Journal of African Earth Sciences 206 (2023) 105043

Contents lists available at ScienceDirect

Journal of African Earth Sciences

journal homepage: www.elsevier.com/locate/jafrearsci

Hydrochemical and isotopic characteristics of the Lodwar Alluvial Aquifer System (LAAS) in Northwestern Kenya and implications for sustainable groundwater use in dryland urban areas

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ARTICLE INFO

Handling Editor: Dr Mohamed Mohamed G Abdelsalam

Keywords:
Deuterium
Oxygen-18
Tritium
Groundwater recharge sources
Lodwar
Turkwel river
Semi-arid regions

ABSTRACT

Groundwater is a crucial resource for dryland regions such as this, where surface water resources are limited and unreliable. This paper presents a study of the Lodwar Alluvial Aquifer System (LAAS) in northwestern Kenya and its hydrochemical and isotopic characteristics, with the goal of understanding how to sustainably manage the groundwater system. As a result, the paper focuses on elucidating the hydrogeochemical and river-groundwater interaction (using environmental isotopes and major ion chemistry) of an aquifer that is located in the northwestern dryland of Kenya. The study utilised environmental isotopes of oxygen-18 (^{18}O), deuterium (^{2}H), and tritium (^{3}H) as tracers for establishing recharge sources and origin of groundwater. A sampling campaign involving 112 water samples was conducted to establish isotopic compositions of rain, spring, surface water (rivers, scoop holes, dams and lake) and groundwater at the peak of the wet season in May 2018. The tritium values in the study area ranged from 1.1 to 2.4 TU. Considering the median values of $\delta^{18}O$ and $\delta^{2}H$ in surface water and groundwater samples, four clusters emerge based on the degree of enrichment; Cluster 1 comprises the lake water ($\delta^{18}O = +6.01$, $\delta^{2}H = +41.9$); Cluster 2 is the Turkwel and Kawalase river water with slightly positive relative to VSMOW and with different $\delta^{2}H$ values (+7.6‰ versus −9.8‰). The third cluster is the groundwater of the Shallow Alluvial Aquifer (SAA) and the Deep Aquifer (DA) ($\delta^{18}O = -0.96$‰ and −0.70‰; and $\delta^{2}H = +0.4$‰ and +0.6‰, respectively). The last cluster comprises the most isotope-depleted waters of water pans, scoop holes, Intermediate Aquifer (IA) and Turkana Grit Shall Aquifer (TGSA) with median values ranging from −2.87‰ to −2.48‰ for $\delta^{18}O$ and −8.6‰ and −16.4‰ for $\delta^{2}H$. While the SAA is mainly recharge by the Turkwel River, a relationship is observed between the values deuterium in the Kawalase (−9.6‰ VSMOW) and IA (−8.6‰ VSMOW). Understanding recharge sources and aquifer vulnerability of similar strategic aquifers helps scientists appropriately advise policymakers and the water community who develop sustainable water use, aquifer protection and conservation strategies. In addition, the study contributes scientific evidence of isotopic compositions of groundwater in the Horn of Africa. Furthermore, the evidence of surface water-groundwater interaction presents a case of a fragile dryland ecosystem. Future work will involve the installation of piezometers in strategic aquifer zones to monitor groundwater levels in relation to river gauging data to quantify the amount of recharge and establish the impacts of rainfall variability in the upstream catchment.

1. Introduction

Groundwater is a crucial component of the Earth's water cycle and plays a vital role in sustaining ecosystems and human activities. It serves as a reliable source of freshwater for drinking, agriculture, and industrial purposes, particularly in areas where surface water resources are limited or unreliable (Hanich et al., 2023). Generally, global water consumption has increased by around 1% annually since the 1980s due to population expansion, socioeconomic development, and shifting consumption patterns (UN, 2019). Particularly, increased demand from population growth, tourism, urbanization, and expanding irrigated agricultural land has resulted in unsustainable withdrawals, resulting in groundwater depletion in many regions (Hanich et al., 2023). Subsequently, groundwater quality is influenced by geological and hydrological processes, climate variability, and human activities. These impacts are exuberated in dryland regions due to scarce rainfall, prolonged droughts

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https://doi.org/10.1016/j.jafrearsci.2023.105043
Received 8 November 2022; Received in revised form 16 August 2023; Accepted 18 August 2023
Available online 21 August 2023

and facing rapid population growth. As a result, around 1 billion people worldwide lack access to safe drinking water, and water is growing scarce in already dry areas of the planet (Cuthbert et al., 2019). These drylands are expanding and currently comprise more than a third of the Earth's surface and are characterized by rainfall of less than 250 mm per annum (González-Trinidad et al., 2017). These regions support a population of about 2 billion people, half of the world's livestock and cultivated land, and are home to internationally important ecosystems (Cuthbert et al., 2019). Furthermore, climate change is expected to reduce rainfall in many drylands by the end of the century (Taylor et al., 2012); therefore, it is critical that we understand how to continue to deliver fresh water in these areas, allowing the rising human population to survive while also maintaining dryland ecosystems healthy (Schlaepfer et al., 2017) (see Table 1).

Although the importance of groundwater in drylands is widely recognised, its sustainable development and management is yet to be achieved (Olago, 2019). In Africa, where many regions experience consecutive droughts and floods, water resource management is a crucial concern (Adloff et al., 2022). Due to the scarcity of ground-based monitoring of water resources, the assessment of groundwater resources mainly relies on remote sensing (Scanlon et al., 2022).

In sub-Saharan Africa, groundwater is considered a strategic resource (Blokker et al., 2019; Falkenmark, 2019; Grönwall and Oduro, 2018) and plays a key role in economic development and the improvement of livelihoods (Lapworth et al., 2017). In the Horn of Africa Drylands (HADs), over 60% of the population lives in drylands with acute water scarcity (Adloff et al., 2022). Since 2000, East Africa has been hit by 16 droughts, resulting in catastrophic food and water crises affecting millions of people. However, sustainable groundwater management in dryland regions worldwide has yet to be achieved due to insufficient data on aquifer characteristics and vulnerability to climate and human-induced risks (Jang et al., 2017; Jasechko et al., 2017). This makes it difficult to sustainably manage the resource to meet rural and urban water demand (MacDonald and Davies, 2000; Prinz and Singh, 2000), particularly in dryland urban areas where it is at risk of over-exploitation (Demirog, 2017; Xiao et al., 2019).

One critical area where there is insufficient knowledge for sustainable development and protection of aquifers relates to groundwater recharge sources (Xu et al., 2019). The stable environmental isotopes of oxygen (^{18}O, ^{16}O), deuterium (^{2}H), and tritium (^{3}H) provide insights into groundwater recharge sources (González-Trinidad et al., 2017; Prada et al., 2016), improve the understanding of hydrological processes, and provide information on the origin and movement of groundwater (Shi et al., 2019) and the age of groundwater (Appleyard and Cook, 2009). Detailed assessment of groundwater quality is also carried out in order to determine the geochemical mechanisms influencing groundwater quality evolution (Gad and El Osta, 2020). In arid regions, surface water-groundwater interaction is a common phenomenon (Dochartaigh et al., 2017; Green, 2016; Yang et al., 2018). In addition, water quality is an important part of surface water management in developing nations, hence assessing surface water quality for drinking purposes is critical (Gad et al., 2020).

