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Groundwater recharge in the Akaki catchment, central Ethiopia: evidence from environmental isotopes (δ^{18}O, δ^2H and ^{3}H) and chloride mass balance

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Abstract:

Recharge patterns, possible flow paths and the relative age of groundwater in the Akaki catchment in central Ethiopia have been investigated using stable environmental isotopes δ^{18}O and δ^2H and radioactive tritium (^{3}H) coupled with conservative chloride measurements. Stable isotopic signatures are encoded in the groundwater solely from summer rainfall. Thus, groundwater recharge occurs predominantly in the summer months from late June to early September during the major Ethiopian rainy season. Winter recharge is lost through high evaporation–evapotranspiration within the unsaturated zone after relatively long dry periods of high accumulated soil moisture deficits. Chloride mass balance coupled with the isotope results demonstrates the presence of both preferential and piston flow groundwater recharge mechanisms. The stable and radioactive isotope measurements further revealed that groundwater in the Akaki catchment is found to be compartmentalized into zones. Groundwater mixing following the flow paths and topography is complicated by the lithologic complexity. An uncommon, highly depleted stable isotope and zero-^{3}H groundwater, observed in a nearly east–west stretch through the central sector of the catchment, is coincident with the Filwoha Fault zone. Here, deep circulating meteoric water has lost its isotopic content through exchange reactions with CO_2 originating at deeper sources or it has been recharged with precipitation from a different rainfall regime with a depleted isotopic content. Copyright © 2006 John Wiley & Sons, Ltd.

KEY WORDS Akaki catchment; chloride mass balance; environmental isotopes; Ethiopia; groundwater recharge; piston and preferential flow

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INTRODUCTION

The volcanic aquifers of the Akaki catchment in central Ethiopia have been a major municipal water source supplying the city of Addis Ababa for more than a century. With a fast-growing population of currently 3 million located along the ill-defined western margin of the Main Ethiopian Rift (MER), Addis Ababa receives more than 35% of its water supply from groundwater in the Akaki catchment (Ijigneh, 1999). Most of this is pumped from the Akaki well field located south of the metropolis. Moreover, a considerable, but unquantified, amount of groundwater is withdrawn informally through individually owned shallow and deep wells scattered throughout the catchment.

These volcanic aquifers are recharged exclusively from precipitation. However, recent monitoring of groundwater level, especially in the Akaki well field by the Addis Ababa Water and Sewerage Authority (AAWSA), shows that the groundwater level is declining. The increased frequency of climatic fluctuations, a common phenomenon for the last couple of decades in East Africa, may result in serious shortages in surface water resources. This increases groundwater demand, further stressing the groundwater resource.

Pollution of a number of shallow wells and springs in the catchment has also been reported (Alemayehu, 2001; Gizaw, 2002). Despite its strategic importance to the city, the groundwater resource is endangered not only by incidences of anthropogenic pollution, but it is also stressed by overexploitation. Thus, it appears that a thorough investigation and characterization of flow patterns, recharge and mechanisms of recharge through conventional hydrogeologic and isotopic methods is pertinent.

The environmental chloride mass balance (CMB) technique not only provides an estimation of the quantity of groundwater recharge, but it also provides information about the processes and mechanisms of recharge. The stable isotopic composition of water coupled with radioactive tritium (^{3}H) measurements in precipitation and groundwater can be used to characterize patterns of groundwater flow, identify the origin of the groundwater, and date and trace active groundwater recharge and mixing between groundwaters of different ages (Clark and Fritz, 1997; Mazor, 1997; Abbott *et al.*, 2000; de Vries and Simmers, 2002).

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This study employs a coupled analysis of the environmental isotopes $\delta^{18}O$, $\delta^{2}H$ and ^{3}H and the CMB method to identify groundwater flow, mechanisms, patterns and rates of recharge in the Akaki catchment of central Ethiopia.

LOCATION AND CLIMATE

The Akaki catchment is located in central Ethiopia along the western margin of the MER. The catchment is situated at the northwestern Awash River basin between 8°46′–9°14′N and 38°34′–39°04′E. It is bounded to the north by the Intoto ridge system, to the west by Mt Menagesha and the Wechecha volcanic range, to the southwest by Mt Furi, to the south by Mt Bilbilo and Mt Guji, to the southeast by the Gara Bushu hills and to the east by the Mt Yerer volcanic centre. The Akaki catchment has an area of about 1500 km^2. Addis Ababa is located at the centre of the catchment (Figure 1). Surface water reservoirs located within the study area include Legedadi, Gefersa, Dire and Abasamuel.

Despite its proximity to the equator, the study area experiences a temperate Afro-Alpine climate. Daily average temperatures range from 9·9 to 24·6 °C and annual mean rainfall is 1254 mm, as measured at Addis Ababa Observatory. The climate of the Akaki catchment is characterized by two distinct seasonal weather patterns. The main wet season, locally known as *Kiremt*, extends from June to September, contributing about 70% of the total annual rainfall (Figure 2). A minor rainy season, locally known as *Belg*, contributes moisture to the region from mid February to mid April.

GEOLOGICAL AND HYDROGEOLOGICAL SETTING

Owing to its location along the western margin of the MER, the geological history of the Akaki catchment is an integral part of the evolution and development of the Ethiopian Plateau and the rift system. The catchment is covered by volcanic rocks overlain by fluvial and residual soils, in which black cotton soils are predominant, varying in thickness from a few centimetres to about 20 m (AAWSA *et al*., 2000). The main lithologies include basalts, rhyolites, trachytes, scoria, trachy-basalts, ignimbrites and tuff (Figure 3). These highly weathered, fractured lithologies favour the circulation and storage of subsurface water. The main structures, joints, fractures, and normal faults, are all related to the extensional rift tectonics in the area. A prime example is the Filwoha Fault, along which thermal activity is observed.

The aquifer properties in the Akaki catchment are controlled by the litho-stratigraphy of the volcanic rocks and the structures that affect them. More specifically, the hydraulic complexity of these volcanic rocks is caused by their complex spatial distribution, their different reciprocal stratigraphic relationships, their significant compositional, structural and textural variability, and their different levels of tectonization and weathering (Vernier, 1993).

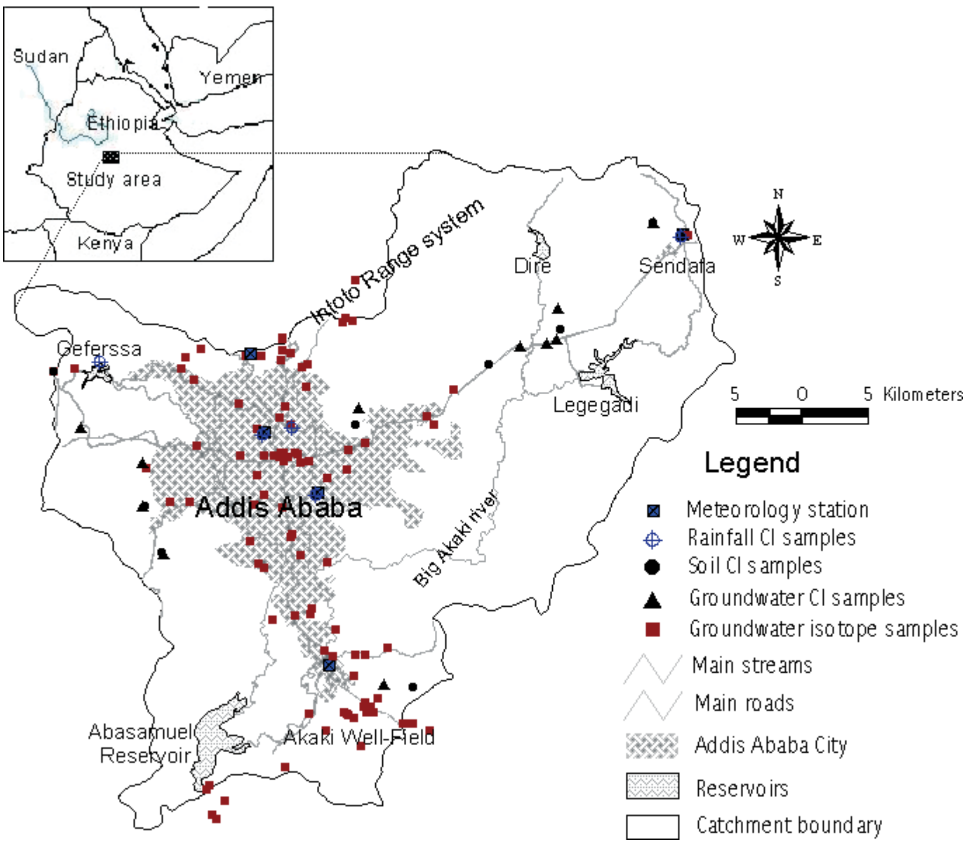

Figure 1. Location map of the Akaki catchment in central Ethiopia and the sampling points

