**Water International (1994) Vol 19, pp 70-76**

# The Role of Wind in Rainwater Catchment and Fog Collection

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**ABSTRACT**
*Water droplets in the atmosphere typically range in size from the smallest cloud or fog droplets, with diameters of lmm, to the largest raindrops with diameters of about 5 mm. The fog droplets have negligible fall velocities and their trajectories are determined by the speed and direction of the wind. Raindrops have fall velocities (2 to 9 m/s) comparable to typical wind speeds and, therefore, will fall at an angle, except in unusual circumstances where the wind speed is zero. An understanding of the fall angle of rain and drizzle drops can lead to a better orientation and design of rooftop rainwater catchment systems and, in certain environments, to the collection of substantially more water.*
*This leads to five recommendations: first, that as the wind speed increases or the drop sizes decrease, the vertical component of rainwater catchment systems should be enhanced; second, wind direction, wind speed, and rainfall rate information should be used to optimize the orientation of the house and the shape and slope of the root third, that use should be made of upwind walls of houses as rain collectors,' fourth, that in foggy environments rainwater catchment systems be modified to collect fog water as well,' and fifth, that tree plantations in arid regions should be designed in a manner that optimizes their role as fog collectors.*

INTRODUCTION
Wind and rain are associated with storms and the worst of weather but together they also offer the opportunity for the collection of large amounts of water. In many regions, the collection of rain from rock pools would have been an early source of water for the inhabitants. Just as likely is the fact that people in coastal or mountain:' environments would have observed fog dripping from trees and attempted to catch it. Glas [I] describes just this in the Canary Islands, in a location where the history of such collection goes back 2000 years. Both of these processes would be enhanced if there is wind. Similarly, modern rainwater catchment systems can be modified to improve their efficiency in windy conditions.
In regions of the world where the precipitation (drizzle and rain) is made up of events with amounts of perhaps I mm a day, the collection and storage of the precipitation is impractical. Even if there are rare events with higher precipitation rates, it may not be possible to maintain a rainfall catchment system just for these sporadic events. However, in some of these arid regions it may be possible to collect fog instead. Locations have been described [2], in the arid regions of 22 countries on six continents, where one might collect high elevation fog and use it for agriculture, tree plantations, or domestic purposes. The inclusion of seasonally arid regions would lead to possibilities in many more countries in Southeast Asia, the Middle East, Africa, South America, Central America, and numerous island groups.
Operational rainwater catchment systems exist worldwide and the results of experimental and applied programs have been widely discussed, e.g., [3]. Applications are limited to areas with substantial annual or seasonal rainfall; however, this encompasses large parts of the developing world. In areas with low annual precipitation rates, I to 500 mm/y, precipitation can only be collected if it falls intensely for short periods of time, in which case the

storage and use periods are often a small fraction of the year. Improvements in rain collection systems can substantially increase the amount of water collected in these cases. In particular, it is important to understand the role wind plays in the interaction of falling precipitation with structures such as rooftops. This is not explicitly mentioned in recent reviews [3,4] as a factor to be considered in the use of rainwater collection systems. The importance of wind in designing rooftop rainwater collection systems has been noted previously [5] but it does not appear to have resulted in significant implementation in field projects. Recent design protocols for rainwater catchment systems [3,6] also do not consider the role of wind in the collection process.

## COLLECTING PRECIPITATION

Rain and drizzle are normally collected by using a catchment area such as a rooftop, e.g., [7], by using natural terrain gradients, or by resurfacing or resloping the terrain to increase and store the runoff, e.g., [8]. In all cases the expected water collection is usually assumed to be the product of the annual rainfall amount and the plan area (horizontal projection) of the roof or terrain. This is the normal approach in the literature. It has long been recognized that this calculation will be incorrect in the presence of wind [9]. In addition, the interaction of precipitation with large-scale terrain features can be different from that with rooftops or small collectors. It will depend on such factors as wind speed, surface roughness, the scale of turbulence, and the size of the obstacle.

