Hydrogeology Journal (2018) 26:2693–2706
https://doi.org/10.1007/s10040-018-1832-0

REPORT

Groundwater age dating and recharge mechanism of Arusha aquifer, northern Tanzania: application of radioisotope and stable isotope techniques

Nyamboge Chacha[1,2] · Karoli N. Njau[1] · George V. Lugomela[3] · Alfred N. N. Muzuka[1]

Received: 18 November 2017 / Accepted: 8 July 2018 / Published online: 27 July 2018

Abstract
The continuous abstraction of groundwater from Arusha aquifers in northern Tanzania has resulted in a decline in water levels and subsequent yield reduction in most production wells. The situation is threatening sustainability of the aquifers and concise knowledge on the existing groundwater challenge is of utmost importance. To gain such knowledge, stable isotopes of hydrogen and oxygen, and radiocarbon dating on dissolved inorganic carbon (DIC), were employed to establish groundwater mean residence time and recharge mechanism. ^{14}C activity of DIC was measured in groundwater samples and corrected using a $\delta^{13}C$ mixing method prior to groundwater age dating. The results indicated that groundwater ranging from 1,400 years BP to modern is being abstracted from deeper aquifers that are under intensive development. This implies that the groundwater system is continuously depleted due to over-pumping, as most of the sampled wells and springs revealed recently recharged groundwater. High ^{14}C activities observed in spring water (98.1 ± 7.9 pMC) correspond with modern groundwater in the study area. The presence of modern groundwater suggests that shallow aquifers are actively recharged and respond positively to seasonal variations.

Keywords Groundwater age · Radioisotopes · Recharge mechanism · Tanzania

Introduction

In the city of Arusha, situated in northern Tanzania, groundwater abstracted through drilled wells and springs is the main source of drinking water supply (GITEC 2011). Most deep wells with large production volume are located in the central part of the study area near the foot of Mt. Meru at an elevation from 1,400 to 1,500 m above sea level (asl) (Ong'or and Long-Cang 2007). According to the Arusha Urban Water Supply and Sanitation Authority (AUWSA) medium-term strategic plan (2015–2020) report, springs contribute 45% of the daily water production, whereas drilled wells and rivers contribute 37 and 18% respectively (AUWSA 2014); however, the proportional contribution from each source varies depending on season of the year. The seasonal variations mainly affect springs and rivers by significant reduction in flows during dry periods but production from wells remains constant (AUWSA 2014). Generally, water production fluctuates seasonally from an average of 35,000 m^3/d (dry season) to 60,000 m^3/d (rainy season), which is significantly low with respect to the current water demand (93,270 m^3/d) in the city (AUWSA 2014).

Despite the lack of reliable information on the extent of groundwater abstraction, there is evidence of groundwater over-pumping in the study area. The decline of water levels (Table 1) and respective yield reduction (Table 2) in wells that have been operational for more than 20 years has been reported (GITEC 2011; Ong'or and Long-Cang 2007).

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s10040-018-1832-0) contains supplementary material, which is available to authorized users.

✉ Nyamboge Chacha
chachan@nm-aist.ac.tz

[1] Department of water, Environmental Science and Engineering, Nelson Mandela African Institution of Science and Technology, P.O. Box 447, Arusha, Tanzania

[2] Ardhi University, P.O. Box 35176, Dar es Salaam, Tanzania

[3] Ministry of Water and Irrigation, P.O. Box 14473, Dar es Salaam, Tanzania

Table 1 Water level trends in the study area (GITEC 2011)

Well details			Water level (year of measurement) (m bgl)				
Location	Well ID	Well depth (m)	GE (1988)	HH (1994)	PBWO (2006)	GITEC (2011)	This work (2016)
Oltulelei	W12	184	36.95	58.90	58.90	–	113.77
Ilboru Sec	W19	105	9.88	17.50	17.50	24.26	–
Ilkloriti	W08	182	13.96	33.80	33.80	–	–
Moivo II	W09	104	2.27	16.60	16.60	27.30	73.43
Mianzini	W17	142	14.75	32.20	32.20	30.54	90.54

GE Gauff Engineers, *HH* Howard Humphreys, *PBWB* Pangani Basin Water Board, bgl below ground level

Additionally, an inventory conducted by Pangani Basin Water Office (PBWO) in 2013 revealed more than 400 drilled wells in the study area, most of them unregistered by the responsible water resources management authority. This suggests that groundwater abstraction in the area is not adequately controlled to meet the needs of present and future use (Kashaigili 2010; Van Camp et al. 2014). However, aquifer storage may be affected by a number of factors other than groundwater over-pumping (Custodio 2002). Natural phenomena such as delayed and transient effects of the aquifer system, earth quakes, tectonic movement and climate change, have been reported in many parts of the world with significant effect in aquifer productivity (Custodio 2002; Gorokhovich 2005; Kitagawa et al. 2006; Kløve et al. 2014; Nigate et al. 2017). Due to the complexity and dynamics of hydrogeological processes, knowledge of a particular aquifer system including recharge mechanisms and age of abstracted groundwater is required to inform the cause and extent of the existing problems. Such a situation leaves a number of questions with respect to sustainability of groundwater utilization in Arusha City for present and future water resources development and for avoidance of likely human impacts (drinking water supply) and ecosystem impacts (such as reduced stream flows and springs drying up and subsequent impacts on aquatic life). The current research was conducted to inform some of the existing problems or fill knowledge gaps in the study area. Among the issues addressed include whether groundwater storage depletion is caused by over-pumping or whether the aquifer system in the study area is not actively recharged.

In order to address some of the experienced groundwater challenges, the study employed the use of isotopic techniques to investigate the groundwater age and recharge mechanism in the study area. Currently, there are a number of tracers used for assessment of groundwater recharge and mean residence time (Chen et al. 2011). These include chlorofluorocarbons (CFCs), tritium/helium ratio ($^{3}H/^{3}He$), krypton-85 (^{85}Kr) and carbon-14 (^{14}C) (Douglas et al. 2007; Hoque and Burgess 2012; Sigstedt et al. 2016). CFCs, $^{3}H/^{3}He$ and ^{85}Kr are mostly used for tracing young groundwater (< 100 years; Mathouchanh and Aeschbach-Hertig 2015; Szabo et al. 1996); however, the current study utilized stable isotopes (hydrogen and oxygen), tritium and ^{14}C to meet the objectives of the current study. The ^{14}C technique uses the decay principle of the activity measured in dissolved inorganic carbon (DIC) to estimate the mean groundwater age of water travelling from the recharge zone to a discharge point along the flow path (Douglas et al. 2007; Hagedorn 2015). These techniques have been undergoing several improvements and are widely used in hydrogeological studies, particularly groundwater recharge

Table 2 Well discharge trends over time in the study area (GITEC 2011)

