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# A geochemical survey of spring water from the main Ethiopian rift valley, southern Ethiopia: implications for well-head protection

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**Abstract** The report discusses the stable isotope values and major solute compositions of 16 springs and river-water samples along a topographic gradient in the main rift valley of southern Ethiopia. Most of the springs used for drinking water supplies discharge from local flow systems at scales of only tens of meters. The  $\delta^{18}\text{O}$  and  $\delta\text{D}$  values of waters unaffected by shallow evaporation form a local meteoric water line of  $\delta\text{D}=8.1\delta^{18}\text{O}+19.0$ , almost identical to that for the eastern Mediterranean area. The  $\delta^{18}\text{O}$  values show an altitude effect of  $-0.5\%$  per 100-m elevation rise. Total dissolved nitrogen concentrations locally exceed 6 mg/L (as N), and phosphate concentrations were elevated above background levels in some springs, exceeding 0.2 mg/L  $\text{PO}_4$ , probably due to agricultural practices upgradient of the springs. Modest well-head protection should be considered to protect public health from the effects of pollution by agricultural waste, given the very local scale of the flow systems providing spring water to Ethiopian villages.

**Résumé** Ce travail discute les teneurs en isotopes stables et les concentrations en éléments majeurs dissous des eaux de 16 sources et de la rivière, le long d'un profil topographique dans la principale vallée du rift en Éthiopie méridionale. La plupart des sources, utilisée pour les adductions d'eau potable, sont l'émergence d'aquifères locaux, à l'échelle de quelques dizaines de mètres seulement. Les valeurs de  $\delta^{18}\text{O}$  et de  $\delta\text{D}$  des eaux qui ne sont pas affectées par l'évaporation à proximité de la surface prennent place sur une droite des eaux météoriques locales de la forme  $\delta\text{D}=8,1\delta^{18}\text{O}+19,0$ , presque identique à celle connue pour les régions de Méditerranée orientale. Les valeurs de  $\delta^{18}\text{O}$  montrent un effet d'al-

titude de  $-0,5\%$  pour 100 m. Les concentrations en azote dissous total dépassent localement 6 mg/L (en N), et les concentrations en phosphates de certaines sources sont au dessus du bruit de fond, dépassant 0,2 mg/L en  $\text{PO}_4$ , probablement à cause des pratiques agricoles en amont des sources. Il faut mettre en place une protection minimale des puits pour protéger la santé publique des effets de la pollution par les rejets agricoles, étant donné l'échelle très locale des écoulements souterrains fournissant l'eau de source pour les villages éthiopiens.

**Resumen** El informe discute los valores de isótopos estables y la composición en iones mayoritarios de muestras de 16 manantiales y de agua de río recogidas a lo largo del gradiente topográfico, en el principal valle de rift (desgarre tectónico) del Sur de Etiopía. La mayoría de los manantiales que se aprovechan para abastecimiento de poblaciones están asociados a sistemas de flujo locales de apenas unas decenas de metros. Los valores de  $\delta^{18}\text{O}$  y  $\delta\text{D}$  correspondientes a las aguas no afectadas por evaporación somera constituyen una línea meteórica cuya ecuación es  $\delta\text{D}=8,1\delta^{18}\text{O}+19,0$ , casi idéntica a la del Mediterráneo Occidental. Los valores de  $\delta^{18}\text{O}$  muestran un efecto altitud equivalente a una reducción del 0,5% por cada 100 m de elevación. Las concentraciones de nitrógeno total disuelto exceden de forma local los 6 mg/L (expresado como N). Las concentraciones de fosfato en algunos manantiales son superiores en 0,2 mg/L de  $\text{PO}_4$  a los valores de base, probablemente debido a las prácticas agrícolas que tienen lugar aguas arriba. Se debería considerar la protección de las aguas subterráneas para salvaguardar la salud pública de la contaminación por lixiviados de origen agrícola, dada la pequeña escala de los sistemas de flujo que proporcionan agua a los pueblos etíopes.

