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Comparison of Sprinkler Droplet Size and Velocity Measurements using a Laser Precipitation Meter and Photographic Method

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Abstract. Kinetic energy of water droplets has a substantial effect on development of a soil surface seal and infiltration rate of bare soil. Methods for measuring sprinkler droplet size and velocity needed to calculate droplet kinetic energy have been developed and tested over the past 50 years, each with advantages, disadvantages, and limitations. A laser precipitation meter and photographic method were used to measure droplet size and velocity from an impact sprinkler at three pressures and one nozzle size. Significant differences in cumulative volume drop size distributions derived from the two measurement methods were found, especially at the highest operating pressure. Significant differences in droplet velocities were found between measurement methods as well. Significant differences were attributed to differences in minimum drop sizes measured; 0.5mm for the photographic method versus 0.2 mm for the laser precipitation meter. The laser precipitation meter provided smaller cumulative volume drop size distributions compared to the photographic measurement method. The laser precipitation meter tended to provide greater drop velocities which were attributed to altitude differences at experimental sites. The difference in calculated droplet kinetic energy per unit volume based on drop and size velocity data from the laser precipitation meter and the photographic method ranged from +12.5 to -28%. The laser precipitation meter generally provided a lower estimate of sprinkler kinetic energy due to the measurement of a greater proportion of smaller drop sizes. Either method can be used to obtain drop size and velocity sprinkler drops needed to calculate sprinkler kinetic energy. The laser precipitation meter requires less skill and labor to measure drop size and velocity.

Keywords. *Sprinkler irrigation, drop size, drop velocity, kinetic energy.*

Introduction

Drop size and velocity have a major influence on sprinkler irrigation system performance due the effect droplet specific power and cumulative kinetic energy has on formation of a soil surface seal and associated reduction in infiltration rate (Thompson and James, 1985; Mohammed and Kohl, 1987; King and Bjorneberg, 2012). Drop size is also an important sprinkler parameter in regards to estimating evaporation and wind drift losses (Kohl et al., 1987; Edling, 1985). Sprinkler drop size distributions have been studied on a limited basis for over 50 years. Four methods have primarily been used to measure drop sizes of agricultural sprinklers. They are:

- Paper stain method in which drops are caught on treated paper and allowed to dry (Hall, 1970; Solomon et al., 1985; Kincaid et al., 1996). The resulting stains are measured and converted to an equivalent drop diameter using a calibration equation which relates stain size to drop size.
- Flour pellet method in which drops are caught in a pan of sifted flour, the flour dried, and dried flour pellets sieved into different size categories (Kohl, 1974; Kohl and DeBoer, 1984; Chen and Wallender, 1985; Kohl and DeBoer, 1990; Li et al., 1994; DeBoer et al., 2001). A calibration equation relating dried flour pellet mass to drop size is used to convert to an equivalent drop diameter.
- Laser techniques where the shadow of a drop passing through a horizontal laser beam is projected onto a linear array of photodiodes where the width of the shadow on the photodiode array is a measure of drop size (Kohl et al., 1985; Solomon et al., 1991; Kincaid et al., 1996) or the attenuation of laser light on a single photodiode is used to infer an equivalent drop size (Montero et al., 2003; Burguete et al., 2007; King et al., 2010)
- Photographic methods that capture a scaled image of drops in flight and the physical size of a drop in the image is used to convert to an equivalent drop size (Sudheer and Panda, 2000; Salvador et al., 2009; Bautista-Capetillo et al., 2009).

In contrast to sprinkler drop size measurement, very few studies have investigated measurement of sprinkler droplet velocity. Drop size measurement methods theoretically capable of concurrent velocity measurement include laser and photography methods. With laser methods, the duration that light is attenuated on a photodiode(s) in combination with known laser beam dimensions and drop size can be used to estimate drop velocity (Solomon et al., 1991; Salles et al., 1999, King et al., 2010). With photographic methods, the distance the drop travels between frames of high speed photography or the distance that a drop travels in the frame of low speed photography can be used to estimate droplet velocity and trajectory angle (Salvador et al., 2009; Bautista-Capetillo et al., 2009). King et al. (2010) used a laser precipitation monitor (LPM) to measure drop size and velocity of moving plate sprinklers and calculate sprinkler kinetic energy. They compared drop size distributions determined using the LPM with those obtained using the flour pellet method and found that there were no significant differences when sprinklers were operated within manufacturer recommendations. They did not independently compare drop velocity measurements but compared computed sprinkler kinetic energy values with published values and found them to compare within 3.5%. Bautista-Capetillo et al. (2009) evaluated a similar laser instrument having a circular laser beam and found that drop velocity measurements were highly inaccurate for an agricultural impact sprinkler when compared to a photographic method.

The objective of this study was to further evaluate the applicability of the LPM used by King et al. (2010) for drop size and velocity measurement of agricultural sprinklers. This was accomplished by comparing drop sizes and velocities measured using the LPM with published values obtained using a photographic method.

Materials and Methods

The experimental sprinkler was a VYR35 impact sprinkler (VYRSA, Burgos, Spain) equipped with a 4.8 mm nozzle. The sprinkler was enclosed in a plastic cylinder as described by Chen and Wallender (1985), with a lateral cutout that allowed a wedge-shaped portion of the sprinkler circular wetted area to be sampled. The enclosure inside was lined with aluminum honeycomb-type material 38 mm thick to minimize splash from the sprinkler jet impacting sides of the enclosure interfering with the sprinkler nozzle jet or its mechanical operation. Vertical edges of the enclosure cutout were fitted with metal strips with sharp edges angled inward to the vertical axis of the sprinkler to minimize splash from the sprinkler jet on the edge of the opening interfering with the nozzle jet as it exited the enclosure. The sprinkler was tested a three operating pressures: 200, 300, and 400 kPa. Fixed pressure regulators were used to minimize pressure fluctuations during tests. A pressure gauge located between the pressure regulator and sprinkler base was used to monitor pressure during a test. Pressure values were within ±7 kPa of the nominal pressure rating.

Drop sizes and velocities were measured using a Thies Clima Laser Precipitation Monitor (TCLPM, Adolf Thies GmbH & Co. KG, Gottingen, Germany) (King et al., 2010). Measurements were conducted indoors with no wind. The TCLPM measures drop sizes from 0.125 mm to 8.0 mm. Drop size measurements were grouped into

0.1-mm increments (±0.05 mm) for analysis starting with 0.25 mm continuing to 7.95 mm. Measured drops less than 0.2 mm in diameter were discarded as they represent less than 0.01% of total volume of drops measured. The sprinkler nozzle was located 0.5 m above the laser beam of the TCLPM. Measurements were collected at 3, 6, 9, and 12 m radial distances from the sprinkler. A minimum of 10,000 drops were measured at each location to characterize size and velocity. Drops from both the main jet and the oscillating impact arm were measured collectively at 3 and 6 m measurement locations. Cumulative volume drop size distributions at each radial location were calculated based on total volume of measured drops at the location. Additional details of the TCLPM and experimental methods are provided by King et al. (2010).