The role and nature of physical aquifer processes such as evaporation, surface water-groundwater interactions and mixing can be evaluated (Adomako et al., 2010; Aggarwal and Froehlich, 2016; Charfi et al., 2012; Yeh et al., 2014). Tritium (^{3}H) has a short half-life of 12.33 years and is used as a tracer for determining the age of groundwater (Aggarwal and Froehlich, 2016; Demirog, 2017; Motzer, 2007; Yeh et al., 2014) with residence times of up to 100 years (Abiye, 2011; Atkinson et al., 2014; Clark et al., 1997; Lee et al., 2006) and groundwater pollution (Ramaroson et al., 2018). The analysis of aquifer chemistry allows for the evaluation of an array of natural and anthropogenic factors that determine groundwater quality (Zhao et al., 2020) since groundwater chemistry is primarily influenced by: recharge water chemistry, hydrogeochemical processes, rock-water interactions, and solute transport (Guay et al., 2006; Mokrik et al., 2014; Motzer, 2007; Zhou et al., 2017), while high electrical conductivity values are associated with groundwater systems with longer residence times (Zhou et al., 2017).

Since most of the supply boreholes are located adjacent to the Turkwel River, it has been assumed that there is a significant recharge of the Lodwar Alluvial Aquifer System (LAAS) through baseflow and river flooding events since rainfall in the area is very low (<250 mm/yr).

Table 1
Compositions of $\delta^{18}O$ and $\delta^{2}H$ in surface water and groundwater samples; the composition of $\delta^{18}O$ in rainfall is −1.33‰ and while $\delta^{2}H$ is 7.4‰; green represents the most depleted isotope ratio followed by yellow, then orange while blue show more enriched values.

$\delta^{18}O$ (‰)					
Description	**Minimum**	**Maximum**	**Mean**	**Median**	**SD**
Lake Turkana	5.41	6.60	6.01	6.01	0.85
Turkwel river (TR)	0.06	0.9	0.55	0.63	0.41
Kawalase river (KR)	0.25	0.67	0.46	0.46	0.3
Water pans	-4.4	0.19	-2.48	-2.67	1.67
Scoop holes (SH)	-3.95	-1.57	-2.75	-2.63	0.9
Shallow Alluvial Aquifer (SAA)	-2.92	0.25	-0.96	-0.8	0.77
Intermediate Aquifer (IA)	-4.09	0.07	-2.53	-2.64	0.83
Deep Aquifer (DA)	-1.17	-0.23	-0.70	-0.7	0.66
Turkana Grits Shallow Aquifer (TGSA)	-4.37	-1.93	-2.87	-2.53	0.8
$\delta^{2}H$ (‰)					
Description	**Minimum**	**Maximum**	**Mean**	**Median**	**SD**
Lake Turkana	41.3	42.4	41.9	41.9	0.8
Turkwel river (TR)	6.5	9.8	7.6	7.1	1.5
Kawalase river (KR)	-10.5	-9.1	-9.8	-9.8	1
Water pans	-33.9	0.9	-16.4	-15.9	13
Scoop holes (SH)	-23.7	-2.4	-12.6	-11.4	7.8
Shallow Alluvial Aquifer (SAA)	-13.1	5.9	0.4	1.4	4.6
Intermediate Aquifer (IA)	-20.1	4.5	-8.6	-9.5	4.1
Deep Aquifer (DA)	-2.7	3.9	0.6	0.6	4.6
Turkana Grits Shallow Aquifer (TGSA)	-24.7	-8.8	-13.2	-10.7	5.5

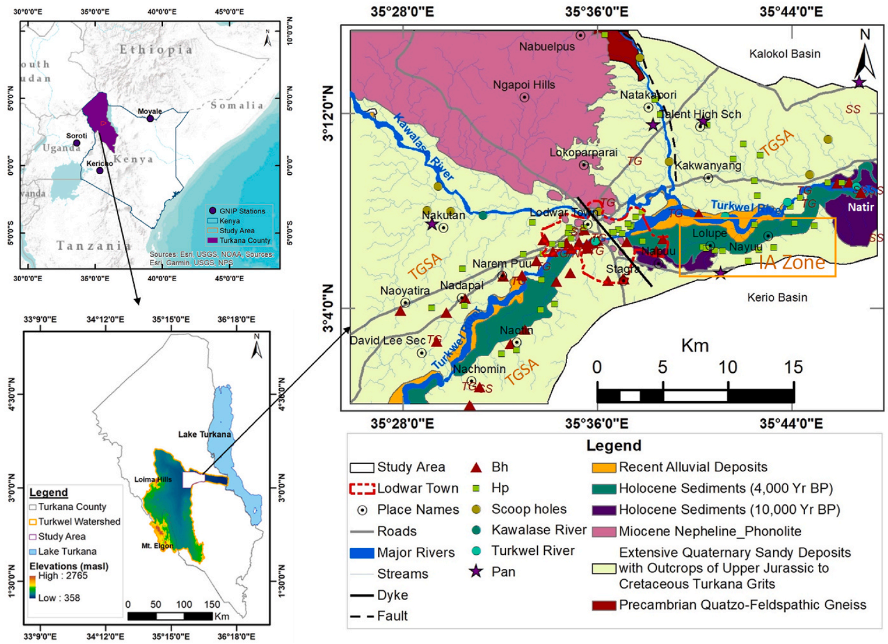

Fig. 1. Turkana County is located in the north-western part of Kenya, and the study area is within the Lower Turkwel River watershed, which includes Lodwar municipality and its environs. Three GNIP stations are located near the investigated site: Kericho in western Kenya, Soroti in eastern Uganda, and Moyale station. The geological map of the area depicts the location of surface water and groundwater samples collected for isotope analysis.

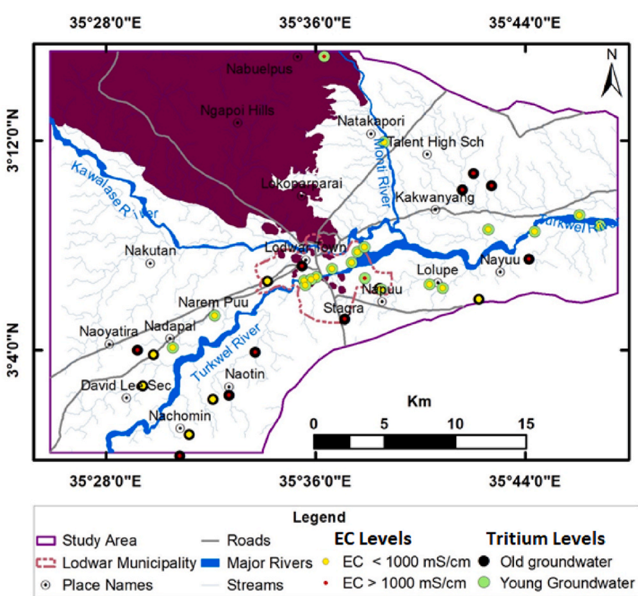

Fig. 2. Distribution of tritium in groundwater in the study are showing high values close to the Turkwel River.