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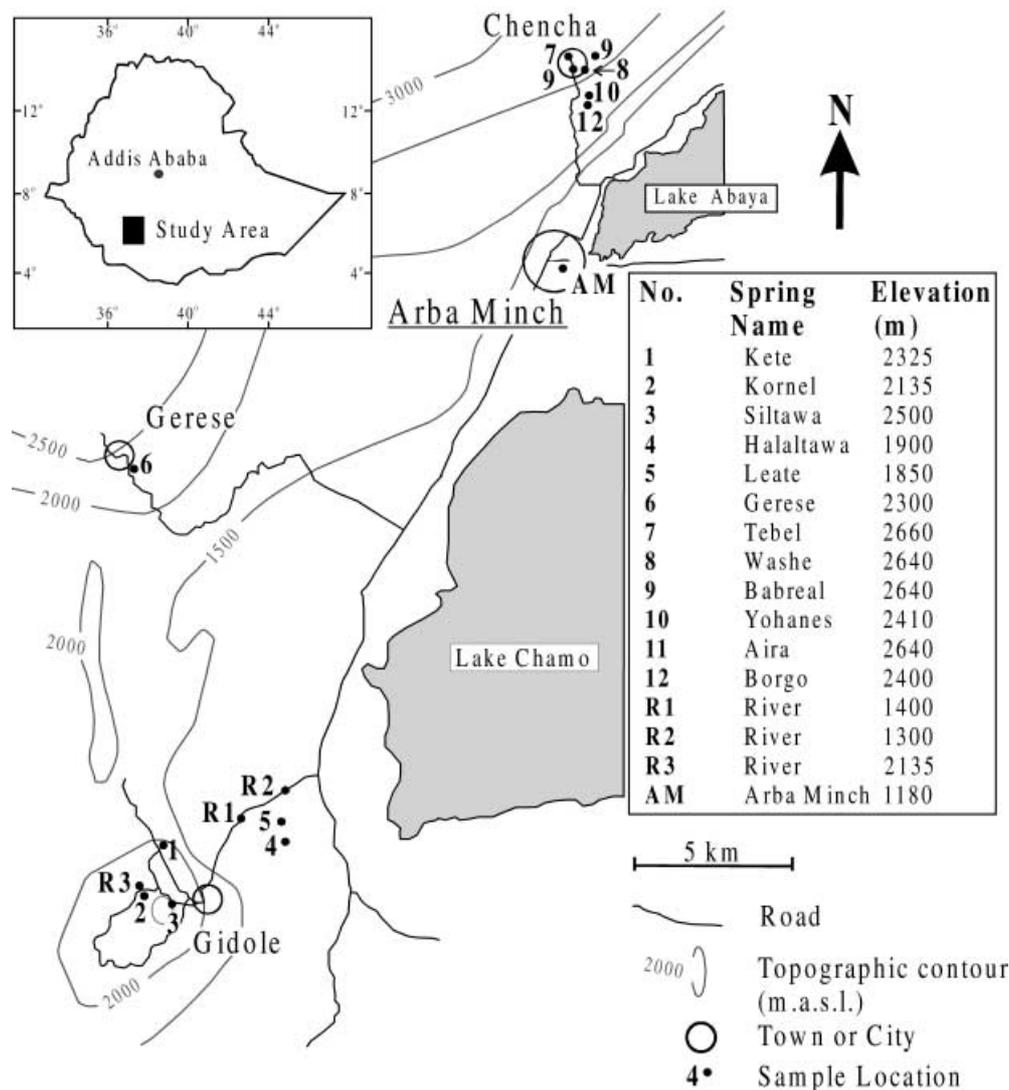
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## Introduction

Ethiopia has been devastated in the past 30 years by famines and a protracted civil war costing over 1 million lives. Despite the generally abundant water resources in Ethiopia, the impoverished rural population usually does

**Fig. 1** Map of the study area, including sampling sites, and spring names with elevations. Lines connecting the towns or cities are seasonal roads



not have access to a clean water supply. Although 36% of people in Sub-Saharan Africa have access to safe drinking water (Ethiopian Central Statistical Authority 1996), only 15% of the population of the southern region of Ethiopia has access to potable water. A survey of the rural population in the southern region of Ethiopia found that the vast majority of people rated water as the most important problem in their communities (Mangin 1991).

Many communities in southern Ethiopia rely on springs and seeps as potable water supplies. Many communities protect these sources of water by collecting and distributing the spring water, a practice commonly referred to as "spring capping." Two potential problems with capped springs are groundwater contamination and variable seasonal yields that diminish during the dry season. Seasonal variation in flow is an important consideration because the flow of some springs is as low as 0.2 L/s, and the slightest decrease can be catastrophic to the supply of potable water for local communities.

To better understand where springs are recharged and where "well-head" protection might be considered, water

samples were taken from springs throughout the Arba Minch region (Fig. 1) and analyzed for major solutes and stable-isotope values of water.

### Study Area

The sampled springs are located in the Main Ethiopian Rift Valley (Nelson et al. 1992), approximately 300 km southwest of the capital, Addis Ababa. The Ethiopian Rift Valley consists of Cenozoic volcanics 1–24 million years old (Baker et al. 1972; Chernet 1988). The bedrock in the region consists of basalt, trachyte, rhyolite, and ignimbrite and the western edges of Lake Abaya and Lake Chamo are covered by approximately a 1- to 2-km-wide plain of lacustrine and swamp deposits (Chernet 1988). Throughout the valley there are extensive north–south fault zones (Baker et al. 1972).

