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The Potential for Scaling Up a Fog Collection System on the Eastern Escarpment of Eritrea

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Fog is an untapped natural resource. A number of studies have been undertaken to understand its potential as an alternative or complementary water source. In 2007, a pilot fog-collection project was implemented in 2 villages on the Eastern Escarpment of Eritrea. The government of Eritrea, buoyed by the project's positive results, has encouraged research into and application of fog-collection technologies to alleviate water-supply problems in this region. In 2014, this study was undertaken to assess the coverage, prevalence, intensity, and seasonality of fog on the Eastern Escarpment of Eritrea and consequently to identify potential beneficiary villages. Three independent methods used in the study—satellite image analyses, personal interviews, and a standard fog collector—produced reasonably similar characterizations of fog coverage and timing. The period with high fog incidence is mainly between November and March, with the highest number of fog days per year (96) on the central Eastern Escarpment and decreasing frequency to the south (78 days) and north (73 days). The fog intensity on the central Eastern Escarpment is very high and in most cases reduces visibility to less than 500 m. In this period, a light to moderate breeze blows predominantly from the north and northeast. More than half of the villages in the region currently have a reliable water-supply system. The rest depend on seasonal roof-water harvesting, rock-water harvesting, and truck delivery and, therefore, could potentially benefit from fog collection as a supplementary water source. In particular, fog water could be useful for a small number of beneficiaries, including public services like schools and health facilities, where conventional water-delivery systems are not viable.

Keywords: *Fog; fog-water collection; water supply, mountains; Eastern Escarpment; Eritrea.*

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Introduction

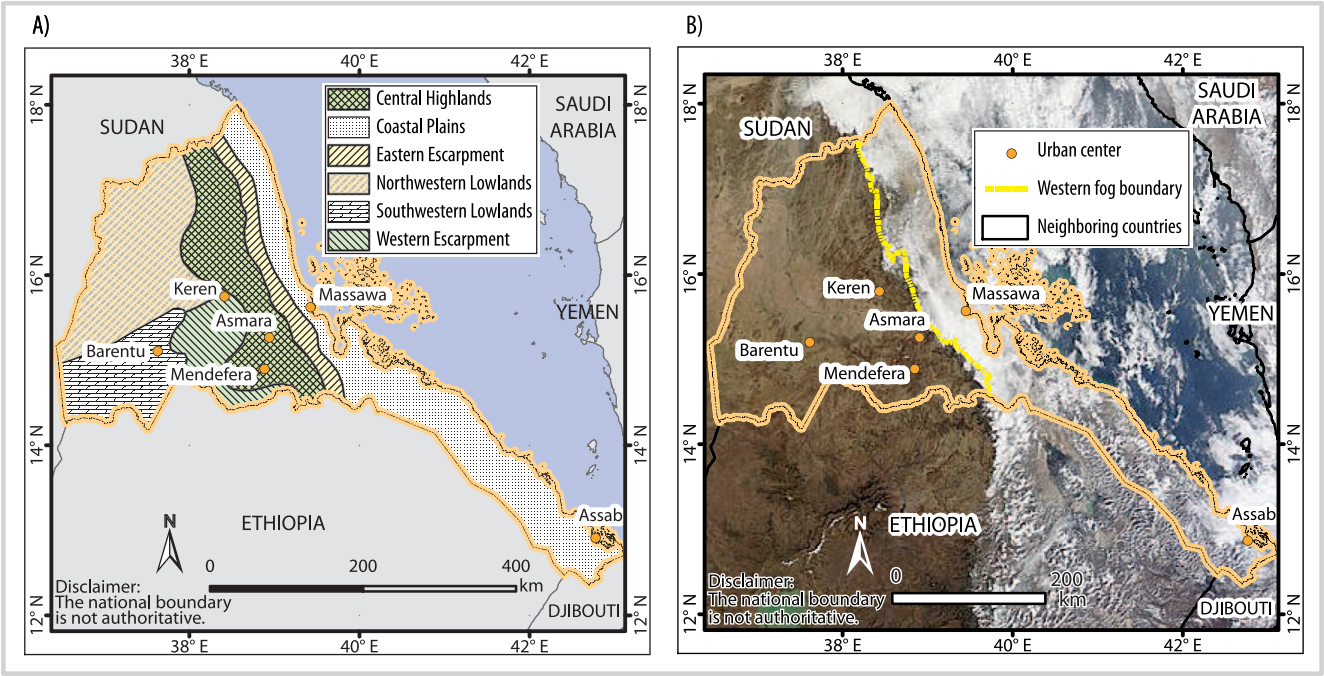
Fog is being studied as a potential water resource, mostly in fog-intense mountainous regions (Klemm et al 2012; Fessehaye et al 2014). A number of pilot and research projects have been undertaken after the success of a fog-water collection project in Chungungo village, Chile (Schemenauer et al 1988). Several fog-collection technologies have been developed, with the most widely used being a large sheet of plastic mesh erected perpendicular to the prevailing winds (Schemenauer and Joe 1989; Schemenauer and Cereceda 1991). This method is simple and effective and does not require a power supply. However, in most regions, fog collection is localized and seasonal, and potential collection areas and periods need to be identified through feasibility studies using standard fog collectors (SFCs) (Schemenauer and Cereceda 1994a) to identify the potential for fog collection prior to the installation of large fog collectors (Schemenauer et al 2005).

