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Fog Drip as a Source of Groundwater Recharge in Northern Kenya

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Fog drip, or mist precipitation, has generally been neglected by hydrogeologists as a source of water, largely because of the difficulty in tracing fog through the hydrosphere. In the arid climate of northern Kenya, light stable isotopes aided in assessing the importance of fog drip. Fog was collected at localized fog-laden montane areas and determined to have δD values of about +3 to +16.6‰. Rain-derived groundwater was found to have δD values of about −25‰. However, groundwater in the fog-laden areas have δD values of about −12.5‰ and appear to be a mixture of fog and rain. It is thought that in special environments such as northern Kenya, fog drip may be an important source of infiltration and groundwater recharge.

INTRODUCTION

Fog drip, or mist precipitation, is the coalescing of fog droplets, 0.01–0.1 mm in diameter, on foliage from blowing fog which produce large drops that rain to the ground. The amount of fog drip that can be produced then is related to the duration of fog, to the type, density, and cross-sectional area of the collecting vegetation, and to the prevalence of wind. Fog drip has been observed by and has intrigued researchers for many years. Most, if not all, of the research, however, has centered around the importance of fog drip to the forest community. *Azevedo and Morgan* [1974] discussed the importance of fog drip on nutrient cycling, species composition of forests, and character of forest soils. *Grubb and Whitmore* [1966] suggest that moisture-laden air moving laterally from the sea against coastal ranges in Ecuador may be one of the most important environmental factors determining the distribution of tropical montane rain forest types. Other researchers emphasize fog drip as a source of water. *Kittredge* [1948] states that fog drip may, during certain seasons, increase the precipitation reaching the ground by amounts of up to 2 or 3 times over the amount recorded in open areas. *Byers* [1953] categorically states that fog drip is an important means of supplying water to the coast redwoods (*Sequoia sempervirens*) in California.

Various researchers have also collected fog drip. This collection is usually done in one of two ways, either by specially outfitting a standard rain gage with screens or other devices to catch blowing fog or by simply placing a standard rain gage under the canopy of trees in foggy areas. Both methods have been successful in demonstrating the existence of fog drip by recording impressive amounts of water.

Marloth [1903, 1905] (quoted by Kerfoot [1968]), in an attempt to mimic the natural environment, mounted bundles of reeds over the orifice of a standard 12.7-cm (5-inch) rain gage on Table Mountain in South Africa. He found that the amount of water caught in misty weather was much greater than that caught by a similar gage without reeds. Much later, *Azevedo and Morgan* [1974] produced as much as 36.3 cm of fog water during the summer dry periods on ridges bordering the Eel River Valley in northern California. They used a rain gage outfitted with an open-ended cyclindrical screen 80 cm high and 10 cm in diameter. In the Green Mountains of Vermont, *Vogelmann et al.* [1968] caught up to 66.8% more water with a rain gage outfitted with 16 cm of screen wrapped in a double coil than with unscreened gages nearby. The usefulness of fog collectors, of various types, is clear. However, the various types of fog collectors have not been standardized, rendering comparisons or interpretations impossible.

Success similar to that of the specially outfitted rain gage method has been obtained by the placement of rain gages under the canopy of trees in foggy areas. Rain gages mounted under Monterey pines (*Pinus radiata*) and eucalyptus trees in the Berkeley hills by *Parsons* [1960] produced as much as 25.4 cm (10 inches) of fog water during the dry summer months. *Oberlander* [1956], however, caught up to 150 cm (58.8 inches) of precipitation on Cahill Ridge in the San Francisco Bay area during a rainless period of about 6 weeks by simply placing a rain gage under a tanbark oak (*Lithocarpus densiflorus*).

Kerfoot [1968] and *Loewe* [1960] both published extensive reviews of the literature pertaining to the collection, measurement, and importance of fog drip by researchers around the world. Both of these reviews demonstrate the consensus in the research community with respect to the existence of fog drip as well as its ecological importance. However, a standard method of collection as well as measurement and interpretation is sorely lacking (H. Lamprey, personal communication, 1986).

