STM JOURNALS

Journal of
Water Resource Engineering and Management

ISSN: 2349-4336
Volume 11, Issue 3, 2024
September–December
DOI (Journal): 10.37591/JoWREM

https://journals.stmjournals.com/jowrem

Research JoWREM

# Precipitable Water for Human Consumption in Rural Areas: Calculation Method and Engineering Design

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***Abstract***

*This work describes a methodological process to estimate the precipitable water for human consumption as a function of meteorological parameters like ambient and dew point temperature, water vapor and ambient pressure, and relative humidity. The paper uses empirical correlations to determine the most accurate procedure for atmospheric rainwater, resulting in a simple relation between precipitable water and dew point temperature as the highest accurate one. The study shows the dew point temperature dependence on vapor pressure and relative humidity, concluding that measuring air temperature and humidity, precipitable water amount can be determined using the developed algorithm. The study analyzes different climates, dry, medium and humid, to determine the required water collection surface to cover daily human water needs. It also concludes that dry climates with relative humidity below 20% are inappropriate and should be discarded. This work includes an engineering development of water collector device, which results in a modular unit whose size depends on the water requirements and geographical zone humidity. The size and shape are optimized to minimize the water collector module number, reducing building costs and simplifying the manufacturing process. The modular unit size is foldable, easy to handle, and requires low storage room.*

**Keywords**: Water precipitation modelling, water human needs, Water collection and servicing, Engineering system design

## INTRODUCTION

Today, freshwater access represents a significant challenge in many world areas to cover human needs since more than a third of the world's population does not have access to drinking water [1–5]. In 2021, more than 2000 million people suffer from water scarcity, a situation that worsens due to climatic change and population growth [6–9]. In 2022, more than 1.7 billion people use polluted water for current uses, suffering from diseases and health problems [10–14]. Water pollution comes from many sources, including fecal waste, inorganic and organic compounds, contaminated water waste, solid human residues, microbial agents, etc., which may produce human deaths [15–17].

It is necessary to have sufficient clean water for practicing adequate human hygiene [18, 19] to prevent digestive and lung problems [20, 21] and many unattended tropical diseases [22–24]. According to current calculations, polluted water causes more than half a million human deaths because of diarrheal diseases [25]. In a world dominated by water, oceans, rivers, and atmosphere, it is shocking that so many people do not have access to drinking water.

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Received Date: July 12, 2024
Accepted Date: September 26, 2024
Published Date: September 28, 2024

**Citation:** Carlos Armenta-Déu. Precipitable Water for Human Consumption in Rural Areas. Journal of Water Resource Engineering and Management. 2024; 11(3): 41–57p.

Fresh water is critical for the human being; nevertheless, the required amount depends on human needs [26, 27]. A person can live for about seven days without drinking water under ideal conditions, but the survival time extends with drinking water; Table 1 shows the average drinking water a human needs to survive [28].

**Table 1.** Daily basic fresh water human needs [29].

| Amount (L/day) | Surviving time (days) |
|---|---|
| 0 | 3-6 |
| 0.5 | 7-14 |
| 1.0 | 15-30 |
| 2.0 | >30 |

People living near the coastline may have access to drinkable water if desalination plants operate in the area and the freshwater production cost is accessible for their purchasing power, which in many cases is not trivial [30–33]. Communities settling down in the river vicinity have access to fresh water; however, the river flow is not always potable since it contains microorganisms and other agents that may cause diseases and even death [34, 35]. This problem is solved in areas with acceptable levels of rainwater if atmospheric precipitation is adequately collected [36–38].

Atmospheric water shows the advantage of being non-polluted water; therefore, if the water collection is produced with adequate healthy measurements, it is a simple and easy access water source for human needs. In this paper, we develop a method to determine how much water can be collected from atmospheric precipitation to evaluate the freshwater coverage of human needs.

## THEORETICAL FOUNDATIONS

Water contained in the atmosphere shows in water vapor form. How much water the atmosphere contains in a specific volume is hard to estimate since it depends on variables whose value cannot be predicted easily. The most reliable way of determining the atmospheric water amount is through a weather survey, an expensive technique not disseminated today. Therefore, the estimation requires simulation techniques and modeling procedures to evaluate the atmospheric water amount reliably and accurately.

Modeling the atmospheric rainwater in a selected area requires the knowledge of specific parameters on which the precipitation depends. These magnitudes should be measured at ground level with simple technical equipment and minimum operational background. The modeling uses the atmospheric pressure, the ambient temperature, the vapor pressure, and the dew point temperature as a base for atmospheric water collection estimation.

We can express the atmospheric water content per surface unit as:

$$w = \int_0^z \rho_v(z)dz \tag{1}$$

$\rho_v$ is the water vapor density, and $z$ is the height.

Applying the hydrostatic law:

$$dp = -\rho g dz \tag{2}$$

$p$ is the atmospheric pressure, and $\rho$ is the air density.

Combining equations 1 and 2:

$$w = -\frac{1}{g}\int_0^z \frac{\rho_v(z)}{\rho}dp \tag{3}$$

The water vapor to air density ratio can be expressed in terms of mass since the volume is the same; therefore:

$$w = -\frac{1}{g}\int_0^z \frac{m_v}{m}\,dp = -\frac{1}{g}\int_0^z q(p)dp \tag{4}$$

*q(p)* is the specific humidity.

The relation between precipitable water and vapor pressure derives from the Cole equation [39]:

$$w = a_1 e^{b_1 p_v^c + d} \tag{5}$$

Parameters $a_1$, $b_1$, $c$, and $d$ are empirical.

On the other hand, we may express the temperature dependence as [40]:

$$w = a_2 e^{b_2 T} \tag{6}$$

The dew point temperature dependence as [41]:

$$w = a_3 e^{b_3 T_{dew}} \tag{7}$$

And the relative humidity dependence as [42]:

$$w = a_4 \frac{H}{pT} = a_4 x \tag{8}$$

As in equation 1, parameters $a_2$, $a_3$, $a_4$, $b_2$, and $b_3$ are empirical.

Equation 8 shows a linear dependence of precipitable water on the variable *x* defined as the ratio of relative humidity to the pressure/temperature product.

## EMPIRICAL CONSTANT DETERMINATION

Mathematical model constants *a, b, c,* and *d* can be easily determined from onsite tests by non-professional people. It only requires basic equipment and simple operational instructions.

Since the highest precipitable water dependence on empirical parameters corresponds to equation 5, where four parameters intervene, the basic empirical constants determination process requires a minimum of four measures; however, it is wise to extend the measuring process for as many checking points as possible to obtain accurate values.

