Theor. Appl. Climatol. 51, 89–96 (1995)

Theoretical and Applied Climatology

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Direct Cloud Water Recovery by Inertial Impaction: Implications for Large Scale Water Supply in the Cape Verde Islands

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With 3 Figures

Received August 9, 1994
Revised November 21, 1994

Summary

In this study, we explore the idea of harvesting cloud water in mountainous areas of the drought prone Cape Verde Islands as a year-round fresh water resource based on three cloud water collection experiments in the islands. Cloud water was collected by impaction on a commercially available, plastic, agricultural shade cloth at Serra Malagueta, Santiago, and at Monte Verde, São Vicente. This shade screen possesses superior properties to other reported materials for cloud water collection, including an impact-efficient mesh shape, high tensile strength and durability, tear resistance, and excellent water drainage characteristics. Collection efficiency of monofilament knitted shade screen varied with the mesh density (50% or 70% shading) and height of the screens, but for Monte Verde all screens above 3 m collected greater than 6 $l\,m^{-2}\,day^{-1}$ on average for 315 days of measurement. Dry season collection for the most effective panel, a double layer of 50% shading screen, ranged from 1.3 $l\,m^{-2}\,day^{-1}$ in December, 1988, to 7.8 and 7.7 $l\,m^{-2}\,day^{-1}$ in November and April, 1988 respectively. Based on these measurements, we discuss a logical next phase for implementation of a large scale cloud water catchment system.

1. Introduction

The Republic of Cape Verde comprises 340,000 mixed African and Portuguese descendants living on a small island chain in the tropical Atlantic Ocean, approximately 600–700 km west of Senegal. A largely agrarian society, the Republic depends heavily on remittance income and foreign aid to support an import/export imbalance of nearly 24:1. While the islands are self sufficient in many areas of food production, such as meat, fruits, and vegetables, most cereal grains (corn, wheat, and rice) must be imported. Of the 429,000 ha of land on the 9 inhabited islands, only about 60,000 ha are considered suitable for agriculture. Of this, only 1800 ha are presently irrigated, largely for production of export crops, such as sugar cane for making alcohol, and bananas (A.I.D., 1984).

The same large scale climate features that cause North Africa's arid climate also limit precipitation in the Cape Verde Islands. Due to the highly variable, and often highly concentrated, nature of rainfall in the area, drought and famine have historically plagued the islands. Three times in the 18th and 19th centuries prolonged droughts decimated a staggering 40% of the population. Even in this century, drought was blamed for the deaths of 50,000 people in 1946 (A.I.D., 1984).

Recent development projects in the country have attempted to ensure a more dependable water supply. Traditionally, shallow wells dug into streambed aquifers provided household water and irrigation by diverting water onto adjacent fields. Watershed development has included schemes to increase infiltration such as contour furrows, rock-stabilized terracing, check dams, and reforestation. While effective, these measures still leave islanders vulnerable to below normal rainfall periods. Exploitation of deeper groundwater reserves has been proposed but awaits a fuller analysis of sensitive aquifers' water balance and sustainable yield. In the city of Mindelo, São Vicente (population 60,000), an oil-fired desalination plant ensures a year-round municipal water supply. While dependable, the extreme cost of desalinated water precludes any agricultural use.

In this article, we explore the idea of harvesting cloud water to supplement rainwater collection for agricultural purposes and as an alternative to desalinization for municipal use. Cloud water collection has many advantages as a water source: it provides fresh water during the dry season and during drought episodes, the high elevation of the collection sites obviates the need for pumps, the collection system is comparatively inexpensive, and the water quality high. Three experiments were conducted at two mountain sites during the 1987 wet season and throughout 1988 that measured cloud water collection potential using a woven monofilament plastic (MONOLON) screen material (brand name WEATHERSHADE, since discontinued and replaced by a virtually identical product brand-named V-J PREMIUM KNIT, distributed by V-J Growers Supply, 500 West Orange Blossom Trail, Apopka, FL, 32703, USA; currently priced at US$1.55/m^2 FOB). The specific goal of the work was to quantify the collection volume per square meter of knit screen material for varying height, density, and season. Based on the results of these experiments, we go on to discuss the potential for large scale cloud water recovery in the Cape Verde Islands.

