Assessing groundwater salinity across Africa

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In Africa groundwater is the principal source of drinking water (https://washdata.org/) and has significant potential to improve food production as a source of irrigation water. Although volumes of stored groundwater are high when compared to surface water, not all the available groundwater is suitable for irrigation. One of the principal factors that limit the development of groundwater is salinity, but quantitative evidence regarding the scale of salinization in Africa has been lacking. This paper presents an initial analysis of the extent of groundwater salinization in Africa, bringing together groundwater salinity data (n=12255) from across the continent. In our dataset *c*.80% of the samples have electrical conductivity values less than 2000 μS/cm. Samples with high conductivity values of more than 2000 μS/cm are restricted to limited geological and climatic environments. The data reveals salinity does not affect the water security status of most countries in Africa. However, salinity compounds water insecurity issues in arid low groundwater recharge environments. The paper discusses the role of anthropogenic processes such as river valley water resources development, extensive groundwater pumping, inter-basin groundwater transfer, and irrigation in altering the salinity of groundwater bodies. The paper further elucidates the origin of groundwater salinity by critically reviewing the natural and human-induced factors that control the salinization of the various groundwater bodies across Africa. Existing case studies reveal several causes of

salinization, including i) human-induced salinization, ii) climate and hydrological change-induced paleo groundwater salinity, iii) rock dissolution, and iv), saltwater encroachment.

1. Introduction

Driven by anthropogenic pressure and climate change, salinity has become a growing water security challenge and the trend in salinity of fresh waters is increasing globally (Thorslund and van Vliet, 2020). Water salinity will have an impact on the ability to meet water related Sustainable Development Goals (SDGs 2, 6, 11, 12, etc.) in some regions (Flörke et al., 2019).

MacDonald et al. (2012) demonstrate that Africa's groundwater resources have the potential to transform rural development if used sustainably. However, (Edmunds, 2012) points out that salinity may be one important factor that restricts the use of groundwater for domestic use and food production, most notably in semi-arid or arid areas. Groundwater quality is also increasingly incorporated into discussions of sustainable groundwater use (Gleeson et al., 2020). High salinity water hampers plant growth, limiting its use for crop irrigation. Irrigation in arid regions can lead to a buildup of soil salinity leaving areas unsuitable for agriculture without significant flushing. Drinking water is also affected, and becomes significantly unpalatable at total dissolved solids (salinity) levels greater than 1000 mg/L (WHO, 2011). High groundwater salinity is one of the primary reasons for abandonment of newly drilled rural water supply boreholes in arid regions (Kebede and Taye, 2021; Rivett et al., 2020; UNICEF, 2008; Pavelic et al., 2012). There is growing evidence that high salinity drinking water is not only unpalatable but compromises livelihoods and human health (Al Nahian et al., 2018;Naser et al., 2020;Dasgupta et al., 2016), for example, salinity has critical health implications for blood pressure and kidney functions (Rosinger et al., 2021). For all these reasons, it is important to know the extent of the salinity challenges facing Africa to help realize the potential sustainable groundwater use has to produce transformative economic growth.

There is growing availability of global groundwater salinity data (Thorslund and van Vliet, 2020) and scientific literature on deciphering the origins of groundwater salinity (Mirzavand et al., 2020), mapping the extent of anthropogenic salinization of surface and groundwaters (Thorslund et al., 2021; Foster et al., 2018), designing groundwater salinity management strategies (Khan et al., 2008; Fitch et al., 2016; Lamontagne et al., 2005) and on assessing impacts of groundwater salinity (Russ et al., 2020). However, because of the paucity of salinity data for Africa, the situation in Africa is poorly reflected in this global debate. The lack of knowledge on the extent, origins, trends, and impacts of groundwater salinity hampers the formulation of policy and management strategies.

The objectives of this paper are to i) highlight the extent of groundwater salinization in Africa and analyze the link between groundwater security (recharge and storage) and groundwater salinity, ii) assess the natural and human-induced causes of groundwater salinization, and iii) highlight emerging groundwater salinity management strategies that are being used or could be used in Africa.

2. Methods

To develop a groundwater salinity map for Africa, we relied on secondary data sources including published and unpublished reports and datasets. Since electrical conductivity (EC, µS/Cm) is easily measured, and because it correlates strongly with total dissolved solids (TDS, mg/L), it is often used as a proxy for salinity and is commonly found in water quality datasets even when anion or cation concentrations are not directly measured. Thus, we used electrical conductivity as a proxy for groundwater salinity in this study. We compiled 12488 data points (Figure 1) from historic records held in published and unpublished reports (list provided in annex i of Supplementary Materials) such as those held by the British Geological Survey (BGS), published IAEA technical documents, UNESCO reports, and national databases. We also digitized 39 regional, national, and sub-national maps held by the BGS which contain data on groundwater salinity from across Africa. The final dataset was used to construct groundwater salinity maps and to conduct statistical analysis. We discarded data points lacking geographic coordinates, leaving a dataset with 12255 individual electrical conductivity measurements. The dataset also includes recently published salinity data points from South Africa (n=23, mean SEC from time-series data) and Eygpt (n=251) (Thorslund and van Vliet, 2020). The groundwater salinity mapping does not include an attempt to interpolate/extrapolate beyond these points. The dataset and digitized maps cover most of Africa, but the humid central Africa region (Congo, DRC, Gabon, and Angola) has a very low data density. The data density mirrors the relative proportions of groundwater use and the geographic focus of past groundwater research. Disregarding the uninhabited deserts in the Sahel and Sahara, the high data density corresponds to regions where groundwater is generally the sole or the primary source of water for all types of use, while the low data density corresponds to humid regions where alternative surface water sources are readily available.