Ambient and dew point temperature, atmospheric pressure, relative humidity, and vapor pressure must be measured over a specific period at regular intervals to improve empirical constant determination accuracy. An automatic measuring device with a built-in data logger is highly recommended to avoid human errors; since modern devices can take data in a fraction of a second, measurement can be programmed every second for a period of a day, obtaining a set of 86400 values, assuring a high accuracy in the constant determination.

We tested the above measuring procedure for various Spanish meteorological stations, obtaining the following results in the empirical constants determination (Table 2):

**Table 2.** Empirical constants determination accuracy

| Constant | $a_1$ | $a_2$ | $a_3$ | $a_4$ | $b_1$ | $b_2$ | $b_3$ | c | d |
|---|---|---|---|---|---|---|---|---|---|
| Accuracy (%) | 94.4 | 91.8 | 94.4 | 96.7 | 93.1 | 91.8 | 99.5 | 99.1 | 99.5 |

We observe the high accuracy in all empirical parameters, which validates the measuring procedure and the period and interval.

## PARAMETER CORRELATION

Since the precipitable water determination depends on various meteorological magnitudes, ambient and dew point temperature, atmospheric pressure, and relative humidity, we correlated all magnitudes to determine the precipitable water dependence level on each magnitude.

We used the database from the empirical parameter determination for the magnitude correlation, obtaining the following results (Table 3):

**Table 3.** Variable correlation.

| | **T** | **$p_v$** | **H** | **$T_{dew}$** | **p** |
|---|---|---|---|---|---|
| w | 0.642 | 0.725 | -0.216 | -0.728 | -0.131 |
| p | 0.023 | -0.113 | -0.111 | -0.117 | |
| $T_{dew}$ | 0.421 | 0.980 | -0.133 | | |
| H | -0.790 | 0.152 | | | |
| z | 0.399 | | | | |

The analysis from Table 3 results shows that precipitable water has a high dependence on the dew point temperature (72.8%) and vapor pressure (72.5%) and relatively high on ambient temperature (64.2%). On the other hand, the dependence on relative humidity is low (21.6%) and almost negligible on ambient pressure (13.1%). We should notice that the dew point temperature correlation to vapor pressure is excellent (98%). This high correlation shows we can omit one of the two variables without affecting the precipitable water determination. Data from Table 3 shows that we should focus the precipitable water determination on one magnitude, the vapor pressure or the dew point temperature.

We retrieved data for a year from the meteorological stations, which served to determine the empirical constant values to validate the precipitable water dependence on the vapor pressure or dew point temperature. To do so, we correlated atmospheric rainwater to the variables intervening in the mathematical model. Table 4 shows the coefficient results of the correlation.

**Table 4.** Correlation coefficients between atmospheric rainwater and meteorological variables.

| | **T** | **$p_v$** | **H** | **$T_{dew}$** | **p** |
|---|---|---|---|---|---|
| $R^2$ | 0.618 | 0.731 | 0.208 | 0.726 | 0.126 |

Results from Table 4 validate using either dew point temperature or vapor pressure to determine precipitable water amount.

Now, developing the correlation between precipitable water and vapor pressure and dew point temperature, yields:

a. For vapor pressure dependence

$$\begin{aligned} a_1 &= -24.995 \pm 1.394 \quad b_1 = -0.022 \pm 0.001 \\ c &= 1.585 \pm 0.089 \qquad d = 26.506 \pm 0.871 \end{aligned} \tag{9}$$

We observe that the correlation coefficient accuracy is high. Table 5 shows the error in the coefficient determination.

**Table 5.** Error in the correlation coefficient determination for vapor pressure dependence.

| **Coefficient** | **$a_1$** | **$b_1$** | **c** | **d** |
|---|---|---|---|---|
| Error (%) | 5.6 | 4.5 | 5.6 | 3.3 |

Therefore, the analytical expression for precipitable water amount dependence on vapor pressure is:

$$w = -24.995 \exp\left[\left(-0.022\right)\left(p_v\right)^{1.585} + 26.506\right] \quad (10)$$

b. For dew point temperature dependence
Repeating the calculation for the dew point temperature yields:

$$a_3 = 9.831 \pm 0.044 \quad b_3 = 0.0620 \pm 0.0005 \quad (11)$$

Analogously, Table 6 shows the accuracy in determining the correlation coefficients.

**Table 6.** Error in the correlation coefficient determination for dew point temperature dependence

| **Coefficient** | **a2** | **b2** |
|---|---|---|
| Error (%) | 0.4 | 0.8 |

Therefore, the analytical expression for precipitable water amount dependence on dew point temperature is:

$$w = 9.831 \exp\left(0.062 T_{dew}\right) \quad (12)$$

Comparing results from Tab les 5 and 6, we observe that the error in correlation coefficient determination is lower for the dew point temperature dependence; therefore, we use equation 12 to determine the precipitable water amount.

## SIMULATION

We simulate a process to determine the precipitable water for variable dew point temperature within reasonable limits for the Earth's surface. The dew point temperature can be estimated as a function of the relative humidity and ambient temperature (Figure 1).

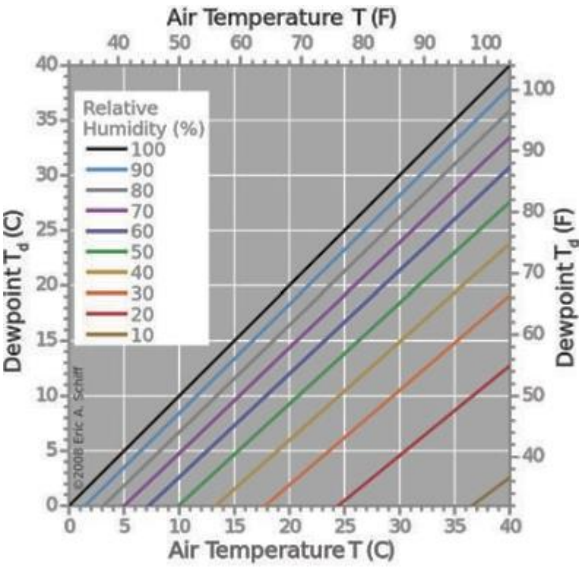



**Figure 1.** Dew point determination as a function of relative humidity and ambient temperature [43].

According to data shown in Figure 1, we can correlate the dew temperature to ambient temperature for every relative humidity through a linear function of the type:

$$T_{dew} = \alpha + \beta T_{amb} \quad (13)$$

$\alpha$ represents the ordinate at the origin and $\beta$ is the linear function slope, which is given by:

$$\beta = \frac{T_{dew(T_{air}=40)}}{40 - T_{amb(T_{dew}=0)}} \tag{14}$$

The numerator corresponds to the dew point temperature for an ambient temperature of 40ºC, while the denominator is the ambient temperature for a null dew point temperature.

