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Teaching Sprinkler Irrigation Engineering by a Spreadsheet Tool

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Abstract: Since being released 40 years ago, computer spreadsheets have proven to be worthwhile for use in educational contexts. There is plenty of evidence for this in practically every scientific discipline and engineering field. In view on this fact, the present work exposes a didactical resource, named the sprinkler irrigation tool, developed in Excel® spreadsheet licensed by 2018 Microsoft©. The objective of this tool is to offer an alternative to students in irrigation engineering, particularly for those training in the design of sprinkler irrigation systems so they can develop their theoretical knowledge and practical skills acquired in laboratory and field experiments. The main findings reported in this paper address well-agreed methodologies for evaluating radial patterns of precipitation rates, diameter distribution frequency, ballistic simulation of water drops' movement through air, kinetic energy, and performance indicators as part of the core parameters of efficient irrigation system management. This computing tool provides outcomes in tabular and graphical formats that are consistent with those found in studies previously published in specialized literature on related topics. Likewise, spreadsheets have been proven to be adequate pedagogical instruments on the path to achieving meaningful learning; however, this assertion still needs to be confirmed through a rigorous study of students who have used the developed tool.

Keywords: solid-set sprinkler irrigation systems; ballistic theory; engineering design training; teaching–learning process

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Citation: Bautista-Capetillo, C.; Robles Rovelo, C.O.; González-Trinidad, J.; Pineda-Martínez, H.; Júnez-Ferreira, H.E.; García-Bandala, M. Teaching Sprinkler Irrigation Engineering by a Spreadsheet Tool. *Water* **2023**, *15*, 1685. https://doi.org/10.3390/w15091685

Academic Editor: Guido D'Urso

Received: 6 March 2023
Revised: 13 April 2023
Accepted: 20 April 2023
Published: 26 April 2023

1. Introduction

The progress of engineering as a scientific discipline [1] and a practicing profession [2] is based on theoretical and experimental knowledge developed over time. Both approaches have contributed to solving a number of physical phenomena which generally can be represented through mathematical arrangements, but also recreated and analyzed with laboratory techniques [3–6]. Proof worthy enough of inclusion is a remarkable evolution that irrigation engineering has achieved as a result of worldwide research carried out to take optimal advantage of water resources allocated to the agriculture sector. For example, new techniques are continuously put forward to enhance efficiency and uniformity of surface and pressurized irrigation methods in an effort to improve water productivity and farming profitability [7,8].

From an academic perspective, the teaching–learning process aims to present pedagogical guidelines to training professionals with suitable capabilities for responding assertively to contemporary society's needs for environmentally friendly scenarios [9]. In this context, one key to success in engineering education lies in innovative instructional curricula design where traditional learning methods, alongside computer tools and digital media, deal with the basal premise surrounding which cutting edge didactical resources have been developed in order to improve the effectiveness of knowledge assimilation by students. Setting aside differences between conceptual frameworks and hands-on experiences, the relevance of strategies will be weighed based on their congruence and ability to intertwine both perspectives. Thus, from a pedagogical point of view, conceptualization and practices would allow teachers to uphold their responsibility to shape highly qualified professionals. Classroom lectures, laboratory and field experiments, and technology supplies remain as complementary pathways for engineering significant learning [10–12]. However, the technological aspect has become more relevant, particularly in recent decades, due to its permanent and continuous upgrades [13]. As a result, current technological tools offer a broad range of choices to achieve the same purpose, but also a diversity of possibilities to address different needs. Regarding water resources management, the market offers multiple software packages to quantify and qualify water assessments from an endless number of scientific, technical, and educational perspectives [14–18].

Strictly speaking of spreadsheet packages, manifold studies have been published in specialized literature to accurately ascertain how far these computational tools support the academic performance of students, either in terms of engineering fundamentals comprehension or properly handling equations which rule water systems [19–21]. In addition, there is documental evidence on the assessment of certain technical scenarios via spreadsheets; although they have been formulated as a didactic tool to bring up engineering professionals, they have also been used to assist decision-making in the domain of work [22–26]. Although a wide range of alternatives currently exist to address topics related to water resources via spreadsheets [27,28], offering a particular approach for engineering irrigation is aimed at evaluating its use for planning and design following some existing methodologies to determine aspects such as crop water requirements, irrigation performance (effective irrigation rate, uniformity of water application in the field, water use efficiency, and water productivity), irrigation scheduling, and irrigation waterworks from a hydraulic design perspective [29–33].

While it is true that, at present, a fair variety of spreadsheets are available to tackle different technical aspects related to sprinkler irrigation systems, it is also true that mathematical simulation models coupled with a numerical procedure for discretely solving equations which govern droplet movement are key inputs for predicting sprinkler irrigation performance given different hardware, operating pressures, and environmental conditions. In spite of this, the literature review conducted for this work suggests there is a lack of computational spreadsheets for use as didactic tools to help in the learning process. By virtue of the foregoing, this study reports on an Excel® spreadsheet tool licensed by 2018 Microsoft© [34] for solid-set sprinkler irrigation assessment to encourage irrigation engineering learning. The main goal is to reinforce mathematical thinking as well establish as its relational value for sprinkler irrigation using a practical spreadsheet tool. A special emphasis on a ballistic model applied to water drop diameter distribution, optimal numerical simulation by means of Runge–Kutta pairs, the application rate for isolated sprinklers, kinetic energy and specific power for water drop impact on surface soil or crop canopy, and sprinkler irrigation performance through uniformity and efficiency indicators were considered for a number of configurations.

2. Background

2.1. Mathematical Model for Sprinkler Irrigation

Ballistics theory is the most technical approach used in sprinkler irrigation modeling, particularly with respect to impact sprinkler systems. Drop diameter, drop velocity, drop trajectory from the sprinkler nozzle until surface contact, operational hydraulic parameters, and environmental conditions are all relevant for this model. Thus, an impact sprinkler is considered to be a device emitting drops of different diameters whose trajectories are influenced by initial velocity, wind velocity, gravitational force, and aerodynamic drag force [35–37]. Figure 1 schematically depicts the acting forces and velocities on a water drop moving through the air.

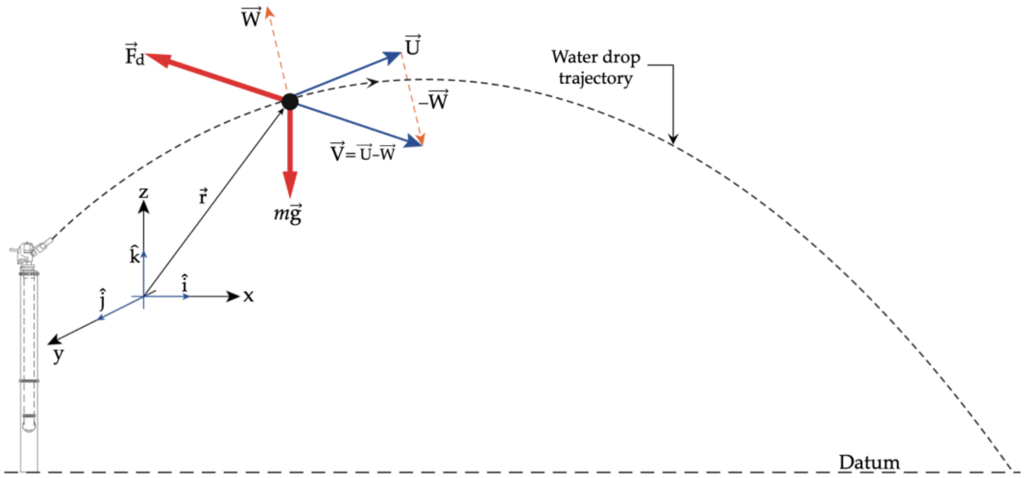

Figure 1. Drop movement schematization from the sprinkler device to reach a datum. Forces acting on water drops traveling throughout the air are drag force ($\vec{F}_d$) and gravitational force ($m\vec{g}$). $\vec{V}$ is the water drop's velocity relative to air and $\vec{U}$ and $\vec{W}$ are water drop velocity and wind velocity relative to the Cartesian coordinate system, respectively; $\vec{r}$ is water drop vector position and m is its mass (following the methodology of Robinson and Robinson [38] for drop forces and velocities).