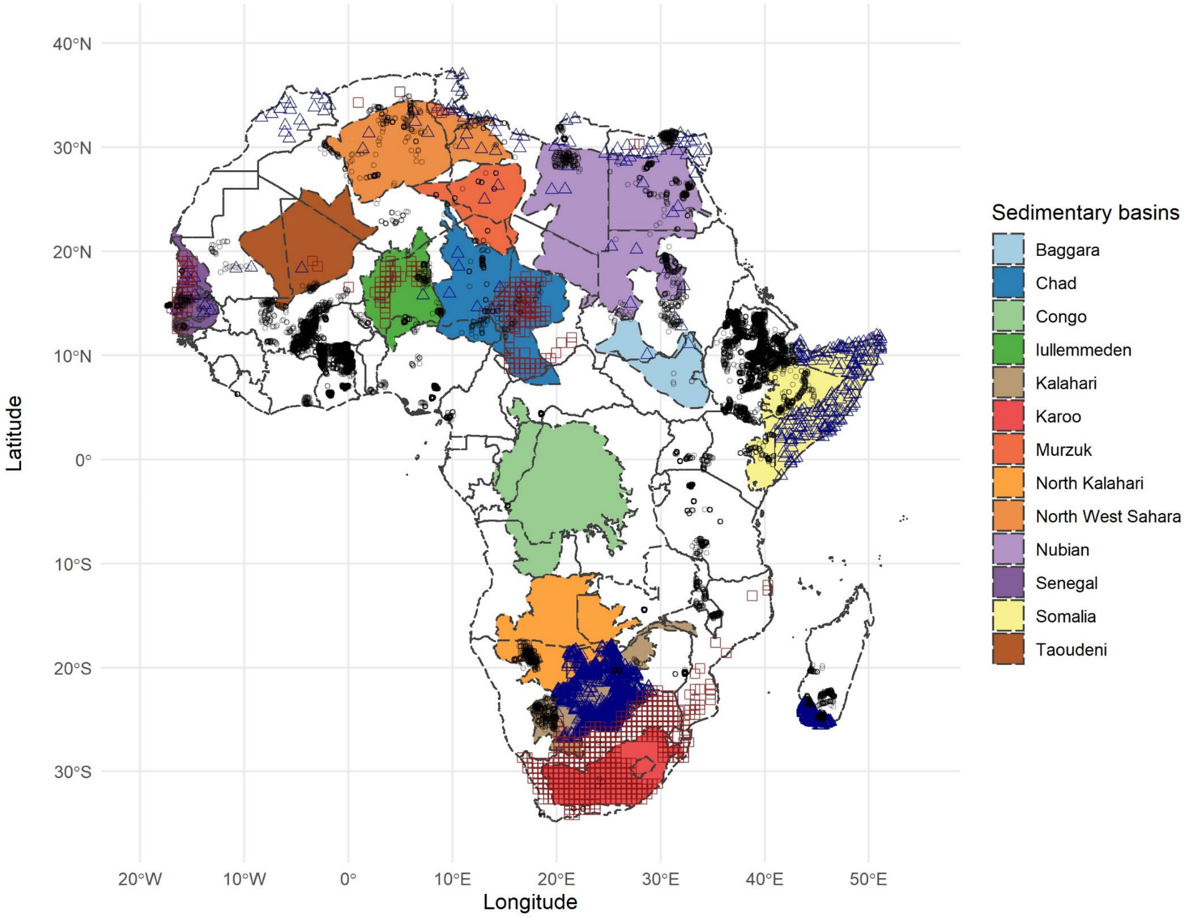

Figure 1. Distribution of groundwater electrical conductivity sample data points (black circles), and data points (blue triangles) and contours (red squares) from digitised maps shown along with country boundaries and large sedimentary basin aquifers from (Bonsor et al., 2018)*. Points in areas with less density of data are lightly coloured whereas points in areas of high data density are darker.*

To produce the salinity map, all data was converted to specific electrical conductivity (EC) in µS/cm. Sample or map data was converted to weight per unit volume in milligrams per litre (mg/l) where necessary and then to electrical conductivity using a conversion factor of 0.7, a reasonable approximation for the range of salinity values within our dataset (Rusydi, 2018). Then the conductivity values were classified into five categories that were loosely based on classifications by (Freeze and Cherry, 1979) and the FAO (1992: https://www.fao.org/3/t0234e/t0234e00.htm): non-saline groundwater (< 500 μS/cm); slightly saline (500 – 1000 μS/cm); moderately saline (1000 – 2000 μS/cm); highly saline (2000 – 15,000 μS/cm); and very highly saline groundwater or brine (> 15,000 μS/cm). Data digitised from maps as polygons were then converted to gridded points at a density of 0.5° and all map and sample point data were plotted on a map of Africa (Figure 1) and coloured by conductivity classification (Figure 2). Often data digitised from maps was only provided as a concentration or conductivity range. Hence, map classes were included within the final classification and presented on our African conductivity map (Figure 2). Due to the nature of the map data these were not included in the analysis described below, where raw values were required.

To assess the compounded risk to water security caused by groundwater salinity, we explore the original point sample data using maps, cross-plots, stacked bar-charts, box-plots (in the supplementary material), and the Kruskal and Wilcox population tests (in the supplementary material). We also compare the original sample point data for which values of electrical conductivity are available with: aridity; groundwater recharge; and groundwater storage estimates (MacDonald et al., 2012)(MacDonald et al., 2021). As stated previously, points converted from map data were not used in this analysis. It should be noted that the dataset and the salinity maps are meant to provide a regional perspective on the state of groundwater salinity and are not appropriate for local scale assessments. The dataset lacks 3D information due to the lack of depth information within the original salinity datasets. The final dataset may be biased towards low salinity groundwaters as high salinity groundwater is not the target for groundwater development through drilling and water well salinity information is lacking. The other data bias is related to the regional disparity in data density. In the hyper-arid, arid, and semi-arid environments, where groundwater is the predominant source of drinking water, the data density is high.

3. Results and Discussion

3.1. The extent of aquifer salinization in Africa and water security

The extent of fresh and saline groundwater:

Figure 2 shows the EC distribution map constructed from the combined data points and the digitized maps (see annex ii for other sets of maps, Supplementary Materials). Approximately 80% of the groundwater samples within our dataset have EC values less than 2000 μS/cm (Figure 3a). More than 50% of the groundwater samples fall in the non-saline category (EC < 500μS/cm).The salinity dataset and map reveal that the majority of the multi-layered sedimentary basin aquifers with large volumes of groundwater storage (e.g. the Nubian Sandstone Aquifer System, The Chad Basin Aquifers, the Iullemeden-Taoudeni Aquifer System, the Bagra basin, etc.) in Africa essentially hold non saline, slightly saline or moderately saline groundwater resources, with salinity problems only encountered in specific regions, zones or depth levels (Figure 3 a-d). The sedimentary basin with the highest frequency of saline groundwater (EC > 2000μS/cm) is encountered in the North Western Saharan Aquifer underlying Tunisia, Algeria and Libya and in the North Kalahari Sedimentary basin aquifer in Southern Africa (Figure 3b). By rock types, all aquifers contain a substantial portion (>60%) of low to moderate salinity groundwaters (EC <2000 μS/cm) (Figure 3c). High groundwater salinity values (EC>2000 μS/cm) are observed in all rock types confirming the localized nature of groundwater salinity in all rocks. Unconsolidated sediments and consolidated sediments with inter-granular porosity host moderate salinity (median EC>1000 μS/cm) groundwater bodies when compared with basement, volcanics and consolidated fractured sedimentary aquifers which host non-saline (EC<500 μS/cm) or slightly saline groundwaters (EC values <1000 μS/cm) (Figure 3c). The unconsolidated sediments and the consolidated sediments with inter-granular porosity aquifers show the most frequent high salinity values with EC>2000 µS/cm. The basement rock areas, which account for 70% of drinking water sources in Africa, hold essentially non-saline groundwater resources (median EC value <500 µS/cm), except for those in arid areas or in areas where wetland induced salinity may be locally encountered. The volcanic aquifers which underlie most of the region in Eastern Africa (Ethiopia and Kenya) contain non-saline and slightly saline groundwaters.