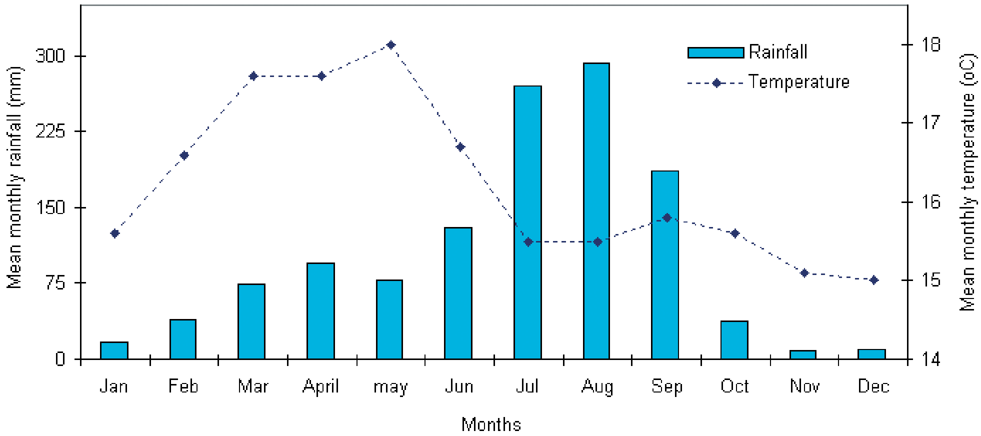

Figure 2. Mean monthly rainfall and air temperature of the Akaki catchment measured in Addis Ababa (data from Ethiopian Meteorology Agency)

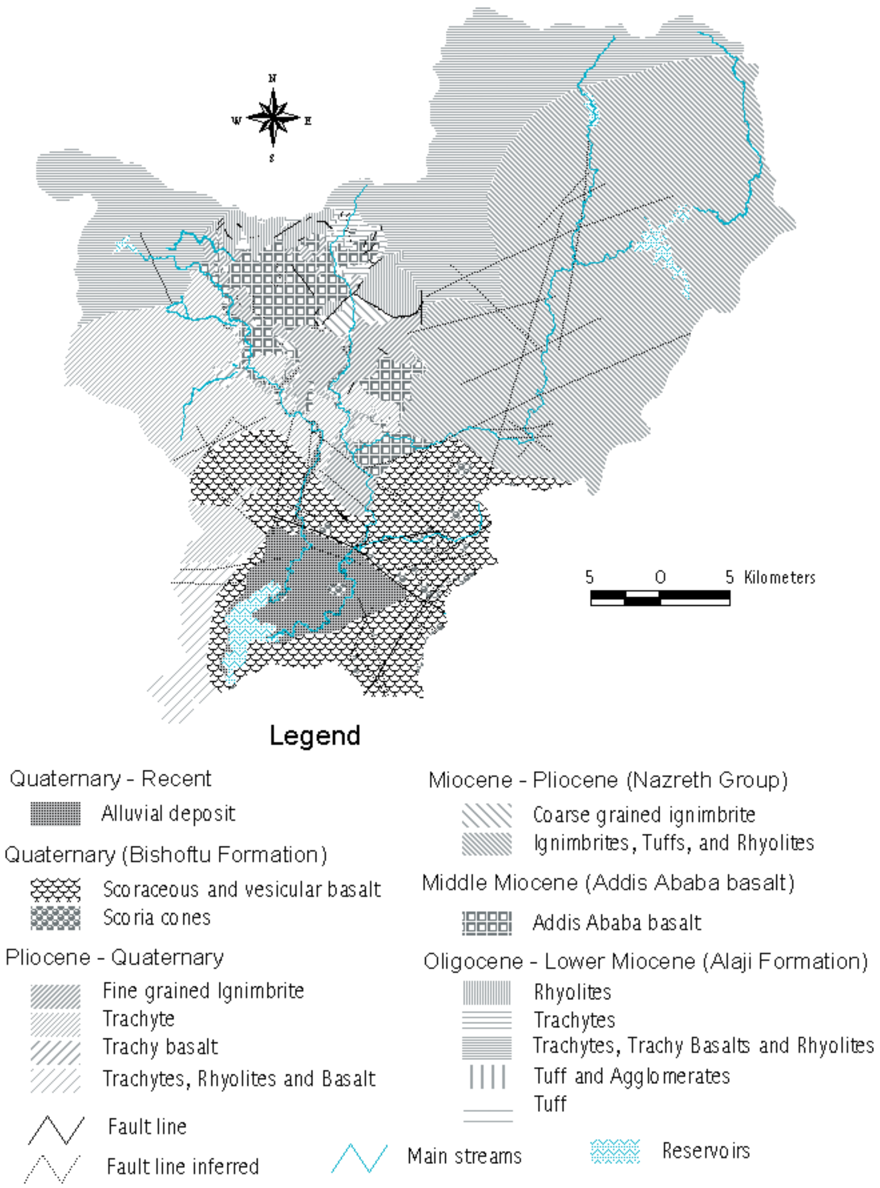

Figure 3. Simplified geological map of the Akaki catchment, central Ethiopia (modified after AAWSA *et al*. (2000))

These volcanic aquifers can be considered as a *double porosity medium* due to the fact that both the matrix and the fracture porosity contribute to the transmission and storage of subsurface water.

- Scoria, scoraceous basalt and intra-formational gravel and sand layers constitute highly productive aquifers with primary porosity and permeability.
- Highly weathered and fractured basalts, fractured tuff, ignimbrite and other pyroclastics constitute highly productive aquifers of secondary porosity and permeability.
- Basalt with some fractures, vesicles and sparsely spaced joints, ignimbrites and agglomerates form moderately productive aquifers in the area (Girma, 1994; AAWSA *et al.*, 2000; Alemayehu, 2001).

These units have been grouped into an uppermost shallow phreatic aquifer constituted by layers of alluvial sediments, weathered and fractured volcanics and a confined–semi-confined volcanic aquifer of widespread areal coverage (Girma, 1994). These multilayered, heterogeneous unconfined, semi-confined and confined aquifers feature multi-stock works. Average values of transmissivity T varying from 4·3 m^2 day^{-1} (for low yield areas) to as high as 27 648 m^2 day^{-1} (for high yield areas) have been reported (AAWSA *et al.*, 2000). Average storativities range from $6{\cdot}5 \times 10^{-3}$ to $4{\cdot}31 \times 10^{-2}$. Furthermore, it was observed that highly transmissive areas do not correspond to high storativity areas, because of differential fracturing and weathering of the volcanic aquifers. Water level observations in wells generally show a north–south groundwater flow in the northern and central sectors of the catchment and a southeasterly flow towards the Akaki well field in the southern sector of the catchment.