In 2007, Vision Eritrea (a local nongovernmental organization) implemented a pilot fog-collection project in the villages of Arborobue (population 877) and Nefasit (population 3990) in the central part of the Eastern Escarpment of Eritrea. These villages were selected based on the results of a feasibility study (FogQuest 2005) funded by the WasserStiftung (Water Foundation, based in Munich, Germany) with technical assistance from FogQuest (a nonprofit organization in Canada) and the collaboration of several implementing partners (the Water Resources Department, zone and subzone administrations, beneficiary communities, and Haben, a local nongovernmental organization). Arborobue and Nefasit were selected because they have high average daily fog-collection rates (7.6 L day^{-1} m^{-2} and 3.3 L day^{-1} m^{-2}, respectively) and a large number of water-poor residents. After 5 years, the pilot project was evaluated, and fog collection was documented as a feasible means of water delivery to small communities located in remote areas

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FIGURE 1 Eritrea: (A) agro-climatic zones (source: FAO 1994); (B) satellite image (source: Terra high resolution 2 km per pixel by the National Aeronautics and Space Administration) taken on 9 January 2015 during a fog episode, showing potential areas for fog water collection. (Maps by Selamawit Tesfay)



where a conventional water supply system is not viable (Fessehaye et al 2015).

Eritrea's Ministry of Land, Water, and Environment recognizes fog's potential as a natural water resource and encourages research into and the application of appropriate fog-harvesting technologies to contribute to alleviating the acute water-supply problem the region faces (Ministry of Land, Water and Environment 2008). Globally, Eritrea is also considered one of the countries that could potentially make use of fog as a water resource (Schemenauer and Cereceda 1994b), especially on the Eastern Escarpment.

Thus, in this study a comprehensive assessment was conducted of the region's potential to scale up fog-water collection (Figure 1A). The objective of this study was to determine the fog's coverage, prevalence, and intensity—as well as altitudinal, spatial, and temporal variation within the Eastern Escarpment of Eritrea. An additional aim was to identify villages that could use fog-collection technology to alleviate their water-supply problems.

Methodology

This study focused on Eritrea's Eastern Escarpment at elevations between 1700 and 2100 m above sea level, the range within which fog is most likely to occur (Fessehaye et al 2015). According to the National Geographical Database (National Statistics Office 2004), there are 24 villages with a total population of 81,578 within this elevation range (*Supplemental material*, Table S1; http://dx.doi.org/10.1659/MRD-JOURNAL-D-15-00013.S1). The study integrated 3 independent data sources: satellite images, personal interviews in representative villages, and fog data in the form of SFC measurements from the aforementioned pilot project.

Satellite image analysis

Spatial and temporal fog coverage on the Eastern Escarpment was assessed by analyzing the daily National Aeronautics and Space Administration Aqua/Terra satellite images. Altogether, 3 different years of satellite images (the SFC study fog period from February 2005 to January 2006, and another 2 randomly selected periods from February 2008 to January 2009 and from February 2014 to January 2015) were analyzed. On the Eastern Escarpment of Eritrea, satellite images give a clear indication of fog episodes because there is a strong planetary boundary layer inversion (Van Buskirk et al 1998). This boundary occurs along the easternmost crest of the highlands; in images the fog bank can be seen to follow this crest, which makes it easy to spot the fog days (Figure 1B). Thus, the spatial fog coverage was analyzed and the fog days were counted for each month based on the daily satellite images.