Using data form Figure 1, yields (Table 7):

**Table 7.** α and β-value for variable relative humidity.

| H | **10** | **20** | **30** | **40** | **50** | **60** | **70** | **80** | **90** | **100** |
|---|---|---|---|---|---|---|---|---|---|---|
| *β* | 0.79 | 0.80 | 0.86 | 0.88 | 0.93 | 0.94 | 0.95 | 0.96 | 0.98 | 1.00 |
| *α* | -28.9 | -19.1 | -15.4 | -11.5 | -.92 | -6.6 | -4.8 | -2.8 | -1.4 | 0 |

We observe an increasing slope value with relative humidity; correlating both parameters, to a linear function, we obtain:

$$\beta = 0.0023H + 0.781 \quad (R^2 = 0.942) \tag{15}$$

Combining equations 13 and 15:

$$T_{dew} = \alpha + \left(0.0023H + 0.781\right)T_{amb} \tag{16}$$

Therefore, we determine the dew point temperature and the precipitable water amount by measuring the ambient temperature and relative humidity, which only requires a simple thermo-hygrometer.

Simulating an air temperature interval from -20ºC (cold weather) to 50ºC (hot climate) and relative humidity from 10% to 100%, we obtain the following results (Figure 2):

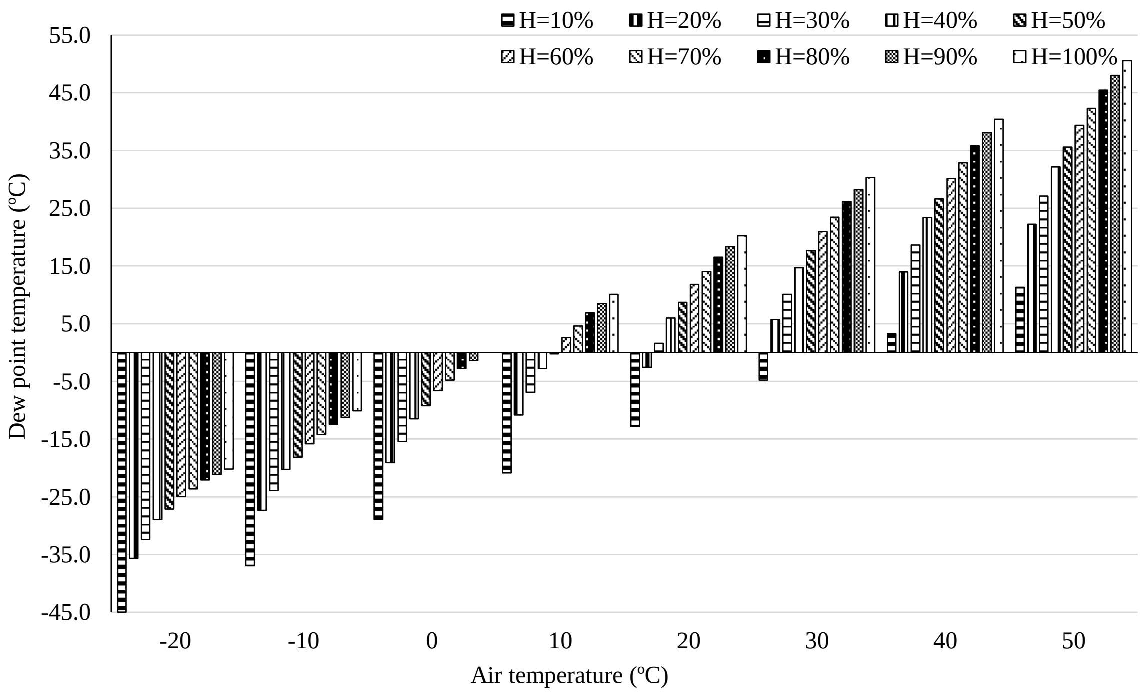



**Figure 2.** Simulation results for the dew point temperature as a function of the relative humidity and air temperature

Now, applying equations 7 and 11, yields (Figure 3):

