AMBIO 2012, 41:221–234
DOI 10.1007/s13280-012-0247-8

REVIEW PAPER

Fog as a Fresh-Water Resource: Overview and Perspectives

Otto Klemm, Robert S. Schemenauer, Anne Lummerich, Pilar Cereceda, Victoria Marzol, David Corell, Johan van Heerden, Dirk Reinhard, Tseggai Gherezghiher, Jana Olivier, Pablo Osses, Jamal Sarsour, Ernst Frost, María J. Estrela, José A. Valiente, Gebregiorgis Mussie Fessehaye

Received: 12 May 2011 / Revised: 6 October 2011 / Accepted: 22 December 2011 / Published online: 12 February 2012

Abstract The collection of fog water is a simple and sustainable technology to obtain fresh water for afforestation, gardening, and as a drinking water source for human and animal consumption. In regions where fresh water is sparse and fog frequently occurs, it is feasible to set up a passive mesh system for fog water collection. The mesh is directly exposed to the atmosphere, and the foggy air is pushed through the mesh by the wind. Fog droplets are deposited on the mesh, combine to form larger droplets, and run down passing into a storage tank. Fog water collection rates vary dramatically from site to site but yearly averages from 3 to 10 l m^{-2} of mesh per day are typical of operational projects. The scope of this article is to review fog collection projects worldwide, to analyze factors of success, and to evaluate the prospects of this technology.

Keywords Fog collection · Large fog collector · Standard fog collector · Sustainability · Water resource

INTRODUCTION

The collection of fog for the purpose of the production of clean water has attracted increasing attention over the past few decades. It is a simple and sustainable technology with the potential to produce precious water in some regions of the world. It is achieved by exposure of mesh material to foggy air masses. There are numerous projects on five continents to collect fog water, of which some are more successful than others. The beneficiaries are often poor people, although successful projects also exist in more prosperous regions. A tri-annual international conference series on fog, fog collection, and dew, since 1998 (http://www.fogquest.org/conferences.html), brings together scientific findings and users of the technique. The scope of this review is to synthesize the current understanding of fog collection and to analyze its potential and limitations for future development. In a sense, this is a follow-up contribution of a summary presented 20 years ago in *Ambio* (Schemenauer and Cereceda 1991). Note that the science of fog physics, chemistry, and its role in the hydrological cycle, which extends to a much wider climatic range than the "fog collection" addressed here, is not within the focus of this article.

CLIMATIC PRECONDITIONS

Fog is a cloud with physical contact to the earth's surface. The fog droplet diameters typically range between from around 1 µm to a few 10s of µm. There are several fog-forming processes (Schemenauer et al. 1988; Eugster 2008), of which only two are briefly mentioned here. In the first method, low stratus clouds can form over a rather cold body of water, e.g., the subtropical SE Pacific Ocean, and the resulting cloud base height above the surface and the cloud's thickness may be a few tens or hundreds of meters. If such a cloud is advected by the regional winds toward the coastal mountains, advection fog may occur in the mountainous region. Another way to produce fog is adiabatic cooling of humid air masses during their uphill transport. Oceans are major sources of humidity so that the combination of an ocean with a near-coast mountainous region is a favorable setting for collecting water from such orographic fog.

Only if fresh water is sparse, is there a motivation to set up a system for fog water collection. In other words, only if rain is a very limited (in many cases virtually non-existent at least for a significant time period of the year) source of fresh water, and groundwater is an unsustainable or expensive source, fog collection projects make sense. These preconditions lead to a concentration of fog collection projects in arid and semi-arid tropical and subtropical climates.

TECHNICAL REALIZATIONS

The collection of fog water is a simple technology. A mesh is exposed to the atmosphere, and the fog is pushed through the mesh by the wind. A fraction of the fog droplets is deposited on the mesh material by impaction. When more and more fog droplets deposit, they combine to form larger droplets, run down the mesh material into gutters and eventually into a storage tank. Differences between various fog collector designs exist regarding their size and shape, as well as the mesh material used. The Standard Fog Collector (SFC) is mainly used in exploratory studies to evaluate the amount of fog water that can be collected at given sites. The construction and use of this flat mesh panel is described in detail in Schemenauer and Cereceda (1994a). The SFC has a 1×1 m^2 surface, with a base 2 m above ground and is installed perpendicularly to the wind direction that is associated with the occurrence of fog. It has now been used to measure fog fluxes in about 40 countries.

The Large Fog Collector (LFC, Schemenauer and Cereceda 1994b) has been widely used for fog collection. The principle is identical to that of the SFC. It is, however, much larger. In most cases, the mesh is 4 m high and 10 m wide. The lower edge of the mesh, with the attached gutter, should be as high off the ground as possible (typically 2 m) in order to increase the collection rate.

In the SFC design, the mesh is stretched over a rigid frame. For the LFC, the mesh is supported by a frame made of cables, which are held tightly between two vertical posts. Figure 1 shows an LFC in Spain.

The collection rate of a fog collector is determined by the fog liquid water content (LWC), the size distribution of fog droplets, the size and arrangement of the mesh material, and the wind speed. The description of the physical processes behind the impaction of fog droplets is beyond the scope of this article and is described in Schemenauer and Joe (1989) and Schemenauer and Cereceda (1994a).

The Raschel shade net material from a Chilean manufacturer is used in most fog collector applications worldwide. The material (Fig. 2) is made of food-safe polyethylene and has a fiber width that is effective at

Fig. 1 Image of the 18 m^2 flat-panel fog collector located at Mount Machos (Valencia region, Spain), together with the water tanks