The outward jet from the sprinkler nozzle involves complex processes for disaggregating drops at a certain distance from the nozzle. These drops, flying at different velocities and directions (3D), with a number of drop diameters landing at different distances from the sprinkler, make them difficult to model and, therefore, to simulate in terms of trajectory [39–42]. As a result, in order to evaluate drops traveling from the sprinkler until they make contact with the surface, some hypotheses have been considered in the ballistic model: (a) the jet breaks up at the nozzle exit into individual spherical drops of different diameters, which move independently in the air; (b) the aerodynamic drag coefficient is independent of sprinkler height with respect to a datum, jet inclination angle, wind speed, and nozzle diameter; (c) wind velocity is parallel to a datum plane but varies as a function of the sprinkler height; and (d) different drop diameters fall at different distances [36,43]. With relative independence from the previous assumptions, Fukui et al. [44] derived the equations of motion for an isolated water drop in a three-dimensional Cartesian system (Equations (1)–(3)).

$$A_x = \frac{d^2x}{dt^2} = -\frac{3}{4}\frac{\rho_a}{\rho_w}\frac{C_d}{\phi}V(U_x - W_x) \tag{1}$$

$$A_y = \frac{d^2y}{dt^2} = -\frac{3}{4}\frac{\rho_a}{\rho_w}\frac{C_d}{\phi}V(U_y - W_y) \tag{2}$$

$$A_z = \frac{d^2z}{dt^2} = -\frac{3}{4}\frac{\rho_a}{\rho_w}\frac{C_d}{\phi}VU_z - g \tag{3}$$

where x, y, and z [L] are Cartesian coordinates relative to the sprinkler nozzle; t is the temporal coordinate [T]; ρ_a is the air density [M L^{-3}]; ρ_w is the water density [M L^{-3}]; A is the water drop acceleration in the air [L T^{-2}]; ϕ is the drop diameter [L]; g is the gravity acceleration [L T^{-2}]; C_d is the aerodynamic drag coefficient, which can be expressed as a function of the Reynolds number [adim] [45,46], or as a function of the operating pressure, drop diameter, equivalent diameter, and nozzle discharge coefficient [adim] [47]; V is the drop's velocity in the air [L T^{-1}]; $U_x = \frac{dx}{dt}$, $U_y = \frac{dy}{dt}$, and $U_z = \frac{dz}{dt}$ are components of drop velocity [L T^{-1}]; and W_x, and W_y are components of the wind velocity [L T^{-1}], both with respects to a coordinate system. Terms between square brackets correspond to dimensions of each variable.

Now, once Equations (1)–(3) are properly integrated and the initial conditions are considered, equations describing the drop movement were obtained. Equations (4)–(6), for velocity components, and Equations (7)–(9,) for trajectory components, are as follows:

$$\frac{dx}{dt} = (v_x - W_x)\left(e^{-bt}\right) + W_x \tag{4}$$

$$\frac{dy}{dt} = (v_y - W_y)\left(e^{-bt}\right) + W_y \tag{5}$$

$$\frac{dz}{dt} = \left(\frac{g}{b} + v_z\right)\left(e^{-bt}\right) - \frac{g}{b} \tag{6}$$

$$x = \left(\frac{1}{b}\right)(v_x - W_x)\left(1 - e^{-bt}\right) + W_x t \tag{7}$$

$$y = \left(\frac{1}{b}\right)(v_y - W_y)\left(1 - e^{-bt}\right) + W_y t \tag{8}$$

$$z = h + \left(\frac{1}{b}\right)\left(\frac{g}{b} + v_z\right)\left(1 - e^{-bt}\right) - \frac{g}{b}t \tag{9}$$

where v_x, v_y, and v_z denote the initial drop velocity at x, y, and z coordinates [L T^{-1}], respectively, and $b = \frac{3}{4}\frac{\rho_a}{\rho_w}\frac{C_d}{\phi}V$ [T^{-1}]. By knowing the vertical distance between a datum and the sprinkler nozzle, it is possible to establish coordinates at which the water drops land, as well as their corresponding velocities. Regarding the aerodynamic drag coefficient (C_d), computed as a function of the Reynolds number (R_e) for a spherical shaped droplet, this has been formulated in several ways by different authors. Equations (10)–(12) are expressions proposed by Okamura [45] to determine this value.

$$C_d = \frac{33.3}{R_e} - 0.0033R_e + 1.2 \quad \textit{if } R_e \le 100 \tag{10}$$

$$C_d = \frac{72.2}{R_e} - 0.0000556R_e + 0.48 \quad \textit{if } 100 < R_e \le 1000 \tag{11}$$

$$C_d = 0.45 \quad \textit{if } R_e > 1000 \tag{12}$$

Another approach to calculate C_d from R_e magnitude was proposed by Park et al. [46], such as that which is argued in Equations (13) and (14).

$$C_d = \frac{24}{R_e}\left(1 + 0.15R_e^{0.687}\right) \quad \textit{if } R_e \le 1000 \tag{13}$$

$$C_d = 0.43\left\{1 + 0.21\left[\left(\frac{R_e}{1000}\right) - 1\right]^{1.25}\right\} \quad \textit{if } R_e > 1000 \tag{14}$$

On the other hand, Li and Kawano [47] stated that C_d can be obtained by accounting for the operating pressure, drop diameter, equivalent diameter, and nozzle discharge coefficient (Equations (15) and (16)).

$$C_d = 51.46P^{-0.179}\varnothing^{-1.181}D_e^{-1.936}C^{-3.318} \quad \textit{if } \varnothing \le 2\text{ mm} \tag{15}$$

$$C_d = 0.3 \quad if\ \varnothing > \ 2\ \text{mm} \tag{16}$$

Hills and Gu [48] introduce a further method for Cd calculation as a result of a regression analysis performed on a set of water droplets falling at terminal velocity; its composition is shown in Equation (17).

$$\begin{gathered} C_d = A_1 (A_2 D)^{A_3} \\ A_1 = 8.44 - 0.041P + 8.48 \times 10^{-5} P^2 \\ A_2 = \left(\frac{D_n^{0.1}}{1.12}\right)\left(0.56P^{0.11}\right) \\ A_3 = 17.69P^{-0.39} \end{gathered} \tag{17}$$

where $R_e = \frac{V\varnothing}{\upsilon}$ [adim]; υ is the cinematic viscosity [$L^2\ T^{-1}$]; P is the operating pressure [$M\ L^{-1}\ T^{-2}$]; $D_e = \frac{4A_h}{P_w}$ is the equivalent diameter [L]; A_h is the hydraulic area of nozzle [L^2]; P_w is the wetted perimeter [L]; C is the nozzle discharge coefficient [adim]; D is the volume mean drop diameter [L]; A_1, A_2, and A_3 are the regression coefficients [adim]; and D_n is the nozzle diameter [L].

All the proposals presented above for computing the drag coefficient (Okamura [45], Park et al. [46], Li and Kawano [47], and Hills and Gu [48]) were separately used in this research work and were discussed in terms of drop simulation (drop coordinates and velocities at different time intervals, wind and no-wind conditions, and wind direction for some drag coefficients).

2.2. Numerical Approach to Simulating Water Drops' Trajectory and Velocity

The ballistic model expressed in Equations (1)–(9) can be approximated to an analytical solution through a numerical solution using discrete intervals of time. Accordingly, a fourth-order Runge–Kutta numerical method is commonly used for water drop simulations computing drop velocity and drop distances, mainly because of its stability and suitability for error control [49]. The rule for numerical integration is shown in Equation (18) [50]; notice that Ψ is an arbitrary variable to represent how to compute discrete values of dynamics equations of motion for acceleration, velocity, and trajectory of water drops in the air. Consequently, subsequent values (Ψ_{n+1}) are estimated on the basis of the preceding value (Ψ_n) added to the product of the time step (Δt) and a weighted slope resulting from estimating the K_1, K_2, K_3, and K_4 constants. It should also be clarified that due to the inherent characteristics of the spreadsheet used, it is difficult to define a time interval for executing an iterative process; instead, the computational tool has, by default, a configuration for performing 750 iterations automatically.

$$\begin{gathered} \Psi_{n+1} = \Psi_n + \frac{\Delta t}{6}(K_1 + 2K_2 + 2K_3 + K_4) \\ K_1 = f(t_n, \Psi_n) \\ K_2 = f\left(t_n + \frac{\Delta t}{2}, \Psi_n + \frac{K_1}{2}\right) \\ K_3 = f\left(t_n + \frac{\Delta t}{2}, \Psi_n + \frac{K_2}{2}\right) \\ K_4 = f(t_n + \Delta t, \Psi_n + K_3) \end{gathered} \tag{18}$$

Error estimation is required in order to build an efficient solution while respecting a certain tolerance level [51]. However, the Runge–Kutta method does not estimate error for each time step, so alternative procedures have been used to compute it [7,52]. It is a common practice, especially at a training level, to make extrapolations in order to infer the best performance for a mathematical function solved with numerical algorithms. The procedure is based on two or more determinations calculated with different step intervals, with the Richardson's extrapolation (Equation (19)) being one of the most used [53,54].

$$\text{Error} = \frac{\Psi_{\frac{h}{2}}(t) - \Psi_h(t)}{2^P - 1} \cong \Psi(t) - \Psi_{\frac{h}{2}}(t) \tag{19}$$

2.3. Kinetic Energy and Power

Evaluating the kinematic energy of drops allows for the estimating of the effects on sprinkler irrigation performance related to alterations of soil characteristics. Water drop diameter and velocity directly influence runoff, erosion, and infiltration processes because of the amount of energy with which the drops impact the soil surface [55]. The drops' kinetic energy ($E_{k\phi}$) [M L^2 T^{-2}] was determined according to the method introduced by Kohl et al. [56] (Equation (20)).

$$E_{k\phi} = \frac{1}{12}\pi\phi^3\rho_W V^2 \tag{20}$$

According to King and Bjorneberg [57], sprinkler kinetic energy ($E_{k\Omega}$) [M L^{-1} T^{-2}] within a domain (Ω) per unit volume of water applied can be determined from the drops' kinetic energy and total volume of a given set of drops of size n (Equation (21)).