Although fog collection and research have been performed for many years, producing a consensus in the research community about its ecological importance, few studies have dealt with the importance of fog drip by augmenting water supplies [*Goodman*, 1985]. To the authors' knowledge, only one study was concerned with the importance of fog drip to the hydrosphere [*Gurnell*, 1976]. This study attempted to relate the occurrence of fog drip to the fluctuation of a small stream in Hampshire, England. Unfortunately, the conclusions were based on circumstantial evidence, and as it was pointed out later by *Gardiner* [1977], several daily freeze-thaw cycles may have controlled the stream discharge rather than the fog drip. Thus the effect of fog drip was not effectively traced to surface water, and hydrogeologists have never been able to ascertain whether or not fog drip contributes to the groundwater supply, a result, we believe, of limitations imposed by the techniques employed.

In this paper we assess the possibility of using the oxygen

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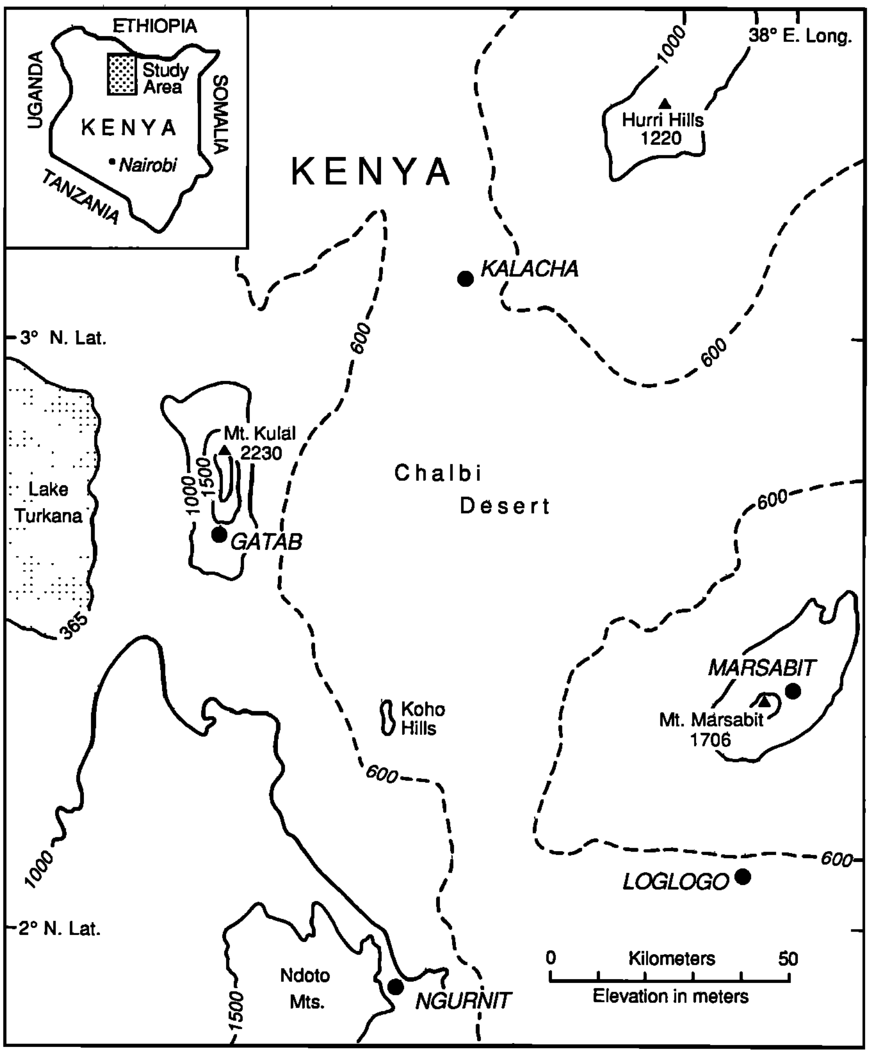

Fig. 1. Location map of the study area in northern Kenya.

and hydrogen isotope ratios of water to determine the contribution of mist precipitation to the groundwater supply. Here the hydrologic importance of fog drip in terms of infiltration and recharge is assessed for northern Kenya.