2. Physical Setting

The Cape Verde Island chain consists of 10 volcanic islands (including an active volcano on Fogo) and 8 smaller islets, bounded by 14° 48′ to 17° 13′ North latitude and 22° 42′ to 25° 22′ West longitude (See Fig. 1). Northeast tradewinds dominate the mean wind field every month of the year averaging between 4 and 7 m s^{-1} over the open ocean, with the lower wind speeds occurring July through November (Sadler et al., 1987). While the surface air contains abundant atmospheric moisture to produce rainfall, a temperature inversion aloft at 500 m and the cold Canary current at the surface produce a stable atmosphere and limit open ocean rainfall to less than 300 mm annually. During the short rainy season, July through October, the intertropical convergence zone reaches its most northerly position in the area, occasionally forming over or even north of the island chain. During these periods, the inversion weakens or disappears and rainfall accompanies the resulting instability. While rainfall seems adequate to support agriculture during the wet season, it has a high interannual variability and is often torrential. An entire season's total may fall during a single storm event. Rainfall variability is particularly pronounced at coastal locations and diminishes with elevation into the wetter highlands (Cunha, 1964).

The islands possess sufficient topographic relief to generate climate gradients over the higher mountains, with distinctly wet windward and dry leeward exposures. On the larger mountains, such as on Fogo and Santo Antao, average annual rainfall exceeds 1000 mm at near 1000 m elevation. Orographic lifting of the moist onshore air mass produces a distinct cloud layer between approximately 400 and 1000 m. In this article, the terms cloud water and fog are used interchangeably and refer to the orographic/stratus cloud layer touching the surface. Above 1000 m, fog frequency diminishes and clear skies typically prevail as the inversion suppresses upward motion and the dry air evaporates rising clouds. During the dry season, *harmattan* winds from North Africa periodically buffet the islands. During these periods wind speed can be high, especially near the mountain crests, the humidity decreases, and the frequency of fog diminishes. Although fog frequency is not recorded, local knowledge suggests the highest frequency during June (just before the start of the rains) through November, with fog occurring on most days during the dry season as well, although often punctuated with periods of completely clear days (Cunha, 1964).

Attempts to prove that fog collectors could provide a reliable and valuable water source began with a series of experiments in the 1960's by the Portuguese using small (20 cm height, 10 cm diameter) cylindrical, wire mesh fog collectors. During 1962 at their four study sites on three islands between 950 and 1400 m, fog water collection greatly exceeded rainfall. During the dry season, the greatest disparity between fog catch and rainfall occurred at the highest sites. Later experiments in 1963 and 1964 utilized 2 m^2 flat

