

Ground Water/Surface Water Interactions in Lake Naivasha, Kenya, Using $\delta^{18}\text{O}$, δD , and $^3\text{H}/^3\text{He}$ Age-Dating

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Abstract

We have analyzed a series of ground water samples from the Lake Naivasha region, Kenya, for their helium isotopic composition. Lake Naivasha is unique among the East Africa Rift Valley lakes in that it is fresh. It has long been thought that the low salinity of this lake is due, in part, to rapid water loss from the lake into the local ground water system. Our results show that the Olkaria geothermal waters, south of the lake, are devoid of tritium and, thus, are more than 50 years old. An important implication of these results is that even if Olkaria geothermal reservoir water originated from Lake Naivasha, it has been underground for a long time, (>50 years) and is not derived from present-day Lake Naivasha water. This flow time is of the same order of magnitude as conservative major solutes, such as chloride, as determined through residence time calculations. On the north side of Lake Naivasha, deep wells (91 m) have water ~ 20 years old. Water from these wells has stable isotopic values resembling those of nearby rivers, and high-elevation eastern Rift water. This indicates that this water recharges from rains from high eastern Rift Valley escarpments. Many of the shallow wells on the south side of the lake have $^3\text{H}/^3\text{He}$ ages between four and 17 years. The young ages and the $\delta^{18}\text{O}$ -enriched signature of the water from these wells indicate that they are recharged by a mixture of water from the lake, Rift flanks, and water from deep pumping wells that is recharged during irrigation. Water mixing ratio calculations using $\delta^{18}\text{O}$ and δD isotopes show that about 50% to 70% of the southern ground water system is derived from the lake, while the Olkaria geothermal reservoir water shows that 40% to 50% of this water is originally lake water. Calculated mean recharge rates range from 0.10 to 1.59 m/yr with a mean of 0.52 ± 0.40 m/yr. Estimated horizontal velocity from $^3\text{H}/^3\text{He}$ age dating between Lake Naivasha and a well about 3 km to the south is 75 m/yr, giving average horizontal hydraulic conductivity of 6 m/day.

Introduction

The role of ground water input and output from lakes has intrigued hydrologists for many years, in part, because it is an extremely difficult flux to determine (Winter 1981). Yet from a water management point of view, this understanding is imperative, particularly in closed-basin systems (Isiorho et al. 1996). The quantification of ground water/lake interactions has been done successfully, particularly in relatively small lakes, where both long-term chemical and hydrological data exist (Krabbenhoft et al. 1990, 1994; Katz et al. 1995). These two studies were conducted on lakes with surface areas of 0.81 km² and 0.12 km², respectively. As the size of the lake increases, accurate ground water flux determinations become even more difficult. In this paper we attempt to document the water flux moving out of Lake Naivasha, Kenya, into the local ground water system. Although attempts have been made to establish these water balances through geochemical means in the past (Gaudet and Melack 1981; Ojiambo and Lyons 1996), our effort presented here represents the first attempt at age-dating the ground

water in the basin. These results have important implications for the agricultural activity and its growing water usage to the south, the health of the lake ecosystem, and the long-term recharge potential to the Olkaria Geothermal plant, a major electricity-producing enterprise in Kenya.

Study Area

The study area is on the floor of the Central Rift Valley of Kenya at an elevation of 1886 m above sea level (masl) (Figure 1). Lake Naivasha itself has an average area and depth of 190 km² and 4.7 m, respectively (Ase et al. 1986; Ojiambo 1992). Because of its shallow nature, the lake area varies in size over time (Ojiambo and Lyons 1996). The highlands surrounding the lake intercept primarily monsoonal rainfall, with the average annual (1951–1980) precipitation being 68 cm, and annual evaporation being 186.5 cm (MacIntyre and Melack 1982; Ase et al. 1986; Verschuren 1999). The lake has two perennial and one ephemeral rivers flowing into it from the north but no surface outflow. The Olkaria geothermal field lies about 5 km south of the lake (Figure 1). The area around the lake shores is covered by Recent lacustrine sediments (Thompson and Dodson 1963; Clarke et al. 1990). Farther south, toward Olkaria, surface geology consists of late Pleistocene to Recent volcanic formations, mainly the Olkaria cementite lava flows, and pyroclastics intercalated with their sediment derivatives (Thompson and Dodson 1963; Clarke et al. 1990). These formations are intersected, especially to the southwest, by younger

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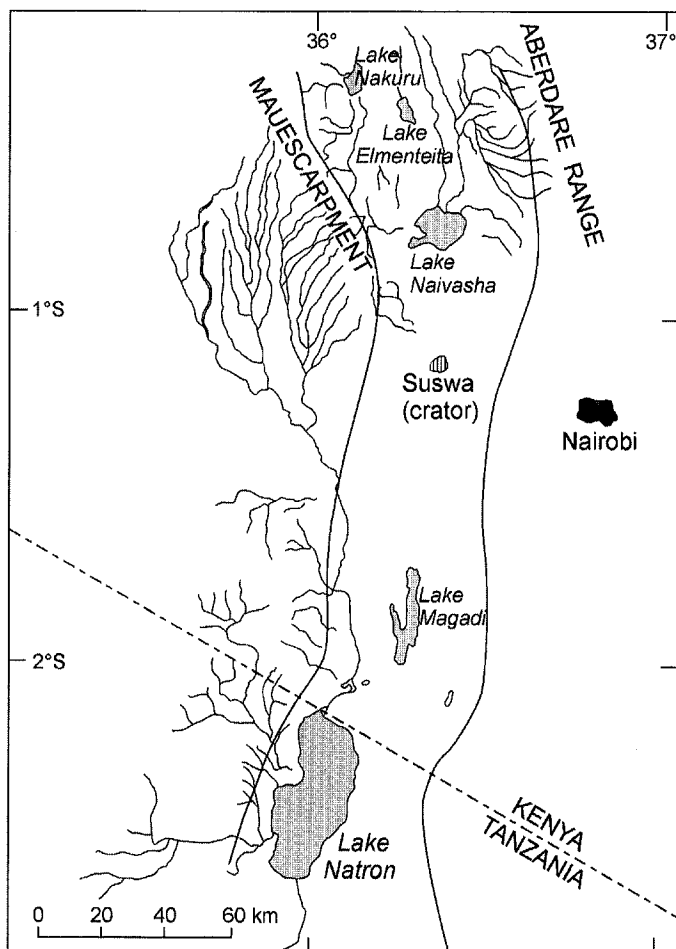