Personal interviews

The goal of the interviews was to collect independent data on fog intensity and diurnal duration and on the details of the village water-supply systems and then to determine whether fog had potential as a water source. Basic population data and information on infrastructure, existing sources of potable water, and social services

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TABLE 1 Demographic characteristics of the study villages and study participants.

Location in the Eastern Escarpment	Village	Number of interviewees			Families	Population
		Female	Male	Total		
Northern	Nakfa	4	20	24	3,200	16,000
Central	Geleb	6	18	24	1,581	7,905
	Fshey	4	16	20	170	720
	Arborobue	4	16	20	329	877
Southern	Qeyh Kor	14	12	26	500	2,000
	Hiebo	4	8	12	397	1,770
Total		36	90	126	6,177	29,272

facilities within each village (such as schools and health services) that could benefit from improved water supply were collected from the respective subzone administrations. The details are provided in *Supplemental material*, Appendix S1 (http://dx.doi.org/10.1659/MRD-JOURNAL-D-15-00013.S1). The villages were then combined into 6 groups according to their locations and proximity to each other. One representative village was selected from each cluster based on the following 4 selection criteria:

1. Adequate number of fog days
2. Shortage of potable water
3. Presence of potential beneficiaries
4. Presence of accessible, permanent (non-nomadic) settlements

In each of the 6 selected villages (Table 1), group discussions and personal interviews were conducted using a structured questionnaire to assess the prevalence, distribution, and intensity of fog and to collect associated data, such as the villages' current water supplies. The details are given in *Supplemental material*, Appendix S2 (http://dx.doi.org/10.1659/MRD-JOURNAL-D-15-00013.S1).

Standard fog collector

The SFC-recorded fog days for the feasibility study undertaken in Arborobue (FogQuest 2005) were also considered to check the accuracy of the data obtained from satellite image analysis and interviews. In the previous feasibility study, the SFCs measured the daily rate of fog-water collection. Details about the construction of the SFCs can be found in Schemenauer and Cereceda (1994a).

Finally, villages that could potentially benefit from fog collection were identified based on local fog potential (according to the results of the satellite image analysis and the interviews) and existing village water supply systems.

Results and discussion

Fog coverage and prevalence in Eritrea

In Eritrea, there is continual fog along the Eastern Escarpment (Figure 2). Annual fog coverage is highest in the central part of the escarpment, which, according to the satellite image analysis, has 96 fog days per year, while the northern and southern parts have 73 and 78 days per year, respectively (Table 2).

The satellite image analysis matched the estimates given by the villagers in the study area quite well. In Fshey, in the central part of the Eastern Escarpment, the interviewees estimated 102 fog days per year, which was in good agreement with satellite data. In Geleb, the match was not as close. In Nakfa, in the northern part of the Eastern Escarpment, the residents estimated 76 fog days per year, also in good agreement with satellite data. However, interviewees in Hiebo and Qeyh Kor, in the southern part, estimated a lower number of annual fog days than that derived from image analysis. In Arborobue, the number of annual fog days was estimated using 3 independent methods: satellite image analysis (90 days), interview comments (87 days), and SFC data (111 days) (Figure 3). In general, the differences between the number of fog days measured through satellite image analysis and estimated by the interviewees may be due to the fact that 3 years of satellite data were analyzed, while the interviewees based their estimates on longer periods of observation. In addition, what is white on the satellite images could in some cases be clouds rather than fog. Generally, the interviewees estimated annual fog days within a moderate range of deviation, while the satellite-image–based estimates of annual fog days from the 3 different years of satellite images indicated lower variation (Table 2).

Analysis of the fog period

On the Eastern Escarpment, the main fog period occurs during winter (November to March).

