COMPARISON OF DROP SIZE AND VELOCITY MEASUREMENTS BY A LASER PRECIPITATION METER AND LOW-SPEED PHOTOGRAPHY OR AN AGRICULTURE SPRINKLER

B. A. King, T. W. Winward, D. L. Bjorneberg

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. Drop size and velocity of an impact sprinkler at three operating pressures and one nozzle size were measured using a laser precipitation meter and compared with published values obtained using a photographic method. 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; 0.5 mm 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 drop 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. *Drop size, Drop velocity, Kinetic energy, Laser, Measurement, Photography, Sprinkler irrigation.*

Drop size and velocity have a major influence on sprinkler irrigation system performance due to the effect droplet specific power and cumulative kinetic energy has on formation of a soil surface seal and associated reduction in infiltration rate and generation of runoff (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 (Edling, 1985; Kohl et al., 1987). 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)

Submitted for review in September 2013 as manuscript number SW 10417; approved for publication by the Soil & Water Division of ASABE in February 2014. Presented at the 2012 ASABE Annual Meeting as Paper No. 131594348.

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- 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 validate 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 rather than rectangular 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.

Methods and Materials

The experimental sprinkler was a 19 mm 26° brass impact sprinkler (VYR35, VYRSA, Burgos, Spain) equipped with a 4.8 mm nozzle and straightening vane and identical to that used by Salvador et al. (2009) and Bautista-Capetillo et al. (2009) with the photographic method. The sprinkler was enclosed in a plastic cylinder similarly 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 at three operating pressures: 200, 300, and 400 kPa. An adjustable pressure regulator was 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 ±10 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 at an air temperature and relative humidity of approximately 16°C and 49%, respectively, with no wind. The TCLPM measures drop sizes from 0.16 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 0.05% 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 and no attempt was made to separate drop source in determination of drop size distribution or drop velocity. 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 average 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 with one can at each radial location, were used to collect water. The sprinkler nozzle height was 0.5 m above can opening. The duration of each test was 30 to 60 min and catch can volumes were measured within 10 min of test completion. Water collected in each can was measured using a graduated cylinder. Average application rate was calculated by dividing the volume caught in a catch can by the area of the catch can entrance and the duration of the 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 at an air temperature of 10°C, while data collected by Salvador et al. (2009) were from outdoor experiments during very low wind conditions. Vertical distance between sprinkler nozzle and drop measurements (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.

Kinetic energy per unit drop volume KE_d (J L^{-1}), at each sprinkler radial measurement location was computed as:

$$KE_d = \frac{\sum_{j=1}^{ND} \frac{\rho_w \pi D_j^3 V_j^2}{12}}{1000 \sum_{j=1}^{ND} \frac{\pi D_j^3}{6}} \tag{1}$$

where ND is the number of drops measured at the radial location, ρ_w is the mass density of water (kg m^{-3}), D_j is the measured diameter (m) of the jth drop, V_j is the measured velocity (m s^{-1}) of the jth drop. The resulting value represents the average kinetic energy per liter of drop volume applied at the radial measurement location.

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:

$$V = a \ln D + b \tag{2}$$

where V is droplet velocity (m s^{-1}), D is droplet diameter (mm), and a and b are regression coefficients. Equation 2 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 equation 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 figure 1. When operated at a pressure of 200 kPa the sprinkler tended to produce a doughnut shaped application pattern with a slight 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 figure 2. The TCLPM detected substantially more drops in the range of 0.2 to 0.5 mm than the photographic method at each radial distance and in the range of 0.5 to 1.0 mm at radial locations 9.0 and 12.0 m. 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 for the experimental sprinkler operated at 200 kPa are shown in figure 3. There was a significant difference between cumulative drop size distributions measured by the TCLPM and Bautista-Capetillo et al. (2009) only for the 3.0 m radial location. There were no significant differences between cumulative drop sized distributions measured by the TCLPM and Salvador et al. (2009). The tendency for measurements by the TCLPM to depict a smaller drop size distribution is due to measurement of numerous drops less than 0.5 mm (fig. 2). Despite the measurement of numerous smaller drops by the TCLPM their cumulative volume was insufficient to cause a significant difference in the cumulative volume drop size distributions compared to those determined by the photographic method except for the 3 m radial location where small drops are prominent for an impact sprinkler. The greater sprinkler height used in the study by Salvador et al. (2009) would have a tendency to reduce measured drop size distribution since drop size increases with distance from the sprinkler and a greater sprinkler height allows drops of a particular size to land farther from the sprinkler. This may partially explain why there were no significant differences in measured drop size distributions between the TCLPM and the study by Salvador et al. (2009).

