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NUMERICAL AND VOLUMETRIC FREQUENCY OF SPRINKLER DROP-SIZE FROM WATER DISTRIBUTION RADIAL CURVE PART I: MATHEMATICAL MODELLING

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ABSTRACT

An analytical approach to correlate the travel distance of the drops from the irrigation sprinkler with the drops water volume was studied.Such approach was used along with a simplified ballistic model, able to define the trajectories of the drops produced by the nozzle of the sprinklers, to develop a rapid and simple method to obtain sprinkler drop-size spectrum from the water distribution radial curves.

Keywords: irrigation, size spectrum, droplet, nozzle, mathematical modelling.

INTRODUCTION

Sprinkler irrigation practices have been shown to have a significant impact on both quantity (rate of growth and biomass produced) and quality of field-grown crops [1-2]. The knowledge of the sprinkler droplet-sizes spectra can help in the selection and design of sprinkler irrigation systems. The size of the water droplets produced from nozzles is of concern to irrigation designers and farmers for two main reasons: 1) the small droplets are subject to wind drift, evaporation losses, and distortion of the water application patterns by the wind [3-5]; 2) large-sized droplets normally impact the crops and the soil with more kinetic energy, causing damages to the leaves and soil crust formation that reduces the soil infiltration rate, especially in soils with the finest texture [6-9]. Both of them may reduce distribution uniformity and efficiency of sprinkler irrigation systems.

Many researchers have reported that droplet formation is mainly affected by pressure, nozzle size, and nozzle configuration [10-14]. In an impact sprinkler, droplet formation is a consequence of both the jet pressure, through the friction with the surrounding air, and the arm impacted by the jet, generating a droplet distribution almost perpendicular to the main jet. The process of jet break-up is quite complex [15]. The relatively high speed of the jet is sufficient to cause disintegration into droplets in the air, a process in which inertia, viscosity, and capillary forces are involved. However, the complexity of the jet-breakup process makes a rigorous theoretical analysis difficult. It seems clear that droplet formation begins on the surface of the jet and continues up to the centre ([16] and [3]). Droplets disintegration occurs as the water stream travels through the air. Considering that the droplet diameter formed in the jet-breakup process is inversely proportional to air speed, the surrounding water of the jet produces small droplets; conversely large droplets are produced by the axis of the jet due to the lower relative speed of the air that is already routing. This is the reason why the medium-sized droplets produced near the nozzle are much smaller than those produced far from the nozzle.

Because this complicated process of jet disintegration is difficult to model, trajectory-simulation studies tend towards simplification, considering the process as a set of spherical and isolated droplets of various sizes which move through the air independently, with air drag coefficients that are functions of droplet diameters only ([10], [16], [17]), or of the Reynolds numbers of the droplets moving in the air ([3], [9], [18], [19]). As the action of the drag force on a set of droplets is significantly lower than that acting on each isolated droplet forming the jet, Kincaid [9] proposed to multiply the velocity by a reducing coefficient when calculating the drag coefficient in the initial zone, where the jet is more compact (15% of the throw radius in an impact sprinkle).

Several studies of rainfall droplets have shown that droplets with a diameter larger than 5.5 mm are unstable and break into small droplets, although there can be greater droplet sizes for short period of time [20]. As droplets interfere each other in the air, it is necessary to introduce a correction coefficient to better adjust the simulation to reflect reality ([3], [13]). All factors affecting the disintegration of the jet into droplets can have various influences on the correction coefficient. The main factors are wind action, pressure, the internal design of the nozzle, and the presence or absence of a jet straightening vane VP, which determines the degree of crossness of the throw and the shape of the water distribution radial curve [21].

Many experimental studies have been carried out to analyse droplet size distribution using different a variety of techniques, more or less simple and more or less accurate, for different types of sprinkler. The reported data were collected using the pellet, stain, and photographic methods. The most commonly used method in the past was the pellet (flour) method ([10], [11], [12], [13], [22], [23]). With the develop of electronics and computer technologies, optical methods using laser equipment ([24], [20]) and optical spectrometric methods [15] have emerged, making it possible to register automatically the data with higher precision. However, Kincaid et al. [20] found that the data from the pellet method compared well with the laser method.