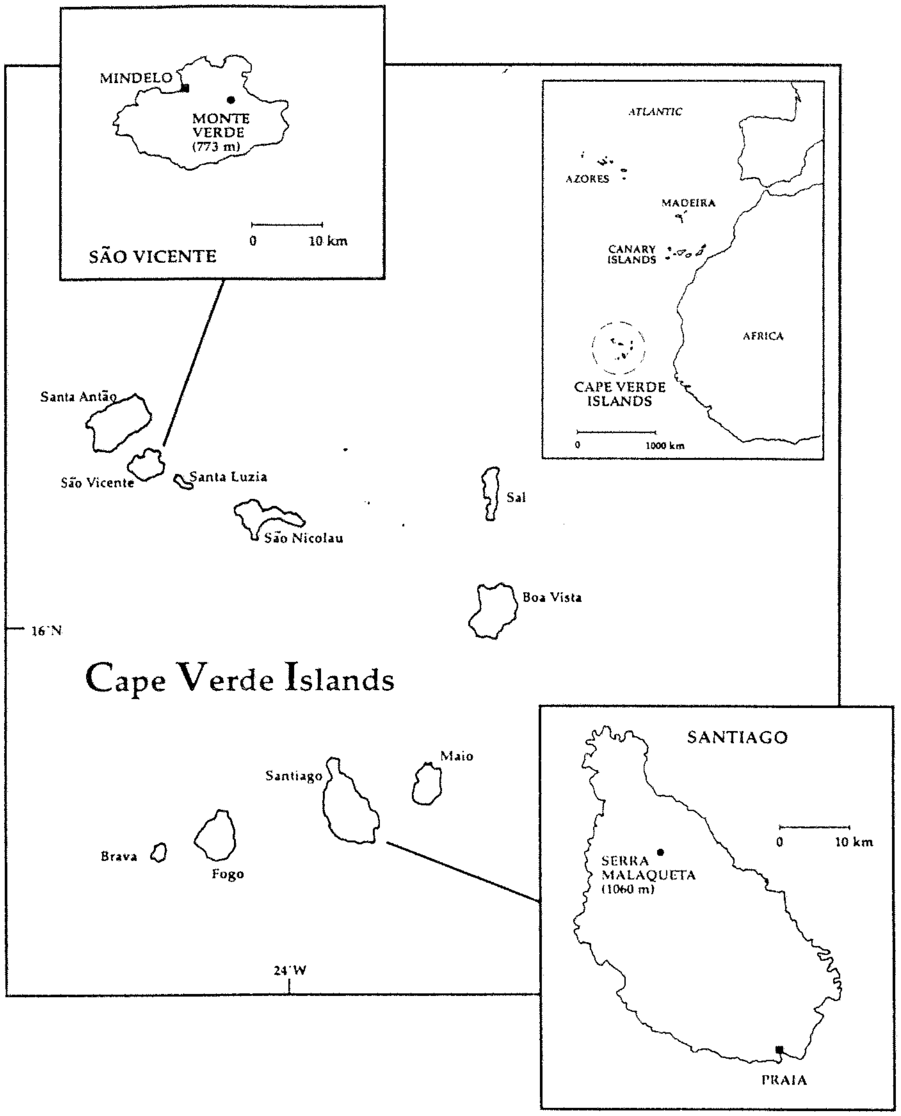

Fig. 1. Location map

wire gauze and mosquito netting panels. At Serra Malagueta, Santiago (1060 m) and Campo das Fontes, Brava (880 m), the panels yielded typical monthly values of 3 to 10 litres per square metre per day ($lm^{-2} day^{-1}$) during the dry season and 10 to 30 $lm^{-2} day^{-1}$ for the wet season (when corrected for rain caught in the impervious 5 m^2 basins below the screens). At Monte Verde, São Vicente (elevation 750 m) collection using a double screen configuration (5 cm separation) averaged 37 $lm^{-2} day^{-1}$ during June, 1963. While these studies documented the substantial volumes of water obtainable with simple screen collectors, the collection material itself deteriorated rapidly, especially the metal screens which lasted only a few months. In addition to the sites discussed above, other areas identified as potential locations for cloud water collection include the uplands (above 500 m) on St. Nicolas, Fogo, and Santo Antao (Cunha, 1964). More recently, in the 1970's and early 1980's the Dutch undertook large scale fog collection experiments in the Agua das Caldeiras area of Santo Antao. In discussions with local residents living near these fog catchments it was clear that all felt the systems had worked well initially but ultimately failed because the plastic screen material ripped out and blew away during periods of strong winds.

3. Study Site and Measurements

For this study, two experimental sites were selected based on site visits and results from previous studies: Monte Verde, São Vicente, just below the 773 m summit at 750 m elevation (annual rainfall ≈ 600 mm), and Serra Malagueta, Santiago, at 1060 m elevation (annual rainfall ≈ 900 mm). The summit of Monte Verde, a northeast facing, gently sloped plateau, seems ideal for fog collection because of the high frequency of cloud cover and proximity to the largest city in the archipelago, Mindelo.

Masts erected at each site supported nine 1 m × 0.46 m rectangles of the knit shade screen as shown in Fig. 2. Both 50% and 70% densities were tested in single and double width (2.5 cm separation) configurations. The 50% and 70% shading screens were installed in a vertical profile at 1–2 m, 3–4 m, and 5–6 m. Double 70% screens were installed at 1–2 m and 5–6 m, and a double 50% screen installed at 3–4 m. The reason for testing different mesh densities and heights was to empirically determine which configuration optimized impaction surface area and the rate air flows through the screen. Higher flow-through rates increase fog catch by making a greater supply of cloud water available. Higher mesh densities increase fog catch by providing a greater surface area for impaction, but if the density becomes too great, the screen blocks the wind and decreases the flow-through rate. Providing a vertical profile allowed us to determine the effect of different wind speeds on this optimizing problem.