Fog Research in East Africa

Fog drip, or mist precipitation, has also been observed and exploited in northern Kenya. The first mention of the possible importance of fog drip in Kenya was by *Nicholson* [1936]. He stated that montane forests in East Africa increased precipitation by at least 25% of the total annual rainfall. Because of the arid nature of northern Kenya, and limited developed power, some settlements rely on cisterns for their water supply. Several of these catchments have also been equipped with fog screens to increase their water supply. Preliminary studies by H. Lamprey (unpublished data, 1986) indicate that about 2 L of water per square meter of screen per hour can be collected from blowing fog at Marsabit in northern Kenya.

The geography and climate of northern Kenya lend themselves readily to the testing of the hypothesis that fog drip is a source of groundwater recharge. Four montane recharge areas surround the desolate Chalbi Desert (Figure 1), a hydrologically closed basin. Three of the montane areas are covered with thick vegetation, and all the peaks are commonly shrouded by a blanket of advective orographic fog for several hours a day during much of the year. One montane region, the Hurri Hills, supports little vegetation because, according to local legend, they were the location of several tribal wars in recent history, the result of which was the burning of the forests. This deforestation has been blamed by the natives for the drying up of the several hand-dug wells in the region.

The elevations of the four montane regions range from 1220 m to over 2700 m, mostly above the elevation of 1500 m suggested by *Pratt and Gwynne* [1977] as being required before the mean minimum temperature falls below the dew point. Average annual rainfall ranges from about 200 mm on the desert floor to about 1000 mm on the thickly vegetated montane areas.

Procedures

Both fog and shallow groundwater samples for stable isotopic analysis were collected for this research. The shallow groundwater was collected from springs and hand-dug wells, while the fog samples were collected on three of the highest peaks surrounding the desert.

Fog samples were collected by two different methods. Continuous collection was obtained from a fog screen, while spot samples were collected by hand. The screen consisted of a fine

TABLE 1. Summary of Data for the Water Samples Used in This Study

Sample Type	Date, 1986	Location	δD	$\delta^{18}O$	Tritium Units	Depth to Water, m	Amount Collected
Fog, grab	June 23	Mount Marsabit	+10.9	−0.9			
Fog, grab	July 14	Mount Marsabit	+16.6	−0.7			
Fog, grab	July 23	Gatab	+12.8	−0.7			
Fog, grab	July 23	Gatab	+12.3	−0.7			
Fog, screen	July 19–29	Mount Marsabit	+9.8	−1.4			10 L
Fog, screen	July 29 to Aug. 10	Mount Marsabit	+2.9	−1.8			10 L
Cistern	July 16	Hurri Hills	+13.5	+0.3			
Spring	June 23	Mount Marsabit	−12.6	−3.6			
Spring	June 23	Mount Marsabit	−12.4	−3.7			
Spring	July 23	Mount Kulal	−12.4	−3.8			
Well, windmill	June 24	Kalacha	−12.8	−2.4		<10	
Well, artesian	June 24	Kalacha	−13.2	−2.5			
Well, hand dug	June 29	Koho	−26.8	−4.9	50	4.5	
Well, hand dug	June 29	Koho	−23.8	−4.1		4.5	
Well, hand dug (in dry river bed)	June 26	Loglogo	−18.9	−3.7		3	
River	July 2	Ngurnit	−20.5	−4.3			

Note that all of the grab samples were collected at 0800 local time.

wire mesh stretched over a 1 m by 3 m square metal frame. The edge of the frame extended below the screen, which allowed it to be inserted in the ground in a vertical position. A gutter was hung below the screen to channel the water to a funnel and into a collecting tank. The screen was located near the top of Mount Marsabit at approximately 1700 m in elevation and positioned perpendicular to the prevailing winds. The collector was visited twice, at which times a sample was taken and the tank was emptied. Fog was also collected by hand by placing a wick in a collection bottle and dabbing droplets which collected on fences and foliage in the early morning. Fog was collected by this method to determine whether the samples collected by the screen had undergone evaporation and isotopic enrichment. Spot sampling was performed on four different occasions at two separate locations.