Figure 1. Location map of Lake Naivasha showing inflow rivers from the north. The two dashed lines are the approximate locations of the east and west scarps of the Rift Valley. After Jones et al. (1977) as modified by Ojiambo and Lyons (1996).

faults and fractures that may act as ground water conduits (McCann 1972, 1974; Clarke et al. 1990; Ojiambo 1992). The regional ground water flow is generally from the flanks of the Rift Valley toward the Rift floor, then southward into and out of the lake (McCann 1972, 1974; Clarke, et al. 1990, Ojiambo 1992). The sub-surface outflow from Lake Naivasha originates from the southern shores of the lake, and then flows southerly and southwesterly toward Olkaria, as deduced from piezometric surfaces (Ojiambo 1992). Wells near the Lake Naivasha shore yield water from lacustrine deposit aquifers and usually have higher discharge yields (200 to more than 2000 m³/day) and higher transmissivities compared to those away from the lake (less than 100 m³/day) (McCann 1974; Ojiambo 1992). Wells away from the lake have aquifers along weathered contacts between different lithological units (old land surfaces) or in fractured volcanic rocks and, generally, have lower yields than those near the lake. Most of the production in the Olkaria geothermal reservoir is from fractured trachytes and basalts, as well as contacts between these lavas and pyroclastics (Ewbank Preece Ltd. 1989; Ojiambo 1992).

Tritium, helium-3, deuterium, and oxygen-18 concentrations of the waters were analyzed as part of a research study on the ground water flow system around the lake. One of the curious aspects of Lake Naivasha is that it has low TDS, compared to other lakes in the East Africa Rift system. Ojiambo and Lyons (1996) determined the TDS of the lake to be 336 mg L⁻¹, with Cl⁻ residence times, or Cl⁻ ages in the lake, of only ~ five years. This compares to lake salinities of ~ 2800 mg L⁻¹ for Lake Elementaita to the north (Mwaura 1999) and > 300g kg⁻¹ in Lake Magadi to the south (Jones et al. 1977). Although numerous investigators have speculated at the quantitative importance of ground water inflow and outflow on Lake Naivasha's water budget (Gaudet and Melack 1981; Ojiambo and Lyons 1996), the lack of ground water age dates and flow velocities have limited the overall understanding of the hydrology of the lake and its watershed. Because of the economic impor-

Table 1
Noble Gases and Interpretations of Vertical Velocities and Recharge Rates

Location	Date Sampled	Elevation (m)	R/R _a	⁴ He ucc/kg	N ₂ cc/kg	Ne ucc/kg	³ He TU	³ He* TU	Age a (yr)	Age b (yr)	NO ₃ mgL ⁻¹	Depth Below Water Level (m)
C3677	7/17/94	1899	1.007	65.5	14.32	216	0.4	0.7	18.3	11.7	3.83	57.6
C3366	7/16/94	1895	0.995	70.4	16.1	190	0.2	0.3	15.1	8.9	3.28	52.4
C3675	7/30/94	1889	1.099	83.3	16.69	221	2	5.2	23	13	3.3	45.1
C562	7/16/94	1900	1.13	120.5	13.38	396	1.6	9.6	34.6	17.5	0.03	28.1
C567	7/19/94	1900	1.244	56.4	9.4	165	0.3	8.1	>50	>50	0.33	51.4
C210	7/16/94	1900	0.97	36.1	7.89	187	1.7	-0.4	<5	<5	0.33	51.4
C7829	7/16/94	1895	1.078	43.7	6.63	198	5.2	2.2	4.4	5.1	0.42	19.3
C4397	3/16/94	1900	0.908	37.5	10.02	99	4	-1.7	0.3	<5	0.07	15.1
C579	7/24/94	1905	1.029	35.7	9.56	170	3	0.8	1.2	4.2	0.02	7
LKI-001	3/18/94	1883	0.99	34.5	6.5	139	2.6	0	41.2	0.4	0.6	0.5
LK-002	3/18/94	1883	0.99	32.7	6.41	134	3.1	0.2	>40*	1.8	9.73	0.5
C2660	7/15/94	1901	1.02	99.8	18.86	291	0.2	1.8	25	25	0.34	8
C3767	3/11/94	1912	2.49	60.1	7.65	156	<0.2	50.4	>40*	>40		36.9
C4366	4/7/95	1893	1.47	28.4	10.3	104	3.4	7.6		>40	0.44	25.2
C6300	4/22/95	1957	1.803	63.9	11	174	0.4	29.1		>40		19.9
OW-101	3/8/94	1990	1.421	5.9	9.05	18	<0.2	1.4				
OW-728	3/10/94						0.3					
OW-725	3/10/94						<0.2					
OW-2	3/10/94						0.1					
OW-26	3/11/94						0.9					
C2071	7/17/94	1900			9.87		3.7					5.3

^aCalculated assuming excess gas solubility due to bubble entrapment during recharge.