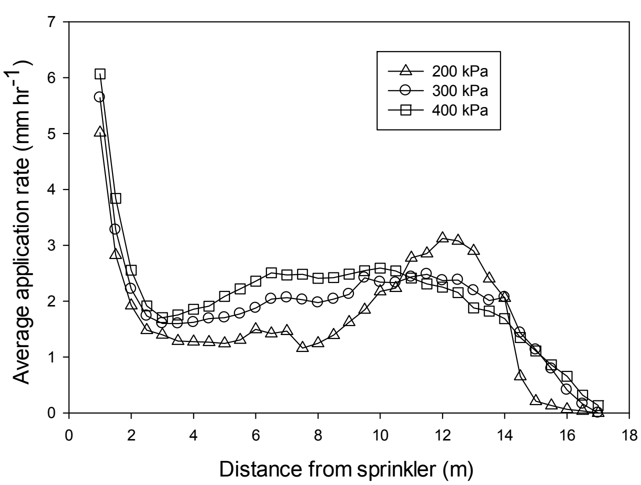

Figure 1. Radial average application profiles for the experimental sprinkler operated at 200, 300, and 400 kPa.

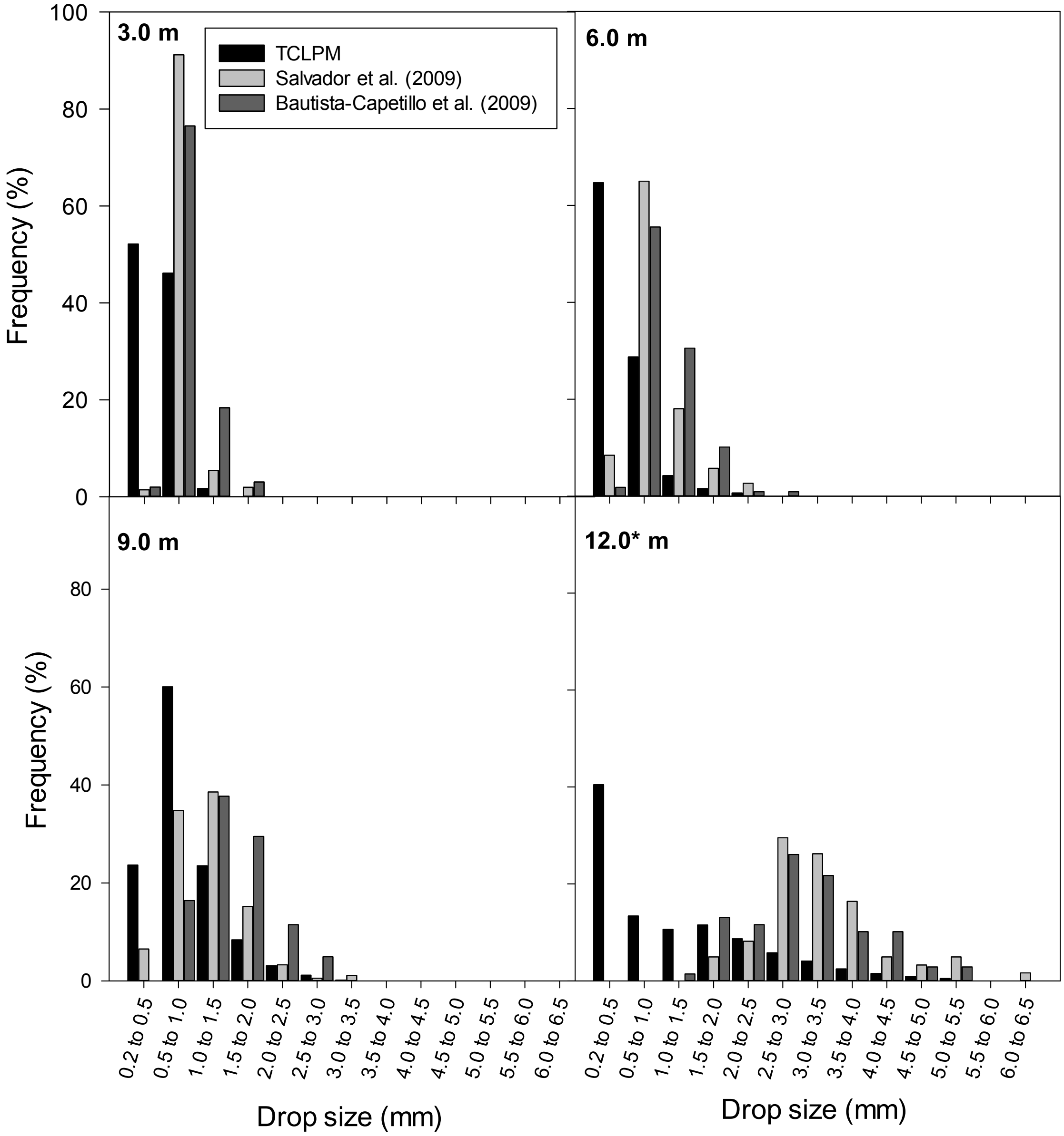

Figure 2. Comparison of drop size frequency histograms for measured drop size using TLCPM compared to the data from Salvador et al., (2009) and Bautista-Capetillo et al., (2009) at four distances from the experimental sprinkler operated at 200 kPa. (*Data from Salvador et al., (2009) is at 12.5 m).

Cumulative volume drop size distributions for the experimental sprinkler operated at 300 and 400 kPa are shown in figures 