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THE USE OF FOG FOR GROUNDWATER RECHARGE IN ARID REGIONS

Robert S. Schemenauer
Environment Canada, 4905 Dufferin Street
Downsview, Ontario, Canada M3H 5T4

Pilar Cereceda
Geography Institute, Catholic University of Chile
Casilla 114-D, Santiago, Chile

ABSTRACT

The collection of fog on coastal mountains has produced substantial quantities of water in Chile, Peru and the Sultanate of Oman and has been shown to be worthy of investigation in at least 22 arid countries. The fog droplets are collected on large arrays of polypropylene mesh collectors. Where the conditions are suitable, 10,000 m^2 of collecting surface can provide 30 to 60 L of good quality water per person per day to a village of 1000 people, in areas of extreme aridity with negligible rainfall. The collectors can also be used to provide water for the afforestation of the mountains, which will result in natural fog collection by the trees and potential augmentation of the groundwater supplies.

1. INTRODUCTION

Precipitation is normally considered as the only source of water for watersheds and measurements of drizzle, rainfall and snowfall in several locations are integrated to estimate the annual input. There are, however, other sources of atmospheric water that, depending on the circumstances, can contribute to surface and underground water supplies. Dew has been studied in arid regions (e.g. Ashbel, 1949) and one may conclude that the amount of water generated is normally quite small, except in very isolated locations, and cannot be managed as a water supply. Fog is an entirely different matter. It is composed of tiny liquid water droplets, which impact in enormous numbers on both natural and artificial collectors of appropriate dimensions (Schemenauer and Joe, 1989).

It has long been recognized that fog (cloud on the ground) contributes substantial water to tropical cloud forests (Kerfoot, 1968; Stadtmüller, 1987) but almost without exception the studies have failed to quantify the water input from the fog. A review of the literature (Schemenauer and Cereceda, 1991) indicates that fog is also of importance as an arid lands water supply in at least 22 countries. But again, field studies such as those of Ekern (1964) in Lanai, Hawaii have confirmed the importance of fog in high elevation forests but have failed to separate quantitatively the fog and precipitation inputs. Large field programs in Chile (Cereceda et al., 1992) have now measured the amounts of water that large fog collectors can generate in a region with an annual average rainfall of only 70 mm. The 2400 m^2 of collecting surface has produced an average of 7200 L of water per day, each day of the year, during a three year drought with annual precipitation values of 10, 50 and 10 mm. The water meets drinking water standards (Schemenauer and Cereceda, 1992a) and is thus, of course, also suitable for use in agriculture and forestry. Experiments in Peru (Schemenauer and Cereceda, 1992b) and in the Sultanate of Oman (Schemenauer and Cereceda, 1992c) have also shown that water can be collected in large quantities from fog, in the absence of precipitation, in arid countries.

2. THE CONCEPT OF NEW WATER

It is essential for the utilization of fog as a water resource in arid lands that the difference between the roles of fog and precipitation be clearly understood. Rain (drops with diameters >0.5 mm) and drizzle (drops with diameters 0.04 to 0.5 mm) have appreciable settling velocities (5 to 1000 cm s^{-1}) and will fall to the ground. The fog droplets (<0.04 mm diameter) have terminal fall velocities that are so low that they are carried horizontally, with the wind, very long distances. In arid coastal locations this means that the fog droplets will be transported inland, often down the backside of the coastal range, and evaporate (Schemenauer and Cereceda, 1991). A vertical obstacle, such as a tree, will intercept both precipitation and fog but the precipitation would have fallen on the ground in any case. It would simply have been spread over a large horizontal ground surface. The fog water is, however, a very different matter. Without the presence of the tree the water would have been lost to evaporation. This led Schemenauer (1989) to introduce the concept of "new water". The erection of vertical fog collecting surfaces, either artificial or natural, can result not only in a managed water supply at a point but additional water in a mountain watershed.

An example, for the conditions in the Dhofar jebel in the Sultanate of Oman (Schemenauer and Cereceda, 1989), will serve to illustrate the importance of this new source of water. The rate of fog collection (R_f) by a tree is

$$R_f = luac \quad (cm^3\ s^{-1}) \qquad (1)$$

where: l is the fog liquid water content in g m^{-3}; u is the wind speed in m s^{-1}; a is the cross sectional area of the tree in m^2; and c is the collection efficiency of the tree (assumed to be 0.5). If l is 0.3 g m^{-3}, u is 7 m s^{-1}, and a is 36 m^2, then R_f is 38 $cm^3\ s^{-1}$ or 3300 L per day. If one assumes the area under the tree is circular with a diameter of 6 m, then this is equivalent to a fog drip rate of 12 cm per day or 5 mm per hour.