$$E_{k\Omega} = \frac{\sum\limits_{i=1}^{n} E_{k\phi}}{\frac{\pi}{6}\sum_{i=1}^{n}\phi^3} \tag{21}$$

while E_{kd} is useful for characterizing individual drops, $E_{k\Omega}$ conveys information regarding the agronomic effects of sprinkler irrigation in a certain sprinkler-irrigated area (R) [L T^{-1}]. If $E_{k\Omega}$ is combined with precipitation falling in domain (R_Ω) [L^3 T^{-1}], kinetic power ($P_{k\Omega}$) [M L^2 T^{-3}] can be determined according to Equation (22). Furthermore, it is also common to obtain specific power (δ_p) [M T^{-3}] as the ratio of sprinkler kinetic energy and sprinkler irrigated area (Equation (23)). Switching from energy to power is important in the context of sprinkler irrigation, since irrigation time (per irrigation event, per season, . . . , among others) is an important management variable. Once the power is obtained, multiplying it times a certain irrigation duration will result in the kinetic energy of a given irrigation event or a set of irrigation events.

$$P_{k\Omega} = E_{k\Omega} R_\Omega \tag{22}$$

$$\delta_p = E_{k\Omega} R \tag{23}$$

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2.4. Irrigation Performance Indices

Field assessment of sprinkler irrigation performance usually follows a procedure adopted by Christiansen [58] to compute irrigation uniformity (CU) [L L^{-1}]. In addition, the distribution uniformity (DU) [L L^{-1}] index, proposed by Merriam and Keller [8], is also widely used. Naturally, both indicators complement each other; while the first one allows one to identify how the applied water is used, the second one provides information on how uniformly this water volume is distributed in the plot. CU and DU are written as Equations (24) and (25), respectively.

$$CU = 1 - \frac{1}{n\overline{x}}\sum_{i=1}^{n}(x - \overline{x}) \tag{24}$$

$$DU = \frac{\text{average depth applied in the lowest one quarter}}{\text{average depth of irrigation water applied}} \tag{25}$$

where x_i [L] is the irrigation water depth received in an individual pluviometer, $\overline{x}$ [L] is the average irrigation water depth received in pluviometers, and n is the number of pluviometers evenly distributed in an irrigated plot. The Christiansen [58] coefficient was also applied to kinetic energy in sprinkler spacing ($CU_{K\phi}$) [F L T^{-1} F^{-1} L^{-1} T]. In standard irrigation evaluation procedures, sprinkler spacing is divided into a matrix of rectangular domains with a catch can network located inside the sprinkler configuration. These collectors are used to estimate the precipitation rate at each domain. In this work, the sprinkler spacing was divided into several cells (Nc) wherein the area is known (A_i) [L^2], then such an indicator is estimated for a particular solid-set sprinkler arrangement conforming to a total area of evaluation (A) [L^2]. As a consequence, $CU_{K\phi}$ can be expressed as Equation (26). Analyzing the kinetic power within the sprinkler spacing allows for the production of power maps. Locating the areas within the sprinkler spacing with high or low kinetic power has relevant agronomic and irrigation management implications from a design point of view.

$$CU_{K\varnothing} = 1 - \frac{1}{N_c E_{k\varnothing} A} \sum_{i=1}^{N_c} \left(\left| E_{k\varnothing_i} A_i - \overline{E}_{k\varnothing} \overline{A} \right| \right) \quad (26)$$

3. Results

The fundamentals for sprinkler irrigation design have been provided in Equations (1)–(26). Now then, from a learning engineering perspective as it relates to sprinkler irrigation design, an Excel® spreadsheet [34] named «Sprinkler irrigation tool» has been developed for use as a didactic tool in order to complement students' theoretical knowledge and that acquired during field practice. Figure 2 shows an overall view of the sheets previously described (Radial pattern, Frequency, Runge–Kutta pairs, Kinetic energy and power, Performance indicators, Toolbox, and Graphs). These categories comprise columns of different colors: blue, green, orange, and white; the data should be input in this order so as to obtain correct information output.

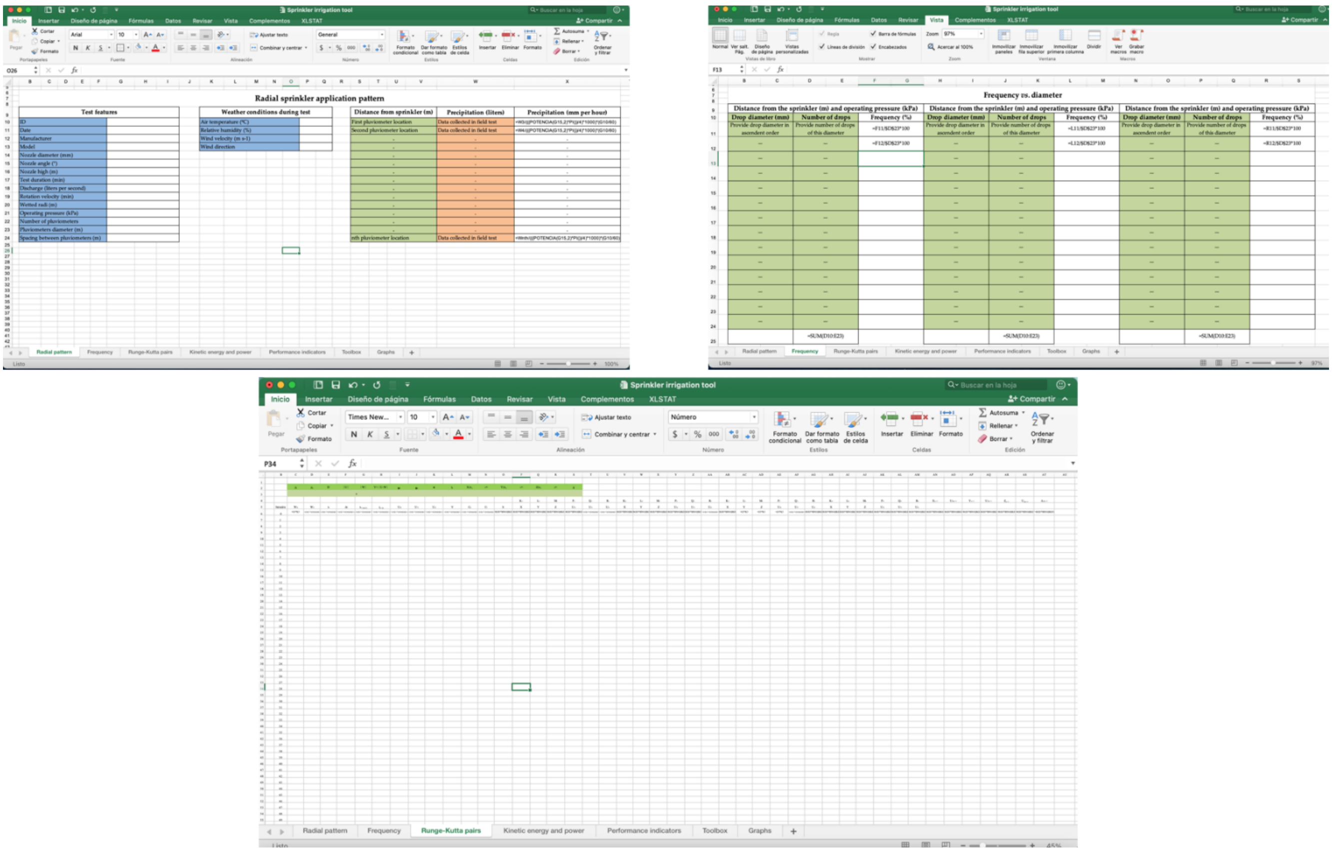

Figure 2. Overview of sprinkler irrigation tool in 2018 Microsoft© Excel® spreadsheet software.

(1) The blue columns provide descriptive information that serves as a guide for students; numerical values should be placed in the respective row, paying attention to the units specified in each case. (2) In green columns, it is necessary to enter numerical values of those variables indicated. (3) The orange columns integrate data results from the experimental readings; for example, in the case of radial pattern assessment, it is necessary to declare the distance between all the pluviometers from the sprinkler until they are covered completely during an irrigation event. Finally, (4) the white columns enable one to assess key arguments of any given sprinkler irrigation analysis included in this spreadsheet; thus, every row shows an implicit equation that supports use of the Excel® platform.

3.1. Sprinkler Irrigation Tool: Radial Patterns and Drop Diameter Frequency

Bautista-Capetillo et al. [59], at indoor laboratory facilities, carried out experimental assessments for an irrigation sprinkler using several characterization techniques. This work produced a data set of water drops (www.eead.csic.es/drops, accessed on 5 September 2022) for a VYR35 impact sprinkler manufactured by VYRSA equipped with a single nozzle (4.8 mm diameter and 26° inclination). Experiments were performed with 0.5 m nozzle elevation and three operating pressures (200 kPa, 300 kPa, and 400 kPa). Aiming to obtain the sprinkler precipitation rate, cylindrical pluviometers (0.16 m diameter) were placed at 0.60 m intervals up to a distance of 18 m and installed along the sprinkler radius. Water drop characterization was obtained at 3, 6, 9 and 12 m from the sprinkler. Their findings have been consulted as a reference to exemplify the outputs of this computational tool; in this sense, Tables 1 and 2 were developed for summarizing water drop characteristics listed in the research work of Bautista-Capetillo et al. [59].