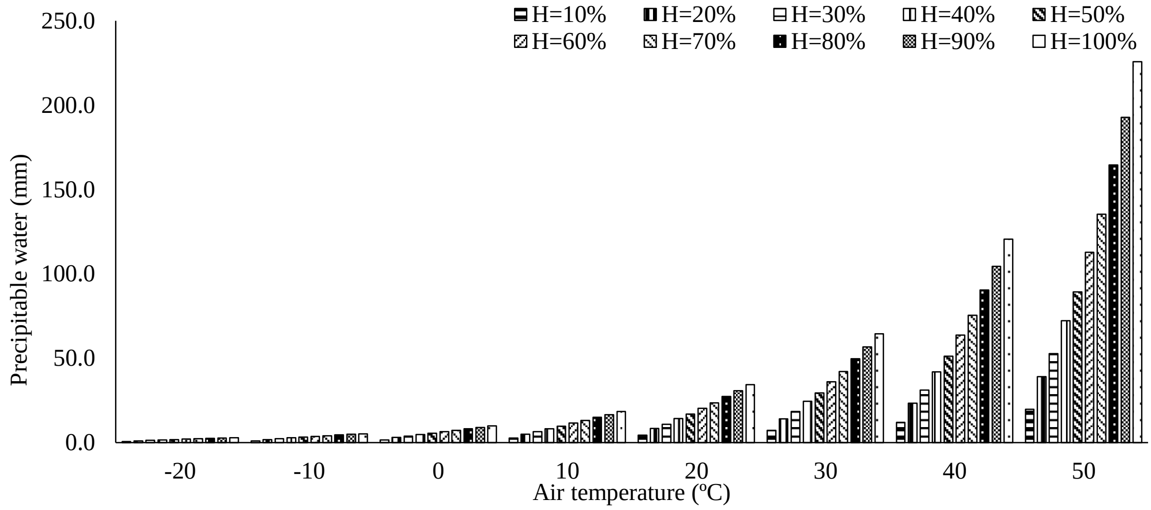
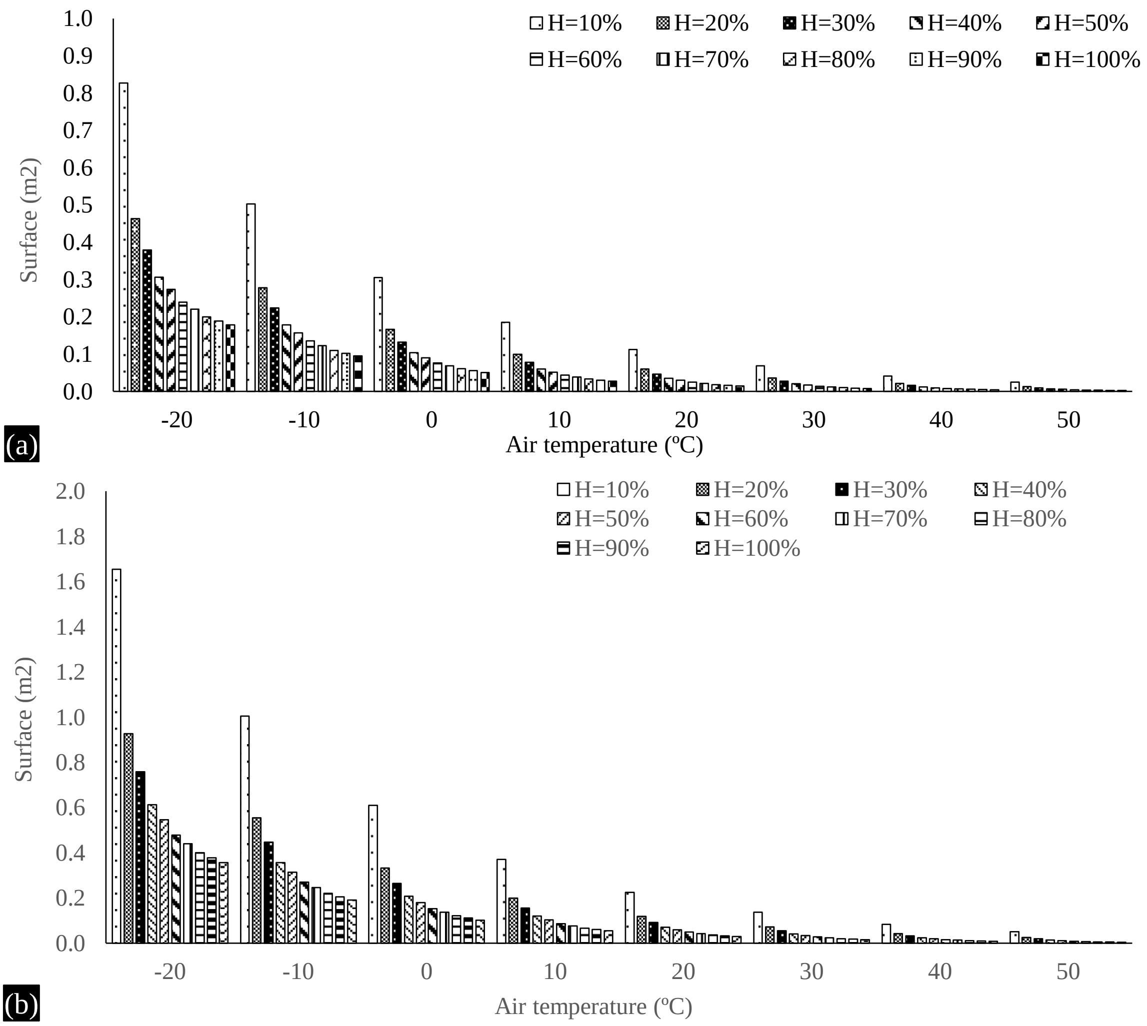
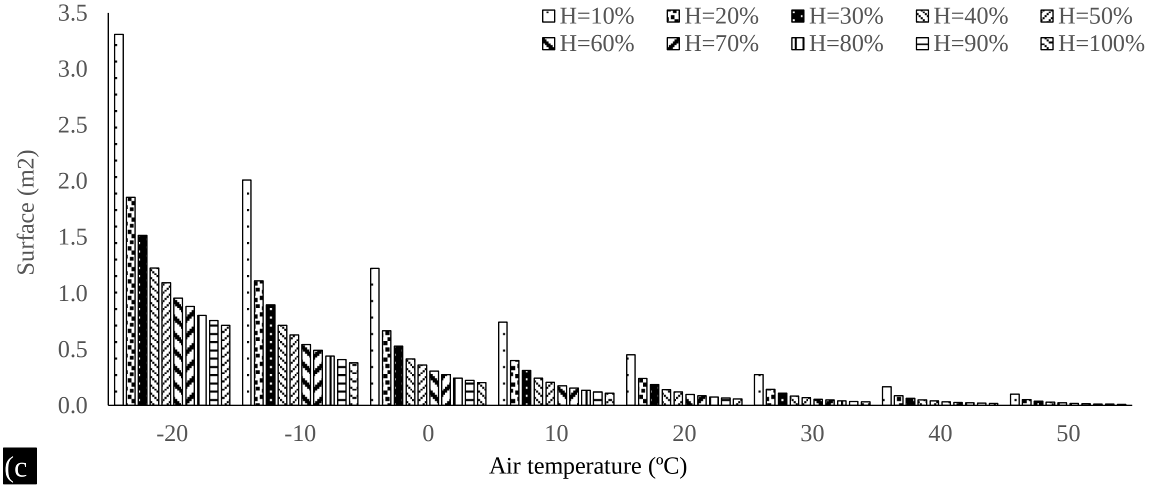



**Figure 3.** Simulation results for the precipitable water amount as a function of the relative humidity and air temperature

Since water precipitation in mm is equivalent to liters per square meter, applying data from Table 1, neglecting the null drinking water value, the required collecting surface for human survival is, in liters per day per person (Figure 4):






(c

**Figure 4.** Water precipitation collectible surface for human survival. (a) (0.5 L/day); (b) (1.0 L/day); (c) (2.0 L/day).