^bCalculated assuming mean air temperature of 24°C and ⁴He solubility @ 2000 m. Age is corrected for storage.

tance of the lake and the local ground water to Kenya (tourism, geothermal power generation, export agriculture), knowledge of the lake/ground water interactions are critical to the future management of the water resource in the area.

We used $^3\text{H}/^3\text{He}$ or $^3\text{He}/^4\text{He}$ dating to better qualify and quantify ground water/lake interactions. Ground water acquires helium from four possible sources: atmospheric ($^3\text{He}/^4\text{He} \sim 1.38 \times 10^{-6}$) (Clarke et al. 1976), crustal ($^3\text{He}/^4\text{He} \leq 10^{-7}$), mantle ($^3\text{He}/^4\text{He} \sim 10^{-5}$) (Craig and Lupton 1981), and from tritium decay. In a closed system where mantle and crustal helium are insignificant compared with tritogenic helium, ages can be calculated (Poreda et al. 1988). Tritium is a radioactive isotope of hydrogen that decays to ^3He with a half-life of 12.4 years. If the initial concentration of ^3H in water is known and the water is kept out of contact with the atmosphere for a period of time, tritogenic helium produced by tritium decay in that water can be determined. A more accurate age-dating of the water can be obtained by considering both the initial ^3He and the tritogenic helium. (Torgersen et al. 1978; Solomon et al. 1993). For this technique to be useful, one assumes that dissolved chemical species are transported at the same rate as ground water and dispersive mixing of the dissolved species is not significant (Solomon et al. 1995). Studies by Solomon et al. (1992, 1993) in well-defined flow systems show this to be the case. Apart from the radioactive decay of ^3H , both ^3H and ^3He can be considered to be geochemically nonreactive. The $^3\text{H}/^3\text{He}$ age dating will agree exactly with the ground water travel time for purely advective transport. Under such conditions, $^3\text{H}/^3\text{He}$ age is independent of the ^3H input function, because it is the $^3\text{He}^*$ (the helium produced via tritium decay) to ^3H ratio that is considered. The $^3\text{H}/^3\text{He}$ age dating is useful due to the fact that ground water age itself, at any point in the system, is a result of the velocity field encountered along the entire upstream flowpath. Thus, a single measurement of age contains memory and encompasses more information than a single measurement of hydrogeological parameters such as hydraulic conductivity or velocity.

Sample Collection and Analysis

Thirty-six water samples (some in duplicate) from 21 sites were collected for analysis of tritium, helium, neon, and nitrogen (Table 1). The tritium samples were collected in 500 cc glass bottles with poly-seal caps. The helium samples were collected, either in copper tubing or evacuated glass flasks, using the method described by Solomon et al. (1992). The copper tubes were sealed with refrigeration pinch clamps. Gas concentrations and isotopes analyses were done at the Rare Gas Facility at the University of Rochester. Gases were extracted on a high-vacuum line as described by Solomon et al. (1992). Gas ratios (N_2 , Ar, O_2 , and CH_4) were analyzed on a Dycor quadropole mass spectrometer fitted with a variable leak valve. The results are combined with capacitance manometer measurements to obtain gas concentrations in cc STP/kg of water at $\pm 2\%$. N_2 and O_2 are removed by reaction with Zr-Al alloy (SAEST-707), and Ar and Ne are absorbed on activated charcoal before analyses of helium isotopes. Helium isotope ratios and concentrations were analyzed on a VG 5400 rare gas mass spectrometer. Helium isotope ratios are expressed as R/R_a , where R is the $^3\text{He}/^4\text{He}$ ratio in the sample and R_a is the $^3\text{He}/^4\text{He}$ ratio in the air standard. Errors in the reported $^3\text{He}/^4\text{He}$ ratios are about 0.5% at 25. Errors in ^3He values are $\sim 3\%$. Ne concentrations were determined by peak height comparison with an error of about 2%.

Table 2
Oxygen and Deuterium Isotopes Data
from Lake Naivasha Basin Water

Location	Temp. °C	$\delta^{18}\text{O} \text{‰}$	$\delta\text{D} \text{‰}$
Olk P/Sta, rw-1		1.4	19
X-2 Camp, rw-4		-1.4	6
Olk. West, rw-5		-1.8	6
Kongoni, rw-6		-1.6	15
Maiella, rw-7		-3.3	-13
Eburru, rw-8		-3.7	-14.5
Naivasha, rw-2		-3.2	-11
Kinangop, rw-3		-1.2	5
Suswa, rw-9		0.2	15
R. Karati (1), r-1		-1.4	-2
R. Malewa (1), r-2	24.1	-2.7	-7
R. Gilgil (1), r-3		-2.3	-7
R. Murindati, r-4	17.7	-2.6	-8
Little Gilgil, r-5		-3.3	-15
R. Malewa (m), r-6	17.2	-3.0	-9
R. Kianjogu, r-7	18.8	-3.6	-14
Gathiriga str., r-8	16.4	-2.4	-6
Nandarashi str.r-9	16.0	-3.3	-12
R. Turasha, r-10	18.4	-3.8	-19
R. Karati (up), r-11	14.7	-1.9	-5
R. Karati (mi), r-12	18.2	-1.6	-5
L. Naivasha, lk-001	27.4	6.4	39
Oloidien Bay lk-002	24.7	10.6	60
Mini-piez, mpzl-1		5.6	34
Mini-piez., mpzl-2		5.8	33
C3366	21.2	-3.9	-21
C3677	22.5	-4.2	-22
C3675	18.3	-2.7	-16
C210	22.8	3.5	19
C562	22.4	4.3	25
C567	20.6	4.2	23
C7829	23.3	3.9	26
C4397	20.2	4.2	21
C4420		3.7	22
C2071	22.5	3.4	18
C579	25.4	3.9	22
C4366		3.4	21
UW-1	21.0	3.6	21
C630-D	44.0	3.6	23
C3767	27.3	2.1	17
C2660	22.1	4.1	22
OW101A		3.1	4
OW-2	92.0	3.4	18
OW-26	94.0	3.7	23
OW-725	84.0	3.4	24
OW-728	74.0	3.7	29

The ^3He in-growth technique (Clarke et al. 1976) was used to determine tritium values. The samples are stored for about 30 days to enable ^3He produced by the decay of ^3H to accumulate in the flask. Blank corrections to ^3He are made using the ^4He content, and assuming that the blank has the air $^3\text{He}/^4\text{He}$ ratio. Errors in the reported ^3H values are dependent on the amount of ^3H and are about 3% at 30 TU.