Table 1. Average precipitation rate (L s^{-1}) at different distances from the irrigation sprinkler (obtained from Bautista-Capetillo et al. [59]).

		Precipitation Rate (L s^{-1})									
Pluviometer		1	2	3	4	5	6	7	8	9	10
Distance (m)		0.6	1.2	1.8	2.4	3.0	3.6	4.2	4.8	5.4	6.0
Operating pressure (kPa)	200	90.0	70.0	46.0	35.0	29.0	28.0	27.0	27.0	26.0	24.0
	300	100.0	80.0	50.0	39.0	32.0	30.0	31.0	31.0	32.0	32.0
	400	120.0	100.0	61.0	45.0	38.0	36.0	34.0	35.0	36.0	37.0
		Precipitation rate (L s^{-1})									
Pluviometer		11	12	13	14	15	16	17	18	19	20
Distance (m)		6.6	7.2	7.8	8.4	9.0	9.6	10.2	10.8	11.4	12.0
Operating pressure (kPa)	200	22.0	21.0	21.0	25.0	33.0	40.0	50.0	54.0	62.0	63.0
	300	31.0	32.0	34.0	38.0	41.0	44.0	48.0	49.0	51.0	50.0
	400	38.0	40.0	44.0	47.0	49.0	51.0	55.0	55.0	55.0	53.0
		Precipitation rate (L s^{-1})									
Pluviometer		21	22	23	24	25	26	27	28	29	30
Distance (m)		12.6	13.2	13.8	14.4	15.0	15.6	16.2	16.8	17.4	18.0
Operating pressure (kPa)	200	59.0	46.0	19.0	2.0	0.0	0.0	0.0	0.0	0.0	0.0
	300	47.0	43.0	36.0	27.0	17.0	6.0	0.0	0.0	0.0	0.0
	400	50.0	48.0	44.0	39.0	32.0	25.0	11.0	2.0	0.0	0.0

Notes: Test durations of 60, 58, and 61 min for operating pressures at 200, 300, and 400 kPa, respectively.

The sprinkler irrigation tool allows the user to manually insert a data set collected in field conditions, which are necessary to compute every parameter previously discussed. The first criterion concerns the determination of the radial sprinkler application pattern as outlined in Table 1. Once the information is entered, outputs can be displayed in tabular or graphical formats, but to avoid redundant information, either one or the other has been chosen in this paper with the intention of illustrating both of them clearly. Figure 3 shows the radial sprinkler application pattern (mm h^{-1}) derived from the precipitation rate accounting for each test duration and operating pressure combination as described in Table 1. This information is useful for students looking to compare radial application patterns for a specific experimental sprinkler setup operating at different pressures. The shape of the radial curves, maximum irrigation distance against pressure, precipitation rate variability along irrigation distance, and maximum and minimum local values of the precipitation rate are some of the magnitudes that can be analyzed, giving an idea of the water drop distribution for each particular impact sprinkler in different experimental conditions.

Table 2. Water drop diameter and velocity characterization for combinations of operating pressure and distance from the sprinkler.

Operating Pressures (kPa)	Variable	Distance from Irrigation Sprinkler (m)			
		3	6	9	12
200	Diameter (mm) Velocity (m s^{-1})	0.86 2.72	1.04 3.06	1.50 4.19	3.08 6.06
300	Diameter (mm) Velocity (m s^{-1})	0.81 2.45	1.03 2.92	1.22 3.82	2.06 5.13
400	Diameter (mm) Velocity (m s^{-1})	0.86 2.43	0.96 2.96	1.19 3.72	1.45 4.42

Notes: Water drop parameters were obtained from the research work of Bautista-Capetillo et al. [59] using the low-speed photographic method from Salvador et al. [60]. Drop diameter and velocity correspond to the arithmetic mean values of the data set.

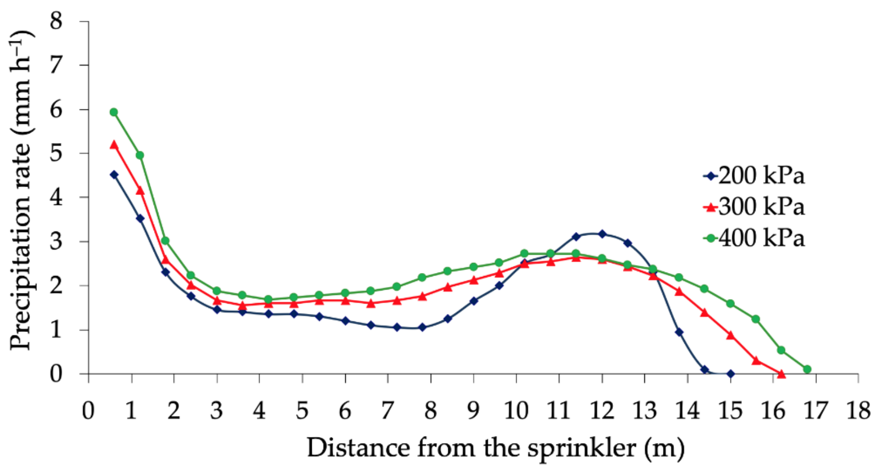

Figure 3. Radial sprinkler application patterns at different operating pressures.

Drops landing at a certain distance cover a wide range of diameters. The range becomes wider with the distance from the sprinkler. In order to illustrate the significance of drop diameter distributed in classes along sprinkler influence radii, the following graphs are useful: spreadsheet-plotted histograms, curves of cumulative frequency, and the cumulative volume for different combinations of operating pressures and distance from the sprinkler. The sprinkler irrigation tool depicts one line for each observation distance under analysis. Figure 4 shows the distribution graphs for a set of drops captured at 3, 6, 9, and 12 m from the sprinkler when it is operating at 200 kPa. Visual information is useful for understanding the relevance of small drops (<2 mm), particularly at large distances from the sprinkler; the frequency of classes and their volumetric contribution can also be studied, e.g., a low number of large drops (>3 mm) represents a quite large volume at 12 m.

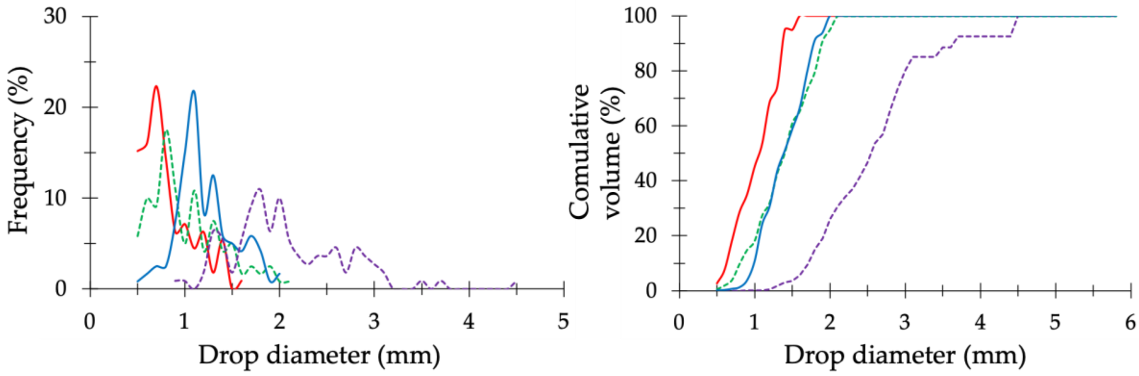

Figure 4. Histogram of drop diameter and curves of cumulative volume at 3 m (red continuous line), 6 m (green dash line), 9 m (blue continuous line), and 12 m (purple dash line) from the sprinkler at 200 kPa.

3.2. Sprinkler Irrigation Tool: Drop Motion Simulation

Ballistic theory is used to determine the trajectory of each drop diameter subjected to the initial conditions described in Figure 1. The drop movement components are expressed by Equations (1)–(3) and can be solved through the fourth-order Runge–Kutta numerical integration technique, taking into account the least numerical stability and the error control as optimization procedure criteria (Equation (18)). In order to understand a physical phenomenon based on mathematical principles without disrupting the solution method rules, the sprinkler irrigation tool described in this work allows the students to be trained in ballistic simulation of sprinkler irrigation under scenarios that include sprinkler irrigation system operating factors (hardware features, hydraulic working conditions, and environmental parameters), an aerodynamic drag model, and a numerical performance from time step selection. Figure 5 shows the trajectory of a single water drop for a specific diameter of 4 mm for unlike time step values (0.025, 0.050, 0.100, and 0.200 s) by applying the Okamura [45] drag coefficient model for the VYR35 impact sprinkler with an operating pressure of 200 kPa and an elevation of 1.75 m from the soil.