Radial application rate distributions for the sprinklers were also measured indoors with no wind. Catch cans, 150 mm in diameter and 180 mm tall, spaced at 0.5 m increments from the sprinkler in one radial direction, were used to collect water. The sprinkler jet height was 0.5 m above can opening. The duration of each test was 30 to 60 min. Water collected in each can was measured using a graduated cylinder. Application rate was calculated based on the diameter of the catch cans and the duration of each test.

Drop size and velocity measurements for the experimental sprinkler using slow speed photography were those collected by Bautista-Capetillo et al. (2009) and Salvador et al., (2009) and are available for download at www.eead.csic.es/drops. Data collected by Bautista-Capetillo et al. (2009) were from indoor experiments while data collected by Salvador et al., (2009) were from outdoor experiments during very low wind conditions. Relative sprinkler height was 1.35 m, measurements were taken at 1.5, 3.0, 4.5, 6.0, 7.5, 9.0, and 12.5 m from the sprinkler, and a single operating pressure of 200 kPa was tested by Salvador et al. (2009). Relative sprinkler height was 0.5 m, measurements were taken at 3, 6, 9, and 12 m from the sprinkler, and operating pressures of 200, 300 and 400 kPa were tested by Bautista-Capetillo et al. (2009). A total of 1,564 drops were measured by Salvador et al., (2009) and a total of 1,229 drops were measured by Bautista-Capetillo et al. (2009). Minimum measured drop size by Bautista-Capetillo et al. (2009) was 0.5 mm and 0.3 mm by Salvador et al. (2009). Drop sizes and velocities were manually derived from the collected photographs and only drops in focus were considered valid and used in data analysis (Bautista-Capetillo et al. (2009). Both experiments analyzed measured drops from the main jet and oscillating impact arm collectively at the 3 m location, but drops measured at 6, 9, and 12 m locations were grouped separately. Drops from the oscillating impact arm did not travel farther than 6 m from the sprinkler.

Significant differences in cumulative drop size distributions between measurement methods were evaluated based on the Kolmogorov-Smirnov two-sample test (Steele and Torrie, 1980) with a significance level of $p \leq 0.05$. Significant differences in drop velocities between measurement methods were evaluated by fitting nonlinear equations to measured velocity data and testing for a significant difference ($p \leq 0.05$) in fit between the nonlinear equations. The nonlinear equation used for the statistical analysis was:

$$V_d = a \ln D + b \tag{1}$$

where V_d is droplet velocity (m $\sec^{-1}$), D is droplet diameter (mm), and a and b are regression coefficients. Equation 1 was found to provide a good overall fit to photographically measured drop velocity by Baustista-Capetillo et al. (2009) and Salvador et al. (2009). Coefficients a and b in eqn. 1 were determined using nonlinear regression and significance differences in resulting equations were evaluated using a sum of squares reduction test (PROC NLIN, SAS 2007).

Results and Discussion

Radial application rate profiles of the experimental sprinkler at the three operating pressures are shown in Fig 1. When operated at a pressure of 200 kPa the sprinkler tended to produce a doughnut shaped application pattern with a peak in application rate at about 12 m from the sprinkler. Drop size frequency histograms for both measurement methods for the experimental sprinkler operated at 200 kPa are shown in Fig 2. The TCLPM detected substantially more drops in the range of 0.2 to 1.0 mm than the photographic method at each radial distance. Since the number of drops measured must sum to 100% the measurement of numerous small drops skews the histograms to small drop sizes compared to the photographic. This is especially true for the data of Bautista-Capetillo et al. (2009) which does not include drops size measurements smaller than 0.5 mm.

Cumulative volume drop size distributions measured for the experimental sprinkler operated at 200 kPa are shown in Fig 3. There was a significant difference between cumulative drop size distributions measured by the TCLPM and Bautista-Capetillo et al. (2009) only at the 3.0 m radial location. There were no significant differences between cumulative drop sized distributions measured by the TCLPM and Salvador (2009). The tendency for measurements by the TCLPM to depict a smaller drop size distribution is due to measurement of a numerous drops less than 0.5 mm (Fig. 2). Despite the measurement of numerous smaller drops their cumulative volume was generally insufficient to cause a significant difference in the cumulative volume drop size distributions compared to those determined by the photographic method.

Cumulative volume drop size distributions measured for the experimental sprinkler operated at 300 and 400 kPa are shown in Figs 4 and 5, respectively. When operated at 300 kPa, there was a significant difference between cumulative drop size distributions measured by the TCLPM and Bautista-Capetillo et al. (2009) only at the 3.0 m radial location. When operated at 400 kPa, there were significant differences between cumulative drop size distributions measured by the TCLPM and Bautista-Capetillo et al. (2009) at the 3.0, 6.0 and 9.0 m radial locations. An increase in sprinkler operating pressure generally results in a decrease in drop size. This decrease in drop size increased the number of small drops measured by the TCLPM relative to the photographic method to the extent that the cumulative drop size distribution were significantly different at three of the four radial locations. The TCLPM measurements had a decrease in arithmetic and volumetric mean drop size (φ_A and φ_V,Table 1) as operating pressure of the experimental sprinkler was increased, consistent with the results found by Kohl (1974) for an impact sprinkler with a 3.97 mm nozzle operated at 400 kPa. Kohl (1974) found 47% and 25% of cumulative drop volume was below 0.5 mm at 2 and 4 m from the sprinkler, which is consistent with 24% measured by the TCLPM at 3 m from the experimental sprinkler at 400 kPa. Drop size measured using the photographic method (Bautista-Capetillo et al., 2009) did not show a consistent decrease in volumetric mean drop size when sprinkler operating pressure was increased from 300 to 400 kPa (Table 1). Drop size measurement with the photographic method was restricted to drops that were in focus which does not ensure a random sampling of drops. Since each drop is measured manually from a photograph there could be a tendency to select drops that are easier to measure which would be larger drops. Thus, a potential bias toward larger drop size measurement using the procedures employed by Bautista-Capetillo et al. (2009) and Salvador et al. (2009) exists. This potential bias could be eliminated by using an automated method of determining drop sizes from a photograph and would substantially reduce the amount of labor involved in drop size measurement. The arithmetic mean drop size for the TCLPM was always smaller than for the photographic method (Table 1), regardless of radial location and operating pressure. This is the result of the smaller drop size measurement by the TCLPM compared to the photographic method, 0.2 mm versus 0.5 mm.

