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Research paper

Hydrogeochemistry of a strategic alluvial aquifer system in a semi-arid setting and its implications for potable urban water supply: The Lodwar Alluvial Aquifer System (LAAS)

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ABSTRACT

Lodwar Municipality is one of the fastest-growing urban areas of Sub-Saharan Africa that depends mainly on groundwater for its municipal water supply. Most of the groundwater sources are located within the riparian zones of the Turkwel River. With limited understanding of its aquifers, the groundwater of Lodwar may be at risk of natural processes and anthropogenic activities. Statistical techniques and geochemical methods were applied to determine the aquifer hydrogeochemistry. Three distinct aquifers, which we collectively refer to as the Lodwar Alluvial Aquifer System, underlie Lodwar and its environs, the shallow alluvial, intermediate, and deep aquifers which are the main source of fresh water. A fourth, the shallow aquifer of the Turkana grit, is highly saline and with fluoride contamination. Just as the Turkwel River, the shallow alluvial aquifer (SAA) was dominated by Ca–HCO_3 water type, while the TGSA was Na–Cl water type and became Na–HCO_3 near the Holocene sediments. The intermediate aquifer (IA) was Na–HCO_3water type. Pockets of Mg–HCO_3 water occurred in the shallow alluvial and intermediate aquifers. The natural processes in the SAA include rock-water interaction, recharge by surface water, and oxidation reactions, while evaporation and dissolution are the major factors controlling the chemistry of the TGSA. Ion exchange, dilution, and dissolution are the major processes in the IA. Elevated levels of NO_3^- and SO_4^{2-} during the wet season within the SAA and the IA reflects their vulnerability to pollution. Saline intrusion into the shallow and intermediate aquifers from the Turkana grit aquifers is likely to occur.

1. Introduction

Globally, groundwater is estimated to supply 36%, 42%, and 27% of water for domestic, agriculture, and industrial use, respectively (Taylor et al., 2012). It is the main source of water supply for municipal, domestic, irrigation, and industrial uses in arid and semi-arid environments where surface water occurrence is limited (Macdonald et al., 2016; Zhao and Pei, 2012; Ruud et al., 2004). Macdonald et al. (2016) described four major hydrogeological environments in Sub-Saharan Africa (SSA); crystalline basement that occupies 40% of the land area with 220 million people, volcanic rocks occupying 6% of the SSA with 45 million people in the horn of Africa, consolidated sedimentary aquifers covering 32% of the land area supporting a population of 110 million, and unconsolidated sediments (alluvial aquifers) that cover 22% of the SSA and sustain a population of 60 million people. Recent advances in mineral and oil exploration in most arid areas have led to the rapid growth in urban populations and subsequent increase in water demand (Olago, 2018). The average population growth rate in SSA is 2.7% and about 2.5% in Kenya (World Bank, 2018). This growth has partially led to the increased demand for water and subsequent expansion of irrigation projects. Lodwar Municipality is particularly experiencing unforeseen demand for large supplies of water from increased urban growth and settlement due to oil development activities, development of mega-transport, and infrastructure projects such as the Lamu-South Sudan-Ethiopia (LAPSSET) corridor, and expansion of commercial and industrial establishments (Olago, 2018). In addition, the government proposes to upscaling the irrigation projects in the region from 2000 ha to 10,000 ha (OECD/FAO, 2016; Olago, 2018) that

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might lead to further stress on groundwater and its possible contamination. The Turkwel River basin has recently been established to be facing three major risks; frequent droughts, the abstraction of water upstream for irrigation, and flow regulation by a hydroelectric project (Hirpa et al., 2018), and which may affect both the quantity and quality of groundwater in the LAAS. Natural contamination of groundwater by fluoride is a major challenge in volcanic and volcano-sedimentary terrains (Brindha et al., 2011; Subramani et al., 2009), particularly in arid and semi-arid areas where alternative potable water resources are scarce.

Aquifers are becoming more important and critical to human societies as population, urban settlements, industrial and commercial demands increase (Olago, 2018; Subramani et al., 2009; Chilton and Seiler, 2006; Newman et al., 2016); at the same time, these societal changes, coupled with risks related to the changing climate (IPCC, 2014; Taylor et al., 2012; Al-Sefry and Şen, 2006; Stromberg et al., 1996; Wright, 1992) and environment (Xu et al., 2019) and inadequate knowledge of the characteristics of the groundwater sources (Xu et al., 2019; Xiao et al., 2019; Banoeng-Yakubo et al., 2010; Olago, 2018) means that the groundwater is being exploited under increasingly uncertain regimes (Roger and Macdonald, 2009; Taylor et al., 2009; Kundzewicz et al., 2008). With limited evidence, it is also impossible to achieve safe water and sanitation for urban and rural settlements (Guppy et al., 2018; Xiao et al., 2019; Yan et al., 2016). The groundwater aquifers exploited for these purposes occur in varied geological contexts (Bernard and Legchenko, 2003; Humphreys, 2001) and may range from simple to highly complex systems (Bloomfield et al., 2008; Chilton and Seiler, 2006). Alluvial aquifers are generally highly susceptible to contamination (Elangovan and Dharmendirakumar, 2013), and climate and hydrological variability (Andrés-Doménech et al., 2015; Kundzewicz et al., 2008), and particularly so because they are strongly dependent on rivers, whether perennial, seasonal or ephemeral, for recharge.

In order to achieve safe water and sanitation for urban and rural settlements in ASALs, there is need for a sufficient evidence-base to sustainably manage the groundwater resources (Xu et al., 2019; Guppy et al., 2018; IWMI, 2016; Jac van der, 2012) and to meet national and international commitments for sustainable development including the SDGs (UN, 2018; IWMI, 2016). Generally, in any area, groundwater chemistry is unique due to several processes (Subramani et al., 2009). More specifically, the groundwater chemistry (and quality) of alluvial aquifers is a function of both natural processes and anthropogenic activities (Khatri and Tyagi, 2014; Hamilton et al., 2015; Muhammad et al., 2015; Pérez Villarreal et al., 2019; Peter, 2001), and thus it is important to characterize each aquifer to better understand its potential for sustainable supply of potable and safe water for various uses under rapidly changing climatic, environmental and developmental scenarios. The natural influences which lead to water chemistry and hence quality changes in the aquifers include intensive evaporation (Li et al., 2014), rock-water interaction (Chenini et al., 2010; Earle, 2013; Okiongbo and Akpofure, 2015; Sheikhy Narany et al., 2014), mixing of different recharge waters (Li et al., 2014; Subramani et al., 2009), and large fluctuations in storage related to a linked river's hydrological regime (Earle, 2013; Yang et al., 2018). Anthropogenic factors contributing to groundwater quality changes include on-site sanitation systems, unregulated sewage, and municipal waste disposal, industrial effluents, and fertilizer/pesticide use in agriculture (Kumari et al., 2014; Garba Abdullahi et al., 2014). These anthropogenic influences can result, for example, in increased concentrations of heavy metals, coliforms, and nutrient loads (Khatri and Tyagi, 2014) and may render a safe groundwater source unusable for millennia once contaminated (Frind et al., 2006; Sharma and Chhipa, 2016). Although Lodwar Municipality depends largely on groundwater for its municipal water supply (Olago, 2018; Hirpa et al., 2018), no comprehensive hydrogeochemical studies have been carried out on the groundwater system. The purpose of this paper is to characterize the hydrogeochemistry of the Lodwar Municipality's strategic alluvial aquifer system in north-western Kenya and to evaluate the natural and anthropogenic factors that influence its water chemistry and quality, providing the evidence base for its sustainable and safe exploitation and management. The research demonstrates, for the first time, the important role of pulsed hydrological recharge in maintaining potable water quality and quantities in the Lodwar Alluvial Aquifer System. A close link between groundwater chemistry and seasonal fluctuations in climate, as well as to land uses in the expansive Turkwel river, and Kawalase river catchments and Lodwar municipality itself reflects the sensitivity of the system to climate variability and change and to human factors that go well beyond the remit of the current water management regime. With the evidence presented, it will be possible to monitor and plan for safe and sustainable water supplies under present and future demands and risks for towns in similar water insecure environments where groundwater may be the critical dimension for sustainability.

2. Materials and methods

2.1. Study area

The study area (longitude 35° 32.0′ to 35° 48.0′ and latitudes 3° 0.0′ to 3°15.0′) covers 1040 km^2 and envelopes Lodwar Municipality which is located in the downstream section of the Turkwel River basin in the north-western part of Kenya (Fig. 1). The Turkwel river originates from the Uganda side of the humid Mount Elgon (Hirpa et al., 2018) and flows north-eastwards to semi-arid Lodwar Municipality where it bends to follow an easterly trend, eventually draining into Lake Turkana. The Turkwel River basin has a catchment area of 23,740 km^2, and rainfall within the basin ranges from 900 to 1749 mm/year in the humid Mount Elgon region (Hirpa et al., 2018) to only 217 mm in Lodwar Municipality (Opiyo et al., 2014). Lodwar Municipality is the largest urban centre in north-western Kenya and is the headquarters of the Turkana County. The municipality depends entirely on groundwater supplies, with supply boreholes located on the riparian zones of the Turkwel River (Hirpa et al., 2018; Olago, 2018).

The study area received brief rainfalls that come with violent storms resulting in flash floods. Long rains are expected from March to May (MAM – "long" rains season) and October to November/early December (OND – "short" rains season) (Opiyo et al., 2014). The surface runoff can be high (Opiyo et al., 2014), and potential evaporation rates (1650–2800 mm/year) are extremely high (NDMA, 2016; Olago, 2018). The two rainy seasons in the year are separated by two dry seasons – the hot, dry season from mid-December to February (DJF) and the relatively cooler dry season from June to September (JJAS).

The geology of the area (Fig. 2), which we updated based on fieldwork, analysis, and ground-truthing of remotely sensed images, comprises the Upper Jurassic-Cretaceous grits, Miocene nephelinephonolites that form the Ngapoi Hills (Feibel, 2011; Walsh and Dodson, 1969), and augite basalts of the Oligocene to Lower Miocene located east of the Ngapoi Hills (Olago, 2018). Due to lack of outcrops, there is a gap in the sedimentation history between the late Miocene and early Pliocene (Feibel, 2011); Quaternary sands are widespread and blanket most of the older geological formations, while Holocene sediments and alluvium deposits are found along the Turkwel River and the major streams in the area (Walsh and Dodson, 1969).

2.2. Water sampling and analysis

2.2.1. Fieldwork

Groundwater and surface water samples were collected from the study area during two dry (February 2018 and February 2019) seasons and one wet (May 2018) season, and the geographical coordinates of all the sampling sites were recorded. The 12 groundwater samples and seven Turkwel River samples that were collected within the study area (and included in this paper) during the 2018 dry season form a subset of a wider sample collection that extended to the western shoreline of Lake