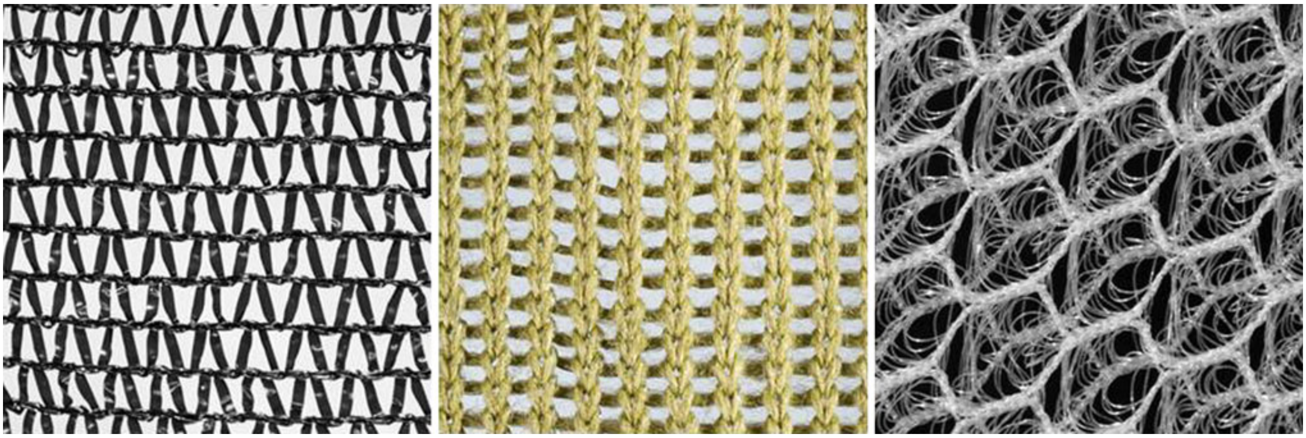

Fig. 2 Three mesh types for fog collection. The Raschel mesh (35% shading, *left panel*, www.marienberg.cl) has been successfully applied for many years in 35 countries in five continents. It is used double layered in SFC and LFC (only one layer is shown here). The *middle panel* shows a robust material with a stainless mesh, co-knitted with poly material (http://www.meshconcepts.co.za), which has been employed in South Africa. The *right panel* shows a newly proposed design of a three-dimensional net structure (1-cm thickness) of poly material (http://www.itv-denkendorf.de). Note that no overall comparison of mesh collection rates and technical performance has been conducted yet. The edge lengths of mesh sections shown are 6.5 cm

collecting fog droplets. The weave consists of vertically stretched triangles enabling rapid run-off of the water. Also, the mesh used is double-layered because the movement of the two layers against each other facilitates the run-off of the collected water.

Extreme conditions can possibly benefit from the use of different mesh material or collector design. A variety of mesh materials have been tested (e.g., Shanyengana et al. 2003). For very windy sites, more robust material with a stronger, stainless mesh, co-knitted with the poly material (Fig. 2) has been tested. Collector designs other than the SFC and LFC have been tested and could prove useful in specific applications. In relatively rare cases where there is no unique wind direction associated with the occurrence of fog, a three-dimensional (3D) structure of mesh material in the landscape may be advantageous. The "Eiffel" collector as used at some sites in Peru (Tiedemann and Lummerich 2010), and a system consisting of nine panels arranged in the shape of four equilateral triangles, as employed in South Africa (van Heerden et al. 2010), are examples of 3D collectors. However, a systematic side-by-side operation of various material or designs, comparing collection efficiencies, deposition of aerosol particles, and economic aspects ("Specific Aspects" section), has not been performed as of yet. Both laboratory and field studies are encouraged.

PAST AND CURRENT FOG COLLECTION PROJECTS

This section briefly characterizes important worldwide fog collection projects over the last 50 years (Fig. 3). It is not within the scope of this article to list all projects or compare their sizes and collection rates. The existing data base is too diverse and incomplete. Instead, various types of projects and some of their specific conditions are mentioned, to set a basis for a more systematic analysis in "Project Schedule" section.

South and Central America

Large sections of the Pacific coast of South America receive only very small amounts of precipitation. Low stratus clouds often form over the cold ocean water and move landwards, leading to fog on the coastal cordillera, but typically no rain. The natural Loma vegetation belt between about 5° S and 30° S is well adapted to these conditions and utilizes water obtained from collecting fog droplets. However, a large portion of the Loma vegetation is degraded or absent today. Fog collection projects aim to support reforestation, agricultural activities, and provide fresh water for the human population. The first large collectors were designed and constructed in Antofagasta (23.5° S) during the 1960s.

Systematic scientific research was conducted in the 1980s in the Coquimbo region around El Tofo (30° S), and 50 fog collectors of 48 m^2 collection surface each were installed (Schemenauer et al. 1988). Forty-one more were installed in the 1990s. The project provided fresh water for about 100 families by taps in their homes. The project, which had initially been supported by foreign partners, was given over to the local population in the mid-1990s. After many years of successful operation (Cereceda et al. 1997), the maintenance of fog collectors stopped when village politics and the substantial growth of the village led to a demand for an expensive water pipeline from a distant groundwater source and a sea water desalination system.

Fig. 3 Map with locations marked that were successful, are successful, or bear the potential for being successful in collecting fog for the production of fresh water in arid or seasonally arid regions. The potential must have been proven by an evaluation project

More projects in Chile were realized in Padre Hurtado (31.5° S, Osses et al. 2000), providing water for visitors to a church sanctuary and for gardening between 1999 and 2004, in Peñablanca (29° S), where the fog water is used for afforestation with native trees and for environmental education, in Falda Verde (26° S, Larrain et al. 2002; Carter et al. 2007), delivering water mainly for *Aloe Vera* fields between 2001 and 2010 and now being operated as a demonstration project, and in Alto Patache (21° S, Larrain et al. 2002, Calderón et al. 2010), which is a site primarily used as a platform for ecosystem and climate research. It has an SFC fog collection record for 14 years, with average fog collection rates of about 6 L m^{-2} day^{-1}.

Peru has a long tradition of fog collection. Many projects have been developed by the communities, with varying degrees of success, from Trujillo in the northern part of the country to Tacna in the South. A major project between 1995 and 1999 near the town of Mejia on Peru's south coast proved the feasibility of fog collectors to provide water for afforestation and restoration of the degraded coastal ecosystems (Schemenauer and Cereceda 1993; Cereceda et al. 1998; Salbitano et al. 2010). This led to an afforestation project in Atiquipa, which has continued to the present (Ortega et al. 2007). Peruvian laws turned out to be supporting factors for fog collection because they demand a reforestation area above the "young villages" outside Lima as a requisite to get the legal land title (Tiedemann and Lummerich 2010). In three current projects, the water collected is used to grow fruits and provide fresh water for the population. As well, the local support for reforestation is strong.

In Ecuador, the potential of fog as a water resource has been studied since the 1990s. Very large collection efficiencies of up to 12 L m^{-2} day^{-1} were identified for high mountain regions. A large scale collection project was in operation from 1995 through 1997 employing 40 LFCs in Pachamama Grande. After the system had been handed over to the local population, it degraded. The lack of technical skills and involvement by the local NGO eventually hindered the project's persistence (Henderson and Falk 2001).