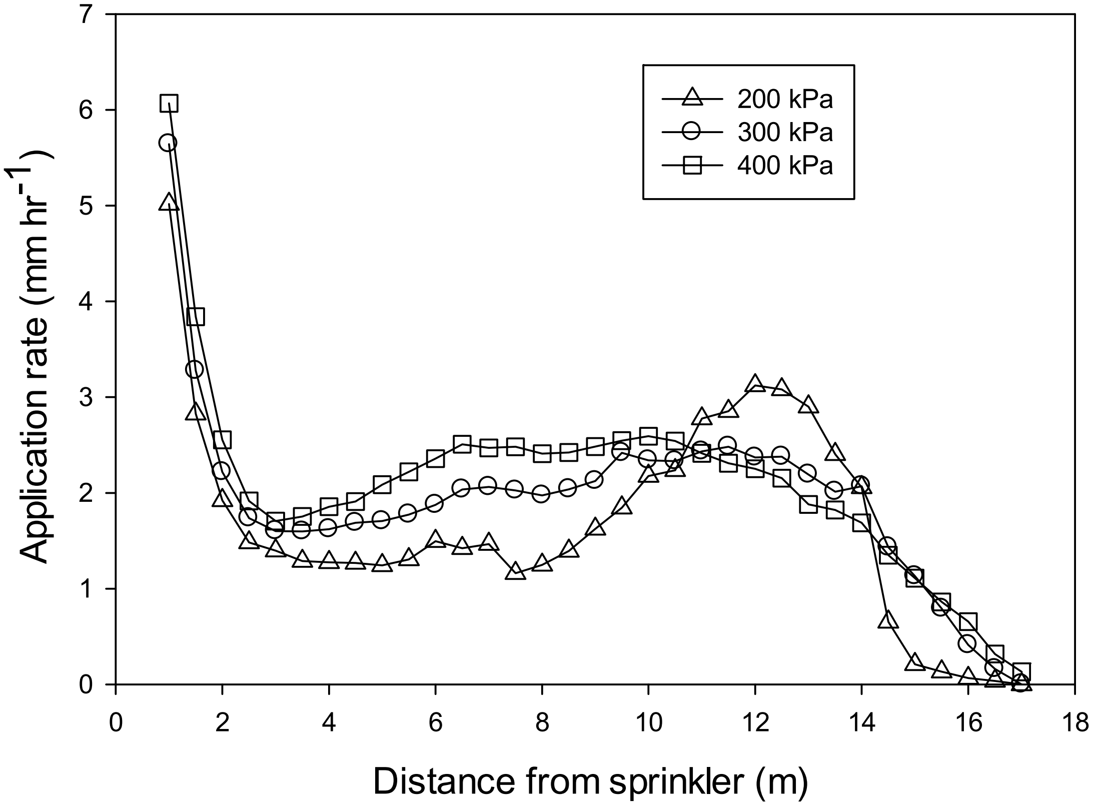

Figure 1. Radial application profiles for the experimental sprinkler operated at 200, 300, and 400 kPa.

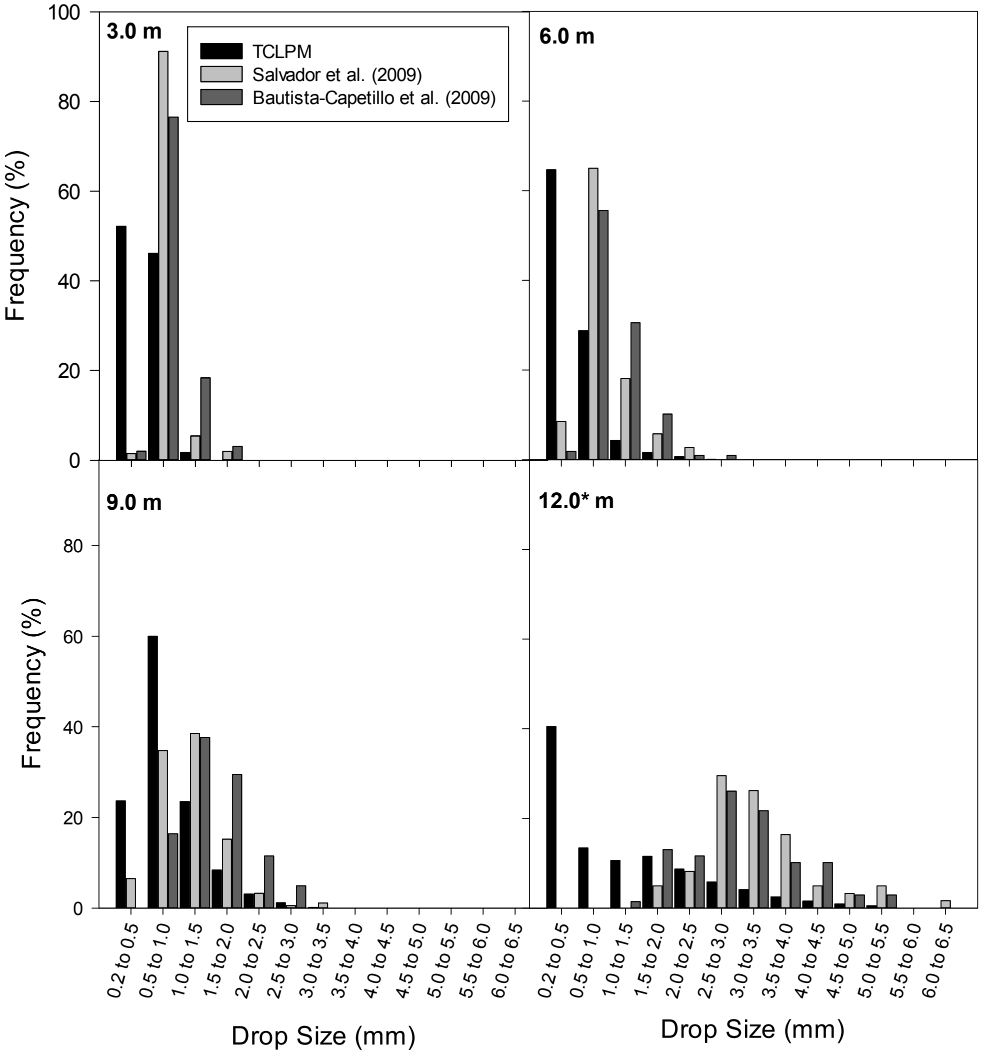

Figure 2. Comparison of drop size frequency histograms for measured drop size using TLCPM compared to the data from Salvador et al., (2009) and Bautista-Capetillo et al, (2009) at four distances from the experimental sprinkler operated at 200 kPa. (*Data from Salvador et al., (2009) is at 12.5 m).