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Because the pellet method is time-consuming and the optical methods using laser or spectrometer require very expensive devices, an indirect method for the determination of droplet size spectrum, based on water distribution radial curve obtained in laboratory, was proposed by von Bernuth and Gilley [16]. In this method, each distance from the sprinkler is associated with a unique droplet diameter. The function between travel distance (throw radius) and diameter was obtained by a ballistic calculation, that is, a numerical integration of the differential equation of the droplet motion using Runge-Kutta technique, without considering evaporation and wind effects.

From the experimental water distribution radial curve, von Bernuth and Gilley [16] determined, for each distance from the sprinkler, the small volume of water associated to the diameter of a droplet with an assigned travel distance. Calculating the ratio between these volume elements and the total volume, they then found the volume frequency of each diameter and thus the droplet size spectrum. Finally, they obtained the cumulative volume frequency curve by summing the volumes of the different droplet diameters and comparing them with the total volume.

To carry out this procedure they discretised the distances of the water distribution radial curve and the droplet diameters, obtaining in the end a step-by-step curve of frequency of the diameters. Von Bernuth and Gilley [16] emphasised that the water distribution radial curve must be obtained in controlled conditions of high air humidity (very low evaporation) and the absence of wind, i.e., in laboratory conditions. For model validation they used the data reported by Kohl [11], obtaining a good accordance.

The same calculation procedure, i.e., the ballistic calculation using Runge-Kutta numerical integration technique together with the association of each droplet diameter with a given distance from the sprinkler and a given water volume obtainable from the laboratory water distribution radial curve, was used by Carriòn et al. [21] in SIRIAS simulation model, which can be used to design new sprinkler irrigation systems that optimize water use or to improve the existing ones.

MATHEMATICAL MODELLING

In the current work the indirect method of von Bernuth and Gilley was used, but the Runge-Kutta numerical integration technique was substituted for the ballistic-analytical model proposed by Lorenzini [19]. Secondly, an analytical approach was developed to correlate the water distribution radial curve with both numerical and volumetric cumulative frequencies.

These modifications served to simplify the calculus, improve the precision of the results and enable implementation of the model in a spreadsheet.

Ballistic model for determination of the droplet trajectory

To determine the trajectory of the droplets, and to therefore obtain the distance covered by the droplets by varying their diameters, a ballistic model proposed and validated by Lorenzini [19] was used. According to this model, the droplet-trajectory determination for each size is based on the following assumptions:

- the physical system considered is the single droplet exiting from the nozzle of the sprinkler and generated exactly in correspondence to the nozzle outlet;
- the forces applied to the system are weight, buoyancy and friction;
- the droplet has a spherical shape until soil impact, a condition which is consistent with photographic studies by Okaruma and Nakanishi [25];
- friction has the same direction as velocity for all the path but the opposite sense;
- the volume of the droplet is invariant during its flight (evaporation is considered as instantaneous and occurring at the end of the flight); and
- there is no wind disturbing the flight.

From these bases it is clear how the model simplifies the phenomenon studied. However, regarding the last two, the experimental data used to reconstruct the water distribution radial curves are usually obtained in the laboratory under conditions of no wind and minimal evaporation losses due to an air humidity close to 100%.
The operating parameters required to complete the modelling are:

- the nozzle height, h (m), with respect to ground level; and
- the exit velocity of the droplet from the nozzle, v_0 (m s^{-1}), inclined at an angle α degrees with respect to the horizontal direction (trajectory angle).

The parametric equations of the Lorenzini's model are:

$$x(t) = \frac{m}{k} Ln\left(\frac{v_{0x}k}{m} t + 1\right) \tag{1}$$

$$y(t) = h - \frac{m}{k} Ln\left[\frac{\cos\left(\arctan\sqrt{\frac{k}{ng}}v_{0y}\right)}{\cos\left(\arctan\sqrt{\frac{k}{ng}}v_{0y} - t\sqrt{\frac{kng}{m}}\right)}\right] \tag{2}$$

and the parametric equations of velocity are:

$$\dot{x}(t) = \frac{mv_{0x}}{m + kv_{0x}t} \tag{3}$$

$$\dot{y}(t) = -\sqrt{\frac{ng}{k}} \tan\left[-\frac{\sqrt{ngk}}{m} t + \arctan\left(\sqrt{\frac{k}{ng}}v_{0y}\right)\right] \tag{4}$$