A large operational fog collection was stated in 2006 in the Guatemalan village of Tojquia in the Western Highlands at 3300 m above MSL. There are now 35 LFCs installed producing an average of 6300 l of water per day during the 4–6 months in winter dry season. In the wet season, the water yield is even larger due to the collection of rain water as well as fog water. High wind speeds are an issue in this region, and people had to be trained on how to repair and maintain the collectors. All the LFCs built since 2006 are fully operational. The year-round availability of fog water in some of these very remote regions impacts the social life of the population immensely as it has traditionally been the women's task to obtain water for the families. Before the installation of the first fog collectors, the women would walk each day to the valley bottom to get water. Strong community involvement is one of the main factors of success for the project in Tojquia (Henderson and Falk 2001; Schemenauer et al. 2007; Rosato et al. 2010).

Islands in the Caribbean are also seasonably dry in the period from October through March and, where there are mountains interacting with the northeast trade winds, there can be an arid zone on downwind side. Good evaluation projects were done in the Dominican Republic and Haiti, and the fog collection rates show that large-scale projects could be successful (Schemenauer et al. 2001).

Africa

The feasibility of using fog collection to supplement domestic water supplies in South Africa was investigated during the late 1960s and again in 1995. SFCs were erected in various parts of South Africa and the water collection rates monitored over a 3-year period. The yields ranged from 1 to 5 L m^{-2} day^{-1} and exceeded 10 L m^{-2} day^{-1} in the mountainous regions at elevations higher than 1700 m above MSL.

Seven LFCs were installed between 2001 and 2008 to provide drinking water at two schools in the Soutpansberg Mountains in Limpopo, at five schools in the Eastern Cape, and at a small West Coast village. Daily water collection rates varied largely (Olivier 2004). Unfortunately, the recipients failed to perform the required maintenance, and only one of these systems, maintained by students from the University of Pretoria, is still in partial operation.

Namibia also offers opportunities to produce fresh water from fog collection. Various exploratory studies, some dating back to the 1950s, showed that there are some sites with good prospects. Seely and Henschel (1998) documented the climatology of fog in the Namib Desert, Seely et al. (1998) discussed the ecology of the fog, and Mtuleni et al. (1998) presented results from fog collection measurements made with 14 SFCs. They found that the quantity and the quality of fog in the Namib Desert were sufficient to justify a fog collection project. However, a large project has not been started in this country as of yet (Shanyengana et al. 2002; Makuti et al. 2004).

There are fog collection projects in Eastern Africa and the Arabian Peninsula. In Eritrea, there are about 700 km of mountains along the Red Sea, where the winds advect moist air from the sea and form advection and orographic fog on the highlands. Twenty LFCs were installed in the villages of Nefasit and Arborobo to increase access to drinking water for schools and 120 families. Results showed a good production of fog water (www.fogquest.org). The project subsequently faced some significant challenges on its management since the collectors needed high maintenance and close supervision during high wind conditions. The fog collectors now serve as a demonstration of the potential for fog collection for the whole of Eritrea. There is also a large evaluation project underway in Tanzania and some work has been done in Ethiopia.

In Oman, a major fog collection experiment was undertaken in the summers of 1989 and 1990. In the upper elevations, from 900 to 1000 m above MSL, very high average collection rates of 30 l m^{-2} day^{-1} for the monsoon period were obtained. However, the fog water is only available for about 2 months of the year, and this puts limits on the use of the water (Schemenauer and Cereceda 1992b). More recent work by Abdul-Wahab et al. (2010) confirmed the productivity of the fog. In Yemen, the potential to collect fog water for fresh water production was investigated in the mountains near Hajja, north of the capital city of Sana'a and inland from the Red Sea in 2003 (Schemenauer et al. 2004). The best sites averaged 4.5 l m^{-2} day^{-1} over the 3-month dry winter period, justifying a large project with 25 LFCs to be implemented in January 2004. After successful initiation, the project was given over to the local people and local organizations. The follow-through at the community level was not sufficient and issues related to occasional high wind speeds were not resolved, and the project stopped after about one year. Other sites in Yemen at higher altitudes (over 2000 m above MSL) were evaluated with SFCs and were successful in terms of water volume produced (Osses et al. 2004). Conditions that are present on the east side of the Red Sea in Yemen are expected to persist northward into Saudi Arabia. Abualhamayel and Gandhisan (2010) report on 3 months of measurements in the Asir region with encouraging fog collection rates of about 2 l m^{-2} day^{-1}.

In the Macaronesian archipelagos (the Azores, Madeira, the Canary Islands, and the Cape Verde Islands) and NW Africa, favorable meteorological conditions exist for fog water collection (Azevedo et al. 1998; Marzol 2005; Prada et al. 2007). The station Bica de Cana (1800 m above MSL) on Madeira collected an amount of about 8 l m^{-2} day^{-1} (Prada et al. 2007). The station Anaga (842 m above MSL) on Tenerife island exhibited the best collection rates (10 l m^{-2} day^{-1}, Marzol and Valladares 1998; Marzol et al. 2010). The efficiency, good performance, and the availability of continuous hourly data for more than 14 years has enabled this station to be used as a model site for studying the characteristics of fog on the island of Tenerife and for comparison with other places (Marzol et al. 2010). In the 2000s, a number of fog collectors were installed in the NW of the island of Tenerife (Marzol 2002), including four LFCs, and four more were added in 2011. The water is used for domestic purposes in the Forestry Commission Office, for irrigation for the reforestation of endemic laurisilva species, and for prevention of and fight against forest fires.

On the desert archipelago of Cape Verde, the aim of the fog collection projects has been to obtain water to meet the needs of the rural population. Many pilot sites were installed, all of them facing to the N and NE. Major projects were realized on various islands, at altitudes between 750 and 1400 m above MSL (Sabino 2004). The water collection rates range between 3 and 75 l m^{-2} day^{-1} (Reis Cunha 1964; Juvik 1988; Sabino 1998, 2001, 2007).

On the NW coast of Africa, fog water collection has been investigated since 2006. Boulaalam—4 km from the coast and 300 m above MSL, and Boutmezguida—30 km from the coast and 1225 m above MSL, were chosen as the two experimental sites in a pilot project. Data obtained after

2 years of investigation indicate that the interior was the more efficient site with more than 7 l m^{-2} day^{-1} compared to only 1.9 l m^{-2} day^{-1} on the coast (Marzol and Sánchez 2008; Marzol et al. 2010). In 2011, 14 LFCs were installed to provide fresh water for small rural communities with serious water shortage problems. The population in this area lives off livestock farming and has to travel long distances on a daily basis to fetch water from wells at the bottom of the valleys.

Europe

Southern Europe is also a region with severe water resource problems. The combination of hot, dry summers with mild, wet winters, together with a strong population pressure, expansion of irrigated lands, and over-exploitation of aquifers has led to water scarcity in most of the countries around the Mediterranean basin. Mountain ranges exceeding 500 m in height near the coast and the constant presence of maritime winds advecting moist air and clouds provide favorable conditions for fog collection.