A total of 46 samples were collected for stable isotope analysis (Table 2). These include nine rain water, 12 rivers, 16 ground water, four Lake Naivasha, Oloidien Bay and sediment pore water samples, and five from geothermal wells. The samples were collected

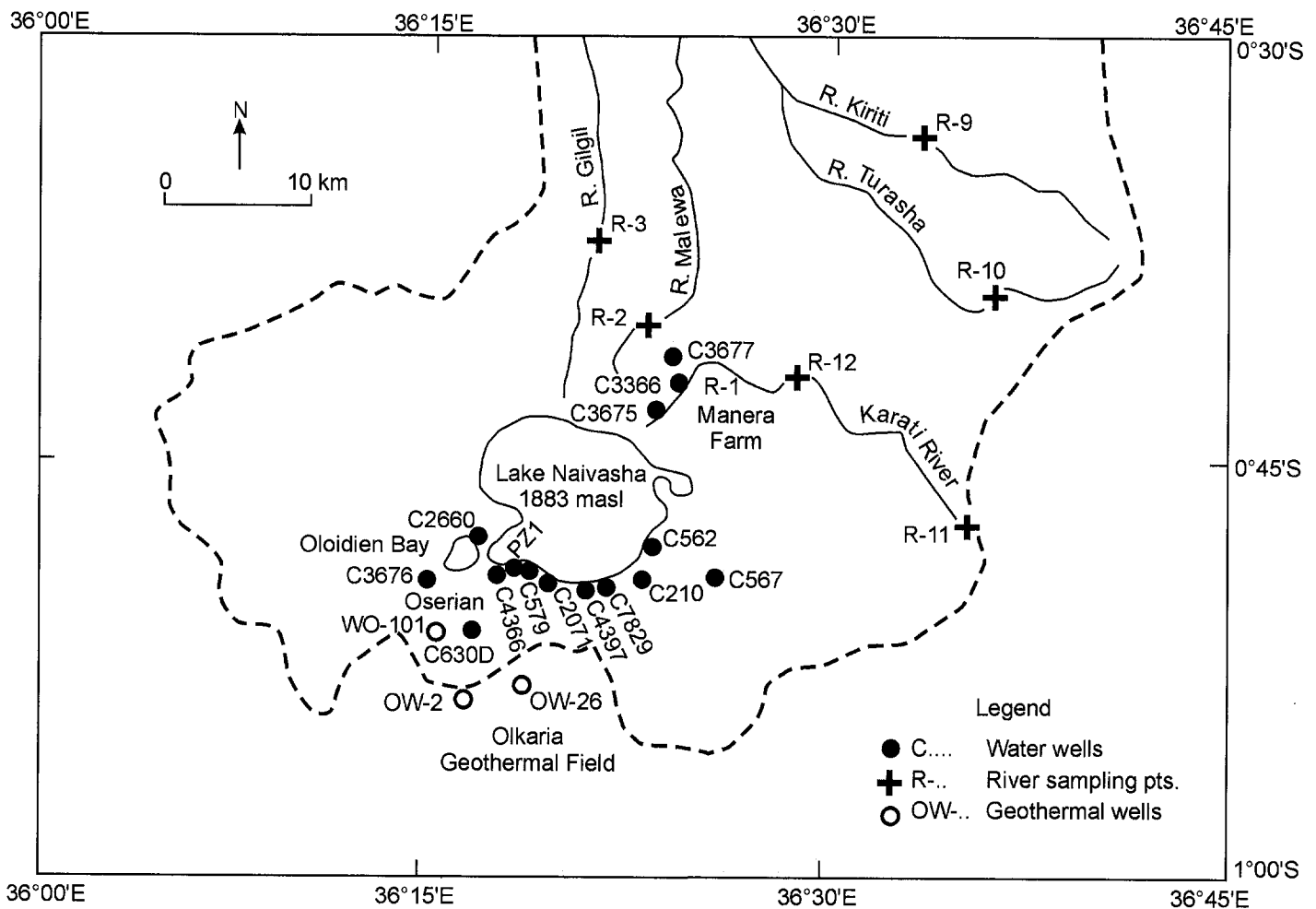


Figure 2. An enlarged map of the study area showing sampling points. Lake Naivasha drainage is outlined (---).

in 30 ml pre-cleaned glass bottles sealed with polyseal caps and taped in the field with electrical insulating tape to prevent leakage and evaporation. The samples were analyzed at the Desert Research Institute, Water Resources Center's stable isotope laboratory in Las Vegas, Nevada. The $\delta^{18}\text{O}$ was analyzed using the technique of Dugan et al. (1985), and δD by the method of Bilgeleisen et al. (1952). All data are reported in standard δ notation with respect to Vienna Standard Mean Ocean Water (VSMOW) with reproducibility of $\pm 1\text{‰}$ and $\pm 0.2\text{‰}$ for δD and $\delta^{18}\text{O}$ values, respectively.