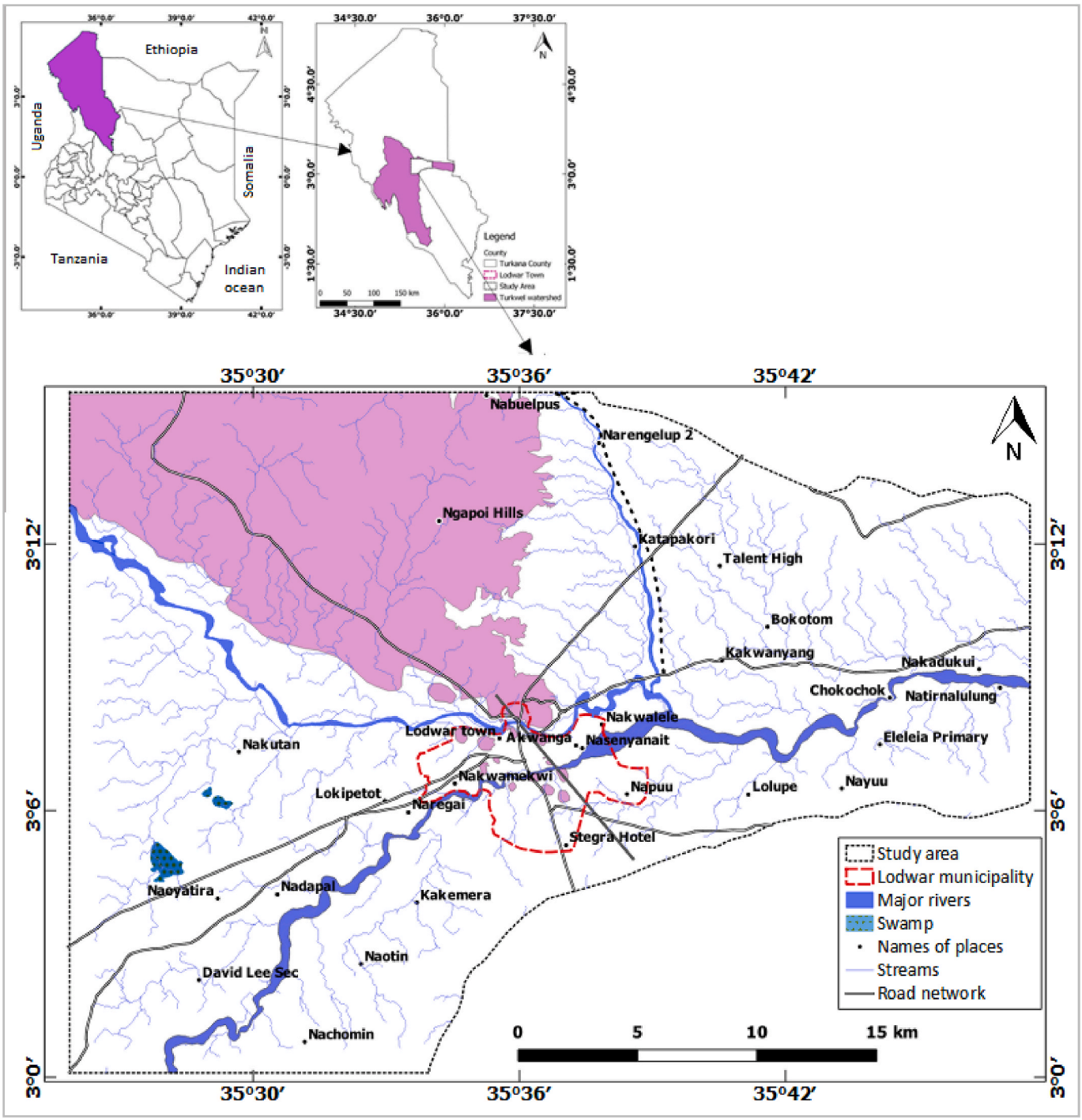


Fig. 1. Location of the study area and key geographical features within the Turkwel watershed in Turkana County of Kenya .

Turkana. During the 2018 wet season, 94 groundwater samples from 53 handpumps and 41 boreholes (electric or solar pump operated) were collected, including re-sampled February 2018 sites. Information on the drilled depth of each handpump and borehole was not fully available. There was information on drilled depth for 28 handpumps (depth range, 5–45 m, with one reported outlier at 75 m); 17 of these were less than 30 m below the site-specific ground-level elevation above sea level, and therefore fall in the shallow aquifer category (cf. Olago, 2018). Likewise, 22 boreholes had drilled depth information, including all nine LOWASCO production boreholes. Their depths ranged from 17 to 110 m. Of these, ten (10) were between 16 and 30 m depth and were categorized as a shallow aquifer. Similarly, the other ten (10) boreholes were in the IA category, and two (2) were in the deep aquifer category. Of the nine LOWASCO production boreholes, seven were in the shallow aquifer category, and two were in the DA category. (cf. Olago, 2018). During the 2019 dry season, 58 of the 94 groundwater sites, comprising 31 handpumps and 27 boreholes, were re-sampled, including all the February 2018 sites. Of these, 16 handpumps and 18 boreholes, all also sampled in the 2018 wet season, had drilled depth information. The number of sampled sites without drilled depth information was: 25 handpumps and 19 boreholes.

The field parameters that were measured (with the exception of the February 2019 set of samples) were electrical conductivity, pH, and temperature using a hand-held Combo Tester HI98129. Two sets of

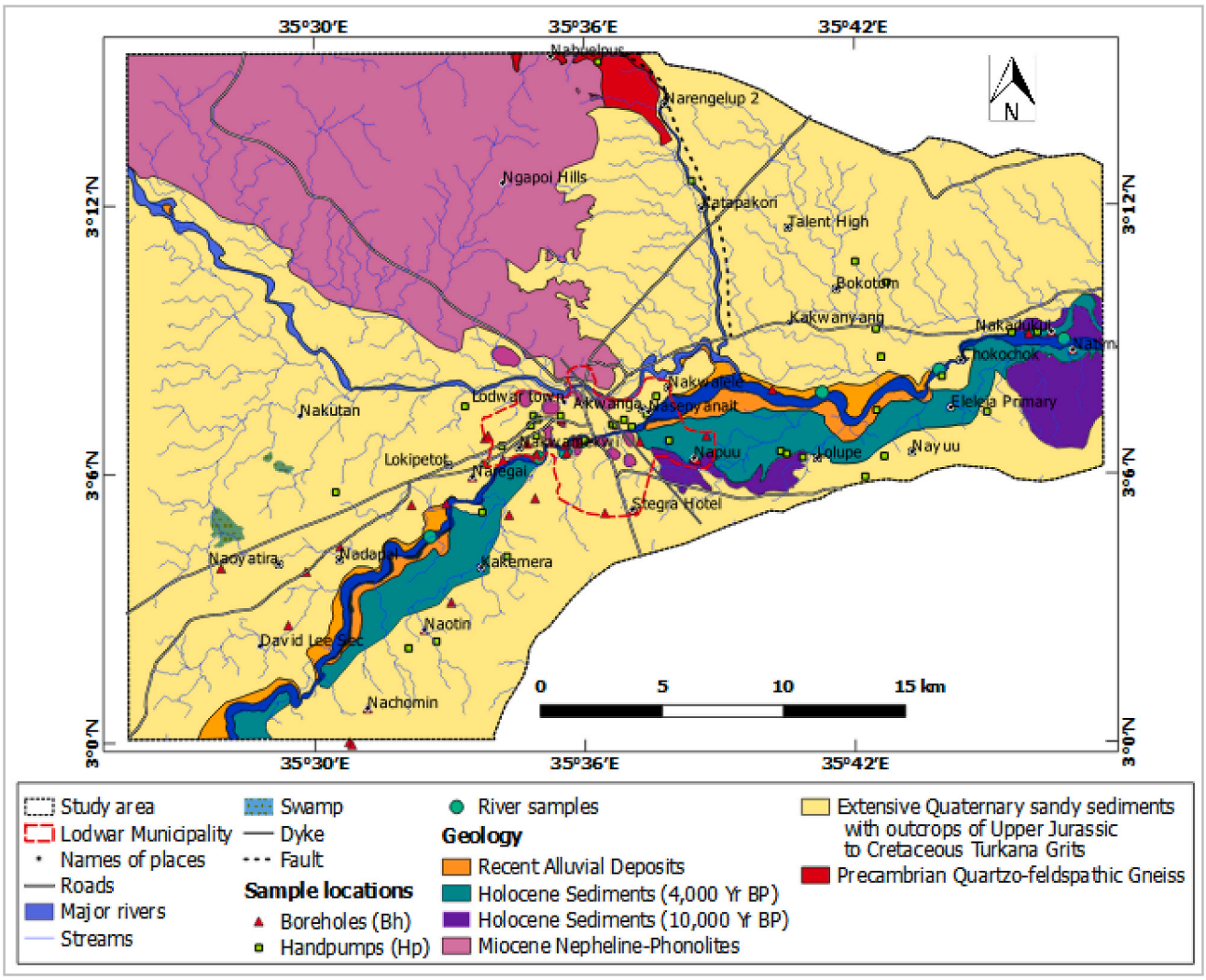


Fig. 2. Geological map of the area showing the samples locations for surface water and groundwater.

water samples were collected from each sampling site for cation and anion determinations, respectively. Clean polythene bottles with air-tight caps were used as sampling containers, and each bottle was rinsed with distilled water before sampling. Three drops of analytical grade 1% nitric acid were used to preserve the cation samples. The bottles were labeled and then stored in a cool box for transportation to Nairobi and refrigerated at 4 °C in the laboratory.

2.2.2. Laboratory

The laboratory analyses included; turbidity, hardness, total alkalinity, major anions (HCO_3, SO_4, F, Cl, CO_3, NO_3, NO_2) and cations (Ca, Mg, Na, K, Fe, and Mn) at the Central Water Testing Laboratory, Nairobi. All samples were first filtered through 0.45 μm membrane filters. All the analytical procedures for anion and cation measurements were undertaken in accordance with the APHA manual (APHA, 1995). Turbidity was measured for all the surface water and groundwater samples in the laboratory using the MRC turbidimeter model and reported in nephelometric turbidity units (NTU). Total hardness, alkalinity, free carbon dioxide, Ca, and Mg were determined using titrimetric methods; Na and K were determined using flame photometric methods utilizing a Jenway PFP7 Flame Photometer while the iron was measured using phenanthroline using a Jenway Calorimeter 6051. Manganese was measured using the persulphate method. The argentometric method was used for Cl, ion-selective electrode method for F, the spectrophotometric method using a UV-VIS spectrophotometer (1240 Shimadzu) for nitrate, the calorimetric method for nitrite with Jenway Calorimeter 6051, and turbidimetric method for sulphate.

2.2.3. Analysis

A total of 38 groundwater samples were classified as shallow aquifer along the Turkwel river while ten were in the Turkana grit further away from the river. The intermediate aquifer (IA) had 44 samples, and the deep aquifer had only two samples. All the groundwater samples (164) had a charge balance error of ±5% (Huh et al., 1998), while for surface water (7), five samples had a charge balance error of ±5% while two samples had a charge balance error less than 10%. Aquachem 2014.2 was used to generate piper diagrams and determine the hydrochemical facies of the surface water and groundwater. Seasonal variations in groundwater facies were evaluated using 58 samples that were collected during the May 2018 wet season and the February 2019 dry season.

Additionally, 11 groundwater samples that were collected in the 2018 and 2019 dry seasons were included in the evaluation. Golden Software Surfer 14.0 was used to plot the spatial maps of the physicochemical parameters while Microsoft Excel and XLSTAT 2019 add-in were used for Principal Component Analysis and hierarchical cluster analysis (HCA) utilizing group average clustering and Euclidean distance methods based on dissimilarities (Islam et al., 2017; Ravikumar and Somashekar, 2015; Zhang et al., 2011) of the groundwater samples. The significance of seasonal variations in water chemistry was determined using discriminant function analysis. The geochemical results

were compared with the World Health Organization (WHO) and the Kenya Bureau of Standards (KEBS) guidelines for drinking water quality, where applicable. Rock-water interactions were examined for each aquifer system using the ionic relations and cation exchange, principal component and hierarchical cluster analyses, and mineral saturation indices. Mineral saturation indices in groundwater were determined using the PHREQC (interactive) software (Ansari and Umar 2019; Coetsiers et al., 2009).

3. Results

3.1. Physico-chemical characteristics

3.1.1. Turkwel River

The electrical conductivity (EC) in the Turkwel River indicates a narrow range from 200.0 to 420.0 μS/cm, with a median value of 209.36.0 μS/cm (Table 1). The pH for the Turkwel River samples was slightly alkaline, ranging from 7.5 to 8.0; slightly less alkaline waters are noted eastwards of the confluence of the Turkwel and Kawalase rivers (Fig. 2). The river water was quite warm, with temperatures ranging from 30.6 °C to 36.1 °C and was slightly cooler than the maximum daily temperature (ca. 38 °C) experienced in the area during the sampling period. The minimum turbidity (median 311 NTU) was 96.00 NTU recorded in the westernmost (upstream) sample, while the maximum value of 834.00 NTU was recorded in the town area (Table 1). No clearly discernible features are observed in the concentrations of the cations from upstream to downstream, except for Na, which increases markedly east of the confluence of Turkwel and Kawalase rivers (Table 1, Fig. 2), and relatively high Fe and Mn content. For the measured anions, sulphate and nitrites were not detected, while the concentrations of nitrate, chloride, and bicarbonate are generally low (Table 1).

3.1.2. Groundwater

(a) Shallow Aquifer
(1) Alluvial Aquifer

The range of EC values varied markedly between the dry seasons and the wet season in the SAA; minimum EC values were more or less similar (195–207 μS/cm for the dry seasons versus 210 μS/cm for the wet season), but the EC maximum in the wet season was three times higher than in either of the dry seasons (1857 μS/cm versus 630–632 μS/cm) (Table 2). Similarly, while the range for the pH during the dry seasons was 7.60–8.22, it was higher during the wet season, ranging from 7.65 to 8.91. Besides, a two- and a five-fold increase is also seen in maximum turbidity values in the wet season as compared to each of the two dry seasons. No significant variations are observed for groundwater temperature, which ranged from 28.1 to 35.7 °C.