Mean drop velocity determined at each of the four radial distances using the TCLPM compared to individual drop velocity measurements by Baustista-Capetillo et al. (2009) and Salvador et al. (2009) are shown in Fig 6 for the experimental sprinkler operated at 200 kPa. There were significant differences (Table 2) in drop velocity measurements between the TCLPM and both photographic measurements at 3, 6 and 9 m measurement locations. There were no significant differences between TCLPM and photographic drop velocity measurements at 12 m from the sprinkler but there was a significant difference between the measurements of Baustista-Capetillo et al. (2009) and Salvador et al. (2009). Mean drop velocity determined at each of the four radial distances using the TCLPM compared to individual drop velocity measurements by Baustista-Capetillo et al. (2009) are shown in Figs 7 and 8 for the experimental sprinkler operated at 300 and 400 kPa. There were significant differences (Table 2) in drop velocity measurements between the TCLPM and both photographic measurements at all measurement locations for both operating pressures. In general, mean velocity measurements by the TCLPM were greater than most of the velocity measurements by the photographic method of Baustista-Capetillo et al. (2009). The TCLPM experimental site had a 500 m greater altitude than the photographic method experimental site of Baustista-Capetillo et al. (2009) which could partially explain the tendency for the higher velocity measurement of the TCLPM. Hinkle et al. (1987) found that a 750 m altitude increase resulted in a 3.5% and 4.6% increase in terminal velocity of 1 and 6 mm drops, respectively. Using a drop ballistic model they found that a 750 m increase in altitude resulted in an increase in droplet velocity of 3.0 and 3.6% for 1 and 6 mm drop, respectively. The increase in drop velocity resulted in a 5.2 and 5.6% increase in radii of throw for 1 and 6 mm drops, respectively. An additional factor contributing to a significant difference between drop velocity measurements using the TCLPM and the photographic method of Baustista-Capetillo et al. (2009) is measurement of velocity for drops smaller than 0.5 mm. Inclusion of velocity data from drops smaller than 0.5 mm combined with slightly different measured drop size distributions influences the resulting coefficients in nonlinear regression analysis used for statistical analysis. Given altitude differences between experimental sites, differences in measured drop size ranges, and differences (though not generally significant) in measured drop size distributions, significant differences between drop velocity measurement methods was not unexpected. Especially given that significant differences in drop velocity measurements by Salvador et al. (2009) and Baustista-Capetillo et al. (2009) were found (Table 2) despite using the same basic photographic method, experimental sprinkler and operating pressure but at different experimental locations, relative sprinkler elevations and ambient environmental conditions.

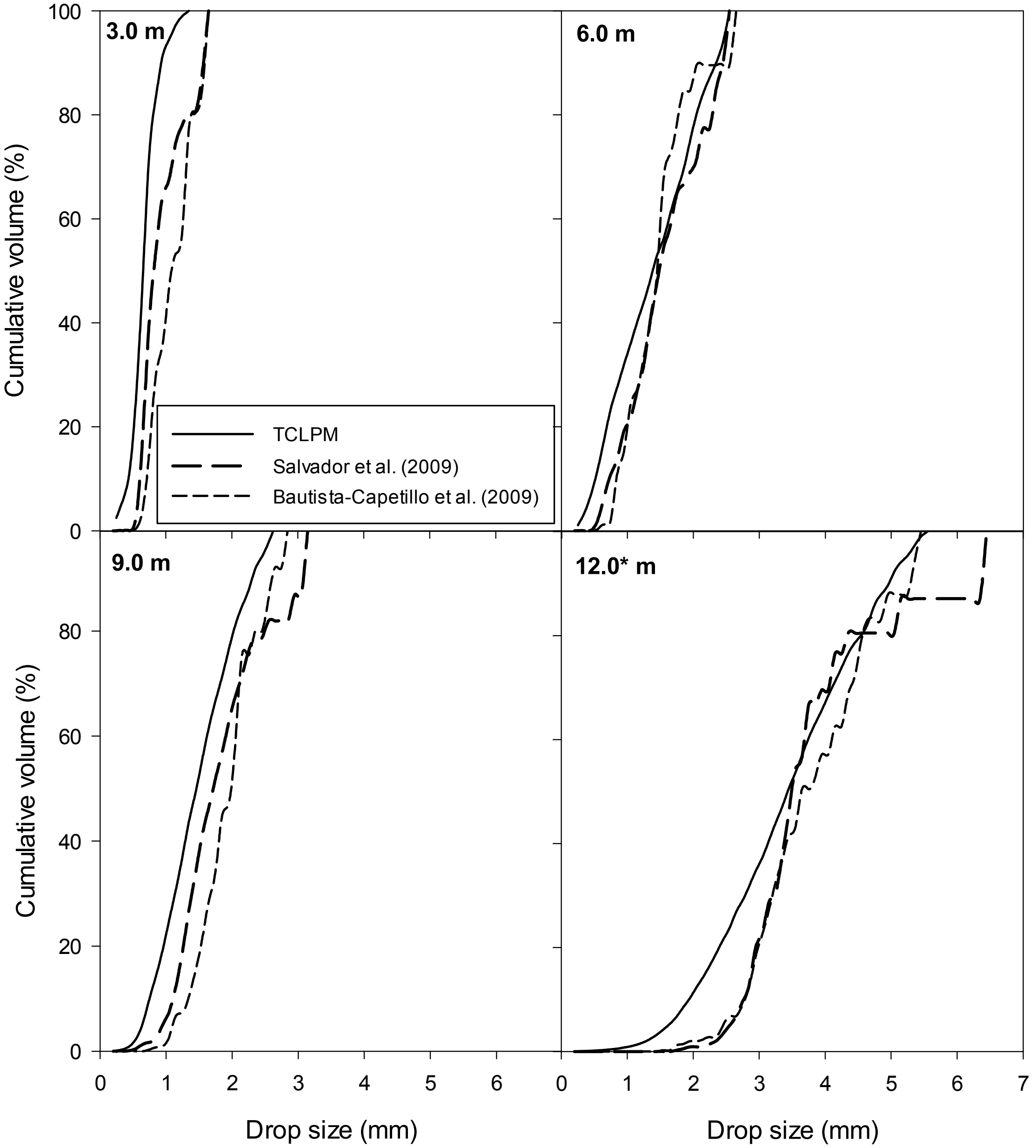

Figure 3. Cumulative drop size distributions for measured drop size using TLCPM compared to the data from Salvador et al., (2009) and Bautista-Capetillo et al. (2009) at four distances from the experimental sprinkler operated at 200 kPa. (*Data from Salvador et al., (2009) is at 12.5 m).