Well details		Discharge (year of measurement) (m^3/h)					
Location	Well ID	GE (1988)	HH (1994)	PBWO (2006)	WB (2010)	GITEC (2011)	This work (2016)
Oltulelei	W12	264	217.7	164.6	148.3	188.1	182.1
Ilboru Sec	W19	220	186.3	128.1	26.5	136	85.7
Ilkloriti	W08	150	84.5	–	–	52.2	34.6
Sanawari P/S	W10	160	–	–	91	75	75.2
Moivo II	W09	120	120	30.98	38.8	58.2	25.2
Mianzini	W17	80	63.9	48.2	49.4	49.4	33.6

GE Gauff Engineers, *HH* Howard Humphreys, *PBWB* Pangani Basin Water Board, *WB* World Bank

and mean age estimation ranging from young (100–1,000 years BP) to old groundwater (1,000 to millions of years (Bakari et al. 2012a, b; Gleeson et al. 2016; Stewart 2012). Despite wide acceptance and global application of isotope techniques, in Tanzania, they have commonly been applied in geology and marine based sediments studies (Muzuka et al. 2010; Muzuka et al. 2004; Öberg et al. 2013). Conventionally, many groundwater assessment studies have been focusing on quality issues and leaving aside aquifer sustainability in terms of potential recharge and groundwater mean residence time (Ghiglieri et al. 2010, 2012; Malago et al. 2017; Van Camp et al. 2014). Lack of such information is likely to threaten sustainability of aquifers under intensive development (Zongyu et al. 2005); thus, this study aimed at establishing groundwater age and recharge mechanism for sustainable groundwater utilization in Arusha City, using ^{14}C, tritium and stable isotope (^{2}H and ^{18}O) techniques. Isotope composition data have been used for interpretation in conjunction with groundwater physical parameters and some hydrogeological information which were established during the borehole drilling and construction stage.

The study area

Location

The study was conducted in Arusha City and Arusha District, which are located on the southern slopes of Mount Meru in northern Tanzania (Fig. 1). The study area is bordered by the three administrative districts of Monduli, Longido, and Meru. The area covers approximately 282 km^2 and lies between latitudes 3°15′ and 3°30′ south and longitudes 36°34′ and 36°46′ east (Fig. 1). According to the population and housing census, Arusha City and Arusha District in 2012 had a population of about 416,442 and 323,198 inhabitants respectively (NBS 2013).

Climatic characteristics

The area is characterized by tropical climate with two distinct seasons, dry and wet. The rainfall pattern in Arusha, as part of northern Tanzania, is bimodal with short rains from October to December and long rains from March to May (Kijazi and Reason 2009; Zorita and Tilya 2002). The long rains and short rains vary from approximately 110 to 200 mm and 60 to 100 mm respectively (Kabanda and Jury 1999). The total annual rainfall ranges between 500 and 1,200 mm with mean value of about 842 mm (Kaihura et al. 2001). The temperature typically ranges between 13 and 30 °C with an average annual temperature of about 25 °C (Nonga et al. 2009). The coolest month is July, whereas the warmest is February and the relative humidity varies from 55 to 75% (Anderson et al. 2012).

Geological and hydrogeological settings

The geology of the study area is dominated by volcanic materials of varying ages and recently deposited alluvial sediments (Ghiglieri et al. 2008, 2010; Ong'or and Long-Cang 2007; Wilkinson et al. 1986). Mt. Meru is the main center of volcanic activity in the region. The main features of the volcanic eruption in the area include main cone deposits, mantling ash, lahars, lava flows, pyroclastic materials, tuffs, pumice, agglomerates and volcanic rocks such basalts (Nanyaro et al. 1984; Ong'or and Long-Cang 2007). Some of these volcanic features have been depicted in a hydrogeologic map (Fig. 2). Volcanic rocks are mainly lava flows (basaltic to phonolitic and nephelinitic tuff). These materials, if not fractured or weathered, act as aquitards which favor groundwater movement down the slope (Flint et al. 2001; Wilson and Guan 2004). Their properties normally change with time due to physical and chemical reactions such as weathering and subsequent erosion and re-deposition of materials (Arıkan et al. 2007; Nesbitt and Young 1984).

The area is also affected by tectonism leading to the development of fractures and faults which act as conduits to groundwater flows in some areas (Ghiglieri et al. 2010). Figure 2 shows the fault system within the main cone deposits of pyroclastic materials with subordinate nephelinitic and phonolitic lavas. The fault lines are assumed to be avenues of huge groundwater flows that manifest through numerous springs that discharge into Themi River (Fig. 2).

Groundwater recharge mainly takes place at high elevation on the slopes of Mt. Meru along fractured formations as well as through infiltration in valleys or depression zones with medium-to-coarse grain sizes (Ghiglieri et al. 2010). Groundwater potentiality in the fractured formation is also supported by a number of springs around the fault zone (Fig. 2), in the northeastern side of the study area. Spring flows from this zone are very high, particularly after or at the end of long rains for example, according to AUWSA daily discharge measurements, 25,698 m^3/d was abstracted from the springs in May 2015 for public water supply. This amount is only the portion of groundwater discharged from springs along this fault; the remaining water flows into Themi River which is one of the perennial and reliable water sources in the study area. Overall, most rivers and streams originate from springs located on the slopes of Mt. Meru.

Materials and methods

Field work and groundwater sampling

Two categories of water samples were collected from the study area for different analyses. The first category was sampled from wells with depth ranging from 22 to 200 m below