However, the nature of this interaction and its seasonal characteristics have not been elucidated. The aquifer is heavily used (100%) for town water supplies, yet its physical and chemical characteristics and aspects of recharge have not yet been established through systematic study. Such data and information are particularly urgent because of a number of potential threats to groundwater quality due to the lack of a proper municipal waste disposal system and a sewerage network, a fast-growing human population, and supply risks related to amplified climate variability due to climate change (Hirpa et al., 2018; Olago, 2019). These threats do not only apply to this particular town, but to towns in dryland regions across sub-Saharan Africa. The objective of this paper is, therefore, to determine the characteristics of the LAAS and river-groundwater interactions through the application of environmental isotopes and hydrochemical analyses of the surface and groundwater in the study area. This information will contribute towards an evidence- and risk-based approach to sustainably manage the groundwater system at scale and will have a significant bearing on, and applications to, the design, development planning and sustainable use of groundwater across dryland urban areas in sub-Saharan Africa and in analogous areas globally.

2. Study area

The study area lies in the downstream section of the Turkwel River basin in Turkana County encompassing Lodwar Municipality and its environs. It is bounded by longitude 35° 32.'0′ to 35° 48. 0′ and latitudes 3° 0.0′ to 3°15.0’ (Fig. 1). The mean annual rainfall is only 217 mm, while the mean annual maximum and minimum temperatures are 36.8 °C and 20.2 °C, respectively (Opiyo, 2014). Due to the prevailing high temperatures, evaporation rates range between 1650 and 2800 mm/year (NDMA, 2016). The mean annual rainfall within the municipality is 217 mm (Opiyo, 2014), receiving the lowest rainfall in the entire Turkana County. The rainfall pattern is bimodal, with the first cycle in March, April, and May and less precipitation in October, November, and December (Opiyo, 2014). The average elevation in the study area is about 506 m above sea level and is characterized by relatively flat terrain with volcanic hills (Ngapoi Hills) and nepheline-phonolite cones within the town (see Fig. 2).

Lodwar Municipality is the largest town in north-western Kenya, with a population of about 83,000 people. The municipal water supplies are from shallow boreholes located on the riparian zones of the Turkwel River (Hirpa et al., 2018; Olago, 2019; Tanui et al., 2020). The amount of water that was being supplied in 2019 was 1.8 MCM/year against a water demand of 2.9 MCM/year (Wanguba, 2018), thus, further development is necessary. More recently, the COVID-19 pandemic has exacerbated water, health, and sanitation problems, possibly increasing household water demand as more regular hand washing is encouraged (Ong'ech et al., 2021). The water services company has responded to the demand challenges by enhancing supply through emergency borehole development. The Turkwel River, which originates from Mount Elgon in western Kenya and traverses Lodwar town as it flows into Lake Turkana, has a large catchment area (23,740 km^2) and is the only perennial river in Turkana County (Hirpa et al., 2018). The Kawalase River, a large and significant ephemeral tributary of the Turkwel River during the rainy seasons, originates from the Loima Hills that lie west of the study area; it joins the Turkwel River at the Napuu-Lolupe area (Fig. 1).

3. Geology and hydrogeological conditions

The regional geology comprises (1) Precambrian basement system rocks (gneisses, granulites, quartzites, and limestones with metamorphosed/non-metamorphosed/anatectic intrusive rocks such as granites (2) Cretaceous-Palaeogene-Neogene sediments (Lapur Formation Cretaceous sandstones and conglomerates, Turkana Grits series; (3) Tertiary volcanics (basalts, pyroclastic volcanic rocks, phonolites, trachy-andesites and nephelinites with numerous intrusive rocks of nephelinite, dolerite, teschenite, lamprophyre and microfoyaite compositions), and (4) Superficial deposits of Plio-Pleistocene to Recent age comprise poorly developed soils, aeolian and alluvial sands, gravels, coarse grits, and lacustrine shales and shelly limestones that are associated with the early Holocene highstand of Lake Turkana (Dodson and Ministry of, 1971; Feibel, 2011; Muia, 2015; Rhemtulla, 1970; Walsh & Dodson, 1969). Within the study area itself, the main rock exposures are the Ngapoi Hills which are constituted by Upper Miocene nepheline-phonolites. Most of the area is blanketed by Quaternary sands and related deposits, and, adjacent to the Turkwel River, by Holocene sandy sediments. Small, rare and partially obscured outcrops of Cretaceous sandstones (*SS*) and grits (*TG*) (spread across the study area), quartzo-feldspathic gneiss (northern part of the study area), and a dolerite dyke associated with Miocene-Pliocene volcanics (trending NW-SE through the northern part of Lodwar municipality), reflect a more complex sub-surface geology than is evident from the surface (Fig. 1).

It has been recently established that potable groundwater can be obtained only from recent alluvial and Holocene age sediments (mostly $<$100 m bgl) while older sediments yield saline water; these all occur in discrete but interconnected aquiferous segments that are collectively referred to as the Lodwar Alluvial Aquifer System (LAAS) (Tanui et al., 2020). The LAAS has three aquifer sub-systems that yield potable water, namely; the shallow alluvial aquifer (SAA - $<$ 30 m bgl; average yield 16.87 m^3/h; Ca-HCO_3 water type), intermediate aquifer (IA - 31–100 m bgl covering the IA Zone indicated by the orange rectangle (Fig. 1); average yield 8.28 m^3/h; Na-HCO_3 water type), and deep aquifer (DA - $>$ 100; average yield 100 m^3/h; Na-HCO_3 water type) while the fourth sub-system, the Turkana Grit Shallow Aquifer (TGSA - $<$30 m bgl; average yield 4.27 m^3/h; Na-Cl water type), yields highly saline groundwater (Olago, 2018).

4. Sampling and methods

This being a pioneering study, the sampling targeted all water points within the study area. The standard sampling and sample preparation procedures outlined by International Atomic Energy Agency, (IAEA, 2016) for isotope analysis and standard procedures documented by American Public Health Association for the determination of water quality (APHA, 1995) were followed. A total of 112 georeferenced water samples were collected during the peak of the wet season in May 2018 as follows: rain (1), Turkwel River (4); Kawalase river (2); water pans (5); Lake Turkana (2) – one at the Turkwel delta and one at its shores at Eliye Spring, and; groundwater (98) - comprising one spring (Eliye Spring), seven scoop holes (all $<$1m bgl) in dry ephemeral streams, 52 samples from wells operated by handpumps, and 38 boreholes. In addition, four samples were obtained from all sources using 500 ml tightly capped polyethylene bottles. The location of all samples was recorded accurately using Germin Global Position System (GPS). In addition, all samples were labelled using unique codes (i.e. BH 001, A, B, C, and D, where samples A and B represented samples for Full Chemical Analysis (FCA) while C and D were isotope samples). Samples for cations (A) and anions (B) were filtered using a 0.45 μm membrane filter, where the cations sample were acidified with 10% concentrated nitric acid for preservation. All the samples were placed in cooler boxes at 4 °C during the fieldwork.