Figure 1 shows that the majority of samples were taken from Arba Minch and rural water supplies in three of the local communities: Chench, Gerese, and Gidole. To

the west and north of Arba Minch are steep hills where the three local communities are located. To the east of Arba Minch are two rift valley lakes, Lake Abaya and Lake Chamo, and extensive plains.

The towns of Chench, Gerese, and Gidole are located 36 km to the north, 28 km to the southwest, and 44 km to the south of Arba Minch, respectively. The city of Arba Minch is situated on a bluff 200 m above the lakes. To the east of the city, at the base of the bluff, are the high-yield Arba Minch Springs.

### **Hydrogeologic Setting**

The average rainfall in the region is between 1,000 and 1,500 mm/year, increasing with elevation (Chernet 1988). The majority of the precipitation occurs between April and September, and is heaviest in July and August (International Atomic Energy Agency/World Meteorological Organization 1998). The eastern rivers and streams that enter Lake Chamo and Lake Abaya are intermittent, and have little to no flow during the dry season. The evapotranspiration potential for the region is approximately 2,300 mm/year (Shahin 1985).

The volcanic aquifers are fractured, and yield modest amounts of water to wells and springs. Water wells usually have a specific capacity of about  $0.5 \text{ L s}^{-1} \text{ m}^{-1}$  and the mean permeability of the aquifer is in the order of 2 m/d (Chernet 1988). The groundwater has very low total dissolved solids, generally less than 500 mg/L (Chernet 1988).

## **Methods**

### **Sample Collection**

During the summer of 1998, 13 springs and three rivers were sampled in the Arba Minch region (Fig. 1) as part of a water-supply development project sponsored by HOPE International Development Agency. All samples were stored in 125-ml Nalgene bottles with no headspace to limit sample evaporation until analysis was done at Syracuse University geochemical laboratories.

Spring water samples were obtained from capped springs used primarily for rural water supply. Capped springs collect water in an enclosed concrete apron and distribute it to a local community by gravity-flow water systems. The storage capability of the capped springs varies from negligible to approximately  $8 \text{ m}^3$ . The mean residence time of the waters in a capped-spring system ranges from minutes for systems without a reservoir, to a day for systems with a reservoir. The stored water in the reservoir system is usually completely drained daily. Based on the short residence times, there should be negligible evaporation from a developed spring system.

### **Field Measurements**

In the field, concentrations of nitrate, nitrite, phosphate, and ammonium were measured in the field in spring wa-

ter using Chemtrics VVR Photometric Water Analysis System kits. The measurements were made within 24 h of sample collection, and the equipment was washed between each measurement with deionized water. The pH of the samples was not measured because the pH meter broke in transit to the field site. The location and elevation of the sampling points were extrapolated from 1:50,000-scale topographic maps (Ethiopian Mapping Authority 1995). All water samples were clear and had minimal turbidity.

### **Laboratory Measurements**

Cation concentrations were measured using direct-current plasma spectroscopy with a Beckman Spectraspan-V. The samples were analyzed three times each for Ca, K, Mg, and Na. Chloride and  $\text{SO}_4$  were measured with high performance liquid chromatography (HPLC) with Waters' instrumentation and the Waters' Millennium<sup>32</sup> data acquisition and processing software. Total alkalinity (the sum of the charged carbonate species) was calculated from the charge-balance equation (Drever 1997) because without accurate field pH measurements, it was not possible to speciate the dissolved inorganic carbon.

Values of  $\delta^{18}\text{O}$  and  $\delta\text{D}$  of water were measured with a mass spectrometer (Finnigan MAT 252, directly coupled to a HDO III water equilibrator), and are reported relative to the Vienna-Standard Mean Ocean Water (VSMOW).

## **Results**

### **Field Tests**

The results and summary statistics of the field testing for  $\text{NO}_2$ ,  $\text{NO}_3$ ,  $\text{PO}_4$ , and  $\text{NH}_3$  are presented in Table 1. Nitrite concentrations were negligible in all samples; less than 0.040 mg/L as N. In contrast, phosphate ranges from undetectable ( $<0.01$ ) to 0.650 mg/L. Ammonium ranges from 0.45–1.15 mg/L as N and the minimum concentration of nitrate is 0.09 mg/L as N. Concentrations of  $\text{NO}_3$  in two samples (the Halaltawa and Leate Springs) were greater than 5 mg/L of  $\text{NO}_3$  as N, the maximum measurable concentration with the Chemtrics kits for  $\text{NO}_3$  as N, and therefore could not be analyzed.