The water drops that make up rain or drizzle will fall at an angle determined by the drop fall velocity and the wind speed. In areas with changing wind conditions this can be a complicated path, but in basic terms it means that there will be a rain shadow behind a vertical obstacle and, equally as important, the vertical or sloping collecting surface will receive not the rain that would have fallen on its horizontal projection but rather all of the rain that would have fallen in the rain shadow. This has implications for the design of rainwater collectors. It means that the stronger the winds, and the smaller the drops, the more vertical the collector should be.

The terminal fall velocities of raindrops in still air can be found in standard cloud physics texts, e.g., [10]. A 0.5 mm diameter drop, which is at the boundary between drizzle and rain, falls at 2 m/s, while the largest raindrops with diameters about 5 mm fall at 9 m/s. Therefore, even wind speeds of a few meters per second will impart a significant angle to the fall of the drops. A calculation [11] of the vertical (top) and horizontal (side) collection of rain by an isolated tree under typical mountain conditions found that the horizontal collection can be nine times higher than the conventionally assumed vertical input of rain. It is because of this effect that criticism was levelled [9] at those who assume that the increased drip rate under a tree, or in a raingauge with a vertical structure attached, is necessarily due to fog collection. It may well be simply due to the additional input of the rain from the rain shadow created by the tree or vertical structure. Others, e.g., [12-15] have come to the same conclusion, i.e., that the collection of rain moving at an angle to the ground is an important factor in understanding throughfall in mountain ecosystems.

If one assumes a rainfall drop size distribution [16] then for each rainfall rate a median drop size can be calculated [17]. Each drop size will have a specific vertical fall velocity, Table 1 [10]. The interrelationships between rainfall rates, drop sizes and drop velocities are shown in Fig. 1. If desired, other drop size distributions can be chosen, e.g., for tropical rain [18], and other parameters of the size distribution chosen, e.g., the mode or the mean volume diameter; however, the principles remain the same. Higher rainfall rates are characterized by larger median droplet sizes and higher fall velocities. In principle, these large drops should be less affected by wind; however, high rainfall rates are produced by deep convection such as thunderstorms, monsoons, and typhoons, which in turn are associated with strong winds. Therefore, even large raindrops can often be expected to fall at significant angles. For example, in a 10 m/s wind, 5 mm diameter raindrops (Table 1) should fall at an angle of about 45° to the vertical. This point has practical significance and should be reflected in the design of rainwater catchment systems.