All the samples (112) were analyzed in the laboratory for $\delta^{18}O$ and δ^2H isotopes. δ^3H was measured in just a few samples as follows: rain (1), Turkwel River (1), Lake Turkana (2), handpumps (24), and boreholes (15). The measurement of oxygen, deuterium and tritium isotopes was carried out at Elemtex Lab, United Kingdom. The $\delta^{18}O$ and δ^2H isotopes were measured using Thermo Scientific high-temperature conversion elemental analyzer (TC/EA), where the temperature was kept at 1400 °C. The compositions of δ^2H and $\delta^{18}O$ in water samples were measured using an isotope ratio mass spectrometer (IRMS) coupled to a high-temperature conversion elemental analyzer (TC/EA) and operated in continuous flow (CF) mode. The isotope ratios were expressed as δ^2H and $\delta^{18}O$ values relative to the Vienna Standard Mean Ocean Water (VSMOW) reference materials, where $\delta^2H = 0‰$ and $\delta^{18}O = 0‰$ (Carter and Barwick, 2011). Thus, the typical analytical precision was ±0.1‰ and ±1.0‰ for oxygen-18 and deuterium, respectively. The samples were distilled and electrolytically enriched before being analyzed for δ^3H using liquid scintillation counting (Morgenstern and Taylor, 2009; Singh et al., 2016). The results were expressed in tritium units (TU) with a 1 TU error for all water samples.

Only one rain sample was collected in the study area ($\delta^{18}O = -1.33‰$; $\delta^2H = 7.4‰$ VSMOW; $\delta^3H = 1.7$ TU), owing to rare and unpredictable rainfall events during the study. This value falls well within the very wide range of isotopic values of rainfall in the Turkana Basin, ranging from −7.3 to 36.4‰ and −1.7 to 5.9‰ for δD and $\delta^{18}O$ (n = 16), respectively, with no obvious seasonal or sub-regional trends, as reported by Henkes et al. (2018a) and hence the isotopic values of rainfall are only considered in the context of published results of isotope analyses of rainfall samples from the wider northern drylands of Kenya (Henkes et al., 2018b; Levin et al., 2009; Sklash and Mwangi, 1991).

Apart from the Turkwel River results published in Tanui et al. (2020) with groundwater chemistry datasets, this study presents results for the major ions chemistry of the Kawalase River, water pans, scoop holes, lake, rain, and spring samples for the first time. The electrical conductivity (EC), pH and temperature (°C) were determined in the field for all the water samples using hand-held Combo Tester HI98129. Laboratory analyses included turbidity, total hardness, major cations (Ca, Mg, Na, K, Fe, and Mn) and major anions (HCO_3, SO_4, F, Cl, CO_3, NO_3, NO_2) at the Central Water Testing Laboratory, Nairobi, Kenya. Microsoft Excel and Golden Software Grapher 17.0 were used to calculate the statistics and box plots, respectively.

5. Results

5.1. Tritium

The tritium values in the study area ranged from 1.1 to 2.4 TU. Lake Turkana has fairly consistent values of tritium - 1.8 TU at the Turkwel delta and 1.7 TU at Eliye area. The highest TU value is recorded in Turkwel River (2.4 TU). Within the groundwater system, tritium values were as follows: SAA (1.1–2.2 TU, 14 samples); IA (1.1–1.9 TU, six out of 19 samples with the rest lacking tritium), and; TGSA (no tritium), and DA (2 samples - Napuu, TU = 1.0; Natir, TU = 2.1). Thus, the tritium-free groundwater, older than 1953, is in the TGSA and in the IA where the thick Holocene sediments about the Turkana Grits southwest of Lodwar town, including Naotin, Nabuin and Nachomin areas. Generally, the values of tritium in groundwater are highest close to the Turkwel river and diminish progressively as one moves further away from the river (Fig. 4).

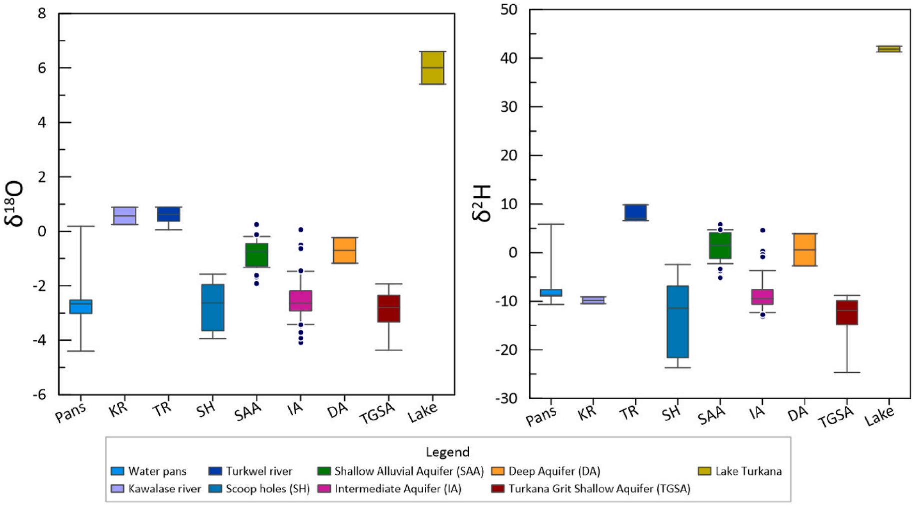

Fig. 3. Variations in the compositions of δ^{18}O and δ^{2}H in the surface and groundwater samples of the study area.

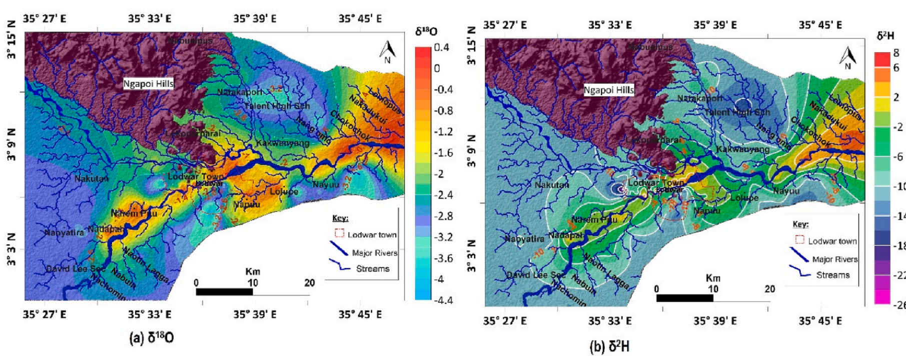

Fig. 4. Spatial distribution of (a) δ^{18}O and (b) δ^{2}H for all the groundwater samples showing isotope enrichment along the Turkwel River, suggesting diffuse recharge; the floodwater of the Kawalase river results in recharge of the LAAS at Napuu-Lolupe areas.

5.2. Compositions of δ^{18}O and δ^{2}H in the various water samples

Considering the median values of δ^{18}O and δ^{2}H in surface water and groundwater samples, four clusters emerge. Cluster 1 is represented by the highly enriched lake water located outside the current study area. With a median value of +6.01 for δ^{18}O and δ^{2}H (+41.9) the isotopic compositions of Lake Turkana are consistent with values obtained by Sklash and Mwangi (Sklash and Mwangi, 1991) and Henke et al. (Henkes et al., 2018b). These results reflect enrichment due to the evaporation of the lake water in the hyperarid environment that the lake occupies. The δ^{18}O values for Turkwel and Kawalase rivers are slightly positive relative to VSMOW; however, these rivers have different δ^{2}H values (+7.6‰ versus −9.8‰) (Fig. 3). The third cluster is the groundwater of the SAA and the DA with δ^{18}O values between −0.96‰ and −0.70‰ and δ^{2}H values between +0.4‰ and +0.6‰, respectively. Finally, the most isotope-depleted waters are the water pans, scoop holes, IA and TGSA with median values ranging from −2.87‰ to −2.48‰ for δ^{18}O and −8.6‰ to −16.4‰ for δ^{2}H.