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) reported 47% and 25% of cumulative drop volume was below 0.5 mm at 2 and 4 m from the sprinkler, respectively, 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 (φ_V, 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

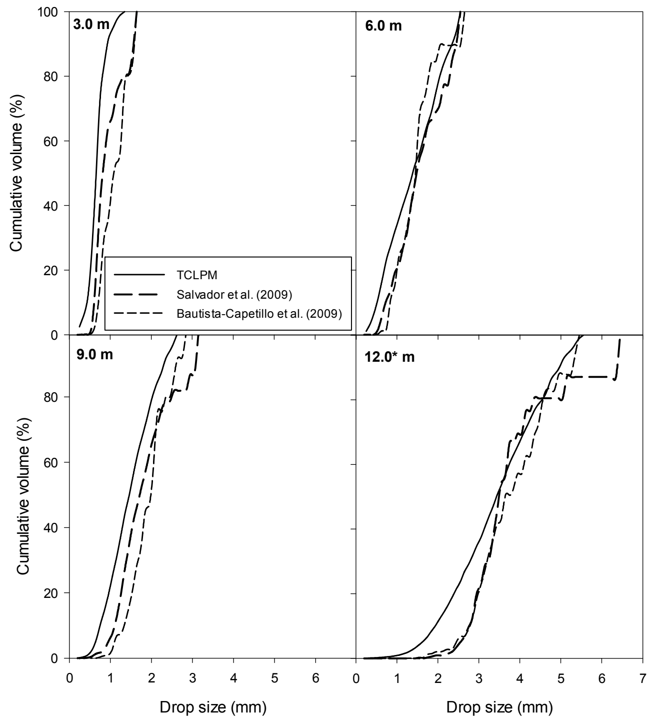

Figure 3. Cumulative drop size distributions for measured drop size using TLCPM compared to the data from Salvador et al., (2009) and Bautista-Capetillo et al. (2009) at four distances from the experimental sprinkler operated at 200 kPa. (*Data from Salvador et al., (2009) is at 12.5 m).