Equation (2) is used to calculate the time of flight τ (s), i.e., the time interval between the moment the droplet exits the nozzle and the moment it reaches the soil:

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$$\tau = m \cdot arc\,sec\left[e^{\frac{hk}{m}} \sqrt{1 + \frac{kv_{0y}^2}{gn}} \right] + m \cdot arctan\left[\sqrt{\frac{k}{ng}} v_{0y} \right] \qquad (5)$$

where: $\dot{x}$ and $\dot{y}$ are respectively the velocities (m s^{-1}) in the horizontal and vertical directions; *m* is the droplet mass (kg); *n* is the actual mass of the droplet accounting for its buoyancy component in air (kg); *g* is acceleration due to gravity (m s^{-2}); and *k* is the friction parameter calculated by $k = \frac{f \cdot \rho \cdot A}{2}$ (here, f is the non-dimensional friction factor according to Fanning, ρ is the air density, depending on temperature, and *A* is the cross-sectional area of the droplet); *t* is time (s); *h* is the nozzle height (m); v_{0x} and v_{0y} represent the horizontal and vertical velocity components (m s^{-1}), respectively, at the beginning of the process and are given as:

$$v_{0x} = v_0 \cos \alpha \qquad (6)$$

$$v_{0y} = v_0 \sin \alpha \qquad (7)$$

Equations (1), (2), (3), (4) and (5) are analytical solutions to the ballistic problem. Therefore, they can be easily applied to any particular configuration of the system, i.e., for each droplet diameter, flow state, air temperature, nozzle geometry, angle of trajectory, height of sprinkler from the ground level, initial flow rate and velocity, in the hypotheses formulated.

Attention must be paid to the choice of the value of *k*, because this friction parameter is a function of the friction factor *f*, which is dependent on the flow state in the air-boundary layer of the droplet. If the droplet has a spherical shape, as considered in the initial assumptions, the possible flow states are three: a) laminar (for Reynolds number $Re \leq 2$); b) transitional (for $2 < Re < 500$); and c) turbulent (for $500 \leq Re < 200{,}000$). The friction factor *f* is given by [26, 27 and 28]:

a) for Reynolds number $0.1 \leq Re \leq 2$:

$$f = \frac{24}{Re} \qquad (8)$$

b) for $2 < Re < 500$:

$$f = \frac{18{,}5}{Re^{0{,}6}} \qquad (9)$$

c) for $500 \leq Re < 200{,}000$:

$$f = 0{,}44 \qquad (10)$$

Case (a) is, statistically speaking, very unlikely to occur in practice with sprinkler irrigation. In fact, at the usual initial flow velocities of irrigation water, values of $Re \leq 2$ would imply droplet diameters on the order of $1 \cdot 10^{-6}$ m (1 μm), which are more typical with chemical-spray applications rather than with irrigation.

While it is unnecessary to use Equation (8), nevertheless the velocity varies during the trajectory and thus *Re* changes. Therefore, on the basis of Equations (9) and (10), the *k* value is variable.

To use the ballistic model given by the analytical equations (1), (2), (3), (4), and (5) in an easier way and maintain a general applicability, Lorenzini [19] proposed calculating the f_0 value and then k_0 at the initial conditions of exit from the nozzle, based on the velocity v_0 and therefore on the pertinent $Re = \frac{\rho v_0 D}{\mu}$, using Equation (9) or Equation (10) depending on the value of *Re*.

Lorenzini [19] applied Equation (4), setting $\dot{y} = 0$ to obtain the time t_{top} at the top of the trajectory, which is when the vertical component of the velocity reverses its direction. At this point the droplet is in motion at the lowest velocity of the entire trajectory, as only the horizontal velocity $\dot{x}_{top}$ is present. The value of this velocity can be calculated from Equation (3) by substituting the time t_{top}. Consequently, $Re = \frac{\rho \cdot \dot{x}_{top} D}{\mu}$, f_{top} can be computed from Equations (8) or (9) according to the flow state and hence k_{top} determined. If both the Re_0 and Re_{top} values belong to the turbulent flow state, then *k* is constant and simply defined by $k = \frac{f \cdot \rho \cdot A}{2}$, using Equation (10) to compute *f*; otherwise, *k*can be computed as an arithmetic mean of k_0 and k_{top}. Finally, the flight time, τ, is determined from Equation (5) and the travel distance, x_t, by Equation (1).