5.3. Hydrochemical characteristics of water samples

Variations are observed in the mineralization of the various waters in the study area. Considering the water types (Fig. 7) and electrical conductivities, the Turkwel river is mainly Ca-HCO_3 waters with a median EC of 216.00 μS/cm. On the other hand, the EC in the Kawalase river is 316.50 μS/cm, with the upstream sample having Mg-HCO_3 waters while the downstream one has Na-HCO_3 water type. Although the water pans have a low EC of 203.00 μS/cm, about three water types were manifested; Na-HCO_3 for Nakutan and Nakariong'ora water pans; Ca-HCO_3 for Namuthia and Kerio water pans and Ca-SO_4 for the Monti water pan.

In the SAA, the major water type is Ca-HCO_3 (59%), followed by Na-HCO_3 (29%) and Mg-HCO_3 (12%) with a median EC value of 448 μS/cm during the wet season and 485 μS/cm in the dry season. The intermediate aquifer mainly comprises Na-HCO_3 waters (95%) and pockets of Mg-HCO_3 waters. Its EC of 764 μS/cm during the wet season and 833 μS/cm during the dry season. The TGSA consists of Na-Cl waters (56%) and Na-HCO_3 (44%) with the highest EC values of 4901 μS/cm in the wet season and 5678 μS/cm during the dry season. The Na-HCO_3 within the Turkana Grits occurs close to the Holocene sediments. The scoop holes located along the ephemeral streams have medium mineralization (EC = 803 μS/cm), with Na-HCO_3 water type (four samples); Mg-HCO_3 (two samples) and Ca-HCO_3 (one sample). Due to the variations observed in the isotopic compositions of the samples of the DA, it is important to evaluate their hydrochemical compositions independently. The Natir Bh (depth = 102 m) located close to the Turkwel River is a Ca-HCO_3 water type with an EC value of 307 μS/cm and 207 μS/cm in the wet and dry seasons, respectively. Conversely, the Napuu Bh in the Holocene sediments is considerably mineralised with an EC of 1221 μS/cm in the wet season and 1392 μS/cm during the dry season. An increasing trend from the SAA, IA, and DA into the TGSA is observed with respect to the electrical conductivities. The Eliye spring belongs to the Na-HCO_3 water type with an EC of 677 μS/cm. Fig. 5 shows the variations in ionic concentrations in rain and surface water samples, while Fig. 6 shows seasonal variations in the ionic concentrations in the groundwater.

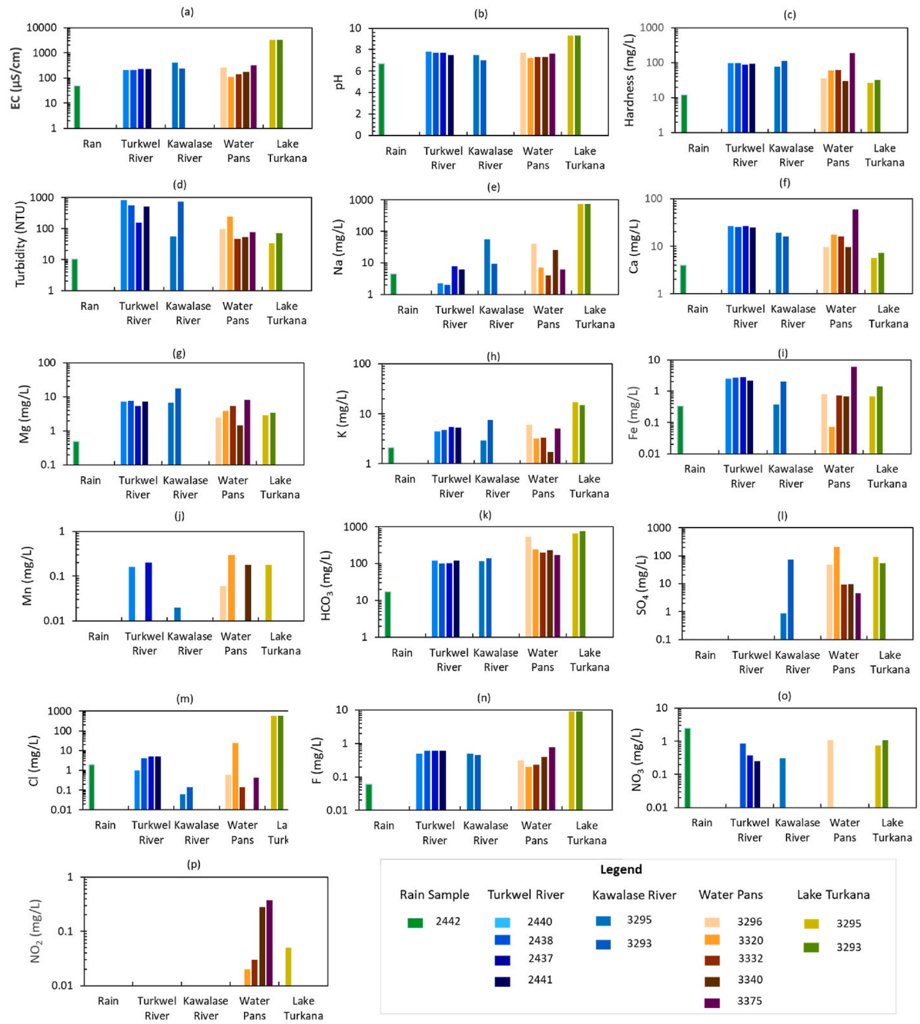

Fig. 5. Variations in the concentrations of major cations and anions in the rain and the surface water of the study area showing relatively low mineral concentration in the rain sample, followed by river water, then water pans, and Lake Turkana samples.

6. Discussion

6.1. *Evaluation of the meteoric water lines*

The Global Network of Isotope in Precipitation (GNIP) provides long-term isotope data across the globe, which is used to characterize the evolution of water through the hydrologic cycle (Bershaw et al., 2018). The study area has a dearth of measurements of environmental isotopes in precipitation, probably because of its low, erratic, and unpredictable rainfall, as well as its remoteness. For this reason, three GNIP stations, Moyale (Ethiopia), Kericho (Kenya), and Soroti (Uganda), that are closest to the study area (Fig. 1) were among those used to evaluate the best-fit line, even though these datasets are also somewhat limited in number of samples (Kericho, n = 24; Moyale, n = 4; Soroti, n = 14). The respective datasets were downloaded from the International Atomic Energy Agency (IAEA)- https://nucleus.iaea.org in October 2019. A fourth equation based on data from the Turkana basin (Ethiopia and Kenya) was also evaluated (Henkes et al., 2018). The Global Meteoric Water Line was generated based on Craig (1961); $\delta^2H = 8.0\ \delta^{18}O + 10$.