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FIGURE 2 A typical fog event on the Eastern Escarpment of Eritrea; photo taken at 15.5762°N, 38.8917°E, and 2489 m above sea level facing northeast on 16 March 2014. (Photo by Mussie Fessehaye)



Diurnal fog duration: Most interviewees agreed that fog starts during the late afternoon (about 16:00 h), intensifies during the night as the colder temperature encourages condensation of water vapor into fog droplets, and then dissipates following sunrise, after 8:00 h (Figure 4). Occasionally, dense fog may persist for a whole day. This high-elevation dense fog is formed during the upward movement of adiabatically cooled humid air masses from the Red Sea (Fessehaye et al 2015). In a study of diurnal fog duration on the west coast of South Africa, Olivier (2002) found similar results where the advection sea fog occurred most often during the cooler nocturnal hours, peaking between midnight and 8:00 h and dissipating soon after 9:00 h.

Fog intensity: The intensity of fog determines visibility; by definition, fog reduces visibility to less than 1000 m (Glickman 2000). Visibility reduction in fog depends on the concentration of cloud condensation nuclei and the resulting distribution of droplet sizes (American Meteorological Society 2014). The fog intensity on the Eastern Escarpment is very high and, in most cases, reduces visibility to less than 500 m (Table 3).

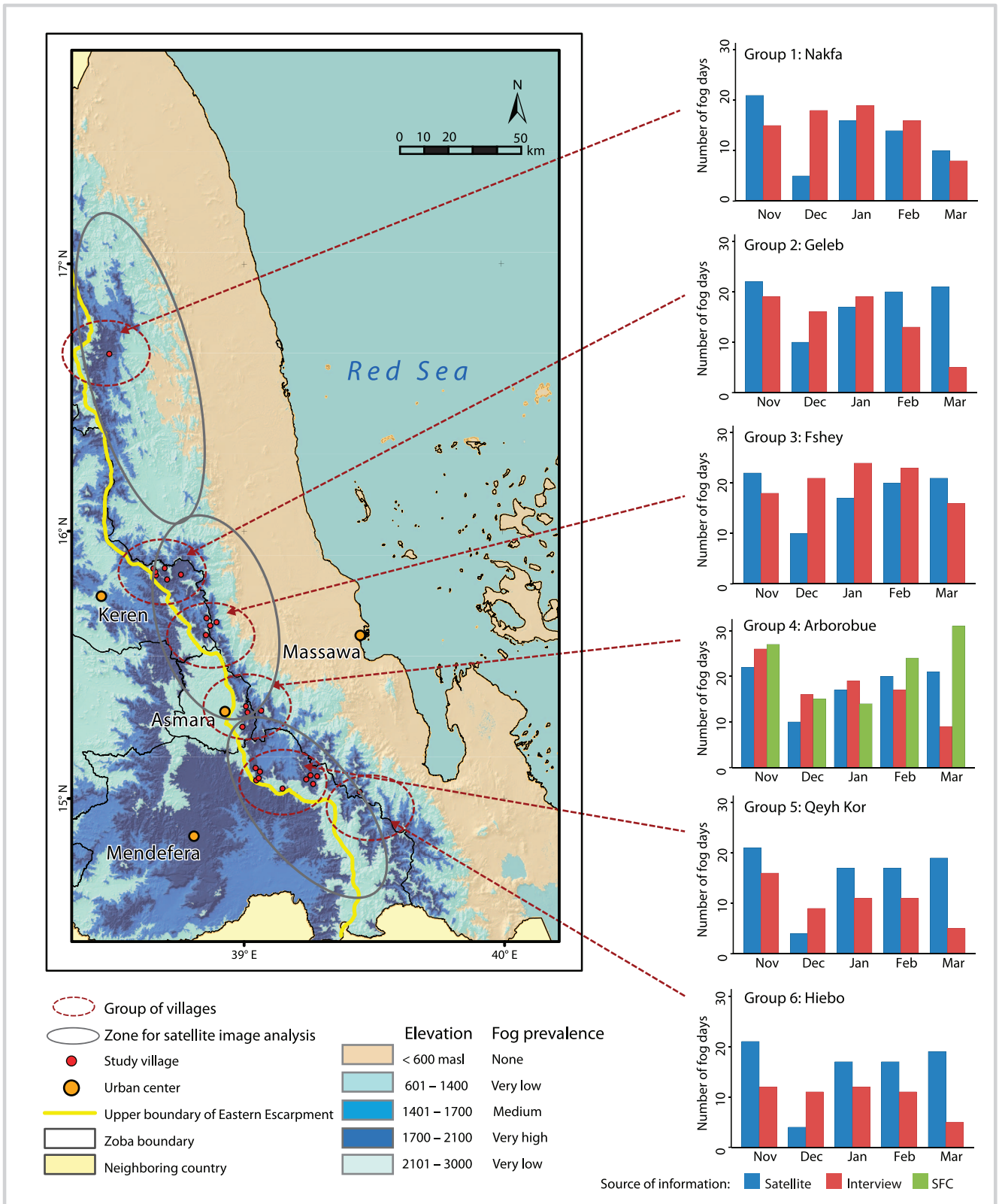
Wind speed and direction: Most interviewees described wind speed as light or moderate (2 or 4 on the Beaufort scale, respectively) (Table 3). This is an optimum range for higher levels of fog collection according to Schemenauer and Joe (1989), who found that an upstream wind speed of