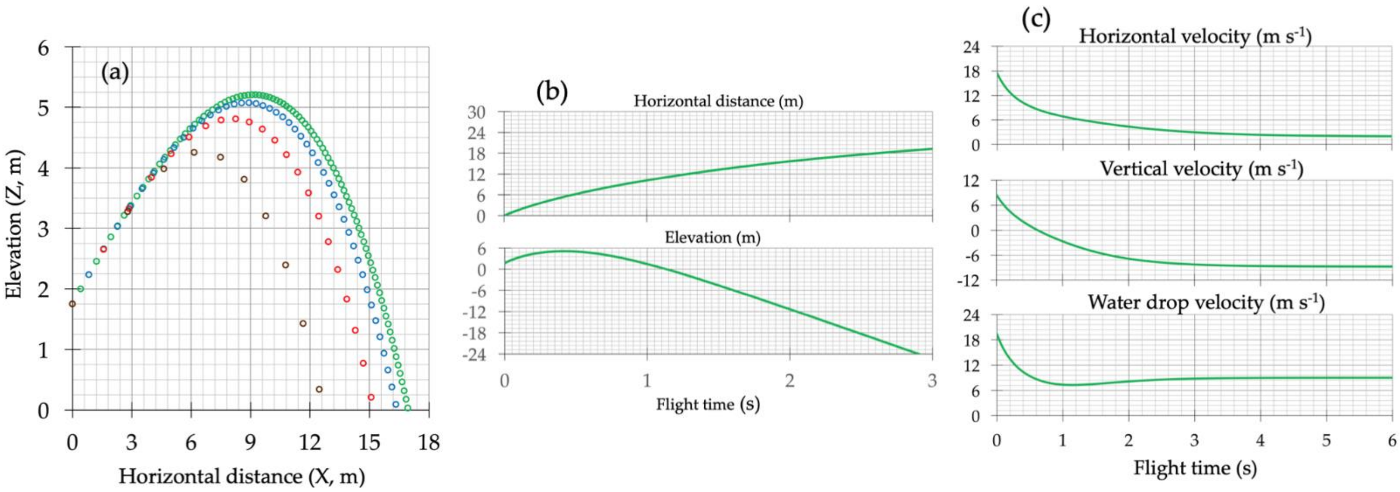

Figure 5. Ballistic movement simulation with the Okamura [45] drag coefficient method for a 4 mm water drop within 0.200 s (brown circle), 0.100 s (red circle), 0.050 s (blue circle), and 0.025 s (green circle and line) as time step values. (**a**) represents the X–Z drops trajectory, (**b**) flight time versus X and Z travel distances, and (**c**) flight time versus X, Z, and water drop velocities.

As a formative perspective, students can observe, with a graphical model, how essential it is to choose a suitable time step size for the numerical solution, while being able to evaluate differences in step increments and reliably understand guidelines related to this aspect found within technical literature [36,60]. In this sense, at a certain horizontal distance considering the ground level and the vertical distance, maximum elevations from the ground level can be compared to each other (Figure 5a); the standard deviations in traveling distances for a 4 mm diameter water drop as a time step is switching are, in the first case, 0.61 m (4%), 1.85 m (11%), and 4.44 m (26%); and in the second one, 0.13 m (3%), 0.40 m (8%), and 0.95 m (18%), achieved by changing from 0.025 s to 0.05 s, 0.10 s, and 0.20 s respectively.

Following the same reasoning, students also put into practice their previously acquired knowledge related to particle kinematics, in particular the projectile motion in a parabolic trajectory. In this regard, the spreadsheet itself displays trends over time for trajectory (Figure 5b) and velocity (Figure 5c) for both horizontal and vertical components, as well as the total velocity of the water drop (Figure 5c). Such aspects are relevant in a pedagogical framework with regards to reinforcing the concepts related to particle movement, as position, displacement, distance travelled, trajectory, relative velocity, terminal velocity, and particle velocity are useful when sprinkler irrigation is simulated [39,61,62].

Now then, strictly speaking of academic training that an irrigation engineering professional should have in terms of sprinkler irrigation, the spreadsheet allows for the simulation of water drop movement in two and three dimensions for an isolated impact sprinkler, according to a set of user-defined parameters related to hardware and conditions of hydraulic operations and wind. In addition, this version of the tool includes four models for determining the drag coefficient. Figure 6 shows 2D simulations following Park et al. [46] (Figure 6a), Li and Kawano [47] (Figure 6b), Hills and Gu [48] (Figure 6c) and Okamura [45] (Figure 6d) methodologies to compute the drag coefficient. Drops were simulated for the same VYR35 impact sprinkler but when considering a height of 1.20 m and a working pressure of 300 kPa. A 0.10 s time step was selected for solving the ballistic model with the fourth-order Runge–Kutta method. Drops' trajectories were simulated for drop diameters of 0.5 mm, 1.0 mm, 2.0 mm, and 3.0 mm marked with green, blue, red, and brown colors in each subfigure, respectively. Depending on the drop diameter to be thrown out, the drop trajectory (distance from the sprinkler-x and drop height-z) was obtained for each time interval. Once the simulation is created, the graphical information allows students to draw comparisons about the movement of water drops with the same diameter but using different models to compute the drag coefficient.

For example, students can discriminate a travel distance for each water drop in terms of its size to settle arguments such as the following: the distance reached by water drops of 1.0 mm and 3.0 mm in diameter was larger for the Hills and Gu [48] model than those proposed by other authors. However, in the particular case of 3.0 mm diameter drops, the landing distance difference is more evident than for 1.0 mm drops. In general, the Park et al. [46] model obtained shorter landing distances for all water drop diameters. On the other hand, the Li and Kawano [47] and Okamura [45] models reached similar water drop travel distances regardless of what claims either asserts in order to determine the drag coefficient. On the basis of information already dealt with, students may shape their mental pictures concerning sprinkler irrigation uniformity for a specific solid-set framework. In other words, the geometric arrangement type and certain spacings between sprinklers, along with the difference between the landing distance for all drops emitted by an isolated sprinkler device, involves, in real terms, the performance of sprinkler irrigation when referring to uniformity. Under indoor conditions, the combination of these factors determines the drops' degree of overlap, which is measured later as irrigation depth in an irrigated area.

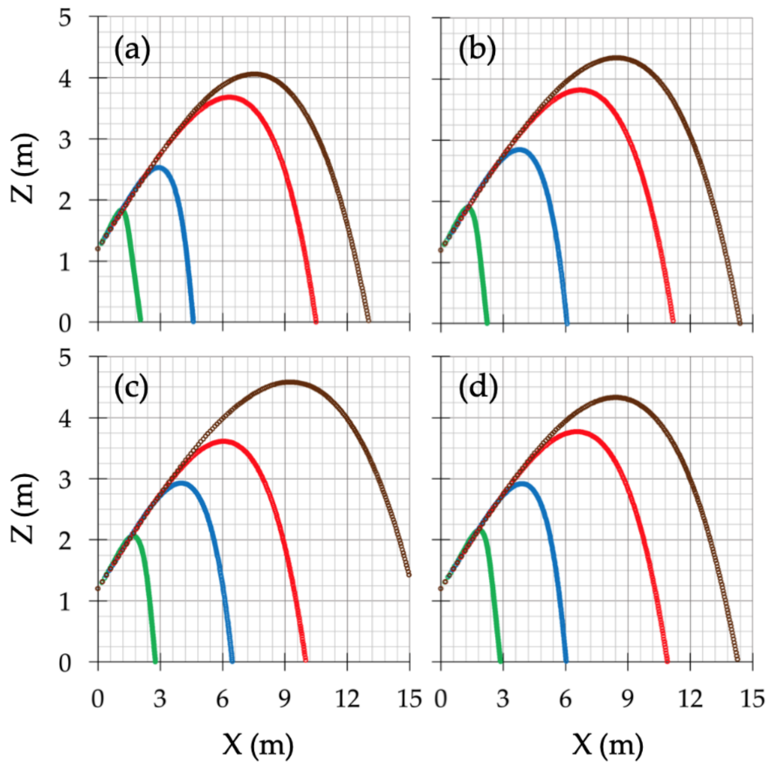

Figure 6. Two-dimensional water drop movement simulation for 0.5 mm (green), 1.0 mm (blue), 2.0 mm (red), and 3.0 mm (brown) diameters with 1.20 m sprinkler elevation, 300 kPa operating pressure, and no-wind conditions. Using the methodology of drag model of (**a**) Park et al. [46], (**b**) Li and Kawano [47], (**c**) Hills and Gu [48], and (**d**) Okamura [45].