Regression models for the three GNIP stations were as follows: Kericho, $\delta^2H = 7.7 \times {}^{18}O + 12.2$; $R^2 = 0.90$; Soroti, $\delta^2H = 8.5 \times {}^{18}O + 13.8$; $R^2 = 0.99$; Moyale, $\delta^2H = 5.7 \times {}^{18}O + 8.3$; $R^2 = 0.98$, and; Turkana Basin, $\delta D = 3.7 \times \delta^{18}O + 9.7$. The best-fit regression model is for Soroti station, which is also closest to the study site. This could be attributed to the regional rainfall characteristics of East Africa, where rainfall primarily originates from southwest winds originating in the Indian Ocean (Henkes et al., 2018; Oiro et al., 2018). Soroti has a much higher mean annual rainfall (1250 mm,(Nyende, 2013)) than Lodwar (217 mm, (Opiyo, 2014) and this suggests that the continental effect is the major control on isotope fractionation in rainwater in the region, resulting in progressively lighter isotopes as one moves inland from the Indian Ocean (cf Levin et al. (2009)).

As observed in the study area, open water bodies such as rivers, water pans, and lake undergo significant evaporation and plot below the LMWL (Wirmvem et al., 2017). The ratios of $\delta^{18}O$ vs. δ^2H (Fig. 8) fall below the LMWL with a few samples from scoop holes and intermediate aquifer plotting above it. The distribution of the surface water and groundwater samples along the meteoric water line shows a progressive isotope fractionation from the Turkwel river, to the SAA, IA and into the TGSA. Similarly, surface water and groundwater mineralization follow a similar trend. This relationship is linked to groundwater flow and increasing residence times away from the river (Levin et al., 2009). The samples of the SAA plot below the LMWL ($\delta^2H = 4.4\ \delta^{18}O + 4.9$) and slightly below those of the Turkwel River, reflecting recharge water comprising a mixture of the Turkwel river water and the local precipitation. Similarities in the water chemistry of this aquifer with surface water of the Turkwel River (Tanui et al., 2020), suggest that river water recharge is greater than recharge from infiltration of the local rainfall (Chen et al., 2019; Yeh et al., 2014). The influence of evaporation occurs in the Turkwel river as the water flows from high altitudes in the upper

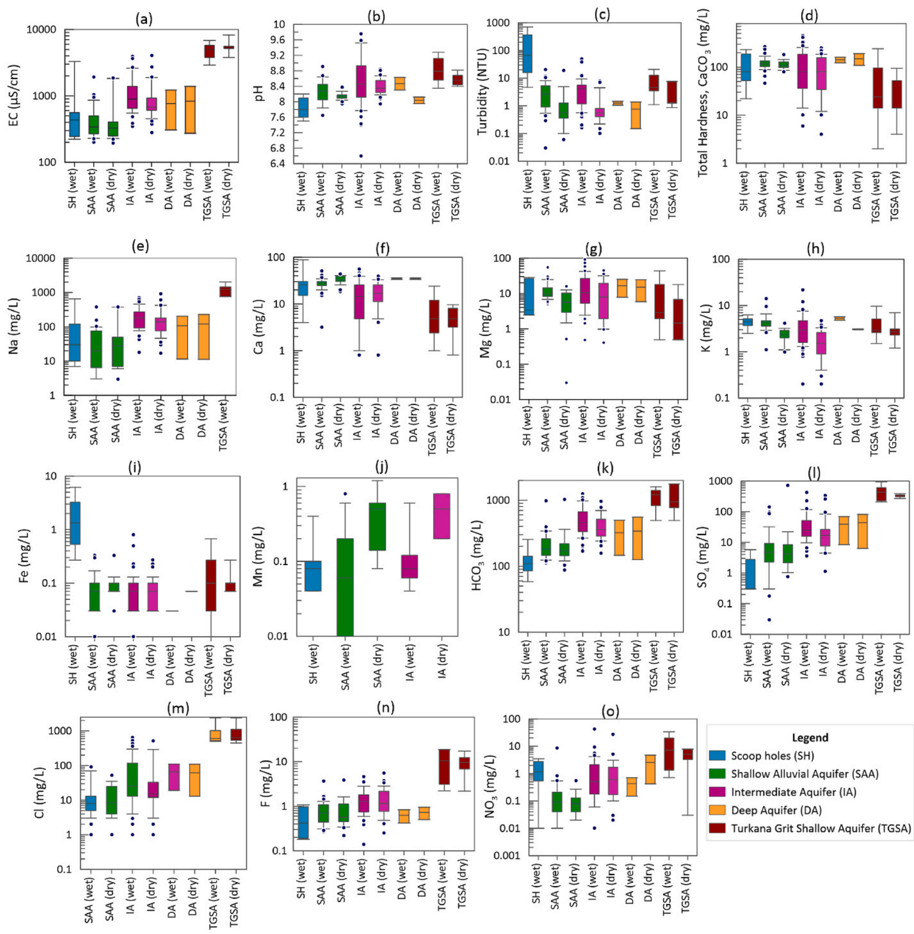

Fig. 6. Variations in the ionic concentrations in the sub-systems of the LAAS; (a) EC increases from the SAA through the IA and DA into the TGSA; (b) the groundwater in all the aquifers are generally alkaline and more turbid (c) in the wet season; (d) the LAAS comprises hard water than the TGSA in dry and wet seasons due to higher levels of Ca^{2+} and Mg^{2+} (f and g) while (e) Na^{+} exceeds 600 mg/L in the TGSA in both seasons; K, Fe^{2+} and Mn^{2+} are generally low in the groundwater of the study area with Mn^{2+} only occurring in the SAA and IA (h–j); tested major anions (k-o)are relatively high in the TGSA and exceeded the drinking water quality limits in most cases.

catchment to the plains (Yeh et al., 2014). In addition, Turkwel Gorge dam flow regulation and frequency of dam release and groundwater baseflows during the dry season may contribute to the depleted isotopic composition of the Turkwel River relative to the precipitation. The findings of this study suggest that the LAAS and the Turkwel River are interconnected. At the same time, deuterium-depleted flood waters of the Kawalase contribute to recharge during the wet season at Napuu-Lolupe areas resulting in groundwater with depleted deuterium. The plots of scoop holes and few samples of the IA above the meteoric water line are associated with direct rainfall infiltration. This study has revealed that the recharge mechanisms into the LAAS are by Turkwel River within the present-day alluvial deposits and the contribution of flood water of the Kawalase river into the intermediate and deep aquifers, especially at the Napuu zone. Rapid infiltration of rainfall during the wet season is also expected to contribute a substantial amount of recharge during the wet season.

6.2. Characteristics of the Lodwar alluvial aquifer system and surface-groundwater interactions

Chemical compositions and isotopic analyses were used to characterize the groundwater of the study area. The classification of water types and electrical conductivities of the various water samples showed a close relationship between the Turkwel River and the groundwater in the present-day alluvial deposits (Tanui et al., 2020). The positive d-excess values in the Turkwel river (6.47) and SAA (2.18) suggest that they are interlinked. $CaHCO_3$ was the dominant water type in water samples obtained from the river, water pans and alluvial deposits and have EC values < 300 µS/cm. The highly enriched isotope compositions of the Lake Turkana samples reflect the effect of evaporation, where lover values observed at the Turkwel delta showed the mixing effect by the surface water.