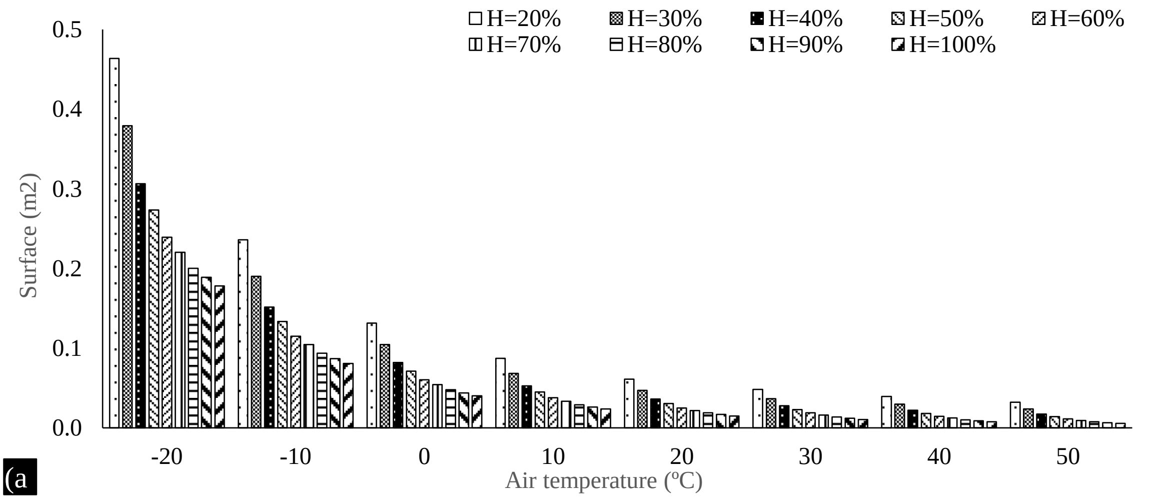
We observe that for severe dry climates, with relative humidity of 10%, the required surface increases significantly related to other humidity values; therefore, the precipitable water is insufficient for human needs in this kind of place. We also observe that the required surface rapidly decreases with increasing humidity, reaching values as low as 0.002 m2/person for a minimum water need, 0.5 L/day, and only 0.009 m2/person for an indefinite survival time (2.0 L/day) for a humid climate with relative humidity of 100%.

Air temperature also influences the human water demand since in hot climates, with air temperatures above 30º C, the human body requires more water to compensate for sweating. Therefore, we should increase the minimum human water needs by a factor depending on air temperature; recent statistical studies demonstrated that human water needs evolve quadratically with air temperature according to the expression [44]:

$$f_w = 0.0007T_{air}^2 + 0.0005T_{air} + 0.7691 \quad (R^2 = 0.998) \qquad (17)$$

$f_w$ represents the correction factor for human water needs.

Applying the ambient temperature dependence to the simulation results, the required surface changes according to the water need correction factor yielding (Figure 5):




(a

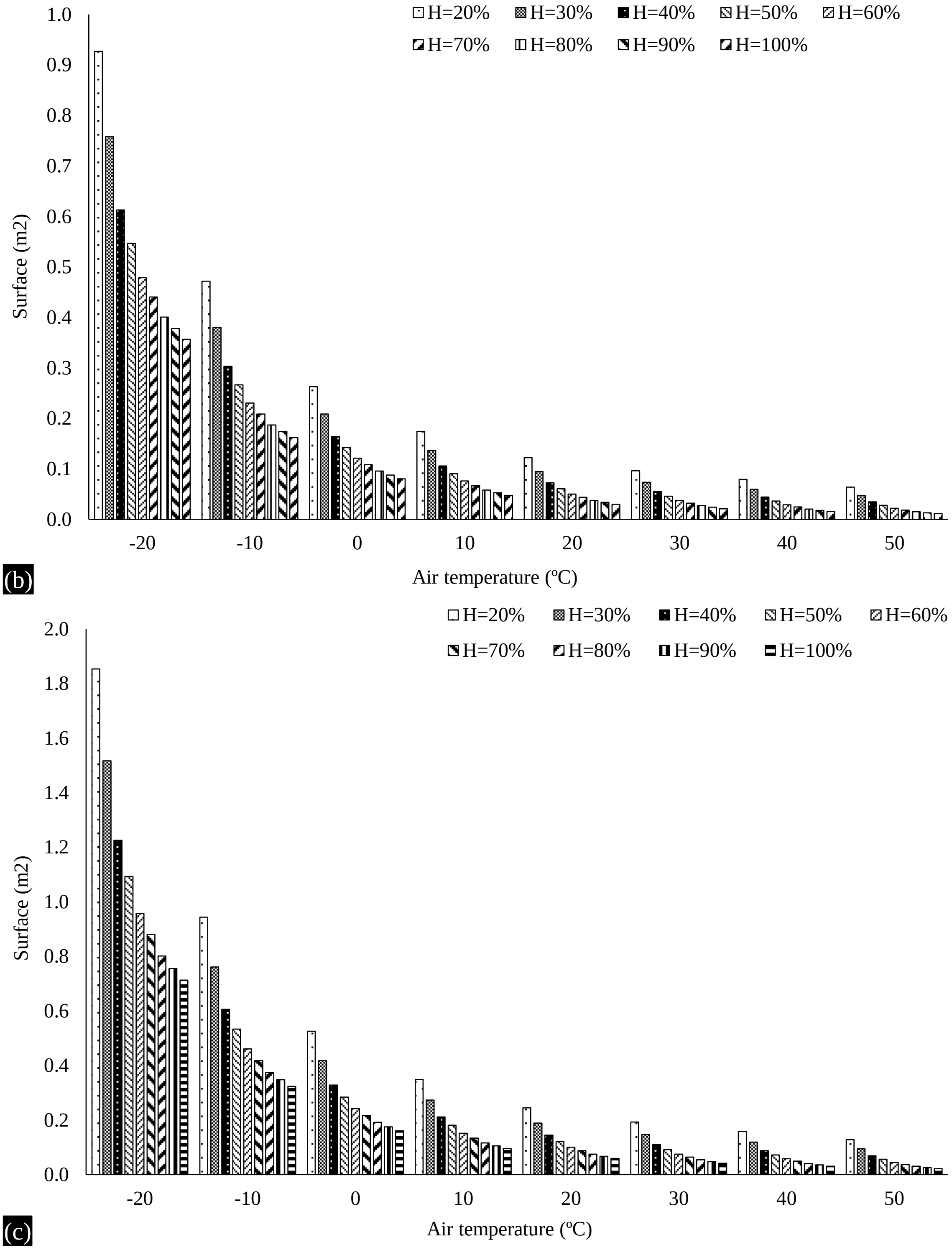



**Figure 5.** Corrected collectible surface for human water needs depending on air temperature based on standard values: (a) (0.5 L/day); (b) (1.0 L/day); (c) (2.0 L/day)

The reader should notice that we omitted the case for dry climate (H=10%), according to the previous statement, which is considered unfeasible in this case because of the high increasing surface.