Croatia was the first country in this region to collect fog water. Since 2000, a SFC has been collecting fog water on Mount Velebit, 1594 m above MSL near the Adriatic Sea. The results show that fog has the potential of being an important source of water, especially during the dry summer season, when collection rates of up to 4 l m^{-2} day^{-1} can be achieved (Mileta 1998, 2001, 2004, 2007; Mileta and Likso 2010).

In Spain, a fog collection network has been maintained since 2003 on the eastern fringe of the Iberian Peninsula, covering an area nearly 800 km long. Twenty-four fog collectors are installed at 19 different locations. Fog water is collected with handmade cylindrical passive fog collectors (i.e., omnidirectional collection efficiency), made of either nylon wire or Raschel mesh, in combination with additional meteorological sensors. Fog can play an important role in the hydrological system in this area, with total values reaching 7 l m^{-2} day^{-1} at some locations (Estrela et al. 2008). Fog water was included as a supplementary water resource in a forest restoration project started in 2007 at Mount Machos, located 60 km from the nearest coastline. An LFC was used to irrigate 620 one-year-old seedlings of *Pinus pinaster* and *Quercus ilex* planted in an area of 2500 m^2. A collection rate of 3.3 l m^{-2} day^{-1} filled up three 1000-l tanks in 5 months (Estrela et al. 2009). The results show that the survival of the two planted species had improved significantly with the use of small controlled irrigations with water from fog.

Asia

The first fog collection project in Nepal was started in 1997 using SFCs for evaluation purposes (MacQuarrie et al. 2001). The climate is characterized by the summer monsoon season with heavy rain and the winter with a lack of rain and water shortages in the mid elevations. Fog collection projects in Nepal are typically in an elevation band around 2000 m above MSL. Following the initial SFC measurements, the techniques for site selection were introduced, and the local NGO staff was trained in the construction of LFCs. Today there are six small fog collection projects in operation in villages and a pilgrim temple. In Nepal, a medium-sized fog collector with 20–30 m^2 mesh area is being developed and tested. There is considerable interest in fog collection in several parts of India where some evaluations are beginning.

PROJECT SCHEDULE

Although the structures and goals of the many fog collection projects worldwide differ widely, there are characteristics that typically appear within a project schedule. In Fig. 4, a flow diagram is presented with numbered tags that will guide the discussion of processes and conditions in this section. Not each and every project evolves along that line. However, the general reasoning helps us to understand the specifics of a fog collection project, and to avoid mistakes in future applications. Cost estimates are provided.

(1) The initial project idea for fog collection typically originates from a person who is directly affected by the future project in his/her daily life. In most cases, it is a person that has seen or heard about a project elsewhere in his country or through some news broadcast. However, the person, or the village, does not have the knowledge or resources to carry out a project without assistance. An approach is then made to a non-governmental organization (NGO), typically a non-profit organization, either in his/her own country or often one based in North America or Europe. The goals of the NGO typically are to support development, to reverse environmental problems, and to foster sustainable development. In some cases, the idea of fog collection does not evolve locally but comes into a region in the form of a scientific study which, when successful, leads the participants to consider whether there may be applications for the people of the region. The introduction of the idea from the outside is, however, a delicate process requiring great respect for local customs, social aspects, traditions, and religion. Once the idea is born and the potential region identified, steps 2, 3, and 4 (Fig. 4), need to be realized. This initial stage has a minimal cost in time (days) and a negligible monetary cost.

(2) Once a working relationship is established between the village, a local in-country NGO, and the external NGO or university with the expertise in fog collection projects, initial funds need to be raised to perform an analysis of the