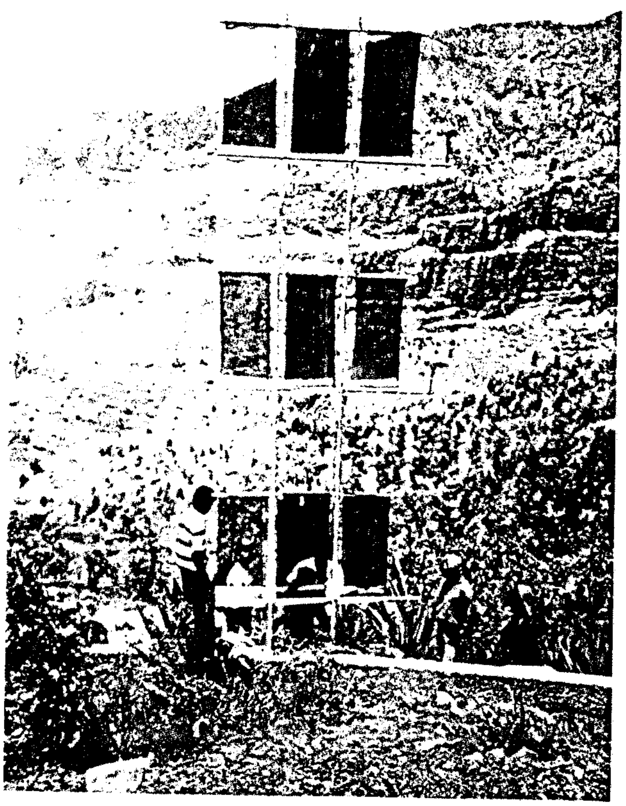

Fig. 2. Experiment configuration at Serra Malagueta. Right panels are 50% shade screen, left panels are 70% shade screen, middle panels are double 70% screen at the top and bottom, and double layer 50% panel at the center. Panels are mounted between 1–2 m, 3–4 m, and 5–6 m, each 0.46 m^2 in area

A 0.125 m^2 trough was installed at the leeward base of each screen to catch falling droplets and funnel them into the collection tubes which drained into nine 25 liter bottles. The bottles were read manually and emptied at intervals ranging from one to several days. The water collected included cloud water, rainfall, and wind-blown rain. Since raindays are rare, however, the bulk of the water collected was direct cloud water interception. For this article, no distinction is made between these three atmospheric moisture sources and collectively they are referred to as cloud water or fog.

The Serra Malagueta site was monitored from 16 June 1987 through 16 July 1987. The Monte Verde site was monitored in two phases: 25 July 1987 through 1 August 1987, and 8 February 1988 through 18 December 1988.

The knit screen, developed to shade crops, has an advantage over previous materials used in fog collection in that it does not decay rapidly (containing UV inhibitors) and has a high tensile strength. In addition, the extruded, monofilament (MONOLON) knitted mesh provides an ideal capture shape and a surface that encourages rapid drainage. The material is commercially available throughout the world.

While all three experiments yielded quality cloud water catchment data, several problems were encountered: 1) anemometers installed at 1.25, 3.25, and 5.25 meters to determine the wind profile and relate cloud water catchment to wind speed failed to operate properly. As a result, the wind speed values presented in Table 2 and reported below are simply the averages of instantaneous measurements using hand held anemometers (at 2 m) taken each time the catchment volumes were recorded, typically in early afternoon. 2) the flared troughs designed to catch wind blown water droplets on the leeward side of the screens were incorrectly installed on the windward bases of the collection screens at Serra Malagueta. We believe this reduced total catchment at the site by 10% to 25%. 3) Although a $0.125\ m^2$ trough was installed as a rain-gauge at Monte Verde, recording ambiguities have rendered the data unusable, and 4) The 25 litre bottles used for collection sometimes overflowed. The data presented below, then, should be considered conservative and somewhat under-representing the true capacity of the fog catch screens.

Table 1. *Fog Screen Interception for Varying Heights and Shade Density of Monofilament Knit Shade Screen Material at Serra Malagueta, Santiago, 16 June Through 16 July, 1987 and Monte Verde, São Vicente, 25 July Through 1 August 1987.* All values expressed in liters per square meter per day

Screen type (% shade)	Height above ground (m)	Serra Malagueta ($l m^{-2} day^{-1}$)	Monte Verde ($l m^{-2} day^{-1}$)
50	5–6	10.2	21.4
50	3–4	5.6	14.2
50	1–2	2.7	11.0
70	5–6	10.7	19.9
70	3–4	7.3	19.8
70	1–2	2.7	11.9
2 × 50	3–4	10.2	24.4
2 × 70	1–2	2.9	12.2