METHODOLOGY

Untreated groundwater samples for isotope and hydrochemical analysis were taken from a north–south and an east–west transect across the catchment. The samples were obtained directly from springs and shallow and deep wells. In the case of previously inactive wells, samples were taken after 10 min of pumping. Isotope samples were sealed in special IAEA bottles (plastic for ^{3}H and glass for ^{18}O and ^{2}H) and analysed at the Laboratory of GSF (Research Center for Environment and Health, Institute for Groundwater Ecology) in Munich, Germany. The hydrochemical samples were analysed in the Department of Applied Geology laboratory at the Ruhr University of Bochum, Germany.

Unsaturated-zone soil chloride samples were taken using a soil auger at numerous predefined points and depths of the non-urbanized flat-land of the catchment. Each soil sample, weighing 200 g, was collected in plastic bags and transported to the laboratory. Then 100 g from each soil sample was elutriated using 1 l of ultrapure deionized water (<1 μS cm^{-1}) according to the S4-test of the German Standard (DIN 38 414-4). The elutriated samples were filtered through a 0·45 μm filter after settling using a centrifuge at a revolution of 3000 rpm. The filtered samples were analysed for chloride content using an ICS-1000 ion chromatograph.

The winter rainfall composite samples of March and April (2004) were collected at five different meteorological stations in the Akaki catchment during a 3 month field campaign. Weekly accumulated summer rainfall samples (June–September, 2003) were collected at the Addis Ababa observatory. It is assumed that the rainfall chloride results closely reflect the total annual deposition for the continental Ethiopian Highlands, with negligible atmospheric dust and a relatively remote location from the sea.

An environmental mass balance of the chloride ion, assuming chloride to be a conservative tracer, was applied for seven sampling sites within the study catchment. This allowed the computation of diffuse recharge (direct) and total recharge (including preferential flow recharge through fractures, fissures and joints) through the following relations:

$$P[\mathrm{Cl}]_{\mathrm{p}} = R[\mathrm{Cl}]_{\mathrm{gw}} \text{ (for total recharge estimation)} \quad (1)$$

$$[\mathrm{Cl}]_{\mathrm{sm}}\mathrm{DR} = P[\mathrm{Cl}]_{\mathrm{p}} \text{ (diffuse or direct recharge)} \quad (2)$$

where P (mm) is the mean areal precipitation, R (mm) is total recharge, DR is the diffuse or direct recharge through the unsaturated zone, $[\mathrm{Cl}]_{\mathrm{p}}$ (mg l^{-1}) is the mean annual chloride concentration in precipitation, $[\mathrm{Cl}]_{\mathrm{gw}}$ (mg l^{-1}) is the chloride concentration in groundwater and $[\mathrm{Cl}]_{\mathrm{sm}}$ (mg l^{-1}) is the mean chloride concentration of the unsaturated zone moisture.

Additional groundwater isotopic data in the catchment were supplied by the AAWSA. Meteorological data for seven stations within the catchment were collected from the Ethiopian National Meteorological Agency. Areal rainfall for the catchment was determined using the Thiessen polygon weighting method under a geographic information system (GIS). Long-term rainfall isotopic data (δ^{18}O, ^{2}H, ^{3}H) at the Addis Ababa Global Network of Isotopes in Precipitation (GNIP) station is available from the International Atomic Energy Agency (IAEA) GNIP database (IAEA/WMO, 2004). The relative residence time of groundwater has been qualitatively and semi-quantitatively estimated (Clark and Fritz, 1997) as follows:

<0·8 TU	sub-modern groundwater recharged prior to 1952
0·8 to 4 TU	mixture of recharge between sub-modern and recent recharge
5 to 15 TU	modern (<5 to 10 years)
5 to 30 TU	(some bomb ^{3}H present)

The above semi-quantitative values were compared with the decay equation of ^{3}H:

$$a_t(^3\mathrm{H}) = a_0(^3\mathrm{H})\mathrm{e}^{-\lambda_t} \quad (3)$$

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where $\lambda = \ln(2/t_{1/2})$ and the half life $t_{1/2}$ of ^{3}H is taken to be 12·43 years. Solving for t gives

$$t = 17{\cdot}93 \ln\left(\frac{a_t(^3\mathrm{H})}{a_0(^3\mathrm{H})}\right) \qquad (4)$$

where $a_0(^3\mathrm{H})$ is the initial ^{3}H activity and $a_t(^3\mathrm{H})$ is the residual activity of ^{3}H remaining after decay over time t.

Spatial variation of groundwater isotopic data and other relevant conventional hydrogeologic information were analysed using a GIS.

RESULTS

Long-term δ^{18}O, δ^2H and ^{3}H measurements in precipitation are available at the Addis Ababa GNIP station, located in the centre of the study catchment. Precipitation at this station has a mean isotopic composition of $\delta^{18}\mathrm{O} = -0{\cdot}29$‰ and $\delta^2\mathrm{H} = 10{\cdot}13$‰, in which δ^2H is positively correlated with δ^{18}O measurements (Figure 4). The line of best fit through data points representing δ^2H vs. δ^{18}O values (Figure 4, data from 1961 to 2001) is given by

$$\delta^2\mathrm{H} = 7{\cdot}15\delta^{18}\mathrm{O} + 12{\cdot}14 \quad (r^2 = 0{\cdot}94) \qquad (5)$$

This is comparable to the regression line for the long-term averages of δ^2H versus δ^{18}O and the precipitation values from the worldwide network of GNIP stations as reported by Rozanski *et al.* (1993) and to the global meteoric water line (GMWL) of Craig (1961).

^{3}H concentrations in precipitation range from a peak value of 189 TU measured in the year 1965 to a present-day average value of about 10 TU (an average value for the last two decades). The ^{3}H content of precipitation at this measuring station has reached a steady-state level with minor annual and monthly fluctuations.

The results of stable oxygen (δ^{18}O), deuterium (δ^2H) and radioactive ^{3}H measurements of groundwater vary according to location. The most depleted values were found from thermal waters sampled at the Filwoha, Ghion Hotel and National Palace thermal wells. In this case, δ^{18}O ranged from -4 to $-5{\cdot}9$‰ and δ^2H varied from about -19 to -28‰ (with reference to Vienna standard mean ocean water), which is characterized by a pre-bomb ^{3}H value (Table I). The relatively enriched samples are associated with most springs and shallow and intermediate wells tapping from the unconfined aquifers of the area. These aquifers are recharged directly from precipitation through fractures. The relatively enriched samples are also characterized by a ^{3}H value of either bomb or post-bomb concentrations. In addition, there are intermediate samples showing mixing between pre- and post bomb recharge.

Notwithstanding its importance, rainfall chemistry data for East Africa in general, and Ethiopia in particular, are limited. The present-day chemical analysis (Table II: summer 2003 rainfall and winter 2004 rainfall) shows apparent variation of major ions with rainfall amount, time and space in the study catchment. Values for chloride concentration varied from 2·2 mg l^{-1} in March to 0·15 mg l^{-1} in August. Table III depicts the mean annual chloride concentration in rainfall, groundwater and soil profile at seven different measuring points, along with estimated mean annual diffuse, *by-pass* and total recharge results.