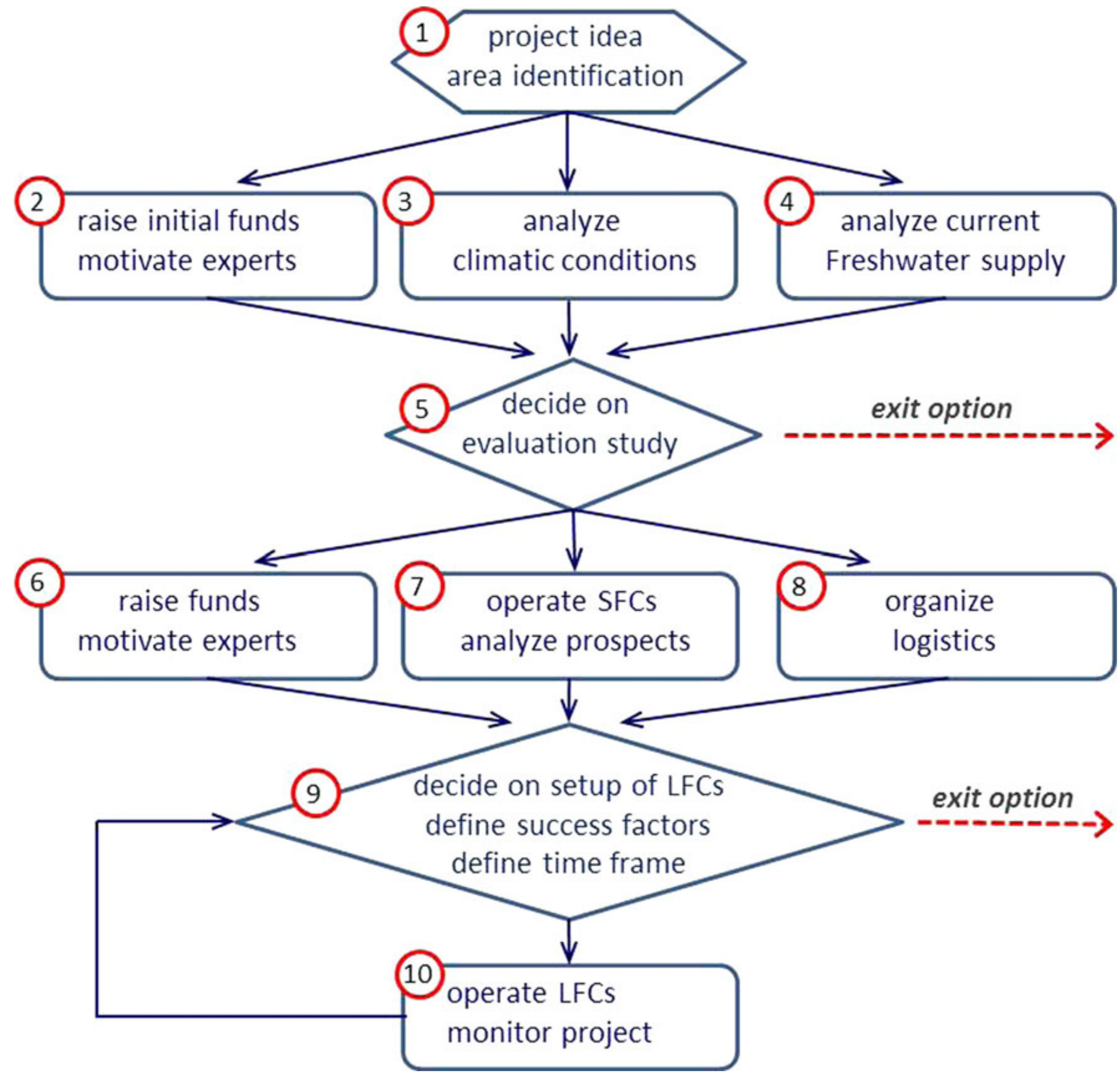

Fig. 4 Flow diagram of a typical fog collection project. Numbered tags are used to discuss processes and discussions in "Project Schedule" section

meteorological conditions and current or potential sources of conventional water (step 4), and to operate several SFCs for an evaluation study that lasts at least through one dry season (step 7). Typically, several trips to the potential fog collection site need to be financed. The cost of materials for one complete SFC setup is around US $150, depending on the local market situation. Often, an external expert on meteorology and water supply should visit the region very early. It is virtually impossible to pay this expert any remuneration; however, the travel costs must be covered somehow. The total initial funds required are, depending on travel distances, in the order of US $3000–5000.

(3) A careful analysis of the prevailing climatic conditions is needed. Unfortunately, regions with large potential for fog collection are often quite far away from recording meteorological stations. Visibility (fog density) data are typically not available. A further difficulty arises from the large local variability of fog and rain, for example, along mountain slopes. The ab initio analysis is therefore based on meteorological and geographical expertise and on interviews with the local population. Specific attention needs to be paid to the potential occurrence of strong winds that may damage fog collectors. Precautions have to be taken in such cases and, if high winds are anticipated, it becomes important to make some measurements. Another tool that can be of great value is the use of satellite imagery, but this is only practical if an archive of images is accessible at no cost. The time involved in this stage is perhaps only a week, and the costs are negligible if the time is donated. If a field program with anemometers is required, then an additional US $5000 in instrument and travel costs may be involved plus time for data analysis.

(4) The analysis of the current freshwater supply needs to be performed carefully and extensively. Where does the water come from currently? Is it trucked from a distant source? Is it carried by people (typically women and girls) from a distant place, for example, a valley bottom? Is it pumped from a well? Is the well likely to be sustainable? How much water is available per day per person? What are the costs involved for the current water supply? Is there a pronounced seasonality in water supply? Are there any plans to connect the people to a centralized water supply system? NGOs use questionnaires and make surveys in the field regarding these issues. This analysis takes about 1 month and travel-related costs may be US $3000. This stage may also require chemical and bacterial analyses of current or proposed sources of water. In some cases, the motivation for using fog collectors is the contamination of current water sources. If analysis for major ions, heavy metals, and bacteria are required, it adds another US $5000 unless analysis is donated.

(5) On the basis of the analysis and success in steps 2 through 4, it may be decided to start an exploratory fog collection project with small SFCs. The decision should be made after discussion with the local population, and after they understand the idea of fog collection. The involvement of the local population is an essential part of the project. Villagers have to commit to make daily observations of the amount of water collected during the evaluation study (step 7).

(6) In anticipation of the start of a large fog collection project (step 10), further funds need to be raised. This process takes more time and needs to be started immediately. Typical funding agencies are NGOs, private and corporate donors, United Nations agencies, the European Union, and other governmental organizations. In many cases, there is a lack of information about potential money sources. For example, there are funds offered by the Peruvian municipalities, private companies, and foreign embassies, but people are not informed about these funds. NGOs may help with the paperwork. The application process together with the village representative can serve as a first test for the commitment and the organizational strength of a village community for a fog collection project. It is ideal if a portion of the funding originates from a local source, potentially the village community itself, but the reality is that most remote communities where projects take place can only contribute their labor. In any case, the connectedness of the people with the project contributes to the success. The involved experts may be identical to those in step 2. The funds required depend on the scale of the project and its location. For a village of 200 people, and a goal of 25 l of fog water per person per day, one typically needs 1000 m^2 of mesh, or 25 LFCs. The cost for materials including water tanks and pipelines, plus travel and shipping costs, would be about US $75 000. This assumes no costs for salaries in external NGOs. Often, the initial project (step 10) would be rather small, as limited funds are available at that stage. If the local NGO requires funds for salaries, vehicles, and other expenses, then this must be considered and the decision factored into the overall costs. This might add an additional US $10 000 or more.

(7) The SFC should be operated over a period of at least 12 months and be operated carefully by a person who lives in the area. In reality, sponsors are often in a hurry to get the main project started, and initial measurements are sometimes limited to the dry season, when rainfall is lacking and fog collection can fill an urgent need. The installation of the SFC needs to be done with the best possible expertise and care. The height above MSL, an unobstructed geographical position and the correct orientation are essential. Precise recording of daily fog collection rates is important and is difficult to achieve in remote areas without extensive training of the observers. If funds and expertise are available, a meteorological station recording standard parameters plus the visibility (as a metric for the density of fog) should be installed as well. The collected water may be used for gardening or similar purposes. Material costs have been given above. This step will require several weeks of analysis and problem-solving time plus the time of the observers. In some countries, the observers have to be paid to get reliable data. This may add US $1000 to the costs.

(8) When the start of a large fog collection project (step 10) becomes likely, its logistics needs to be organized. The mesh (see "Technical Realizations" section) needs to be ordered, and construction materials for the LFCs, tanks, and pipelines (if required) organized. The setup of the LFCs is technologically simple, but great care must be taken in their construction, and it is crucial that the local population be heavily involved in the construction process. Building materials, except for the mesh, can be purchased in the country. The manual labor should be done by the beneficiaries in the interest of the sustainability of the project. Sewing the edges of the mesh is an example of a task that involves women in the construction process. A concept for water storage and water distribution needs to be developed. In most countries, poly-ethylene storage tanks can be purchased or cement cisterns built. The series of processes and decisions are complicated and guided by experience. The social impact of a new source of freshwater should be anticipated and communicated. This involves a series of community meetings and specific meetings with the women of the village who may be excluded from the formal village organizational structure. The financial structure for the construction and on-going operation of an LFC system need to be agreed on. This stage may require funds for travel, perhaps US $3000, and time measured in weeks or months.