### **Laboratory Measurements**

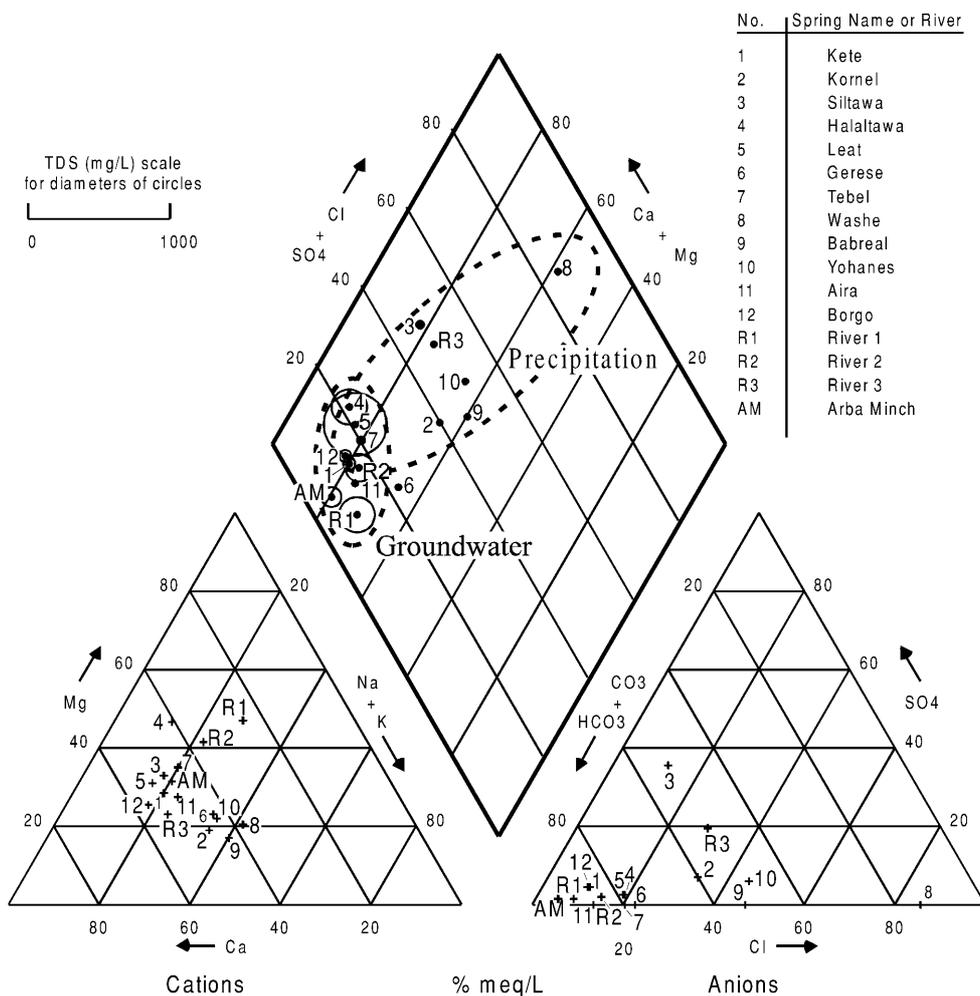
The results and summary statistics of the laboratory measurements of major ions (Ca, Mg, K, Na, Cl, and  $\text{SO}_4$ ) are presented in Table 1. Calcium ranges from 2.7–100 mg/L, Mg ranges from 0.88–36 mg/L, K ranges from 0.14–3.8 mg/L, and Na ranges from 1.3–34 mg/L. Chloride ranges from 0.62–32 mg/L and  $\text{SO}_4$  ranges from undetectable ( $<0.1$ ) – 11 mg/L. Alkalinity, calculated by mass balance, ranged from 8.3–495 mg/L as bicarbonate.

The values and summary statistics of the stable isotopes in water are presented in Table 1 and Fig. 2. The

**Table 1** Concentrations of nutrients, major solutes, and values of stable isotopes in spring water and river water from the Arba Minch region of southern Ethiopia. All measurements are in mg/L, except for  $\delta^{18}\text{O}$  and  $\delta\text{D}$  values which are in ‰ VSMOW