If we consider a small community of 100 people and a small village of 1000 habitants, the required surface is (Figures 6 and 7):

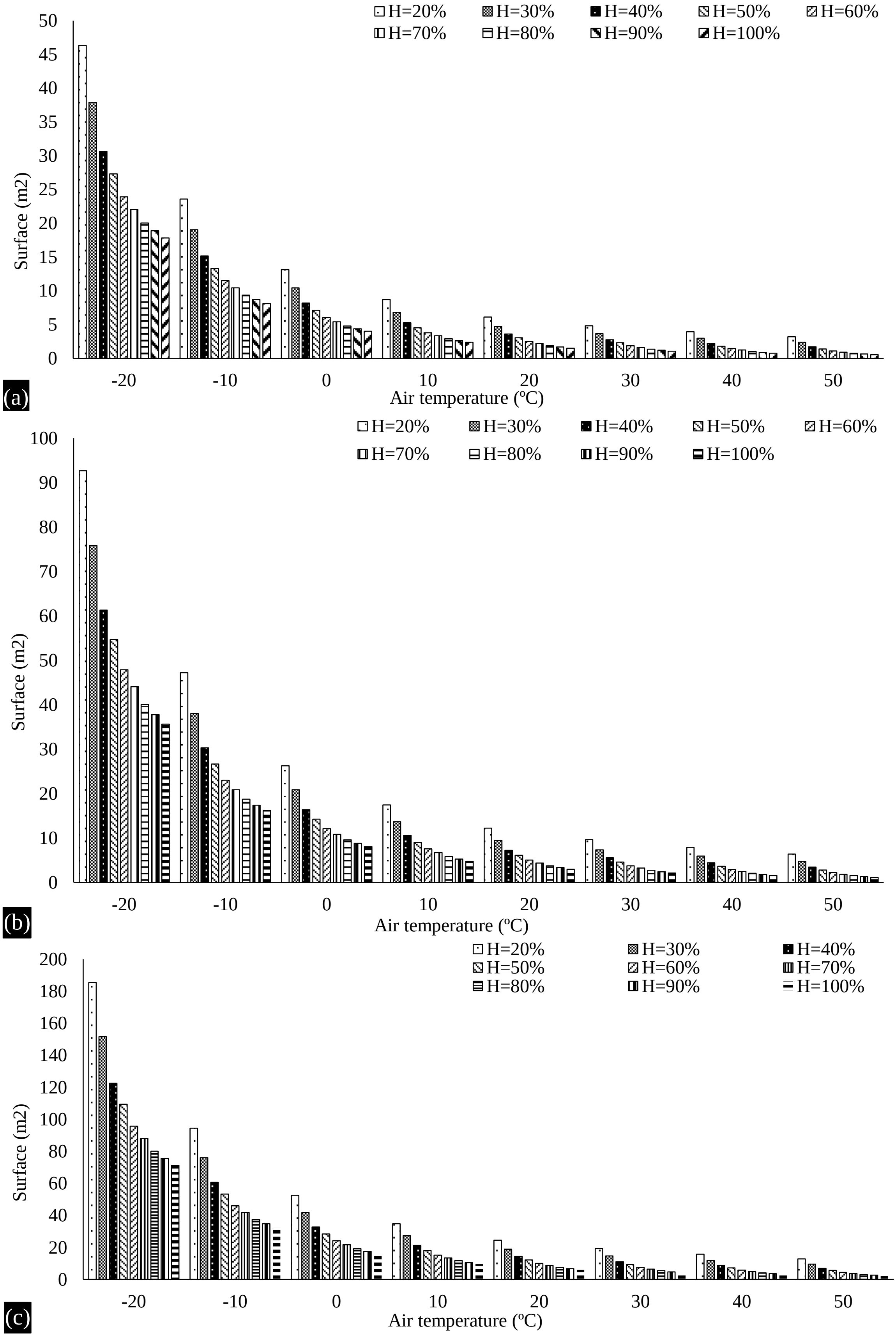



**Figure 6.** Collectible surface for human water needs for a small community of 100 people considering air temperature influence. Standard base values: (a) (0.5 L/day); (b) (1.0 L/day); (c) (2.0 L/day)