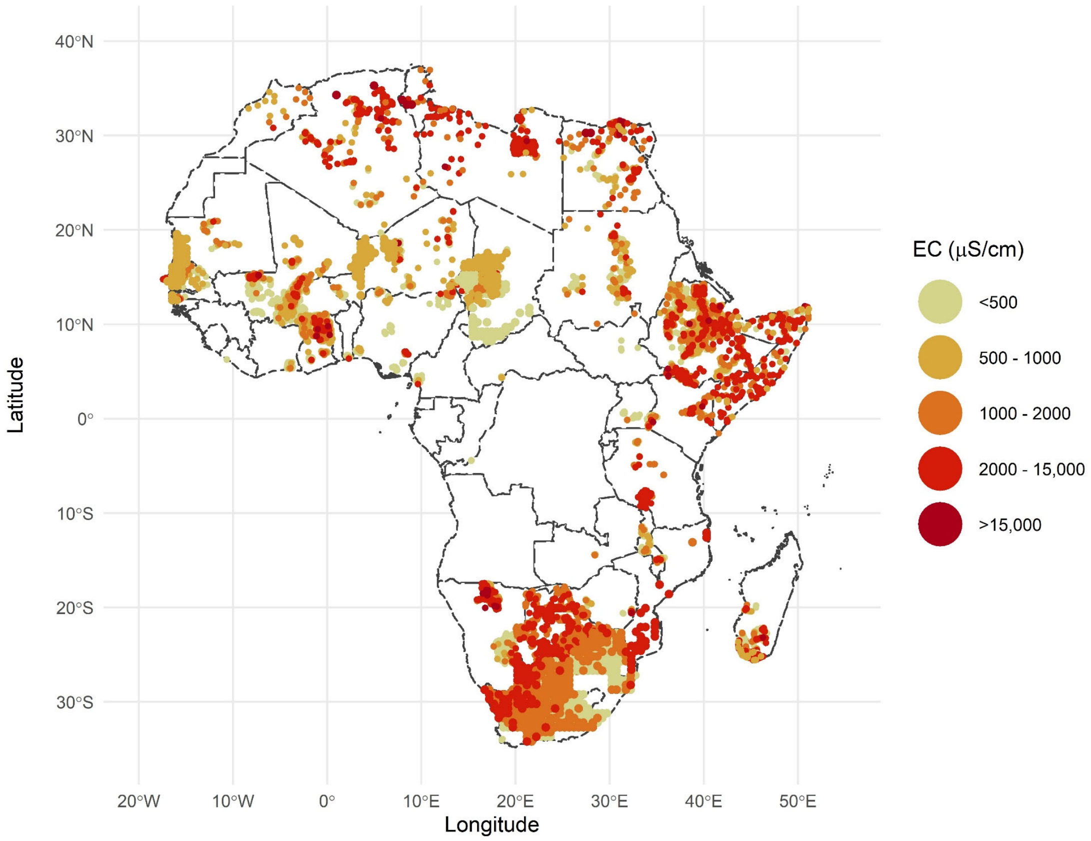

Figure 2. Distribution of EC in groundwaters across Africa.

Comparing salinity levels with aridity (figure 3d) reveals that aridity is the best predictor of groundwater salinity with the most arid environments hosting higher salinity groundwaters compared to humid environments. There is a progressive increase in salinity with the increase in the degree of aridity (Figure 3d). In hyper arid, arid and semi-arid environments, the median EC value exceeds 1000 µS/cm, while in dry sub-humid and humid environments the median groundwater EC value is <1000 µS/cm (see annex ii, Supplementary Materials). Outlier, high EC values, however, exist in all aridity regimes. Aquifers which contain higher EC values (>1000 µS/cm) are unconsolidated sediments and consolidated inter-granular porosity aquifers located in arid, semi-arid and hyper arid zones. Hyper-arid environments also show an abundance of moderate- to non-saline groundwaters; the most likely cause is the paleo climate regime (wetter and humid) under which recharge took place. The vast majority of the groundwater in the Sahel and Northern Africa have been recharged under the humid and wet climate regime of the Pleistocene or Holocene (Jasechko, 2019).

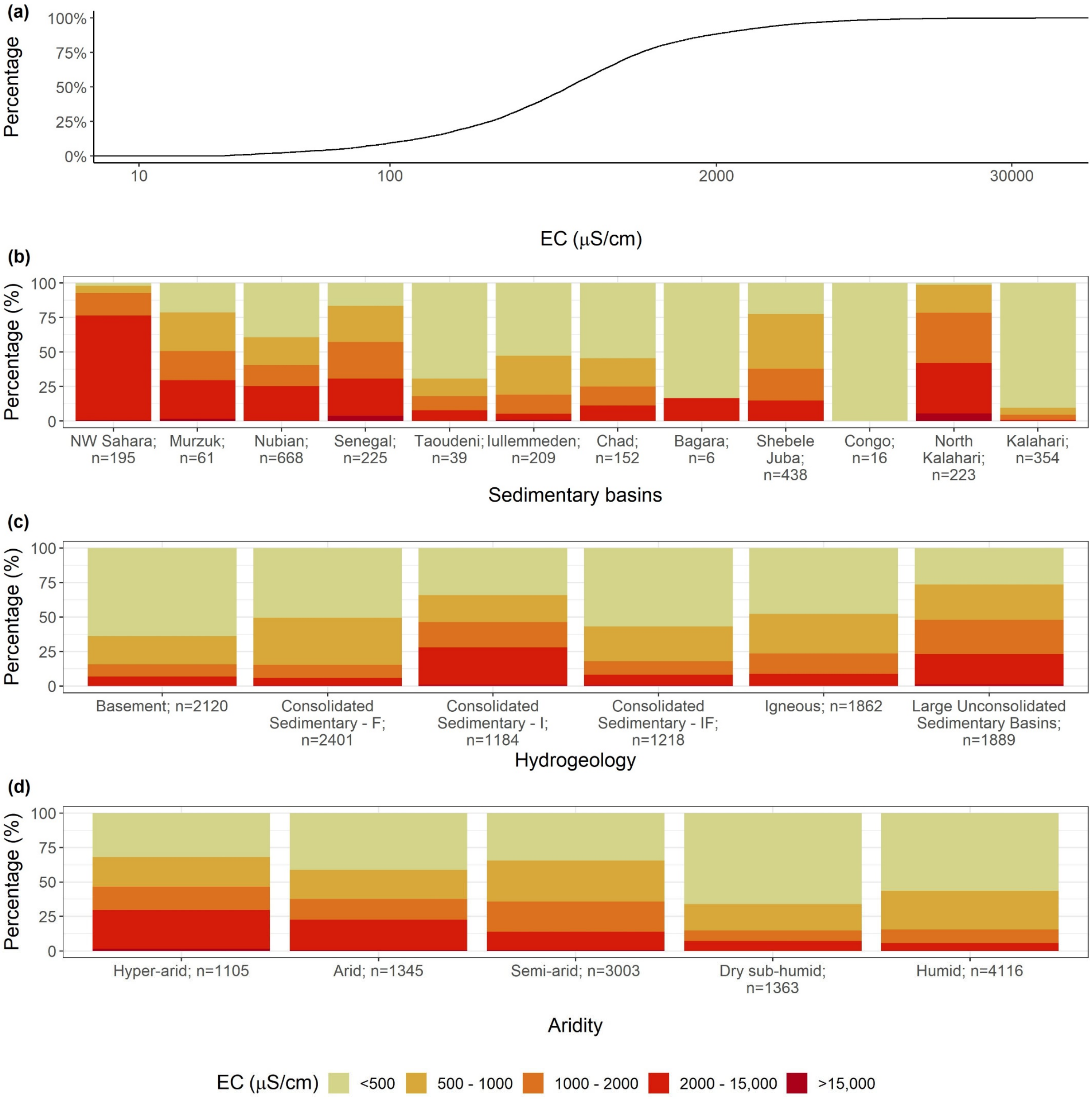

Figure 3. Frequency plot of salinity distribution, b) salinity statistics for the major sedimentary basins, c) salinity distribution by geology (I- inter-granular, F-Fracture) and d) salinity distribution by aridity.