No.	Spring Name	NO <sub>2</sub> as N	PO <sub>4</sub>	NH <sub>3</sub> as N	NO <sub>3</sub> as N	Cl	SO <sub>4</sub>	Ca	Mg	K	Na	HCO <sub>3</sub>	$\delta^{18}\text{O}$	$\delta\text{D}$
1	Kete	0.01	0.10	1.1	0.58	3.0	1.6	16	5.5	1.3	6.5	88	-3.6	-10
2	Kornel	0.03	0.05	0.80	0.17	4.3	1.3	5.8	1.4	0.34	4.7	29	-3.1	-10
3	Siltawa	0.03	0.15	0.75	0.09	2.7	11	9.5	3.8	0.16	3.8	42	-3.6	-16
4	Halaltawa	0.02	0.15	0.80	>5	17	3.2	51	22	3.0	17	248	-2.6	-3
5	Leate	0.01	0.15	1.15	>5	32	5.7	100	36	3.8	33	495	-2.2	-7
6	Gerese	0.02	0.65	0.45	0.26	2.4	<0.1	5.1	1.6	1.2	3.9	30	-3.1	-4
7	Tebel	0.01	0.2	0.60	0.67	3.8	<0.1	9.3	4.4	0.92	4.5	54	-3.1	-6
8	Washe	0.02	0.05	0.55	2.6	13	<0.1	5.3	1.8	0.14	6.6	8.3	-4.2	-13
9	Babreal	0.04	0.35	1.0	1.4	3.4	<0.1	3.6	0.9	1.5	2.9	14	-4.1	-11
10	Yohanes	0.03	0.05	0.80	1	4.5	0.85	4.3	1.4	0.68	3.6	18	-4.1	-15
11	Aira	0.04	0.10	0.95	0.22	0.62	<0.1	2.7	0.90	0.28	1.3	14	-4.4	-21
12	Borgo	0.02	0.20	0.7	0.15	3.0	1.8	19	5.1	3.1	5.0	93	-1.5	-4
R1	River-1					8.2	1.7	27	31	2.0	34	318	-2.4	-4
R2	River-2					11	2.2	31	22	2.3	21	233	-1.6	1
R3	River-3	0.02	<0.01	0.45	1.0	2.9	2.7	5.0	1.3	0.26	2.3	19	-3.3	-8
AM	Arba Minch					2.4	1.1	27	10	1.6	12	164	-2.3	4
Maximum		0.04	0.65	1.15	>5	32	11	100.0	36	3.8	34	495	-1.5	4
Minimum		0.01	<0.01	0.45	0.09	0.62	<0.1	2.7	0.88	0.14	1.3	8.3	-4.4	-21
Range		0.03		0.70		31.4		97.3	35.1	3.66	32.7	486	2.9	25
Average		0.02	0.17	0.78	1.8	7.1	2.1	20.1	9.3	1.4	10	117	-3.0	-8