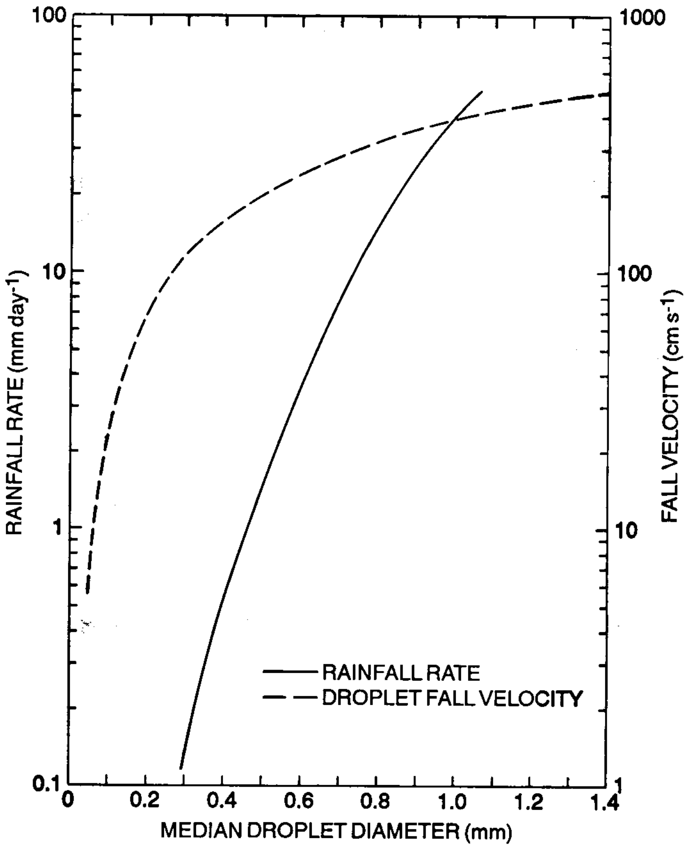


**Figure 1. The relationship between rainfall rate, the droplet fall velocity, and the median droplet diameter for drizzle and light rain. Data sources are given in the text.**

Table 1. Terminal fall velocities of water drops in still air [10].

| Drop Diameter (mm) | Terminal Velocity (cm/s) | Drop Diameter (mm) | Terminal Velocity (cm/s) |
|---|---|---|---|
| 0.01 | 0.3 | 1.6 | 565 |
| 0.02 | 1.2 | 2.0 | 649 |
| 0.03 | 2.6 | 2.6 | 757 |
| 0.04 | 4.7 | 3.0 | 806 |
| 0.05 | 7.2 | 3.6 | 860 |
| 0.10 | 25.6 | 4.0 | 883 |
| 0.20 | 71 | 4.6 | 903 |
| 0.40 | 160 | 5.0 | 909 |
| 0.50 | 204 | 5.6 | 916 |
| 0.80 | 325 | | |
| 1.00 | 403 | | |

## COLLECTING FOG

Fog droplets (<40 $\mu$m diameter) have fall velocities ranging from << 1 cm/s to approximately 5 cm/s. These settling rates are normally negligible compared to the horizontal component of the wind and the droplets travel parallel to the surface of the terrain in virtually any wind conditions. This implies that a fog collector should be a vertical surface. It can be fixed or rotating but to enable estimates to be made for large collectors, a fixed orientation into the prevailing wind during fog events is preferred. A 1 m x 1 m standard fog collector has been used in Chile, Peru, Ecuador, and Oman to evaluate fog water collection potential [19]. It is covered with a double layer of 35 per cent shade coefficient polypropylene mesh. The base is 2 m above ground. The mesh is an efficient fog collector and will also collect drizzle and rain.

In operational fog collection systems, the collection panels are typically 4 m high and 12 m long and are located in mountainous areas with frequent fog and moderate wind speeds. In Chile, there is an operational array of fog collectors where 3,600 $m^2$ of mesh have been providing more than 11,000 L of water per day to a village of 330 people since March 1992. This allows for an average consumption of 33 L/person/d, which is more than twice the amount of water [20] that was previously being supplied by truck, 14 L/person/d. Major fog collection experiments have also been undertaken in the Sultanate of Oman [21-23] and in Peru [24]. The understanding of the relative amounts of fog and precipitation that can be collected at a site is vital to the optimization of the collecting surfaces to be used.

## MODIFYING ROOFTOP RAINWATER COLLECTORS

A vertical rise in the configuration of a roof will increase the collection of wind-driven rain, and the stronger the winds (within reason), the greater will be the increase in catch. A flat roof is a highly efficient collector only when there is zero wind. Houses often are built with a center-peaked roof and though this can increase collection, it is not an optimum design either. A better design would be a single slope facing the prevailing wind during rain events. If the slope angle was maintained the same, this may double the rain shadow water that can be collected. The vertical wall on the upwind side will also collect a substantial amount of rainwater and should have a trough at its base. The vertical wall on the downwind side could also have a trough at the base, if rain sometimes occurs with winds from the opposite direction. In some areas a single slope will be impractical or undesirable, in such cases, increasing the slope angle of the center-peaked roof will increase the catch of wind-driven rain.