Results and Discussion

The results of ^3H and ^3He isotope ratio determinations and the ^4He , N_2 , and Ne analyses are shown in Table 1. $^3\text{He}/^4\text{He}$ ratios relative to air are close to 1 except for C3767 and C630D, which have $^3\text{He}/^4\text{He}$ ratios of 2.5 and 2.8. These samples have too much $^3\text{He}^*$ to be from ^3H based on our estimate of input of the ^3H input function. This suggests discharge of thermal water into a shallow ground water system. This complicates the interpretation of the helium data throughout the region. Tritium values are low, ranging from 0 to 5.3 TU. Geographical positions of the wells relative to Lake Naivasha are given in Table 1 and shown in Figure 2. All the wells to the north of the lake (Manera Farm) and a few to the south have excess ^4He , N_2 , and Ne (Table 1). Heaton and Vogel (1981) noted similar excess gases in ground water from South Africa and attributed this to bubble entrainment during recharge and

later bubble dissolution deeper down in the subsurface. Incomplete purging of the copper tubing or cavitation in the pump assembly could also result in excess gas concentrations of ^4He . We have shown two $^3\text{H}/^3\text{He}$ ages in Table 1 calculated as follows: (1) assuming ^4He supersaturation with respect to air due to bubble entrainment during recharge; and (2) assuming ^4He saturation with air at the mean annual temperature (24°C) and that excess ^4He resulted from incomplete purging or cavitation bubbles with the purging water stream (Poreda et al. 1988).

In the first case,

$$^3\text{He}^* = ^3\text{He}_{t=0} - ^4\text{He}_{\text{total}} (^3\text{He}/^4\text{He})_{\text{air-saturated}}$$

where $^3\text{He}^*$ is the tritiogenic ^3He , $^3\text{He}_{t=0}$ is the total ^3He present at the time of the collection of the sample, $^4\text{He}_{\text{total}}$ is the measured amount of ^4He , and $(^3\text{He}/^4\text{He})_{\text{air-saturated}}$ is the $^3\text{He}/^4\text{He}$ ratio for water in isotope equilibrium with the atmosphere.

In the second case, the apparent excess ^3He must be corrected for the ^3He content of the purging water stream. The correction equation in this case is

$$^3\text{He}^* = [^3\text{He}_{t=0} - ^4\text{He}_{\text{total}} (^3\text{He}/^4\text{He})_{\text{air-saturated}}] [^4\text{He}_{\text{solubility}, T} / ^4\text{He}_{\text{total}}]$$

where $^4\text{He}_{\text{solubility}, T}$ is the solubility of helium in water at the temperature T of interest (Poreda et al. 1988).

Table 1 shows that water ages in the study area range from 0.3 years for the lake water to more than 40 years for the geothermal

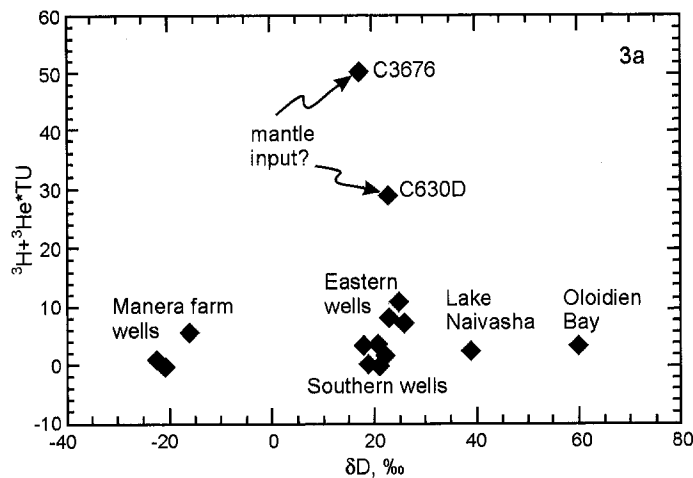


Figure 3a. Plot of $^3\text{H}+^3\text{He}$ versus δD for ground water from Lake Naivasha region.

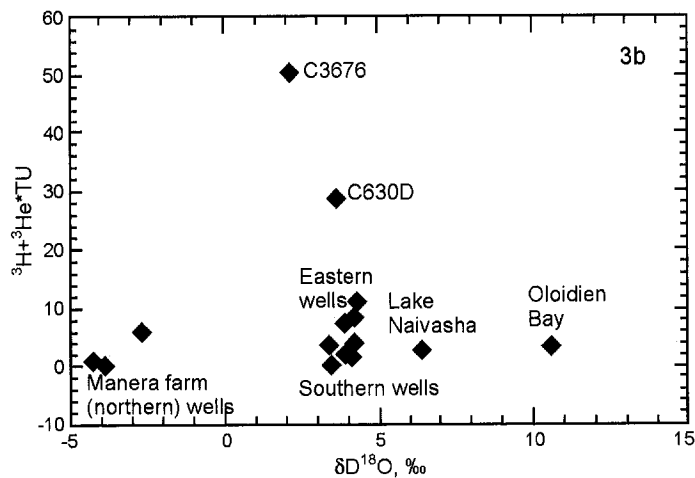


Figure 3b. Plot of $^3\text{H}+^3\text{He}^*$ versus $\delta^{18}\text{O}$, ‰ for ground water from Lake Naivasha region.