In addition to the visual information shown in Figure 6, the spreadsheet tool also provides tabular data on the error that results from assuming a specific time step value, as well as time of flight, travel distance of the sprinkler drops relative to a datum (soil surface or crop canopy), and terminal velocity, which is particularly useful when computing drops' kinetic energy or specific power. Table 3 summarizes the corresponding output for particular conditions, which leads to Figure 6a–d. In this way, it is feasible to discern numerically the differences between methods for computing the drag coefficient in estimation of those referred variables for a specific water drop diameter. Even more, qualitative judgments that students can make from Figure 6 are complemented on a quantitative basis by the findings listed in Table 3. A comparative analysis between the Hills and Gu [48] model and other models used to determine drag coefficient would result in assertions such as the following: water drops of 0.5, 1.0, and 3.0 mm in diameter simulated with the Hills and Gu [48] model travel longer distances than those obtained with models proposed by Park et al. [46] and Li and Kawano [47]; in general, these differences are 35%, 41%, and 22% in the first case, and 24%, 6%, and 11% in the second one. It is important to note that this same trend occurs in the Okamura [45] approach for 1.0 mm and 3.0 mm sizes (7% and 11% in each case). However, the opposite is true for water drops of 0.5 mm diameter, i.e., they reach 3% less distance when obtained with the Hill and Gu [48] methodology compared with the Okamura [45] one. In contrast, a significant difference is shown in simulating 2.0 mm diameter water drops with relative distances; these drop sizes are 5%, 11%, and 8% smaller using the Hills and Gu [48] model compared with the Okamura [45], Park et al. [46] and Li and Kawano [47] models, respectively.

Table 3. Time of flight, travel distance, error, and terminal velocity for each simulation drag coefficient model used for the sprinkler features and operating pressure under no-wind conditions. This was adapted from the originals for presentation purposes within this paper.

Drag Coefficient Model	Drop Diameter (mm)															
	Time of Flight (s)				Travel Distance (m)				Error (m)				Terminal Velocity (ms^{-1})			
	0.5	1.0	2.0	3.0	0.5	1.0	2.0	3.0	0.5	1.0	2.0	3.0	0.5	1.0	2.0	3.0
Okamura [45]	2.74	1.93	1.92	2.02	2.87	6.03	10.90	14.29	0.24	0.10	0.09	0.11	2.21	4.01	6.45	7.82
Park et al. [46]	3.37	1.89	1.92	1.92	2.05	4.59	10.49	13.02	0.38	0.34	0.13	0.10	1.97	3.54	6.34	7.74
Li and Kawano [47]	2.48	1.82	1.93	2.02	2.23	6.07	11.19	14.39	0.12	0.12	0.08	0.07	2.18	4.31	6.57	7.87
Hills and Gu [48]	2.13	1.82	1.90	2.05	2.77	6.46	10.01	15.91	0.22	0.14	0.11	0.12	2.56	4.49	6.08	8.45

Concurrent to such numerical evaluations, terminal velocity is also interesting to analyze from a training point of view because of its significance to the kinetic energy with which water drops make impact on the soil surface. Therefore, comparing the theoretical magnitude of this physical variable versus those values obtained by each model to determine the aerodynamic drag coefficient included in the spreadsheet is a learning exercise derived from the data enclosed in Table 3. Nave [63] states that the terminal velocity for a water drop of 0.5 mm diameter is 3.18 m s^{-1}; meanwhile, for 1.0 mm it is 4.50 m s^{-1}, for 2.0 mm it is 6.37 m s^{-1}, and for 3.0 mm it is 7.80 m s^{-1}. Regarding this matter, the resulting values for all four reference alternatives are significantly lower in drops of water with a diameter of 0.5 mm, but as diameter increases, the differences between Nave [63] and those calculated by Okamura [45], Park et al. [46], Li and Kawano [47] and Hills and Gu [48] decrease, with an increase in the terminal velocity for a 3.0 mm drop diameter. If the average and range for the different options are taken into account, the percentage differences are $\gtrsim$2% (0.8% to +8%), 45% (24% to 72%), 10% (0.2% to 27%) and 0.2% (5% to +3%), respectively. An analogous procedure can be followed in relation to drops' flight time, such that values obtained with the sprinkler irrigation tool can be compared with those reported in the literature for similar experimental conditions, e.g., those reported by Thompson et al. [64] and Lorenzini [65], and show the contrasts between them.

Beyond the differences in flight time, it is noteworthy that the findings of Thompson et al. [64] indicate that the elapsed time when small water droplets (<1.0 mm) leave the nozzle and reach a datum is greater when their diameter is smaller, and from this threshold, the flight time increases as drop size increases, while the study by Lorenzini [65] indicates that traveling time always tends to increase as drop diameter increases. In light of the above, the evidence shown in Table 3 corresponds, in all cases, to that reported by Thompson et al. [64]. Indeed, water drops with a diameter less than 1.0 mm decrease their terminal velocity as the diameter approaches that value, and thereafter terminal velocity begins to increase as a function of increasing diameter. Based on an analytical procedure of linear regression, it is possible to define both positive and negative trend patterns and thus draw inferences about inherent issues for each case while showing relative explanations between different models. Accordingly, linear regression test outcomes return values of (−1.62, 0.05) mm s^{-1} (Okamura [45]), (−2.96, 0.02) mm s^{-1} (Park et al. [46]), (−1.32, 0.10) mm s^{-1} (Li and Kawano [47]), (−0.62, 0.12) mm s^{-1} (Hills and Gu [48]), and (−1.82, 0.07) mm s^{-1} (Thompson et al. [64]). All refer to the negative slope in the first case, and to the positive slope in the second drop velocity, which is computed from the respective tabular data.

In sprinkler irrigation studies, the wind velocity and the wind direction play a major role in water application uniformity on a plot scale. In this sense, in a 3D scenario, the spreadsheet helps to evaluate the potential water drop trajectory considering a wind vector proposed by the users. Figure 7 shows several simulations of the VYR35 impact sprinkler with an elevation of 1.50 m using different combinations of wind vector and drop diameter. The drag coefficient calculated according to Okamura [45] was the same for all of them. In order to compare the drop movement at the X–Z plane, Figure 7a represented simulations for a 2.0 mm water drop traveling in air under 2.1 m s^{-1} of wind velocity for wind directions of 60°, 180°, 225°, 270°, and under no-wind conditions. It is evident that there is an effect of wind on water drop trajectory: as wind maintains a greater opposition to the direction in which the water drop travels, a shorter distance is reached, and vice versa. In other words, when wind direction is totally opposite to drop direction (180°), its distance to a datum is 7.2 m, while for those cases in which wind direction is 60°, 225°, and 270°, drop distance reaches 13.3 m, 8.4 m, and 11.2 m, respectively.

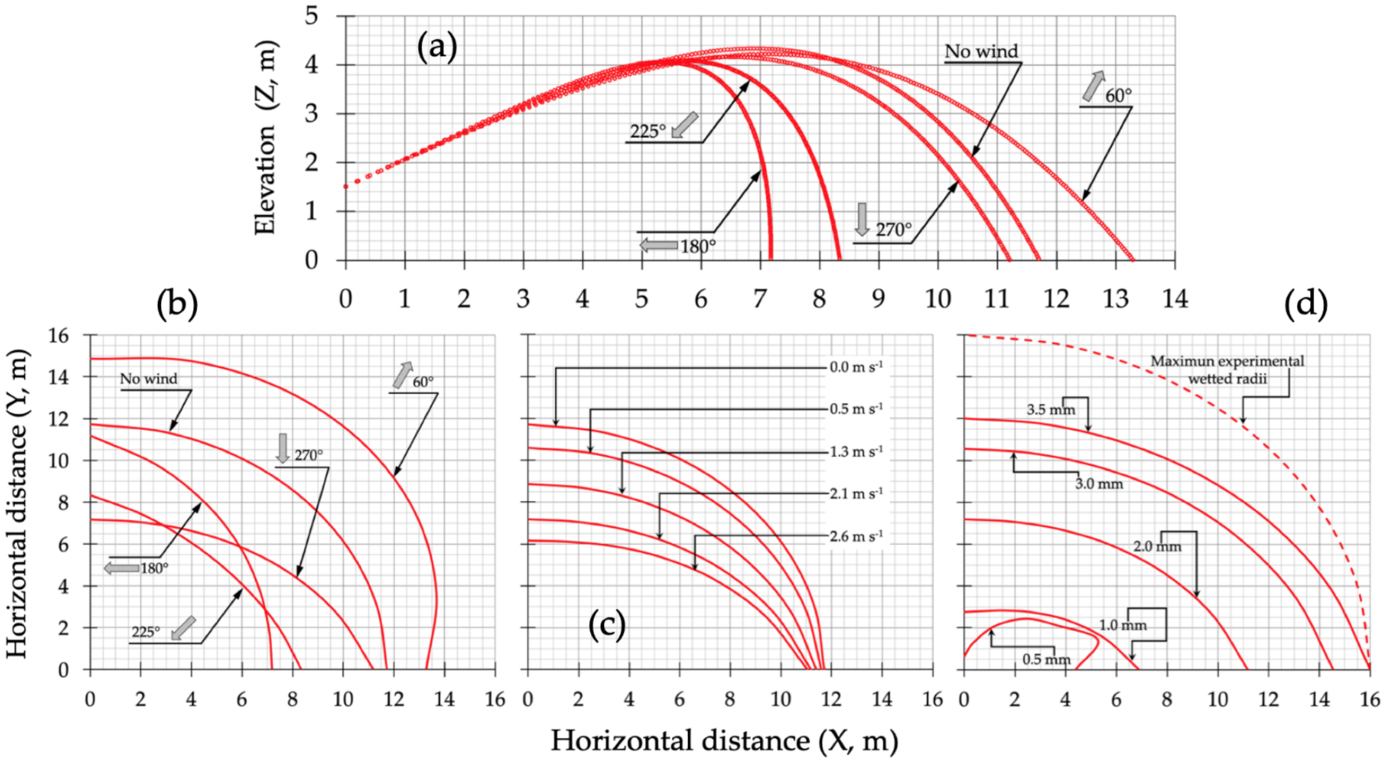

Figure 7. Three-dimensional water drop movement simulation under different velocities and directions of wind. This shows results using a 1.50 m sprinkler elevation, 200 kPa operating pressure, and Okamura [45] as the drag coefficient model. (**a**,**b**) are the drop elevation and the drop movement in Y axis for different wind conditions in function of the distance from the sprinkler, respectively, meanwhile (**c**) shows the drops landing from the sprinkler in both X and Y axis, finally, (**d**) shows the wetted radii in X and Y axis in function of the drop diameter.