4. Results

Results from the three data collection efforts are shown in Tables 1 and 2. The data in these tables have been converted to litres per square metre per day (actual screens were $0.46\ m^2$). The highest collection totals at Serra Malagueta (Table 1) were over $10\ l m^{-2}\ day^{-1}$ for the 50% and 70% layer screens at 5–6 m height, and the double width 50% screen at 3–4 m height. It should be noted that during the 30 days of data collection, virtually no measurable rainfall fell at the site. Water collection increased with height in accordance with the logarithmic wind profile, with catchment at 5–6 m averaging 3 to 4 times greater than catchment at 1–2 m height for the single 70% and 50% screens. The increase in catchment with height near the ground is expected and matches the wind speed profile. Average wind speed for the sampling period at 3.5 m height averaged 5 to $6\ ms^{-1}$.

Catchment was substantially higher at Monte Verde than at Serra Malagueta as shown in Table 1. The July, 1987 experiment yielded catchment volumes of 2–3 times greater than the Serra Malagueta site, averaging as high as $24.4\ l m^{-2}\ day^{-1}$

Table 2. *Fog Screen Interception at Monte Verde, São Vicente, 8 February Through 18 December, 1988.* All values expressed in liters per square meter per day (original values multiplied by 2.17 to correct for $0.46\ m^2$ screen surface area). Fog days refers to the number of days during the month that cloud water collection was recorded. Superscripts indicate the number of times during the month that the 25 liter collection bottles overflowed (equivalent to 54 liter overflow for $1\ m^2$ panel)

Screen type (% shade)	Height above ground (m)	Fog water collection ($l m^{-2} day^{-1}$)											
		1988 Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ave
50	5–6	4.8^{1}	5.2	7.8	5.6^{1}	6.6^{2}	21.4^{5}	14.6^{3}	18.4^{3}	3.8	2.6	0.4	8.7
50	3–4	4.9	5.5	7.0^{1}	5.4^{1}	6.3^{2}	15.7^{4}	5.8^{1}	8.0	4.6	1.5	0.4	6.2
50	1–2	2.8	3.6	3.3	2.5	2.4	17.3^{2}	11.9^{1}	13.4^{1}	2.9	2.9	0.3	6.1
70	5–6	2.4	4.9^{1}	8.7^{1}	5.0^{1}	6.1^{2}	15.6^{3}	10.5^{1}	8.4	2.2	0.9	0.1	6.2
70	3–4	4.2^{1}	5.0	6.8^{1}	4.4^{1}	5.1^{1}	16.5^{2}	8.9^{1}	11.1	4.1	3.0	0.5	6.6
70	1–2	2.1	2.5	3.5	2.6	2.5	12.1^{1}	7.5^{1}	9.0	3.2	3.1	0.4	4.6
								5^{1}					
2 × 70	5–6	4.2^{1}	4.4^{1}	7.3^{1}	5.0	5.6^{1}	16.9^{3}	12.4^{1}	9.6	4.0	3.2	0.5	7.0
2 × 50	3–4	5.4^{1}	6.2^{1}	7.7^{1}	5.6^{1}	6.6^{2}	25.1^{7}	18.2^{4}	21.1^{4}	9.6	7.8	1.3	10.9
2 × 70	1–2	3.0	2.5	3.1	2.3	2.3	12.6^{1}	8.3^{1}	11.0	3.5	3.4	0.4	5.0
wind speed (ms^{-1})		4.1	7.8	6.4	7.8	7.8	3.7	4.0	4.9	4.9	5.6	—	5.7
fog days		4	4	12	5	6	28	23	20	15	10	2	

for the double layer 50% screen at 3–4 m. No clear advantage was evident when comparing the collection efficiencies of the 50% and 70% screens, with the 50% screen outperforming the 70% screen at 5–6 m and the reverse at 3–4 m. As at Serra Malagueta, catchment increased with height, especially for the 50% screen. The higher yield at the Monte Verde site is probably due to its lower elevation, near the cloud base. At higher elevations, downward mixing of dry air through the inversion evaporates cloud droplets and decreases the liquid water content of the air.

Table 2 presents the results of 315 days of cloud water catchment measurements at the Monte Verde site summarized by month. Wind speeds over the period averaged 5.7 ms^{-1}, with a distinct wind drop at the inception of the rainy season in July. Once again, the double layer 50% screen at 3–4 m outperformed all other combinations, with no clear advantage for the 50% versus 70% shading screens. It appears that the double layer 50% screen optimizes the relationship between screen density and flow-through rate. While maximum values were recorded at 3–4 m, it is possible that ever better results could have been obtained had we installed the double layer 50% screen at 5–6 m, rather than the double layer 70% screen. In accordance with a logarithmic wind profile, catchment clearly increased between 1–2 and 3–4 m.