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.

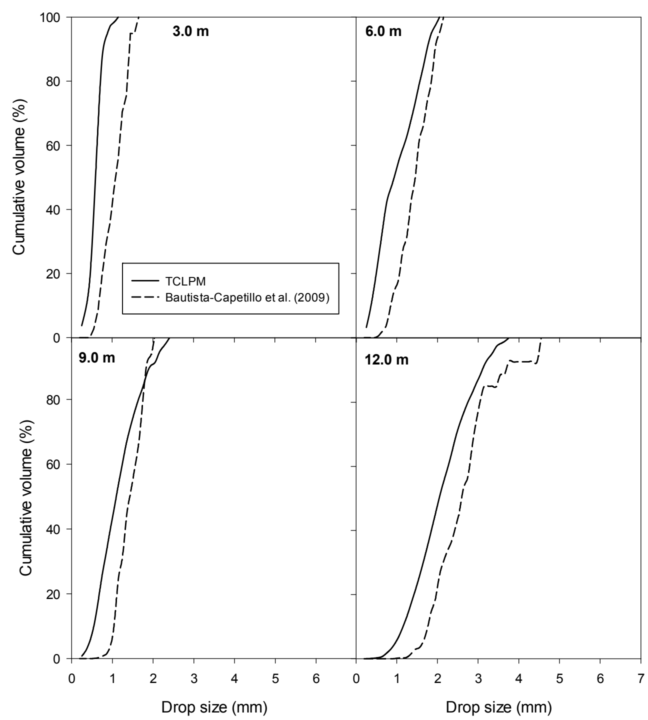

Figure 4. Cumulative drop size distributions for measured drop size using TLCPM compared to the data from Bautista-Capetillo et al. (2009) at four distances from the experimental sprinkler operated at 300 kPa.

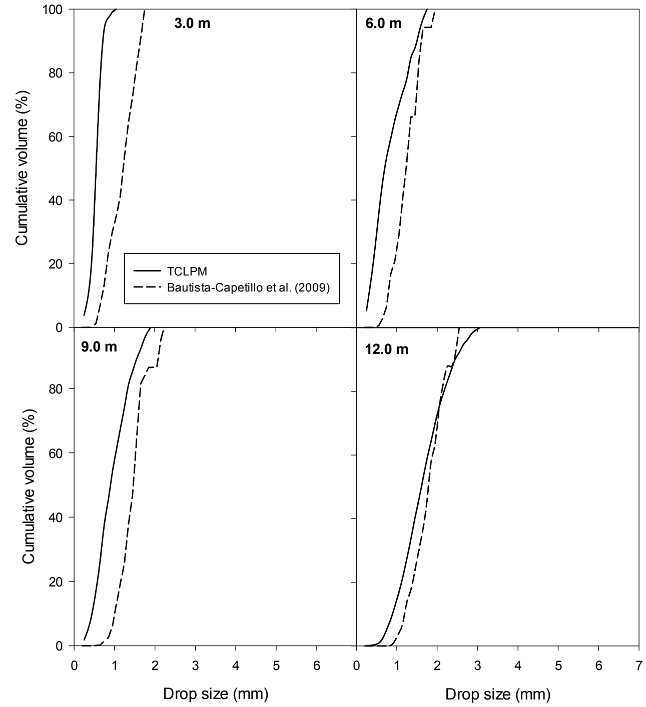

Figure 5. Cumulative drop size distributions for measured drop size using TLCPM compared to the data from Bautista-Capetillo et al. (2009) at four distances from the experimental sprinkler operated at 400 kPa.

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 for the photographic method (φ_A, table 1), regardless of radial location and operating pressure. This is the result of the lower minimum drop size measurement by the TCLPM compared to the photographic method, 0.2 mm versus 0.5 mm.