DISCUSSION

Comparative analysis and interpretation of rainfall isotopic data measured at East African GNIP stations, namely at Addis Ababa (2360 m a.m.s.l.) in Ethiopia, Kericho (2130 m a.m.s.l.) in Kenya, Geneina (805 m a.m.s.l.) and Khartoum (382 m a.m.s.l.) in Sudan, Entebbe Airport (1155 m altitude) in Uganda, Dar Es Salaam (55 m a.m.s.l.) in Tanzania, Ndola (1331 m a.m.s.l.) in Zambia, and Harare (1471 m) in Zimbabwe

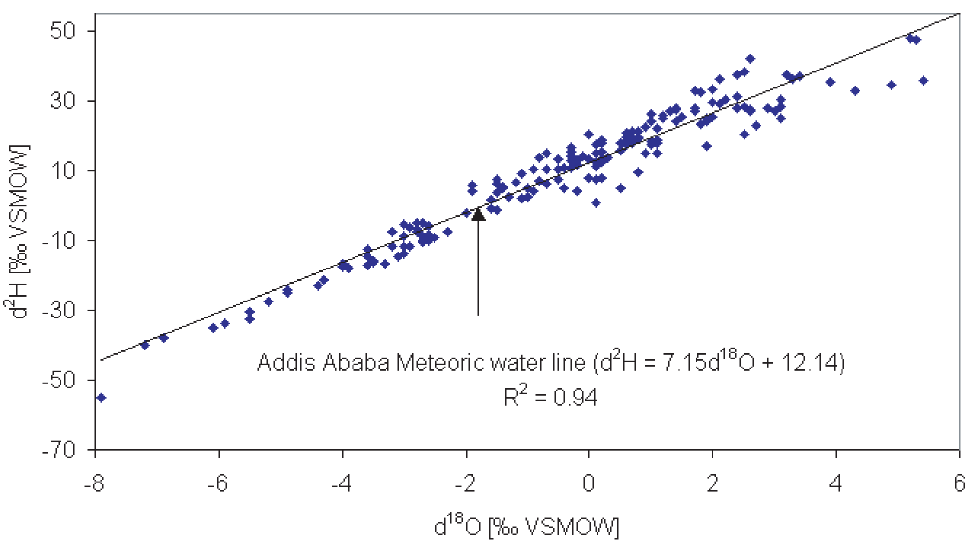

Figure 4. Plot of δ^{18}O versus δ^2H of precipitation at Addis Ababa GNIP station (data from IAEA/WMO (2004)). A regression line through the data points represents the local meteoric water line (LMWL) at Addis Ababa

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Table I. Environmental isotopic and major ion chemical composition of groundwaters in the Akaki catchment, central Ethiopia

Sample ID	Sample location		Sample date	Borehole depth (m)	EC[a] (μS cm^{-1})	T (°C)	pH	Chemical concentration (mg l^{-1})							$\delta^{18}O$ (‰)	δ^2H (‰)	^3H (TU)	Ref.
	Lat.	Long.						Na^+	K^+	Ca^{2+}	Mg^{2+}	Cl^-	SO_4^{2-}	NO_3^-				
I-1	468 009	969 206	6 May 04	Spring	720	22·7	7·3	26·5	6·1	57·4	19·7	—	—	—	−2·53	−10·3	1·6	—[b]
I-2	482 459	976 111	6 May 04	198	797	23	7·6	35·8	4·8	58·1	24	4·1	4·7	3·8	−1·76	−5·6	1·1	—[b]
I-3	481 266	981 756	6 May 04	Spring	713	21·8	7·6	35·5	3·7	44·1	24·9	8	12	16·7	−1·87	−5·3	1·1	—[b]
I-4	473 429	996 367	6 May 04	200	—	81·9	—	952	20	4·3	0·8	42·6	71	0·8	−5·28	−24·3	0·7	—[b]
I-5	473 417	996 301	6 May 04	80	—	39·8	7·3	786	29	5·1	1·3	39·8	59·2	<0·1	−4·70	−19·8	—	—[b]
I-6	503 833	1 012 823	6 May 04	Spring	330	20·9	8	12·1	3·4	50·4	11·4	17·6	3·7	21·2	−1·09	2·7	5	—[b]
I-7	493 895	1 005 051	6 May 04	90	215	18·8	7·3	10·2	3·2	28·1	5·7	1·2	0·5	0·8	−2·63	−4·9	0·7	—[b]
I-8	479 954	977 334	7 May 04	—	674	24·5	7·7	23·6	3·6	40·1	26·8	6	5·4	13·2	−1·44	−0·2	0·7	—[b]
I-9	473 226	1 003 832	9 May 04	Spring	94	16·4	7·2	2·4	2	6·6	1·4	0·4	0·7	6·2	−3·63	−11·9	—	—[b]
I-10	473 372	1 005 069	9 May 04	9	72	15·8	6·9	2·5	1·3	6·2	1·3	1·3	0·4	5	−3·12	−8·3	—	—[b]
I-11	474 780	1 002 955	9 May 04	Spring	341	17·1	6·6	9·5	2·8	27·8	5·9	22·7	5·6	—	−1·23	1·8	4·9	—[b]
I-12	474 020	990 175	9 May 04	—	785	22·7	7·4	15·6	3·6	758	18·5	—	10·1	—	−1·14	3·9	—	—[b]
I-13	471 574	998 091	9 May 04	—	—	21·8	7·1	21·6	4	56·8	11·9	2·4	2	1·4	−2·23	−5·7	0·7	—[b]
I-14	474 325	984 188	9 May 04	125	764	22·6	7·7	20·7	4·8	58·8	26	19·4	8·9	13·6	−1·44	−4·5	—	—[b]
I-15	476 568	981 554	9 May 04	—	1014	22	7·1	33	5·6	83·8	26·7	28·3	20·9	—	−1·48	−4·2	—	—[b]
I-16	465 900	1 002 875	11 May 04	110	171	19	6·8	25	7	12·3	4	1·98	4·29	<0·1	−4·12	−14·7	0	—[b]
I-17	483 250	999 600	11 May 04	—	358	20	6·6	17·5	3·3	52·8	11	2·03	46·8	<0·1	−4	−19·5	0·7	—[b]
I-18	475 405	995 881	11 May 04	—	135	16·9	7·1	4·8	1·7	15·4	4·07	4·87	2·2	3·25	−1·3	23·9	8·01	—[b]
I-19	486 219	1 001 227	11 May 04	—	530	21·3	7·4	103	1·5	20·5	6·1	0·84	0·98	0·76	−2·95	−1·36	1·3	—[b]
I-20	474 600	995 500	11 May 04	201	3630	28·3	8·3	9·68	9·7	3·26	7·8	43·6	62·6	1·38	−5·88	−28·3	—	—[b]
EP-6	479 600	977 550	24 Jan 02	96	550	24·7	7·53	25	2·9	—	—	5	10·2	1·9	−1·31	0·51	0·85	—[c]
SP-20	473 998	1 004 000	31 May 02	Spring	77·3	18·1	6·33	—	—	—	—	10	0·4	0·3	−3·57	−10·28	0	—[c]
SP-14/15	478 600	1 006 350	11 Jun 02	Spring	—	15·5	6·25	—	—	—	—	—	—	—	−3·3	−8·01	14·96	—[c]
BH-13/69	478 695	976 491	27 Jan 02	69	272	23	7·41	—	—	—	—	—	—	—	−0·71	3·22	1·41	—[c]
TW-1/72	477 945	976 985	26 Jan 02	72	430	25·4	9·02	—	—	—	—	—	—	—	−5·04	−27·2	0	—[c]
BH-5B	476 575	975 607	27 Jan 02	78	269	23·4	7·33	—	—	—	—	—	—	—	−1·32	−1·17	0·2	—[c]
SP-13	470 750	1 003 800	31 May 02	Spring	—	—	—	—	—	—	—	—	—	—	−3·2	−1·43	0·39	—[c]
SP-18	478 850	1 009 500	24 Jun 02	Spring	—	18·9	7·52	—	—	—	—	—	—	—	−3·2	−4·08	3·92	—[c]
SP-17	478 350	996 700	25 Jun 02	Spring	—	20·6	6·42	—	—	—	—	—	—	—	−3·2	−4·36	5·7	—[c]
SP-19	477 320	983 180	25 Jun 02	Spring	—	22·1	7·43	—	—	—	—	—	—	—	−3·2	−2·34	0	—[c]
P-1	478 200	976 850	26 Jan 02	63	165	25·6	7·32	25	4	—	—	8	17·4	2·6	−1·47	−1·6	0·33	—[c]
P-2	469 050	970 300	15 Mar 02	71	182	23·2	8·15	25	5·7	—	—	5	4·6	1·3	−2·27	−7·21	2·47	—[c]
BH-13/57	478 695	976 491	26 Jan 02	57	250	23	7·46	—	—	—	—		—	—	−0·71	2·28	1·3	—[c]
TW 2	477 945	976 985	8 Jan 02	116	536	26·7	7·81	39	7·4	—	—	7	9·5	1·4	—	—	0	—[c]
BH 3A	473 576	972 821	24 Jan 02	77	620	25·4	7·74	—	—	—	—	—	—	—	—	—	7·35	—[c]