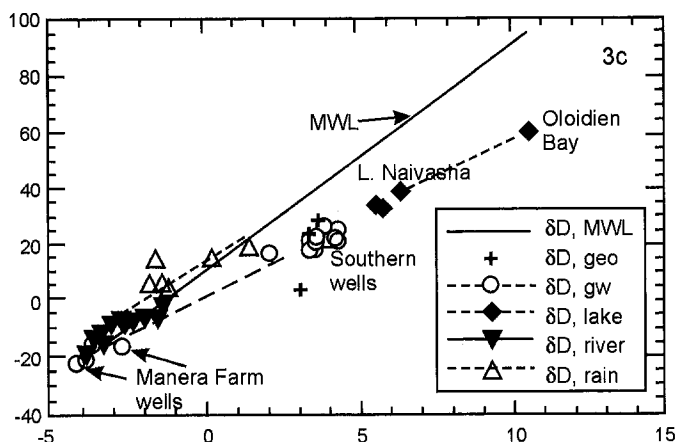


Figure 3c. Plot of $\delta^{18}\text{O}$ and δD for rain, surface, and subsurface water from Lake Naivasha region drawn separately and then the regression lines combined to compare with the Meteoric Water Line.

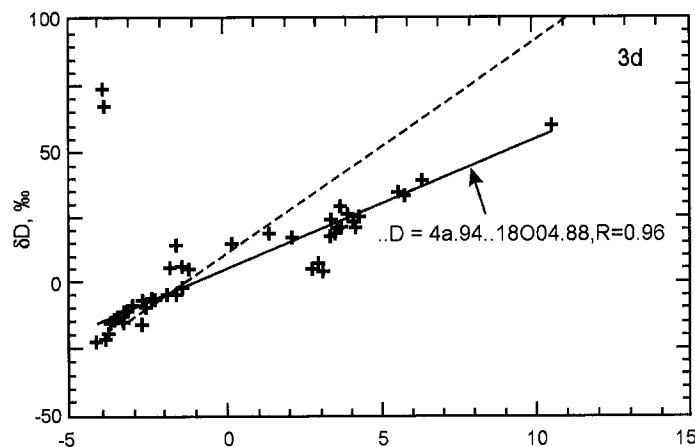


Figure 3d. Plot of deuterium versus oxygen-18 of Lake Naivasha water. Meteoric Water Line (MWL).

and intermediate ground water wells to the east and further south toward Olkaria (C210, C567, C3767, and C630D). Wells C630D and C3767 have mantle helium, as deduced from their R/R_a ratios and C3767 has an absence of tritium (Table 1). Apart from these wells, all other wells to the south of the lake have water ages identical to, or slightly older than Lake Naivasha water (Table 1). Figures 3a and 3b are plots of $^3\text{H}+^3\text{He}^*$ against δD and $\delta^{18}\text{O}$ isotopes, and they both show that the Manera Farm, southern wells, and lake water all have identical $^3\text{H}+^3\text{He}^*$ values but different δD and $\delta^{18}\text{O}$ values. Both δD and $\delta^{18}\text{O}$ are progressively enriched from the Manera water compared to the geothermal and the southern wells and Lake Naivasha, with Oloidien Bay having the highest value. Wells to the east have similar δD and $\delta^{18}\text{O}$ values as the southern wells but are more enriched in $^3\text{H}+^3\text{He}^*$ than the latter. Effects of mantle helium input in wells C3767 and C630D is further seen in Figures 3a and 3b by the fact that these wells have water with identical δD and $\delta^{18}\text{O}$ values as the southern wells, but three to five times the ^3H and $^3\text{He}^*$ values. This indicates that these wells have identical source water to the other southern wells and also have mantle helium input. The stable isotope values for the geothermal wells (OW- 102, 226, 725, and 728) are the reservoir fluid values corrected for steam separation using the continuous steam model (Truesdell et al. 1977; Ojiambo and Lyons 1993). The geothermal

reservoir water is lighter than that from the eastern and southern wells. If the lake contributed water only to the Olkaria field, the water there would demonstrate a more evaporative signal. From the standard δD vs. $\delta^{18}\text{O}$ plot, a mixing line can be drawn between the eastern and southern wells and the lake with Oloidien Bay/Lake Naivasha and the Manera Farm wells, and Nandarashi stream (sample no. R-9, Table 2) on the eastern escarpment of the Rift Valley as the end members (Figures 3c and 3d). Except for the Manera Farm wells, which fall on the World Meteoric Line (Figure 3c), all other ground water is depleted in δD , but enriched in $\delta^{18}\text{O}$. This suggests that ground water has become heavier in $\delta^{18}\text{O}$, either from chemical reaction with the aquifer rocks through which it flows, or through evaporation. Because of the higher nitrate levels in the Manera Farm ground water, we favor an evaporative source for the heavier $\delta^{18}\text{O}$. There is little doubt that Lake Naivasha and Oloidien Bay water has gained its $\delta^{18}\text{O}$ signature through evapoconcentration. Oloidien Bay is more enriched and more saline because it becomes highly evaporated for long periods during drought periods (Verschuren 1999). During such periods, it receives no fresh water from the rivers. The Manera Farm and river water is depleted compared to the other ground water in the basin. It falls on, or close to, the meteoric line indicating direct recharge from the Rift flanks rain water (Figure 3c); rain samples (Table 2) RW-1 and