Instead of replacing them, one way of modifying center-peaked roofs would be to place a vertical panel along the center ridgeline. It could be removed, or laid flat, in periods with high winds. A solid panel will increase the catch of wind-driven rain. A mesh panel, of suitable material, will collect both fog and rain. A profile of a modified rooftop is shown in Fig. 2 to illustrate the interaction of wind-driven rain with a structure. The house is 7 m long by 5 m wide, with a 1 m high ridgeline. The ridgeline has a 2 m high panel on it running the length (7 m) of the ridgeline. The example chosen is for an assumed wind speed of 9 m/s and a conventionally measured rainfall rate (R) of 10 mm/d (or 10 L/$m^2$/d) on a horizontal surface. The median droplet diameter for this rainfall rate is 0.76 mm (Fig. 1). The fall velocity for a droplet of this diameter is 3 m/s (Fig. 1). A drop of median size will thus fall at an angle of 72° to the vertical (18° to the horizontal).

It is now possible to calculate the amounts of rain that would have fallen into the rain shadows behind the different parts of the house (Fig. 2). A rain shadow is produced when an obstacle intercepts the rain that would otherwise have fallen on the ground. The areas of the different rain shadows are:

$A_1 = 7 \times 7.5 = 52.5\ m^2$ sidewall rain shadow

$A_2 = 7 \times 5.5 = 38.5\ m^2$ conventional roof rain shadow

$A_3 = 7 \times 6.0 = 42.0\ m^2$ panel rain shadow

$A_r = 7 \times 5.0 = 35.0\ m^2$ roof horizontal projection

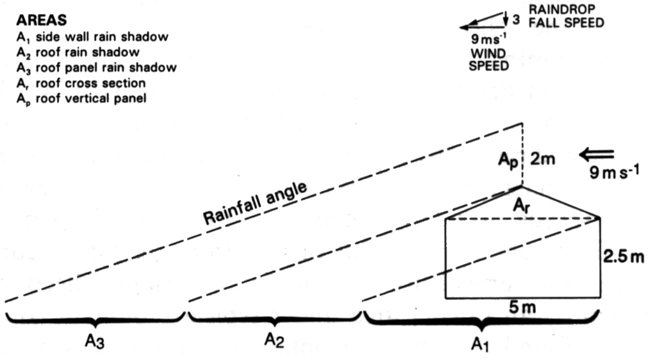


Figure 2. The interaction of a 7 m long and 5 m wide house with wind-driven rain and fog. The peak is 1 m high and there is a 2 m panel along the ridgeline. The rain shadow areas for the different portions of the structure are shown. The wind speed is 9 m/s and the raindrop fall velocity 3 m/s (see text).

$A_p = 7 \times 2.0 = 14.0\ m^2$ panel area

The conventional calculation of rainfall striking the roof is:

$A_r \times R = 350$ L/d

The real catch by the roof in this case is:

$A_2 \times R = 385$ L/d

The conventional calculation underestimates the rain striking the roof by 10 per cent.

The rain collected by the panel is:

$A_3 \times R = 420$ L/d

The rain collected by the upwind sidewall of the house is:

$A_1 \times R = 525$ L/d

In this example, the addition of a trough at the base of the sidewall of the house would increase the total interception of rain by the unmodified house from 385 L/d to 910 L/d. The collection of water could be more than doubled. The addition of a 2-m panel to the roof would increase the total collection to 1,330 L/d, which is more than three times the catch of the conventional roof alone. The actual catch of a house will depend on its shape, the characteristics of the rainfall, and the wind and turbulence distribution around the house. The catch ratio, of the modified to flat roof, will be 1:1 with no wind and it will increase with increasing wind speed and with decreasing drop size. In turn, turbulence and sheltering effects caused by surrounding trees or other buildings may mask some of the rain shadow effects noted in the above example.

A practical consideration, if using a vertical panel on the roof, is that it must be mounted strongly enough to withstand the pressure of the wind on it. A 2 m high panel may be appropriate in light to moderate winds but have to be reduced in height if wind speeds are consistently higher. On the other hand, the construction of a trough at the base of a sidewall of a house is simple to do and will be valuable when the wall is made of a nonporous material such as painted wood or galvanized iron.

