P*=0.031). USG declined in relation to the salinity of the household drinking water source. But as with the bivariate plot of BP and water salinity, there was again a curvilinear relationship, likely because of the more active and traditional communities at the two ends of the water salinity spectrum (Supplemental Figure A.2).

Using the same modeling and covariate sequence as for hypertension, logistic regression models estimated each 100 mg/L increase in water salinity to be significantly associated with 36% (95% CI: 1.04–1.78, *P*=0.025) higher odds of hyperdilute urine adjusted for sex, age, BMI, time of day and heat index, respectively (Table 4, model 5). This association was of a similar magnitude but no longer statistically significant in the model (Table 4, model 6) that further adjusted for milk consumption, tea and coffee, kidney and diabetes, wealth, and mobility (OR=1.34, 95% CI: 0.97–1.84, *P*=0.075). Consuming milk once or more daily was again highly protective, as it was associated with 63% (95% CI: 0.15–0.90, *P*=0.029) lower odds of hyperdilute urine relative to those who consumed no milk in the previous week. In examining the predicted probability of hyperdilute urine in relation to water salinity using the fully adjusted model, we found a similar pattern to hypertension, but with a smaller relative increase. The predicted probability increased from 18.9% at 120 mg/L up to 39.4% at 520 mg/L (Figure 4).

To examine whether hypertension mediated the relationship between water salinity and hyperdilute urine, we added it as a predictor. Again, we did not find evidence of mediation as hypertension was not significantly associated with hyperdilute urine (OR=0.72, 95% CI: 0.36–1.44, P=0.35), and the association between water salinity and hyperdilute urine was slightly stronger and statistically significant (OR=1.38, 95% CI: 1.00–1.89, p=0.049) with the main analyses (Supplemental Table A.1, Model 2).

3.4. Sensitivity analyses

In the primary analysis, we included 13 women with missing pregnancy status to avoid unnecessary exclusions and reduce power. Women with missing pregnancy data did not have significantly different age, blood pressure, percent hypertension, or hyperdilute urine than non-pregnant women without missing pregnancy status (36.2 vs 35.3 years; water salinity 374 vs 365 mg/L; systolic 118 vs 113 mmHg, diastolic 84 vs 82 mmHg, USG 1.010 vs 1.010 g/ml, all P>0.2). Results of the linear and logistic regression analyses when excluding these 13 women were consistent with the main analyses for systolic and diastolic BP, hypertension, and hyperdilute urine (Supplemental Table A.2).

Our second sensitivity analysis was to exclude participants (n=51) from the two remote communities that lived more traditional and mobile lifestyles and consumed water with the lowest (120 mg/L) and highest (520 mg/L) measured salinity levels (Supplemental Table A.3). In the fully adjusted models, we found stronger associations between each 100 mg/L and systolic (β=4.6 mm Hg, 95% CI: 1.7–7.5, P=0.002, n=172; Model 1) and diastolic BP (β=4.2 mm Hg, 95% CI: 2.2–6.3, P<0.001; Model 2) with the restricted sample. In fully adjusted logistic regression analyses, we found larger associations between each 100 mg/L and odds of hypertension (OR=1.89, 95% CI: 1.18–3.05, P=0.009, n=172; Model 3), but the association with odds of hyperdilute urine was not statistically significant (OR=1.46, 95% CI = 0.80–2.68, P=0.22, n=174; Model 4).

Finally, our third sensitivity check was to further exclude adults who reported having any kidney problems or diabetes (n=14). Results of the magnitude of association were stronger than the primary models (Supplemental Table A.4). Each 100 mg/L was associated with systolic (β=4.6 mmHg, 95% CI: 1.7–7.6, P=0.002, n=158; Model 1) and diastolic BP (β=4.3, 95% CI: 2.1–6.4, P<0.001; Model 2) and hypertension (OR=1.82, 95% CI: 1.12–2.95, P=0.015; Model 3). The association was still positive but not significantly associated with odds of hyperdilute urine (OR=1.55, 95% CI: 0.83–2.89, P=0.17; Model 4).

4. Discussion

This study had three aims: 1) to describe the water salinity of drinking and non-drinking water sources in hot-arid northern Kenya among Daasanach experiencing socioecological changes; 2) to test how the salinity of drinking water is associated with BP and hypertension; and 3) to test how drinking water salinity is associated with hyperdilute urine as an indicator of kidney function. Water quality data demonstrated that the salinity of drinking water used by households in our sample ranged between 120–520 mg/L, with all but one source (a pond that pools rainwater) being above the threshold (200 mg/L) of what might generally not be acceptable to taste and satisfaction (Benneyworth et al. 2016; World

Health Organization 2008). Several drinking sources approached the classification of brackish water (500–1000 mg/L), while water sources that were not usually used for drinking, including Lake Turkana and standpipes, exceeded that (1100 to 2300 mg/L). In line with our hypotheses, our results demonstrate that increased water salinity in drinking water sources was associated with higher odds of hypertension and marginally associated with hyperdilute urine. These results were sensitive to multiple specifications. Overall, our findings imply that water salinity may raise the risk of hypertension and possibly impair kidney function at mild salinity concentrations in a lean, pastoralist population, while milk consumption may be protective against these conditions.

The World Health Organization (WHO) recommends a daily maximum salt intake of 5000 mg and 2 g of sodium (World Health Organization 2012). Total salt intake could be relatively high among these Daasanach communities given that the lake and standpipes had salinity levels approaching and exceeding 2,000 mg/L, which some people reported drinking if they were out in the "Fora" with livestock or if they were fishing and they had no other available water, and that this water is used for cooking. Past non-governmental organization projects in the area have built boreholes and handpumps, but many have been placed in dry riverbeds and were subsequently destroyed during flooding. There may be unintended health consequences when new water sources are provided to communities that have high salinity content. During a follow-up in September 2020 in the dry season, we found that the standpipes in and around Illeret were used for drinking despite being generally eschewed during the wet season when the groundwater levels are high enough to dig shallow wells by hand. These results should inform future water projects in the region that shallow dug wells may provide lower salinity levels than deep boreholes or wells that draw upon older, higher salinity water (Van Weert et al. 2009). Therefore, water programs should verify the salinity status of water and major ionic contents, particularly sodium, chloride, and fluoride, prior to building new wells.

Compared to other groundwater wells in parts of East Africa, most of the hand-dug wells used during the course of this study would be classified as acceptable in terms of their TDS levels (<600 mg/L). Some countries like Malawi have maximum permissible limits of 2000 mg/L with drinking water upper limits of 500 mg/L while the WHO has a maximum limit of TDS of 1000 mg/L (Rivett et al. 2019; Rivett et al. 2020). Yet, the composition of the salinity is important for understanding the health implications. When the groundwater ionic concentration is predominantly composed of sodium and chloride, the potential harm is substantially greater than when it includes substantial amounts of other cations, like calcium, magnesium, or potassium. Prior studies have demonstrated that sodium and chloride are the major ions of groundwater in the Lake Turkana basin (Hopson 1982; Mugai 2004). Therefore, salinity levels of groundwater in the range of 400–500 mg/L here may be more detrimental to chronic health risks compared to the same salinity levels in other environments with less sodium and chloride and more magnesium and potassium (Naser et al. 2019). East African countries where many residents rely on groundwater, like Malawi, as well as the WHO should re-evaluate guidelines surrounding groundwater salinity, taking into account the specific groundwater ionic composition to better understand the varying health risks different sources might pose.

The broader health implications of these results for Daasanach and other populations are not straightforward. On one hand, Daasanach are exposed to high temperatures and, especially when actively tending to their livestock or fetching water, may be losing more body water and sodium through sweat. In such conditions, saline oral hydration solutions can be hugely beneficial relative to plain, non-saline water for ensuring adequate rehydration (Lifshitz and Wapnir 1985; Shirreffs et al. 1996). Daasanach may, therefore, be able to tolerate a greater degree of sodium intake than a sedentary person living in a climate-controlled environment. Nevertheless, the regular consumption of high saline solutions, even when not losing large amounts of body water from physical exertion or heat exposure, could result in levels of sodium absorption that surpass those merely needed to maintain adequate water balance. This could be contributing to higher BP among Daasanach and other populations in which elevated BP has been observed in relation to higher salinity concentrations of drinking water (Khan et al. 2014; Scheelbeek Pauline et al. 2017; Shammi et al. 2019). While we do not have data on sodium composition, but rather all dissolved salts, our findings raise important questions about what impact the degree of water salinity we observed might have on more sedentary populations living in more moderate climates.