P-5	484 475	975 622	14 Jan 02	126	544	36·2	8·53	51	12	—	—	7	16·2	0·2	—	—	0·15	—[c]
TW 3	489 950	976 019	13 Oct 01	126	714	—	7·74	29	3·7	—	—	2·5	2·6	2·2	—	—	0·3	—[c]
TW 4	485 798	968 308	2 Oct 01	120	535	24·2	—	—	—	—	—	2·5	1·2	1·7	—	—	0·78	—[c]
TW 5	480 517	977 974	19 Nov 01	120	678	29·1	7·42	33	6·3	—	—	2	0·9	1·8	—	—	0·01	—[c]
TW 1	481 134	958 713	24 Nov 01	210	1107	34	8·51	188	5·7	—	—	190	51·9	0·3	—	—	0	—[c]
D-1	481 344	953 107	03 Jun 01	—	535	25·8	7·68	34	10	—	—	3	11·4	1·7	—	—	0	—[c]
D-2	472 500	953 100	3 Jun 01	120	1120	32	7·17	224	32	—	—	—	—	—	—	—	0	—[c]
D-3	485 968	962 532	4 Jun 01	Spring	668	35·2	7·22	—	—	—	—	—	—	—	—	—	0·26	—[c]
D-4	483 232	961 543	4 Jun 01	—	562	—	7·54	33	11	—	—	4	4	2·5	—	—	0·01	—[c]
D-5	483 150	976 100	4 Jun 01	—	564	—	8·18	—	—	—	—	5	14·5	2·2	—	—	0·03	—[c]
D-6	475 400	976 800	6 Jun 01	—	526	—	7·87	34	10	—	—	5	—	1·9	—	—	0	—[c]
P-3	482 950	963 800	7 Jun 01	50	729	21·2	8·09	37	6·9	—	—	6	16·7	5·5	—	—	2·32	—[c]
P-4	475 780	956 477	10 Dec 01	79	524	23·5	8·22	27	5·8	—	—	4·5	5·4	1·4	—	—	0	—[c]
G-1	471 215	992 561	30 May 99	Spring	860	21·8	7·3	—	—	—	—	—	12·6	116	−1·73	1	6·5	—[d]
G-2	470 934	989 795	21 May 99	—	310	23·4	7	16·5	6·4	30·3	8·2	2·26	1·79	3·04	−3·01	−10·3	0	—[d]
G-3	473 226	996 424	10 Jun 99	200	3850	67·1	7·1	965	21	51	0·68	37	68·1	0·73	−5·36	−25·6	0	—[d]
G-4	466 425	992 809	21 May 99	—	281	20·6	6·6	13·6	3·9	30·6	8·6	2·65	1·74	6·35	−2·79	7·7	0	—[d]
G-5	466 896	996 961	29 May 99	Spring	318	18	6·8	32	2·6	35·4	11·6	4·51	4·42	7·89	−1·85	0·4	3·2	—[d]
G-6	470 227	996 307	8 Dec 00	—	406	25·2	8·1	25	2·1	35·5	12·5	23·6	7·03	41·8	−3·13	−10·8	—	—[d]
G-7	471 418	998 260	4 Jun 99	—	1301	20	6·5	14·4	2·6	153	56·1	209	18·6	241	−1·72	2·81	10·4	—[d]
G-8	474 009	998 554	3 Jun 99	—	1263	21·5	7	19·5	4·8	160	44·6	134	99·4	32·9	−1·47	3·1	11·4	—[d]
G-9	473 735	996 188	25 May 99	300	3520	78	6·6	992	16	1·62	5·82	41·3	82·4	0·68	−5·2	−24	0	—[d]
G-10	474 754	988 714	30 May 99	Spring	880	17·4	7·4	43	2·2	129	19	146	57·1	66·6	−1·1	4·2	9·4	—[d]
G-11	479 562	997 182	12 Jun 00	—	177	21·3	6·3	13·3	2·2	16	3·7	3·58	2·66	8·58	−2·8	−7·4	—	—[d]
G-12	472 675	996 208	3 Jun 99	—	653	22	6·5	16·7	1·7	85·5	25·6	41·8	33·7	55·3	−1·49	2·4	10	—[d]
G-13	471 942	996 209	4 Jun 99	—	785	27·4	6·9	19·5	2·2	82·2	41	59·4	20·1	89·9	−1·88	−1·2	8·5	—[d]
G-14	473 476	995 836	3 Jun 99	—	2970	33·5	8·1	795	11	0·46	5·98	25·9	34·4	0·17	−4·77	−21	0·4	—[d]

[a] Electrical conductivity.
[b] Original data.
[c] AAWSA (archive data).
[d] Gizaw (2002).

Table II. Rainfall major ion chemistry at selected sampling stations in the Akaki catchment, central Ethiopia

Sample ID	Location (UTM)		Chemical concentration (mg l^{-1})								Na/Cl	Sampling date
	X	*Y*	Na^+	K^+	Ca^{2+}	Mg^{2+}	Cl^-	NO_3^-	SiO_2	SO_4^{2-}		
RS561	472 136	996 721	0·52	0·2	4·64	0·4	0·9	—	1·23	3·58	0·58	7–25 Jun 2003
RS562	472 136	996 721	0·15	0·11	2·63	0·24	0·38	—	0·65	2·39	0·4	25 Jun–11 Jul 2003
RS563	472 136	996 721	0·13	0·11	1·63	0·13	0·32	—	0·72	2·27	0·42	11–18 Jul 2003
RS564	472 136	996 721	0·13	0·12	1·18	0·13	0·28	—	0·36	1·86	0·45	18–25 Jul 2003
RS565	472 136	996 721	0·09	0·1	0·98	0·04	0·21	—	0·33	1·81	0·44	25 Jul–1 Aug 2003
RS566	472 136	996 721	0·08	0·12	0·66	0·07	0·16	—	0·25	1·29	0·49	1–8 Aug 2003
RS567	472 136	996 721	0·07	0·11	0·59	0	0·15	—	0·26	1·23	0·47	8–19 Aug 2003
RS568	472 136	996 721	0·12	0·13	0·72	0·03	0·29	—	0·29	1·47	0·43	19–26 Aug 2003
RS569	472 136	996 721	0·18	0·07	1·44	0·06	0·38	—	0·27	2·38	0·46	26 Aug–2 Sep 2003
RS5610	472 136	996 721	0·23	0·16	1·39	0·23	0·52	—	0·5	2·65	0·43	2–10 Sep 2003
RS5611	472 136	996 721	0·56	0·42	0·2	0·03	0·52	—	0·12	0·48	1·07	16 Sep 2003
RS5612	472 136	996 721	0·55	0·34	0·86	0·17	0·54	—	0·17	1·64	1·01	21 Sep 2003
RS1	474 208	998 523	0·2	0·2	<0·20	<0·10	0·3	<0·10	—	3·9	0·67	1–31 Mar 2004
RS2	474 208	998 523	0·3	0·4	0·1	<3	0·4	0·7	—	1·2	0·75	1–15 Apr 2004
RS3	474 208	998 523	0·3	0·4	<0·30	0·1	0·4	1·8	—	1·7	0·75	16 Apr–5 May 2004
RS4	459 777	1E+06	0·2	0·3	<0·30	0·2	0·6	1·8	—	1·4	0·33	1–31 Mar 2004
RS5	459 777	1E+06	0·2	0·4	<0·4	0·2	0·6	1·3	—	2·1	0·33	1 Apr–5 May 2004
RS6	472 136	996 721	0·8	1·5	7·5	0·6	2·2	18·7	—	30	0·36	1–31 Mar 2004
RS7	472 136	996 721	0·3	0·5	<3	0·2	0·9	3·4	—	11·3	0·33	1 Apr–5 May 2004
RS8	475 977	993 369	0·7	1	3·5	0·4	1·8	12·2	—	6·3	0·38	1–31 Mar 2004
RS9	475 977	993 369	0·3	0·3	<2	0·1	0·7	2·3	—	2·7	0·42	1 Apr–5 May 2004
RS10	503 448	1E+06	2·2	4	8	0·9	6·5	5·3	—	10·8	0·34	15 Mar–5 May 2004