It is informative to look at what would happen if the solid roof panel was replaced with a fog collecting mesh of the same size. Assuming a fog collection rate (F) of 10 L per square meter of vertical surface per day gives a fog collection of:

$A_p \times F = 140$ L/d

This is only one-third of the rain collected by the conventional roof in the above example but it is a significant amount of water in arid regions. Indeed, it could support a family of five for a day. Therefore, if the house is in a foggy environment, as many mountain communities are, it would be valuable to add a fog collection panel with its own collection trough and pipe. It should be noted that this panel would also collect all or almost all of the precipitation incident on it. The cost of the 14 $m^2$ of mesh (double layer) used in this example would be only US$3 and, if the supporting structure was locally made, this would be a cost-effective addition to certain rain catchment systems.

## COMPARING RAIN AND FOG COLLECTION

The areas with fog collection projects in Chile, Peru, and Oman all had annual precipitation values of between 10 and 100 mm. In most cases the precipitation events consisted of light drizzle, producing rates from 0.1 mm to at most a few mm per day. In the mountains of Dhofar, in the south of Oman, some people have made an effort to collect the precipitation falling during the southwest monsoon (mid-June to mid-September). In coastal Peru and the north coast of Chile, the annual precipitation amounts are too low (10 mm at Lima) and the events too rare, to make efforts at collecting the drizzle practical. The relative importance of precipitation during the fog events can be gauged qualitatively by observing the ground. In Chile the ground stays dry while the fog is being collected. In Peru the ground is damp and supports the loma vegetation [24]. In Oman the ground becomes very wet and supports more extensive vegetation. Therefore, Oman represents the transition from essentially fog only environments to one with important contributions from both fog and precipitation.

**Areas with fog collection projects . . . all had annual precipitation values of between 10 and 100 mm**

The potential importance of fog collection in Oman has been recognized for some time [23] but the nature of the process has not been well understood. The necessity to differentiate between fog and rain contributions to the water balance of the Dhofar Jebel in Oman has been discussed [25] and a series of specialized collector experiments was proposed. It was found [26] that a roof at the Aghshay site, at a 30° angle to the horizontal, collected 55 per cent more precipitation per square meter than a standard raingauge. This could be explained by drops falling at an angle of 25° to the horizontal, which is in excellent agreement with calculations using a mean drop size of 0.3 mm, a fall speed of 1 m/s, and the measured mean wind speed of 2.5 m/s. At a higher altitude in the Dhofar Jebel, at Qeiroon Heiritti, with smaller drops and higher wind speeds, the same roof collected 530 per cent more water per square meter than a horizontal raingauge. This is due to the collection by the sloped roof of drizzle and rain whose drops had a strong horizontal component.

The drops in this case were calculated to fall with an angle of only 5° to the horizontal.

Two 1 $m^2$ mesh panels, which could rotate with the wind, were also installed [26] at each of the above sites in Oman. In addition, one collector at each site was under a 5 m x 5 m roof. This provided a reasonable shielding effect from precipitation. At Aghshay (elevation 480 m), the authors found that the ratio of fog to precipitation collected ranged from 5:1 at rainfall rates of 0.5 mm/d, to 1:1 at rainfall rates of 5 mm/d. Subsequent experiments [27] at Ashinhaib (elevation 900 m), comparing collection by 1 $m^2$ vertical solid plates and 1 $m^2$ mesh collectors, led to the conclusion that the ratio of the fog to precipitation being collected by the standard fog collectors was also about 5:1.

The conclusions from the work at the sites in Oman are that vertical collectors and sloping roofs collect much more precipitation than do horizontal surfaces; that fog contributes more water to the vertical fog collectors in Oman than does precipitation; and that, therefore, one can add new water to the mountains by erecting vertical collecting surfaces, i.e., the precipitation would have fallen on the ground in any case but the fog collection represents new water. It is new water because, in the absence of trees or fog collectors, the fog droplets are blown by the wind over the mountain ridgeline and they evaporate as they move downslope into the Empty Quarter (Rub Al Khali) of the Arabian Peninsula.