Polynomial representation of water distribution radial curve and droplet-travel distance

The water distribution radial curve *I* (mm h^{-1}) can be defined as the water flow rate *Q* with respect to the wetted surface unit area, A_w:

$$I = \frac{Q}{A_w} \left(\frac{mm^3}{h \cdot mm^2} \right) \qquad (11)$$

It is determined in laboratory (tests) by measuring the application rates of the water accumulated in collectors laid out in a radial pattern. The water distribution radial curve is a function of the distance *x* from the sprinkler:

$$I = f(x) \qquad (12)$$

To find the function *f(x)*, and hence to mathematically represent the water distribution radial curve, a polynomial of degree six was obtained by the least-squares method. This sixth-degree polynomial regression was applied to 37 water distribution radial curves obtained in indoor tests under conditions of no wind and high relative humidity (near 100 %). The tests

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were conducted in accordance with ISO 7749-2 and ASAE Standard S330.1. All the water distribution radial curves were taken while maintaining the trajectory angle fixed at 30° and the sprinkler height at 0.65 m and then varying the sprinkler manufacturer, the nozzle diameter and the operating pressure. One of these curves is shown in Figure-1; the determination coefficient, R^2, varied between 0.965 and 0.996, with a mean value of 0.984 (Table-1).

In the previous paragraph the correlation between the travel distance, x_t, and the mass, and therefore the droplet diameter, was found by introducing the total flight time, given by Equation (5), into Equation(1). The travel distance x_t is obviously a function of the sprinkler height and the exit velocity from the nozzle, v_0, and hence of the nozzle diameter d, flow rate Q, and trajectory angle α.

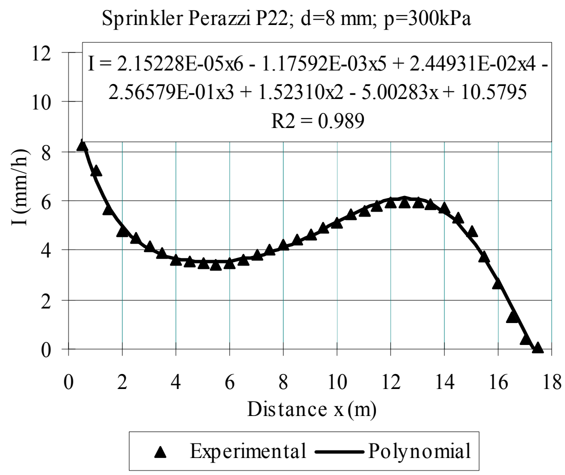

Figure-1. Experimental water distribution radial curve I (mmh^{-1}) and 6° polynomial regression with R^2=0.989 vs. distance x (m) from the Perazzi P22 sprinkler with an 8-mm nozzle diameter at 300 kPa pressure.

Applying the ballistic model to the 37 water distribution radial curves, the link between the travel distance x_t and the droplet diameter $D$was found and hence its mathematical representation:

$$x_t = p(D) \tag{13}$$

The function $p(D)$ best approximating the results was a fourth-degree polynomial obtained by mean polynomial regression. This polynomial presented a very high determination coefficient (R^2) of 0.999, which was nearly constant with varying maximum jet-travel distance. One of the 37 polynomial curves of Equation(13), along with the values computed by the ballistic model, is shown in Figure-2.

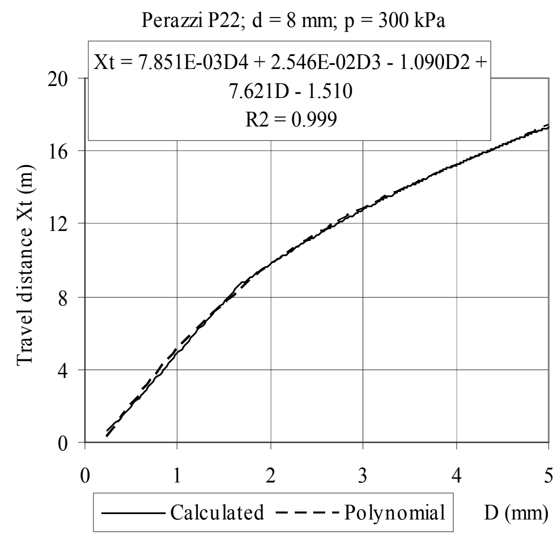

Figure-2. Calculated travel distance and 4° polynomial regression (R^2=0.999) vs. droplet size for sprinklerPerazzi P22 with 8-mm nozzle diameter at 300 kPa.