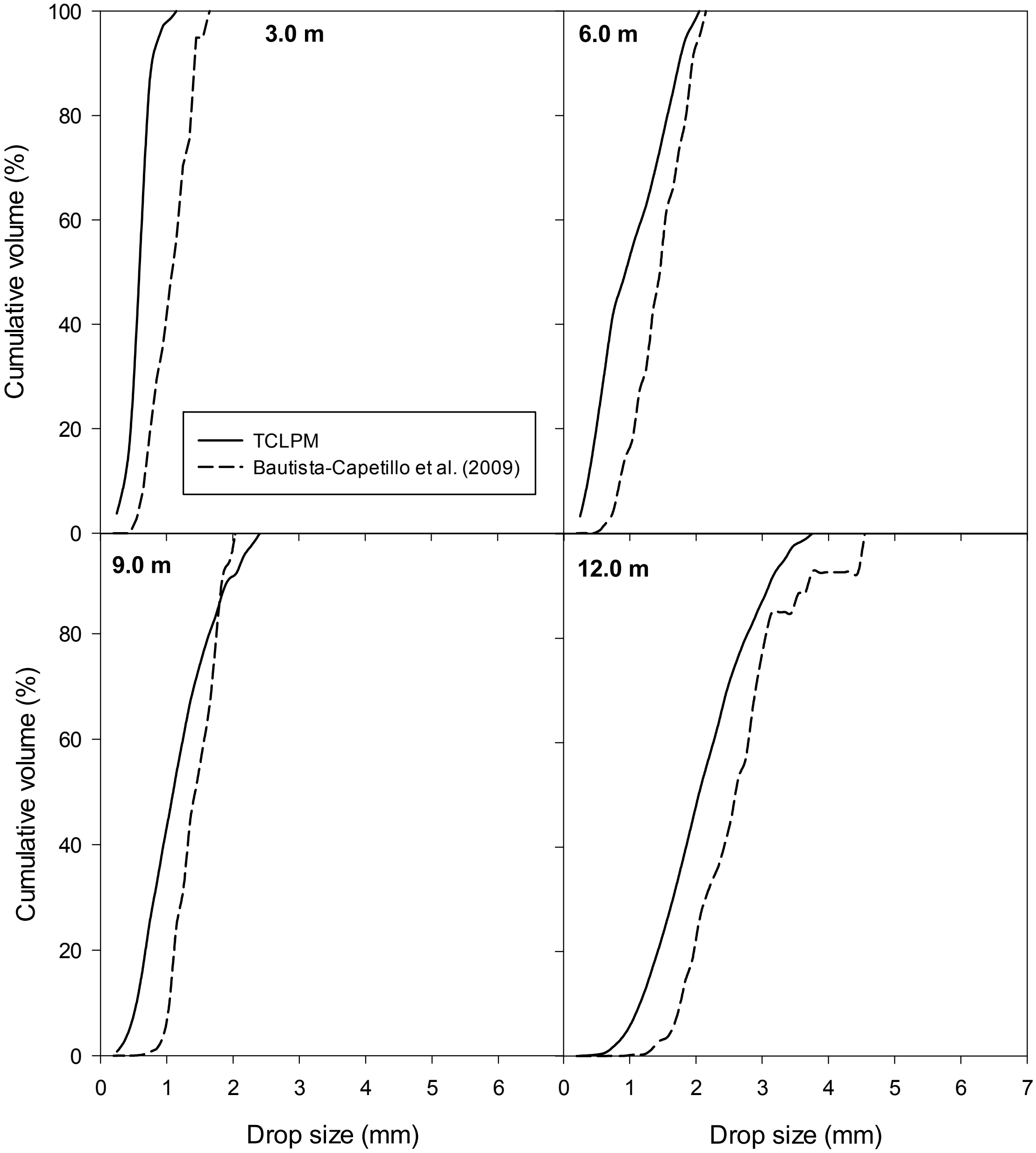

Figure 4. Cumulative drop size distributions for measured drop size using TLCPM compared to the data from Bautista-Capetillo et al. (2009) at four distances from the experimental sprinkler operated at 300 kPa.

Droplet kinetic energy per unit volume calculated based on drop size and velocity data from the TCLPM, Baustista-Capetillo et al. (2009) and Salvador et al. (2009) for each measurement location and operating pressure are shown in Table 3. The difference in kinetic energy per unit volume using drop size and velocity measurements from the TCLPM and Baustista-Capetillo et al. (2009) ranged from +12.5 to -28%. Drop size and velocity measurements from the TCLPM generally provided a lower estimate of droplet kinetic energy due to the measurement of a larger proportion of smaller drop. The difference between calculated kinetic energy per unit drop volume was greatest when using drop size and velocity measurements from Salvador et al. (2009) and Baustista-Capetillo et al. (2009). This was unexpected as both used the same basic photographic method, experimental sprinkler and operating pressure but at different experimental locations, relative sprinkler elevations and ambient environmental conditions. From a practical point of view, kinetic energy of a sprinkler is a relative number which provides some sense of the potential for a sprinkler to create a soil surface seal reducing infiltration rate. Critical threshold values of sprinkler kinetic energy for minimizing or eliminating runoff and erosion hazard for various soil types in unknown. Thus, highly accurate values of kinetic energy are of limited value, but easy, reliable, and highly reproducible estimates are of value for field purposes. Since the differences in velocity measurement appear to be consistent with respect to drop sizes, the relative ranking between sprinklers in regards to kinetic energy would likely be similar regardless of which method was used to characterize drop size and velocity. King et al. (2010) obtained sprinkler kinetic energy estimates within 3.5% of those obtained using the flour pellet method to estimated drop size distribution and a ballistic model to estimate drop velocity.

The labor and skill required to measure sprinkler drop size and velocity using the photographic method is quite extensive. Salvador et al. (2009) estimated that 200 h were required to conduct the experiment and process the photographs to determine size, velocity and trajectory from a sprinkler at one operating pressure. A limited number of drop measurements were used to characterize sprinkler drop size and velocity at one measurement location, approximately 60-200 by Salvador et al. (2009) and approximately 100 by Baustista-Capetillo (2009). King et al. (2010) estimated that about 20 h or less with minimal labor requirement beyond equipment setup, infrequent observation of operation, and computerized data analysis was required to measure drop size distribution and velocity of a sprinkler using the TCLPM. At all but the most radial extent a minimum of 10,000 drops are used to determine drop size distribution. The cumulative drop size distributions of Bautista-Capetillo (2009) (Figs. 3 thru 5) show considerable irregularities resulting from a limited number of measured drops. The limited number of drops used by Bautista-Capetillo (2009) and Salvador et al. (2009) underscores the amount of effort required by their photographic method and makes it impractical for characterizing sprinklers on a large scale.