Figure 3 illustrates the annual pattern of cloud water catchment for the double layer 50% shading screen. For the dry season, November through June, catchment ranged from a low of 1.3 lm^{-2} day^{-1} in December to 7.8 and 7.7 lm^{-2} day^{-1} in November and April respectively. These data include several overflows as shown in Table 2.

5. Discussion

The volume of water per unit collector area recorded in this study using 0.46 m^2 strips of the knit screen compared favorably with collection from 2 m^2 mosquito netting panels conducted in the 1960's. The design of any vertical fog collection panel must maximize the impact surface available but, at the same time, remain porous enough to allow a free flow of air through the panel rather than forcing to flow around as it would a solid obstacle. Based on the results presented here, the double 50% screen configuration clearly optimizes these criteria and offers the greatest collection efficiency for the knit screen material. The durability, strength, proven collection potential, and low cost of the knit screen argue strongly for it's selection in the next phase of a fog-collection project.

Sufficient cloud water collection data are available to suggest a demonstration scale catchment system and make preliminary estimates of its yield. Monte Verde offers the ideal location for a demonstration project based on the high cloud water catch recorded at the summit, its proximity to a

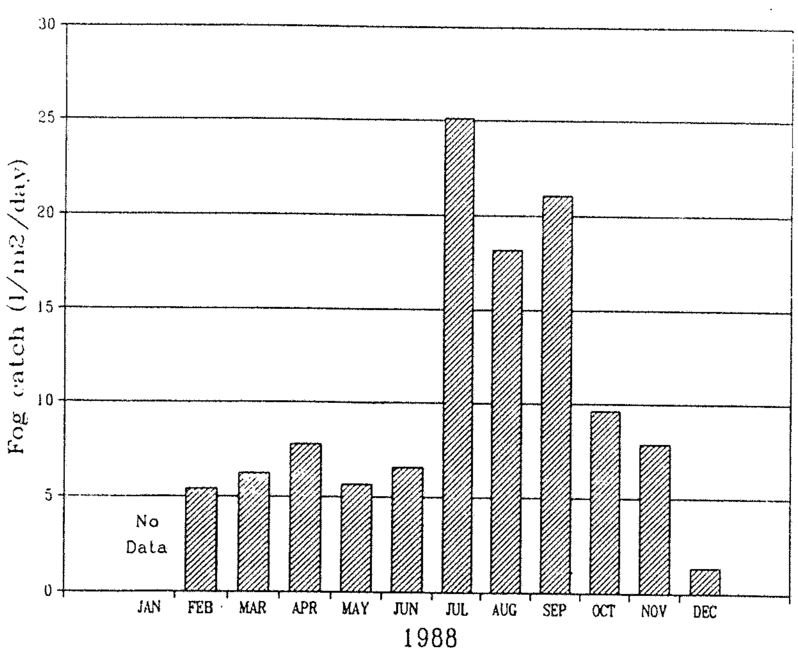

Fig. 3. Annual pattern of cloud water collection for our most effective collecting surface, the double layer 50% shade screen mounted at 3–4 m, at Monte Verde in 1988. Dry season (November through June) collection ranged from 1.3 lm^{-2} day^{-1} in December to 7.8 lm^{-2} day^{-1} in November. Maximum collection was 25.1 lm^{-2} day^{-1} in July

major urban center, Mindelo, and its topography. The summit area consists of a gently sloping plateau directly facing the northeast tradewinds broad enough to support the large-scale construction of a cloud water collection system over 70 hectares. This project would include construction of two initial catchment system segments of approximately 1000 m^2 each (positioned in two parallel lines perpendicular to the tradewinds and separated by about 10 times the segment height to determine upwind blocking effects on yield), a concrete or asphalt water collection surface beneath the catchment, a water storage facility, and a small diameter pipe line to deliver water from the plateau. We estimate the cost of installing these collectors on Monte Verde to be approximately US$60,000, or about US$30/m^2 for the 2000 m^2 demonstration array. Assuming a working life of 10 years, the system would yield fresh water at a cost of about US$0.75 per m^3 for fresh water, significantly below the current cost of desalinization. Operational costs would be minimal, consisting principally of reattaching the catchment screen following high wind episodes.