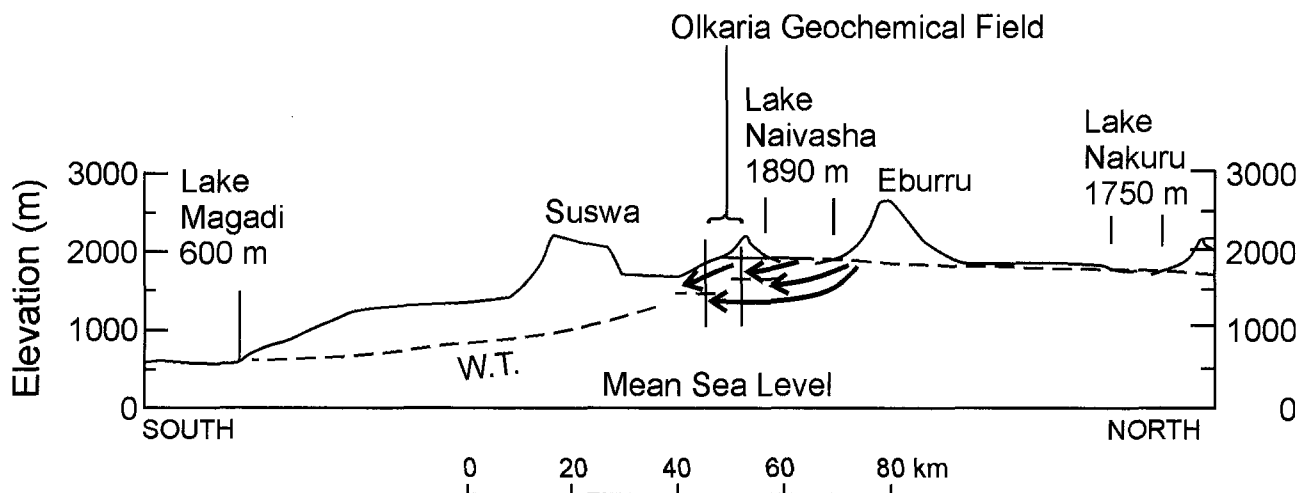


Figure 4. A north-south topographical profile of the Rift Valley floor from Lake Nakuru to Lake Magadi. Our conceptual model of ground water flow in the Naivasha region is shown via arrows. Postulated ground water level is shown as a dashed line. From Ojiambo (1992).

3 are from the Rift floor and are highly evaporated compared to elevation rain water, which is similar to the Nandarashi stream water (Rozanski et al. 1996). The Rift floor rain water is enriched in the stable isotopes, probably due to an evaporation effect (Mazor 1991).

Using the mean δD and $\delta^{18}O$ concentrations of Manera Farm, southern wells and lake water, the following mixing computation was done to establish the proportional ratios in the southern water. The $\delta^{18}O$ and δD compositions of Lake Naivasha, Manera Farm, and southern ground water are: 6.4, 39; 3.9, 21; 4.2, 21, respectively. The resulting δD and $\delta^{18}O$ would be

$$\begin{aligned} 6.4 \delta^{18}O_x + \{-3.6 \delta^{18}O (1-x)\} &= 4.2 \delta^{18}O \\ 10 \delta^{18}O_x &= 7.8 \delta^{18}O \\ x &= 0.78 \text{ or } 78\% \\ 39 \delta D_x + \{-21 \delta D (1-x)\} &= 21 \delta D \\ 60 \delta D_x &= 42 \delta D \\ x &= 0.7 \text{ or } 70\% \end{aligned}$$

This mass computation shows that the southern water is composed of about 70% to 80% lake water and 30% to 20% water similar to Manera Farm water and/or recharge water from the eastern Rift escarpment. A similar computation using Ololdien Bay water instead of Lake Naivasha water gives a lake water proportion at 50% to 55%, and 50% to 45% from the Rift flanks recharge water. Calculations using oxygen isotopes give higher proportions of lake water than using deuterium alone. The average percentages using deuterium are 50% to 70% lake water and 50% to 30% recharge water. Using similar mixing ratio calculations as those mentioned previously for the geothermal reservoir water shows that 45% to 60% of the water is from the deep circulated ground water and 55% to 40% is from lake water. These percentages are similar to the 30% to 60% previously calculated by Ojiambo and Lyons (1996) using major element data. This lake water in the deep subsurface is not present-day lake water, as the geothermal fluids are devoid of tritium indicating that they are at least 50 years old. Our conceptual model of ground water flows in the region is shown in cross section in Figure 4.

The mean annual air temperature in the study area is 24°C (Ewbank Price Ltd. 1989; Ojiambo 1992). Using this temperature, and at this elevation (~2000 m), the estimated solubilities of 4He , Ne, and N_2 at 24°C are 33.3, 136.2 ucc/kg, and 8.6 cc/kg STP,

respectively (Weiss 1970, 1971; Mazor 1991). All northern wells, plus C562 and C2660, are supersaturated with respect to these gases. There is no evidence of N_2 production through denitrification. The excess 4He , Ne, and N_2 gases are most likely due to bubble entrainment during sampling, since there are no known hydrothermal manifestations around these wells. In fact, wells C3767 and C630D, which have mantle helium input, are undersaturated with respect to Ne and N_2 and only about 15% supersaturated with respect to 4He . The rest of the wells have water close to 4He , Ne, and N_2 solubility equilibrium values for the mean annual temperature. As mentioned previously, the northern Manera Farm wells have distinctly higher concentrations of nitrate. We speculate that these levels are due to nitrate input from irrigation water used for growing lucerne grass (alfalfa).

Vertical Velocities and Recharge Rates

One of the primary uses of $^3H/^3He$ age values has been to estimate vertical ground water velocities and recharge rates in unconfined aquifers (Solomon et al. 1993, 1995). The study of Solomon et al. (1993, 1995) was done in aquifers whose flow characteristics were well known and the measurements were taken from multilevel piezometers and wells. Therefore, the vertical profiles of tritium and helium were well controlled. Unfortunately, our sampling controls were not as good as in the Solomon et al. (1993, 1995) work, as we have no multilevel collection. However, an attempt has been made to estimate ground water velocities and recharge rates using calculated depths from the sampled wells.