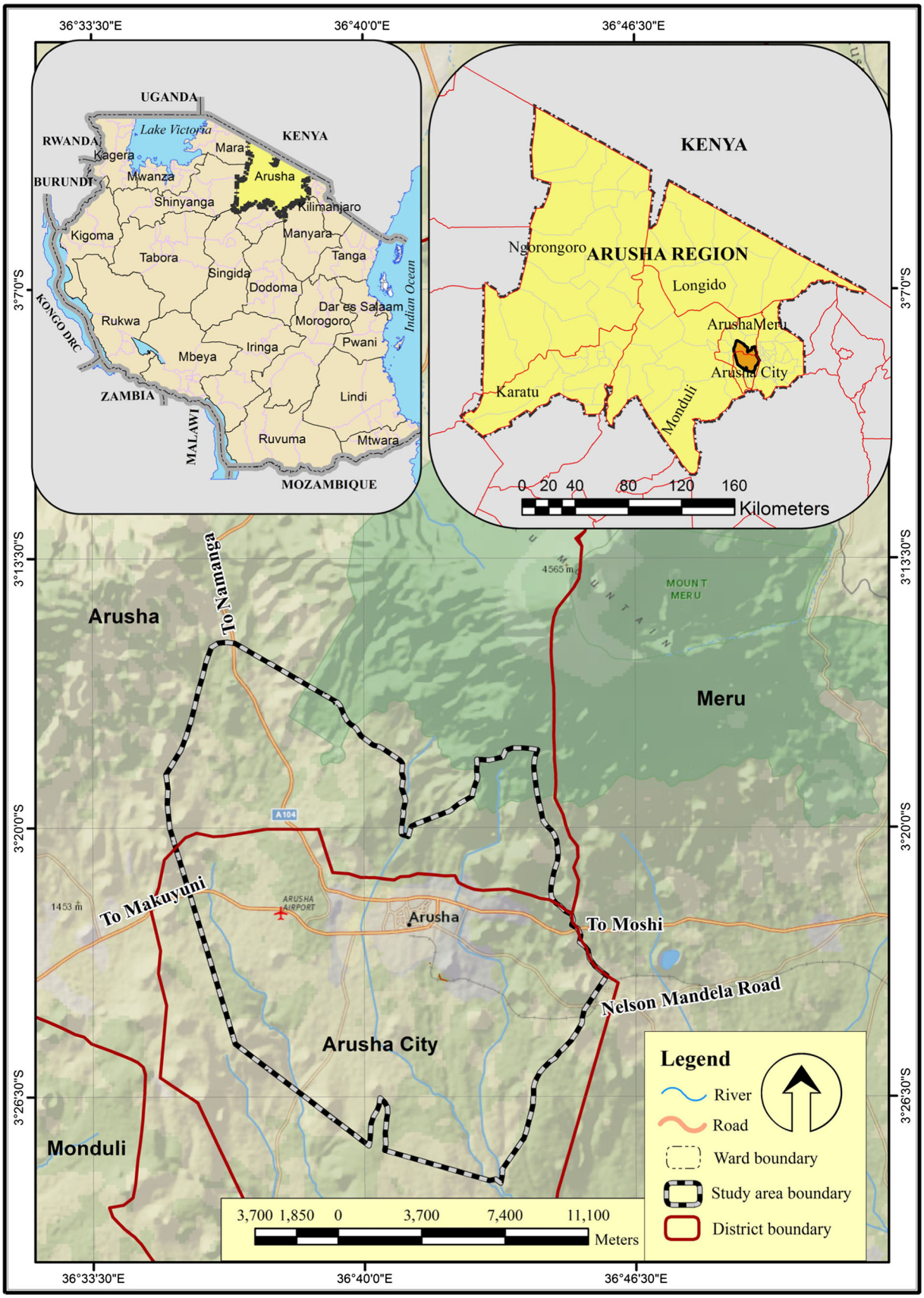

Fig. 1 Location of the study area

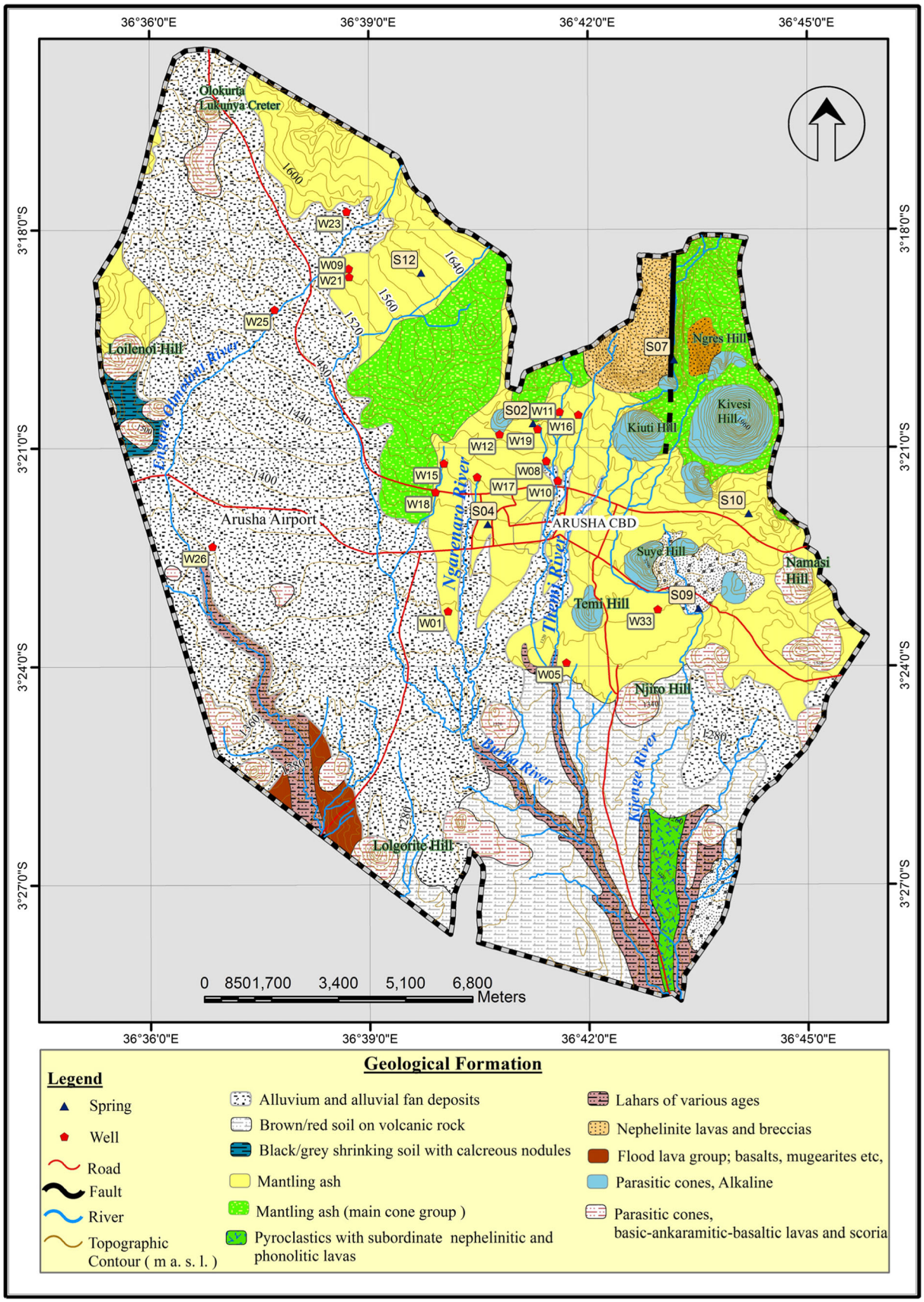

Fig. 2 Hydrogeological map showing location of sampling sites (AA.VV. 1983)

the ground surface. All wells considered in this study were tapping water at different depths depending on screen position and pump location (Figs. S1 and S2 of the electronic supplementary material (ESM)). The second category included samples from springs. Spring water samples were collected close to the point of discharge in order to minimize the effect of atmospheric contamination. Figure 2 shows the locations of sampling sites in the study area. All samples were collected in May 2016, which marked the end of the rainy season in the study area. The rainy season started early April 2016.

Physical parameters such as pH, temperature and electrical conductivity (EC) were measured in situ using a multiparameter meter (model HI 9828, Hanna Instruments) that was calibrated before use. The readings were taken after the instrument has stabilised. Alkalinity as bicarbonate (HCO_3^-) was determined in the laboratory immediately after sampling by an acid-titrimetric method using standard sulfuric acid and bromocresol green indicator for end-point detection (Rice et al. 2012)

A total of 25 samples were collected for both stable isotopes (^{18}O and ^{2}H) and radioisotopes analyses (^{14}C and ^{3}H), while 6 samples were from springs and the rest from boreholes. During field work, standard procedures and techniques for groundwater sampling and preservation detailed by Clark and Fritz (1997) were systematically applied prior to laboratory analyses.