The same model tree will collect drizzle and rain. If the tree is a cylinder with a diameter of 6 m and a height of 6 m, one needs to calculate the amount of precipitation falling into the top of the tree, the vertical component (R_v); and the horizontally driven precipitation collected by the vertical cross section of the tree (R_h). The total precipitation collected (R_p) is

$$R_p = R_v + R_h \qquad (2)$$

R_v is the product of the rainfall rate and the horizontal cross sectional area of the top of the tree (28 m^2). R_h is the amount of precipitation the side of the tree (36 m^2) intercepts, which would otherwise be spread out over the ground. R_h depends on the fallspeed of the droplets and the windspeed. For a mean droplet diameter of 0.3 mm, a terminal velocity of 1 m s^{-1}, a wind speed of 7 m s^{-1} and a rainfall rate of 0.2 mm h^{-1}, R_v equals 135 L day^{-1} and R_h equals 1210 L day^{-1}. Therefore, the total precipitation intercepted is 1345 L day^{-1}. This is equivalent to an average drip rate under the tree of 4.8 cm day^{-1} or 2 mm h^{-1}.

The total amount of water (R) collected by our model tree is

$$R = R_f + R_p \qquad (3)$$

which in this example is 3300 L plus 1345 L or about 4750 L per day. This is perhaps somewhat high since the fog and precipitation were assumed to last a full 24 h, which is not always the case. About 70% of the water is from fog collection. This is in general agreement with Barros and Whitcombe (1989) who measured a dominance of fog over precipitation in the mountains of Dhofar. Expressed in another way, the tree will collect three times as much water when planted in a foggy location compared to a location with only precipitation.

3. MEASURED COLLECTION RATES

Average collection rates for artificial collectors vary substantially in the locations referenced above: 3 L m^{-2} day^{-1} for 12 months in Chile; 8.5 L m^{-2} day^{-1} for 7 months in Peru; and 30 L m^{-2} day^{-1} for two months in Oman. On an annual basis, however, the values are similar and are 3 - 5 L m^{-2} day^{-1}. The Chilean value is for fog, the Peruvian data include a small amount of drizzle, and the Omani data include drizzle in about the proportion calculated in the above example.

Finding reliable values for the collection by trees is much more difficult. Tables 1a,b give examples of some measurements that have been made in different parts of the world. The collection rates, normalized to an average daily collection rate, ranged from 100 to 1000 L d^{-1}. The maximum measured rates were a few thousand L d^{-1}. The collection rates were higher in windier environments and in areas with drizzle and/or rain present in the fog. The average depth of water produced under the tree canopies was 1 to 5 cm d^{-1}. This should be a function of tree type, size and shape but the data are too limited to draw any conclusions in this regard. If one calculates the average volume of water collected per unit area of the vertical cross section of the tree exposed to the wind driven fog and precipitation, the range is from 10 to 100 L m^{-2} d^{-1}.

As was discussed above, the tree relocates precipitation and concentrates it under the tree. At the same time it generates new water from the fog droplets that it captures. At the Chilean site, there are no trees that grow naturally. The only existing trees have been planted. The few trees at lower elevations were planted in preferred locations where there is groundwater. The trees at higher elevations were watered until they grew to about two meters in height and now survive, and regenerate, on the fog water they collect. Cereceda and Schemenauer (1991) have shown these sites are in fog about 50% of the days in the year and in patchy fog an additional 25% of the days. If one

Expt. #	Location	Year	Source*	Tree Type	Alt. (m)	Total Rain (mm)	Ave. Wind Speed ($m\ s^{-1}$)
1	Masroob, Oman[1]	1989	F/D	Olea europaea	920	-	-
2	Shabob, Oman[2]	1990	F/D	Ficus sycomorus	800	149	calm
3	Masroob, Oman[2]	1990	F/D	Olea europaea	920	-	7.4
4	El Tofo, Chile	1990	F	Eucalyptus glob.	780	0	-
5	El Tofo, Chile	1991	F	Eucalyptus glob.	780	0	low
6	El Tofo, Chile	1991	F	Eucalyptus glob.	780	0	high
7	Lanai, Hawaii[3,4]	1955-8	F/D/R	Araucaria excelsa	840	3800	5

Table 1a. Measurements of the collection of fog (F), drizzle (D), and rain (R) by trees.
[1] Barros and Whitcombe (1989); [2] COWIconsult (1990); [3] Carlson (1961); [4] Ekern (1964).