**Fig. 2** Piper trilinear diagram with TDS plotted as circles



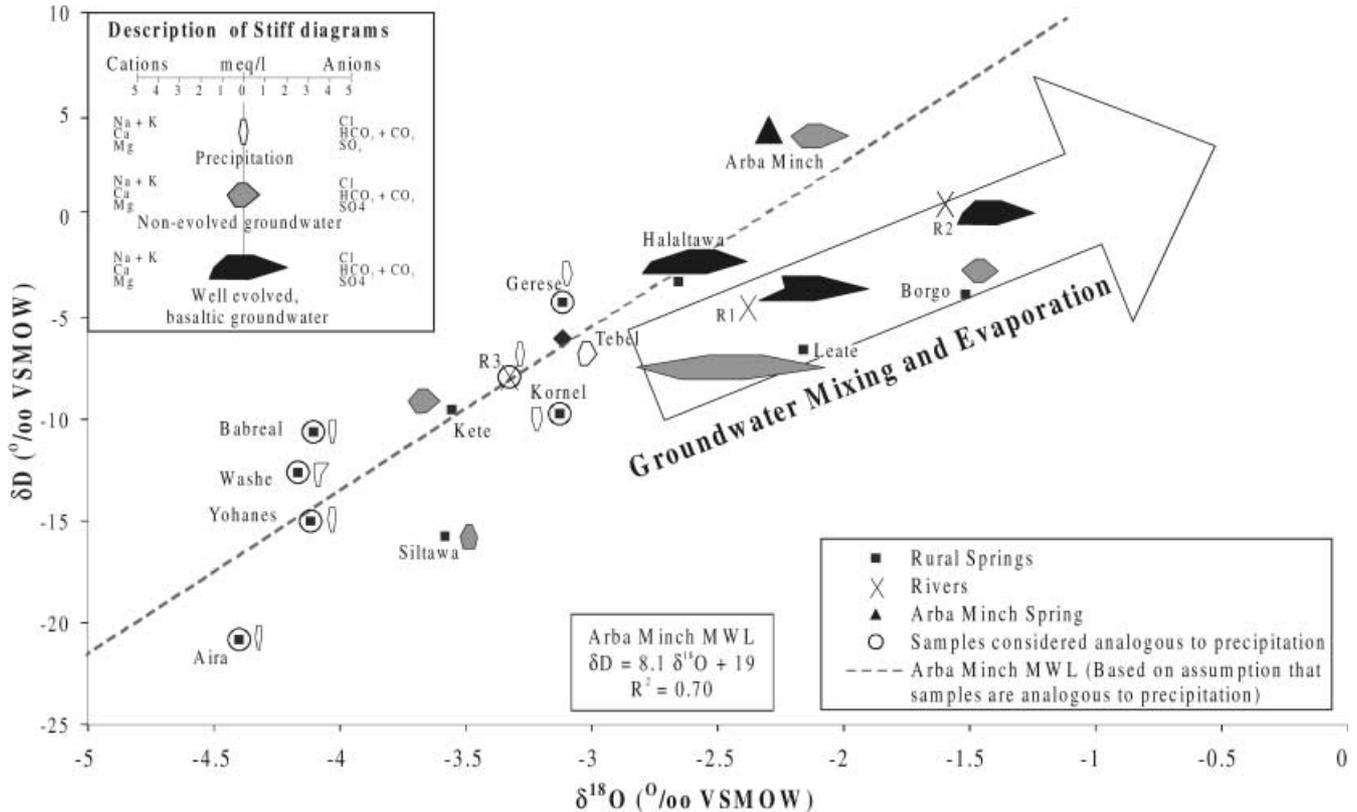


Fig. 3 Plot of  $\delta D$  versus  $\delta^{18}O$  values overlaid with Stiff diagrams

$\delta^{18}O$  values range from  $-4.4$  –  $-1.5$ ‰ VSMOW and the  $\delta D$  values range from  $-21$  –  $4$ ‰ VSMOW.

## Interpretation

Figure 2 shows the major solute concentrations plotted on a Piper trilinear diagram (Piper 1944). Two geochemical groupings are defined: (1) Ca-Mg-HCO<sub>3</sub>-type waters with TDS values between 100 and 500 mg/L and (2) a weak trend with low TDS plotting between the Ca-Mg-HCO<sub>3</sub>-type water and a point midway between the Ca-SO<sub>4</sub>- and Na-Cl-type waters. The Ca-Mg-HCO<sub>3</sub>-type waters are consistent with what is expected from the water-rock interactions in basaltic terrain of the main rift valley (Hounslow 1995).

Stiff diagrams (Stiff 1951; Fig. 3) demonstrate that seven of the samples are very dilute and consist of precipitation that has reacted minimally with the aquifer minerals (Kornel, Gerese, Washe, Babreal, Yohanes, and Aira Springs, and River-3). The size of the Stiff diagram is related to the extent of geochemical evolution of the water by water-rock interaction and/or evaporation. Precipitation in nearby Uganda has concentrations of Na, K, Ca, and Cl of 1.7, 1.7, 0.05, and 0.9 mg/L respectively (Berner and Berner 1987), slightly less than the respective concentrations in the most dilute Ethiopian spring waters.

In contrast, waters from River-1, River-2, and Halaltawa Spring have TDS >200 mg/L and the Stiff diagrams of the proportions of base cations and ligands are in the shape of an “arrowhead,” typical of water found in basalt aquifers (Hounslow 1995). The Stiff diagrams of the remainder of the spring samples, Kete, Halaltawa, Leate, Borgo, Arba Minch, and River 1, have “hexagonal” shapes and TDS concentrations consistent with a mixture of water that has reacted with basalt and the less chemically evolved dilute waters (Hounslow 1995).

The concentration of TDS is generally inversely related to the elevation of the springs as shown in Fig. 4. TDS increases from 13 to 446 mg/L over a descent of almost 100 m. This decrease in TDS is consistent with the concept that recharge from precipitation at higher elevations moves downward and laterally to spring-discharge points downslope, resulting in the discharge downslope having the longest subsurface residence time.