High-density linear polyethylene (HDPE) sampling bottles were used to collect and store samples from taps located near the well heads. All boreholes used in this study were installed with electric submersible pumps which provide positive pressure systems with no atmospheric contact. Almost all samples from boreholes were collected after the pump had ran for at least 6 h and in some cases it was found that pumps had been operating for more than a day nonstop for public water supply. This ensured that the water samples collected represent the aquifer formation being sampled and not stagnant water in the wells. All samples were kept in cool box and subsequently stored in a refrigerator (~4 °C) after field work. Samples for stable isotopes analyses were sent to Stable Isotope Facility at University of California Davis, USA, whereas analyses of radioisotopes were carried out at Environmental Isotope Laboratory, University of Waterloo, Canada.

Laboratory analyses

Stable isotopes ($\delta^{18}O$ and $\delta^{2}H$) measurement

Simultaneous analysis of $\delta^{18}O$ and $\delta^{2}H$ isotopes in groundwater samples were carried out at Los Gatos Research, Inc., Mountain View, California, USA, using a Laser Water Isotope Analyzer V2. Sample isotope ratios were standardized using a range of working standards calibrated against Vienna Standard Mean Ocean Water (VSMOW). The isotope values of hydrogen and oxygen are reported in δ-notation relative to VSMOW (Eq. 1). The δ-values are expressed as parts per thousand or permil (‰). The precision for analyzed groundwater samples was ≤0.3‰ for $\delta^{18}O$ and ≤ 0.8‰ for $\delta^{2}H$. The average and standard deviation for an internal check dispersed throughout the run with known isotope ratio values for the calibrated water is given in Table 3.

$$\delta = \left(\frac{R_{\text{sample}}}{R_{\text{std}}} - 1\right) \times 1,000 \quad (1)$$

where R_{sample} is $^{18}O/^{16}O$ or $^{2}H/^{1}H$ ratio of the water sample and R_{std} is for the standard in VSMOW.

Radioisotopes measurement

Tritium (^{3}H) Tritium was determined by the direct tritium method with a precision of ±8 TU using a PerkinElmer LKB-WALLAC Quantulus 1220–002, USA. The results are expressed as tritium units (TU), whereby 1 TU = 3.221 picocuries(pCi)/L or 1 TU = 0.11919 Bq/L.

Carbon isotopes The determination of $\delta^{13}C$ of dissolved inorganic carbon (DIC) was by mass spectrometry method using a Micromass PRISM-II, UK, 1990. The results are reported in δ values relative to Pee Dee Belemnite (PDB) standard with precision of ±0.2‰. Radiocarbon (^{14}C) activity was determined using accelerator mass spectrometry (National Electrostatics Corporation 1.5SDH-1 Pelletron Accelerator). The results are reported in percent modern carbon (pMC) with precision of ±0.3. According to (Clark and Fritz 1997), the activity of modern carbon represents 95% of the ^{14}C activity in 1950 of the NBS oxalic acid standard equivalent to the activity of the wood grown in 1890 in a fossil CO_2-free environment. For the purpose of age dating, the measured ^{14}C activity values were normalized to values corresponding to $\delta^{13}C$ –25‰ to account for sample background contamination during the process of graphitization.

Groundwater age dating and ^{14}C correction methods

The groundwater age dating by ^{14}C is governed by the principle of radioactive decay given by Eq. (2). The normalized ^{14}C activity was applied together with initial ^{14}C activity of DIC in the recharge area for each sample to estimate the

Table 3 Mean and standard deviation (SD) of water used for calibration

Measurable	$\delta^{2}H$ (‰)	$\delta^{18}O$ (‰)
Known value	−55.65	−8.04
Mean	−54.59	−7.79
n	7.00	7.00
1 SD	0.60	0.15

respective groundwater ages. Groundwater radiocarbon age was expressed as years before present (BP).

$$A = A_o e^{-\lambda t} \quad (2)$$

where t is the mean residence time from recharge to discharge point in years, A is the measured ^{14}C activity of DIC in the sample expressed in pMC, while A_o is the initial ^{14}C activity in the recharge, λ is the decay constant which equals $\ln 2/T_{1/2}$, and $T_{1/2}$ is the ^{14}C half life (5730 years).

Radiocarbon ages were determined from the measured ^{14}C activities. The first approach (Table 5) assumed that no dilution occurs other than natural decay of ^{14}C. This assumption is commonly applied in groundwater age interpretation particularly in basaltic formations characterized by lack of organic carbon which may contain minor amounts of calcite in vesicles. This was reported by Bosworth (1989) as cited (Raiber et al. 2015). The initial ^{14}C activity is assumed to be 100 pMC which gives uncorrected ages; however, this assumption ignores any subsequent geochemical reactions from the point of groundwater recharge and along the flow path. Due to the complexity of the geochemical reactions and unidentified sources of carbon in the aquifer system, it is always necessary to correct radiocarbon ages for addressing any possible dilution effects from both known and uncertain sources (Clark and Fritz 1997). There are several existing age correction techniques applied in different environmental conditions depending on available data. This work applied the statistical correction (Vogel 1970) and $\delta^{13}C$ mixing method (Pearson and Hanshaw 1970) for ^{14}C age correction. The $\delta^{13}C$ mixing method indirectly accounts for carbon chemistry in terms of mixing of different components. Apart from mixing, the process includes an isotope exchange process which is considered as a simple addition of one of the two components, CO_2 or solid carbonate, into the mixing (Fontes and Garnier 1979). Fontes and Garnier (1979) concluded that the Pearson method provides good approximation to the initial ^{14}C activity of the total dissolved carbon with respect to their new approach. The initial activity of the total dissolved carbon is estimated based on the ^{13}C content of each species (Clark and Fritz 1997). The correction factor (q) is given by:

$$q = \frac{\delta^{13}C_{DIC} - \delta^{13}C_{carb}}{\delta^{13}C_{rech} - \delta^{13}C_{carb}} \quad (3)$$

where the following terms are as defined:

$\delta^{13}C_{DIC}$ Measured ^{13}C in groundwater
$\delta^{13}C_{rech}$ $\delta^{13}C$ value for DIC in the infiltrating groundwater
$\delta^{13}C_{carb}$ $\delta^{13}C$ of the calcite being dissolved

In this work, the values of $\delta^{13}C_{rech}$ and $\delta^{13}C_{carb}$ were opted to be −23 and 0‰ respectively (Clark and Fritz 1997). The statistical correction method as described by Vogel uses initial ^{14}C activity of 85% of the modern carbon (Vogel 1970). However, this approach gives ages which are probably too old and does not account for the occurrence of recent waters in the recharge area (Fontes and Garnier 1979).