(9) The decision to set up a large fog collection project needs to be carefully made. In particular, the potential benefit needs to be projected. How much water collection is expected? How much water will be potentially needed, and for what purpose? How large will the water storage capacities have to be? How many LFCs should be built in the first place? Who will be responsible for the operation of the LFCs and for the distribution of the water? Who will cover the costs of operation, which may be in the order of US $1000–2500 per year? How much will the water cost? Will it be sold? Is strong enough commitment within the community of beneficiaries to be expected? In a real application this is an effective "exit" point.

Along with the decision about the LFC project, success factors should be defined and coupled to a time frame. For example, if the system is capable of supporting a school for 5 years with fresh water so that students have drinking water in the school, this may be defined as a full success. A social benefit may arise if a specific societal group will receive an advantage, such as the women in Guatemala, Morocco, or Eritrea, who do not have to carry all the fresh water long distances every day (e.g., Rosato et al. 2010). Overall, this is a difficult process as a novel appreciation of values may be introduced into the societal system of a village community. If full success is achieved, a review (step 10) and potential re-decision about the further development of the project should be envisaged.

(10) Once the project is operational, it needs to be conducted very carefully and responsibly. The installation must be maintained, and the collected water volume and quality need to be recorded. The success of the project should be evaluated with appropriate and realistic success factors previously defined (step 9). This is the weakest point of many past projects. Once in operation, the fog collectors were not observed carefully enough, which led to deterioration. The success of a project should be quantified so that follow-up decisions can be made. Under optimum conditions, step 9 is re-entered, so that an ongoing loop (steps 9 and 10, Fig. 4) perpetuates the project. This implies that there is an on-going commitment of time and money by the village community, the local NGO, or the experienced international NGO. If travel costs are involved, they are likely to be in the order of several 1000s of US $ per year.

If fog collectors fail to operate successfully within the project period, a rapid and unbiased analysis should be performed, potentially by external experts as mentioned in steps 2 and 6. Step 9 should be re-entered as soon as possible. The discouragement of the local population through malfunction of the collectors must be avoided as it may dominate their attitude toward the fog collection idea itself. The main problems that occur are lack of basic maintenance, such as keeping the cables tight, using poor quality cables, and not having the mesh installed properly initially. The role of the local NGO is critical both to identify these types of problems early on, and also to continue the education program in the village to ensure good water quality and an appropriate and functional village water management program.

The exit options in Fig. 4 indicate that for a project that seems unfeasible or not feasible any more, a clear stop should be set. This may happen very early, i.e., before any test measurements are being started (step 5), before the actual construction of large collectors (step 9), or after operation of a LFC project (step 10) with limited success. Another eventuality is that after a period of a few years with a fog collection project, a village may grow in population significantly or funding from the local government may increase and suddenly a village may get an adequate conventional water supply such as a pipeline. Optimum conditions in terms of sustainability are fulfilled if the external experts (steps 2 and 6) exit a successful project at step 9, while the project continues to operate. For example, the project in Tojquia, Guatemala, is nearing this point as the last LFC was built by the local Mayan villagers, and they are assisting new villages to utilize the technology. Another example is the community Peña Blanca in Chile, where fog collection was initiated and operated with the assistance of Pontifical Catholic University (Santiago) in 2005 for about 2 years. After 6 years, the system is in sustainable operation, and three new projects have been started, related to fog collection, biodiversity, environmental education, and school projects on fog and dew, to stop further desertification.

SPECIFIC ASPECTS

Fog Water Quantity

The daily output from a fog collector is the product of the fog flux in $\mathrm{l\ m^{-2}\ day^{-1}}$ and the area of the collecting surface. Although the quantification of this flux is straightforward, there is no standard routine followed by investigators worldwide. Some numbers presented are annual averages, some averages for the fog season only, and some maximum observed values. Both SFCs and LFCs are also able to collect rain efficiently, so that their water yield may include rain in some climates. Another issue is the installation height of fog collectors above ground. The higher an installation is the greater the yield is due to higher wind speeds and often due to higher LWC in the fog. Last but not least, data quality control procedures and uncertainties are often not reported. This combination of uncertainties limits inter-comparison of fog collection rates at various sites.

The total quantity of water produced by LFCs depends on the number of fog collectors installed and the collection rate at the site. The fog collector array at El Tofo, Chile (see "Technical Realizations" section), produced an average of 15 000 l of water per day. The daily water output varies at all sites, and at this location, the LFCs on some days produced over 100 000 l of water, and on other days none or very little. Existing fog collection projects are producing average quantities in the dry season of 6300 l day^{-1} at Tojquia in Guatemala from 1400 m^2 of collecting surface (4.5 l m^{-2} day^{-1}, Rosato et al. 2010), viable amounts in South Africa (van Heerden et al. 2010), Peru (Tiedemann and Lummerich 2010) and in Colombia (Escobar et al. 2010). In Europe, Valiente et al. (2010) discuss an application in eastern Spain where the 2007 annual fog flux, measured with a cylindrical collector, was 3.3 l m^{-2} day^{-1}.

Evaluations with SFCs have shown that on mountains in the dry areas of Chile (e.g., Carter et al. 2007; Larrain et al. 2002), Colombia (Garcia and Arango 2004), Yemen (Osses et al. 2004; Schemenauer et al. 2004), Guatemala (García et al. 2004), Oman (Schemenauer and Cereceda 1992b), Peru (Bresci 2001), and Eritrea, seasonal average fluxes, measured with SFCs, ranged from 1.5 to 8 l m^{-2} day^{-1}. In certain locations of other countries with fog collection potential, measurements of fog fluxes have shown annual average values as low as 1 l m^{-2} day^{-1} in Namibia, and fog season values as high as 70 l m^{-2} day^{-1} in Oman. Many previous measurements of substantial collection rates at fog collection sites have been reported: e.g., Cape Verde (Sabino 2004), Dominican Republic (Schemenauer et al. 2001), Namibia (Shanyengana et al. 2002), Nepal (MacQuarrie et al. 2001), and South Africa (Olivier and Rautenbach 2007) where viable amounts of fog water can be collected.

Fog Water Quality

There are several aspects of water chemistry that are important in fog collection projects. The first is the chemical composition of the fog in the air before it strikes any collecting surface. This is what is often measured in scientific projects using scientific active or passive collectors with careful collector cleaning procedures. At sites worldwide where fog and rain were collected at identical sites, the fog water generally exhibits higher concentrations of solutes than comparable rain water. This has to do with the droplet-forming processes in rain and fog and the more intense exposure of fog to near-surface emissions.