Clearly, such distances are related to wind velocity magnitude that either favors or counteracts drop velocity due to hydraulic operating pressure. From the previous results, a student can draw comparisons between different simulations: (1) when wind speed is parallel to the X-axis and opposite to drop motion (180° direction), drop distance reached is the smallest with respect to the no-wind condition, in this particular case, there is 1.6 times less distance to the datum; (2) for a case where the wind speed is also opposed to drop motion, but now 50% of its modulus is parallel and remains 50% perpendicular to the X-axis (225° direction), the distance traveled difference is 1.4 times less; (3) if the wind direction is perpendicular to the X-axis (270° direction), then the difference between both distances is only 0.6 m (1.05 times); (4) finally, when wind acts to the advantage of drop movement, the distance that it reaches increases; thus, for simulation conditions when the wind speed modulus is 25% and 75% parallel and perpendicular to the X-axis (60° direction), the drop travels until reaching a datum 1.1 times further in comparison to the no-wind condition drop motion.

From the point of view of sprinkler irrigation, the analysis of Figure 7a becomes more relevant in the X–Y plane, based on the assumption that such a surface represents a certain plot where water is distributed by this irrigation method. Figure 7b illustrates similar simulations, but now horizontally. Accepting that the Y-axis is perpendicular to the initial velocity vector, some complementary findings were highlighted. The first one, being general in nature, exists to note that water drop trajectory is directly influenced by wind direction, and except in cases where it divides in two equal portions any of the four quadrants of the Cartesian coordinate system, or wind is absent, in other instances, the distance reached by the drops is different in the X and Y axes. The other aspects for specific evaluation include, for example, for a wind direction opposite to drop movement, its trajectory is the inverse when it is parallel and perpendicular to the X-axis; this fact can be verified with the distance that drops reach on the Y-axis (11.2 m and 7.2 m for 180° and 270°, respectively); magnitudes that could be inferred from Figure 7a. However, for many students, this is complicated to understand until they corroborate it through an exercise such as that indicated. In addition to the above-mentioned judgments, the sprinkler irrigation tool offers the possibility of estimating trajectories under conditions of specific interest. Figure 7c shows a water drop trajectory with the same diameter (2 mm) traveling at different wind speeds maintaining the same direction (270°), while Figure 7d shows the drop's trajectory for a different diameter for the same wind vector (2.1 m s^{-1} and 270°).

3.3. Sprinkler Irrigation Tool: Add-On Resources

The spreadsheet provides complementary options to estimate the energy and power of water drops impacting on the soil surface; it also allows for the determination of sprinkler irrigation performance rates. In both cases, the information is presented in tabular form, although it is possible to record it visually. Impact sprinklers for agricultural irrigation are commonly arranged at fixed spacings (rectangular or triangular). Sprinkler spacings are usually expressed by an R or T letter followed by the distances between the sprinklers (e.g., T18 m × 18 m). At a given point, the overlapping of the drops supplied by all contributing sprinklers determines the received water and the kinetic energy of the water drops. These amounts depend on the operating pressure and on the sprinkler spacing.

In order to assess the kinetic energy of water drops emitted by an isolated impact sprinkler, Table 4 shows the summary of geometrical and kinematic drop characterizations, taking into account information presented by Bautista-Capetillo et al. [59] in their low-speed photographical data set that corresponds to an operating pressure of 400 kPa (www.eead.csic.es/drops, accessed on 5 September 2022). Kinetic energy was determined for each drop and its distance from the irrigation sprinkler, then the drop diameter range, volumetric mean diameter, drop velocity range, drop velocity average, drop kinetic energy range, sprinkler kinetic energy, precipitation rate, kinetic power, and specific power were included in Table 4. Drop kinetic energy clearly increased with the distance from the sprinkler; indeed, the average values amounted to 16.87×10^{-7} J, 33.73×10^{-7} J, 96.98×10^{-7} J, and 242.28×10^{-7} J for 3 m, 6 m, 9 m, and 12 m, respectively. A similar trend follows for the $E_{k\Omega}$, $P_{k\Omega}$, and δ_p variables. It is worth noting that the values reported here are comparable to the previous findings of Kincaid [39] and DeBoer [66] for different impact sprinklers and operating conditions and those of DeBoer and Monnens [67] for a rotating spray plate sprinkler. However, it should also be pointed out that generally these data are not reliable, but the potential effects are linked to the energy with which the water drops impact the soil surface to cause soil erosion, alterations in infiltration rates, and soil surface sealing, among others.

Table 4. Geometrical and kinematical drop characterization at 3 m, 6 m, 9 m, and 12 m of distance from a sprinkler operating at 400 kPa of pressure.

Drops	**Distance from the Sprinkler (m)**			
	3	**6**	**9**	**12**
Number	114	106	102	98
ϕ_{range} (mm)	0.50–1.70	0.50–1.90	0.50–2.20	0.80–2.50
$\forall_m$	1.19	1.25	1.46	1.78
V_{range} (m s^{-1})	1.55–3.55	1.96–4.39	2.20–5.35	3.28–5.79
V_m (m s^{-1})	2.43	2.96	3.72	4.42
$E_{k\phi range}$ (J $\times 10^{-7}$)	0.62–134.53	1.03–359.08	1.77–711.99	19.37–1422.98
$E_{k\Omega}$ (JL^{-1})	3.640	5.530	8.880	12.150
P_{rate} (mm h^{-1})	1.880	1.830	2.420	2.620
$P_{k\Omega}$ (W $\times 10^{-6}$)	0.002	0.003	0.006	0.009
δ_p (W $m^{-2} \times 10^{-3}$)	1.900	2.800	6.000	8.800

ϕ is water drop diameter, $\forall_m$ is volumetric mean diameter, V and V_m are velocity and average velocity, respectively, J is Joules, L is liters, and W is watts. Values correspond to 400 kPa of operating pressure (www.eead.csic.es/drops, accessed on 5 September 2023).

A deeper understanding of the spatial and temporal distribution of kinetic energy with which water drops impact a certain surface can be achieved by plotting contour maps. Nevertheless, the sprinkler irrigation tool only provides tabular information (Table 4), so it is necessary to make recourse to other computational tools suitable for interpolating and generating such maps. The data shown in Figure 8 were made with the commercial software XLSTAT® Premium version, licensed by Addinsoft 2022.5.1 1394. Kinetic energy under no-wind conditions for rectangular and triangular sprinkler spacings are discussed for spacings R18 $\times$ 18, R15 $\times$ 15, T18 $\times$ 18, and T15 $\times$ 15. Maps were produced for combinations of each spacing and 400 kPa of hydraulic working pressure for an irrigation time of 1 h. The contrast of kinetic energy per unit of time on each surface is visible in each subfigure. Its distribution depends, to a large extent, on the spacing between sprinklers and arrangement choice. In an R18 $\times$ 18 configuration, the kinetic energy attained maximum values at the central part of the framework (around 6000 J h^{-1}); such value gradually decreases, reaching 1000 J h^{-1}, as it is moves closer to the framing edges. In relation to the R15 $\times$ 15 arrangement, the kinetic energy varies from the sprinklers towards the central portion of surface; its value is close to 5000 J h^{-1} around the sprinklers and then decreases to 1000 J h^{-1} before increasing to 4700 J h^{-1} and again decreasing to 3000 J h^{-1}. As for the triangular arrangements, in T18 $\times$ 18 most of the surface receives, in the course of one hour, a kinetic energy approaching 3800 J, although in some areas values oscillate between 1200 and 1600 J, and in certain small circular portions, the value reaches 4680 J. For T15X15, kinetic energy increases from the base to the upper vertex and height becomes an axis of symmetry; these values are between 3000 J h^{-1} and 6400 J h^{-1}.

For the measurement of sprinkler irrigation performance is one of major indicators used in order to quantify water use efficiency in agriculture, the sprinkler irrigation tool provides performance indicators, as described in Equations (23)–(25). Table 5 includes percental values of CU and DU for 15 $\times$ 15 and 18 $\times$ 18 rectangular and triangular frameworks under 200 kPa, 300 kPa, and 400 kPa operating pressures. In a certain sense, these values reflect the methodological procedures already reviewed, and should therefore be used to define the best possible combination of field configuration, irrigation system sizing and hydraulic operating conditions in order to achieve efficient water use with less damage to the soil surface.