Results

Stable isotopes and tritium

Results of stable isotopes of hydrogen and oxygen (Table 4) already plotted and parallel to both East African local meteoric water lines (LMWLs) and the global meteoric water line (GMWL; Fig. 3). The GMWL ($\delta^2H = 8.13\delta^{18}O + 10.8$) is based on the refined Craig's line (Clark and Fritz 1997), whereas the LMWL for Dar es Salaam, Tanzania ($\delta^2H = 7.01\delta^{18}O + 6.83$), and for Entebe, Uganda ($\delta^2H = 7.38\delta^{18}O + 10.78$),are reported (Rozanski et al. 1996). The

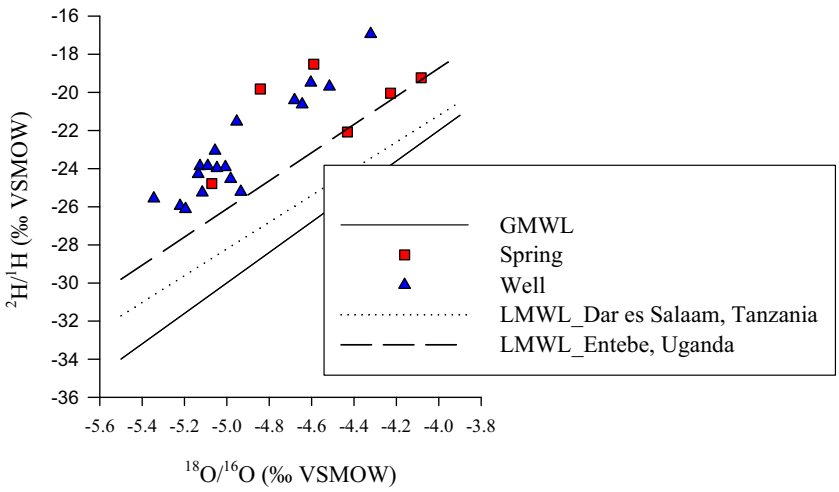

Fig. 3 Stable isotope signatures of groundwater in the study area

best fit line for the analyzed stable isotopes is $\delta^2H = 6.7\delta^{18}O + 9.8$. Water samples from springs had δ^2H values that ranged from −24.8 to −18.5‰ VSMOW, while samples of $\delta^{18}O$ ranged from −5.1 to −4.1‰ VSMOW. In samples from wells, δ^2H varied from −26.1 to −17.0‰, while $\delta^{18}O$ ranged from −5.34 to −4.32‰. The results indicate that spring water is more enriched in ^{18}O and ^{2}H compared to deep groundwater samples. The deuterium excess, $d = \delta^2H - 8\delta^{18}O$ is considered as a measure of the relative proportions of the sample and an index of deviation from the GMWL (Dansgaard 1964). The deuterium excess varied from 13 to 18‰ for the analyzed groundwater samples. All samples were also analyzed for tritium content; however, the results were less than analytical detection limit (6.0 TU) for all samples.

^{14}C and ^{13}C of dissolved inorganic carbon (DIC)

The values of the stable carbon isotope, $\delta^{13}C$, varied from −14.9 to −11.9‰ PDB in spring water, while in well water the values ranged from −15.6 to −8.3‰ PDB. Depending on the prevailing pH condition, $\delta^{13}C$ values are higher as water infiltrates through the soil matrix, signifying enrichment (Clark and Fritz 1997). The values of $\delta^{13}C$ correlated positively with bicarbonate HCO_3^- [$r = 0.597$ ($n = 13$), $p < 0.01$] and EC [$r = 0.926$ ($n = 13$), $p < 0.01$] for well samples; however, groundwater sampled from springs showed weak correlation with respect to HCO_3^- (Fig. 4). The bicarbonate is mainly formed as water dissolves soil carbon dioxide during the infiltration process. Enrichment with $\delta^{13}C$ has been observed more in well water samples than springs (Table 4). Low values of EC (347 ± 179 µS/cm) were observed in springs compared to well waters (540 ± 232 µS/cm) with the exception of spring S04 (671 µS/cm) which is located in the city center.

Measured ^{14}C activities of water samples varied from modern in spring water (87.00–106.20 pMC) to low values (49.49–92.56 pMC) corresponding to great age in well water samples (Table 4). The high values of ^{14}C activity observed in spring water imply modern groundwater. Samples from wells had relatively low values of ^{14}C activity which indicates longer mean residence times. ^{14}C activities correlated positively ($r = 0.49$ ($n = 12$), $p < 0.01$) with altitude in samples collected from wells (Fig. 5). In addition, samples with higher ^{14}C activities were relatively enriched in both ^{2}H and ^{18}O (Fig. 6).

Groundwater age

Radiocarbon dating revealed that groundwater in the study area was recharged in the Quaternary period during late Holocene. The groundwater ages determined based on corrected ^{14}C activity ranged from 1,400 years BP to modern age. All spring water samples fell under modern groundwater; however, samples S10 and S12 were observed to have relatively lower ^{14}C activities compared to others (Table 5), whereas samples from wells of different depths had groundwater ages ranging from 1,400 to 100 years BP. The ^{14}C activities (directly related to estimated groundwater ages) were positively correlated ($r = 0.49$) with altitude but no clear trends were observed with well depth (Fig. 5). Young groundwater was observed in most wells located at high altitude and vice versa.

Discussion

Moisture source

The stable isotope results gave a regression line with a slope of 6.7, which is close to but less than the one established by Rozanski et al. (1993) for the GMWL, i.e., 8.13 (Fig. 3;

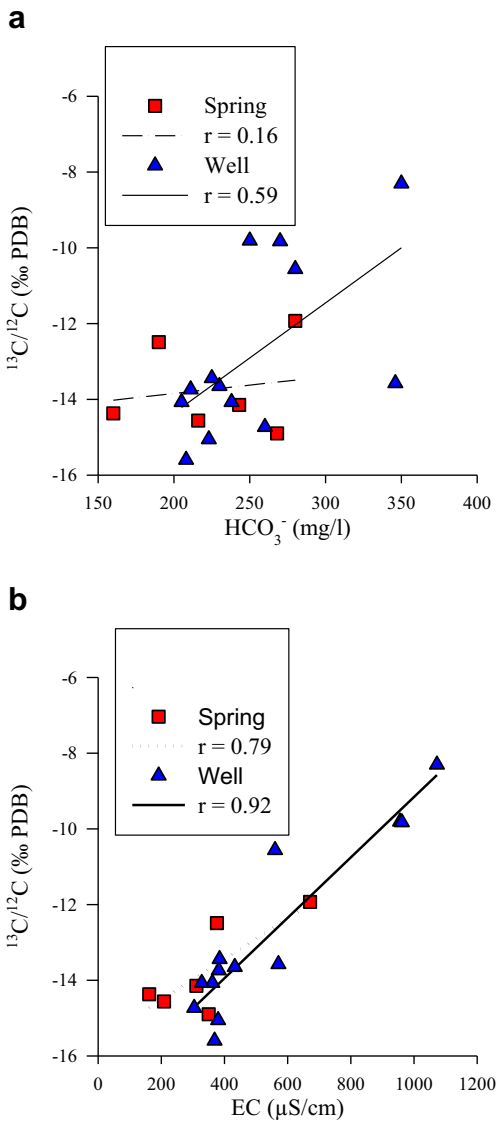

Fig. 4 Scatter plot for $\delta^{13}C$ with **a** bicarbonate and **b** electrical conductivity in water samples