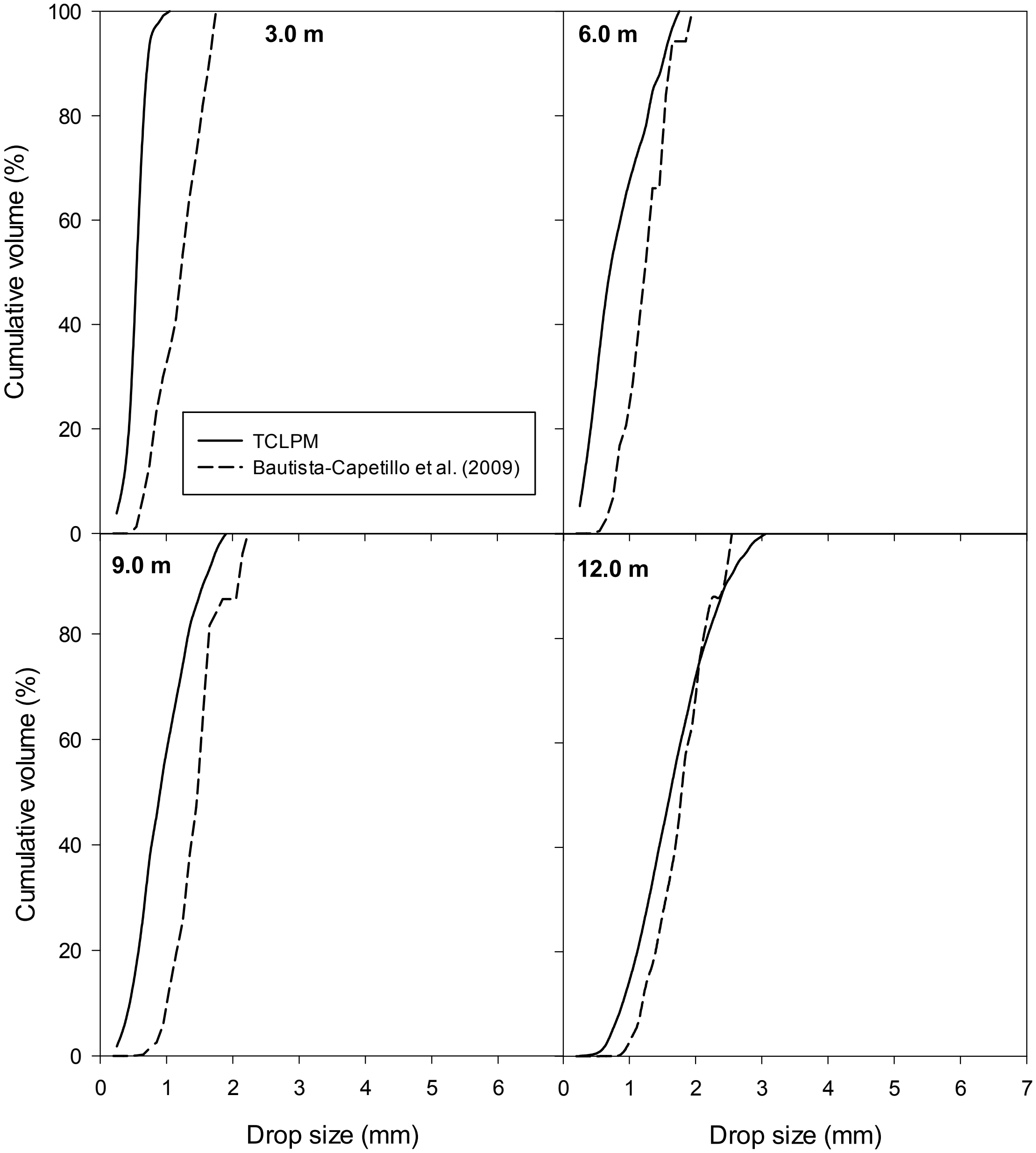

Figure 5. Cumulative drop size distributions for measured drop size using TLCPM compared to the data from Bautista-Capetillo et al. (2009) at four distances from the experimental sprinkler operated at 400 kPa.

Table 1. Statistical parameters for measured drop diameter and velocity using the TCLPM for combinations of operating pressure and distance from the sprinkler compared to values reported by Bautista-Capetillo (2009) for a photographic method. Statistical parameters include number of drops (N), arithmetic means (φ_A, V_A), standard deviations (SD_D, SD_V) and coefficients of variation (CV_D, CV_V) for diameter and velocity, volumetric mean diameter (φ_V) and the volume median diameter (φ_{50}).

Operating Pressure (kPa)	Variable	Parameter	TCLPM				Photographic			
			Distance from Sprinkler (m)				Distance from Sprinkler (m)			
			3	6	9	12	3	6	9	12
200	Diameter (mm)	N	11003	11766	13884	10321	98	108	61	69
		φ_A	0.49	0.50	0.85	1.27	0.86	1.04	1.50	3.08
		φ_V	0.75	1.44	1.76	3.43	1.12	1.48	1.93	3.28
		φ_{50}	0.60	0.56	1.00	2.20	1.05	1.40	1.92	3.59
		SD_D	0.21	0.33	0.49	1.14	0.26	0.37	0.49	0.88
		CV_D	44.1	64.8	57.5	90.1	30.2	35.6	32.7	28.6
	Velocity ($m\ s^{-1}$)	V_A	2.08	2.06	3.15	3.60	2.72	3.06	4.19	6.06
		SD_V	0.68	0.82	1.01	1.92	0.34	0.64	0.75	1.04
		CV_V	32.9	39.8	32.1	53.4	12.5	20.9	17.9	17.2
300	Diameter (mm)	N	12176	13255	14692	10671	112	120	120	110
		φ_A	0.45	0.42	0.56	1.15	0.81	1.03	1.22	2.06
		φ_V	0.64	1.00	1.16	2.09	1.08	1.43	1.44	2.65
		φ_{50}	0.54	0.44	0.66	1.42	1.06	1.40	1.39	2.55
		SD_D	0.18	0.23	0.31	0.65	0.26	0.38	0.30	0.61
		CV_D	40.3	55.0	55.7	56.5	32.1	37.0	24.6	29.6
	Velocity ($m\ s^{-1}$)	V_A	1.95	1.82	2.41	3.93	2.45	2.92	3.82	5.13
		SD_V	0.62	0.70	0.94	1.16	0.19	0.61	0.59	1.00
		CV_V	31.9	38.4	38.9	29.6	7.76	20.89	15.45	19.49
400	Diameter (mm)	N	11516	11185	13177	13183	114	106	102	98
		φ_A	0.43	0.38	0.48	0.98	0.86	0.96	1.19	1.45
		φ_V	0.59	0.83	0.98	1.68	1.19	1.25	1.46	1.78
		φ_{50}	0.51	0.40	0.56	1.14	1.17	1.18	1.42	1.73
		SD_D	0.16	0.19	0.26	0.49	0.30	0.30	0.34	0.40
		CV_D	37.3	49.9	54.7	49.9	34.9	31.3	28.6	27.6
	Velocity ($m\ s^{-1}$)	V_A	1.89	1.68	2.14	3.71	2.43	2.96	3.72	4.42
		SD_V	0.60	0.66	0.88	0.98	0.31	0.51	0.66	0.80
		CV_V	31.6	39.2	40.9	26.5	12.8	17.2	17.7	18.1

Table 2. Results of statistical comparisons ($p \leq 0.05$) for drop velocity measured using the TCLPM for combinations of operating pressure and distance from the sprinkler compared to the values reported by Bautista-Capetillo et al. (2009) and Salvador et al. (2009) for photographic method.

	200 kPa				300 kPa				400 kPa			
Data Source	3m	6m	9m	12m*	3m	6m	9m	12m	3m	6m	9m	12m
TCLPM	a**	a	a	a	a	a	a	a	a	a	a	a
Bautista-Capetillo et al. (2009)	b	b	b	ab	b	b	b	b	b	b	b	b
Salvador et al. (2009)	c	c	c	ac	-	-	-	-	-	-	-	-

*Data from Salvador et al., (2009) is at 12.5 m.

**Different letters in the same column denote significant differences in drop velocity measurements between data sources.

Table 3. Kinetic energy per unit volume of water ($J\ L^{-1}$) for the experimental sprinkler at four radial distances from the experimental sprinkler and three operating pressures based on drop size and velocity measured using the TCLPM and values reported by Bautista-Capetillo et al. (2009) and Salvador et al. (2009) for the photographic method.

	200 kPa				300 kPa				400 kPa			
Data Source	3m	6m	9m	12m*	3m	6m	9m	12m	3m	6m	9m	12m
TCLPM	3.79	7.74	11.1	21.7	3.17	5.53	7.76	14.5	2.84	4.97	6.47	12.1
Bautista-Capetillo et al. (2009)	4.45	6.88	11.5	21.4	3.66	5.94	8.86	16.2	3.64	5.53	8.93	12.1
Salvador et al. (2009)	2.98	7.77	13.7	12.6	-	-	-	-	-	-	-	-

*Data from Salvador et al., (2009) is at 12.5 m.