TABLE 2 Annual fog day estimates based on interviewees' reports and satellite image analysis.

Location in the Eastern Escarpment	Village	Estimated annual fog days			
		Based on interviews		Based on 3-year satellite images analysis	
		Average	Standard deviation	Average	Standard deviation
Northern	Nakfa	76	23	73	6
Central	Geleb	72	19	96	7
	Fshey	102	19	96	7
	Arborobue	87	21	96	7
Southern	Qeyh Kor	51	10	78	10
	Hiebo	52	8	78	10

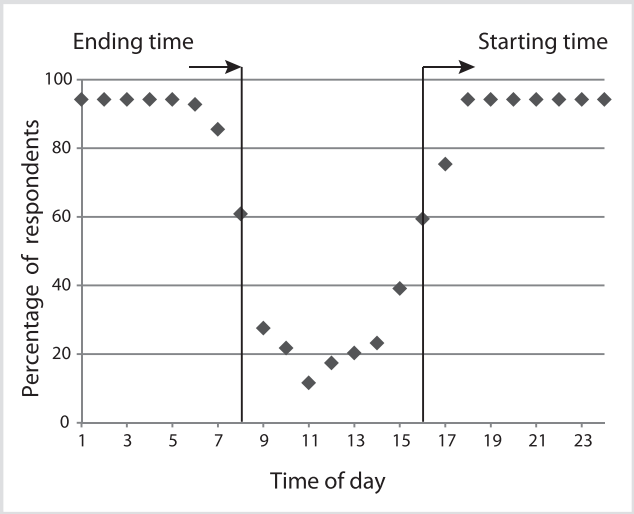
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FIGURE 3 Fog coverage in the study villages. (Map by Selamawit Tesfay)



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FIGURE 4 Diurnal fog occurrence on the Eastern Escarpment, according to respondents.



12.6 km h^{-1} corresponded to the maximum collection efficiency (65%) at the center of a fog collector.

Residents observed that the wind blows predominantly from the north and northeast during the period of fog (Table 3). As Van Buskirk et al (1998) elaborated, winds in Eritrea are produced by strong horizontal air temperature gradients during the dry season, which is the time of the northeast monsoon. Regional pressure gradients during this season are produced primarily by the Central Asian high pressure system and the Equatorial African low pressure system.

Potential beneficiary villages for fog-water collection

Current water-supply system: The current water supply systems in the study villages are diverse (Table 4). Of the 24 villages on the Eastern Escarpment between 1700 m and 2100 m, 11 have safe drinking water from a full water-supply system. Three villages get their water from unsafe shallow wells and 4 villages from unsafe shallow pits locally called *sheyak*. Two villages get their supplies from hand pumps and another 2 villages through water-truck delivery (*Supplemental material*, Table S1: http://dx.doi.org/10.1659/MRD-JOURNAL-D-15-00013.S1). The remaining 2 villages depend on seasonal roof-water and rock-water harvesting during the rainy season (the school uses fog-water collection) and fetching water from unsafe shallow wells or seasonal streams at about 3 hours' round-trip walking distance in the bottoms of the valleys.