Table 4 Physical-chemical and isotopic characteristics of groundwater in the study area

Location name	SID	Depth	Pump Posit.	Altitude	EC	HCO_3^-	pH	δ^2H	$\delta^{18}O$	d-excess	$\delta^{13}C$	^{14}C		^3H	
		(m)	(m bgl)	(m asl)	(μS/cm)	(mg/L)		(‰ VSMOW)	(‰ VSMOW)	‰ VSMOW	± 0.2‰ (PDB)	(pMC)	1σ error	±8.0 (TU)	1σ error
Rainwater	–	–	–	–	21.3	4	6.2	20.2	−0.10	20.99	–	–	–	<6.0	1.76
Ilboru Sec	S02	–	–	1,479	311	243	7.03	−19.2	−4.1	13.42	−14.1	106.20	–	<6.0	1.73
Engarendolu	S04	–	–	1,406	671	280	6.56	−20.0	−4.2	13.77	−11.9	101.80	–	<6.0	1.68
Masama Kati	S07	–	–	1,582	162	160	7.83	−22.1	−4.4	13.36	−14.4	100.71	–	<6.0	1.73
Machare	S09	–	–	1,286	350	268	6.42	−18.5	−4.6	18.19	−14.9	103.60	–	<6.0	1.74
Baraa	S10	–	–	1,429	209	216	6.76	−19.8	−4.84	18.91	−14.56	87.40	0.44	<6.0	1.72
Njoro	S12	–	–	1,601	376	190	7.67	−24.8	−5.07	15.78	−12.49	89.04	0.31	<6.0	1.71
Sombetini Sec	W01	100	–	1,348	601	188	7.18	−23.9	−5.01	16.13	–	–	–	–	–
Lemara P/S	W05	22.5	–	1,322	640	270	6.59	−19.7	−4.52	16.42	–	–	–	–	–
Ilkloriti	W08	68	–	1,463	362	238	7.50	−21.5	−4.95	18.09	−14.07	61.36	0.24	<6.0	1.68
Moivo II	W09	103.5	85	1,556	369	208	7.89	−19.5	−4.60	17.33	−15.60	70.95	0.25	<6.0	1.67
Sanawari P/S	W10	142	125	1,433	380	223	7.94	−20.4	−4.68	17.02	−15.06	61.73	0.27	<6.0	1.69
Lvani Bondeni	W11	63	–	1,511	328	205	7.71	−23.9	−5.13	17.14	−14.08	61.87	0.26	<6.0	1.69
Oltulelei	W12	183.5	157	1,509	382	211	7.12	−25.6	−5.34	17.19	−13.74	82.53	0.31	<6.0	1.79
Ilkiurei	W13	100	–	1,435	494	215	7.84	−24.3	−5.14	16.79	–	–	–	–	–
Kiranyi	W15	189	–	1,431	468	254	7.37	−25.3	−5.12	15.67	–	–	–	–	–
Lorovani No. 4	W16	182.5	172	1,510	304	260	7.60	−20.6	−4.64	16.52	−14.73	68.51	0.31	<6.0	1.71
Mianzini	W17	141.5	121	1,452	433	230	8.27	−24.0	−5.05	16.40	−13.65	66.58	0.43	<6.0	1.73
Sakina	W18	91.4	–	1,412	456	210	7.56	−26.0	−5.22	15.81	–	–	–	–	–
Iliboru Sec	W19	105	102	1,501	385	225	7.95	−23.9	−5.09	16.86	−13.44	49.49	0.25	<6.0	1.75
Moilo	W21	65	62	1,560	560	280	7.98	−26.1	−5.19	15.43	−10.56	79.05	0.27	<6.0	1.65
Missiori	W23	–	–	1,589	956	250	7.54	−25.2	−4.93	14.25	−9.81	92.56	0.31	<6.0	1.73
Mnadani No. 3	W25	130	–	1,488	962	270	8.43	−24.5	−4.98	15.31	−9.83	89.75	0.23	<6.0	1.77
Magereza	W26	134	–	1,371	1073	350	7.40	−23.1	−5.06	17.38	−8.30	64.20	0.25	<6.0	1.74
Banana No. 5	W33	110	87	1,353	571	346	6.85	−17.0	−4.32	17.62	−13.57	107.00	–	<6.0	1.69

SID sample ID *S* spring, *W* well, *bgl* below ground level, *asl* above sea level, *EC* electrical conductivity, *d-excess* deuterium excess, *VSMOW* Vienna Standard Mean Ocean Water, *PDB* Pee Dee Belemnite, *pMC* percent modern carbon, *BP* before present, *RC* radio carbon

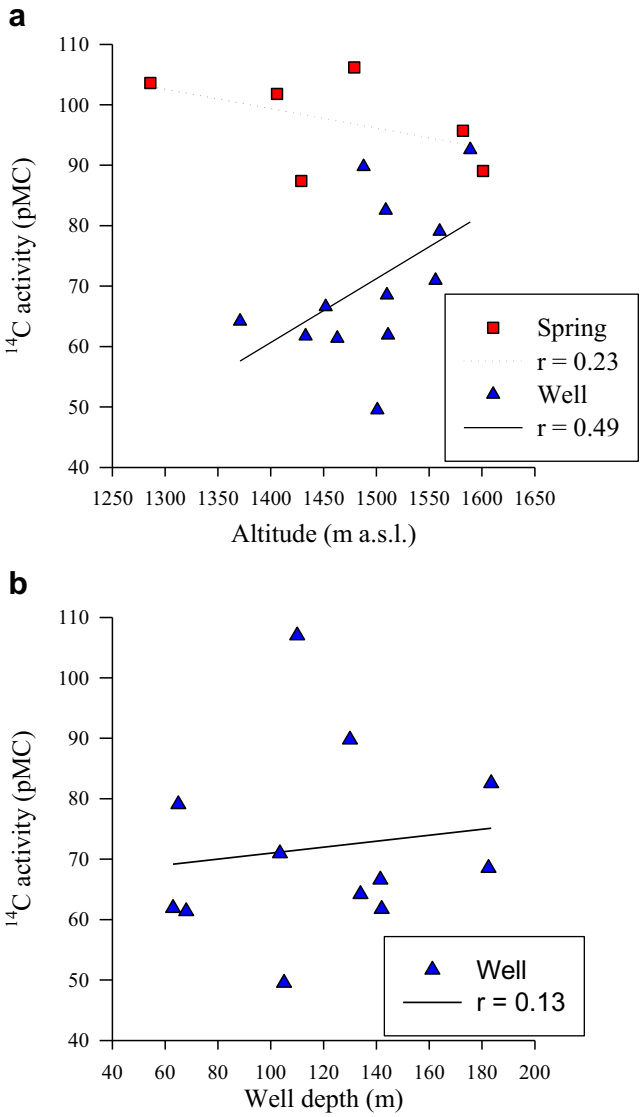

Fig. 5 Scatter plot for ^{14}C activity associated with **a** altitude and **b** well depth