Table III. Chloride mass balance for the Akaki catchment, where $[Cl]_{sm}$ and $[Cl]_{gw}$ are the soil moisture and groundwater chloride concentrations respectively. No input of chloride ions from geogenic and anthropogenic sources other than precipitation is assumed

Station no.	Location (UTM)		Chloride concentration (mg l^{-1})			Precipitation		Recharge (mm)		Remark
	X	*Y*	Soil moisture[a]	Groundwater[b]	Precipitation (ave.)	Sample alt. (m)	Amount (mm)	Diffuse	Total	
I	456 121	1 002 559	0·4	7·1	0·5	2605	1253	—[c]	88·2	$[Cl]_{sm} \ll [Cl]_{gw}$
II	463 040	992 413	1·4	1·3	0·45	2400	1207	387·9	417·8	29·9 mm[d]
III	464 233	988 926	1·4	6·7	0·94	2444	1207	—[c]	169·34	$[Cl]_{sm} \ll [Cl]_{gw}$
IV	478 878	998 531	0·5	2·5	0·83	2300	1063·9	—[c]	353·2	$[Cl]_{sm} \ll [Cl]_{gw}$
V	488 858	1 003 086	0·5	3·2	0·83	2300	1063·9	—[c]	275·9	$[Cl]_{sm} \ll [Cl]_{gw}$
VI	494 228	1 005 724	1·3	2·3	0·68	2300	1063·9	—[c]	314·5	$[Cl]_{sm} \ll [Cl]_{gw}$
VII	501 208	1 013 728	5	3·2	0·68	2550	1110·9	151	236	85 mm[d]
Mean annual groundwater recharge: 265·00 mm										

[a] Profile average.
[b] From 60–100 m deep intermediate wells.
[c] Relatively low soil moisture chloride concentration for the computation of diffuse recharge.
[d] The 'by-pass' or 'preferential flow' component of recharge.

(IAEA/WMO, 2004), show that the Addis Ababa rainfall, not withstanding its location and higher altitude, is highly enriched compared with the other stations (Figure 5). Similar observations have been made by Gizaw (2002), Rozanski *et al.* (1993) and Kebede (personal communication).

Rainfall in the study area varies seasonally and with altitude. The seasonal rainfall patterns caused corresponding seasonal variations in the isotopic composition due to changes in moisture source, moisture transport mechanisms and amount of moisture. Higher monthly precipitation results in increasingly negative $\delta^{18}O$ and δ^2H values (Mazor, 1997). A clear monthly rainfall amount effect for the Addis Ababa station is observed (Figure 6). Plotting the mean monthly rainfall versus mean monthly $\delta^{18}O$ (‰) produces a coefficient of determination r^2 of 0·89 excluding the so-called winter *non-rainy* dry months. The dry months are characterized by episodic rains that deviate from the above relation and could be attributed to rainfall produced by localized moisture sources different from winter (Indian Ocean) and summer (Atlantic Ocean) moisture sources.

Stable isotopic data comparison between precipitation and groundwaters in the catchment apparently shows relatively enriched precipitation compared with groundwater, which poses the problem of recharge sources. Figure 6 shows the seasonal variation of precipitation and a corresponding monthly amount effect of precipitation on the $\delta^{18}O$ values. Hence, comparative analysis of summer rainfall isotopic values, particularly those of July

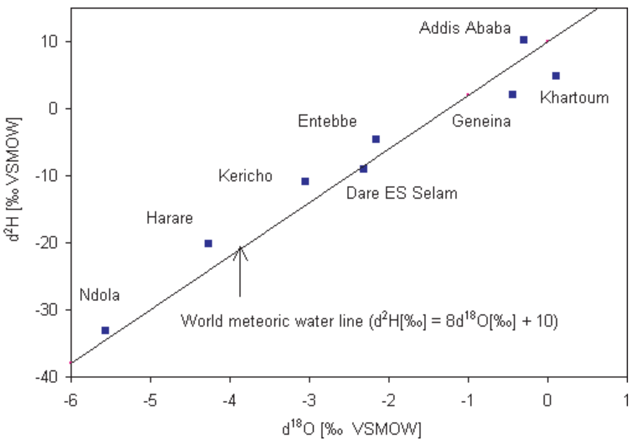

Figure 5. Plot of $\delta^{18}O$ versus $\delta^{2}H$ for selected East African GNIP stations (data from IAEA/WMO (2004))

and August (Figure 7a and b), with the isotopic values of groundwater clearly explains summer rainfall being the source of recharge. This, in turn, implies that recharge in the Akaki catchment is limited to the summer rainy months of late June to early September (mainly to the months of July and August). It appears that winter rainfall is lost through high evaporation–evapotranspiration rates that take place within a few metres of the unsaturated zone after relatively long dry periods and accompanying high accumulated soil moisture deficits. However, some 'by-pass' recharge (confirmed by infiltration tests through a Geulph infiltrometer at different points of the catchment) occurs from the winter rainy months of March and April, during which its isotopic signature in the groundwater may have been lost through dilution by a relatively higher summer recharge amount.

Field investigation of moisture profiles at two representative sites (one through a shallow soil to bedrock and the other in an area of relatively thick unsaturated soil) at the end of the winter rainy season (Figure 8) show that the winter rainfall has not penetrated more than a maximum depth of 50 cm, supporting our isotopic evidence of a very poor contribution of winter precipitation to groundwater recharge.

GIS analysis of the variation of stable isotopic composition and ^{3}H values of groundwater in the Akaki catchment spatially and with depth reveals four spatial zones (Figure 9) and two flow systems:

- Zone 1 groundwaters are located at a relatively higher altitude (Intoto ridge system) and, with the exception of a few samples, the groundwater is found to have high ^{3}H values (some bomb ^{3}H and younger) and moderately depleted stable isotope content. Groundwater in this group is interpreted to have been recharged by summer rainfall dominantly through fractures (preferential or 'by-pass' recharge mechanisms), which is in line with geologic evidence. In most cases such water types plot above the LMWL, implying that recharge is taking place prior to evaporation (Figure 10).
- Zone 2 groundwaters in the central sector of the catchment show bomb or post-bomb ^{3}H values and a relatively enriched stable isotopic composition. This group of waters is found in the unconfined aquifer systems of the catchment and is recharged directly from precipitation, both through diffuse and preferential recharge mechanisms.
- Zone 3 groundwater is located at the centre of the central sector of the catchment and is characterized by pre-bomb ^{3}H (zero) values. This is isotopically the most depleted groundwater in the catchment, coincident to the Filwoha Fault zone. This category of groundwater is characterized by a high-temperature thermal system and its stable isotopic composition is uniquely depleted. As a result, recharge could have taken place either from a different precipitation regime having a depleted isotope content or the present meteoric water has circulated deep and the isotope signal has been altered by isotope exchange with CO_2 gas originating from deeper sources, or both. Such a negative $\delta^{18}O$ shift has been attributed to interaction of