The Turkwel and Kawalase rivers showed varied isotopic compositions, where the Kawalase river samples are more enriched than in the Turkwel river. Turkwel river obtains its water from the humid Mt Elgon forest where heavy rainfall may impart this signature, though storage in the Turkwel dam could play a role in keeping the values relatively enriched. The Loima hills, represent a semi-humid enclave (Oiro et al., 2018; Yusuf et al., 2018) in the semi-arid/arid area of northwestern Kenya where the Kawalase river emanates. The Kawalase River carries copious amounts of rainwater that result in flooding and subsequent destruction of property and loss of lives in Lodwar area. This suggests that the rainfall in the catchment area tends to be slightly enriched. This river meets with the Turkwel river slightly upstream of the Napuu/Lolupe areas where slightly enriched values were observed.

The isotopic compositions of ^{18}O and ^{2}H and tritium in surface water and groundwater of the study area provide evidence of recharge sources. The plots of the groundwater samples below the LMWL indicate that the recharge water has undergone slight evaporation. In addition, direct rainfall recharge may occur in the study area, as indicated by the water samples above the LMWL. However, the lack of water level monitoring in the area, coupled with few rainfall samples collected in this study, is a limitation to the evaluation of the impact of rainfall in the aquifer. In addition, the determination of isotopic compositions of more rainfall samples in the study area will help to generate a new local meteoric water line relevant to future similar studies.

The tritium results revealed that the SAA comprises fully modern groundwater with ^{3}H levels between 1.0 and 2.2 TU. The decreasing d-excess values from the SAA (2.18) to the intermediate aquifer (−6.81) and TGSA (−8.14) indicate isotope fractionation during the lateral

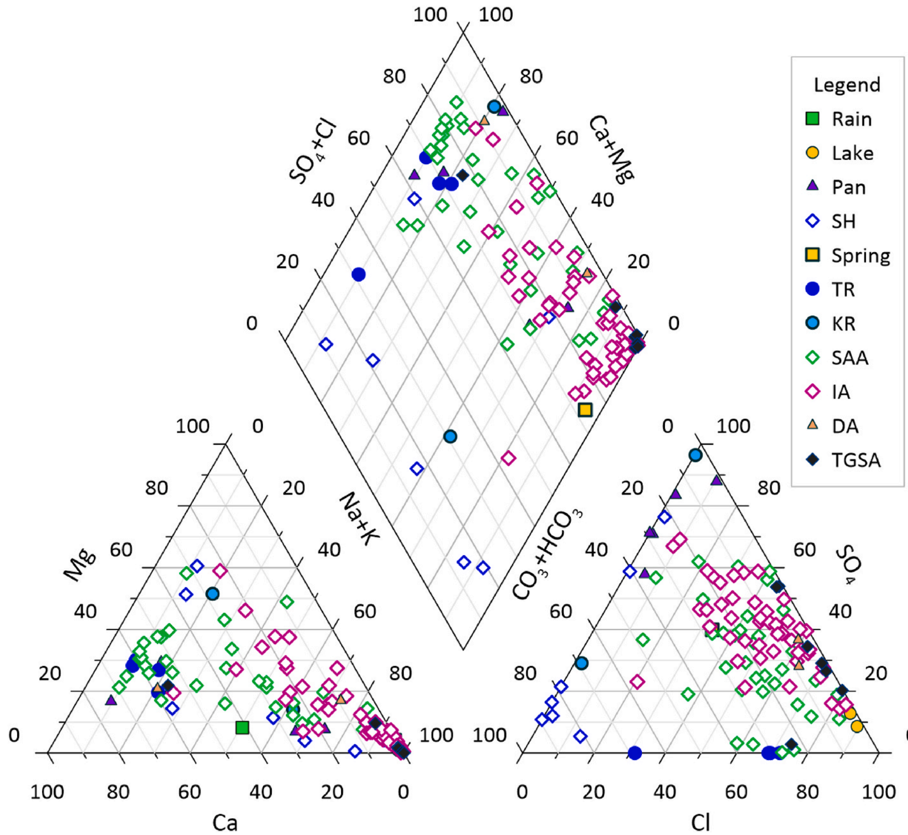

Fig. 7. Water types of the rain, spring, surface water and groundwater samples obtained from the study area.

groundwater flow. Thus, tritium-bearing groundwater of the IA results from the dilution of originally tritium-free groundwater by a lateral flow of diffuse river recharge through the alluvial aquifer (Hamutoko et al., 2017, 2018; Vu et al., 2020). Aquifer mineralization is also observed to increase from the SAA, which is hydraulically connected to the Turkwel River, to the intermediate aquifer in the Holocene sediments and into the Turkana Grits (Tanui et al., 2020). Thus, the most negative values of δ^2H are associated with the highest EC values. The mixing of the Kawalase and Turkwel River water results in relatively depleted δ^{18}O and δ^2H signatures in groundwater at Napuu-Lolupe areas. The more depleted values of the δ^{18}O and δ^2H in the TGSA and the lack of tritium in its waters are consistent with the highly mineralised groundwater (Tanui et al., 2020), suggesting long groundwater residence time. However, closer to the Holocene Sediments, the groundwater in the Cretaceous Turkana Grits displays similar chemical and isotopic signatures with the tritium-free groundwater of the intermediate, indicating that the two systems are interconnected. This evidence suggests that the Turkwel river recharges the TGSA through lateral flow via subsurface channels and buried geological structures (Sklash and Mwangi, 1991) in the Holocene sediments and the Turkana grits.

6.3. Implications for groundwater planning, development and sustainable use in Africa's Dryland urban areas

African climate is defined by unpredictable precipitation, which is very variable at inter and intra-seasonal (Alahacoon et al., 2021; Gaughan et al., 2016), and decadal to millennial timeframes (Olago et al., 2009). Groundwater resources in African drylands are vital supplies of freshwater, but they are being strained by population growth and climate change (Appelgren, 2008). As a result, it is becoming increasingly vital to manage groundwater supplies in a sustainable manner. Significant increases or decreases in rainfall can result in long-term changes in groundwater (Kebede et al., 2021). Groundwater and its replenishment through recharge are crucial to sustaining livelihoods and alleviating poverty in tropical drylands, yet the mechanisms by which groundwater is recharged remain little studied and understood. Furthermore, the lack of observational data limits current knowledge of groundwater recharge mechanisms in semi-arid regions (Seddon et al., 2021).

Urban groundwater systems, particularly shallow alluvial aquifers, are susceptible to pollution (van Rooyen et al., 2021). Given inadequate sanitation facilities and appropriately designed sanitary facilities in most small cities in sub-Saharan Africa, shallow urban aquifers are at risk of contamination. These risks are amplified by the fast-growing population, lacking a sewerage network and municipal solid and liquid waste disposal system, in addition to increasing climate variability. This study used evidence- and risk-based approach used by this study to understand the recharge mechanisms of a dryland alluvial aquifer system. The approaches involved the determination of stable isotopes of oxygen-18, deuterium, and tritium, as well as seasonal chemical compositions of groundwater. While δ^{18}O and δ^2H are used to determine the groundwater recharge sources, tritium is a well-known tracer used to assess the age of present groundwater (50 years) and hence collect information on the longer-term components of aquifer recharge (Jerbi et al., 2019).