In terms of chemistry, the groundwater can be categorized as non-saline except for Napuu 1 borehole, which was slightly saline in the February 2018 dry season, the only time that it was sampled. With respect to the median concentrations of the cations, Ca is similar across the two dry and one wet season, Mg and K are depleted in the February 2019 dry season compared to the February 2018 dry season and the May 2018 wet season, and Na in the wet season is strongly depleted relative to the two dry seasons. For the anions, the February 2018 season has the highest concentrations for HCO_3, SO_4, and Cl, while the May 2018 wet season has the least. The F concentrations are comparable across the three seasons. Nitrate levels are generally low. Relative to the entire dataset, significant site-specific anomalies are noted for Ca (very low, Kakemera Primary handpump – wet season May 2018), Na (high, BH7 – dry season February 2019), K (high, KFS handpump – wet season May 2018) and SO_4 (very high, BH7 – dry season February 2019; high, Napuu 1, dry season February 2018).

(2) Turkana Grit Aquifer

For this aquifer, data are available for one dry season (February 2019) and one wet season (May 2018) (Table 3). Few handpumps were targeting this aquifer, probably as a consequence of its water, which falls in the moderately saline category. No marked differences are observed in the EC of some samples between the dry and wet seasons, except for the Bokotom handpump. However, the EC range for the shallow groundwater of the Turkana grit was slightly lower in the wet (3410–6840 μS/cm) than in the dry (5170–8260 μS/cm) season. As in the case of the SAA, while the minimum pH values were more or less the same (8.35 versus 8.40) the maximum pH for this aquifer was markedly higher in the wet (9.28) than in the dry (8.68) season, and there was a

Table 1
Physico-chemical results for the Turkwel River samples collected during the dry season of February 2018 highlighted fields are values exceeding the guidelines for drinking water. See Fig. 2 for sample location. NB: The samples have been arranged from upstream to downstream (left to right), and 'nd' refers to not detected.

Sample Code	2434	2435	2437	2438	2439	2440	2441	Min	Max	Median
EC	210	380	220	200	420	200	210	200	420	210.00
pH	8.65	7.70	8.82	9.11	8.92	8.73	9.53	7.70	9.53	8.82
Temp.	33.4	33.7	36.1	32.6	30.6	31.7	34.0	30.6	36.1	33.4
Turb.	311	228	154	549	96	834	521	96	834	311
Ca	25.60	25.60	26.40	25.60	24.00	26.40	24.80	24.00	26.40	25.60
Mg	6.33	7.79	5.36	7.79	8.76	7.30	7.30	5.36	8.76	7.30
Na	2.10	2.00	7.70	2.00	2.80	2.20	6.00	2.00	7.70	2.20
K	5.1	4.6	5.4	4.7	4.3	4.4	5.3	4.3	5.4	4.7
Fe	2.06	2.37	2.76	2.7	1.66	2.46	2.13	1.66	2.76	2.37
Mn	0.16	0.16	<0.01	0.16	0.12	0.16	0.2	0.12	0.2	0.16
HCO_3	96.63	96.83	101.97	99.25	116.19	121.23	121.61	96.63	121.61	101.97
SO_4	nd	nd	nd	nd	nd	nd	nd	N/A	N/A	N/A
Cl	2	10	5	4	1	1	5	1	10	4
NO_3	0.32	<0.01	0.37	0.86	0.17	<0.01	0.25	0.17	0.86	0.32
NO_2	nd	nd	nd	nd	nd	nd	nd	N/A	N/A	N/A

Table 2
Results for the physico-chemical parameters during the dry season of February 2018 and February 2019 and for the wet season of May 2018 for the shallow alluvial (highlighted fields are values exceeding the guidelines for drinking water, 'nm' refers to not measured while 'nd' refers to not detected).

Shallow alluvial aquifer (SAA)- Dry season (February 2018)																		
No	**Sample ID**	**Code**	**EC**	**pH**	**Temp.**	**Turb.**	**Ca**	**Mg**	**Na**	**K**	**Fe**	**Mn**	**HCO_3**	**SO_4**	**Cl**	**F**	**NO_3**	**NO_2**
1	Bh 1A	2455	209.00	7.9	28.9	1.06	26.4	6.33	3	4.6	0.03	0.01	118.6	1.82	3	0.46	0.03	nd
2	Bh 1B	2454	220.00	7.6	28.1	0.17	28	7..31	2	4.4	0.17	0.01	124	3.41	2	0.47	nd	nd
3	Bh 2C	2453	262.00	8	29.5	0.42	33.6	7.31	5.2	4.1	0.07	0.5	125.6	1.78	4	0.5	nd	nd
4	Bh 3	2448	233.00	7.8	29.3	0.91	28	10.2	2.6	4.3	0.03	0.01	123.7	2.22	2	0.41	nd	nd
5	Bh 5	2449	265.00	7.6	29.8	0.69	32	8.28	5.5	4.6	0.03	0.01	138.5	nd	5	0.44	nd	nd
6	Bh 6	2444	561.00	8.2	34.2	0.36	20.8	1.31	100	4	0.03	0.01	230.6	19	28	0.45	0.16	0
7	Bh 9	2450	257.00	7.7	29.2	1.59	36.8	7.31	2.4	4.6	0.03	0.01	126.3	2.63	4	0.43	nd	Nd
8	Bh 7	2445	207.00	7.9	28.8	1.01	25.6	5.85	5	4	0.1	0.01	99.25	2.69	2	0.39	0.2	Nd
9	Napuu 1	2451	1256.00	8	32.7	1.02	47.2	22.9	190	5.1	0.07	0.01	422.8	109	114	0.99	0.68	Nd
12	Lolupe Hp	2456	630.00	8	33.4	2	25.6	22.4	70	4.2	0.9	0.01	321.3	13.5	12	0.75	nd	Nd
Summary statistics		Min	207.00	7.6	28.1	0.17	20.8	1.31	2	4	0.03	0.01	99.25	1.78	2	0.39	0.03	0
		Max	1256.00	8.2	34.2	2	47.2	22.9	190	5.1	0.9	0.5	422.8	109	114	0.99	0.68	0
		Median	410.00	7.87	30.39	0.92	30.40	10.21	38.57	4.39	0.15	0.06	183.05	17.34	17.60	0.53	0.27	0.02
Shallow alluvial aquifer (SAA)_February 2019 (Dry season)																		
	Sample ID	Code	EC	pH	Temp.	Turb.	Ca	Mg	Na	K	Fe	Mn	HCO_3	SO_4	Cl	F	NO_3	NO_2
1	Akibululu Hp	2256	360.00	7.95	nm	1.20	33.60	5.85	32.00	2.70	0.07	0.60	195.89	3.70	9.00	0.51	0.11	nd
2	Bh 1A	2225	195.00	8.13	nm	0.58	27.20	2.93	6.10	3.10	0.10	nd	103.52	1.10	15.00	0.44	0.02	nd
3	Bh 1B	2226	224.00	8.09	nm	0.10	33.60	2.94	6.60	1.10	0.07	nd	125.33	2.26	nd	0.45	nd	nd
4	Bh 2C	2227	241.00	8.13	nm	4.92	40.80	0.51	6.90	1.00	0.13	0.60	146.85	1.55	4.00	0.57	0.05	nd
5	Bh 3	2263	228.00	8.00	nm	0.49	32.00	4.39	6.00	2.00	0.07	nd	86.97	5.19	25.00	0.34	0.13	nd
6	Bh 5	2224	249.00	8.15	nm	NIL	33.60	5.37	7.40	1.90	0.07	nd	120.30	3.83	5.00	0.52	nd	nd
7	Bh 7	2269	1857.00	8.04	nm	0.41	44.00	0.03	375.00	3.20	0.10	0.12	205.15	7.21	5.00	0.33	0.04	nd
8	Bh 9	2223	309.00	8.10	nm	0.22	31.20	2.45	30.00	2.80	0.07	nd	139.76	5.88	29.00	0.50	0.03	nd
9	Kakwanyang Dispensary Bh	2258	280.00	8.08	nm	0.85	33.60	3.91	17.00	3.10	0.10	nd	156.71	4.39	2.00	0.41	0.19	nd
10	Lodwar Mixed Pri 2	2249	403.00	8.18	nm	0.36	39.20	5.37	40.00	1.40	0.07	nd	218.72	3.84	8.00	1.62	0.10	nd
11	Lolupe 3 Hp	2214	496.00	8.20	nm	1.26	31.20	1.96	75.00	2.40	0.03	nd	283.42	5.87	4.00	1.16	nd	nd
12	NadapalHp	2233	392.00	8.15	nm	0.68	18.40	8.76	50.00	1.10	0.07	1.20	218.94	2.16	14.00	1.18	0.07	nd
13	NakwamekwiPriBh	2237	239.00	8.22	nm	0.06	33.60	6.34	3.00	2.30	0.07	nd	144.00	1.02	1.00	0.56	0.02	nd
14	NaregaiBh	2264	387.00	8.11	nm	0.80	25.60	16.05	30.00	4.10	0.07	nd	183.08	10.60	3.00	0.22	nd	nd
15	NasenyanaitHp 2	2251	256.00	8.15	nm	0.40	40.00	1.48	8.20	3.10	0.07	nd	144.36	6.62	nd	0.63	0.07	nd
Summary statistics		Min	195.00	7.95	N/A	0.06	18.40	0.03	3.00	1.00	0.03	0.12	86.97	1.02	1.00	0.22	0.02	N/A
		Max	1857.00	8.22	N/A	4.92	44.00	16.05	375.00	4.10	0.13	1.20	283.42	7.21	29.00	1.62	0.19	N/A
		Median	280.00	8.13	N/A	0.54	33.60	3.91	17.00	2.40	0.07	0.60	146.85	3.84	5.00	0.51	0.07	N/A
Shallow alluvial aquifer (SAA)- Wet season (May 2018)																		
No	sample ID	Code	EC	pH	Temp.	Turb.	Ca	Mg	Na	K	Fe	Mn	HCO_3	SO_4	Cl	F	NO_3	NO_2
1	KakemeraPriHp	3300	528.00	8.7	32.9	5.3	3.2	9.23	99	1.1	0.07	<0.01	259.4	9.15	12	0.93	0.21	nd
2	NakwamekwiPriBh	3307	270.00	8.3	29.7	5.12	26.4	12.2	6	3.5	0.03	<0.01	145.5	3.44	3	0.57	>0.01	nd
3	NaregaiBh	3312	350.00	8.4	32.8	4.51	20.8	19	20	5.7	0.07	<0.01	191.6	10.2	3	0.93	>0.01	nd
4	NadapalHp	3313	324.00	7.8	31	7.09	29.6	15.6	8.7	3.2	0.07	0.6	173.9	2.38	1	1.18	0.02	nd
5	LokipetotBh	3329	380.00	8.3	29	5.15	24.8	16.1	29	4.3	>0.01	<0.01	218.7	6.36	1	0.56	0.14	nd
6	NakwaleleHp 2	3338	632.00	8.7	32.6	5.28	24.8	8.28	98	4.2	0.07	0.04	281.9	19.9	36	0.99	0.13	nd
7	AkibululuHp	3344	306.00	8.5	31.4	2.65	29.6	8.28	20	3.8	0.1	0.4	170	0.03	8	0.79	0.12	0.1
8	Locher A AkalaleHp	3346	297.00	8.5	31.1	1.85	16.8	5.35	37	2.6	0.07	0.1	145	6.4	8	0.74	0.17	nd
9	NasenyanaitHp 2	3351	320.00	8.2	32	1.78	32	14.6	6.4	4.1	0.07	0.06	171.5	5.8	3	0.66	0.16	nd
10	Natotol	3354	271.00	8.2	30.2	6.05	28	9.74	9	4.1	0.17	0.6	138	1.03	2	0.63	0.54	nd
11	Lodwar Mixed Pri 1	3355	353.00	7.8	30.3	8.05	29.6	6.82	32	2.9	0.03	0.2	180.4	2.77	8	1.68	0.04	0
12	Lodwar Mixed Pri 2	3356	332.00	7.7	31.8	1.23	34.4	8.77	18	3.7	0.03	0.6	159.8	4.22	11	1.08	0.07	nd
13	Lolupe 3 Hp	3360	594.00	8.1	34.4	1.41	27.2	11.7	80	4.3	>0.01	<0.01	341.6	7.37	12	0.81	0.04	nd
14	Nabulon water well	3365	236.00	8.4	31.3	0.29	28	4.88	10	4.4	0.07	<0.01	116.8	2.65	7	0.53	>0.01	nd
15	Bh 1B	3380	240.00	8.6	29.8	0.03	26.4	7.79	4	4.9	0.03	<0.01	124.1	6.49	6	0.32	0.36	nd
16	Bh 1A	3381	260.00	8.9	28.9	5.94	36.8	6.82	3	4.7	0.03	0.04	126.8	2.07	13	0.31	0.3	nd

17	Bh 2C	3382	310.00	8.2	30.4	3.3	34.4	9.25	8	4.3	0.07	0.5	156.1	2.7	12	0.31	0.15	nd
18	Bh 3	3383	240.00	8.5	30	0.43	28	8.76	3	4.7	>0.01	<0.01	121.5	2.73	6	0.29	0.06	nd
19	Bh 7	3384	210.00	8.6	29.9	0.54	25.6	8.28	3	4.2	0.03	0.14	111.8	2.28	5	0.29	>0.01	nd
20	Bh 5	3387	270.00	8.3	29.9	1.87	33.6	7.79	3	4.7	0.03	0.08	160.5	2	5	0.32	>0.01	nd
21	Bh 9	3388	260.00	8.4	28.7	0.66	29.6	11.7	3	4.5	0.03	<0.01	133.4	4.83	5	0.27	0.09	nd
22	KFS Hp	3390	424.00	7.9	28.7	10.5	30.4	14.1	27	14	0.17	0.5	216.7	23.9	12	0.6	0.08	nd
Summary statistics		Min	210.00	7.7	28.7	0.03	3.2	4.88	3	1.1	0.03	0.04	111.8	0.03	1	0.27	0.02	0
		Max	632.00	8.9	34.4	10.5	36.8	19	99	14	0.17	0.6	341.6	23.9	36	1.68	0.54	0.1
		Median	259.50	7.90	29.40	0.96	28.00	7.31	5.10	4.35	0.05	0.01	125.94	2.69	4.00	0.46	0.18	N/A

Table 3
Physico-chemical parameters for the Turkana grit shallow aquifer during the dry season (February 2019) and the wet season (May 2018) (highlighted fields are values exceeding the guidelines for drinking water, 'nd' refers to not detected).