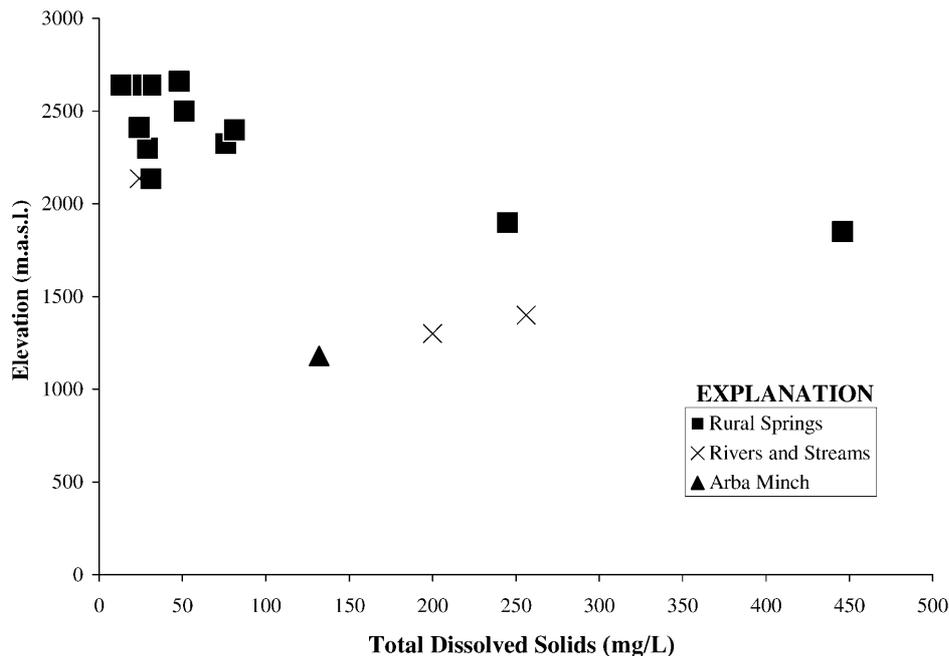
### Arba Minch Meteoric Water Line

The springs and rivers with low TDS best document the stable-isotope values of precipitation. If these samples are an analog for the precipitation chemistry, they form a local meteoric water line (MWL) for the Arba Minch Region (Fig. 3) with an equation of:

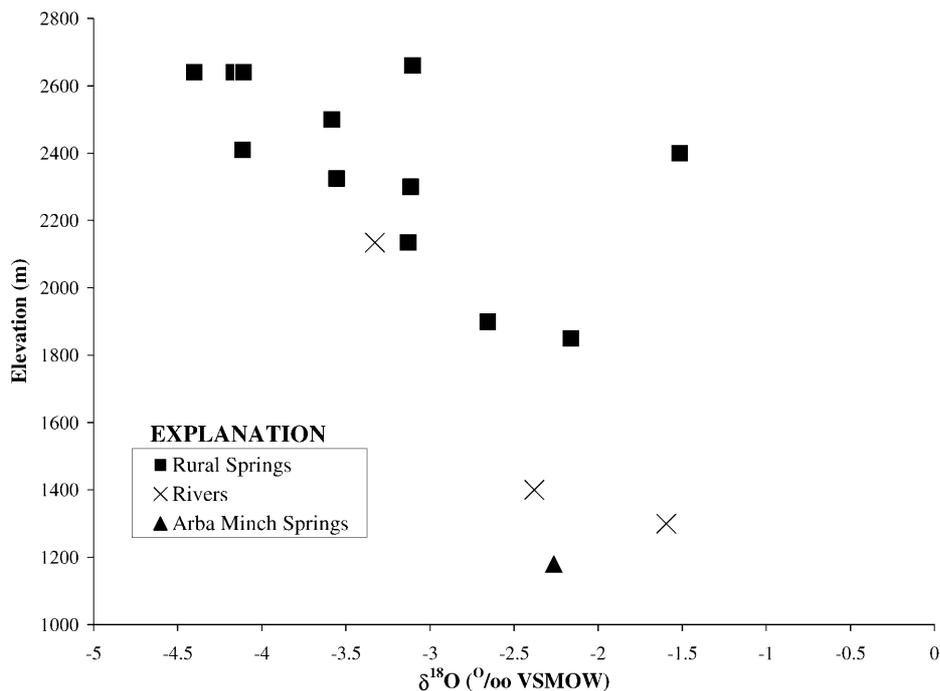
$$\delta D = 8.1 \delta^{18}O + 19 \quad (1)$$

and a coefficient of determination,  $R^2$ , of 0.70. The scatter of the data around the proposed MWL may be due to microclimatic changes between the sampling points. Ad-

**Fig. 4** Bivariant plot of TDS versus elevation



**Fig. 5** Plot of elevation versus  $\delta^{18}\text{O}$  values



ditionally, it should be noted that the local MWL is nearly identical to the MWL for eastern Mediterranean waters (Gat and Carmi 1970):