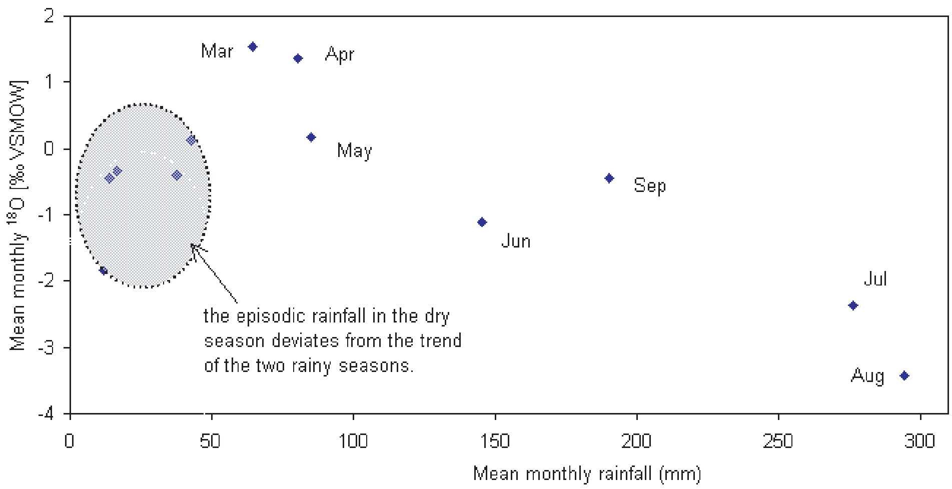

Figure 6. Monthly rainfall (mean) amount effect on ^{18}O values at Addis Ababa (isotope data from IAEA/WMO (2004) and rainfall data from the Ethiopian Meteorological Authority)

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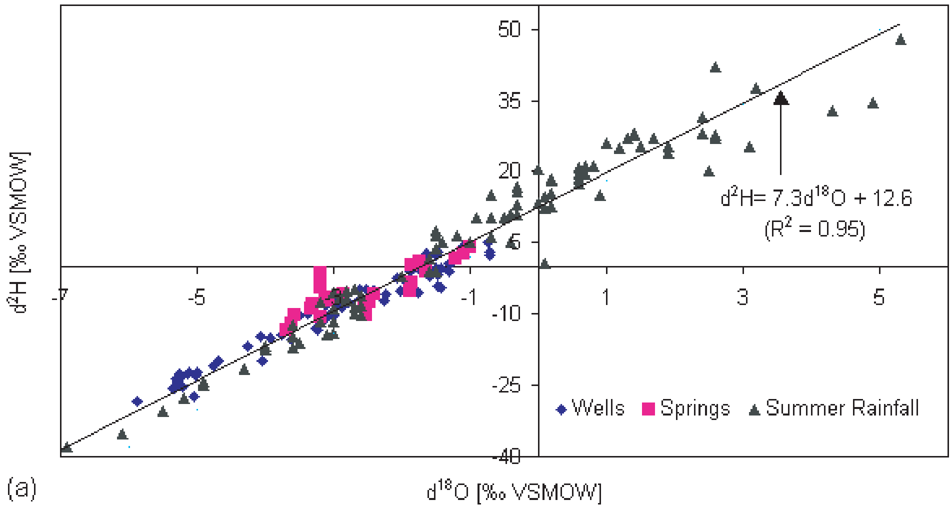

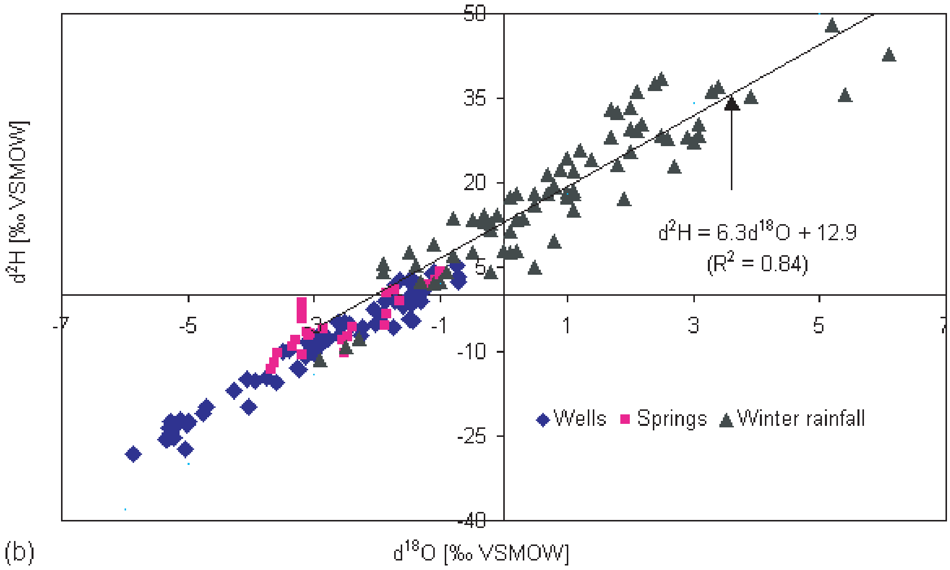

Figure 7. Graph showing comparative stable isotopic plot of (a) summer rainfall and (b) winter rainfall with groundwater in the Akaki catchment, central Ethiopia

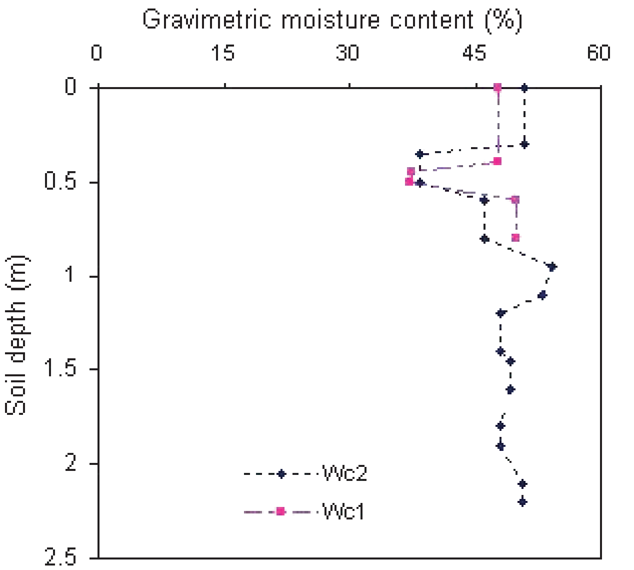

Figure 8. Soil moisture profile measured at two different locations after the winter rain of 2004 in the Akaki catchment, central Ethiopia

meteoric H_2O with deep CO_2-rich sources (Clark and Fritz, 1997). A similar negative $\delta^{18}O$ shift in South African thermal springs was also observed by Mazor (1997).