The consumption of high-saline water is a key emerging environmental health risk factor for millions of people worldwide, including in East Africa (Damania et al. 2019; Rahman et al. 2019; Rivett et al. 2019). Prior work by Rivett and colleagues (Rivett et al. 2019) found that the groundwater used by many wells have high TDS and were composed of NaCl and that rock weathering and evaporation likely lead to salinity. Previous studies have found, similar to our study, that consuming water with a high sodium concentration is associated with higher BP and hypertension (Khan et al. 2014; Scheelbeek Pauline et al. 2017; Talukder et al. 2016), which is the biggest risk factor of cardiovascular disease (Bromfield and Muntner 2013). Only a few studies have examined the relationship between groundwater salinity and health outcomes in non-coastal sites experiencing saltwater intrusion (Faust 1982; Hallenbeck et al. 1981). However, our study results are similar to a recent cohort study in conducted in a coastal region of Bangladesh that reported a 0.95 mmHg and 0.57 mmHg systolic and diastolic BP difference in relation to each 100 mg/L decrease in drinking water sodium concentration and a 13.8% decline in odds of hypertension (Scheelbeek Pauline et al. 2017). In our primary analyses, we found a similar, though non-significant, effect size in systolic BP (β=0.80 mmHg, P=0.36), while we found a larger association for diastolic BP (β=1.10 mmHg, P=0.055) and 44% higher odds in hypertension. That we found a stronger association for diastolic BP and water salinity is consistent with one study among teenagers in Chicago, Illinois (Hallenbeck et al. 1981). However, in our robustness analyses, excluding the two most remote communities produced much stronger and more significant associations for systolic (β=4.4 mmHg) and diastolic BP (β=4.2 mmHg) in relation to each 100 mg/L increase in water salinity. These results drive home the point that even among physically active farming (Mir and Newcombe 1988) and pastoralist populations (Page et al. 1981), sodium intake, regardless of its dietary source, is associated with risk of hypertension when controlling for other lifestyle factors.

The high prevalence of hyperdilute urine (30.7%) among Daasanach adults was surprising. Unpublished data on urine samples collected from 1989–1994 from neighboring Turkana communities did not produce evidence of hyperdilute urine (Dr. Paul Leslie, UNC-Chapel

Hill, personal communication). Hyperdilute urine usually indicates severe tubular epithelial damage in the kidneys which could be acute or chronic, but it is often caused by repeated injury (Qi and Yang 2018) and the loss of the renal concentrating mechanism (Agaba et al. 2012; Sands 2012). Aging is typically associated with a loss of nephrons and the ability to concentrate urine (Lindeman et al. 1985; Lindeman et al. 1960), though evidence from two other relatively healthy and active small-scale populations suggests that the ability to concentrate urine may be preserved with aging (Rosinger et al. 2019). While a healthy kidney can dilute and concentrate urine effectively in response to changes in body water homeostasis, typical hydration levels for the 11^{th} to 90^{th} percentile in USG are between 1.012 and 1.027 and rarely below 1.005 (Armstrong et al. 2010). One study in Zambia, which examined the effect of water provisioning on cognition, found that 28% of the children in the treatment group used the study as a competition to drink as much water as possible and ended up having a USG <1.003 (Trinies et al. 2016). It is possible, but highly unlikely, that the high prevalence of hyperdilute urine in our study reflected excessive water consumption because we measured ad libitum hydration state and provided water only after the urine sample collected. Further, we were able to statistically control for time of day which would adjust for any specific times when higher intake of water or tea may occur.

Several other potential explanations exist for the high prevalence of hyperdilute urine we observed in our sample population beyond water salinity. Hyperdilute urine can be caused by toxicity such as heavy metals or chemicals in water or food, like high fluoride, which has been documented in the region (Hopson 1982), and water hardness which at toxic levels has also been proposed as causing CKD of unknown etiology (Dharmaratne 2019; Imbulana et al. 2020; Wasana et al. 2016). Second, repeated severe dehydration may cause tubular epithelial damage, which is likely in a hot environment, since epithelial cells are very sensitive to ischemia. This hot-arid environment where 93% of the households report water insecurity may increase the risk of CKD (Bethancourt et al. In Press). The mean USG of adults (1.010) was low compared to other populations living in hot environments (mean 1.018–1.020) (Rosinger et al. 2019), and the 31% prevalence of USG<1.003 does not reflect the expected physiological water requirements of adults inhabiting an environment with temperatures regularly exceeding 40°C. Evidence from other populations experiencing extreme heat, repeated dehydration, and heavy exercise demonstrates subclinical kidney injury which can lead to permanent kidney damage and CKD (Barraclough et al. 2017; Clark et al. 2016; Glaser et al. 2016; Jha et al. 2013). However, these studies generally indicate this risk through highly concentrated urine, indicative of dehydration, not hyperdilute urine.

Other potential causes for hyperdilute urine may be current or previous malaria infection, which can circulate in Illeret in the rainy season. Malaria can cause acute kidney injury and acute tubular necrosis (Mishra and Das 2008), and chronic lesions that do not resolve may lead to gradually deteriorating renal function (Houba 1975). In rare cases, malaria can cause diabetes insipidus (Akarsu et al. 2006; Premji et al. 2016). We did not collect information on previous malaria infection, though at the time of the study there was no malaria circulating, so we can rule out acute infections as a cause of the high prevalence of hyperdilute urine. Another possible cause of hyperdilute urine is diabetes insipidus. This rare condition (generally 3 cases per 100,000) manifests through the kidneys developing resistance to anti-diuretic hormone vasopressin and is clinically demonstrated by USG<1.005, polyuria, and polydipsia (Agaba et al. 2012). However, polydipsia or compulsive water drinking is another rare psychiatric condition that together with diabetes insipidus would not explain 30% of the sample having hyperdilute urine (Schrier 2006). Dietary factors can also play a role in urine concentration, as lower USG can be caused by high sodium, low protein diets compared to other diets, though even these diets do not result in USG<1.003 (Grillo et al. 2019; Meroney et al. 1958; Miller et al. 1941). Finally, prolonged hypertension is known to damage kidney tissue as well as the blood vessels, arterioles, and glomeruli in kidneys and is a major risk factor for CKD and kidney function decline (Lindeman et al. 1984). However, our results indicated that hypertension was not associated with hyperdilute urine and was not a mediator between water salinity and hyperdilute urine, therefore it is likely not the cause of the kidney damage.

Shifts away from traditional pastoralist livelihood strategies and heavy reliance on milk as a source of calories and hydration may mean consuming more saline water. The finding that daily milk intake was associated with lower odds of both hypertension and hyperdilute urine is important given that milk has approximately 440 mg of sodium per L (Barłowska et al. 2011), similar to many of the water sources in the area. However, milk has three times the quantity of potassium relative to sodium, very high calcium content, and a substantial amount of magnesium (Barłowska et al. 2011). All three of these minerals have protective effects on hypertension even when consuming water high in sodium (Naser et al. 2019; Naser et al. 2020b). Additionally, milk can increase the solute load in urine, therefore increasing USG. Higher milk consumption may also be a proxy for a more traditional lifestyle and moving with animals more frequently; physical activity and less reliance on carbohydrates for calories may provide protective benefits. Research from neighboring Turkana pastoralists indicates that those who moved to more sedentary communities have worse measures of cardiometabolic health compared to nomadic Turkana (Lea et al. 2019). Therefore, lifestyle variation may exacerbate the health effects of water salinity as we found much stronger associations when we excluded the two more remote communities. Further, it is possible that the shrinking of lake Turkana (Hodbod et al. 2019) will increase water salinity of the lake and accompanying groundwater (Tebbs et al. 2020). Therefore, monitoring of salinity levels with accompanying health outcomes is critical for future research.