Turkana Grit Shallow Aquifer (TGSA)- Dry season (February 2019)																		
	Sample ID	Code	EC	pH	Temp.	Turb.	Ca	Mg	Na	K	Fe	Mn	HCO_3	SO_4	Cl	F	NO_3	NO_2
1	Talent High SchHp	2252	5600.00	8.56	nm	7.64	3.20	1.46	1280	1.20	0.27	nd	941.73	350	1120.00	9.60	7.81	nd
2	BokotomHp	2253	8260.00	8.40	nm	1.24	8.00	17.98	1850	3.10	0.07	nd	492.68	268	2395.00	2.19	3.27	nd
3	LoyoPriHp	2266	5170.00	8.68	nm	1.38	4.80	0.49	1182	2.70	0.10	nd	1769.51	351.6	446.00	17.24	5.03	nd
4	Trumpet of Hope Ministries	2267	5570.00	8.82	nm	0.86	0.80	0.49	1280	2.30	0.10	nd	1773.54	388	541.00	12.28	7.82	nd
Summary statistics		Min	5170.00	8.40	N/A	0.86	0.80	0.49	1182	1.20	0.07	N/A	492.68	268	446.00	2.19	3.27	N/A
		Max	8260.00	8.82	N/A	7.64	8.00	17.98	1850	3.10	0.27	N/A	1773.54	388	2395.00	17.24	7.82	N/A
		Median	5585.00	8.62	N/A	1.31	4.00	0.98	1280	2.50	0.10	N/A	1355.62	350.8	830.50	10.94	6.42	N/A
Turkana Grit Shallow Aquifer (TGSA)- Wet season (May 2018)																		
	Sample ID	Code	EC	pH	Temp.	Turb.	Ca	Mg	Na	K	Fe	Mn	HCO_3	SO_4	Cl	F	NO_3	NO_2
5	Talent High SchHp	3331	6370.00	9.06	35.70	12.70	4.80	2.92	1453	2.60	0.27	nd	1407.19	426	1020.00	10.41	19.81	nd
1	NamuthiaHp	3333	3410.00	9.12	36.00	20.86	4.00	2.92	770	1.50	0.67	nd	828.27	207.03	525.00	3.09	7.15	nd
3	BokotomHp	3334	6840.00	8.35	36.90	4.26	12.00	18.04	2020	2.90	nd	nd	492.38	610	2390.00	2.22	4.76	nd
6	Trumpet of Hope Ministries	3394	5340.00	9.28	35.40	6.74	<1	0.49	1226	2.70	0.17	nd	1333.31	608.06	500.00	15.31	33.64	nd
2	Al Noor Community	3396	6270.00	8.62	33.10	1.10	9.60	13.60	1400	5.10	0.10	nd	1215.15	934.6	780.00	18.74	1.34	nd
4	LoyoPriHp	3399	5190.00	8.79	33.50	4.56	2.40	1.95	1190	3.70	0.03	nd	1602.75	324.71	590.00	18.67	7.92	nd
Summary statistics		Min	3410.00	8.35	33.10	1.10	2.40	0.49	770	1.50	0.03	N/A	492.38	207.03	500.00	2.22	1.34	N/A
		Max	6840.00	9.28	36.90	20.86	12.00	18.04	2020	5.10	0.67	N/A	1602.75	934.6	2390.00	18.74	33.64	N/A
		Median	5805.00	8.93	35.55	5.65	4.80	2.92	1313	2.80	0.17	N/A	1274.23	517.03	685.00	12.86	7.535	N/A

three-fold difference in maximum turbidity between the dry (7.64 NTU) and wet (20.86 NTU) seasons. Temperature, which was only measured during the wet season, ranged from 33.1 to 36.9 °C, indicating that overall, the shallow Turkana Grit aquifer is warmer than the SAA.

In comparison with the SAA, the Na, Cl, and HCO_3 concentrations are much higher, and in most cases, the concentrations of all three parameters each exceed 1000 mg/l. Also, of note is that: (i) the Ca concentrations are lower in the TGSA compared to the SAA; and (ii) the SO_4, F, and NO_3 concentrations are much higher than in the SAA. Contrasts between the dry and wet seasons in the TGSA relate to (i) higher median values for Mg, SO_4, F, and NO_3 concentrations in the wet compared to the dry season, except for the Loyo Primary handpump where the reverse is observed, and (ii) lower median Cl concentration values in the wet compared to the dry season though direct comparison of wells reveals that this is not necessarily so for some of them. The relatively high sulphate concentration in this aquifer suggests the presence of sulphate-reducing bacteria and the existence of a reducing environment. Handpumps with the highest SO_4 concentration (Bennett et al., 2000; Keesari and Ramakumar, 2015), Bokotom Hp (610 mg/l), and Trumpet of Hope (608.06 mg/l) had a strong hydrogen sulphide smell, suggesting that SO_4^{2-} was being reduced to H^2S in the aquifer.

(b) Intermediate Aquifer

For this aquifer, data was available for the two dry and one wet season but is limited for the first dry season of February 2018 (2 samples only) (Table 4). Based on the EC, the groundwater in the IA is mostly non-saline, but there are some slightly saline pockets. Similar to the SAA, while the minimum EC values were similar in both the dry and wet seasons, the EC maximum was higher in the wet season, but not markedly as in the SAA. The pH range during the wet season (7.61–9.76) was wider than in the dry season (8.10–8.67). Also, similar to the SAA and TGSA, the maximum turbidity during the wet season was much higher than in the dry season, and in this aquifer, a seven-fold increase is observed for the maximum turbidity values recorded in the wet versus the dry season. The temperature range of the groundwater is 31.3–36.0

Table 4
Results for the physico-chemical parameter for the intermediate aquifer during the dry seasons of February 2018 and February 2019 and in the wet season of May 2018 (highlighted fields are values exceeding the guidelines for drinking water. 'nm' refers to not measured while 'nd' refers to not detected).

Intermediate aquifer (IA) Dry season- February 2018																		
No	Sample ID	Code	EC	pH	Temp.	Turb.	Ca	Mg	Na	K	Fe	Mn	HCO_3	SO_4	Cl	F	NO_3	NO_2
1	Napuu 4	2452	503	8.1	32.6	0.94	23.20	7.79	72.0	3.9	0.03	0.01	260.2	6.8	18	1.29	0.2	Nd
2	Nayuu Hp 1	2460	596	8.6	35.7	2.06	1.60	2.43	130.0	1.3	0.07	0.01	253.4	10.65	19	1.26	2.34	Nd
Intermediate aquifer (IA) Dry season- February 2019																		
No	SampleID	Sample ID	EC	pH	Temp.	Turb.	Ca	Mg	Na	K	Fe	Mn	HCO_3	SO_4	Cl	F	NO_3	NO_2
1	ChukultomHp	2228	736.00	8.56	nm	nd	7.20	0.98	160.00	1.1	0.07	nd	282.5	35	62	1.56	0.13	nd
2	EleleiaPriHp	2216	906.00	8.67	nm	0.49	nd	0.97	206.00	0.2	0.03	nd	396.2	32.14	50	2.15	3.07	nd
3	Kakemera Church	2222	1182.00	8.18	nm	7.12	39.20	22.38	180.00	0.9	0.23	nd	661	11.34	538	1.75	0.15	nd
4	NachominBh	2217	1025.00	8.41	nm	0.33	9.60	1.95	220.00	1.7	0.1	nd	547.1	22.76	15	2.85	0.29	nd
5	Nadapal Supply bh	2234	510.00	8.29	nm	0.10	16.80	8.27	80.00	1.5	0.07	0.2	275.2	7.49	10	1.14	0.02	nd
6	Nakwamekwi Hp	2230	678.00	8.63	nm	nd	4.00	0.97	150.00	0.4	0.04	nd	301.9	26.3	29	1.05	0.63	nd
7	Napuu 2	2246	420.00	8.24	nm	0.55	22.40	2.93	65.00	2.4	0.07	nd	239.8	1.15	3	0.88	0.76	nd
8	Napuu 4	2245	614.00	8.23	nm	nd	24.80	8.76	100.00	2.3	0.03	nd	311.9	16.9	21	0.71	0.17	nd
9	Nareng'elup 2	2261	1051.00	8.11	nm	4.49	21.60	31.6	160.00	2.8	0.27	nd	623.9	24.7	nd	0.77	1.71	nd
10	NatotPriBh	2244	375.00	8.36	nm	0.66	26.40	11.68	35.00	1.9	0.03	nd	202.7	7.31	4	1.72	<0.01	nd
11	NaurenPuu	2235	545.00	8.24	nm	nd	18.40	8.76	86.30	1.8	0.07	nd	285.4	9.08	14	1.54	nd	nd
12	Nayuu Hp 1	2211	607.00	8.55	nm	0.59	4.80	nd	135.00	0.7	0.1	nd	308.7	19.55	14	1.23	2.14	nd
13	Nayuu HP4	2212	813.00	8.41	nm	0.45	15.20	1.47	170.00	1.2	0.2	nd	337.8	33.87	55	0.69	1.79	nd
Summary statistics		Min	375.00	8.11	nm	0.10	4.00	0.97	35.00	0.2	0.03	0.2	202.7	1.15	3	0.69	0.02	N/A
		Max	1182.00	8.67	nm	7.12	39.20	31.6	220.00	2.8	0.27	0.2	661	35	538	2.85	3.07	N/A
		Median	678.00	8.36	nm	0.55	17.60	5.6	150.00	1.5	0.07	N/A	308.7	19.55	18	1.23	0.63	N/A
Intermediate aquifer (IA) wet season- May 2018																		
No	Sample ID	Code	EC	pH	Temp.	Turb.	Ca	Mg	Na	K	Fe	Mn	HCO_3	SO_4	Cl	F	NO_3	NO_2
1	Bh 6	3389	590.00	8.33	32.9	0.75	20.00	14.59	76.00	4.4	0.03	0.04	281.3	25	25	0.35	0.3	nd
2	Chokochok Pry	3341	929.00	7.77	33.4	3.77	32.00	42.29	93.00	4.7	nd	0.6	326.8	20.92	118	0.84	0.14	0.1
3	ChukultomHp	3386	888.00	9.28	35.3	2.03	1.60	7.77	186.00	2.6	0.03	nd	337.3	47.13	93	0.67	0.17	0
4	Comboni Girls	3398	1220.00	9.58	33.6	0.16	nd	1.46	272.00	1.6	0.03	nd	382.8	73.67	140	1.41	0.57	0.1
5	EleleiaPriHp	3364	1557.00	9.59	35.7	1.44	4.00	12.15	330.00	1.1	0.1	nd	812.4	29.87	25	4.58	0.37	nd
6	Kakemera Church	3302	1308.00	7.61	35	6.00	42.40	24.81	203.00	2.7	0.07	nd	757.7	15.71	24	1.25	0.2	nd
7	KochodaHp	3391	850.00	9.76	33.9	2.17	nd	3.89	187.00	1.2	0.1	nd	436.8	22.24	15	1.62	0.15	nd
8	LimyounsimBh	3309	1673.00	7.93	34.7	4.72	56.00	13.15	227.00	6.4	0.07	nd	701.3	41.22	44	1.43	1.08	nd
9	Loporkou-EleleaiHp	3366	914.00	9.52	35.3	1.30	nd	2.43	205.00	1.3	0.07	nd	383.2	36.49	57	1.64	3.45	nd
10	NachominBh	3306	1060.00	8.48	36	4.15	6.40	4.86	188.00	1.5	0.03	nd	497.7	23.1	3	2.24	0.54	nd
11	Nadapal Supply Bh	3314	750.00	7.76	32.6	4.65	20.80	35.48	86.00	3.2	0.1	0.12	446.1	12.32	13	0.95	nd	nd
12	NagisBakhitaBh	3317	520.00	7.98	33.5	4.08	24.80	22.85	53.00	2.6	0.07	nd	296.4	12.23	20	0.14	nd	nd
13	Nakwamekwi Hp	3310	805.00	9.33	34.5	5.10	nd	5.34	174.00	1.4	0.07	nd	393.9	31.11	26	0.95	0.66	nd
14	Napuu 2	3373	370.00	8.9	32	1.01	15.20	8.27	44.00	3.6	0.07	nd	198.8	5.13	4	0.77	1.17	nd
15	Napuu 4	3374	520.00	8.52	32	0.48	24.00	10.22	63.00	4.3	0.07	nd	263.9	14.43	2	0.81	0.37	nd
16	Nareng'elup 2	3323	1040.00	7.86	33.8	49.28	45.60	73.89	45.00	0.2	0.5	nd	511.6	41.63	22	2.01	3.71	0.2
17	NatotPriBh	3357	370.00	8.68	31.3	1.18	25.60	12.65	33.00	3	0.03	nd	207.8	6.53	4	1.55	nd	nd
18	NaurenPuu	3392	600.00	8.2	34	0.20	16	9.73	91.00	4.2	0.03	nd	334.9	9.55	16	0.86	0.07	nd
19	Nayuu Hp 4	3368	820.00	8.56	34.5	2.32	8.8	6.81	164.00	2.9	0.2	nd	384.3	32.48	61	0.48	2.1	nd
20	Nayuu Hp 1	3363	650.00	9.3	35.4	1.17	0.8	1.94	144.00	1.4	0.1	nd	317	20.52	21	0.97	2.44	nd
Summary statistics		Min	370.00	7.61	31.3	0.16	0.8	1.46	33.00	0.2	0.03	0.04	198.8	5.13	2	0.14	0.07	0
		Max	1673.00	9.76	36	49.28	56	73.89	330.00	6.4	0.5	0.6	812.4	73.67	140	4.58	3.71	0.2
		Median	835.00	8.54	34	2.10	20.4	9.975	154.00	2.7	0.07	0.12	383	22.67	23	0.96	0.54	0.1