Clark and Fritz 1997) and the East African LMWL for Tanzania and Uganda with slope values of 7.01 and 7.38 respectively. Such a value indicates minimum or limited evaporation of infiltrated rain water during the recharge period in the study area. These findings are also supported by high deuterium excess values recorded by most groundwater samples ranging from 13 to 18‰ VSMOW (Table 4). Similar results were reported in a study conducted by Ghiglieri et al. (2012) at the North Eastern part of Mt. Meru where the values of deuterium excess varied from 10 to 17‰ VSMOW. Generally, at global scale the deuterium excess values range from −2 to about 10–15‰ VSMOW (Froehlich et al. 2001) depending on weather conditions. Moreover, other work reported in the literature shows that warm and dry conditions enhance evaporation, which leads to low or even negative deuterium excess values (Katsuyama et al. 2011, 2015; ; Steen-Larsen et al. 2014). High deuterium values observed in the current study indicate dominance at low temperature and low humidity during groundwater recharge (Plummer et al. 2012).

Groundwater recharge

High ^{14}C activities observed in spring water (98.1 ± 7.9 pMC) correspond with recently recharged groundwater in the study area (Fig. 6). The results indicate that the shallow aquifer is actively recharged and responds to seasonal variations. This is supported by spring flows (Fig. 7) whereby high flows are experienced during or immediate after the rainy season and vice versa during dry conditions. The spatial distribution of ^{14}C activities shows weak correlation ($r = 0.49$) with altitude (Fig. 5). The weak correlation may be due to groundwater mixing from different layers probably recharged at different times. High ^{14}C activity values were observed from wells

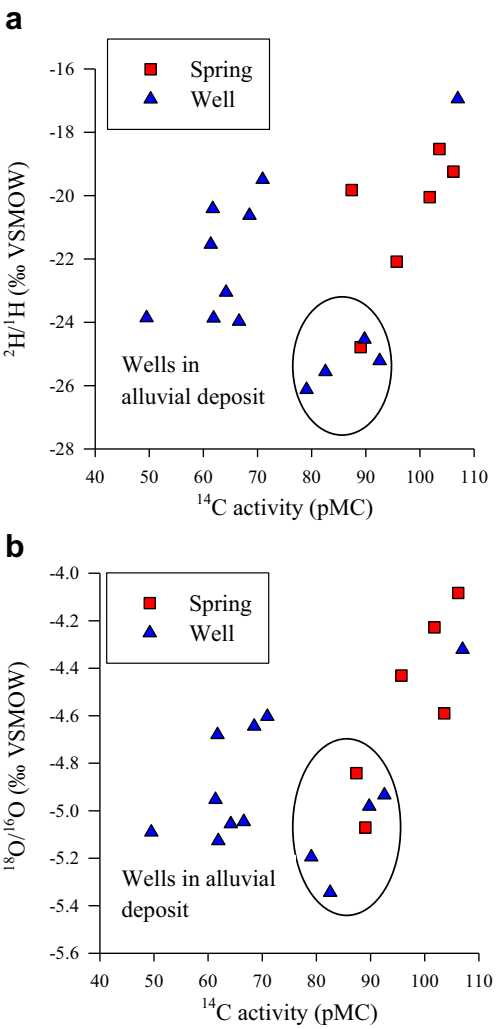

Fig. 6 Relationship between stable isotopes and ^{14}C activity in water samples: **a** hydrogen, and **b** oxygen isotopes. The wells inside the *ellipse shape* are located in alluvial deposits

Table 5 Groundwater ^{14}C ages rounded to the nearest 10^2 years

Location name	SID	^{14}C (pMC)	Uncorrected age	Corrected age	
				Vogel model (1970)	Pearson model (1970)
Ilboru Sec	S02	106.2	Modern	Modern	Modern
Engarendolu	S04	101.8	Modern	Modern	Modern
Masama Kati	S07	100.7	Modern	Modern	Modern
Machare	S09	103.6	Modern	Modern	Modern
Baraa	S10	87.4	1100	Modern	Modern
Njoro	S12	89.0	900	Modern	Modern
Ilkloriti	W08	61.4	4000	2700	300
Moivo II	W09	70.9	2800	1500	Modern
Sanawari P/S	W10	61.7	3900	2600	500
Lorovani Bondeni	W11	61.9	3900	2600	100
Oltulelei	W12	82.5	1500	200	Modern
Lorovani No. 4	W16	68.5	3000	1800	Modern
Mianzini	W17	66.6	3200	2000	Modern
Ilboru Sec	W19	49.5	5700	4500	1400
Moilo	W21	79.0	1900	600	Modern
Missiori	W23	92.6	600	Modern	Modern
Mnadani No. 3	W25	89.7	900	Modern	Modern
Magereza	W26	64.2	3600	2300	Modern
Banana No. 5	W33	107.0	Modern	Modern	Modern

SID sample ID

located at high altitudes, the area which receives more rainfall compared to low altitudes in the southern slopes of Mt. Meru. This suggests that groundwater recharge is actively taking place in areas of high altitude on the slopes of the Mountain; however, no clear trends were established between ^{14}C activity and well depth (Fig. 5) probably indicating that most deep wells are tapping water from the same aquifer but at different depth. Additionally, spring waters are relatively more enriched with respect to hydrogen and oxygen isotopes (Table 4). This implies a higher fractionation effect due to evaporation in shallow groundwater than in deep wells; however, the difference in stable isotopic signatures is somehow narrow which implies that the recharge of both shallow and deep groundwater took place under similar climatic conditions (Hoque and Burgess 2012).

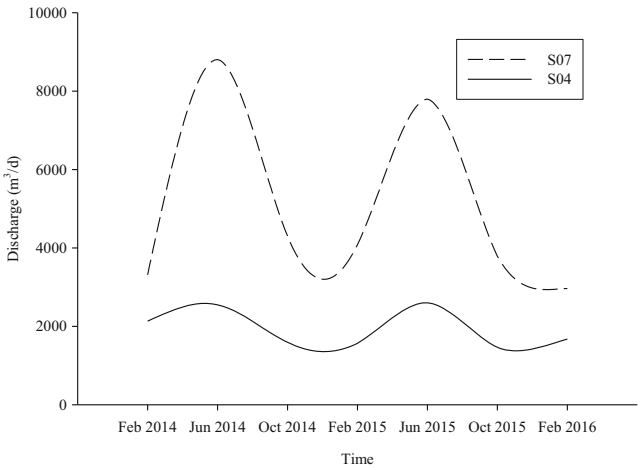

Fig. 7 Seasonal variations of spring flows (S04 and S07) characterized by modern groundwater. Source: The data were compiled from daily flow measurements conducted by Arusha Urban Water Supply and Sanitation Authority. The flow is measured by means of a broad-crested weir with a rectangular control station

Apart from ^{14}C dating, recent groundwater in springs was also evidenced by seasonal variations of spring-flow data established for two springs (S04 and S07) from 2014 to 2016 (Fig. 7). The flows respond positively during the rainy season by increasing significantly and vice versa during dry months. This indicates that protection of these springs is of utmost importance otherwise the recharge cycle will be interfered by rapid urbanization and subsequently drying up or decrease of discharges; nevertheless, the springs S10 and S12 recorded relatively lower values of ^{14}C activities, i.e., 87.4 and 89 pMC respectively. These activities probably indicate that the two springs originate from stable aquifers which do not respond easily to recharge from local precipitation.