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 figure 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). Drop velocity measurements from Salvador et al. (2009) tend to be greater for drop sizes greater than 1.0 mm at 6 and 9 m locations compared to Baustista-Capetillo et al. (2009) and the TCLPM (fig. 6). This may be due to the greater sprinkler height used in the study of Salvador et al. (2009) as the drops have farther to fall and could be increasing velocity if they are below terminal velocity.

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.

Operating Pressure (kPa)	Variable	Parameter[a]	TCLPM Distance from Sprinkler (m) 3	6	9	12	Photographic Distance from Sprinkler (m) 3	6	9	12[b]
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})	N	11003	11766	13884	10321	92	103	58	54
		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	120	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})		12176	13255	14692	10671	116	118	118	91
		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})		11516	11185	13177	13183	112	106	99	90
		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

[a] 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}).
[b] 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) are shown in figures 7 and 8 for the experimental sprinkler operated at 300 and 400 kPa, respectively. 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 can 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

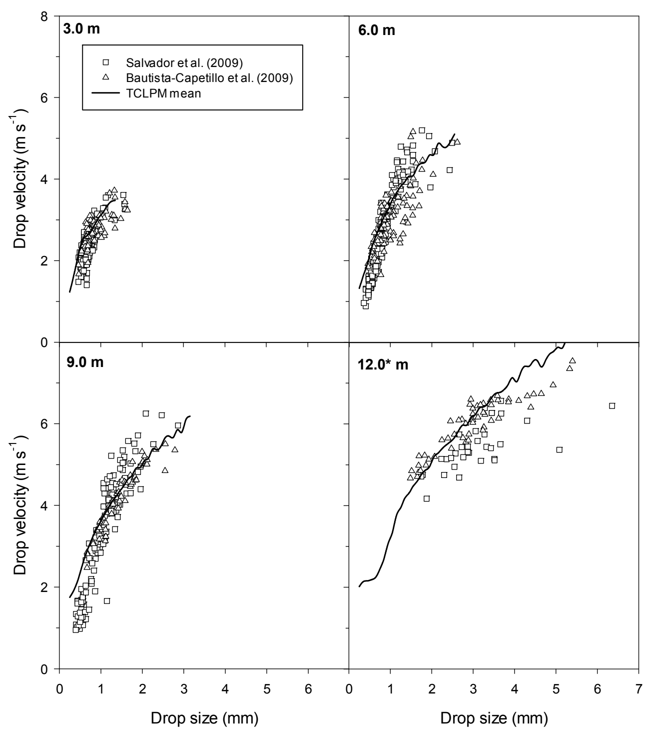

Figure 6. Measured drop velocity obtained using TLCPM compared to data from Salvador et al., (2009) and Bautista-Capetillo et al. (2009) at four distances from the experimental sprinkler operated at 200 kPa. (*Data from Salvador et al., (2009) is at 12.5 m).

Table 2. Results of statistical comparisons ($p \le 0.05$) 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[a]	3m	6m	9m	12m	3m	6m	9m	12m
TCLPM	a[b]	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	-	-	-	-	-	-	-	-

[a] Data from Salvador et al., (2009) is at 12.5 m.

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

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.

Droplet kinetic energy per unit drop 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 drop 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 drops. Differences in calculated kinetic energy per unit drop volume was greatest when calculated using drop size and velocity measurements from Salvador et al. (2009) compared to 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 are unknown. Thus, highly accurate values of kinetic energy are of limited value, but easy, reliable, and highly reproducible estimates are of value for purposes of comparing sprinkler selection choices. Since 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