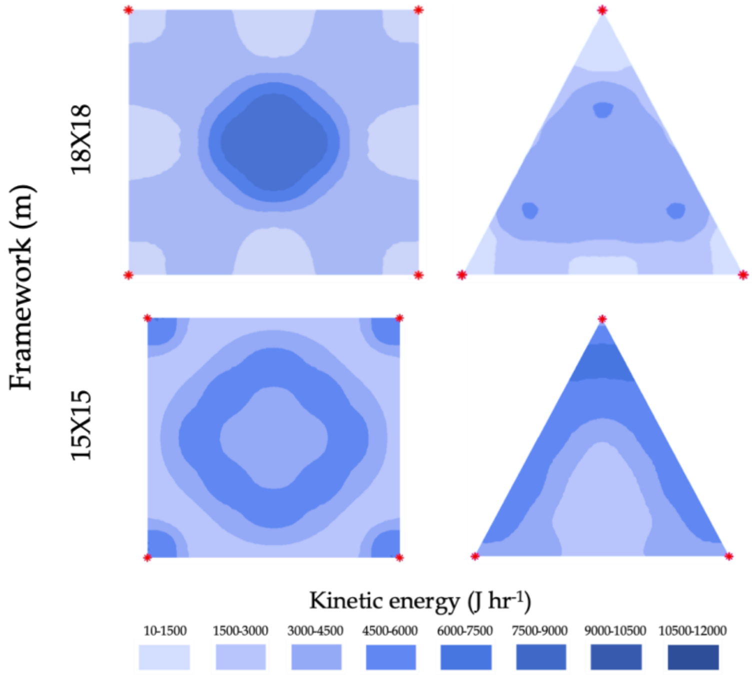

Figure 8. Kinetic energy contour maps for rectangular and triangular arrangements for a 1 h irrigation time.

Table 5. Irrigation and kinetic energy performance indicators for rectangular and triangular arrangements.

Framework (m × m)	Operating Pressure (kPa)											
	200	300	400	200	300	400	200	300	400	200	300	400
	CU (%)			DU (%)			$CU_{K\Phi}$ (%)			$DU_{K\Phi}$ (%)		
R15 × 15	83.4	79.7	66.1	88.6	77.4	67.5	57.2	53.4	27.8	44.1	38.1	10.8
R18 × 18	68.2	75.9	76.3	67.4	77.9	81.2	22.9	22.1	45.6	20.3	40.3	31.9
T15 × 15	63.8	78.3	84.5	64.5	73.9	85.1	60.2	62.1	52.8	19.1	64.4	47.2
T18 × 18	66.0	80.3	87.3	67.5	82.0	87.9	47.7	73.3	41.4	37.0	21.2	22.9

Based on the conditions depicted in Figure 8, some reasoning is addressed, as derived from the data displayed in Table 5, which tends to provide evidence to assist with the selection of an alternative that best achieves the two criteria highlighted before. For an irrigation system with impact sprinklers operating at 400 kPa, a triangular framework of 18 m × 18 m presented the best conditions of uniformity in terms of water application with 87.3% and 87.9% for CU and DU, respectively. However, the triangular arrangement of T15 × 15 obtained very similar percentages for both indicators (84.5% for CU and 85.1% for DU). Before making any decision on whether to use a sprinkler framework, it is essential to evaluate the drops' kinetic energy on the soil surface. Although uniformity indices are a useful key for choosing the best irrigation performance, they should be considered with care with respect to evaluating kinetic energy because, in this respect, it is not adequate to distribute the drops as evenly as possible. In fact, it is more important to minimize the potential degree of affectation. Hence, the CU and DU percentages for T15 × 15 are comparatively higher than those for T18 × 18 (52.8% vs. 41.4% and 47.2% vs. 22.9%, respectively). Also, the amount of kinetic energy received by the first sprinkler frame is higher than that of any other.

4. Discussion

The demands of a contemporary ever-changing world raise a challenge to train socially pertinent professionals under the precepts of excellence and quality, and in the meantime to constitute them under guiding axes to forge morally ethical, technically competent, and environmentally conscious citizens, in order to contribute to solutions for pressing social, environmental, economic, and cultural problems in present-day societies. Deeming this to be of the utmost importance, it is imperative to reevaluate teaching–learning processes with a view towards including meaningful actions in curricula that, together with changes in student behavior, could allow them to engage in pathways of significant learning to match theory with practice. Hence, this could allow them to achieve real appropriation of knowledge within a frame of autonomy and innovation, leaving behind the traditional role in which they just received information through a simple transmissive teaching process.

The optional spectrum is wide and varies from one methodological criterion to another. A specific call for using computer spreadsheets as didactic tools for education first appeared more than 40 years ago; since then, countless documented expressions attest to their potential to contribute to a constructivist learning model in teaching mathematics, physics, chemistry, and biology; indeed, virtually any branch of science or engineering discipline field makes recourse to them [20,68–75]. In an effort to contribute to formal education in irrigation engineering, particularly in sprinkler irrigation systems, in a learning environment that privileges multiple perspectives or interpretations of reality, knowledge construction, and activities based on enriched experiences in context [76], this work evidences the articulation of theoretical and experimental learning through an Excel® spreadsheet which includes methods and techniques that support an efficient engineering design of sprinkler irrigation systems equipped with stationary devices. The sprinkler irrigation tool provides outcomes in tabular (Tables 3–5) and graphical formats (Figures 3–7) with the aim of offering students with alternatives that will allow them to acquire knowledge of sprinkler irrigation design. However, the spreadsheet only generates numerical values as far as the evaluation of the kinetic energy is concerned; hence, XLSTAT® software has been selected to perform an interpolation process using the ordinary Kriging method and then plot contour maps, as illustrated in Figure 8.

Sprinkler irrigation efficiency depends on the morphology and kinematics of the water drops emitted by the hydraulic system traveling in the air until they reach a soil surface [60,77]. On the other hand, the size and movement of the drops are influenced by their initial velocity, gravity, wind speed, and aerodynamic resistance; these can be known via advanced experimental techniques, then be applied to irrigation simulation models to identify their potential effects on agricultural land or to optimize the uniformity and efficiency of water use [78–80]. Due to the relevance linked to a detailed characterization of water drops, a number of techniques have been developed to support this task [60,81–92]. Ballistic theory is a widely used method in modeling sprinkler irrigation [35,36,44,93] based on the supposition that drops are spherical in shape [35–37,93,94], which causes differences between the experimental data and simulated results, and thus calls for the application of procedures to correct or eliminate such questionable values [95].

Geometric and kinematic drop characteristics are determinant traits for preserving soil [96,97], increasing irrigation uniformity, upgrading water use efficiency, and simulating sprinkler irrigation behavior [37,59,98,99]. In view of this, the sprinkler irrigation tool has been used in a waterworks design subject within the undergraduate student engineering curriculum for those pursuing the science and technology of water bachelor's program at the Universidad Autónoma de Zacatecas «Francisco García Salinas». The computing work complements traditional lectures and experimental tasks, aiding objective readings of phenomena by means of a learning process that confronts theoretical knowledge and practice in different scenarios of sprinkler irrigation system design realities. This interpretation corresponds to those who, in one way or another, participated in the development of the informatic tool, so that an effective assessment of its implementation as a pedagogical resource can still be made.

For its ability to provide reliable information on technical considerations to be carried out discerns its effectiveness as a decision support tool for deciding on an optimal option for solid-set sprinkler irrigation systems. This evidence indicates an existing correspondence with previous research, which was already alluded to in advance. However, the sprinkler irrigation tool was mainly developed as an option for people in training; in this sense, students who use it may still have doubts with regards to the system of variables included in this proposal. The most obvious question is that of the relationship between kinetic power and specific power, using a ratio of 1 L m^{-2} equal to 1 mm, first to calculate kinetic power in watts and then using that same equivalence to determine the specific power in watts m^{-2}, brings serious difficulties in understanding; clearly this is an aspect of formative deficiency that must be solved in the the first years of undergraduate studies when taking basics subjects in science and engineering. In spite of this, such academic weakness arises as a possibility for improving the computer sprinkler irrigation tool and is therefore an option for further research for enhancing the Excel® spreadsheet.

Author Contributions: Conceptualization, C.B.-C., J.G.-T. and H.E.J.-F.; methodology, C.B.-C., C.O.R.R. and H.P.-M.; computer tool development, C.B.-C., M.G.-B. and C.O.R.R.; computer tool validation, J.G.-T. and H.E.J.-F.; formal analysis, C.B.-C., C.O.R.R. and H.P.-M.; writing—original draft preparation, C.B.-C., M.G.-B. and C.O.R.R.; writing—review and editing, C.O.R.R. and H.P.-M.; supervision, J.G.-T. and H.E.J.-F. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Acknowledgments: Thanks to the Consejo Zacatecano de Ciencia y Tecnología and to the Sindicato del Personal Académico de la Universidad Autónoma de Zacatecas for the financial support.

Conflicts of Interest: The authors declare no conflict of interest.

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