Although we cannot examine the variation in salinity with depth using the dataset we compiled, a review of the literature shows that there is no clear systematic relation between salinity and depth to the groundwater bodies. For example, the deeper section of the sedimentary formation in Northern Africa contains fresh groundwater bodies (e.g., the Continental Intercalair), while aquifers at a shallow depth such as the continental complex aquifer and the Djifara aquifer in coastal North Africa contain locally mineralized waters (Trabelsi et al., 2009). The complex salinity pattern in Tunisia, Algeria and Libya (Figure 2) reveals groundwater wells tapping into these different aquifers bearing different salinities. Additionally, in the transboundary Lower and Upper Kalahari aquifers in Namibia, Angola, and Botswana, the deep aquifers (Lower Kalahari Aquifer) hold fresh groundwater compared to the unconsolidated shallow aquifers as also revealed by Bäumle et al., (2019). Contrary to the two examples given above, in the Shebelle-Juba basin, the deeper sedimentary layers contain more saline groundwaters compared to the shallow aquifers in Ethiopia as revealed by Hadwen et al., (1973). An increase in salinity with depth is also a common feature in volcanic terrains in the East Africa region (Kebede et al., 2005).

Groundwater salinity and water security:

There is a clear inverse correlation between groundwater recharge and salinity (Figure 4a, c) and thus groundwater salinity adds to the water insecurity in environments with low groundwater recharge. While most of the high recharge areas (Western Africa, Central Africa, East Africa highlands, Central African

Republic) show a low level of groundwater salinity (Figure 4a, c), the low to very low recharge regions in North Africa are characterized by variable salinities with more frequent saline groundwater wells. Generally, groundwaters in arid and semi-arid areas with minor recharge (Botswana, Namibia, Somalia, the Rift Valley in Ethiopia, Somalia, Kenya, Tanzania, and Malawi, as well as arid coastal areas in Northern Africa) contain complex salinity patterns with saline groundwaters occurring side by side with fresh groundwaters (Figure 4a).

Salinity adds to groundwater insecurity in both high and low groundwater storage environments. There is a weak positive correlation between groundwater storage and salinity (Figure 4b, d). Groundwater salinity increases with storage volume likely because the high groundwater residence times in aquifers with high storage lead to a longer time for rock water interactions to occur and minerals equilibrate between groundwater and host rocks (e.g. Edmunds et al., 2003).

Combining the groundwater salinity with the long-term annual groundwater recharge and storage (Figure 4d) provides a basis to assess water security on a country-by-country basis. Figure 4e illustrates on average how each groundwater salinity class corresponds to specific groundwater recharge and storage conditions. Non-saline (EC<500 μS/cm) and moderately saline (500>EC>1000 μS/cm) groundwater environments are characterized by high recharge and low storage, while high salinity corresponds to low recharge and high storage areas. While regions with large groundwater storage, high recharge, and low salinity are the most water secure, regions with low groundwater storage, low recharge, and high groundwater mineralization are fragile with respect to their groundwater resources. In this regard, countries that have been identified as the most water-secure based on groundwater recharge and storage alone (Nigeria, Guinea Bissau, Congo, Angola, Democratic Republic of Congo) (MacDonald et al., 2021) remain water-secure when the groundwater salinity dimension is considered. Except in some specific areas (e.g, Southern Angola, coastal regions of Nigeria, Figure 2), groundwaters in these countries are predominantly low salinity (EC<1000 μS/cm).

Out of the five countries (Eritrea, eSwatini, Lesotho, Zambia, and Zimbabwe) with the lowest water security by the measure of groundwater recharge and storage, eSwatini, Zambia, Zimbabwe and Lesotho, water security issues are not compounded by high groundwater salinity. With the exception of recorded local high groundwater salinity, the aquifers underlying the four countries hold generally low salinity groundwaters.

In Eritrea on the other hand, high groundwater salinity is prevalent in coastal areas in the east as well as in the western lowlands. Low salinity groundwaters are restricted to the crystalline aquifers in the highlands of Eritrea. By this measure, this makes Eritrea the most groundwater insecure country on the continent. In Zimbabwe, high groundwater salinity is restricted to the arid south and southern part of the country associated with alluvial sediments.

Five of the countries with the highest groundwater recharge and low storage (Burundi, Liberia, Guinea, Equatorial Guinea, Ivory Coast), i.e. countries underlain by aquifers vulnerable to drought but capable of withstanding long-term depletion because of sustained recharge, are characterized by aquifers bearing low salinity groundwaters. Thus, groundwater salinity does not exacerbate groundwater security in these countries.

The situation is more complex for countries with the highest groundwater storage and low recharge (Egypt, Algeria, Tunisia, Niger, and Botswana), i.e. countries underlain by aquifers vulnerable to long-term depletion but capable of withstanding short-term droughts. Groundwater salinity adds an additional layer of water insecurity in Tunisia, Egypt, Algeria, and Botswana as these countries are underlain by saline groundwaters associated with fresh groundwater zones. In contrast, Niger is generally exempt from the compounded effect of salinity induced groundwater insecurity as groundwater salinity in Niger appears only a localized problem. Countries with intermediate storage and recharge characteristics (<50 mm) but sustained episodic recharge (e.g. Somalia, Botswana, Namibia, South Africa) face the additional challenge of groundwater insecurity when groundwater salinity is taken into consideration. These countries are underlain by aquifers with high salinity and complex salinity patterns.