All water samples were collected in polysealed glass bottles. The hydrogen isotope ratios were determined by the quantitative conversion of water to hydrogen gas using zinc [*Kendall and Coplen*, 1985] as a reducing agent. The hydrogen gas was introduced directly into the mass spectrometer. The method of completely converting water to CO_2 by guanidine hydrochloride [*Dugan et al.*, 1985] was used for the oxygen isotope analyses.

The hydrogen gas was analyzed in a modified GD150 6-60 double-collector mass spectrometer. The reproducibility of the δD values is 1‰. The CO_2 was analyzed in a Nuclide triple-collector mass spectrometer with a reproducibility of 0.2‰ for the resulting $\delta^{18}O$ values. All data are reported in the standard δ notation with respect to SMOW.

RESULTS

The type of sample, date and location of collection, stable isotopic ratios, and, where appropriate, depth to water, as well as amount collected, are shown in Table 1. The isotopic ratios are also plotted in Figure 2, where all of the data plot close to the meteoric water line originally described by *Craig* [1961].

The water samples collected as fog, independent of method as well as location, have positive δD values and thus are more enriched than SMOW. All of the groundwater samples, however, are substantially more depleted than SMOW with respect to deuterium and range from about −10‰ to −25‰.

DISCUSSION

Stable Isotopic Ratios of Fog and Rain

At the foundation of this research are fundamental reasons as to why, assuming similar sources, the stable isotopic ratios of fog and rain are different. Fog, in order to be effective as fog drip, must condense at an altitude no higher than that of the collecting vegetation. This is much lower than the level of formation of rain. Fog condensation occurs at higher temperatures than rain and is accompanied by a smaller isotopic fractionation. Fog is generally an early stage condensate and in this environment is condensed out only when the condensing air mass is orographically uplifted over the mountains. The air mass producing rain, however, continuously condenses out water across the desert, producing isotopic compositions of more advanced stages. The coupling of these two effects (warmer condensation temperatures and an early stage condensate) would produce more isotopically enriched fog than the opposite conditions (colder condensation temperatures and a later stage condensate), which produce rain.

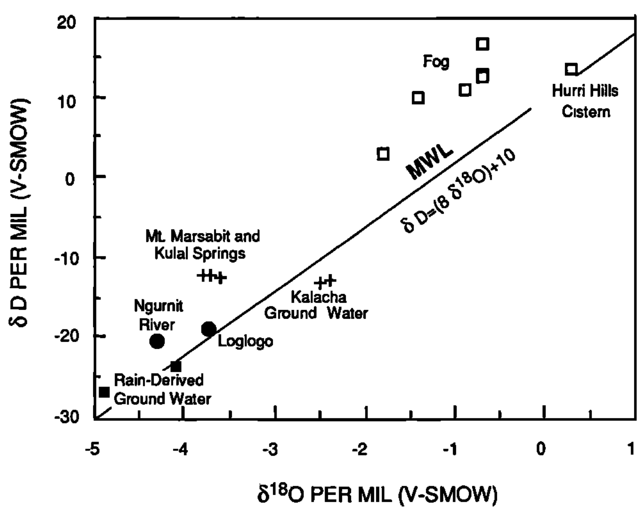

Fig. 2. Stable isotopic ratios of the samples used in this study. The Koho Hills groundwater is rain derived.

It is not known whether the Chalbi Desert behaves as an isotopically closed hydrologic system. If so, the fog water as well as rain may be, in part, the condensation of terrestrially evapotranspired water upwind, a mechanism serving to hydrologically, and perhaps isotopically, close the Chalbi Desert [*Ingraham and Taylor*, 1986]. Nonetheless, fog would still tend to be more enriched isotopically than rain because of its lower altitude and earlier stage of condensation.

Two factors, different condensation stages and different temperatures of condensation, may serve to produce fog of an enriched stable isotopic ratio compared to that of rain. Whichever factor or combination of factors is dominant, the fog samples are indeed more enriched than the other samples, as shown in Figure 2.

One precipitation sample was collected from a cistern in the Hurri Hills which is equipped with a fog screen. The collection was made during the dry months in the hope of obtaining a sample consisting predominantly of fog. The sample is substantially enriched in its hydrogen isotope ratio (Figure 2) and yet more enriched in its oxygen isotope ratio than the other fog samples. It is unclear whether this sample is produced primarily by the collection of fog or whether its enriched nature results from high humidity evaporation of the water in the cistern.