4.1. Limitations and future directions

This study is subject to limitations. First, as this study is cross-sectional, all relationships should be viewed as associations. Second, salinity levels may fluctuate throughout the year and in relation to varying degrees of precipitation, therefore the amount of salt consumed from water may differ throughout the year. Additionally, dietary intake shifts throughout the year. Pastoralist neighbors of Daasanach, Turkana, reportedly consumed 30% of their calories from milk during the dry season but this increased to 89% during the rainy season (Galvin 1992). Our study took place after the rainy season during the early dry season, when milk consumption may have been lower than during the wet season, potentially leading to relying more on saline water sources for hydration. Another limitation of this study was that we were not able to estimate salt content consumed from cooking and in food, or total water intake. Therefore, we were unable to estimate total salt intake among our study sample, nor disaggregate the effects of dietary differences between participants and hypertension risk. However, other studies that have done so have found independent and stronger effects of salinity in water relative to salt consumed in food (Scheelbeek Pauline et al. 2017).

Furthermore, we did not test water quality in the household but rather at the point source since no households had water sources in their homes. This may have resulted in less fine-grained resolution than testing water that has been collected and stored in a person's house, especially if water was mixed from multiple sources. Nevertheless, it presents an accurate reflection of the point source salinity levels. Future research could ask participants to provide a sample of their stored water used for drinking as well as testing the point source.

Finally, spot urine samples collected in an ad libitum hydration state do not provide evidence regarding individuals' abilities to concentrate urine in response to water restriction. Rather, this data provides evidence of a high prevalence of hyperdilute urine in the sample, which may be indicative of kidney damage given the expected hydration levels of such a physiologically water demanding thermal environment (Bethancourt et al. In Press; Sawka et al. 2005). Future research could collect 24-hour urine samples on a representative sample of adults to analyze urine volume as a potential diagnostic for polyuria and to analyze urinary concentrations of sodium and other cations like potassium, magnesium, and calcium, which may be protective of hypertension (Naser et al. 2019). Previous work has found that sodium (827 mg Na/L) is the primary cation composing Lake Turkana's and the surrounding groundwater's salinity, whereas potassium (15.7 mg/L), magnesium (2.3 mg/L), and calcium (6.9 mg/L) are all in very low concentrations in the groundwater and the Omo River that feeds it (Otachi et al. 2015; Yuretich and Cerling 1983). Further, while our study does not have sodium or chloride concentrations, shallow groundwater and springs near Lake Turkana have been documented as having similar conductivity 850 mS/cm as our study (average 700, range 450–1010), and in those samples, sodium was 193 mg/L, chloride was 76 mg/L, potassium was 7.8 mg/L, calcium was 7.8 mg/L, and magnesium was 3.6 mg/L (Hopson 1982). Therefore, the water salinity in groundwater is primarily driven by sodium and chloride. Finally, future research should also do more detailed water quality to assess other components like fluoride [which is high in lake Turkana 9.4 mg/L, but lower in the Omo River and Illeret groundwater 1.16–2.25 mg/L (Yuretich and Cerling 1983)] which may also affect kidney health. Future work should carefully examine the ionic composition of groundwater consumed by Daasanach to estimate intake and overall exposure to Na^+, Cl^- along with Fl.

Nevertheless, our study results were robust to adjustment for a wide range of covariates and exclusions. As salinity in freshwater sources is expected to be a growing problem with climate change and population growth in East Africa (Comte et al. 2016; Damania et al. 2019; Rivett et al. 2019), longitudinal studies in affected areas are urgently needed to understand the full health implications of consuming increasingly saline water. Further, future studies should examine a range of salinity levels and conduct detailed analyses to understand how varying ionic concentrations, such as sodium and chloride compared to other potentially protective cations, affect health measures and outcomes.

5. Conclusions

Drinking water salinity has critical implications for chronic health and the risk of hypertension for millions of people around the world. In this study, we extend those implications to lean pastoralists living in East Africa experiencing socioecological changes. We also found suggestive evidence that higher water salinity concentration may be associated with hyperdilute urine which may indicate a reduced ability to concentrate urine and, potentially, decreased kidney function. More data with additional biomarkers of kidney function are needed to confirm these findings. Water projects in regions dealing with water salinity should test the ionic composition prior to building new wells or boreholes as we found that standpipes from wells were saline. Further, site-specific guidelines across regions and countries should consider not only groundwater salinity but also the specific ionic composition of that groundwater to understand varying health risks.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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References:

Agaba EI, Rohrscheib M, and Tzamaloukas AH. 2012. The renal concentrating mechanism and the clinical consequences of its loss. Nigerian medical journal: journal of the Nigeria Medical Association 53(3):109. [PubMed: 23293407]

Akarsu E, Buyukhatipoglu H, Aktaran S, and Geyik R. 2006. The Value of Urine Specific Gravity in Detecting Diabetes Insipidus in a Patient with Uncontrolled Diabetes Mellitus: Urine Specific Gravity in Differential Diagnosis. Journal of General Internal Medicine 21(11):C1–C2.

Akter S. 2019. Impact of drinking water salinity on children's education: Empirical evidence from coastal Bangladesh. Science of The Total Environment 690:1331–1341.

Armstrong LE, Pumerantz AC, Fiala KA, Roti MW, Kavouras SA, Casa DJ, and Maresh CM. 2010. Human hydration indices: acute and longitudinal reference values. Int J Sport Nutr Exerc Metab 20(2):145–153. [PubMed: 20479488]

Atkins RC. 2005. The epidemiology of chronic kidney disease. Kidney International 67:S14–S18.

Avery S. 2013. What future for lake Turkana. African Studies Centre, Oxford: University of Oxford.

Avery S, and Eng C. 2012. Lake Turkana & the Lower Omo: hydrological impacts of major dam and irrigation developments. African Studies Centre, the University of Oxford.

Avery ST, and Tebbs EJ. 2018. Lake Turkana, major Omo River developments, associated hydrological cycle change and consequent lake physical and ecological change. Journal of Great Lakes Research 44(6):1164–1182.

Barłowska J, Szwajkowska M, Litwińczuk Z, and Król J. 2011. Nutritional Value and Technological Suitability of Milk from Various Animal Species Used for Dairy Production. Comprehensive Reviews in Food Science and Food Safety 10(6):291–302.

Barraclough KA, Blashki GA, Holt SG, and Agar JWM. 2017. Climate change and kidney disease-threats and opportunities. Kidney International 92(3):526–530. [PubMed: 28807256]

Benneyworth L, Gilligan J, Ayers JC, Goodbred S, George G, Carrico A, Karim MR, Akter F, Fry D, Donato K et al.. 2016. Drinking water insecurity: water quality and access in coastal south-western Bangladesh. International Journal of Environmental Health Research 26(5–6):508–524. [PubMed: 27277537]

Bethancourt HJ, Swanson ZS, Nzunza R, Huanca T, Conde E, Kenney WL, Young SL, Ndiema E, Braun D, Pontzer H et al.. In Press. Hydration in relation to water insecurity, heat index, and lactation status in two small-scale populations in hot-humid and hot-arid environments. American Journal of Human Biology.

Brenner BM, Garcia DL, and Anderson S. 1988. Glomeruli and Blood Pressure: Less of One, More the Other? American Journal of Hypertension 1(4_Pt_1):335–347. [PubMed: 3063284]

Bricker NS, Dewey RR, Lubowitz H, Stokes J, and Kirkensgaard T. 1959. Observations on the concentrating and diluting mechanisms of the diseased kidney. The Journal of clinical investigation 38(3):516–523. [PubMed: 13641402]

Bromfield S, and Muntner P. 2013. High Blood Pressure: The Leading Global Burden of Disease Risk Factor and the Need for Worldwide Prevention Programs. Current Hypertension Reports 15(3):134–136. [PubMed: 23536128]

Chobanian AV, Bakris GL, Black HR, Cushman WC, Green LA, Izzo JL Jr, Jones DW, Materson BJ, Oparil S, and Wright JT Jr. 2003. Seventh report of the joint national committee on prevention, detection, evaluation, and treatment of high blood pressure. hypertension 42(6):1206–1252. [PubMed: 14656957]

Choukroun G, Schmitt F, Martinez F, Drüeke TB, and Bankir L. 1997. Low urine flow reduces the capacity to excrete a sodium load in humans. American Journal of Physiology-Regulatory, Integrative and Comparative Physiology 273(5):R1726–R1733.