## THE ROLE OF FORESTS IN COLLECTING PRECIPITATION AND FOG

The collection of drizzle, rain, and fog by individual trees and by forests is an important process but it is often misunderstood. A hectare of land with or without a forest will receive, or collect, a similar amount of rain, i.e., on the larger scale the top of the forest canopy acts like a raised ground level. On the scale of a tree, however, the rain that would have fallen in the rain shadow will be relocated to drip under the tree. Only forests located in specific sites, for example near the crestline on a ridge, can relocate a small amount of precipitation from one watershed to another. But this effect is small on the scale of a region.

Precipitation and fog are also interrelated in the hydrologic implications of deforestation in upland areas. As has been noted, cutting the trees on a hillside will not change the amount of precipitation falling on the hillside, though it will change runoff characteristics, water retention in the soil, evapotranspiration, etc. What can change dramatically, however, is the total water input to the hillside. This is because the trees are no longer there to collect the cloud/fog droplets that blow over the terrain. There is a net loss of water to the ecosystem.

A major field investigation into the collection of fog by trees has been conducted in Japan [28]. The mechanisms of fog capture by trees have also been discussed more recently, e.g., [29]. The primary capture mechanism is by the impaction of wind-driven droplets onto the foliage. Sedimentation of the droplets into the forest is much less important. Most fog collection takes place at the canopy top or on exposed upwind edges of the forest. Fog collection by trees can be augmented by increasing the spacing between trees, or reducing the width of the trees, to allow the wind-driven fog to enter the forest [30].

The role of forests in the collection of enormous amounts of fog water has often been neglected in studies of upland areas. This has led, for example, to a conclusion that fog collection is unimportant as a water resource in the Dhofar Mountains of the Sultanate of Oman [31]. Indeed, fog collection during the southwest monsoon is of great importance to this region. Reforestation of the upland areas may in fact be a key to the generation of increased subsurface runoff to the Salalah Plain.

## CONCLUSIONS

Wind should be thought of as one of the elements to be utilized to maximize the production of water from precipitation and fog water collection systems. The wind at the site should influence both the design and orientation of the collection system. In the case of rainfall and drizzle catchment systems, this can result in small increases in catch in some cases and more than double the water in cases with moderate winds and small droplets. Since these later conditions are often encountered in arid and semiarid regions, one may in fact be able to utilize precipitation collection systems in areas where the use, at present, is at best marginal. Fog collection systems only work because the wind moves the fog droplets to the surface of the collector. Therefore, an understanding of the wind conditions at the site is essential to any field installation.

A number of suggestions can be put forward to improve current precipitation catchment systems and the collection of the wide range of drop sizes present in fog and precipitation. Specifically:

i) wind direction information should be used to optimize the orientation of the house or other catchment device;
ii) wind speed and rainfall rate information should be used to optimize the shape and slope of the roofs of buildings;
iii) when precipitation strikes the upwind wall, or walls, of houses, it should be collected with suitable troughs;
iv) where conditions permit, consideration should be given to the construction of vertical panels on rooftops to increase the collection of wind-blown precipitation;

**Wind should be thought of as one of the elements to be utilized to maximize the production of water**

v) in foggy locations, the addition of rooftop panels made of a suitable mesh would provide both fog water and rainwater for the household; and

vi) consideration should be given, in arid regions, to designing tree plantations to maximize interception of fog water (if fog is present).

## ACKNOWLEDGMENTS

We would like to thank the agencies that have supported our field work on fog collection. The International Development Research Centre (IDRC, Ottawa) in Chile; the Canadian International Development Agency (CIDA, Ottawa) in Peru and Ecuador; and the United Nations Development Programme, the World Meteorological Organization, and the Government of the Sultanate of Oman in Oman.

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