- Zone 4 groundwaters are located at the south central and southern sectors of the catchment, including the Akaki well field. They are relatively enriched isotopically, containing both pre-bomb and younger waters. Zone 4 waters are similar in terms of stable isotopic signatures to zone 2 waters, but they have a relatively lower ^3H content that suggests a relatively longer residence time and hence a wider recharge area including zones 1 and 2. In most cases, samples in this zone plot below the LMWL (Figure 10), indicating evaporation during recharge. This suggests possible ponding effects by a less permeable soil horizon from precipitation events and surface water recharge sources. This group also includes waters having relatively high ^3H values, whereby recharge is probably taking place through the

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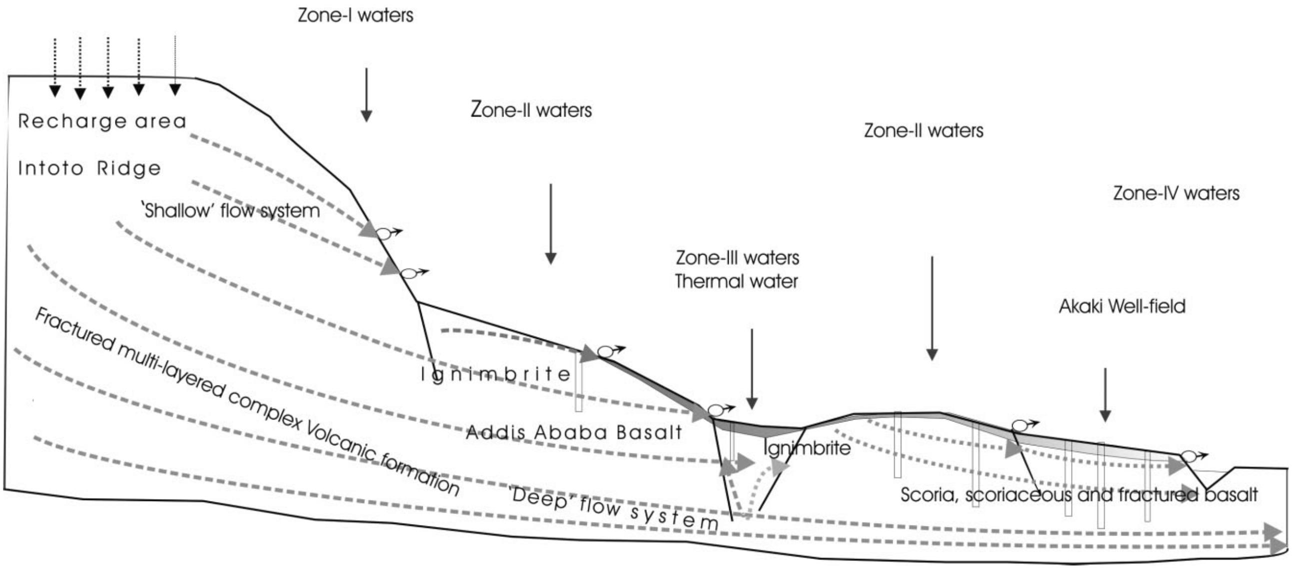

Figure 9. A conceptual model of groundwater flow and occurrence in the Akaki catchment, central Ethiopia

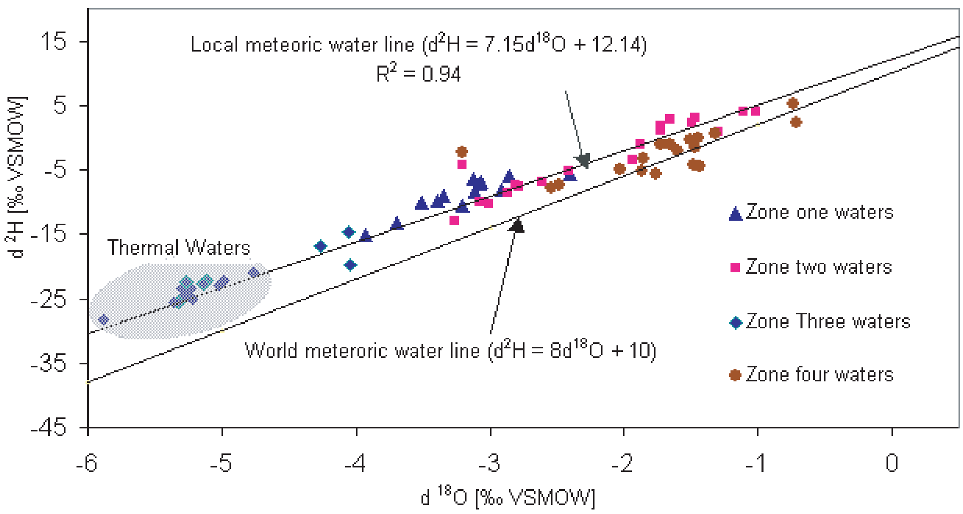

Figure 10. Plot of $\delta^{18}O$ versus δ^2H of groundwater in the Akaki catchment, central Ethiopia, along with the LMWL and GMWL

hydrogeologic windows of the scoria deposits, which are the major aquifers of the area. Localized circulation through the fracture systems within this sector of the catchment have also contributed to the high ^3H signals.

The high ^3H content of groundwater in the central sector of zone 2 is also characterized by high total electrical conductivity values, which suggest the system's vulnerability to any form of anthropogenic pollution. Notably, this area is one of the most populated and developed sectors of the Akaki catchment. Further observation of the ^3H values of the groundwater in the catchment also reveals two conceptual flow systems. The first occurs at a shallow depth (up to about 100 m) with a relatively modern ^3H value and is confined to the unconfined and shallow confined aquifer system. The second is a deep flow-system taking place at a depth below 100 m, probably continuous from the Intoto ridge down to the Dukem plain out of the Akaki catchment in the south, where most of the waters are pre-bomb.

The CMB estimation of mean annual groundwater recharge of seven sites (Table III) for the study catchment is calculated to be 265 mm, which amounts to 23% of the weighted mean annual areal precipitation of the catchment. This value appears to overestimate the groundwater recharge compared with previous estimates (TAHAL Consulting Engineers Ltd, 1992; AAWSA *et al.*, 2000) and with what is expected for a sub-humid tropical catchment with considerable runoff and evapotranspiration components. Hence, further recharge estimates through relatively rigorous methods are required. However, the result has explained and supported the isotopic evidence for the existence of diffuse and preferential recharge mechanisms. The dominant mechanism varies depending on the thickness of the unsaturated soil horizon and the degree of fracturing in the outcropping bedrock.

CONCLUSIONS

Recharge patterns, possible flow paths and the relative age of groundwater in the Akaki catchment, central Ethiopia, have been investigated using stable environmental isotopes $\delta^{18}O$ and $\delta^{2}H$ and radioactive ^{3}H coupled with conservative chloride measurements. Only summer monsoon rainfall stable isotopic signatures are encoded in the groundwater of the area, implying that significant recharge occurs predominantly in the months of late June to early September of the major Ethiopian rainy season. It appears that winter recharge is lost through high evaporation–evapotranspiration taking place in the unsaturated zone after relatively long dry periods with high accumulated soil moisture deficits. CMB coupled with the isotope results demonstrate both preferential and piston flow groundwater recharge mechanisms.

It was found that the CMB estimate of the annual mean groundwater recharge for seven sites is 265 mm, which amounts to 23% of the weighted mean annual areal precipitation of the catchment. The CMB method, with limited data, has overestimated the mean annual groundwater recharge rate. However, the CMB method coupled with the isotopic evidence has explained the contribution of both preferential and piston flow mechanisms to groundwater recharge in the Akaki catchment. As a result, catchment-scale soil-water balance models, which only take into consideration the piston-type flow recharge mechanism, are insufficient to quantify groundwater recharge in the Akaki catchment.

The stable and radioactive isotope measurements further revealed that groundwater in the Akaki catchment is compartmentalized into zones and it appears that a complete mixing following the flow paths is lacking and commensurate with lithologic complexity. The unconfined aquifer in the central sector of the catchment (zone 2) contains a relatively high ^{3}H value. These young waters with active recharge are highly vulnerable to anthropogenic pollution and, thus, require protection. An uncommon highly depleted stable isotope and pre-bomb groundwater observed in a nearly east–west stretch in the central sector of the catchment is coincident with the Filwoha Fault zone. Here, deep circulating meteoric water has either lost its isotopic content through exchange reactions with CO_2 originating from deeper sources or has recharged with precipitation from a different rainfall regime with a depleted isotopic content.

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