The second aspect is the chemistry of the water coming off a LFC. The chemical composition of that water is also influenced by gases and aerosol particles that have deposited on the collection surface and are washed off by the fog water. Particularly during the onset of fog events, this may lead to enhanced concentrations of compounds ("first flush"). Schemenauer and Cereceda (1992a, b) reported on the quality of both the incoming fog water and the water from the fog collectors at the El Tofo site in Chile and in Ashinhaib in the Dhofar Mountains in Oman, respectively. They found that both sources of water met the World Health Organization (WHO) drinking water standards for ions and for 23 heavy metals. Eckardt and Schemenauer (1998) found that ion concentrations measured in fog water collected in the Namib Desert near Gobabeb were well within the WHO limits. An unpublished 2008 study by the Bavarian Water Ministry (Hruschka, personal communication), from a fog collection project in Eritrea, showed that water from fog collectors that had passed through a pipeline to water faucets at schools, also met WHO standards. Acceptable fog water quality was also reported for South Africa (Olivier and van Heerden 2002). However, Sträter et al. (2010) report that enhanced concentrations of some ions and metals were found at a coastal site in Chile. They hypothesize that power plant and industrial plant emissions on the west coast of South America exhibit an influence on the chemical composition of fog water. Overall, the composition of fog water will in most cases be safe to drink. Whenever there is potential of fog water contamination, the water quality must be checked before human consumption as for any type of water supply.

The third aspect is the potential alteration of fog water composition during storage in tanks. As this is an issue generally important in any drinking water storage, we consider it as beyond the scope of our analysis.

Economic Aspects

Fog collection projects are undertaken only in areas with very little rainfall on an annual or seasonal basis, favorable climatic conditions, and a scarcity of other competing fresh-water sources. The beneficiaries of many projects are poor people. The projects are typically initiated after donation of money and personal time ("Project Schedule" section). Over the years, the operational costs need to be compared to the costs of other sources for freshwater supply.

One of the experiences in development aid is that financial participation of the recipients enhances people's motivation to maintain the respective infrastructure. The population of the villages in Peru that operated a fog collection project ranged between 100 and 200 people. The community with the lowest number of inhabitants showed the highest level of independence. It seems that individual persons feel more responsible for the project in a small community. On the other hand, the work load is very high especially during construction of the reservoir. Therefore, the community should consist ideally of a minimum of 80 people, which means about 20–30 adults.

There is a specific advantage to fog collection projects, i.e., they do not only provide water but also money. Therefore, people could regard their participation rather as an investment and themselves, not only as a group of neighbors trying to improve their living conditions, but also as a group of investors starting their own business. In the outskirts of Lima, for example, in the so-called young villages, people practice this concept. They elect their village "junta" (Spanish for "board") and representatives, and meet weekly or monthly to discuss and organize village affairs. Another example is the potable water committee in Chungungo, Chile, which was formed by the villagers to manage the fog water supply there in the 1990s (Schemenauer and Cereceda, 1994b).

The cost of water per m^3 is difficult to calculate, much less to agree upon, as many assumptions are involved about what costs to include and the amortization periods for expenses. Cereceda et al. (1992) concluded for Chile that the fog water could be produced for about US $1 per m^3 and delivered to homes in a distant village for about another US $ per m^3. In the projects near Lima, once the fog collector and the corresponding infrastructure were set up, the elected water committee started selling the water within the community at a lower price, i.e., US $2.50–3.00 per m^3, than that paid for the delivery by water trucks. Part of the money is saved for future maintenance of the collectors. In some cases, it can be useful to pay one or two people for routine repairs and the distribution of the water, just like in any other company.

PERSPECTIVES

It has been shown that the collection of fog water as a fresh-water resource is a feasible technology in various regions of the world. Fog water may be a valuable source of fresh water for afforestation, gardening, and also as a drinking water source for human consumption.

It is mostly a poor population for which a fog collection project provides the largest advantages. Often, these people live in very traditional ways. Once the idea of collecting fog water as a fresh-water resource has been positively evaluated, a project is started. Initial funds and expertise typically originate from outside. A careful operation of LFCs provides numerous villages in many countries with large amounts of fresh water. Motivation, education, training, and involvement of the local people are key success factors. It has proven useful to create novel structures such as water committees to manage a project. Under optimum conditions, the operational costs are covered by selling the collected water to the beneficiaries for prices that are lower than those of alternative sources of fresh water. This concept works well for relatively small units. Problems in individual projects often arise after the operation of a collection system has been handed over to the local people or authorities. Poor maintenance can lead to malfunction of the collectors and eventually to the end of fog collection. It seems that these projects did not have a plan for successful and sustainable management.

Consideration should be given to a much greater role by governments. In some cases, it may be preferable to forward the project responsibility to local government control rather than directly to the community. Advantages may be the greater resources on longer scales of time and distance, and continuity contributing to sustainability. Disadvantages can include lack of motivation.

Unlike developing countries, developed countries have little difficulty covering their basic needs in terms of water supply. However, even though human consumption is usually guaranteed (not without some restrictions in certain places and seasons), there are other uses that are directly affected by the scarcity and/or erratic time and spatial distribution of rainfall. In this context, water produced by fog water collection systems might be a complementary source of water. This is the case of forest activities (such as reforestation projects), water tanks with water availability to be used in fighting forest fires, and even insuring a regular drinking water supply, strategically located in mountain areas, for the use by monasteries (Nepal and Ethiopia), hikers (Chile), or for the different species of animals that live there. Such activities, often led by forest rangers and scientists, are gaining momentum in Southern Europe, particularly Spain, and on some subtropical East Atlantic islands and in NW Africa. Ecological factors should be considered. Fog collectors are passive structures. The projects require no on-going energy inputs and could dock on to carbon sequestration projects in connection with reforestation. Environmental education programs and ecological parks may benefit from the concept of fog collection. Companies or governmental bodies could show their ecological responsibility by working with this technology. In such cases, money is often not the greatest obstacle in setting up a project.

Finally, the exchange of information, education of experts, and all other actors in potential and ongoing fog-collection projects is critical. This analysis is intended to contribute to this process.

Acknowledgments The authors express their gratitude to the many funding agencies, NGOs, and individual persons throughout the world, who all support fog collection projects, too many to be mentioned here individually. Two anonymous reviewers helped us to improve this manuscript, to whom the authors are indebted.