Tritium results indicated low concentrations in all samples (<6.0 TU); however, the detection limit (6 TU) of the method used was not able to delineate exactly the amount in each sample which is expected to be low. In a similar study conducted on the northeastern Mt. Meru slope (Ghiglieri et al. 2012), the

maximum and mean values of 2.6 and 1.42 TU respectively were recorded in groundwater samples. The study also indicated tritium content of 2.8 TU in a rainwater sample. The low tritium content from both the previous and current studies suggest that groundwater in the study area is recently recharged.

Groundwater exploitation

The estimated uncorrected groundwater ^{14}C ages for investigated wells ranged from 5,700 to about 600 years BP. Based on the Pearson corrected ^{14}C ages (Table 5), only four wells (W08, W10, W11 and W19) revealed old groundwater (1,400 to 100 years). In terms of geological time scale, the ages seem to be very young; however, it is quite a long period of time for the case of continuous groundwater exploitation and its respective replenishment through vertical recharge from local precipitation. The rest of the sampled wells have modern groundwater, which suggests that the aquifer is actively recharged. The persisting water-level decline (Table 1) is probably a result of an over-pumping practice as the groundwater development is not adequately controlled in the study area. Nevertheless, groundwater ages have been measured and reported worldwide ranging from months to millions of years (Sturchio et al. 2004). Examples include (Bretzler et al. 2011) who reported groundwater radiocarbon age in the main Ethiopian rift systems ranging from 800 to 5,000 years BP at 80 to 260 m depths. In southeast Tanzania (Bakari et al. 2012a) reported ^{14}C age of groundwater was found to be ranging from 13,000 years BP in deep confined aquifers to 1,300 years BP in shallow unconfined aquifers. Based on the current and previous studies, most groundwaters in the Rift valley systems were recharged in late Pleistocene and Holocene in the Quaternary period.

The age of groundwater is mainly affected by a number of factors, including aquifer type and geology of the area (Bretzler et al. 2011; Sukhija et al. 1996; Wassenaar et al. 1991). In the current study, young and modern groundwater (high ^{14}C activity values) were observed in wells located at high altitude on the slopes of Mt. Meru, which is the potential recharge zone of the study area (Ong'or and Long-Cang 2007). Other wells observed to have young water are located in areas dominated by alluvial deposits in the northwest (Figs. 2 and 6). The oldest groundwater (1,400 years BP) was observed in a well located at low altitude (W19) in the central part of the study area. This zone is mainly dominated by the basalts formation, ranging from slightly weathered to fresh rocks (Fig. S1 of the ESM). Some of these wells are tapping water from different geological layers because of well-screen positions (Figs S1 and S2 of the ESM). The position of screens at different depths within a single well could mean that the samples collected represented mixed groundwater, i.e., young and old waters together. The mixed groundwater components could only be identified by applying a combination of tracers suitable for dating young groundwater (less than 50 years) such as $^{3}H/^{3}He$ or ^{85}Kr (Corcho Alvarado et al. 2007; Mazor 1993; Sültenfuβ et al. 2011). The use of ^{14}C tracer facilitated only identification of groundwater component with age greater than 100 years, whereas other components below this limit were categorized under modern groundwater. Generally, all samples considered in this research represent groundwater recharged in late Holocene.

Decrease in water levels and subsequent decline in well yields in the research area have been reported (Ong'or and Long-Cang 2007). This is in line with estimated groundwater ages of up to 1,400 years BP, as such a long period of time is required to replenish the continuously abstracted groundwater through production wells. Additionally, potential groundwater recharge due to local precipitation is expected to be reduced because most production wells are located within built-up residential areas and more development is still taking place, expanding towards potential recharge areas. The development is likely to be interfering with groundwater recharge mechanisms, particularly the infiltration rate of precipitation (Han et al. 2017; Rose and Peters 2001; Zomlot et al. 2017). Based on estimated ^{14}C ages, the aquifer storage depletion in the study area is a result of groundwater over-pumping; however, future investigation on other factors likely to affect recharge mechanisms need to be undertaken. These may include effects due to climate variability, earthquakes and tectonic movement, as the region is also affected by these natural phenomena.

Conclusions

The use of carbon-14 and stable isotope techniques for groundwater investigations has revealed abstraction of relatively old groundwater from Arusha aquifers. Groundwater ages estimated in the study area ranged from 1,400 to 100 years BP; a long period of time like this is required to replenish the continuously abstracted groundwater through production wells. Generally, all groundwaters considered in this study were recharged in the late Holocene; however, no clear trends were established between ^{14}C activity and well depth, probably indicating that most wells are tapping water from the same aquifer but at different depths or layers depending on screen positions. The oldest groundwater (1,400 years BP) was observed in a well located at low altitude in the central part of the study area. This zone is mainly dominated by basalts formation, ranging from slightly weathered to fresh rocks.

The ^{14}C results revealed young and modern groundwater in samples collected from shallow aquifers i.e., spring water and wells located in areas dominated by alluvial deposits at high altitudes. The presence of modern groundwater suggests that shallow aquifers are actively recharged and respond positively to seasonal variations. Additionally, spring flow data showed positive response during the rainy season by increasing flows significantly and vice versa during dry months, indicating that water sources including recharge zones in the study area require a

protection strategy to avoid drying up impact as well as decrease of discharge. Potential groundwater recharge due to local precipitation is expected to be reduced because most production wells and springs are located within built-up residential areas and more development is still taking place, expanding towards the recharge areas. The development is likely to be interfering with groundwater recharge mechanisms, particularly the infiltration rate of precipitation. Due to continuous pumping of groundwater for public water supply in the study area and high mean residence times, as revealed by ^{14}C results, the existing groundwater abstraction rate in the study area will not sustain the future demand. However, future investigation on other factors likely to affect recharge mechanisms needs to be undertaken. These may include effects due to climate variability, earthquakes and tectonic movement, as the region is also affected by these natural phenomena.

Acknowledgements The authors appreciate the technical support offered by Arusha Urban Water Supply and Sanitation Authority (AUWSA) during fieldwork (sample collection). We also extend our sincere gratitude to the laboratory scientists from the Water and Environmental Science and Engineering Laboratory at the Nelson Mandela African Institution of Science and Technology, and Ardhi University, particularly the Department of Environmental Engineering, for their technical support during chemical analyses of water samples.

Funding This work was supported by the Government of Tanzania through the Commission for Science and Technology (COSTECH).

Compliance with ethical standards

Conflicts of interest None.

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