The recharge sources for the urban alluvial aquifer presented in this study is linked to diffuse recharge from the perennial and ephemeral river. Various scientific studies have identified evidence of similar aquifers associated with diffuse recharge in drylands (Abdelshafy et al., 2019; Kebede et al., 2021; Seddon et al., 2021; Wirmvem et al., 2017). Furthermore, identification of the age of groundwater using radioactive tritium helps to delineate aquifer zones that are vulnerable to pollution. The tritium-bearing groundwater systems are considered vulnerable to human and climate-induced risks. Not only is modern groundwater a renewable resource, but it is also sensitive to climate change and modern pollution (Abdullah et al., 2018). The groundwater in the SAA, IA and

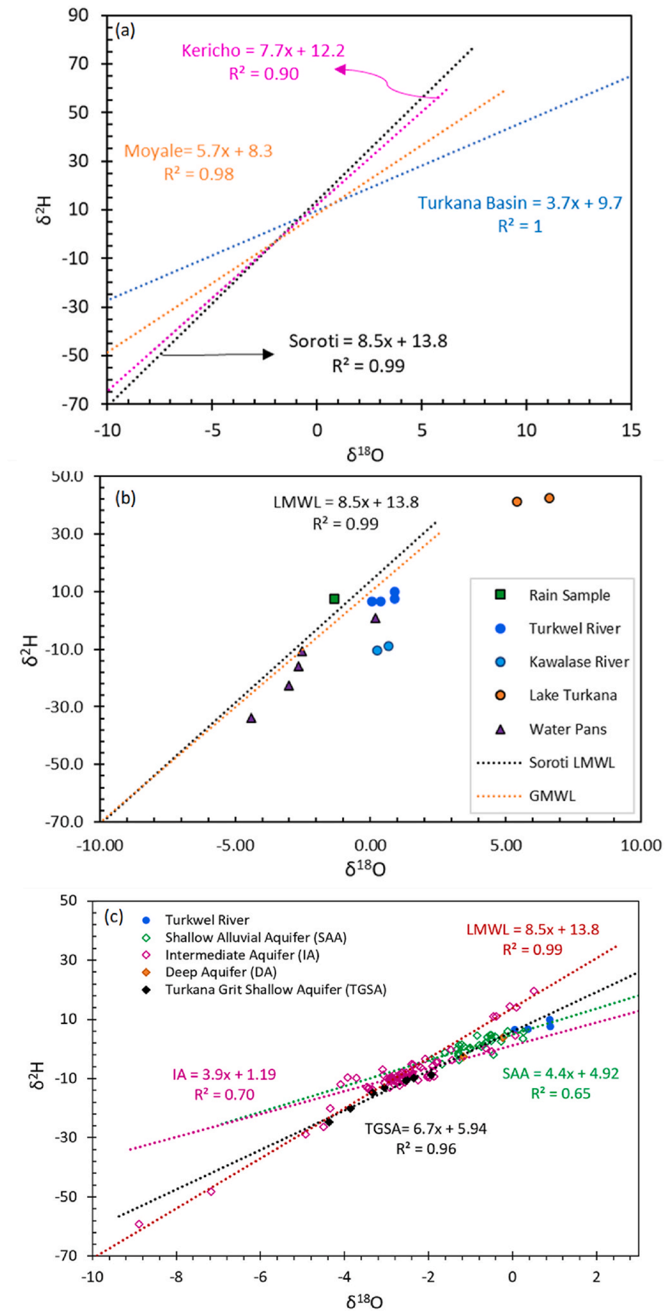

Fig. 8. (a) Regression lines of δ^2H versus $\delta^{18}O$ for the nearby GNIP stations; (b) surface water samples; rain, rivers, scoop holes, water pans, lake and spring samples; and (c) of the sub-systems of the LAAS; shallow alluvial aquifer (SAA), intermediate aquifer (IA), and deep aquifer (DA) and in the TGSA. Except for a few samples from the LAAS's intermediate sub-system, which plot above the LMWL, the groundwater samples from the study area plot below the Soroti LMWL, suggesting an influence of evaporation prior to recharge.

DA have varying levels of tritium between 1.1 and 2.4 TU. Tanui et al. (2020) established a deteriorating water quality index in these three systems during the wet season, linked to contaminants flushed into the aquifers by recharge water. In contrast, old groundwater is more likely to be separated from the polluting activities common in urban and suburban areas, like in the case of the TGSA.

The interaction between groundwater and surface water is important for creating acceptable approaches for assessing ecological water requirements among water use interdependencies. In addition, the understanding of recharge sources and aquifer vulnerability of similar strategic aquifers helps scientists to appropriately advise policymakers and the water community who develop strategies for sustainable water use, aquifer protection and conservation.

6.4. *Local and regional implications of the study*

Understanding the hydrochemical and isotopic characteristics of LAAS is crucial for sustainable groundwater management in dryland urban areas. This is a landmark study investigating the $\delta^{18}O$ and δ^2H and δ^3H of groundwater and surface water in northwestern Kenya. In addition, contributes scientific evidence of isotopic compositions of groundwater in the Horn of Africa, where aquifer studies are limited. Furthermore, the study provides insights into the identification of recharge sources and aquifer vulnerability of strategic aquifers, which can help scientists and policymakers develop strategies for sustainable water use, aquifer protection, and conservation.

The study has revealed that sustainable groundwater management in the LAAS requires comprehensive monitoring networks, periodic water quality assessments, and the establishment of sustainable groundwater abstraction practices. A similar approach can be replicated in managing groundwater supplies, particularly in dryland urban areas that experience unpredictable precipitation and increasing climate variability. The identification of tritium-bearing groundwater indicates that shallow aquifers are susceptible to human activities and climate change. This is particularly important as dryland areas are vulnerable to the impacts of climate change and threats posed by human activities. As a result, the implications of this research are not limited to the local study area but can be applied globally in dryland areas with similar hydrogeological conditions. The research will also benefit policymakers, scientists, and water resource managers in dryland urban areas regarding sustainable groundwater management, thus addressing the water supply challenges in these regions.

7. Conclusion

This study presents the results of stable ^{18}O, ^2H and ^3H isotopic investigation and hydrochemical analyses of rain, surface water (rivers, water pans and Lake Turkana samples) and groundwater. The study aimed to determine the hydrochemical characteristics and isotopic composition of the Lodwar Alluvial Aquifer System (LAAS) and establish the dynamics of surface water-groundwater. Understanding recharge sources and the vulnerability of similar strategic aquifers helps scientists appropriately advise policymakers and the water community who develop sustainable water use, aquifer protection and conservation strategies across dryland urban areas in sub-Saharan Africa and analogous areas globally. Furthermore, the evidence of surface water-groundwater interaction presents a case of a fragile dryland ecosystem. Future work will involve the installation of piezometers in strategic aquifer zones to monitor groundwater levels in relation to river gauging data to quantify the recharge amount and establish the impacts of rainfall variability in the upstream catchment. The research has the potential to contribute significantly to the understanding and management of groundwater resources in dryland areas and improve access to safe and sustainable water resources for communities living in these regions.

Declaration of competing interest

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.

Data availability

Data will be made available on request.

Acknowledgements

This document is an output from the REACH programme funded by UK Aid from the UK Foreign, Commonwealth and Development Office (FCDO) to benefit developing countries (Programme Code 201880). However, the views expressed and information contained in it are not necessarily those of or endorsed by FCDO, which can accept no responsibility for such views or information or for any reliance placed on them.

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