The measurement point in a well was taken as the midpoint between the bottom of the plain casing and the total depth of the well. The water column height between the water level and the calculated measurement point is the vertical distance (ℓ) traveled by the water particle. It was also assumed that the atmospheric helium and tritium dissolved at the time of recharge had not been modified as the water flowed through the vadose zone. The flow was also taken as being advective, with negligible dispersion, as shown by (Solomon et al. 1993). The vertical velocity was calculated according to

$$V_o = \frac{\ell}{t \frac{^3H}{^3He^*}}$$

Table 3
Calculated Recharge Rates in the Lake Naivasha Region

Well Location	r m/yr	Direction from Lake
C 3677	1.59	N
C 3366	0.64	N
C 3675	0.67	N
C 562	0.63	E
C 567	0.24	E
C 210	0.39	E
C 7829	0.93	S
C 4397	0.53	S
C 579	0.2	S
C 2660	0.1	SW
C 3767	0.28	S
C 4366	0.43	S
C 630 D	0.15	S

where ℓ is the distance between the static water level, and the calculated measurement point, divided by the tritium-helium age. Recharge rate, r , is then calculated as $r = V\theta$ where the effective porosity was taken to be 0.30, based on the aquifer properties, and the porosity measurements obtained from rocks in the area (Mwangi 1987). Calculated values of V_0 are shown in Table 3.

The northern wells have the highest recharge rates of 0.97 ± 0.50 m/yr, and the wells near the lake (C562, C7829, C4366, and C4397) have mean recharge rates of 0.63 ± 0.22 m/yr. Wells more than a kilometer from the lake (C210, C567, C3767, and C630D) have mean recharge rates of 0.27 ± 0.10 m/yr. Well C579 has a low recharge rate (0.20 m/yr). Its water level was deeper, and it is drilled into volcanic rock. Well C2660, to the southwest of the lake, has the lowest recharge rate (0.10 m/yr). The water from this well is also old (>40 yrs), indicating that it has traveled long distances. Taking all these data into consideration, the recharge rates in the study area vary from 0.10 to 1.59 m/yr with a mean of 0.52 ± 0.40 m/yr. Calculated vertical recharge rate on the southern side of the lake, using a chloride mass balance equation (Ojiambo 1996) gave a value of 0.47 m/yr, which is in excellent agreement with the mean recharge rate from these tritium-helium age calculations. The average annual precipitation rate on the valley floor is only slightly larger than the mean recharge rate (0.68m/yr versus 0.52m/yr), suggesting that much of the ground water reaching the Lake Naivasha basin is derived from the highlands above the lake, where rainfall can be as high as $2 \text{ m} \cdot \text{yr}^{-1}$. Much of the monsoonal rainfall destined for the central Rift Valley is intercepted by the surrounding highlands, causing a strongly negative hydrological balance near the Rift Valley lakes (Verschuren 1996).

Well C630D is about 3 km from the lake and its water level is 26 m below the lake level. This yields a hydraulic gradient, I , of 0.01. From Table 1, this well has water >40 years old. Assuming that the water in well C630D was recharged beneath Lake Naivasha, the maximum horizontal velocity would be $3000\text{m}/400\text{yr} = 75 \text{ m/yr}$ or less. Horizontal hydraulic conductivity, K_x , was calculated according to

$$K_x = \frac{V_x \theta}{I}$$

This gives a hydraulic conductivity of 2250 m/yr or 6 m/day (or 2 m/day using a porosity value of 0.1). This is within the 0.1 to 40

m/day calculated by Ojiambo (1992), but higher than the 0.001 to 0.1 m/day calculated by Clarke et al. (1990). Aquifer pumping test results carried out during this study in well C579 show hydraulic conductivity values of 10 to 15 m/day depending on the value used for aquifer thickness (Ojiambo 1996). Therefore, our value of 6 m/day from the tritium-helium analyses is quite comparable to the pumping test results.

Summary and Conclusions

Tritium, helium, oxygen, and deuterium isotope concentrations have been used to demonstrate spatial differences in ground water ages and sources around Lake Naivasha. Water ages in the study area range from 0.3 year for the lake water to more than 40 years for the geothermal and intermediate ground water wells to the east and further south toward Olkaria (C210, C567, C3767, and C630D). Wells C630D and C3767 have mantle helium as deduced from their R/Ra ratios of 2.50 and 2.83, and their low ^3H concentrations. All the other wells to the south of the lake have water ages identical to or slightly older than Lake Naivasha water. Vertical recharge rates calculated from tritium and helium ages range from 0.10 to 1.59 m/yr with a mean of 0.52 ± 0.40 m/yr. The northern wells have the highest recharge rates of 0.97 ± 0.50 m/yr, and the wells near the lake (C562, C7829, C4366, C4397) have mean recharge rates of 0.63 ± 0.22 m/yr. Wells more than a kilometer from the lake (C210, C567, C3767, and C630D) have mean recharge rates of 0.27 ± 0.10 m/yr. Horizontal ground water velocity of 75 m/yr was calculated between the lake and well C630D near the Olkaria geothermal field.

Rain, river, and ground water to the north of the lake has the lightest stable isotope values, ranging from -4.2% to 1.4% $\delta^{18}\text{O}$ and -22% to 19% for δD . A $\delta^{18}\text{O}/\delta\text{D}$ plot shows a mixing line having a slope of 5 (Figure 3a). Ground water to the north shows the most depletion, and Oloidien Bay is the most enriched end member. The isotopic composition gets progressively heavier, from the northern ground water to the geothermal, eastern, and southern wells, respectively, with Lake Naivasha and Oloidien Bay having the heaviest isotopes (Figure 3a). This further corroborates our hypothesis that the southern water is formed by the mixing of recharge water from the eastern Rift flanks with Lake Naivasha water, and that the lake has a subsurface outflow from its southern shores. The calculated composition of the southern water, using deuterium data, is 50% to 70% lake water and 50% to 30% recharge water from the eastern Rift Valley escarpment. Using similar mixing ratio calculations as mentioned previously, the geothermal reservoir water shows that 45% to 60% is from the deep circulated ground water and 55% to 40% may be from lake water having percolated deeper into the reservoir.

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