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AUTHOR BIOGRAPHIES

Otto Klemm (✉) is a professor of Climatology at the University of Münster, Germany. His research interests include, besides fog, aerosols, urban air pollution, and micrometeorological exchange processes between the atmosphere and the surface. He hosted the 5th International Conference on Fog, Fog Collection, and Dew (http://meetings.copernicus.org/fog2010/).
Address: Climatology Working Group, University of Münster, Robert-Koch-Str. 26, 48149 Münster, Germany .
e-mail: otto.klemm@uni-muenster.de

Robert S. Schemenauer PhD in Cloud Physics, Executive Director of *FogQuest: sustainable water solutions*. Previously: Research Scientist and Emeritus Research Scientist with Environment Canada, specializing in cloud microphysics and fog physics and chemistry, Adjunct Professor Thompson Rivers University, Chair of the 1st and 2nd International Conferences on Fog and Fog Collection.

Address: FogQuest: Sustainable Water Solutions, 448 Monarch Place, Kamloops, BC V2E 2B2, Canada.
e-mail: fogquest@shaw.ca

Anne Lummerich is a teacher of Biology and English. She is the president of the NGO Alimon e.V. (www.alimon.org) and has been working in applied sciences for 6 years designing and managing fog collecting and reforestation projects.
Address: Alimón e.V, Akazienweg 3, 41372 Niederkrüchten, Germany.
e-mail: alummerich@alimon.org

Pilar Cereceda is a professor of Climatology and Biogeography at the Pontifical Catholic University of Chile. Her research includes arid and semiarid climates and ecosystems, geographical aspects of fog and fog water collection. She hosted the 4th International Conference on Fog, Fog Collection, and Dew in La Serena, Chile
Address: Atacama Desert Center, Pontificia Universidad Católica de Chile, Santiago, Chile.
e-mail: dcereced@uc.cl

Victoria Marzol is a professor of Geography at the Universidad de La Laguna, Tenerife, Spain. Her research includes the field of climatology of Atlantic islands and the conditions of fog and fog water collection.
Address: Department of Geography, University of La Laguna, 38071 La Laguna, Canary Islands, Spain.
e-mail: mmarzol@ull.es

David Corell is a PhD student and a junior researcher in CEAM Foundation. His research includes meteorological aspects of fog water and fog water harvest. He has been working managing an automatic weather station network, including automatic fog collectors, for the last 9 years.
Address: Laboratory of Meteorology-Climatology, Mixed Unit CEAM-UVEG, The CEAM Foundation, Paterna, Valencia, Spain.
e-mail: dacocus@ceam.es

Johan van Heerden is an Emeritus Professor in Meteorology, the University of Pretoria, South Africa. He has more than 40 years of experience in most aspects of meteorology, and he has been involved in development and application of fog collection systems in Southern Africa.
Address: Department of Geography, Geoinformatics and Meteorology, University of Pretoria, Pretoria, South Africa.
e-mail: jvhplett@mweb.co.za

Dirk Reinhard graduated in Industrial Engineering and Management and has more than ten years of experience in the sustainability and finance industry sector. He is vice-chairman of the Munich Re Foundation, which addresses global challenges—climate change, water as a resource and risk factor, population growth, and disaster prevention.
Address: Munich Re Foundation, Königinstr. 107, 80791 Munich, Germany.
e-mail: dreinhard@munichre-foundation.org

Tseggai Gherezghiher PhD in Biomedical Sciences, the University of Oklahoma, College of Medicine. Retired Professor, Founder, and Director of Vision Eritrea, the National NGO in Eritrea, East Africa. Primary focus on Sustainable Development Projects in Developing Countries including fog collection.
Address: Vision Eritrea, Teshome Irgetu St 3/5, PO Box 5571, Asmara, Eritrea.
e-mail: drtseggai@gmail.com

Jana Olivier is a professor Emeritus in the Department of Environmental Sciences at the University of South Africa. Her research includes applied climatology and indigenous plant use. She has been involved in fog water harvesting since 1994 and was co-organizer of the 3rd International Conference on Fog and Dew in Cape Town, South Africa in 2004.
Address: Department of Environmental Science, University of South Africa, Florida, South Africa.
e-mail: jana1@mweb.co.za

Pablo Osses is Geographer, MSc in Economies, and a professor at the Institute of Geoprapthy in the Pontifical Catholic University of Chile. He has been involved for decades in the research of fog as a water resource and leading the implementation of projects to provide with fresh water, communities in poor countries in Latin America, Caribbean, Asia, and Africa.
Address: Atacama Desert Center, Pontificia Universidad Católica de Chile, Santiago, Chile.
e-mail: posses@puc.cl

Jamal Sarsour is a project engineer at the Institute of Textile Technology and Process Engineering Denkendorf, a center of textile research in Germany.
Address: Institut für Textil- und Verfahrenstechnik, Körschtalstraße 26, 73770 Denkendorf, Germany.
e-mail: jamal.sarsour@itv-denkendorf.de

Ernst Frost is co-founder and president of the WaterFoundation, a Germany-based NGO that provides assistance to people in rural regions worldwide with insufficient or polluted drinking water.
Address: Water Foundation, Lechnerstr. 23, Ebenhausen, 82067 Munich, Germany.
e-mail: wasserstiftung@t-online.de

María J. Estrela is a professor of Physical Geography at the University of Valencia, Spain. Her research interests focus on the field of Climatology, including the variability and stational distribution of precipitation in the Mediterranean area, the meteorological risks and the geographical aspects of fog and fog water collection.
Address: Laboratory of Meteorology-Climatology, Mixed Unit CEAM-UVEG, Geography Department, University of Valencia, 46010 Valencia, Spain.
e-mail: Spainmajoesna@uv.es

José A. Valiente is a research scientist at the Mediterranean Centre of Environmental Studies (Fundacion CEAM), Valencia, Spain. He obtained his PhD degree at the Department of Geography and Environmental Studies of the University of Tasmania, Australia. Current research activities involve fog collection and its use as an environmental resource, field instrumentation, and meteorological satellite remote sensing.
Address: Laboratory of Meteorology-Climatology, Mixed Unit CEAM-UVEG, The CEAM Foundation, Paterna, Valencia, Spain.
e-mail: josean@ceam.es

Gebregiorgis Mussie Fessehaye is a PhD student in University of Bern, Switzerland. His research area mainly focuses on fog water harvest and water management both for domestic and agricultural purposes.
Address: Vision Eritrea, Teshome Irgetu St 3/5, PO Box 5571, Asmara, Eritrea.
Address: University of Bern, National Centre of Competence in Research, Wildhainweg 3, POBox 8232, 3001 Berne, Switzerland.
e-mail: mfessehaye@yahoo.com