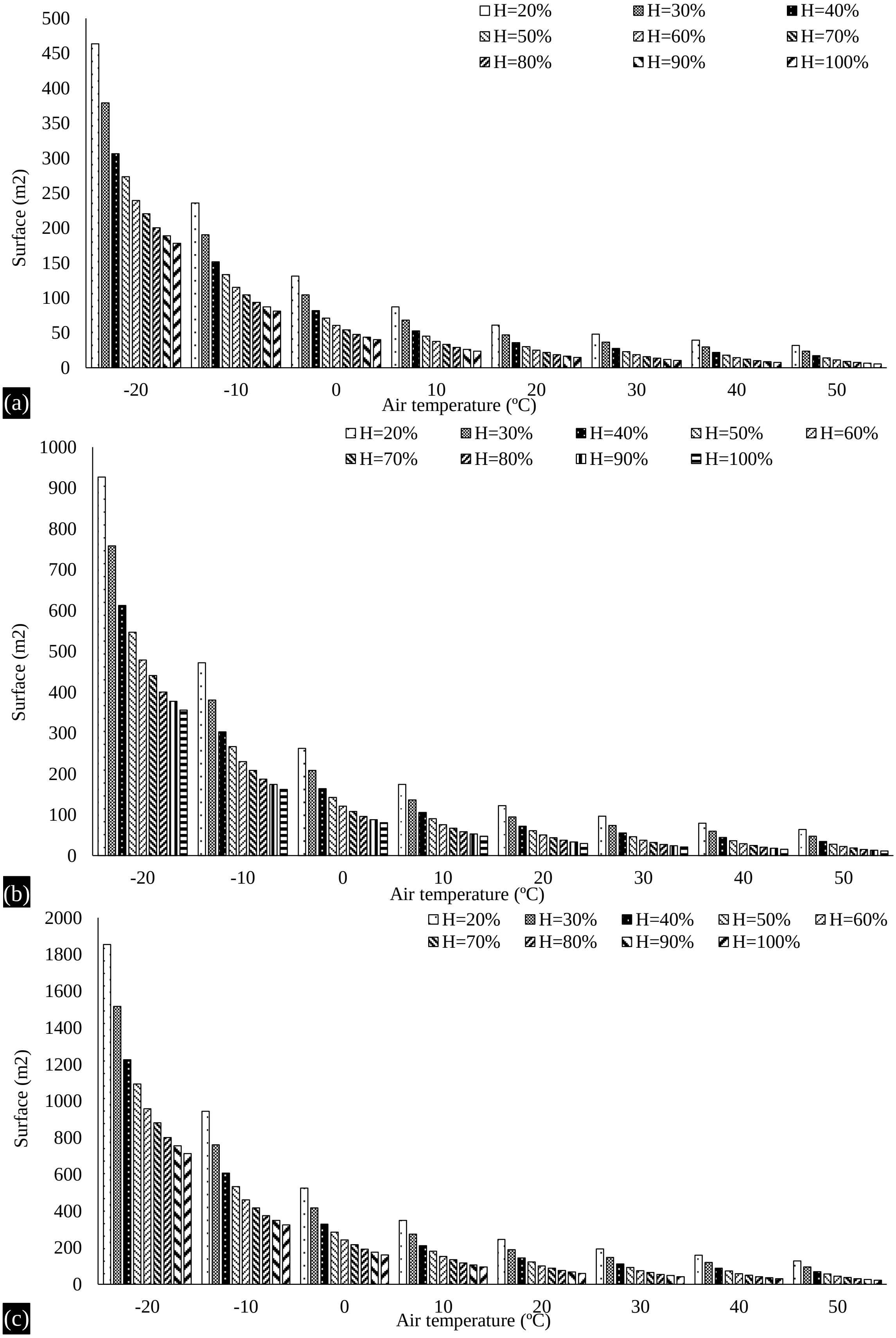



**Figure 7.** Collectible surface for human water needs for a small village of 1000 people considering air temperature influence. Standard base values: (a) (0.5 L/day); (b) (1.0 L/day); (c) (2.0 L/day)

We notice that for the small community, the required surface ranges from a minimum of 0.6 m$^2$ for scorching (50ºC) and humid climate (H=100%) to a maximum of 331 m$^2$ for icy (-20ºC) and arid climate (H=20%). A similar situation occurs for the small village case with surface variation from a minimum of 5.5 m$^2$ to a maximum of 3308 m$^2$ for the same climatic conditions.

## ENGINEERING PLANNING AND DESIGN

The high surface variation avoids a simple engineering design for all climatic conditions and daily human water consumption; therefore, we propose a modular system that adapts to the specific needs depending on daily water requirements, air temperature, and humidity.

To this goal, we divide the operational conditions into climatic types according to ambient temperature, cold and icy (type 1), warm (type 2), and hot and torrid (type 3); the temperature range for every climatic type is (Table 8):

**Table 8.** Climatic type classification by temperature

| | Cold & Icy | Warm | Hot & Torrid |
|---|---|---|---|
| Temperature range (ºC) | [-20,0] | [10,20] | [30,50] |

Regarding the humidity, we divide the climatic conditions into three types, dry (type A), normal (type B), and humid (type C), with the following humidity ranges (Table 9):

**Table 9.** Climatic type classification by humidity.

| | Dry | Normal | Humid |
|---|---|---|---|
| Humidity range (%) | [20,40] | [50,70] | [80,100] |

Combining all the climatic types, we have nine climatic sub-groups: 1A, 2A, 3A, 1B, 2B, 3B, 1C, 2C, and 3C. Despite it may look like a large case number, we have reduced the engineering configuration number by eight, representing a significant simplification in designing, manufacturing, and managing.

According to this classification the water collection device surface range is (Table 10):

**Table 10.** Required water collection surface for the climatic sub-groups

| Type | 1A | 2A | 3A | 1B | 2B | 3B | 1C | 2C | 3C |
|---|---|---|---|---|---|---|---|---|---|
| $S_1$(m$^2$) | [8.2,46.3] | [3.6,8.7] | [1.7,4.8] | [5.4,27.3] | [2.2,4.5] | [0.9,2.3] | [4,20] | [1.5,2.9] | [0.6,1.4] |
| $S_2$(m$^2$) | [82,463] | [36,87] | [17,48] | [54,273] | [22,45] | [9,23] | [40,200] | [15,29] | [6,14] |

Because the engineering design should minimize the number of surface models for water collection, we select a surface module for every humidity climatic type, imposing the condition that the combination of the global surface for the module set and the number of modules for every temperature climatic sub-group is minimal. Table 11 shows the engineering design optimization results for the nine climatic sub-groups and for the three daily water consumption.

**Table 11.** Module surface and number for the climatic sub-groups. (Small community of 100 people)

| w(L/day) | Type | 1A | 2A | 3A | 1B | 2B | 3B | 1C | 2C | 3C |
|---|---|---|---|---|---|---|---|---|---|---|
| 50 | S(m$^2$) | 1.75 | | | 1.15 | | | 0.75 | | |
| | N | 32 | 8 | 4 | 29 | 6 | 3 | 33 | 6 | 3 |
| 100 | S(m$^2$) | 2.6 | | | 1.6 | | | 1.2 | | |
| | N | 43 | 10 | 6 | 42 | 9 | 5 | 41 | 8 | 4 |
| 200 | S(m$^2$) | 5.3 | | | 3.1 | | | 2.4 | | |
| | N | 42 | 10 | 6 | 43 | 9 | 5 | 41 | 8 | 4 |

If we try to simplify the engineering design, minimizing the module number, we can select for every daily water demand, *w*, a single water collector module, thus, reducing the manufacturing process and reducing costs. To this goal, we simulated the number and total surface for the whole set adopting for the common module size every single option in the previous optimization process, yielding (Table 12):

**Table 12.** Comparison of global surface and number of modules for the three climatic sub-groups. (Data for a small community of 100 people)

| | **Module surface ($m^2$)** | | | |
|---|---|---|---|---|
| | 1.75 | 1.15 | 0.75 | w (L/day) |
| Module number | 92 | 136 | 203 | 50 |
| Global surface ($m^2$) | 161 | 156 | 152 | |
| | 2.6 | 1.6 | 1.2 | |
| Module number | 123 | 192 | 253 | 100 |
| Global surface ($m^2$) | 320 | 307 | 304 | |
| | 5.3 | 3.1 | 2.4 | |
| Module number | 121 | 196 | 253 | 200 |
| Global surface ($m^2$) | 641 | 608 | 607 | |
| Humidity | Low | Medium | High | |

The same module surface applies for the 1000 habitants' small town, with the difference in the module number and global surface that values in Table 12 must be multiplied by ten.

Analyzing the results from Table 12, we notice that the optimum configuration corresponds to the higher module size for every daily water demand. This option slightly increases the global surface module set by 5% but reduces the number of modules by 44%, justifying the module size selection.

Since we intend to service the community fresh water supply for a permanent survival time, the engineering configuration consists of 121 modules of 5.3 m2 each. As an alternative solution for drier climates without enough rainwater, the system engineering proposes 92 modules of 1.75 m2 each for the lowest daily water demand (0.5 L/day) and 123 modules of 2.6 m2 for intermediate water requirement (1 L/day).