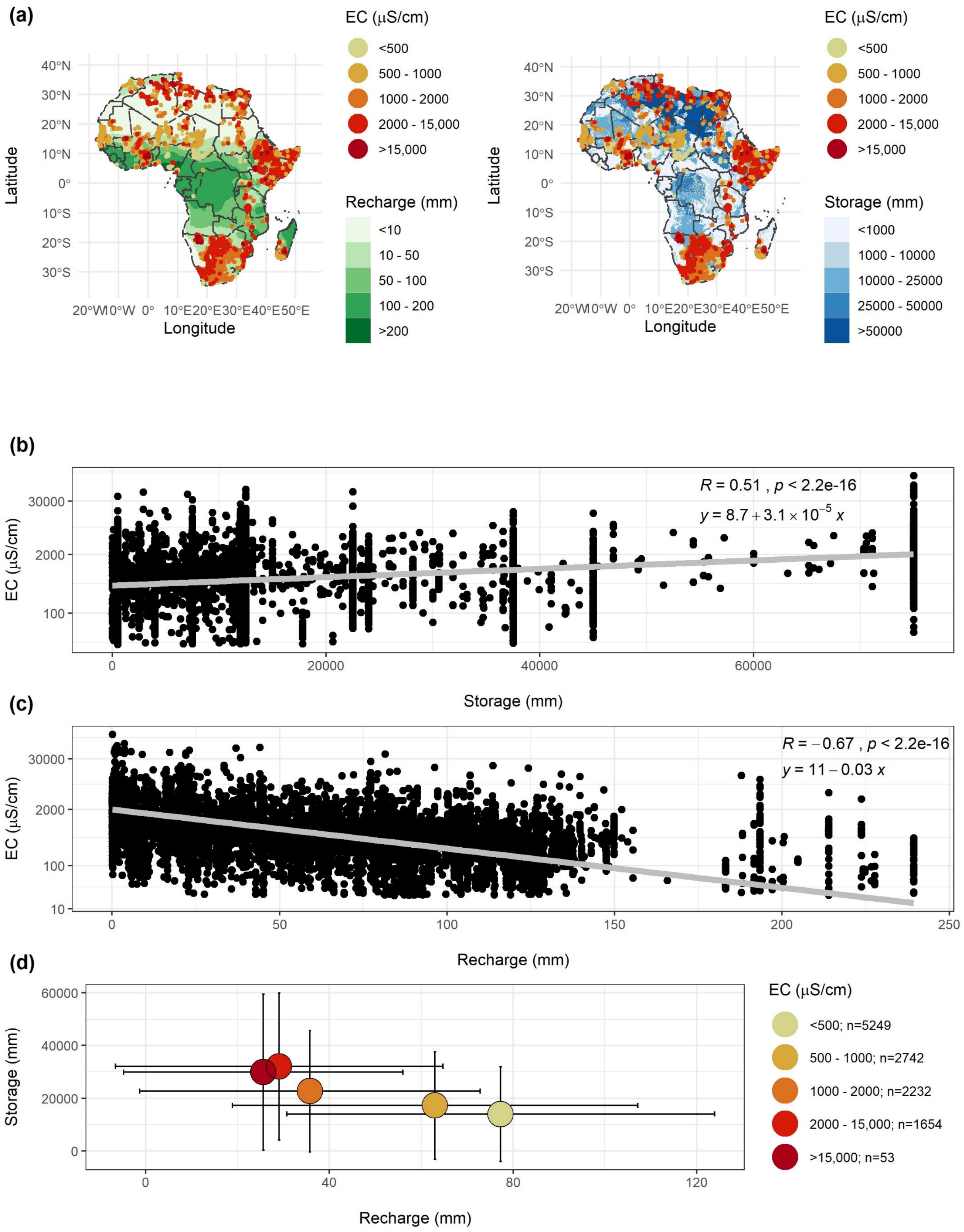
(a)
EC (μS/cm)
<500
500 - 1000
1000 - 2000
2000 - 15,000
>15,000
Recharge (mm)
<10
10 - 50
50 - 100
100 - 200
>200
Storage (mm)
<1000
1000 - 10000
10000 - 25000
25000 - 50000
>50000
Latitude
Longitude
40°N
30°N
20°N
10°N
0°
10°S
20°S
30°S
20°W10°W 0° 10°E20°E30°E40°E50°E
(b)
R = 0.51 , p < 2.2e-16
y = 8.7 + 3.1 × 10^−5 x
EC (μS/cm)
30000
2000
100
0
20000
40000
60000
Storage (mm)
(c)
R = −0.67 , p < 2.2e-16
y = 11 − 0.03 x
EC (μS/cm)
30000
2000
100
10
0
50
100
150
200
250
Recharge (mm)
(d)
Storage (mm)
60000
40000
20000
0
0
40
80
120
Recharge (mm)
EC (μS/cm)
<500; n=5249
500 - 1000; n=2742
1000 - 2000; n=2232
2000 - 15,000; n=1654
>15,000; n=53

Figure 4: a) salinity vs recharge and storage spatial plot, b) salinity vs storage correlation, c) salinity recharge correlation, d) storage-recharge-salinity relation ($R^2=0.94$, $p=0.016$)

In summary, groundwater salinity does not affect the water security status of most countries in Africa. However, salinity compounds water insecurity issues in arid low groundwater recharge environments such as Eritrea, Djibouti, Somalia, Botswana, Namibia, Chad, Ethiopia, Senegal, Mauritania, parts of Kenya and Tanzania, and South Africa as well as in arid large groundwater storage environments such as Egypt, Libya, Tunisia, and Algeria.

3.2 Impacts of groundwater salinization on local water supply

Despite the general finding that 80% of the water wells show EC value less than 2000 µS/cm and may be acceptable for drinking use, groundwater salinity is an issue in many localized aquifers and has implications for primary users of groundwater. For example, high groundwater salinity has been shown to be responsible for the abandonment of water wells (Pavelic et al., 2012) (UNICEF, 2008) limiting access to safe drinking water for the primary users. However, the lack of systematic data on boreholes and abandoned boreholes limits our understanding of the scale of impact of salinity on the abandonment of boreholes at national and continental scales. Several studies report the more than 30% abandonment in local environments including, for example, Mozambique (UNICEF, 2008) and Sudan (Fragaszy and Closas, 2016), Abandonment of boreholes caused by the saline groundwaters is most severe in alluvial aquifers and coastal aquifers. For example, in the Shire Valley, southern Malawi, persistent non-functionality or abandonment of boreholes tapping alluvial aquifer was typically ascribed to salinity (Rivett et al., 2020), (Lapworth et al., 2020) reported that for upscaled country estimates >10% of handpump borehole sources in Malawi TDS exceeded 1000 mg/L and these were focused in southern Malawi. High salinity resulted in the abandonment of up to 70% of drilled boreholes in the vast sedimentary aquifers of the Horn of Africa countries such as Somalia, Ethiopia, and Kenya (Kebede and Taye, 2021). In Libya, 75% of boreholes have been lost to saltwater intrusion in the coastal region (Steyl and Dennis, 2010). In the coastal plains of Comoros island, fewer than 30% of water wells provide groundwater of acceptable quality (Comte et al., 2016) when measured by the salinity levels. In Kenya, (Foster et al., 2018) show for every 100 μS/cm EC increase there is a 3% rise in the risk of failure of rural water wells.

3.3. Typologies of groundwater salinization in Africa

To effectively manage the challenge of groundwater salinity in Africa, there is a need to understand the underlying drivers and causes which can be broadly categorized as anthropogenic, hydrologic, geologic, and saline water encroachment, all of which we discuss further below. Since most of the high salinity environments are local in extent, not all these zones may be visible in Figure 2.

Anthropogenic related: The major causes of anthropogenic salinization include irrigation practices, mining, and land-use changes. Human induced salinization of groundwater has been reported in some river basins and aquifers in Africa. Given the fact that river basin irrigation development in Africa is scarce in the large river basins such as the Congo and Niger, irrigation-induced salinization of groundwater is restricted to those intensively developed river and aquifer basins such as the Nile, Senegal, Orange, Shire, Zambezi, Volta, Vaal and Awash basins. Substantial portions of groundwaters in the Nile Valley, the Senegal River Delta (Gning et al., 2017), and the Val River in South Africa are now seriously threatened by salinization that has led to the abandonment of many irrigated areas and loss of water wells to salinization (Fragaszy and Closas, 2016). In Tunisia and Algeria, irrigation return water led to the high salinity of the shallow groundwater (Yangui et al., 2012). The mechanisms that lead to irrigation induced groundwater salinity involve multiple processes (Foster et al., 2018)(Mirzavand et al., 2020). Firstly, successive evaporative concentration of water in the irrigation ponds, primary and secondary channels leads to the increase in salinity of irrigation water. Subsequent downward flux of salt causes an increase in the salinity of groundwaters. Secondly, the salinity of groundwater increases because of the addition of fertilizers and plant protection products. Thirdly, rising water tables can result in the dissolution and mobilization of salt that accumulates in the shallow soils to the groundwater and increase the salinity further. In coastal areas, upstream damming of rivers discharging into the coastal plains has caused saltwater intrusion in Kenya and Tanzania (Steyl and Dennis, 2010).