The average daily water consumption for more than half of the households in the study area was 74 L day^{-1} (Table 4). Given that the average family size in Eritrea is 5 people, this is well below the World Health Organization's (2011) recommendation of 20 L $individual^{-1}$ day^{-1} for developing countries. Water is scarce and inconvenient to access, and most families use it cautiously to decrease the time and effort spent fetching it.

Villages that depend on an unconventional water-supply system, like roof-water and rock-water harvesting, have the lowest daily water consumption levels. This is because the water source is limited and dependent on the rainy season (mid-June to mid-September). Thus, these communities usually undertake intensive water management and opt for supplementary water-supply systems.

Months with critical shortages of potable water: Generally, all the villages in the study area face water shortages, which are most severe between February and June (Figure 5), after the rainy season when the underground and surface water bodies start to deplete. Most interviewees agreed that from March onward, drinking-water acquisition becomes increasingly difficult until the next rainy period. The first critical period (February to March) overlaps with

TABLE 3 Interviewees' estimates of fog intensity, wind direction, and wind speed during the fog period.

Parameters		Percentage of respondents
Visibility during fog episode	<100 m	41
	100–500 m	55
	500–1000 m	4
Wind speed (Beaufort scale)	2 (light breeze, about 5.6–11 km h^{-1})	43
	3 (gentle breeze, about 12–19 km h^{-1})	14
	4 (moderate breeze, about 20–28 km h^{-1})	30
	5 (fresh breeze, about 29–38 km h^{-1})	13
Wind direction	East	12
	North	68
	Northeast	20

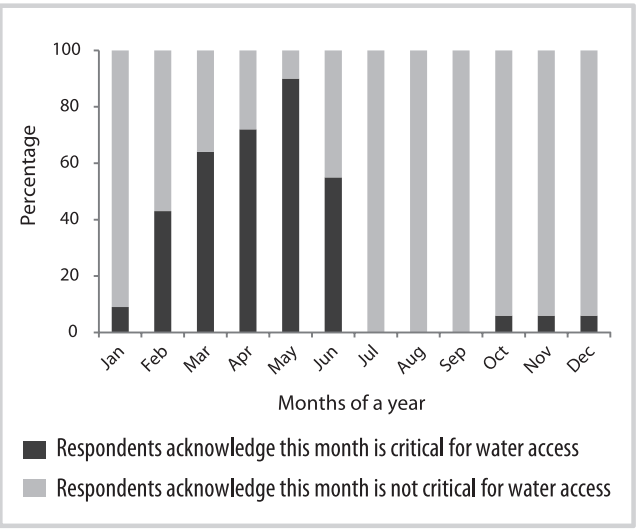
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TABLE 4 Current water supply systems and water consumption rates.

Water supply system	Description	Number of villages	Average household consumption (L day^{-1})
Full system	Water from a well or borehole is pumped to a reservoir and distributed through a gravity-fed system.	11	85
Hand pump	A low recharging borehole is mounted with a hand pump.	2	69
Rock- and fog-water harvest	A canal is constructed at the mountain foot to collect and divert the harvested water to an underground reservoir. In addition, a hand-dug well and fog-water harvest system mainly serve the school.	1	62
Roof-water harvest	Water is collected from a roof during the rainy period, stored in a large cistern, and managed efficiently to serve throughout the dry period.	1	67
Shallow pits (*sheyak*)	Water sources are excavated by hand on sandy riverbeds.	4	73
Shallow wells	Water is drawn manually from wide-diameter, hand-dug, mostly uncovered wells by a dipping bucket tied to a rope.	3	83
Water truck	Water is delivered by truck to a central point where individual households queue with their barrels.	2	77
Total villages/average consumption		24	74

the greatest period of fog. The water supply during the remainder of the shortage period (April to June) could be supplemented by stored water from fog collection, as is done in Arborobue. In particular, smaller communities and social service institutions, such as schools and health facilities, are potential beneficiaries of fog collection, because it is localized and seasonal (Fessehaye et al 2014).

FIGURE 5 Difficulty accessing potable water by month, according to respondents.



Fog as a potential resource: The best candidates for using fog as a water source are villages in fog-intense areas where conventional water-supply systems are not in place or are not viable for future installation.