***Engineering Design***

A simple inverted umbrella-shaped module is conceived as the simplest and easiest manufacturing device for water precipitation collection. The device is foldable to use the most reduced space when not working. The device consists of a collecting surface reminding of an inverted umbrella with a sink in the middle to channel collected rainwater flow (Figure 8); the sink connects to a cylindrical duct, which serves as a mast, ending in a detachable funnel to verse water into the water storage tank.

Every collector wing folds over or under the adjacent one to reduce space for storage when the device is not working. The collector wings slightly tilt to the center, so the water flows to the sink, which collects rainwater and carries it to the duct (Figure 9).

The water duct (Figure 9) is also detachable to facilitate the unit storage when it is not working. The coupling system uses a locking ring that allows the duct to rotate and seal the joint to prevent leaks. The duct comprises rings joined together by a flexible waterproof membrane that allows the duct to fold like an accordion for easy transportation, just like the water collector (Figure 10). The funnel-to-duct attachment is the same locking ring type as the duct-to-sink coupling.

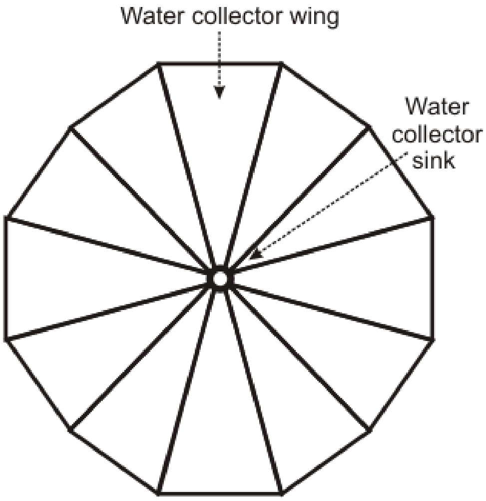



**Figure 8.** Upper view of the water collector.

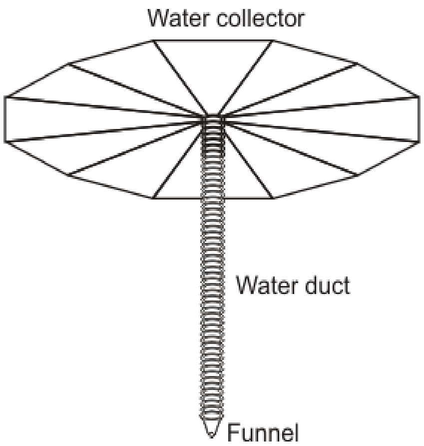



**Figure 9.** Side view of the water collector.

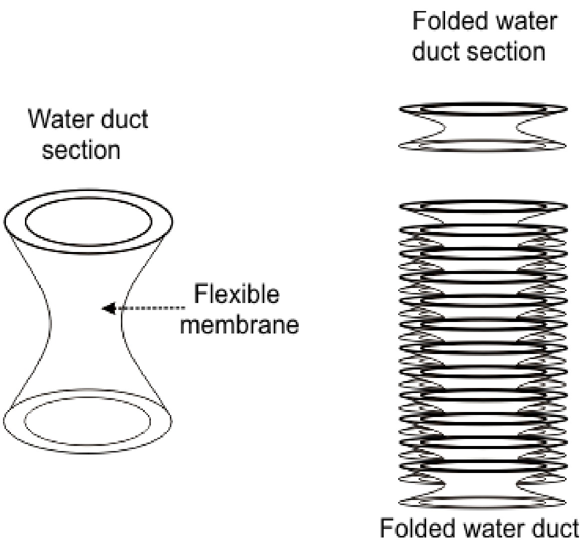



**Figure 10.** Detailed view of the water duct section. Left side: single element; Right side: folded element and folded duct.

The water collector diameter should correspond to a circle whose area matches the simulation size. Since we operate with a surface of 5.3, 3.1, and 2.4 $m^2$, depending on the humidity range, yields:

$$D = \begin{cases} \left(\frac{4}{\pi} S\right)^{1/2} = \left(\frac{4}{\pi} 5.3\right)^{1/2} = 2.6\ m \\ \left(\frac{4}{\pi} S\right)^{1/2} = \left(\frac{4}{\pi} 3.1\right)^{1/2} = 2.0\ m \\ \left(\frac{4}{\pi} S\right)^{1/2} = \left(\frac{4}{\pi} 2.4\right)^{1/2} = 1.75\ m \end{cases} \quad (18)$$

The diameter values in equation 18 correspond, from top to bottom, to low, medium, and high humidity range.

We notice that the diameter is not excessively high since conventional umbrellas used for sun protection currently have up to 2.4 m in diameter.

**CONCLUSIONS**

We have developed a method to estimate the precipitable water from atmospheric rain for human consumption; the collectible water amount depends on meteorological factors like ambient and dew point temperature, water vapor pressure, relative humidity, and atmospheric pressure.

The study develops an algorithm to determine the amount of precipitable water as a function of easy-to-measure meteorological parameters like ambient temperature and relative humidity; the algorithm relates both parameters to the dew point temperature, through which we estimate the precipitable water.

The precipitable water dependence on the dew point temperature is obtained using an expression based on statistical data with high accuracy, around 95%; this high accuracy proves the validity of the proposed method and guarantees the accuracy of the predicted results.

The simulation shows that dry climates are inappropriate for collecting precipitable water for human consumption since the collected water amount does not reach the minimum human survival daily consumption.

Since collectible water amount depends on geographical zone humidity, the study develops a specific methodology to determine the required collector surface for every relative humidity and daily human water requirement. The study applies to climatic sub-groups where relative humidity is within a defined range: low, medium, and high.

The water collection method applies to any World's place provided we measure the key parameters, ambient temperature, and relative humidity, which is easy with a simple thermo-hygrometer. Since this device is cheap and easy to manage, the measurements are accessible to people with basic professional training.

The work develops an engineering design and sizing process to optimize the water collector system; since the total required area is high, we have designed a modular system comprising a water collectors set of variable size according to climatic sub-group. The engineering modularity system design allows the global water collection surface enlargement, adapting to population growth.

We uniformize the engineering design to simplify the manufacturing process and reduce building costs. The selected design corresponds to the highest surface model derived from the optimization process in the simulation run. The engineering process designs a different size for every relative humidity range group.

The water collector design corresponds to an inverter umbrella shape with a diameter from 1.75 to 2.6 m, compatible with the manufacturing process, and easy to handle. The water collector is modular, comprising detachable elements that allow easy handling and transportation and reduce storage room.

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