Extractive resource industries, such as coal mining, have also caused aquifer and surface water salinization. One of the mechanisms of salinization is acid and non-acid mine drainage causing mobilization of ions and metals, leading to waters of very high salinity. This is a widespread problem in coal mining areas in South Africa (Nephalama and Muzerengi, 2016). Mixing of petroleum mine waste water with groundwater during petroleum extraction is reported to have caused high groundwater salinities in South Sudan (Rueskamp et al., 2014). Local salinization of aquifers is reported to occur in Egypt from disposal of brine from desalination plants into the pumped aquifer(Jahnke et al., 2019).

Other human induced land-use changes are reported to have impacted groundwater quality. For instance, groundwater salinity is reported to have increased accompanying the rise in recharge owing to conversion of bushlands to agriculture land in Sahel Africa (Favreau et al., 2009). Subsequent to the increase in groundwater recharge, the water table migrates towards the surface causing ponding of water, the evaporative concentration of the water, and thereby an increase in salinity of the groundwaters. The high groundwater salinity in the capital city of Mauritania, Nouakchott, results from the inter basin water transfer from the Senegal River meant to supply the city. The excess water from the newly diverted water supply resulted in water table rise of the pre-existing saline groundwater body leading to water logging and very high salinity levels in the shallow coastal aquifer (Mohamed et al., 2017). More generally, increases in groundwater salinity can also be the direct result of a range of urban land use pressures, including waste water recharge from various industries as well as domestic waste water and sanitation sources(Lapworth et al., 2017).

Paleo hydrology related: Groundwater salinity observed in several parts of Africa relates to paleo hydrological processes. There are a number of mechanisms by which past hydrological processes govern present day salinity patterns in groundwater.

Firstly, the direct entrapment or intrusion of paleo saline waters (e.g. paleo marine water, connate water) causes groundwater salinization observed in many coastal regions observed in Figure 2 (see Supplementary Material, annex ii for details for example for Senegal). Saline water entrapment/intrusion in coastal aquifers during the paleo regression-transgression cycles is a notable source of groundwater salinity in many places (Kafri, 1984) including the Senegal River Delta (Gning et al., 2017); the coastal aquifer of Western Africa (Akouvi et al., 2008); the Danakil Depression, Ethiopia (Kafri, 1984); the Nile Delta, Egypt (van Engelen et al., 2019); in complex volcano sedimentary aquifers, Djibouti (Awaleh et al., 2017); in the coastal aquifers in Togo (Akouvi et al., 2008), in coastal aquifer of Mozambique (Stigter and Zhou, 2018), the coastal aquifers of Tanzania (Walraevens et al., 2015); and in some portion of the North Western Saharan Aquifer System in Tunisia (Edmunds et al., 2003) and explains the observed high groundwater salinities that extend far inland in the coastal region such as in Senegal, Tunisia, Egypt and Libya (van Engelen et al., 2019).

Secondly, paleo hydrological conditions can lead to the formation of hydrogeologic environments favoring groundwater salinization. For instance, the aridification of the North and Horn of Africa since the mid-Holocene has resulted in the deposition of many large paleolake sediments. Paleolakes, by their nature, contain sediments of different grain sizes and permeability conditions. Differential permeability leads to different groundwater flow velocities, causing stagnation of groundwater in some zones and faster flows in other zones and eventually leading to a complex pattern of salinity as well as exceptionally high salinities.

Fine grained sediments often contain high salinity groundwaters when compared with coarse grained sediments with higher permeability. Paleolakes explain the salinity pattern observed in unconsolidated aquifers in many parts of Africa (Figure 3c), including for example the complex salinity patterns in the alluvial-lacustrine sediments in the Kalahari region of Zambia (Banda et al., 2019), in the Shire River Basin in Malawi (Rivett et al., 2020), and the alluvial lacustrine sediments of the East African Rift Valley (Ligate et al., 2021). Salinity caused by paleolake sediments is common in arid environments since there has been insignificant flushing to remove salts from the layers since the time of aquifer recharge.

Extensive deposits of paleolake sediments explain the complex salinity pattern observed in Somalia, Chad, Namibia, Botswana, Ethiopia, and Kenya for example. Salinity may also be imparted owing to the shallow depth of most of the alluvio-lacustrine sediments and the groundwaters hosted in these aquifers. The shallow water table allows direct evapotranspiration from aquifers leading to the formation of groundwater troughs with pockets of saline groundwater. The high salinity groundwaters in Sudan in 'Khors' (groundwater troughs adjacent to the Nile River) is a typical example of this type of salinization(Kebede et al., 2017; Abdalla, 2009). The high salinities seen in the Okavango delta, northern Botswana is caused by direct groundwater evapotranspiration leading to a build-up of TDS in groundwaters (Zimmermann et al., 2006). When paleo sediments are located in arid and semi-arid environments with the deeper water table, the episodic recharge mobilizes the salt from the shallow soil zone to the water table enhancing the salinity of groundwaters (Sami, 1992). However, such localized, evaporation induced salinity also occurs in wet environments associated with loose sediments and wetlands and explains high localized salinities in Lake Tana basin- Ethiopia (Kebede et al., 2011), and in the Kisumu aquifer around the eastern fringe of Lake Victoria (Olago, 2019). Groundwater salinity associated with wetlands may be temporal and shifting in time depending on the hydrography/hydrology of the wetland environment (Mabidi et al., 2018). The salinization induced by differential permeability, direct evapotranspiration from shallow aquifers, and successive evaporation-dissolution cycles of paleo alluvio-lacustrine sediments is exacerbated in endorheic basins which are found in places such as the Lake Chad, Lake Chilwa, the East African Rift (Ethiopia, Kenya, Tanzania).

Rock dissolution: Aquifer matrix dissolution adds ions to groundwaters. Aquifers containing intercalations of readily soluble minerals such as gypsum, anhydrite, and halite if present only in small quantities results in high salinity groundwater. Such soluble rock materials are often times associated with paleo lake sediments, marine deposits including for example shales and carbonates. Because of the high solubility of evaporites, even groundwaters with short residence time may acquire high salinities. Rock dissolution explains the high groundwater salinity (Figure 2) encountered in large sedimentary aquifer basins such as the Juba Shebelle basin in Somalia, the North Western Saharan Aquifer basin in Tunisia and Algeria (Pina et al., 2017; Yangui et al., 2012), and Karoo sediments in South Africa. However, other factors play a role in exacerbating rock dissolution induced salinization. For example, in the greater rift valley region, in Ethiopia, Kenya and Tanzania heat from geothermal activity and carbon dioxide influx from deeper earth accelerate the dissolution of the otherwise less soluble volcanic rocks and result in high salinity groundwaters (Darling et al., 1996). Geothermal induced salinization of groundwater is commonly observed, for example, in Ethiopia (Darling et al., 1996), Kenya (Darling et al., 1996), Tanzania, Djibouti (Awaleh et al., 2017) and Eritrea (Lowenstern et al., 1999). Groundwater residence time controls the degree to which groundwater salinity increases due to rock dissolution. Oftentimes deep circulating groundwaters with longer residence time are more saline (Edmunds et al., 2003) than more shallow circulating short residence time groundwaters. Groundwater residence time control on groundwater salinity is evident in the volcanic aquifers of Eastern Africa (Ethiopia, Kenya, Tanzania) whereby shallow aquifers generally show low salinity compared to the deep circulating long residence time groundwaters (Kebede et al., 2005) (Banks et al., 2021).