Almost half of the villages on the Eastern Escarpment at the relevant elevation have full water-supply systems based on groundwater (Table 4). Their water is safe and largely covers current domestic demand. If there is a need to sustain or enhance the water supply, it is preferable to undertake water conservation measures upstream to recharge or enrich the groundwater reserves rather than to supplement additional water by fog collection.

The same is true for the 7 villages depending on shallow pits *(sheyak)* and shallow wells. Their water is mostly unsafe but is sufficient during the rainy season and for a few months afterward, according to the villagers. In these villages, the primary option for a safe, year-round water supply might be to exploit river-base flow by constructing subsurface dams, since the groundwater table is generally shallow. The 5 villages that depend on shallow wells or hand pumps could improve their water supply by covering the wells and building recharging structures upstream to ensure sustainability.

The primary potential beneficiaries of fog collection in Eritrea are therefore Fshey and Arborobue, the 2 villages that depend on roof water and rock water as their primary sources, and Nakfa town, where water supplies are adequate but have a high mineral content (*Supplemental material*, Table S1: http://dx.doi.org/10.1659/

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FIGURE 6 Fshey village during a fog episode on 16 March 2014. (Photo by Mussie Fessehaye)



MRD-JOURNAL-D-15-00013.S1). Arborobue's pilot fog-collection system, installed in 2007, has proven viable and socially acceptable. Fshey, located on isolated mountainous terrain where conventional water supply and truck delivery are not economically feasible, is in a similar situation to Arborobue's before the pilot scheme and fully dependent on roof-harvested water with intensive management throughout the year (Figure 6). In Nafka town, fog harvesting could provide soft water to supplement the hard water delivered by truck.

The technical expertise required to install fog-collection systems is available in Eritrea, thanks to the Arborobue pilot project, which is still in full use. The challenge is to convince the local communities identified earlier to accept fog collection as a viable drinking water source. Of the participants in the interviews and group discussions described earlier, 64% perceived fog as a source of water mostly for grasses and crops; 15% stated that fog could have an indirect benefit for irrigated crops and domestic animals because animals and plants do not need much water during the fog season. Thus, prior to the introduction of fog-collection technology, activities need to be undertaken to raise community awareness and assess whether the technology is socially acceptable (Harvey and Reed 2007). Once the communities accept the technology, they are likely to cooperate with installation and operate the system sustainably.

In addition, fog water holds potential for other productive uses, such as afforestation. In the Eastern Escarpment of Eritrea there is a pocket of evergreen forest, locally referred to as the "green belt," which thrives due to summer rainfall and winter fog. The indigenous trees in the area are conifers that intercept and drop substantial amounts of fog water to the ground through their needle-shaped leaves. Afforestation with well-selected trees and properly managed plantations (Estrela et al 2008) could enhance overall water availability, including groundwater reserves (Bruijnzeel et al 2005).

Conclusions and recommendations

On the Eastern Escarpment of Eritrea, there is intensive fog prevalence between November and March. In this region, water-poor communities can benefit from fog collection. The knowledge for the installation and sustainable management of this technology is available in the country due to the practical experience gained by the Arborobue pilot scheme, installed in 2007 and still in operation. Specifically, villages that currently depend on seasonal roof-water and rock-water harvesting and truck delivery of hard water could benefit from fog collection as a supplementary water source. However, most villages on the Eastern Escarpment have viable conventional alternatives for water provision; about half have a full

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water-supply system. This reflects the high priority the Eritrean government has given to rural water supply, since the country's independence, in all areas of the country, including remote and topographically difficult areas such as the Eastern Escarpment.

As an alternative to community-level projects, fog-collection systems could be developed for individual households and integrated with roof-water harvesting and storage facilities to supplement their water supply. In this way, the technology could spread by individual initiative rather than by project interventions, and households might be motivated to adopt the technology, since the fog period (November to March) overlaps with the period, from February to June, with the most critical water shortages.

To conclude, while the potential for harvesting fog in the study region is limited by the seasonality of fog and the availability of conventional water supplies, fog water also has a potential for afforestation with well-selected trees.

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Supplemental material

TABLE S1 Fog-intense areas and villages with potential for fog collection.

APPENDIX S1 Questionnaire for interviewees representing government institutions.

APPENDIX S2 Questionnaire for individual interviewees.

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