Clark WF, Sontrop JM, Huang SH, Moist L, Bouby N, and Bankir L. 2016. Hydration and Chronic Kidney Disease Progression: A Critical Review of the Evidence. American Journal of Nephrology 43(4):281–292. [PubMed: 27161565]

Comte J-C, Cassidy R, Obando J, Robins N, Ibrahim K, Melchioly S, Mjemah I, Shauri H, Bourhane A, Mohamed I et al.. 2016. Challenges in groundwater resource management in coastal aquifers of East Africa: Investigations and lessons learnt in the Comoros Islands, Kenya and Tanzania. Journal of Hydrology: Regional Studies 5:179–199.

Cook JD, Caplan YH, LoDico CP, and Bush DM. 2000. The Characterization of Human Urine for Specimen Validity Determination in Workplace Drug Testing: A Review. Journal of Analytical Toxicology 24(7):579–588. [PubMed: 11043663]

Damania R, Desbureaux S, Rodella A-S, Russ J, and Zaveri E. 2019. Quality Unknown: The Invisible Water Crisis. The World Bank.

Dharmaratne R 2019. Exploring the role of excess fluoride in chronic kidney disease: A review. Human & Experimental Toxicology 38(3):269–279. [PubMed: 30472891]

Doria MdF, Pidgeon N, and Hunter PR. 2009. Perceptions of drinking water quality and risk and its effect on behaviour: A cross-national study. Science of The Total Environment 407(21):5455–5464.

Faust HS. 1982. Effects of drinking water and total sodium intake on blood pressure. The American journal of clinical nutrition 35(6):1459–1467. [PubMed: 7081127]

Galvin KA. 1992. Nutritional ecology of pastoralists in dry tropical Africa. American Journal of Human Biology 4(2):209–221. [PubMed: 28524353]

Gebre Y. 2012. Environmental Change, Food Crises and Violence in Dassanech, Southern Ethiopia. Berlin, Germany: Freie Universität Berlin.

Glaser J, Lemery J, Rajagopalan B, Diaz HF, García-Trabanino R, Taduri G, Madero M, Amarasinghe M, Abraham G, Anutrakulchai S et al.. 2016. Climate Change and the Emergent Epidemic of CKD from Heat Stress in Rural Communities: The Case for Heat Stress Nephropathy. Clinical Journal of the American Society of Nephrology 11(8):1472–1483. [PubMed: 27151892]

Grillo A, Salvi L, Coruzzi P, Salvi P, and Parati G. 2019. Sodium Intake and Hypertension. Nutrients 11(9):1970.

Hall ME, do Carmo JM, da Silva AA, Juncos LA, Wang Z, and Hall JE. 2014. Obesity, hypertension, and chronic kidney disease. International journal of nephrology and renovascular disease 7:75. [PubMed: 24600241]

Hallenbeck WH, Brenniman GR, and Anderson RJ. 1981. High sodium in drinking water and its effect on blood pressure. American journal of epidemiology 114(6):817–826. [PubMed: 7315830]

Hodbod J, Stevenson EGJ, Akall G, Akuja T, Angelei I, Bedasso EA, Buffavand L, Derbyshire S, Eulenberger I, Gownaris N et al.. 2019. Social-ecological change in the Omo-Turkana basin: A synthesis of current developments. Ambio 48(10):1099–1115. [PubMed: 30623361]

Hopson AJ. 1982. Lake Turkana. A report on the findings of the Lake Turkana Project, 1972–1975.

Houba V. 1975. Immunopathology of nephropathies associated with malaria. Bulletin of the World Health Organization 52(2):199. [PubMed: 1083308]

Houston MC, and Harper KJ. 2008. Potassium, Magnesium, and Calcium: Their Role in Both the Cause and Treatment of Hypertension. The Journal of Clinical Hypertension 10(7):3–11. [PubMed: 18607145]

Imbulana S, Oguma K, and Takizawa S. 2020. Evaluation of groundwater quality and reverse osmosis water treatment plants in the endemic areas of Chronic Kidney Disease of Unknown Etiology (CKDu) in Sri Lanka. Science of The Total Environment 745:140716.

James GD, and Gerber LM. 2018. Measuring arterial blood pressure in humans: Auscultatory and automatic measurement techniques for human biological field studies. American Journal of Human Biology 30(1):e23063.

Jha V, Garcia-Garcia G, Iseki K, Li Z, Naicker S, Plattner B, Saran R, Wang AY-M, and Yang C-W. 2013. Chronic kidney disease: global dimension and perspectives. The Lancet 382(9888):260–272.

Kaushal SS, Groffman PM, Likens GE, Belt KT, Stack WP, Kelly VR, Band LE, and Fisher GT. 2005. Increased salinization of fresh water in the northeastern United States. Proceedings of the National Academy of Sciences of the United States of America 102(38):13517–13520. [PubMed: 16157871]

Khan AE, Scheelbeek PFD, Shilpi AB, Chan Q, Mojumder SK, Rahman A, Haines A, and 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. [PubMed: 25268785]

Killer SC, Blannin AK, and Jeukendrup AE. 2014. No evidence of dehydration with moderate daily coffee intake: A counterbalanced cross-over study in a free-living population. PLoS ONE 9(1):e84154. [PubMed: 24416202]

Koroboki E, Manios E, Psaltopoulou T, Vemmos K, Michas F, Alexaki E, and Zakopoulos N. 2012. Circadian variation of blood pressure and heart rate in normotensives, white-coat, masked, treated and untreated hypertensives. Hellenic J Cardiol 53(6):432–438. [PubMed: 23178426]

Lea AJ, Martins D, Kamau J, Gurven M, and Ayroles JF. 2019. Urbanization and market-integration have strong, non-linear effects on cardio-metabolic health in the Turkana. bioRxiv:756866.

Leslie PW, and Fry PH. 1989. Extreme seasonality of births among nomadic Turkana pastoralists. American Journal of Physical Anthropology 79(1):103–115. [PubMed: 2750875]

Leslie PW, and Little MA. 1999. Turkana herders of the dry savanna: ecology and biobehavioral response of nomads to an uncertain environment: Oxford University Press on Demand.

Lifshitz F, and Wapnir RA. 1985. Oral hydration solutions: experimental optimization of water and sodium absorption. The Journal of pediatrics 106(3):383–389. [PubMed: 3973775]

Lindeman RD, Tobin J, and Shock NW. 1985. Longitudinal Studies on the Rate of Decline in Renal Function with Age. Journal of the American Geriatrics Society 33(4):278–285. [PubMed: 3989190]

Lindeman RD, Tobin JD, and Shock NW. 1984. Association between blood pressure and the rate of decline in renal function with age. Kidney International 26(6):861–868. [PubMed: 6533397]

Lindeman RD, Van Buren HC, and Raisz LG. 1960. Osmolar renal concentrating ability in healthy young men and hospitalized patients without renal disease. N Engl J Med 262(26):1306–1309. [PubMed: 14417083]

Mackinnon E, Ayah R, Taylor R, Owor M, Ssempebwa J, Olago lD, Kubalako R, Dia AT, Gaye C, L C. Campos et al.. 2018. 21st century research in urban WASH and health in sub-Saharan Africa: methods and outcomes in transition. International Journal of Environmental Health Research:1–22.

McCabe JT. 2010. Cattle bring us to our enemies: Turkana ecology, politics, and raiding in a disequilibrium system: University of Michigan Press.

Meroney W, Rubini M, and Blythe W. 1958. The effect of antecedent diet on urine concentrating ability. Annals of internal medicine 48(3):562–573. [PubMed: 13521585]

Miller M, Price JW, and Longley LP. 1941. EFFECT OF VARYING INTAKE OF PROTEIN AND SALTS ON THE COMPOSITION AND SPECIFIC GRAVITY OF URINE. The Journal of Clinical Investigation 20(1):31–38. [PubMed: 16694805]

Mir M, and Newcombe R. 1988. The relationship of dietary salt and blood pressure in three farming communities in Kashmir. Journal of human hypertension 2(4):241–246. [PubMed: 3236325]

Mishra SK, and Das BS. 2008. Malaria and Acute Kidney Injury. Seminars in Nephrology 28(4):395–408. [PubMed: 18620962]

Mugai EN. 2004. Salinity characterization of the Kenyan saline soils. Soil Science and Plant Nutrition 50(2):181–188.