Summary and Conclusions

Drop size and velocity from an impact sprinkler operated at three pressures were measured at four radial distances from the sprinkler using a TCLPM. Measured drop size distributions at each radial location and pressure were compared to photographic measured drop size and velocity for the same sprinkler, radial locations and operating pressures but at different experimental sites and ambient environmental conditions. In general there were no significant differences in cumulative drop size distributions between measurement methods. The TCLPM tended to measure smaller cumulative volume drop size distributions which were attributed to the fact that the photographic method did not measure drop sizes below 0.5 mm where as the

TCLPM measured drop sizes 0.2 to 8.0 mm. The photographic method was restricted to the measurement of drops in focus which does not ensure a random sampling of drops. Additionally only approximately 100 drops were used to characterize drops size distribution at a measurement location while the TCLPM used 10,000 drops. The effect of using a relatively small number of drops to characterize drop size distribution with the photographic method is evident from the irregular cumulative drop size distributions obtained.

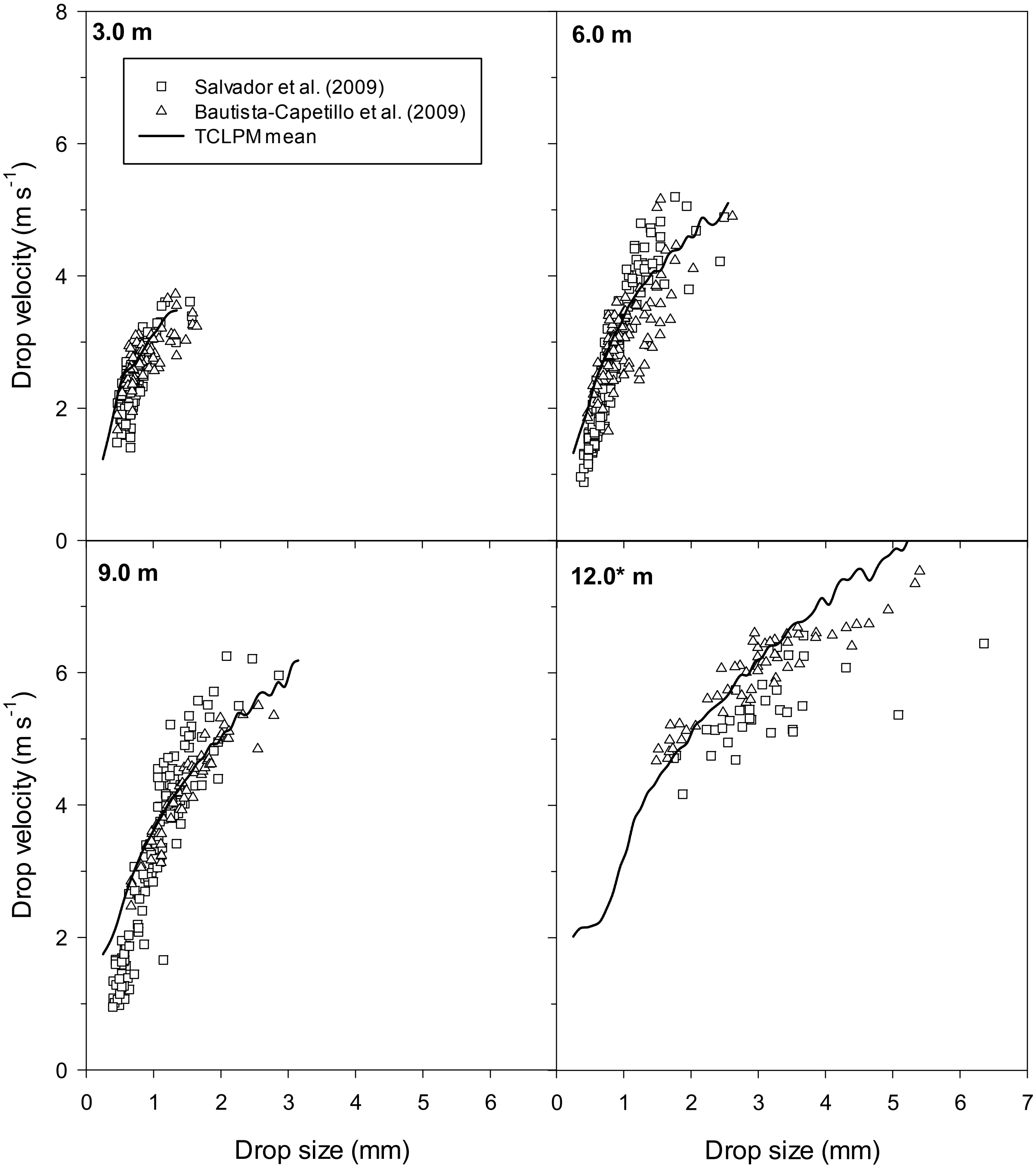

Figure 6. Measured drop velocity obtained using TLCPM compared to data from Salvador et al., (2009) and Bautista-Capetillo et al. (2009) at four distances from the experimental sprinkler operated at 200 kPa. (*Data from Salvador et al., (2009) is at 12.5 m).

There were significant differences in drop velocity between the two measurement methods. The existence of significant differences in drop velocity was not unexpected given the presence of a substantial differences (although not significant) in drop size distribution between the measurement methods. A significant difference in drop velocity was also present between measurements collected using the same photographic technique, sprinkler, and operating pressure but at a different altitude, relative sprinkler height and ambient environmental conditions. Differences in measured drop size distributions and drop velocities resulted in a difference in calculated drop kinetic energy per unit volume ranging from +12.5 to -28%. Drop size and velocity measurements from the TCLPM generally provided a lower estimate of droplet kinetic energy due to the measurement of a larger proportion of smaller drop sizes.