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Table-1. Determination coefficient $R^2$of 6° polynomial regression of water distribution radialcurve for various sprinklers, nozzle diameters and pressures.

Sprinkler	**Nozzle diameter** (mm)	**Pressure** (kPa)	R^2
Komet R8	6	200	0.986
		250	0.988
		300	0.989
		350	0.989
		400	0.989
	7	200	0.985
		250	0.989
		300	0.985
	8	200	0.994
		250	0.994
		300	0.996
	10	200	0.976
		250	0.986
		275	0.993
Perazzi P22	6	200	0.986
		250	0.989
		300	0.993
		350	0.995
		400	0.995
	8	200	0.968
		250	0.989
		300	0.989
	10	200	0.981
		250	0.990
		300	0.992
Rossi R15	7	200	0.980
		250	0.975
		300	0.973
	8	200	0.975
		250	0.967
		300	0.965
Sime K1	8	200	0.985
		250	0.975
		300	0.975
	9	200	0.980
		250	0.970
		300	0.973
Average			0.984

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Mathematical approach for determining the droplet population from the experimental water distribution radial curve

As the water distribution radial curve I is identical to the specific flow rate with respect to the distance x from the exit point, in the absence of wind the wetted area has a circular shape (Figure-3).

In this area, a radial direction, x, with origin in the centre, where is located the sprinkler, and a circular ring with infinitesimal width dx and average radius x_t can be individuated.

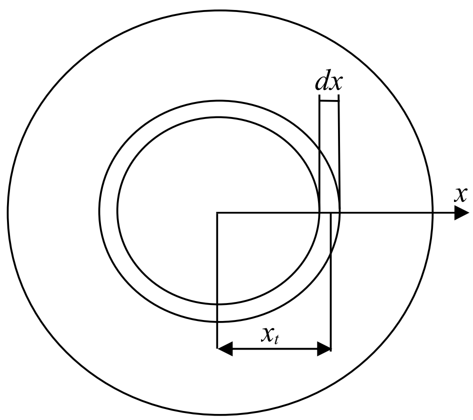

Figure-3. Circular wetted area obtained from a sprinkler without wind and infinitesimal ring associated with a given droplet diameter.

The area covered by this ring represents an infinitesimal, dS:

$$dS = 2\pi \cdot x_t \cdot dx \tag{14}$$

Given a one-hour time basis, for simplicity and to maintain general applicability, into the circular ring with infinitesimal area dS falls a water volume, also infinitesimal, dV.

As x_t is the travel distance of a well-defined and unique droplet diameter D, with volume V_D, the infinitesimal volume dV must be equal to the droplet volume V_D multiplied by the infinitesimal number of droplets dn (all of diameter D) which have fallen into the circular ring dS in one hour:

$$dV = V_D \cdot dn \tag{15}$$

Also, the water distribution radial curve I, which is equal to the water volume falling on the surface in an hour, with respect to an infinitesimal circular ring and hence to the travel distance x_t, is:

$$I = \frac{dV}{dS} = V_D \frac{dn}{dS} \tag{16}$$

Substituting Equation (12) and (14), Equation (16) becomes:

$$I = f(x) = \frac{\pi}{6} D^3 \frac{dn}{2\pi x_t \cdot dx} = \frac{D^3}{12 \cdot x_t} \cdot \frac{dn}{dx} \tag{17}$$

The derivative of Equation (13) is given by:

$$dx = p'(D)dD \tag{18}$$

Substituting x_t and dx, respectively, with (13) and (18), we obtain from Equation (17):

$$I = f[p(D)] = \frac{D^3}{12 \cdot p(D) \cdot p'(D)} \cdot \frac{dn}{dD} \tag{19}$$

Hence, the derivative of the droplet number n with respect to the diameter D is:

$$\frac{dn}{dD} = \frac{12}{D^3} \cdot f[p(D)] \cdot p(D) \cdot p'(D) \tag{20}$$

If a dimensional class of droplets is fixed, for the ith class, for example from 0.49 to 0.51 mm, represented by the diameter D_i (in the example of 0.5 mm), the corresponding value of the derivative $\left(\frac{dn}{dD}\right)_i$ is obtained from Equation (20).