Muller CJ, and MacLehose RF. 2014. Estimating predicted probabilities from logistic regression: different methods correspond to different target populations. Int J Epidemiol 43(3):962–970. [PubMed: 24603316]

Musyoki J, Wachira N, Mwitari P, Tolo F, Kuria J, Adipo N, Mutuku C, and Mutunga J. 2016. Use of maerua decumbens as a natural coagulant for water purification in the dry lands of kenya. Int J Sci 2:1–9.

Naser AM, Doza S, Rahman M, Unicomb L, Ahmed KM, Anand S, Selim S, Shamsudduha M, Narayan KMV, Chang H et al.. 2020a. Consequences of access to water from managed aquifer recharge systems for blood pressure and proteinuria in south-west coastal Bangladesh: a stepped-wedge cluster-randomized trial. International Journal of Epidemiology.

Naser AM, Rahman M, Unicomb L, Doza S, Ahmed KM, Uddin MN, Selim S, Gribble MO, Anand S, Clasen TF et al.. 2017. Drinking water salinity and kidney health in southwest coastal Bangladesh: baseline findings of a community-based stepped-wedge randomised trial. The Lancet 389:S15.

Naser AM, Rahman M, Unicomb L, Doza S, Gazi MS, Alam GR, Karim MR, Uddin MN, Khan GK, Ahmed KM et al.. 2019. Drinking Water Salinity, Urinary Macro-Mineral Excretions, and Blood Pressure in the Southwest Coastal Population of Bangladesh. Journal of the American Heart Association 8(9):e012007. [PubMed: 31060415]

Naser AM, Rahman M, Unicomb L, Parvez SM, Islam S, Doza S, Khan GK, Ahmed KM, Anand S, Luby SP et al.. 2020b. Associations of drinking rainwater with macro-mineral intake and cardiometabolic health: a pooled cohort analysis in Bangladesh, 2016–2019. npj Clean Water 3(1):20.

Needleman SB, Porvaznik M, and Ander D. 1992. Creatinine analysis in single collection urine specimens. Journal of Forensic Science 37(4):1125–1133.

Nthunya LN, Maifadi S, Mamba BB, Verliefde AR, and Mhlanga SD. 2018. Spectroscopic Determination of Water Salinity in Brackish Surface Water in Nandoni Dam, at Vhembe District, Limpopo Province, South Africa. Water 10(8):990.

Nurminen ML, Niittynen L, Korpela R, and Vapaatalo H. 1999. Coffee, caffeine and blood pressure: a critical review. European Journal of Clinical Nutrition 53(11):831–839. [PubMed: 10556993]

Ohrel RL, and Register KM. 2006. Voluntary Estuary Monitoring: A Methods Manual: US Environmental Protection Agency, Office of Wetlands, Oceans and Watersheds.

Ojwang W, Obiero K, Donde O, Gownaris N, Pikitch E, Omondi R, and Avery S. 2016. Lake Turkana: World's largest permanent desert Lake (Kenya). The wetland book: II: Distribution, description and conservation:1–20.

Opiyo F. 2014. Trend Analysis of Rainfall and Temperature Variability in Arid Environment of Turkana, Kenya** Francis Opiyo," Moses Nyangito,"“ Oliver Vivian Wasonga and “Phillip

Omondi” Department of Land Resources Management and Agricultural Technology. Environmental Research Journal 8(2):30–43.

Otachi EO, Plessl C, Körner W, Avenant-Oldewage A, and Jirsa F. 2015. Trace elements in water, sediments and the elongate tigerfish Hydrocynus forskahlii (Cuvier 1819) from Lake Turkana, Kenya including a comprehensive health risk analysis. Bulletin of environmental contamination and toxicology 95(3):286–291. [PubMed: 26193834]

Page LB, Vandevert DE, Nader K, Lubin NK, and Page JR. 1981. Blood pressure of Qash’qai pastoral nomads In Iran in relation to culture, diet, and body form. The American Journal of Clinical Nutrition 34(4):527–538. [PubMed: 7223703]

Perrier E, Demazières A, Girard N, Pross N, Osbild D, Metzger D, Guelinckx I, and Klein A. 2013. Circadian variation and responsiveness of hydration biomarkers to changes in daily water intake. European Journal of Applied Physiology 113(8):2143–2151. [PubMed: 23604869]

Perucca J, Bouby N, Valeix P, and Bankir L. 2007. Sex difference in urine concentration across differing ages, sodium intake, and level of kidney disease. American Journal of Physiology - Regulatory, Integrative and Comparative Physiology 292(2):R700–R705.

Pescatello LS, Franklin BA, Fagard R, Farquhar WB, Kelley GA, and Ray CA. 2004. Exercise and hypertension. Medicine & Science in Sports & Exercise 36(3):533–553. [PubMed: 15076798]

Premji R, Roopnarinesingh N, Cohen J, and Sen S. 2016. Cerebral Malaria: An Unusual Cause of Central Diabetes Insipidus. Case Reports in Endocrinology 2016:4.

Qi R, and Yang C. 2018. Renal tubular epithelial cells: the neglected mediator of tubulointerstitial fibrosis after injury. Cell Death & Disease 9(11):1126. [PubMed: 30425237]

Rahman MM, Penny G, Mondal MS, Zaman MH, Kryston A, Salehin M, Nahar Q, Islam MS, Bolster D, Tank JL et al.. 2019. Salinization in large river deltas: Drivers, impacts and socio-hydrological feedbacks. Water Security 6:100024.

Rivett MO, Budimir L, Mannix N, Miller AVM, Addison MJ, Moyo P, Wanangwa GJ, Phiri OL, Songola CE, Nhlema M et al.. 2019. Responding to salinity in a rural African alluvial valley aquifer system: To boldly go beyond the world of hand-pumped groundwater supply? Science of The Total Environment 653:1005–1024.

Rivett MO, Symon S, Jacobs L, Banda LC, Wanangwa GJ, Robertson DJC, Hassan I, Miller AVM, Chavula GMS, Songola CE et al.. 2020. Paleo-Geohydrology of Lake Chilwa, Malawi is the Source of Localised Groundwater Salinity and Rural Water Supply Challenges. Applied Sciences 10(19):6909.

Rosinger A. 2015. Heat and hydration status: Predictors of repeated measures of urine specific gravity among Tsimane’ adults in the Bolivian Amazon. Am J Phys Anthropol 158(4):696–707. [PubMed: 26213151]

Rosinger AY, Pontzer H, Raichlen DA, Wood BM, Tanner SN, and Sands JM. 2019. Age-related decline in urine concentration may not be universal: Comparative study from the U.S. and two small-scale societies. American Journal of Physical Anthropology 168(4):705–716. [PubMed: 30706445]

Rosinger AY, and Young SL. 2020. The toll of household water insecurity on health and human biology: Current understandings and future direction. WIREs Water.

Rowles LS, Alcalde R, Bogolasky F, Kum S, Diaz-Arriaga FA, Ayres C, Mikelonis AM, Toledo-Flores LJ, Alonso-Gutiérrez MG, Pérez-Flores ME et al.. 2018. Perceived versus actual water quality: Community studies in rural Oaxaca, Mexico. Science of The Total Environment 622–623:626–634.

Sagawa T. 2006. Wives’ Domestic and Political Activities at Home: The Space of Coffee Drinking among the Daasanetch of Southwestern Ethiopia. African Study Monographs 27(2):63–86.

Sandberg K, and Ji H. 2012. Sex differences in primary hypertension. Biology of Sex Differences 3(1):7. [PubMed: 22417477]

Sands JM. 2009. Urinary Concentration and Dilution in the Aging Kidney. Seminars in nephrology 29(6):579–586. [PubMed: 20006789]

Sands JM. 2012. Urine Concentrating and Diluting Ability During Aging. The Journals of Gerontology Series A: Biological Sciences and Medical Sciences 67(12):1352–1357.

Sands JM, and Layton HE. 2014. Advances in Understanding the Urine-Concentrating Mechanism. Annual Review of Physiology 76(1):387–409.