Modern saline water encroachment: Saline water encroachment is the process whereby saline water from surface or groundwater sources intrudes the freshwater aquifer, as a result of sea water intrusion, down or up welling of groundwater from saline aquifers into the fresh water zones, and ingress of saline sea water from tidal waves and storm surges, and to a lesser extent due to geothermal water ingress into fresh groundwater bodies.

Of all the salinization processes so far discussed, sea water intrusion is the most widely researched salinization mechanism in Africa. Firstly, sea water intrusion into coastal groundwater results from hydraulic perturbance owing to groundwater pumping from coastal aquifers or because of the action of tides or sea level rise. In coastal environments, with geological time, a fragile hydraulic equilibrium is established between fresh and saline water bodies. Groundwater abstraction can affect this delicate hydrological balance leading to rapid salinization of groundwaters (Vengosh, 2013).

Because of its diverse geologic setting, the 40,000 km long coast of Africa is comprised of a myriad of aquifer systems (Steyl and Dennis, 2010) with remarkable differences in the state of seawater intrusion. The high groundwater salinity observed in Northern Libya, Egypt, and Tunisia (Figure 2) is partly attributed to this process. Seawater intrusion induced by overexploitation of coastal aquifers has led to a salinity increase in a number of aquifers. In Northeastern Tunisia, as the result of overexploitation of the coastal Ras el Jabel aquifer the range of groundwater salinity has increased from 1.5–4 g/L in 1969 to 5–10 g/L in the 1990s (Khater, 2019). Well fields in coastal southern Kenya show a gradual increase from less than 400 µS/Cm in the 1970s to 1100 µS/cm in 2017 (Oiro and Comte, 2019). In Djibouti a similar increase in the salinity of coastal aquifers has been observed (Houssein and Jalludin, 1996). Pumping induced salinization is reported in coastal plains of Libya (Al Farrah et al., 2011), Egypt (Eissa et al., 2016), and Tunisia (Ziadi et al., 2019). Seawater intrusion owing to pumping of the coastal aquifers has been noted in a few other coastal aquifers in East Africa (Comte et al., 2016), South Africa, and West African coasts (Hounsinou, 2020)(Nlend et al., 2018). Saline water encroachment is more pronounced in arid coastal areas of North Africa whereby there is limited recharge to sustain the delicate hydraulic balance between fresh groundwater and saline seawater. However, in more humid coastal regions such as in West Africa, combined seawater intrusion and dissolution of aquifer matrix impact salinization of coastal aquifers as observed in the 1000 km stretch of the coastal regions. In the coastal region of western Africa, the saline groundwaters are often overlain by lenses of fresh groundwaters, and the extent of the saline zone is limited to the coastal strips(Steyl and Dennis, 2010). In some coastal cities (e.g., Abidjan, Douala) salinization of the coastal aquifer is more often related to rock dissolution or pollution than to seawater intrusion (Ramatlapeng et al., 2021) (Nlend et al., 2018).

Coastal aquifer pumping is not the only process that perturbs the hydraulic gradient leading to salinization of coastal aquifers. The natural seasonal and diurnal variations of sea level and associated tidal fluctuations have an important impact on coastal groundwater level and salinity. Tidal effects, including those exacerbated by storm surges, explain groundwater salinity patterns observed in coastal aquifers in Morocco (Fadili et al., 2018), Gambia (Bagbohouna et al., 2018), and Senegal (Ngom et al., 2016), although there is no agreement on such salinization mechanism in western Africa (Ramatlapeng et al., 2021) (Fantong et al., 2016). The other mechanism of seawater related salinization is through sea spray and dry deposition in coastal environments. Sea spray and dry deposition are reported to have increased groundwater salinity in many locations including in South Africa (van Gend et al., 2021) and West Africa (Osiakwan et al., 2021).

Salinization of fresh groundwater bodies by encroachment of salt waters also occurs in continental setting whereby saline groundwater leaks up or downwards into fresh groundwater aquifers owing to natural hydraulic gradient or pumping induced perturbations of the hydraulic gradients. The perturbation of the hydraulic equilibrium can cause previously isolated saline groundwaters to mix with fresh groundwater as a result of pumping. Such processes occur predominantly in the North Western Saharan Aquifer system (Tunisia, Libya, Algeria) where intensive groundwater pumping is taking place (Meyer, 2011). In Tunisia, the Miocene sand aquifer is salinized by the capture of saline water from the shallow aquifers (Trabelsi et al., 2009). Pumping induced salinization is evoked in a number of places including, for example, the Merti Aquifer in Kenya(Oord et al., 2014) and, the Djibouti Aquifer in Djibouti (Houssain and Jalludin, 1996).

Groundwater-surface water salinity exchange: In addition to the processes described above, many of which explain the large-scale salinity patterns observed across Africa, localized connectivity between surface water and groundwater has been noted to impact groundwater salinity patterns in many locations. Groundwater found in the proximity of streams bodies typically shows low salinity compared to groundwater bodies at furthest distance from streams. In other instances, particularly in arid and semi-arid environments, it can be the surface water discharge into the riverbed aquifers that drives the salinization. For instance, in Okavango delta, groundwater flow directed from river into adjacent aquifer and subsequent evaporative concentration of the dissolved salt in the aquifer by evapotranspiration accumulate salt in the aquifer leading to localized groundwater salinization adjacent to the streams (Zimmermann et al., 2006). This type of salinity pattern has been observed in a number of locations other locations including along the banks of the Nile River in Sudan (Kebede et al., 2017) and in Omo River Delta region.

Groundwater discharge to streams explain high salinities in streams waters in several river basins. Saline groundwater discharge into surface waters causes river water salinization in Awash Valley in Ethiopia (Kebede et al., 2021), in Hombolo dam in Tanzania (Shemsanga et al., 2017), in Molo Basin in Kenyan Rift Valley (Chebet et al., 2020). In the Berg River Basin in South Africa, stream water salinization has been noted because of saline groundwater discharge from the underlying geologic formations (Demlie et al., 2011).