At this point it is possible to calculate the number of droplets Δn_i belonging to the ith dimensional class, given that this class is represented by a lower limit (0.49 mm) and an upper limit (0.51 mm) and hence a ΔD_i equal to 0.02 mm:

$$\Delta n_i = \left(\frac{dn}{dD}\right)_i \cdot \Delta D_i \tag{21}$$

The volume of liquid, ΔV_i, of the ith class is readily computed as:

$$\Delta V_i = V_{Di} \cdot \Delta n_i = \frac{\pi}{6} D^3 \cdot \Delta n_i \tag{22}$$

This is the droplet volume of intermediate diameter D_i, and therefore representative of the above-mentioned class, multiplied by the number of droplets Δn_i of the class.

Application of the ballistic model and mathematical approach

The calculation of the sprinkler droplet-size spectrum must follow a procedure (algorithm) built of some steps.

The first step consists of finding the minimum, x_{tmin}, and maximum, x_{tmax}, travel distances, which depend on the sprinkler characteristics and are deducible from the experimental water distribution radial curve.

The second step consists of the application of the analytical ballistic model by varying the diameter $D_i$with a chosen rise, for example 0.02 mm, beginning from a droplet of diameter D_1 equal to the minimum travel distance x_{tmin} and ending with a droplet of diameter D_{max} equal to the maximum travel distance x_{tmax}.

The third step consists of finding the Equation (12), by applying a sixth-degree polynomial regression to the graph of the water distribution radial curve.

Subsequently, the fourth step concerns the determination of the polynomial $x_t = p(D)$ regarding to the Eq. (13), by the creation of a plot of x vs. D and applying a fourth-degree polynomial regression; thus, the derivative $p'(D)$ will be a polynomial of degree three.

The fifth step consists of finding, for each diameter D_i, the derivative $\left(\frac{dn}{dD}\right)_i$ by applying Equation (20). Hence, as the range of each class of diameters $\Delta D_i$is fixed (in this case 0.02 mm), the fifth step finishes with the calculation of the number of droplets Δn_i, belonging to each class, according to Equation (21).

The sixth step concerns the calculation of the values of the water volume ΔV_i for each class, according to Equation (22).

As the total number of droplets $N = \sum \Delta n_i$ is defined, the seventh step consists to finding the numeric frequency for each class f_{ni}:

$$f_{ni} = \frac{\Delta n_i}{N} \cdot 100 \tag{23}$$

and thus the numeric cumulative frequency, F_{ni}, for each class, that is, the ratio between the total number of droplets from the first class to the ith class and the total number of droplets, N:

$$F_{ni} = \frac{\sum_{j=1}^{i} \Delta n_j}{N} \cdot 100 = \sum_{j=1}^{i} f_{nj} \tag{24}$$

Calculation of the percentage ratio between the water volume ΔV_iobtained from Equation (22) and the total volume $V_t = \Sigma \Delta V_i$ gives the volumetric frequency for each class:

$$f_{vi} = \frac{\Delta V_i}{V_t} \cdot 100 \tag{25}$$

Finally, as for the numerical cumulative frequency, it is possible to define the volumetric cumulative frequency, F_{vi}, for each class:

$$F_{vi} = \frac{\sum_{j=1}^{i} \Delta V_j}{V_t} \cdot 100 = \sum_{j=1}^{i} f_{vj} \tag{26}$$

From the columns of the cumulative number frequency and the cumulative volume frequency, plots of each vs. droplet size can be drawn. These diagrams are the desired droplet-size spectra.

CONCLUSIONS

Starting from the experimental water distribution radial curve, an analytical approach based on a mathematical analysis was developed to obtain a correlation between the water volume of the drops falling at a given distance from the sprinkler nozzle and their diameter. The equations of a ballistic model proposed by Lorenzini [19] for the calculation of the trajectories of the drops exiting from the nozzle were included in this mathematical procedure.

The result of this work was the implementation of an indirect method for the determination of the spectrum of the drops diameters produced by the nozzle that is a method able to give the numerical and volumetric frequency of the diameters of the drops.

This indirect method can be used in models for the design of sprinkler irrigation systems, useful to obtain a good uniformity of water distribution to optimize water use, but it needs to be validated by using experimental data, as expected in part II.

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