Expt. #	Tree Cross Sect. (m^2) Vertical	Horz.	Volume (L)	Days #	Ave. Vol. ($L\ d^{-1}$)	Max. Vol. per Day (L)	Depth (cm) Total	Day^{-1}	Ave. Coll. Vertical c/s ($L\ m^{-2}\ d^{-1}$)
1	12.3	18	67,747	79	860	2105	376	4.8	70
2	-	-	7,565	83	91	250 est.	-	-	-
3	12.3	18	48,165	83	580	1200 est.	268	3.2	47
4	28	33	180	0.5	360	-	-	1.1	13
5	28	33	23	0.13	177	-	-	0.5	6
6	28	33	62	0.17	365	-	-	1.1	13
7	28	28	278,000	1100	250	4300 est.	995	0.9	9

Table 1b. Collection rates for the experiments in Table 1a. The average and maximum daily volumes, the total and daily average depths under the tree, and the average collection on the vertical cross section are given.

assumes a eucalyptus is in fog for 12 hours on 183 days in a year, and the collection rate is as in experiment #4 in Tables 1a,b, then the tree will produce 66,000 L of water, which will drip onto the ground below the tree in a year. The tree's water requirements are unknown but since it grows in a very humid environment, and since it generates enough water to support mosses and new seedlings under its canopy, perhaps 15%, or 10,000 L a year, might be surplus to its needs and might be contributed to the groundwater supply in the area. All of this is new water.

In Oman the annual water production for a tree in the mountains of Dhofar is similar to that in Chile, except it is produced in 2 months not 12 months. Examination of the trees on the jebel during the monsoon confirm that the trees do not use all the water they collect. When the trees are located on a slope, there is considerable erosion under the trees and rocks are exposed. In addition, there is a visible surface flow of water away from the trees. This suggests that at least the 15% of the collected water, suggested above, is surplus to the trees needs and will eventually augment the groundwater supplies in the area.

4. RECHARGE IN ARID LANDS

If one took a small semicircular watershed, with a diameter of 13 km, a strip 20 km long and 500 m wide could be planted with trees at an altitude with frequent fog. This would be an area of 1000 ha. If trees were planted with a generous spacing, 10 m apart, to allow for the passage of the fog when the trees are mature, one could plant 100 trees per ha or 100,000 trees in total. If the contribution to the groundwater supply was 10,000 L or 10 m^3 per year per tree, as calculated above, a total of 10^6 m^3 would infiltrate the ground in a year. This is equivalent to having an extra 100 mm of precipitation fall on the 10 km^2 plantation in a year. The water would be generated every year during the lifetime of the trees. In arid regions, such as northern Chile, this exceeds the average annual rainfall.

In order to ensure that the tree seedlings survive when planted, it may be necessary to provide them with water from artificial collectors for a period of one or two years until they are established and reach a productive height. Based on the results discussed above, this could be achieved with 1 or 2 m^2 of collecting surface per tree. When one group of tree seedlings is established, the collectors could provide water for new seedlings.

5. CONCLUSIONS

The collection of fog, or fog and drizzle, by manmade fog collectors in arid lands is well established. The collected fog water has been used to grow trees in northern Chile, southern Peru and the Dhofar region of Oman. None of these projects have been large in scope. The largest is in Chile where 3 ha of mixed species have been grown at the El Tofo site.

Both field observations and calculated collection rates by trees strongly suggest that trees in foggy, windy environments will collect more water than they require to sustain themselves. The excess water would enhance the groundwater supplies in the basin since little water would be lost to evaporation in these arid but humid environments. Indeed, some additional groundwater must be created since it is impossible for the water dripping off the trees to be confined under the trees in these sloping mountainous regions. It is proposed that a value of 10,000 L per year per tree be used as a conservative estimate of the fog water contribution of trees to the groundwater supply. The value is of course approximate and will depend on the fog frequency, fog liquid water content, wind speed, tree type, tree exposure, topography and subsurface geological structure. These parameters should be examined at each specific site. The essential point is that in treeless mountainous regions, which are arid but with frequent fog, it should be possible to augment the groundwater supplies through well designed tree plantations.

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