°C, broadly comparable to that of the TGSA.

In this aquifer, the median concentration values of Ca, Mg, K, HCO_3, SO_4, and Cl are higher during the wet season compared to the dry season, and much more so for Mg and SO_4 in particular. More generally, the ranges of the concentrations of the measured cations and anions are wider and more variable during the wet season than in the dry season.

(c) Deep Aquifer

The results for the Physico-chemical parameters for the DA during the dry seasons (February 2018 and 2019) and during the wet season (May 2018) are given in (Table 5).

For each of the two-deep borehole sites, there are no marked wet-dry season differences in the physico-chemical parameters, suggesting that recharge occurs over timescales longer than the seasonal cycles. However, the Natir borehole is non-saline, while the Napuu 1 borehole is slightly saline, but they have relatively similar pH, temperature, and turbidity values, as well as Ca, K, and Fe concentrations. Relative to the SAA, and IA, the Ca concentrations are comparable. Mg and Na concentrations in Napuu 1 are similar to those of the IA, while in Natir, they are similar to the SAA dry season values.

3.1.3. Spatial variations of physical parameters

The spatial variations in the physical parameters (EC, pH, and temperature) indicate a number of features of the LAAS (Fig. 3). The EC values are lowest in the groundwater along with the quasi-perennial Turkwel river profile, in the Holocene-age alluvial sediments, and also where there exist seasonal and ephemeral feeder streams, and more generally, increase in the directions perpendicular (N and S) to the streamflow trend (E). Highest EC values are associated with where the

Table 5
Results for the deep aquifer (2 boreholes) during the dry and wet seasons (highlighted values exceed the guideline value for drinking water).

Sample ID	Napuu 1			NatirnalulungBh (Natir)	
Period	Dry		Wet	Dry	Wet
Parameters	Feb-18	Feb-19	May-18	Feb-19	May-18
EC	1256	1392	1250	273	320
pH	8	8.12	8.3	7.95	8.63
Temperature	32.7	N	33	N	32
Turbidity	1.02	0.15	1.06	1.37	1.46
Ca	47.2	36	22.4	33.6	36
Mg	22.87	24.32	25.28	5.85	7.8
Na	190	230	203	11.2	11.5
K	5.1	3.1	5.7	3	4.8
Fe	0.07	0.07	0.03	0.07	0.03
Mn	0.01	nd	nd	nd	nd
HCO_3	422.76	553.88	495.27	125.76	145.67
SO_4	109	81.4	69.08	6.29	8.41
Cl	114	110	111	13	19
F	0.99	0.95	0.83	0.5	0.42
NO_3	0.68	0.42	0.71	4.69	0.15
NO_2	nd	nd	nd	nd	nd

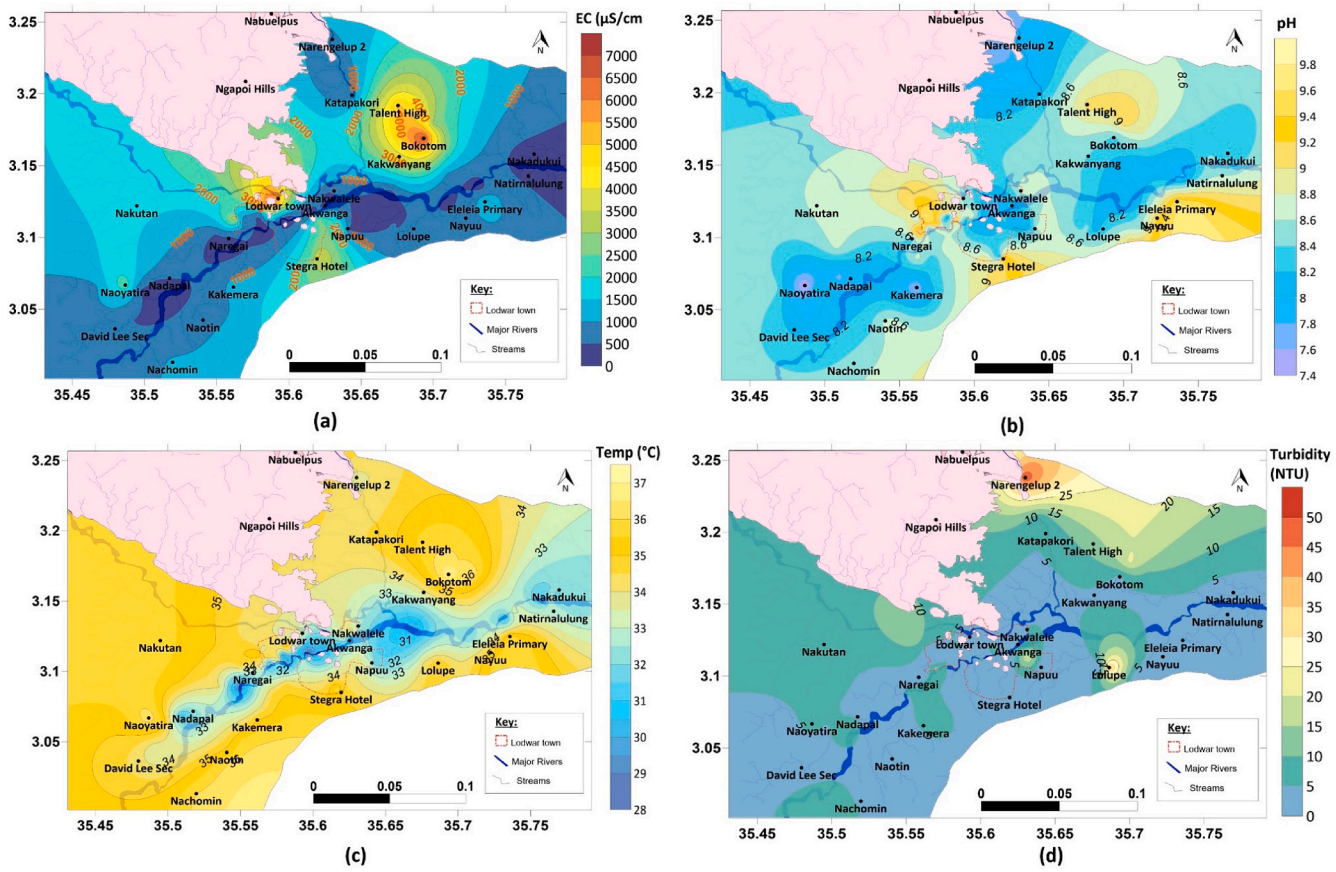


Fig. 3. Spatial variation of (a) electrical conductivity, (b) pH, (c) temperature, and (d) turbidity for the groundwater samples of the shallow alluvial aquifer, Turkana grit shallow aquifer, intermediate aquifer and from the deep aquifer during the wet season.

Turkana Grits or the Miocene nepheline-phonolites outcrop or lie close to the surface, masked by Quaternary deposits. Similar trends are observed for the pH and temperature. Where the lowest pH and temperature are next to the Turkwel River and its associated tributaries and the highest pH and temperatures are associated with the Turkana Grits and the nepheline phonolites.

3.2. Hydrochemical facies

Based on the Piper diagram (Fig. 4a), four water types were

identified from the surface water and groundwater samples of the study area; Na–HCO_3, Ca–HCO_3, Na–Cl, and Mg–HCO_3. All the surface water samples were Ca–HCO_3 type of water. In the SAA, the facies are Ca–HCO_3(59%) > Na–HCO_3 (29%) > Mg–HCO_3 (12%). In the TGSA, the facies are Na–HCO_3 (56%) > Na–Cl (44%), with the former characterizing the contact zone area of the grit and Holocene sediments, and the latter characterizing the grit proper. The IA facies was Na–HCO_3(95%) >>> Mg–HCO_3(5%), with only Katapakori and Narengelup handpumps belonging to the Mg–HCO_3 water type. The two samples of the DA had different facies: Napuu was Na–HCO_3, and Natirnalulung was Ca–HCO_3. Mg–HCO_3 water type occurred in isolated areas such as Akwanga, Nakadukui, and Naregai.

There is evidence of some seasonal variations in hydrochemical facies. For example, some samples (55%) with dominant Na–HCO_3 water type during the dry season changed to dominant Ca–HCO_3water type during the wet season (Fig. 4b). Bh 7, a municipal water supply borehole, changed from Ca–HCO_3 in the wet season of May 2018 to Na–HCO_3 during the dry season of February 2019. Also, the Kakemera church Hp of the IA, which was Na–HCO_3 type in the wet season, became Na–Cl water type during the dry season.

3.3. Rock-water interactions

3.3.1. Ion exchange and mineral saturation indices

Sodium in natural waters originates from the dissolution of feldspars or cation exchange reactions. The source for Cl^- is as an impurity in minerals (e.g., biotite) or rocks (e.g., limestone). Thus, natural concentrations are typically below about 15 mg/l for each ion and are highly variable (Hem, 1970). If the Na/Cl ratios are generally greater than 1, it suggests the sodium sources other than halite-albite and therefore from ion-exchange reactions, a ratios of Na/Cl = 1 (i.e., 1:1) indicates sources from halite dissolution or sea aerosol spray and a Na/Cl ratio < 1 suggests sources from reverse ion-exchange (Abid et al., 2011; Parnachev et al., 1999; Zhu et al., 2008). Higher Na^+/Cl^- ratio in the wet season (3.09) compared to the dry season (2.74) suggests remobilisation of some Na^+ into solution during recharge. The Bokotom Hp sample is unique in that it is the only sample that falls on the halite dissolution line (Fig. 5a and b). The TGSA had the highest Na^+ concentrations followed by those of the IA, then those with unknown depths and lastly those in the SAA (Fig. 5c and d); these data suggest that most of the samples with unknown depth lie within SAA and in the geological transition zone of the TGSA and the IA (Grits and the Holocene sediments, respectively). The majority of the groundwater samples during the wet season (87) and in the dry season (54) had Na^+/Cl^- ratios >1.0 suggesting dominant ion exchange while reverse ion exchange occurs in a few samples. Ion exchange is a major hydrochemical process in the aquifer system in both the wet and dry seasons (Fig. 5c and d; cf. Fisher and Mullican, 1997).