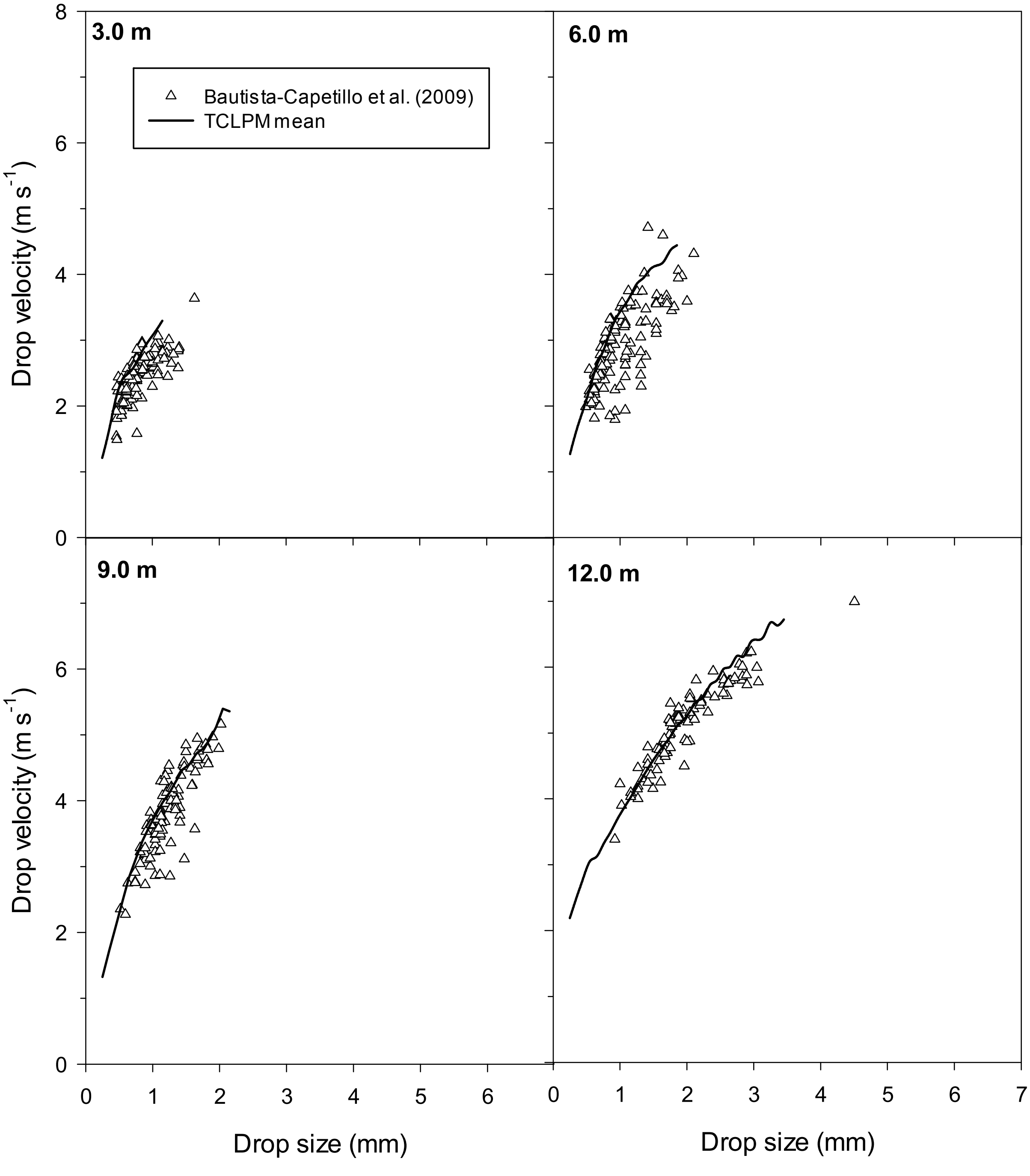

Figure 7. Measured drop velocity obtained using TLCPM compared to data from Bautista-Capetillo et al. (2009) at four distances from the experimental sprinkler operated at 300 kPa.

The TCLPM requires substantially less skill and labor to measure sprinkler drop size and velocity. From a practical point of view, kinetic energy of a sprinkler is a relative number which provides some sense of the potential for a sprinkler to create a soil surface seal reducing infiltration rate. Critical threshold values of sprinkler kinetic energy for minimizing or eliminating runoff and erosion hazard for various soil types in unknown. Thus, highly accurate values of kinetic energy are of limited value, but easy, reliable, and highly reproducible estimates are of value for field purposes.

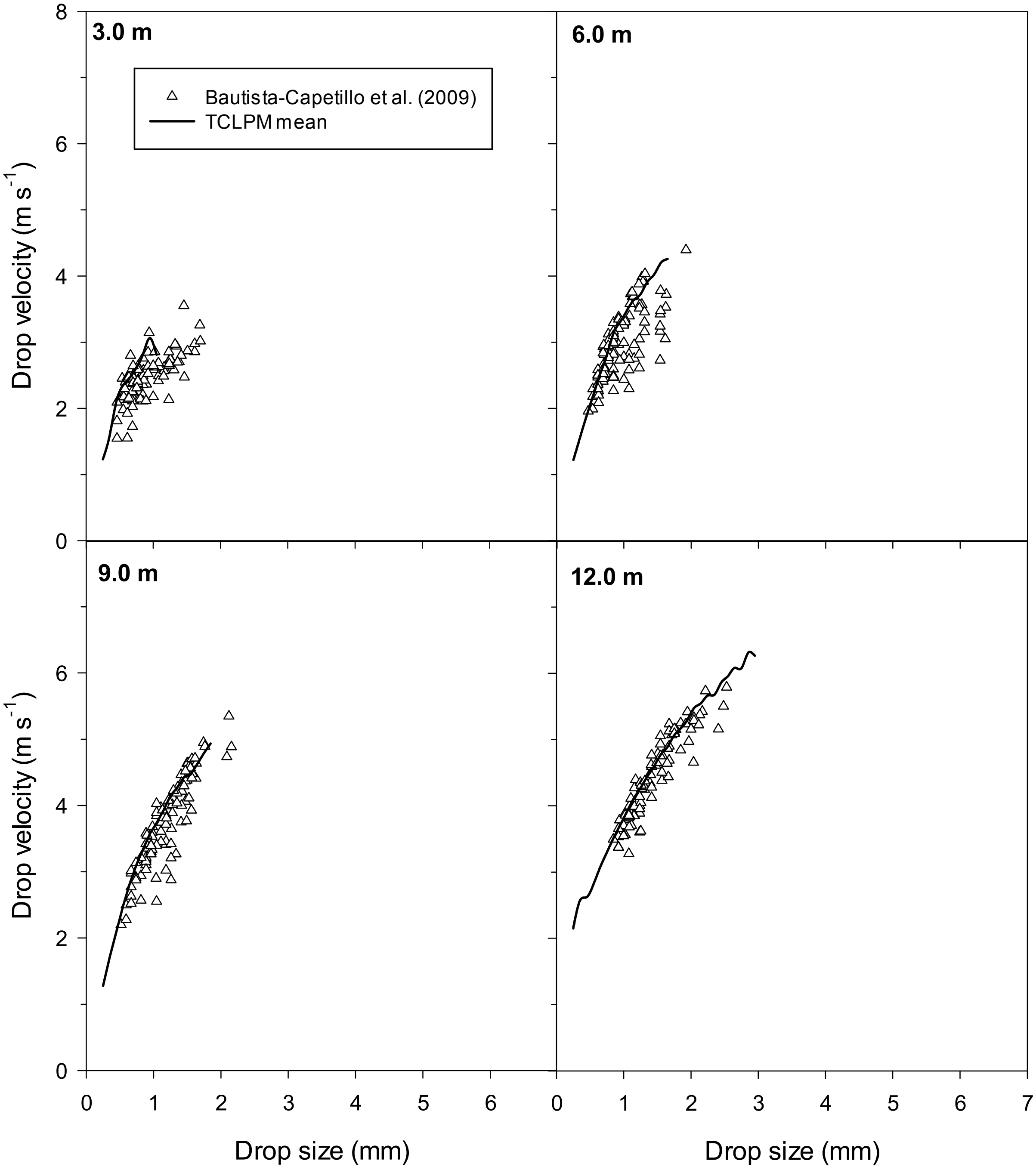

Figure 8. Measured drop velocity obtained using TLCPM compared to data from Bautista-Capetillo et al. (2009) at four distances from the experimental sprinkler operated at 400 kPa.

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