4. Emerging management strategies in Africa

There is a lack of a systematic approach to the management of groundwater salinity in Africa. Existing policies or guidelines, instead of finding technological or management approaches to meet the drinking water quality requirements (e.g. WHO, 2011), often focus on relaxation of the WHO guidelines. For example, in the Comoros islands, where fewer than 30% of the wells provide groundwater of acceptable quality, the local drinking water salinity guideline is usually taken as 3000 mg/L instead of 1000 mg/L as recommended by the World Health Organization (Comte et al., 2016). High concentrations of dissolved solids, which are generally present throughout the Horn of Africa, for example, have necessitated the introduction of higher water quality standards. In Somalia, the electrical conductivity (EC) of up to 3,500 µS/cm is considered safe for human consumption (Idowu and Lasisi, 2020). The republic of Djibouti enacted policies to abandon boreholes that return saline water and drill new boreholes until fresh groundwater is encountered. South Africa implements controlled release of saline mine waters into streams during floods when dilution capacities of the streams are high (Idowu, 2007).

To overcome the water insecurity risk posed by high groundwater salinity, concerted management strategies are required. The first and the most cost-effective strategy is to identify the scale of the salinity issues by more concerted monitoring. Currently, there are no national guidelines on the management of groundwater salinity in Africa. However, below we discuss a number of technical measures that can be taken to reduce the salinity risks and describe some existing initiatives in operation across Africa.

Salinity safe sourcing: this technique involves finding low salinity groundwaters in otherwise high salinity groundwater environments by mapping salinity micro variations in alluvio-lacustrine sediments or by mapping vertical stratification in salinity in multi-layered aquifer systems. For example, in Malawi, shallow large-diameter wells are shown to be less saline and more durable than deeper small-diameter boreholes (Comte et al., 2016). In multi-layered aquifers it may be possible to find fresh groundwater layers at deeper levels as observed in the Kalahari (Bäumle et al., 2019) and North Western Saharan Aquifer System asserting that salinity does not always increases with depth. Basement and volcanic bedrock aquifers may contain low salinity waters compared to overlying loose alluvio-lacustrine sediments. This may be particularly true in arid environments whereby the deeper aquifers were recharged under different climate conditions that allow fresh groundwaters. Deeper paleo-river channels may also provide low salinity groundwater (Rivett et al., 2020).

Pumping management: There are a number of ways managed pumping of groundwater lowers groundwater salinity. In drylands, intentional groundwater pumping can lead to lowering of the water table preventing progression of dryland salinity (Dogramaci, 2004). In low lying coastal environments where a thin lens of fresh groundwater rests on deeper saline water, controlled pumping of the deeper saline water can lead to deepening of the interface between the fresh and salt water. The newly created space can be used to as a storage space in the shallow aquifer (Mainuddin et al., 2021). Despite various models and field practice based demonstrations in other parts of the world (Stein et al., 2019)(Mainuddin et al., 2021) the use of groundwater pumping to manage salinity is not widely reported in Africa. One exception may be the exploitation of the shallow fresh water in the Djibouti aquifer by limiting pumping from the shallow fresh water aquifer so as to limit the encroachment from deeper salt water (Houssein and Jalludin, 1996).

Managed Aquifer Recharge: Managed aquifer recharge to augment water supply and simultaneously preventing seawater intrusion in coastal aquifers is already practiced in South Africa. One such example is the Atlantis scheme, which separates the domestic and industrial wastewater and storm water runoff based on salinity, recharges the low salinity water into the inland aquifer used for domestic supply, and recharges the more brackish water into the coastal aquifer to prevent seawater intrusion (Horriche and Benabdallah, 2020). Managed aquifer recharge is a proven approach in reducing the salinity of coastal aquifers and in overcoming the challenges of seawater intrusion in a few places such as in Tunisia, (Horriche and Benabdallah, 2020), Namibia (Tredoux et al., 2009), and South Africa (Bugan et al., 2016). As well as the large scale managed aquifer recharge, salinity management is also being done on a smaller scale through rainwater harvesting and river recharge schemes in dryland systems in South Africa and small island aquifer systems (Hohne et al., 2021).

Inter-basin water transfer: This involves the transfer of water from water secure environments to water insecure environments using artificial infrastructure such as channel and pipes but these are often controversial schemes. The Great Man Made River in Libya to channel the fresh groundwater from the Kufra (Nubian sandstone) in the south to the salinity affected region in the coastal plains is an example. Several projects of inter basin groundwater transfer have been initiated in Africa but the sustainability of the infrastructure and the financial feasibility of such projects often present insurmountable barriers to implementation (Luedeling et al., 2015)(Oord et al., 2014)(Kebede and Taye, 2021). Nevertheless, inter basin transfer is practiced or has been initiated in a few locations in Africa, including the transfer of the Merti Aquifer waters to supply the City of Wajir (Luedeling et al., 2015). The transfer of lake water from the Lac de Guier in the North of Senegal to supply Dakar is another example although it is not a groundwater transfer. The transfer was needed because of the dire water quality conditions that have arisen locally in Dakar in part due to pumping induced salinization (Re et al., 2011). Although published literature is lacking, there are dozens of long-distance rural water transfer schemes in Ethiopia meant to address water salinity challenges and known to the authors.

5. Conclusions and future outlook

Our analysis demonstrates that groundwater salinity across Africa is generally low (<2000 μS/cm) and is suitable for irrigation and drinking water uses. The major sedimentary basins which account for 80% of the groundwater storage contain predominantly fresh groundwater resources with high salinities localized to specific zones and layers. The basement aquifers, which supplies 70% of Africa's rural population with drinking water sources, contain predominantly fresh groundwater resources (<500 μS/cm) with high salinities (> 2000 uS/cm) restricted to certain lithologies or minor alluvial sediments overlying the basement aquifers. Groundwater salinity is extremely variable in sediments of paleo hydrological systems that contain inter-fingering of fresh and saline groundwater bodies.

Groundwater salinity strongly correlates with groundwater recharge. Groundwater salinity increases with the degree of aridity, with higher salinities found in hyper-arid environments as compared to humid environments. Regions with high groundwater recharge generally have lower salinities than regions with low groundwater recharge. Conversely, in regions with high groundwater storage, for example in arid environments groundwater salinity is generally higher. The consideration of groundwater salinity as a water security indicator will not alter the groundwater security status of the countries in humid high recharge environments. Nigeria, Guinea Bissau, Congo, Angola, Democratic Republic of Congo Burundi, Liberia, Guinea, Equatorial Guinea, Ivory Coast remain groundwater secure even when groundwater salinity is considered. On the other hand, groundwater salinity adds to groundwater insecurity in arid countries with low groundwater recharge including Namibia, Botswana, Somalia, Egypt, Libya, Tunisia, Morocco, Senegal, and Algeria.

Since data on very high salinity groundwaters are not often the target of groundwater development or use, the dataset compiled for this study may be biased towards low salinity groundwaters. The dataset lacks depth information, therefore, a concerted effort is needed to produce quantitative 3D maps of groundwaters based on information from boreholes as well as other tools such as geophysics, or other sources of data including those from commercial drinks companies, petroleum/oil wells, and abandoned wells. Concerted effort must be made to quantify, delineate and monitor salinization of groundwaters in Africa. A significant challenge however remains the paucity of accessible data, particularly in the vast humid regions such as in the Congo basin and Central Africa. Organizations that hold groundwater quality data are often located outside Africa. Groundwater quality data is dispersed across local and international institutions that do not often have data sharing protocols. Accessibility of such datasets would further enhance our knowledge of the scale of groundwater salinization and its drivers. Our study provides the basis for planning future groundwater salinity monitoring plans and design management strategies, and formulating policies at the continental level.

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