In the entire aquifer system, calcium and magnesium carbonates were generally at or near saturation during both the wet and dry seasons, with fluorite being slightly undersaturated and anhydrite/gypsum (Ca sulphates) moderately so (Fig. 6). Siderite is slight to moderately undersaturated with the exception of the TGSA, where it is near saturation in the wet season and saturated in the dry season. Sylvite is moderate to strongly undersaturated except in the SAA, where it is only slightly undersaturated, while halite is moderate to strongly undersaturated in all cases. Mn carbonate is close to saturation in SAA, TGSA and IA (saturated in the dry season), but strongly undersaturated in the DA. The behaviour of the Mn oxyhydroxides is quite interesting: in the SAA, they are moderate to strongly undersaturated in the wet season and moderately to strongly saturated during the dry season, while in the TGSA, the reverse is the case. In the IA, they are saturated in both the wet and dry seasons, and in the DA, they are moderate to strongly undersaturated in both seasons. Further, the Mn behaviour in the DU is similar to the SAA (see Fig. 7).

3.3.2. Hierarchical cluster analysis

The hierarchical cluster analysis very neatly differentiates the three main sub-components of the aquifer system (TGSA, SAA, and IA), particularly in the dry season. It also indicates that, of the two DA samples, one is closely affiliated with the SAA and the other with the IA. The wet season is more mixed, probably as a consequence of spatial and temporal differentials in flow rates and amounts and/or dilution across a heterogeneous aquifer system by pulsed dynamic recharge. The groundwater of the SAA belongs to Cluster 1 (C1) sub-group 1,

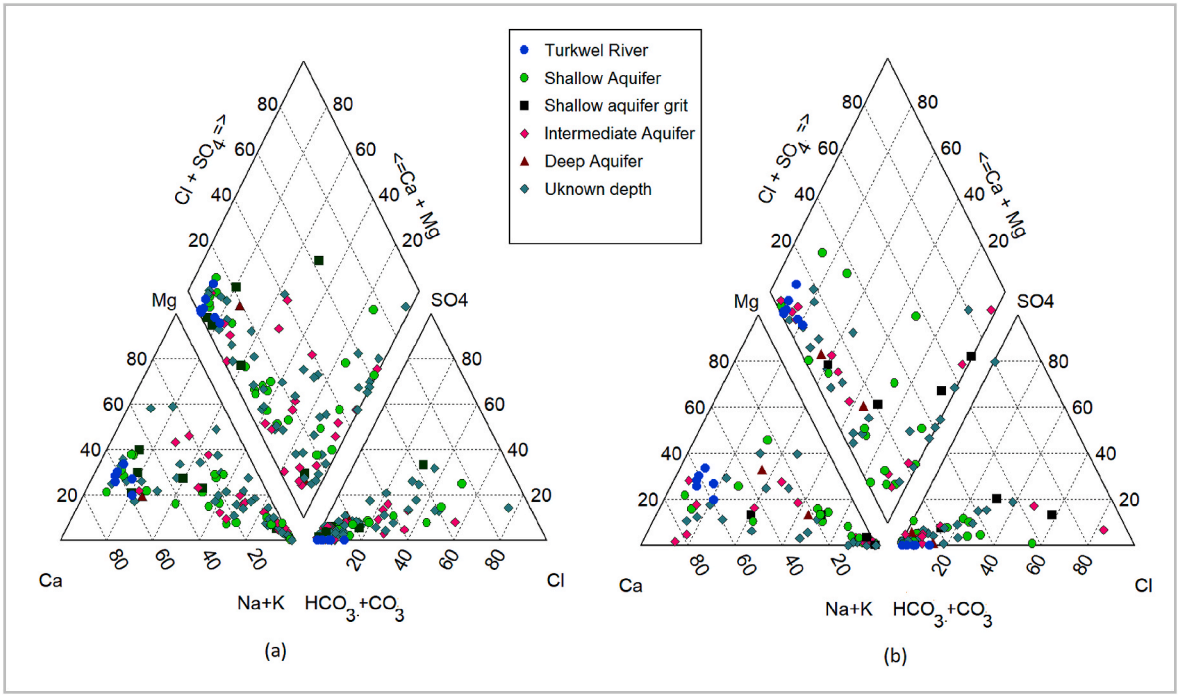


Fig. 4. Piper diagram for groundwater (shallow alluvial aquifer, Turkana grit shallow aquifer, intermediate aquifer, and deep aquifer) and surface water during the (a) wet season and (b) dry season.

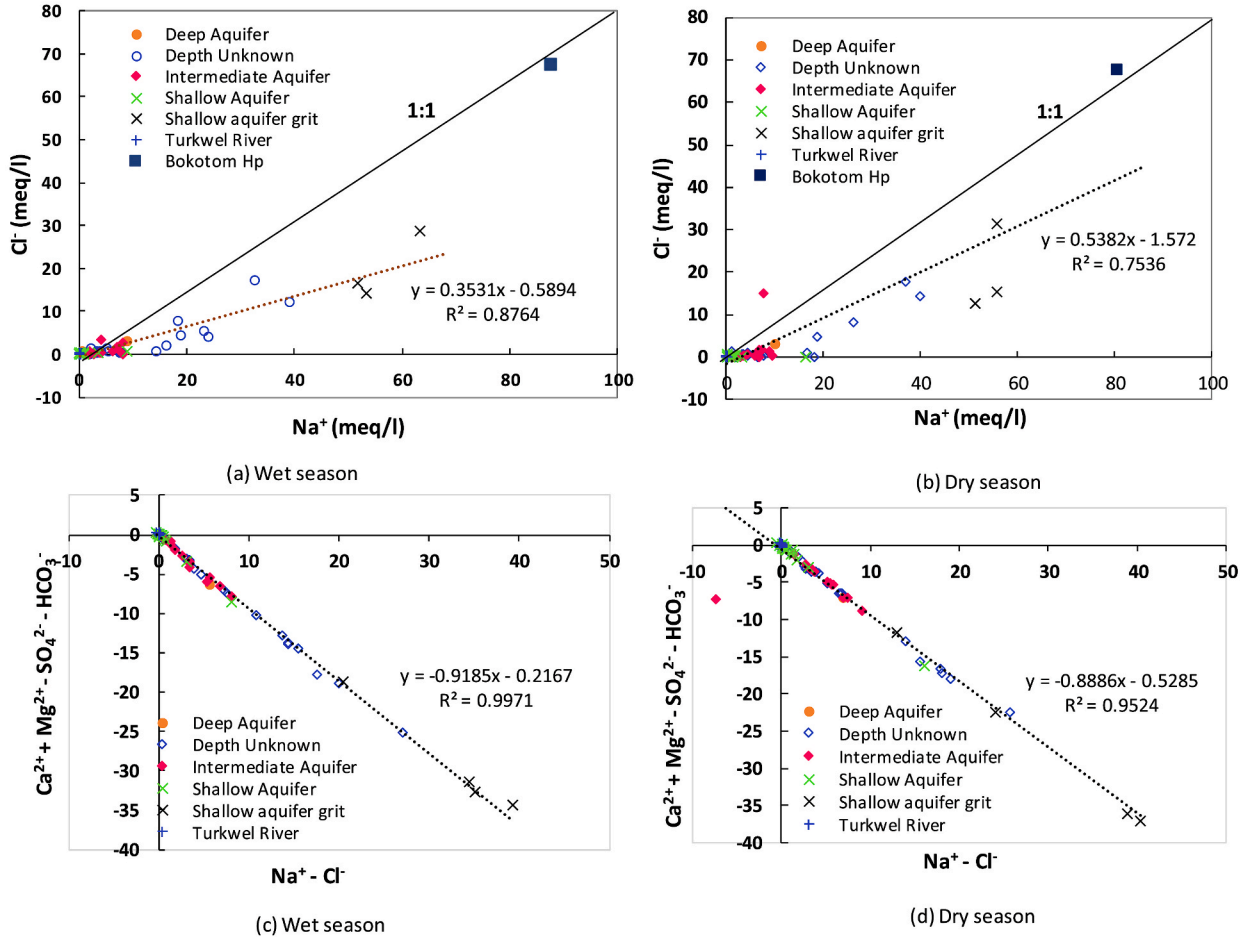


Fig. 5. Plots for Na^+/Cl^- in groundwater during the (a) wet season and (b) dry season. The plot is also interesting in that it enables the identification of which aquifer (shallow [SAA or TGSA], intermediate, or deep) the handpumps for which no drilled depth data (open diamond symbol) was available belonged to the intermediate aquifer and in the transition zone between the SAA and the TGSA. Relationship between $[Ca^{2+} + Mg^{2+} - SO_4^{2-} - HCO_3^-]$and $[Na^+ - Cl^-]$ (c) and (d) in the surface water, shallow, intermediate and deep groundwater. (In this relationship, $[Na^+ - Cl^-]$ represents the amount of Na^+ gained from halite dissolution while $[Ca^{2+} + Mg^{2+} - SO_4^{2-} - HCO_3^-]$ represents the amount of Ca^{2+} and Mg^{2+} gained from gypsum, calcite and dolomite dissolution. If cation exchange is a major hydrochemical process, a linear relationship would be achieved with a slope of −1) (Fisher and Mullican, 1997). Both the groundwater and the surface water of the study area displayed a linear relationship with a slope close to −1 in the wet and dry seasons.

characterised by low mineral content during the wet and dry season (Fig. 8). The highly mineralised groundwater in the TGSA belongs to Cluster 3 (C3) during the wet and dry season, with the unique Bokotom Hp forming Cluster 4 (C4) in both seasons (Fig. 8). The HCA suggests that two factors influence the groundwater chemistry of the IA in the wet and dry seasons; (1) the proximity to the Turkwel river (Cluster C1) and (2) proximity to the Turkana grits formation (C1 Sub-group 2 and C2a) For the DA, the HCA revealed that the groundwater of Natirnalulung Bh belongs to Cluster C1 during the wet and dry season while that of the Napuu Bh belongs to C1 Sub-group 2 during the wet season and C2a during the dry season, an indication of enriched mineral concentrations. The HCA of the samples during the wet and dry seasons revealed that of the 44 boreholes and handpumps with unknown drilled depth, 22 belonged to the SAA (Cluster 1), 13 in the IA, seven (7) in the transition zone between the Holocene sediments and the Turkana Grits and while only two (2) were in the Turkana grit aquifer.

3.3.3. *Principal components analysis*

The first two PC scores explain 58.5% and 57.7% of the variance in the dataset in the wet and dry seasons, respectively. Similar to the HCA, there is a clear and matching differentiation of the different sub-components of the aquifer system. The TGSA exhibits the highest positive PC1 scores, which decline progressively through the DU, the IA, and finally, the SAA, which exhibits the most negative PC1 scores; this progression holds for both the wet and dry seasons. During the wet season, the parameters with high positive PC1 scores are EC, Na, HCO_3, SO_4, Cl, and F, while the one with a high negative PC1 score is only Ca. For wet season PC2, high positive scores are noted for Ca, Mg, and K, and a high negative score for pH. During the dry season, high positive PC1 scores are exhibited by pH, EC, Na, HCO_3, SO_4, Cl, F and NO_3 (similar to the wet season but with the addition of F and NO_3), and a high negative score by Ca (similar to the wet season), while PC2 has a high positive score only for K (as opposed to Ca, Ma and K for the wet season), and high negative scores for pH, Ca and Mg (as opposed to only Ca in the wet season). It is likely, therefore, that the positive PC1 for both wet and dry seasons reflects, predominantly, the mineralisation gradient of the aquifer system, with older aquifer sub-components such as the TGSA being the most mineralised. Ca, with a negative PC1 in both seasons, likely strongly participates in dissolution-precipitation reactions; this is supported by the mineral saturation indices (Fig. 8) which show that it is saturated in all the aquifer systems. The inclusion of F and NO_3 in the PC1 dry season could reflect preferential leaching and degradation of organic matter accumulated in the aquifer during recharge processes, respectively. PC2 during both seasons appears to be reflective of ion exchange processes involving Ca, Mg and K primarily in the wet season and strongly pH modulated Ca, Mg reactions, inclusive of dissolution-