$$\delta\text{D} = 8.0\delta^{18}\text{O} + 22 \tag{2}$$

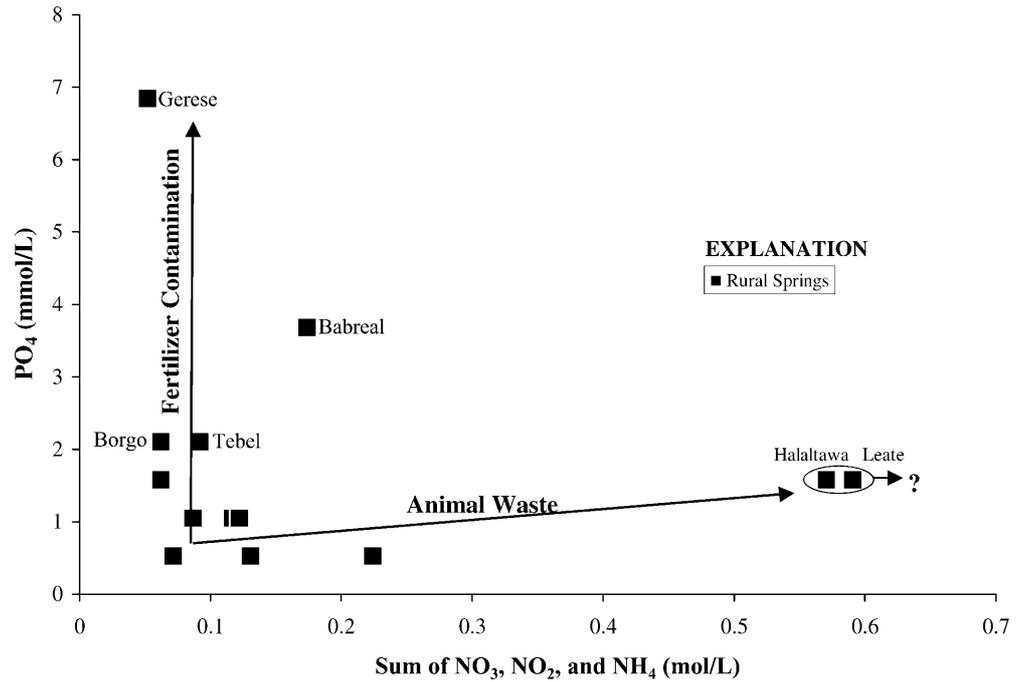
The Leate and Borgo Springs appear to fall on an evaporative trend with a lower slope than that of the Arba Minch MWL. The discharge at these springs is small, less than 0.2 L/s, suggesting that groundwater flow is focused in near-surface fractures susceptible to enrichment by evaporation from the water table. The River-2 and

River-3 samples also fall on an evaporative trend with a slope lower than the Arba Minch MWL. These rivers, located in a more arid region of the study area, were sampled at low flow and, volumetrically, were more susceptible to evaporative enrichment.

**Elevation Effect**

There is a significant inverse correlation between the isotope values of the water samples and the elevation of the springs. Assuming that the spring samples reflect the

**Fig. 6** Plot of  $\text{PO}_4$  vs. total nitrogen, the sum of  $\text{NO}_3$ ,  $\text{NO}_2$ , and  $\text{NH}_4$  for the rural spring samples



isotope value of precipitation, the region has an elevation effect of approximately  $-0.5\text{‰}$   $\delta^{18}\text{O}$  per 100-m rise, as shown in Fig. 5, near the high end of the globally observed range (Clark and Fritz 1997).

Some of the spring water does not plot close to the inverse trend. For example, the  $\delta^{18}\text{O}$  values of water in the Arba Minch Springs is  $-2.2\text{‰}$ , about 2‰ more depleted than would be predicted from the inverse relationship. Spring samples with a  $\delta^{18}\text{O}$  value similar to the Arba Minch Spring water are found at an elevation approximately 800 m higher, at approximately 2,000 m. Therefore, it is concluded that the Arba Minch Springs discharge from a flow cell that starts near an elevation of 2,000 m in the hills west of the city of Arba Minch.

### Agricultural Contamination

Some of the rural springs are contaminated with nitrate and phosphorus that are likely derived from agricultural waste. The Halaltawa and Leate Springs have greater than 5 mg/L of  $\text{NO}_3$  as N, probably the result of animal waste because the samples do not have elevated phosphate concentrations (Fig. 6; Hem 1985). For comparison, the maximum contaminant level for  $\text{NO}_3$  is 10 mg/L as N in the USA (Hem 1985). The Gerese, Babreal, Borgo, and Tebel Spring samples have  $\text{PO}_4$  levels above normal background levels of 0.1 mg/L (Hem 1985). Figure 6 shows that the source of  $\text{PO}_4$  is probably agricultural because increasing  $\text{PO}_4$  concentrations occur with only minor total N concentrations (Hem 1985).

The isotopic and geochemical analyses show that many of the spring waters consist predominantly of precipitation that moves along very short flow paths from infiltration areas to spring-discharge sites. Therefore, in

order to prevent contamination from animal and fertilizer waste, it is imperative that the area directly upgradient of the springs is not used for livestock grazing or holding, and farming. Livestock could be kept away from the immediate upgradient area with fencing or thorn-bush hedges, thus protecting the spring-water source.

### Conclusions

The major conclusions of this study are:

1. Assuming that some of the spring waters are equivalent chemically to precipitation, an MWL for the Arba Minch region can be derived with the equation:
 
$$\delta D = 8.1 \delta^{18}O + 19 \quad (3)$$
2. There is a significant inverse relationship between the elevation of the spring site and the geochemical composition and isotope values of the spring waters.
3. The elevation effect can potentially be used to discern the scale of the flow paths; for example, the source of the water for the Arba Minch Springs is approximately 800 m higher in the catchment area.
4. Some of the spring waters contain some nitrate contamination derived from animal waste. In order to protect against this problem, animals must be restricted from entering the area immediately upgradient of the rural springs. Additionally, some springs probably are contaminated with  $\text{PO}_4$  from agricultural fertilizers.

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