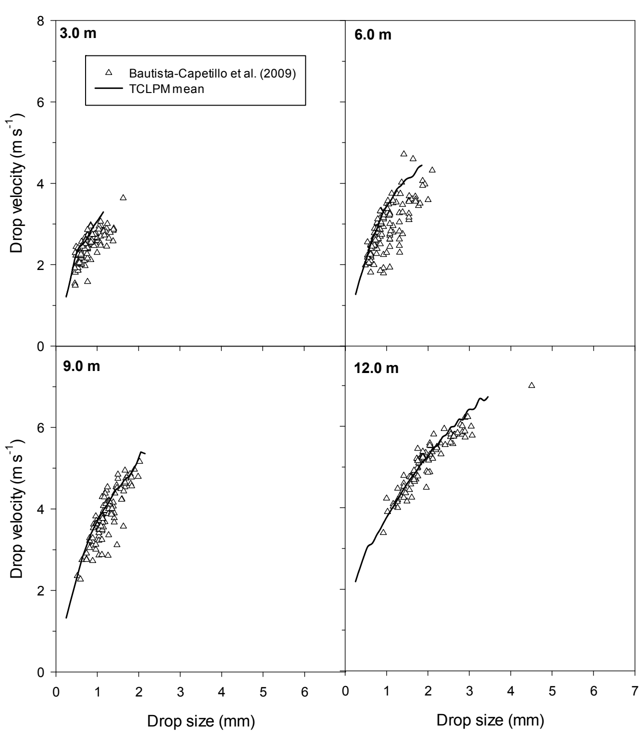

Figure 7. Measured drop velocity obtained using TLCPM compared to data from Bautista-Capetillo et al. (2009) at four distances from the experimental sprinkler operated at 300 kPa.

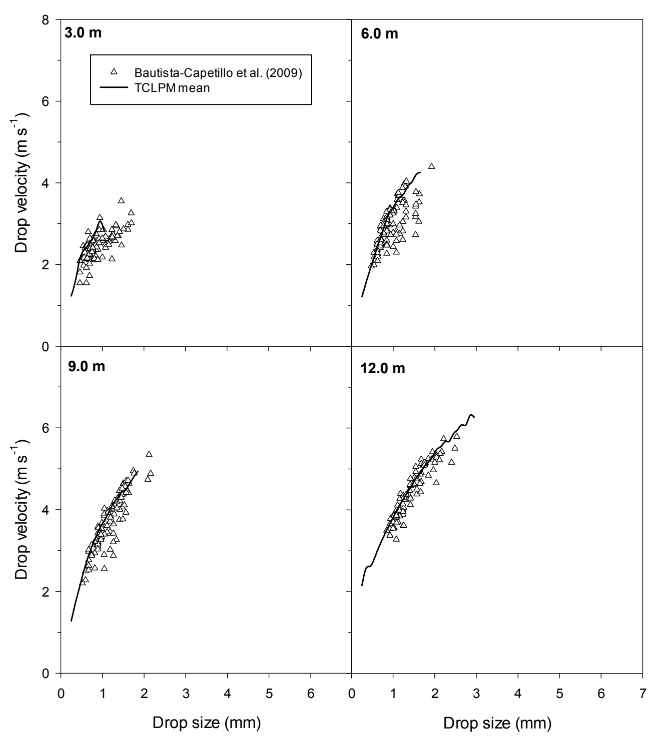

Figure 8. Measured drop velocity obtained using TLCPM compared to data from Bautista-Capetillo et al. (2009) at four distances from the experimental sprinkler operated at 400 kPa.

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[a]	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	-	-	-	-	-	-	-	-

[a] Data from Salvador et al., (2009) is at 12.5 m.

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 drop size, velocity, and trajectory from a sprinkler for one operating pressure at eight radial locations. A limited number of drop measurements were used to characterize sprinkler drop size and velocity at one measurement location, approximately 60 to 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 were used to determine drop size distribution. The cumulative drop size distributions of Bautista-Capetillo (2009) (figs. 3-5) 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.

Summary and Conclustions

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 whereas the TCLPM measured drop sizes as small as 0.2 mm. The photographic method was restricted to the measurement of drops in focus and manual size and velocity determination 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. One distinct advantage of the photographic method is the ability to measure droplet angle from which a droplet angle distribution can be determined.

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.

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 are 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.

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