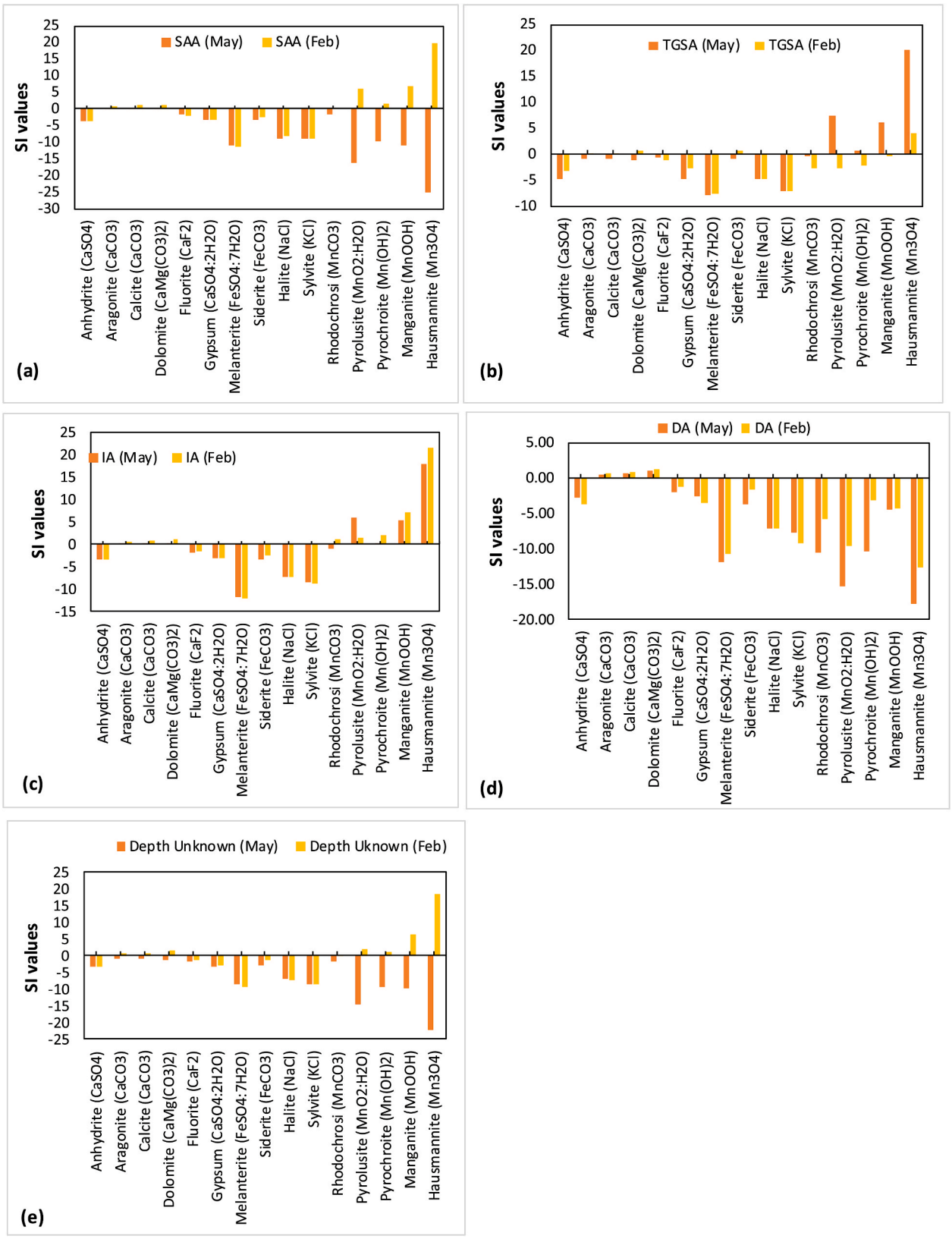


Fig. 6. Mineral saturation indices during the wet season (May) and in the dry season (February) for (a) shallow alluvial aquifer (SAA); (b) Turkana grit shallow aquifer (TGSA); (c) intermediate aquifer (IA); (d) deep aquifer (DA) and for the groundwater sources without drilled depth information.

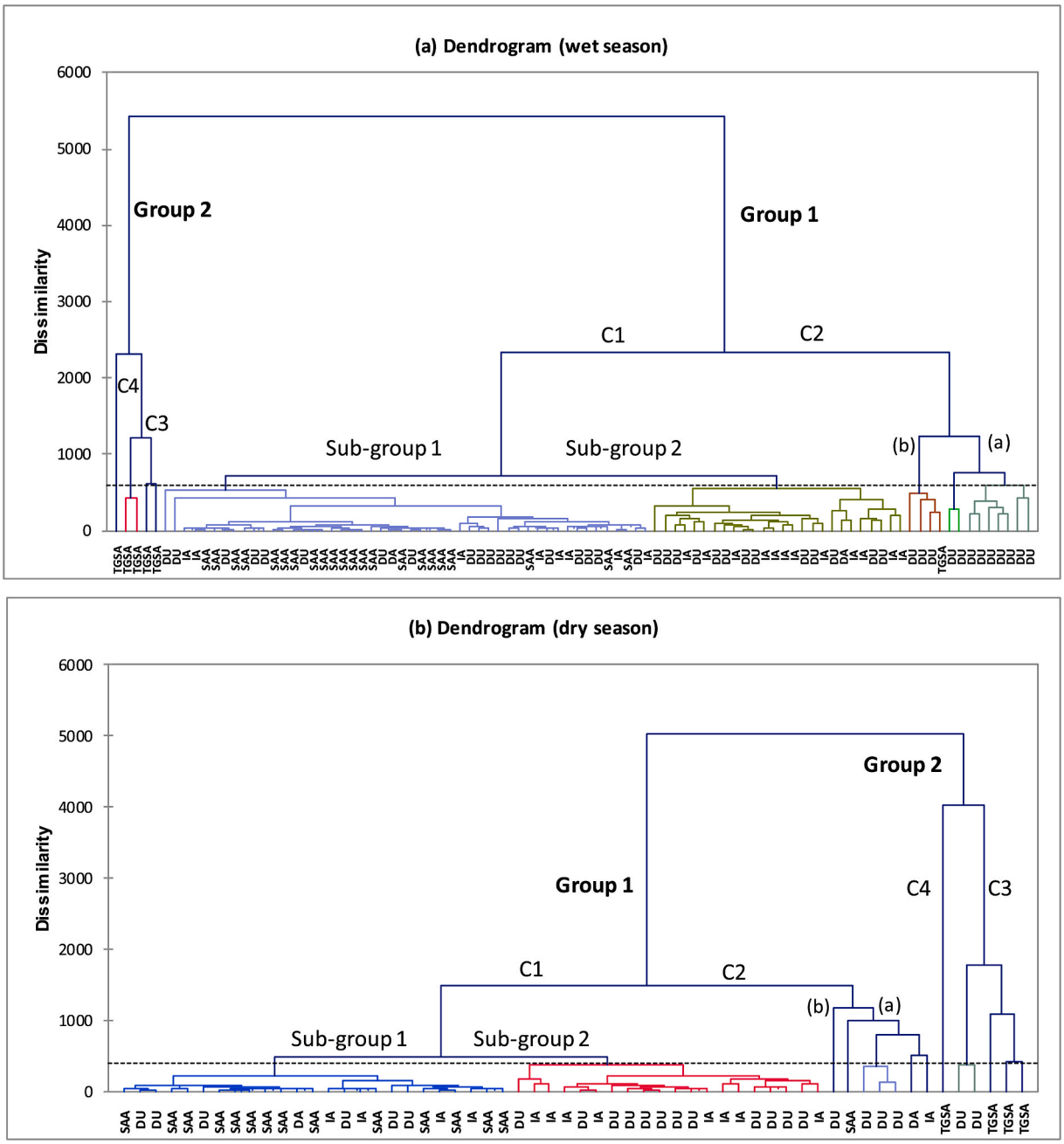


Fig. 7. Dendrogram for the groundwater samples(a) during the wet season and (b) during the dry season for the shallow alluvial aquifer (SAA), intermediate aquifer (IA), Turkana grit shallow aquifer (TGSA), Deep aquifer (DA), and for the boreholes and handpumps with an unknown depth.

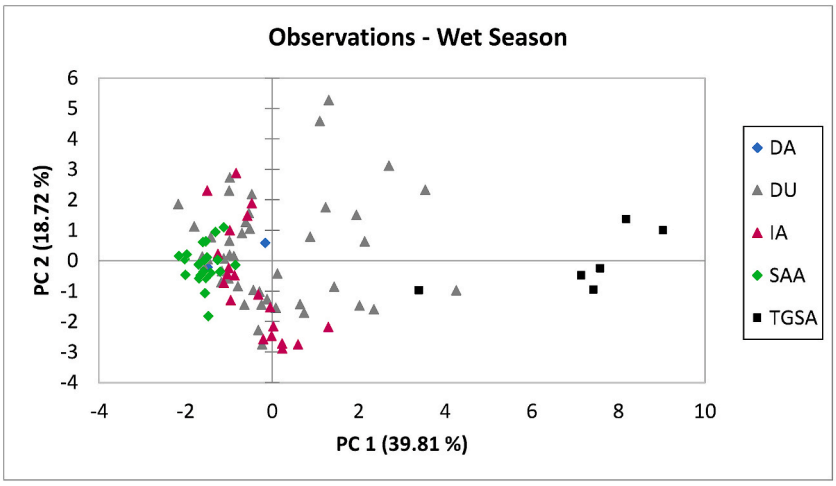
precipitation reactions, during the dry season.

4. Discussion

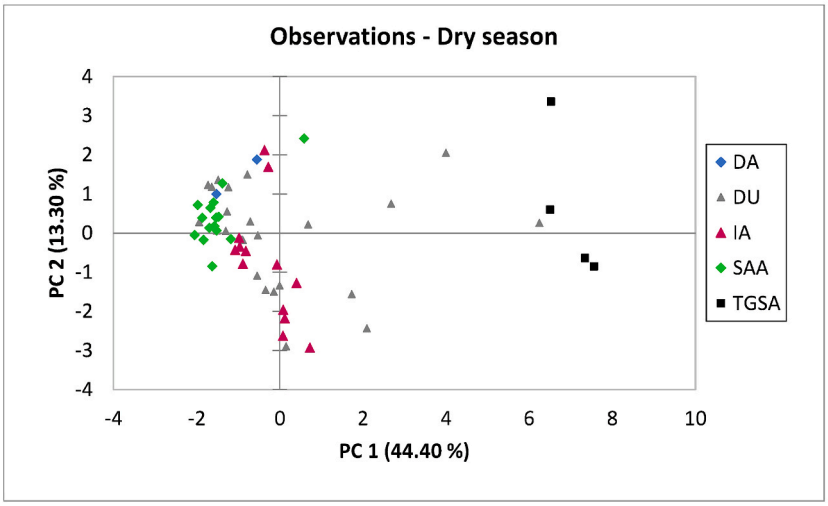
4.1. Natural factors influencing groundwater chemistry

As is common for tropical rivers, the EC values for the Turkwel river are low, but a downstream increase is observed, coupled with an increase in pH, which is likely related to high baseflow contribution to river flow and higher ion contributions relative to surface runoff contributions. Higher turbidity in the town area could reflect inputs of fine sediments from disturbances/agricultural activities along the riverbanks. Subsidiary seasonal/ephemeral streams such as the Kawalase also contribute to higher dissolved ion species content as reflected by the marked increase in Na concentrations east of its confluence with the Turkwel river. The Ca–HCO_3 water facies suggests that the water is derived from a primarily metamorphic-volcanic terrain with plagioclase feldspars being the main source of the Ca ion.