Sawka MN, Cheuvront SN, and Carter R. 2005. Human water needs. Nutr Rev 63(suppl 1):S30–S39. [PubMed: 16028570]

Scheelbeek Pauline FD, Chowdhury Muhammad AH, Haines A, Alam Dewan S, Hoque Mohammad A, Butler Adrian P, Khan Aneire E, Mojumder Sontosh K, Blangiardo Marta AG, Elliott P et al.. 2017. Drinking Water Salinity and Raised Blood Pressure: Evidence from a Cohort Study in Coastal Bangladesh. Environmental Health Perspectives 125(5):057007. [PubMed: 28599268]

Schrier RW. 2006. Body Water Homeostasis: Clinical Disorders of Urinary Dilution and Concentration. Journal of the American Society of Nephrology 17(7):1820–1832. [PubMed: 16738014]

Serem D. 2012. For villages in Turkana, Kenya, a new initiative that brings clean water to the community is life-changing. UNICEF.

Shammi M, Rahman MM, Bondad SE, and Bodrud-Doza M. 2019. Impacts of Salinity Intrusion in Community Health: A Review of Experiences on Drinking Water Sodium from Coastal Areas of Bangladesh. Healthcare 7(1):50.

Shirreffs SM, Taylor AJ, Leiper JB, and Maughan RJ. 1996. Post-exercise rehydration in man: effects of volume consumed and drink sodium content. Medicine and Science in Sports and Exercise 28(10):1260. [PubMed: 8897383]

Stengel B, Tarver–Carr ME, Powe NR, Eberhardt MS, and Brancati FL. 2003. Lifestyle factors, obesity and the risk of chronic kidney disease. Epidemiology 14(4):479–487. [PubMed: 12843775]

Talukder MRR, Rutherford S, Phung D, Islam MZ, and Chu C. 2016. The effect of drinking water salinity on blood pressure in young adults of coastal Bangladesh. Environmental Pollution 214:248–254. [PubMed: 27089422]

Tebbs EJ, Avery ST, and Chadwick MA. 2020. Satellite remote sensing reveals impacts from dam-associated hydrological changes on chlorophyll- a in the world’s largest desert lake. River Research and Applications 36(2):211–222.

Trinies V, Chard AN, Mateo T, and Freeman MC. 2016. Effects of Water Provision and Hydration on Cognitive Function among Primary-School Pupils in Zambia: A Randomized Trial. PLOS ONE 11(3):e0150071. [PubMed: 26950696]

U.S. Geological Survey. 2016. Saline Water and Salinity. The World’s Water: Water, water, everywhere.

Unger T, Borghi C, Charchar F, Khan NA, Poulter NR, Prabhakaran D, Ramirez A, Schlaich M, Stergiou GS, Tomaszewski M et al.. 2020. 2020 International Society of Hypertension Global Hypertension Practice Guidelines. Hypertension 75(6):1334–1357. [PubMed: 32370572]

Van Weert F, Van der Gun J, and Reckman J. 2009. Global overview of saline groundwater occurrence and genesis. International Groundwater Resources Assessment Centre.

Wasana HMS, Aluthpatabendi D, Kularatne WMTD, Wijekoon P, Weerasooriya R, and Bandara J. 2016. Drinking water quality and chronic kidney disease of unknown etiology (CKDu): synergic effects of fluoride, cadmium and hardness of water. Environmental Geochemistry and Health 38(1):157–168. [PubMed: 25859936]

Wilde FD, Radtke D, Gibs J, and Iwatsubo R. 1998. National field manual for the collection of water-quality data. US Geological Survey Techniques in Water-Resources Investigations, Book 9.

World Health Organization. 2008. Guidelines for Drinking-water Quality 3rd Ed. Incorporating the First and Second Addenda Volume 1, Recommendations. World Health Organization, Geneva, Switzerland Available from: www who int/water_sanitation_health/dwq/gdwq3rev/en/index html.

World Health Organization. 2012. Guideline: Sodium intake for adults and children: World Health Organization.

World Health Organization. 2019a. Progress on household drinking water, sanitation and hygiene 2000–2017: special focus on inequalities: World Health Organization.

World Health Organization. 2019b. Safer water, better health. 2019 update. Geneva: World Health Organization.

World Weather Online. 2020. Lodwar Monthly Climate Averages.

Wright CJ, Sargeant JM, Edge VL, Ford JD, Farahbakhsh K, Shiwak I, Flowers C, Gordon AC, and Harper SL. 2018. How are perceptions associated with water consumption in Canadian Inuit? A cross-sectional survey in Rigolet, Labrador. Science of The Total Environment 618:369–378.

Wutich A, Rosinger AY, Stoler J, Jepson W, and Brewis A. 2020. Measuring Human Water Needs. American Journal of Human Biology 32(1):e23350. [PubMed: 31702101]

Yeh H-C, Lin Y-S, Kuo C-C, Weidemann D, Weaver V, Fadrowski J, Neu A, and Navas-Acien A. 2015. Urine osmolality in the US population: Implications for environmental biomonitoring. Environ Res 136:482–490. [PubMed: 25460670]

YSI ProDSS X. 2017. ProDSS Calibration Guide. In: YSI, editor. Yellow Springs, Ohio.

Yuretich RF, and Cerling TE. 1983. Hydrogeochemistry of Lake Turkana, Kenya: Mass balance and mineral reactions in an alkaline lake. Geochimica et Cosmochimica Acta 47(6):1099–1109.

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Highlights

- Salinity of drinking water is a growing global environmental health concern.
- We analyzed water quality and health of Daasanach pastoralists near Lake Turkana.
- Drinking water salinity was associated with hypertension and hyperdilute urine.
- Milk consumption was protective against odds of hypertension and hyperdilute urine.
- Water salinity and milk may play critical roles in lean pastoralists' chronic health.

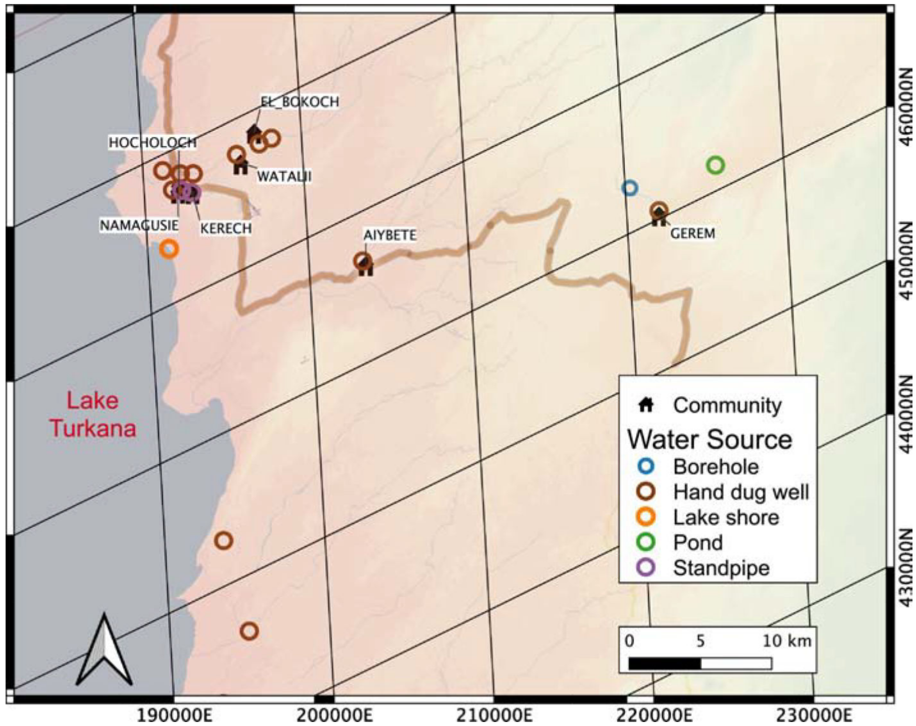

Figure 1:
Map of the study area and water sources sampled.