No data are available to determine whether or not 1988 represented a "normal" year climatologically for Monte Verde. (The only reported data for the Cape Verde Islands for 1988 come from the island of Sal (Monthly Climatic Data for the World, National Climatic Data Center, US Government Printing Office). July through October, the wet season, rainfall was reported as 0, 20, 40, and 0 mm; the August and September values being above normal. The only dry season months reported were March and May which received zero rainfall). Assuming the 1988 measurements presented here represented an average year for cloud water collection, the collector would provide a total of $10.9\ l m^{-2}\ day^{-1} \times 2000\ m^2 \times 365$ days = 8 million liters per year of fresh water based on results from the double layer 50% shade screen. Approximately 35% of this water would be collected during the dry season, amounting to about 12,000 liters per day under virtually rainless conditions. Using a more conservative estimate of $6\ l m^{-2}\ day^{-1}$ (a rate exceeded by all six knit screen panels above 3 m) the 2000 m^2 of catchment surface would yield 4.4 million liters annually, with about 6300 liters per day during the dry season. Ultimately, these two large segments would serve as models for an expansion to 100 or more providing municipal water to Mindelo. Such catchment systems, on a smaller scale, have already been installed in the fog deserts of Chile where larger versions are planned to provide water for coastal fishing villages (Schemenaur and Joe, 1989). These Chilean collectors use a flat weave plastic screen. In general, the flat weave has poorer drainage characteristics and a lower tensile strength than the monofilament knitted mesh, and requires a rigid, framelike, support structure. Local officials in Mindelo have indicated a need for 1000 m^3 per day of fresh water, approximately the amount now supplied by desalination. Using the figures mentioned above, a 100 segment array of 1000 m^2 collectors would provide a daily average of 600 to 1100 m^3 per day.

With respect to Serra Malagueta and other mountain areas on Santiago and on other islands such as Santo Antao, it may be more useful to initiate reforestation schemes using tree species particularly suited for fog water interception. Norfolk Island pine trees (*Araucaria excelsa*), for example, have been shown to be particularly effective cloud water catchers in Hawai'i due to the morphology of their branches and leaves (Ekern, 1964).

Finally, based on the vertical profile data, we suggest that, if small knit screen panels are used to provide household water for families living in mountainous areas, the panels should be mounted at least 3 meters above the ground. As Tables 1–3 show, water catchment at this height is substantially greater than at ground level, especially during the dry season.

6. Conclusion

Fog collection studies in the orographic cloud layer of several locations in the Cape Verde Islands have shown the great potential of large scale fog collectors as an important source of year-round fresh water. Previous studies have documented this potential, but the structural and durability properties of collection screens have been inadequate to initiate any large scale development. The knit shade screen material used in this study provides the necessary strength, durability, and collection efficiency at low cost to finally begin a demonstration scale fog collection project. Monte Verde is the suggested location.

The Cape Verde Islands have historically suffered catastrophic drought, often lasting over a decade. Failure of rainfall during the brief growing season in the agrarian society has led to the full "range of physical and mortal miseries (Cunha, 1964)." While the islanders are somewhat protected against famine today through international aid, and rainwater conservation measures have increased infiltration and water availability during the wet season, local agriculture still suffers during drought episodes and the long dry season. Large scale development of cloud water collection could not only supplement rainwater during the wet season, but provide an inexpensive, low technology, and significant source of fresh water during these dry periods. A sufficiently large collection array could also provide an economicaly attractive alternative to expensive desalination for nearby Mindelo. This study has shown that even a modest sized (2000 m^2) collection system could supply 6300 (conservatively) to 12,000 liters per day on average during the virtually rainless, 8 month dry season, and by inference, a similar yield during wet season drought conditions.

Acknowledgements

We wish to particularly thank Director General Mr. Horácio Da Silva Soares (Centro De Estudos Agrarios, Ministério Do Desenvolvimento Rural) and his staff (Ms. Malla Lobo and Mr. Luis Alves) for encouraging this research and providing logistic and technical assistance. Financial support was provided by a grant from U.S.A.I.D.-Praia through the help of local U.S.A.I.D. personnel. T. Luche (Station Chief) and A. Hartman (Agricultural Officer). U.S.A.I.D. also provided an undergraduate scholarship for one of the authors (C. Dos Anjos) at the University of Hawai'i at Hilo.

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