Stable Isotopic Ratios of Rain and Koho Hills Groundwater

The stable isotopic composition of rain can be highly variable, so long-term integrated samples of precipitation are required to accurately determine the average isotopic ratios of rain. The closest International Atomic Energy Agency precipitation network stations to the study are at Entebbe, Uganda, and Addis Abbaba, Ethiopia. Therefore shallow groundwaters from the flanks of the Koho Hills were sampled to determine the isotopic composition of recent rain-derived groundwater. The Koho Hills are located in the center of the study area and rise to only a few tens of meters above the valley floor (Figure 1). At this elevation they are not high enough to be vegetated or to produce fog. The shallow groundwaters also have tritium concentrations of 50 tritium units (Table 1), which indicates that the water was precipitated under current climatic conditions. The isotopic composition of this water also reflects local rain that has undergone partial evaporation prior to infiltration, a process that would enrich the resultant infiltrate.

The Koho Hills groundwater samples are more depleted in both deuterium and oxygen 18 than are most other samples. They are up to 15‰ more depleted in their hydrogen isotope ratios than the water collected from high-elevation springs on Mount Marsabit and Mount Kulal; yet high-elevation springs generally produce the most depleted water. Since the Koho groundwater samples are positioned near the geographic center of the study area, their depleted nature cannot be explained by the raining out of the heavier isotopes as storm clouds migrate across the desert.

CONTRIBUTION OF FOG TO THE GROUNDWATER SYSTEM

On the basis of the discussion above, the Koho Hills groundwater samples are considered to represent the isotopic composition of rain-derived groundwater. Local rain must therefore have an average δD value no more enriched than -25‰. The fog has been demonstrated to be more enriched than SMOW, that is, has positive δD values. The remaining samples appear to fall on a mixing line between the Koho Hills samples and the fog samples (see Figure 2).

Mount Marsabit, Mount Kulal, and Kalacha Samples

The Mount Marsabit and Mount Kulal spring samples and the Kalacha groundwater samples are recharged from high elevations that either are or have recently been densely covered with fog-drip-producing arboreal vegetation. All of the samples from these three locations are very similar in their hydrogen isotope ratios, a condition perhaps produced by the closed hydrologic nature of the Chalbi Desert. However, the Kalacha samples are a little more than 1‰ more enriched in their oxygen isotope ratios than the other samples. The oxygen isotopic enrichment in the Kalacha samples over the Mount Marsabit and Mount Kulal samples parallels the oxygen isotopic enrichment observed in the Hurri Hills cistern sample over the other fog samples. Both of the more enriched samples (Kalacha and Hurri Hills cistern) may have been subjected to evaporation. The enriched nature of all of these samples (Mount Marsabit, Mount Kulal, and Kalacha) compared to the Koho Hills samples cannot be due to partial evaporation prior to infiltration, since the δD values of Koho Hills groundwater already contain these effects. Instead it is thought that the δD of mountain spring samples are produced by the mixing of both rain and fog in some ratio.

Ngurnit River and Loglogo Samples

The Ngurnit River, the only perennial river in the study area, drains the Ndoto Mountains and disappears into alluvium. The river was sampled after a large rainstorm which kept the river flowing farther down the canyon during the dry season. The Loglogo sample was collected from a hand-dug well in a dry sandy riverbed. The hydrogen isotope ratios of about -20‰ of these samples indicate that runoff in intermittent and ephemeral streams is dominated by rain: recent rain, as with the Ngurnit River, or previous season's rain, as with the Loglogo sample. Thus it is not proposed here that fog drip contributes any significant portion to direct runoff [cf. Gardiner, 1977].

SUMMARY

The total hydrogen isotopic variation of 15‰ observed in the shallow groundwater cannot readily be explained by any systematics of stable isotopic fractionation. The best explanation is the infiltration and recharge of water of two separate origins, the most important being rain and only other potential source being fog drip. However, because of the short-term nature of the fog samples it is unclear from this study what portion of the groundwater actually originates as fog drip. Both the oxygen and the hydrogen isotopic ratios presented herein indicate that it may indeed be substantial.

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