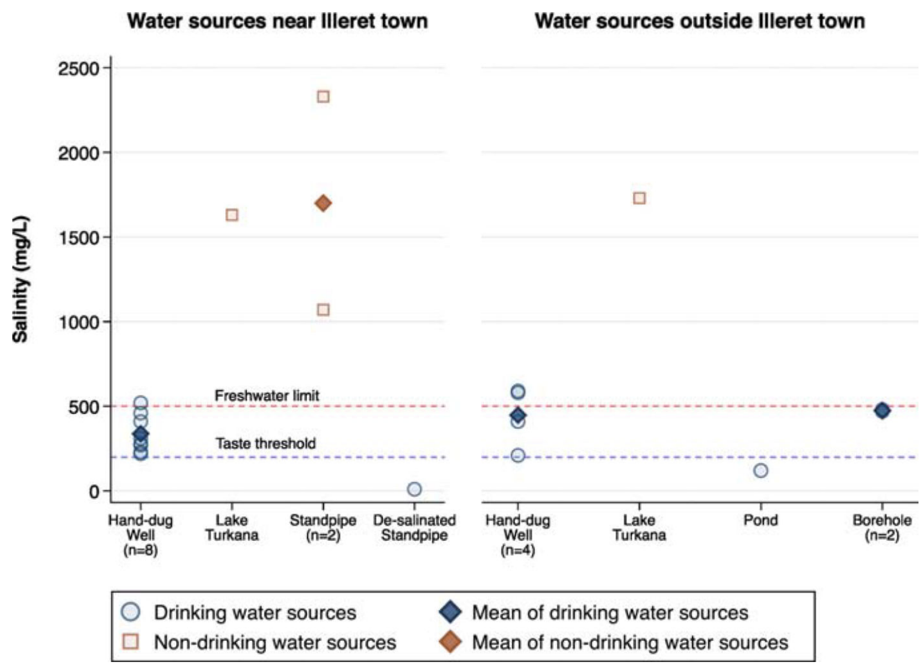

Figure 2:
Salinity concentration of water sources in the study area, in and around Illeret used for drinking and (primarily) non-drinking purposes. Note: samples indicate different water sampling sites (i.e., different wells); each source was measured three times with the mean presented.

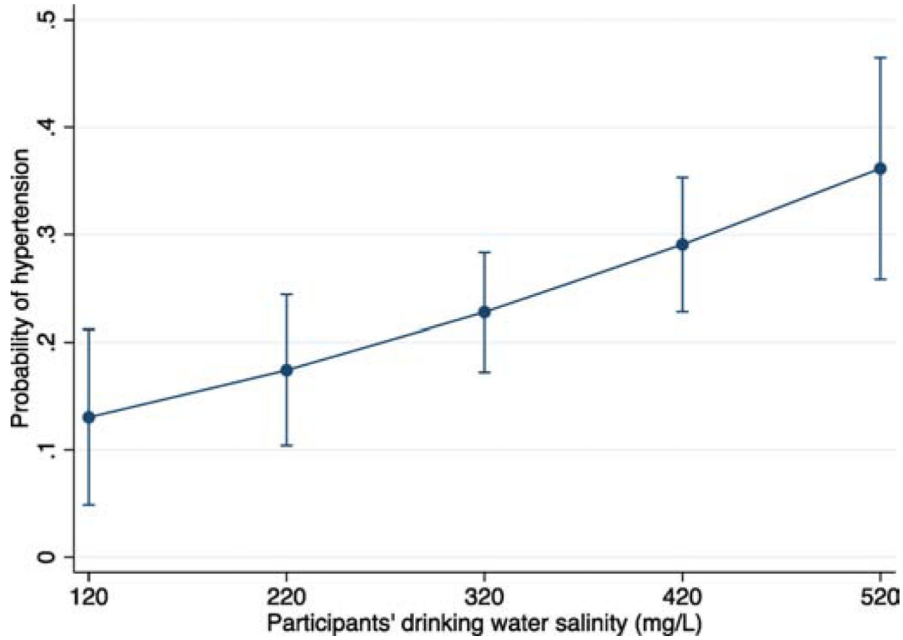

Figure 3.
Predicted probability and 95% confidence intervals of hypertension by drinking water salinity

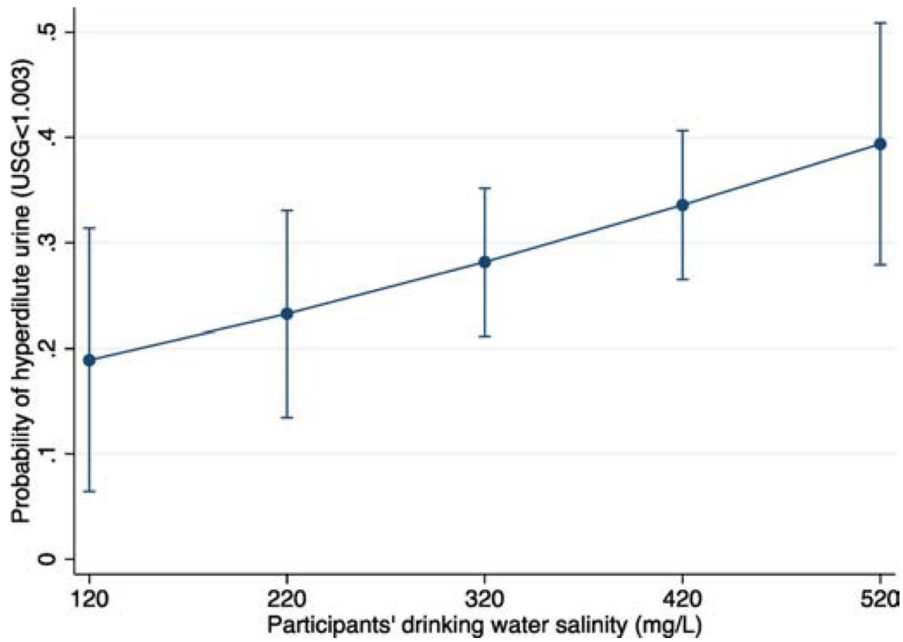

Figure 4.
Predicted probability and 95% confidence intervals of hyperdilute urine by drinking water salinity

Table 1.

Summary of water quality data for select water sources in and near Illeret and surrounding pasture land, Northern Kenya

	Water sources in or near Illeret town						Water sources in undeveloped pasture land beyond Illeret					
	Dug wells (n=8) [a]			Lake [b]	Standard Standpipes (n=2) [c]	De-salinated Standpipe	Dug wells (n=4) [d]			Pond [e]	Lake [f]	Boreholes (n=2) [g]
	Mean (SD)	*Min*	*Max*		*Mean (SD)*		*Mean (SD)*	*Min*	*Max*			*Mean (SD)*
Salinity (mg/L)	338 (112)	220	520	1630	1700 (891)	10	448 (179)	210	590	120	1730	475 (7)
Temperature (C°)	30.1 (1.0)	28.9	31.3	30.8	32.3 (1.2)	32.7	27.7 (1.4)	26.0	29.4	30.3	29.7	31.0 (2.4)
Specific Conductivity (mS/cm)	0.70 (0.23)	0.46	1.07	3.16	3.27 (1.62)	0.03	0.92 (0.35)	0.45	1.20	0.27	3.34	0.98 (0.01)
Resistivity (ohm)	1424 (439)	835	2036	285	305 (146)	26593	1217 (633)	781	2128	3402	275	922 (44)
Total Dissolved Solids (mg/L)	455 (439)	296	695	2053	2126 (146)	21	596 (633)	289	780	173	2171	634 (44)
pH	8.2 (0.2)	7.7	8.5	9.4	8.1 (0.4)	7.4	8.4 (0.5)	7.8	9.0	8.9	9.4	8.1 (0.8)
Turbidity (FNU)	99.6 (94.0)	11.5	247.1	103.7	1.1 (0.4)	0	153.6 (84.4)	62.5	245.6	77.2	7.4	0.9 (1.4)

[a] Mean, SD, minimum, and maximum values for 8 unprotected dug wells tested in and near Illeret town and used by communities 1–6.

[b] Measurements for sample taken from Illeret shore of Lake Turkana.

[c] Mean and SD of 2 standard standpipes.

[d] Mean, SD, minimum, and maximum values for 4 unprotected dug wells used by nomadic Daasanach communities (none of which were used by our WISH 2019 sample).

[e] Pond used by community 7.

[f] Measurements for sample taken from Koobi Fora Basecamp shore of Lake Turkana.

[g] Mean and SD of 2 boreholes in remote pasture areas used by nomadic Daasanach communities

Measurements presented are the average of three recordings at each water source.