This study has determined that the shallow alluvial aquifer in recent alluvial deposits, the intermediate aquifer in mid-Holocene alluvial deposits, and the deep aquifer in early Holocene alluvial deposits (Fig. 2) are an interlinked system whose chemistry varies with geology, the degree of interaction with the Turkwel River, and the age of the groundwater. It confirms the earlier hypotheses that the Turkwel river replenishes the shallow groundwater of the study area (Hirpa et al., 2018; Olago, 2018). The Turkana grit shallow aquifer, however, represents a separate and distinct sedimentary groundwater source that is found on either side of the river. As is common for shallow alluvial aquifers in arid areas where the river and groundwater facies are similar (Ledesma-Ruiz et al., 2015; Varol and Şekerci, 2018), the Ca–HCO_3



Description	PC 1	PC 2	PC 3
pH	0.348	-0.741	-0.122
EC	0.977	0.170	-0.024
Ca	-0.471	0.721	-0.073
Mg	-0.018	0.794	0.223
Na	0.976	0.081	-0.057
K	0.056	0.714	-0.312
Fe	0.098	0.171	0.413
Mn	-0.314	0.290	-0.240
HCO_3	0.815	0.159	0.149
SO_4	0.907	0.137	-0.098
Cl	0.810	0.177	-0.138
F	0.818	0.003	0.054
NO_3	0.034	0.037	0.816
Eigenvalue	5.175	2.434	1.119
Variability (%)	39.807	18.723	8.611
Cumulative %	39.807	58.530	67.141



Description	PC 1	PC 2	PC 3
pH	0.691	-0.576	0.043
EC	0.946	0.225	0.038
Ca	-0.671	0.582	-0.047
Mg	-0.191	0.545	0.313
Na	0.958	0.171	0.024
K	0.231	0.609	-0.492
Fe	0.143	0.299	0.755
Mn	-0.222	-0.077	0.485
HCO_3	0.844	-0.077	0.105
SO_4	0.749	0.261	-0.145
Cl	0.722	0.359	0.102
F	0.823	-0.110	0.080
NO_3	0.634	0.024	-0.107
Eigenvalue	5.772	1.729	1.212
Variability (%)	44.401	13.298	9.325
Cumulative %	44.401	57.699	67.024

Fig. 8. PC 1 and PC 2 for the shallow alluvial aquifer (SAA), intermediate aquifer (IA), Turkana grit shallow aquifer (TGSA), Deep aquifer (DA), and for the boreholes and handpumps with unknown depth (DU). High positive factor loadings are shaded green; high negative factor loadings are shaded orange. Upper panel – wet season; Lower panel – dry season.

water type was the dominant water facies in the SAA which was similar to that of the Turkwel River. The geology at the source and along the reach of the Turkwel river, which comprises volcanics in the highlands, metamorphics in the midlands, and a mix of metamorphics and volcanics in the lowlands, influence the chemistry of the Turkwel river, and consequently that of the groundwater in the SAA, IA, and DA. East of the confluence of the Turkwel and Kawalase rivers, the higher alkalinity, Na and Fe concentrations in the river, and the associated alluvial aquifer system are related to the dominantly metamorphic source and reach of the Kawalase river. Generally, electrical conductivity is lowest in the SAA, which has a Ca–HCO_3 water type, intermediate in the IA and DA, and highest in the TGSA, which has a Na–HCO_3 – Na–Cl water type – these transitions reflect increasing mineral content of the groundwater.

Seasonal recharge pulses from the Turkwel river strongly influence the aquifer chemistry in the SAA and IA, while direct rainfall recharge has a similar effect on the TGSA. In the DA, however, there are no marked wet-dry season differences in the physico-chemical parameters, suggesting that for this aquifer, recharge occurs over timescales longer than the seasonal cycles, although HCA suggests that there is some interaction between the IA and the Napuu bh. Higher turbidity in the SAA, IA, and TGSA groundwater during the wet season as compared to the dry season relate to the river recharge pulses that convey colloids into the groundwater system; the river itself is visibly loaded with mud and silt during the rainy season. Evaluation of the seasonal variation in the water facies showed that the Na–HCO_3 water type of the groundwater in the transition zone between the recent alluvial deposits and the Holocene alluvial sediments switched to Ca–HCO_3 during the wet season, indicating dilution processes related to Turkwel river recharge. The Mg–HCO_3 water facies occurred as pockets in the SAA and the intermediate aquifer and is related to localised geological formations such as dolomite (Abid et al., 2011; Ansari and Umar, 2019; Liu et al., 2019); and in our case likely reflects the remobilisation of discrete micrite crystals that may have been precipitated in the matrices of the soil and upper layers of the unconfined groundwater (Cf. Johnson and Graham, 2000) and their dissolution and remobilisation during recharge (rainfall) events. The hydrochemical characteristics of the TGSA is typical of a highly mineralised groundwater system suggesting a very long groundwater residence time (Pilla et al., 2006; Tay and Kortatsi, 2008 Joshi et al., 2018), and in addition to rock-water interactions, the relative mineral enrichment in the dry season as compared to the wet season could also be related to evaporation processes (Chowdhury et al., 2018).

Rock-water interactions are also key in evaluating the hydrochemical evolution of groundwater (Okiongbo and Akpofure, 2015; Toran and Saunders, 1999; Yazdizadeh et al., 2019). The existence of Na–HCO_3 water type (subsidiary to Ca–HCO_3 in the SAA and dominant in the TGSA) is an indication of dominant ion exchange processes in the aquifer The complex chemistry of the groundwater of the study was simplified using the HCA where Cluster 1 represents dilute groundwater

(SAA) and Cluster 4 represents highly mineralised groundwater (TGSA). The HCA revealed that two factors influence the groundwater chemistry of the IA in the wet and dry seasons; (1) the proximity to the Turkwel river (Cluster C1) and (2) proximity to the Turkana grits formation (C2 and C3). HCA was also useful in identifying the categories in which the boreholes and handpumps with unknown drilled depth belonged within the SAA, IA, and the TGSA. Of interest is the similarity in groundwater chemistry of the Natir Bh of the DA and that of the SAA while the Napuu Bh has typical characteristics of the IA – the former could likely be related to a strong hydrological recharge pulse at the confluence of the Turkwel and Kawalase rivers during rainy seasons. A unique feature in the TGSA is the Bokotom Hp, where halite dissolution (Abid et al., 2011; Ansari and Umar 2019; Chenini et al., 2010; Zhu et al., 2008) is prominent in both seasons. The principal components analysis revealed that the PC1 in the dry and wet seasons reflects the mineralisation gradient in the aquifers with the TGSA being the most mineralised, and mineral enrichment during the dry season was a common characteristic in all the aquifers. PC2 during both seasons was reflective of ion exchange processes involving Ca, Mg and K primarily in the wet season and strongly pH modulated Ca, Mg reactions, inclusive of dissolution-precipitation reactions, during the dry season.

4.2. Anthropogenic activities influencing groundwater chemistry

Shallow alluvial aquifers are considered highly vulnerable to pollution (Muhammad et al., 2015; Yidana et al., 2010). The concentrations of nitrate and sulphate in the groundwater were used to evaluate the anthropogenic influence on the groundwater quality, with the consideration that microbially mediated reactions within the aquifer can also be major contributors to their concentrations (Lapworth et al., 2017; McMahon, 2001) and there is one handpump where the latter process is dominant. The presence of sulphate in groundwater is due to leaching of dissolved salts and other sulphate-rich minerals from domestic wastes (Jhariya et al., 2018). On the other hand, nitrate in groundwater is due to domestic sewage and agricultural chemicals (Guo et al., 2019; Lathamani et al., 2015; Morán-Ramírez et al., 2016). Natural nitrate concentration in groundwater is generally far below 10 mg-N/l (WHO, 2011); concentrations above this value reflect contributions from human activities (Miljević et al., 2012). The TGSA has non-potable groundwater and is not discussed further in this section.

Although SO_4^{2-} and NO_3^- concentrations were within the guideline values for drinking water in the shallow alluvial, intermediate, and deep aquifers, the concentrations were observed to increase during the wet season except for the DA Napuu bh. Poor sanitation, unregulated waste disposal, and the lack of sewerage facilities (Olago, 2018; Hirpa et al., 2018) pose critical human-induced risks to the LAAS. The geological characteristics and urban setting make the SAA, IA, and DA highly vulnerable to pollution, but it is still generally uncontaminated. With no networked sewerage infrastructure, on-site sanitation (septic tanks or pit latrines) are prevalent, enhancing the threat of direct contamination of the aquifer system, particularly through leakages and flooding. Increased SO_4^{2-} and NO_3^- concentrations in the wet season may also be attributed to upstream farming activities. On-site animal watering contributed to higher NO_3^- concentrations in Natirnalulung Bh. The proposed large-scale irrigation projects (NDMA, 2016; OECD/FAO, 2016; Olago, 2018) upstream of the Lodwar Municipality may lead to high levels of nitrates and sulphates in the SAA, IA, and DA. It has been noted that the drivers of the groundwater problems such as over-exploitation and contamination are often outside the water sector, and thus, the solutions must be based on interventions from several sectors (Baki et al., 2017; Shady et al., 2005; Shen, 2015).

4.3. Aquifer exploitation and management

The shallow alluvial and intermediate aquifers are the main sources of drinking water to an estimated population of 91,766 in 2019 and up to 140,914 people in 2030 living in Lodwar Municipality. This trend in population increase will subsequently lead to an increase in water demand. A study of the Turkwel River Basin that considered linked scenarios of climate change and water demand in the 2030s and 2080s indicates that increased water demand, particularly due to expanded irrigation, along with droughts and climate variability adversely affects (depletes) the river basin's water resource system, including the groundwater resource (Hirpa et al., 2018). The LAAS, characterised in this study as being highly sensitive to natural and anthropogenic factors and pressures, including those in the distant upstream areas of Turkwel River, is, therefore, a strategic resource that needs to be protected from both regional and local perspectives.

The findings of this study revealed that, apart from Fe and Mn in some of the boreholes and handpumps in both seasons, and turbidity during the wet season, the chemical concentrations in the SAA were within the drinking water guidelines (WHO, 2011; KEBS, 2014); these excesses can be managed with relatively inexpensive treatment systems. This study has shown that the TGSA aquifer should be completely avoided as the EC, Na, Cl, F, and NO_3 concentrations in the TGSA exceed the recommended guideline values (WHO, 2011; KEBS, 2014) for drinking water during the wet and dry seasons. Some water sources of the intermediate aquifer during the wet and dry seasons had pH, Na, HCO_3, and F above the recommended guidelines for drinking water (WHO, 2011; KEBS, 2014) in both seasons. High turbidity in some wells of this aquifer may also indicate possible bacterial contamination (Bennett et al., 2000; Khatri and Tyagi, 2014; Lapworth et al., 2017), and microbial content should be investigated. Fluoride is in some cases, only slightly more than the recommended limit for drinking water. Apart from slightly higher Na concentration in the Napuu bh in the wet and dry seasons (not a major concern), the groundwater of the deep aquifer meets the drinking water quality standards.

Evaluation of the groundwater chemistry in these aquifers indicates high vulnerability to both natural and anthropogenic pollution. The current groundwater management approaches depend majorly on the institutional strengths in the individual countries (Shen, 2015) with no major considerations to the varied hydrogeological regimes, domestic, industrial, and agricultural water demands. Based on the current knowledge of the Lodwar aquifers, and the related prevailing threats to the Turkwel basin (Hirpa et al., 2018), strengthening the institutions that oversee or manage the resource, a multi-sectoral approach towards the protection and sustainability of the Turkwel watershed, are required. In addition, effective and regulated aquifer exploitation (Foster and Chilton, 2003; Sanz et al., 2016) will ensure optimum pumping rates aimed at minimizing over-abstraction, managing the seasonal variability of water chemistry, and avoiding mixing of saline and fluoride-rich aquifer zones. Regular groundwater quality monitoring (Kumar et al., 2009; Sanz et al., 2016) will also help to evaluate if pumping rates are affecting the water quality beyond the current established range of expected seasonal water quality variability of the aquifers in the area.

5. Conclusions

The purpose of this investigation was to determine and characterize the hydrogeochemistry of Lodwar Municipality's strategic alluvial aquifer and evaluate the natural and anthropogenic factors influencing its chemistry and quality, providing scientific evidence for sustainable, safe exploitation and management. Integration of statistical approaches and geochemical methods were applied to investigate the groundwater system that is used by the Lodwar Municipality for water supplies. The results revealed heterogeneous aquifer systems with significant temporal and spatial variations in groundwater chemistry. Generally, two distinct shallow aquifers of depth <30 m underlies Lodwar and its environs; the SAA along the Turkwel River, which is the main source of freshwater and the shallow aquifer of the Turkana grit that is highly saline and with fluoride contamination. Localised human activities such

as over-pumping and localised rock-water interactions resulted in alteration of the groundwater chemistry in the area. The use of PCA has enabled the determination of the aquifer processes during the wet season and in the dry season related to complex geological, hydrological and climatic variations. The application of HCA to the groundwater samples led to the classification of the groundwater with unknown drilled depth within the SAA, IA, and the TGSA, where the majority were in the transition zone between the Holocene Sediments and the Turkana Grits formations. The overall groundwater chemistry in the area is subject to seasonal variability and varied geological formations. Most shallow alluvial aquifers are dominated by Ca–HCO_3 water facies comprising freshwater in the region. Investigation of changes in hydrochemical facies indicated that increased pumping activities result in an alteration of Na–HCO_3 water type to Na–Cl, which is unsuitable for drinking. Thus, regulation on abstraction activities in such aquifers in arid areas is key to keeping the groundwater chemistry stable, within the bounds of natural variability. Fluoride contamination is a major problem in many aquifers in arid areas globally, while irrigated agriculture and the use of fertilizers within the Turkwel river basin as a whole has both quantity and quality implications for the LAAS and other groundwater systems in the region. In the face of the water security challenges in arid and semi-arid regions, urban water suppliers should undertake more comprehensive hydrogeological and hydrochemical surveys to assess aquifer sustainability and current and future risks. Besides, careful land management and multi-stakeholder approaches in watershed management are required to ensure that water quality risks to Turkwel River and the LAAS are identified and mitigated. There is a need for further groundwater monitoring to establish short to long-term trends in water quality and quantity to inform on adaptive management of the aquifer system.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gsd.2020.100451.

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