Table 2:

Descriptive characteristics of Daasanach adults, aged 18 years and over, overall and by blood pressure and hyperdilute urine status

	Total	Hypertension (n=223) ‡		Hyperdilute urine (n=225)	
	(n=226)	Hypertension (n=58)	Normotension (n=165)	Hyperdilute urine (n=69)	Non-hyperdilute urine (n=156)
	Mean or % (SD)	Mean or % (SD)	Mean or % (SD)	Mean or % (SD)	Mean or % (SD)
Male	46.9%	48.3%	46.7%	42.0%	49.4%
Age (years)	40.7 (15.1)	45.1 (15.7)	38.9 (14.4)	42.4 (13.4)	40.1 (15.8)
Weight (kg) ‡	51.3 (9.3)	51.4 (10.1)	51.5 (8.9)	50.5 (7.5)	51.6 (10.0)
Height (cm)	167.7 (7.6)	167.7 (7.1)	167.9 (7.8)	168.4 (6.9)	167.4 (8.0)
BMI (kg/m^2)	18.2 (3.1)	18.3 (3.2)	18.3 (3.1)	17.8 (2.4)	18.4 (3.4)
Salinity (mg/L)	361 (117)	393 (83)	348 (126)	386 (93)	349 (126)
BP systolic (mmHg)	116 (16)	133.0 (16.7)	110.3 (10.8)	116.7 (14.5)	116.1 (16.8)
BP diastolic (mmHg)	83 (11)	96.9 (8.7)	78.0 (6.4)	84.0 (10.3)	82.5 (11.2)
Hypertension	26.0%	--	--	29.4%	24.7%
USG (g/mL)	1.010 (0.008)	1.010 (0.009)	1.010 (0.008)	1.0016 (0.0008)	1.014 (0.007)
USG<1.003 (%)	30.7%	34.5%	29.3%	--	--
Time of sample collection	11.26 (2.5)	10.4 (2.1)	11.5 (2.5)	10.4 (2.2)	11.7 (2.5)
Heat index (C)	34.1 (3.6)	33.7 (3.7)	34.3 (3.6)	33.3 (3.8)	34.5 (3.4)
No milk (%)	43.6%	58.6%	37.6%	53.6%	39.1%
Milk < daily (%)	19.6%	19.0%	20.6%	26.1%	16.7%
Milk daily (%)	36.9%	22.4%	41.8%	20.3%	44.2%
Times/day of tea or coffee	2.1 (0.8)	2.2 (0.9)	2.0 (0.8)	2.1 (0.9)	2.1 (0.7)
Kidney problems or diabetes (%)	7.1%	10.3%	5.5%	10.1%	5.8%
Livestock wealth (USD)	2,059 (5,562)	1,781(6054)	2,188 (5441)	1,885 (6113)	2,146 (5336)
Times moved	4.1 (6.0)	3.3 (7.5)	4.4 (5.3)	3.7 (7.0)	4.3 (5.5)

‡3 adults missing blood pressure information, 1 adult missing USG information

hypertension: systolic BP ≥ 140 or diastolic BP ≥ 90 mm Hg; hyperdilute urine: USG<1.003

Table 3:

Linear regression examining the association between water salinity and systolic and diastolic BP

VARIABLES	(1) Systolic Beta (95% CI)	(2) Systolic Beta (95% CI)	(3) Systolic Beta (95% CI)	(4) Diastolic Beta (95% CI)	(5) Diastolic Beta (95% CI)	(6) Diastolic Beta (95% CI)
Water salinity (per 100 mg/L)	1.05 (−0.62 – 2.73)	1.04 (−0.67 – 2.75)	0.81 (−0.93 – 2.54)	1.64*** (0.47 – 2.80)	1.58*** (0.42 – 2.74)	1.15* (−0.03 – 2.33)
Male (ref=female)		3.35 (−0.73 – 7.43)	3.20 (−0.90 – 7.30)		−0.24 (−2.94 – 2.46)	−0.15 (−2.82 – 2.52)
Age (years)		0.24*** (0.07 – 0.41)	0.22*** (0.06 – 0.39)		0.15*** (0.05 – 0.26)	0.13** (0.03 – 0.23)
BMI (kg/m^2)		0.37 (−0.25 – 0.99)	0.39 (−0.29 – 1.08)		0.01 (−0.35 – 0.37)	0.07 (−0.30 – 0.44)
Hour of day		−1.16* (−2.36 – 0.04)	−0.96 (−2.21 – 0.29)		−0.73* (−1.56 – 0.10)	−0.59 (−1.46 – 0.28)
Heat Index (C)		−0.01 (−0.76 – 0.74)	−0.11 (−0.89 – 0.67)		0.12 (−0.38 – 0.62)	0.05 (−0.47 – 0.58)
Milk consumption (none=ref)			ref			ref
<1 time/day			−5.35** (−10.65 – −0.05)			−4.95** (−9.03 – −0.86)
1+ times/day			−5.60** (−10.09 – −1.10)			−5.02*** (−7.86 – −2.18)
Tea/coffee yesterday			1.67 (−0.82 – 4.17)			1.17 (−0.48 – 2.82)
Kidney/diabetes			5.01 (−3.23 – 13.25)			2.39 (−2.76 – 7.55)
Wealth (100 USD)			−0.01 (−0.03 – 0.02)			−0.01 (−0.03 – 0.005)
Mobility			0.06 (−0.29 – 0.41)			−0.08 (−0.27 – 0.11)
Water fetch time (10 minutes)			0.02 (−0.52 – 0.56)			0.17 (−0.20 – 0.55)
Observations	223	223	223	223	223	223
R-squared	0.01	0.13	0.17	0.03	0.10	0.17

*** $p<0.01$

** $p<0.05$

* $p<0.1$

Robust standard errors clustered on 134 households

Table 4:

Logistic regression examining association between water salinity and odds of hypertension and hyperdilute urine

VARIABLES	(1) Hypertension OR (95% CI)	(2) Hypertension OR (95% CI)	(3) Hypertension OR (95% CI)	(4) Hyperdilute urine OR (95% CI)	(5) Hyperdilute urine OR (95% CI)	(6) Hyperdilute urine OR (95% CI)
Water salinity (per 100 mg/L)	1.42***(1.10 – 1.84)	1.45***(1.12 – 1.89)	1.45**(1.09 – 1.94)	1.32**(1.01 – 1.73)	1.36**(1.04 – 1.78)	1.34*(0.97 – 1.84)
Male (ref=female)		0.85 (0.42 – 1.73)	0.87 (0.42 – 1.80)		0.61 (0.33 – 1.12)	0.60 (0.33 – 1.12)
Age (years)		1.02*(1.00 – 1.05)	1.02*(1.00 – 1.04)		1.01 (0.99 – 1.03)	1.00 (0.98 – 1.03)
BMI (kg/m^2)		1.00 (0.91 – 1.09)	1.02 (0.92 – 1.12)		0.90*(0.81 – 1.01)	0.92 (0.82 – 1.03)
Hour of day		0.74***(0.60 – 0.92)	0.77**(0.61 – 0.95)		0.79**(0.64 – 0.96)	0.81*(0.66 – 1.01)
Heat Index (per 1C)		1.08 (0.95 – 1.23)	1.07 (0.93 – 1.23)		0.99 (0.88 – 1.12)	0.98 (0.85 – 1.12)
Milk consumption (none=ref)			ref			1
<1 time/day			0.42*(0.17 – 1.02)			0.97 (0.40 – 2.34)
1+ times/day			0.39**(0.18 – 0.84)			0.37**(0.15 – 0.90)
Tea/coffee yesterday			1.37 (0.91 – 2.05)			1.01 (0.60 – 1.68)
Kidney/diabetes			1.53 (0.49 – 4.73)			1.49 (0.45 – 4.96)
Wealth (per 100 USD)			1.00 (1.00 – 1.00)			1.00 (1.00 – 1.00)
Mobility			1.00 (0.94 – 1.08)			1.02 (0.96 – 1.09)
Water fetch time (per 10 minutes)			1.04 (0.96 – 1.12)			1.03 (0.95 – 1.12)
Observations	223	223	223	225	225	225

*** $p<0.01$

** $p<0.05$

* $p<0.1$

Robust standard errors clustered on 134 households; hypertension: systolic BP ≥ 140 or diastolic BP ≥ 90 mm Hg; hyperdilute urine: USG<1.003