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Evaluation of Center Pivot Sprinkler Wind Drift and Evaporation Loss

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***Abstract*.** Wind drift and evaporation losses (WDEL) that occur under sprinkler irrigation have been a research topic since the advent of sprinkler irrigation. Numerous research studies have reported WDEL values ranging from 0.7 to 45% of applied water. The wide range of sprinkler irrigation WDEL values reported in the literature has lead to misconceptions and confusion as to the amount of water lost to wind drift and evaporation among irrigation experts, irrigation industry personnel and the general public. The objective of this project was to develop and evaluate a methodology for measurement of WDEL from center pivot sprinklers using a combination of applied water collectors, bromide tracer and air samplers. The evaluation criteria were the magnitude of water volume balance error. A methodology for measuring wind drift and evaporation loss from center pivot sprinklers was developed and field tested under limited wind speed conditions. Volume balance errors ranged from 0.1 to 7.1%. The cause for the large errors on two occasions has not yet been determined. The percent of applied water aerosolized and measured as drift was found to be linearly correlated with wind speed. Overall, the limited tests show the methodology to be feasible for measuring WDEL from center pivot sprinklers. Tests in higher wind speeds are needed to validate the methodology as is determination and elimination of the cause for the high volume balance errors.

Keywords. *Sprinkler irrigation, Center pivot, Evaporation, Wind drift, Irrigation efficiency.*

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Introduction

Wind drift and evaporation losses (WDEL) that occur under sprinkler irrigation have been a research topic since the advent of sprinkler irrigation. Christiansen (1942) performed some of the earliest work to evaluate WDEL in California. He found WDEL from a single sprinkler ranged from 10 to 40%. Numerous WDEL studies have been undertaken over the past 70 years (Frost and Schwalen, 1955; George, 1955; Kraus, 1966; Sternburg, 1967; Robinson, 1973; Yazar, 1984; Kohl et al., 1987; Abo-Ghobar, 1992; Faci et al., 2001; Ocampo et al., 2003; Playán et al., 2005; Silva, 2006; Ortiz et al., 2009). Wind drift and evaporation loss values obtained from these studies were not defined in common terms nor were common methods of measurement employed (table 1). This has resulted in reported values for WDEL ranging from 1 to 45%.

All WDEL studies have utilized water collection devices of some form or another to capture water applied by one or more sprinklers to determine water applied soil and plant surfaces. Several studies (table 1) defined WDEL as the difference between sprinkler discharge based on application depth and average depth of water captured in collectors. This approach is subject to several sources of measurement error including collector catch efficiency, evaporation from collector interior surfaces, evaporation from water surface in collector, measurement of collector water volume (depth), measurement/estimation of sprinkler discharge, and spatial variability in water application depth. Of these potential measurement error sources, collector catch efficiency is likely the largest. Livingston et al. (1985) evaluated the effect wind has on collector catch efficiency in a wind tunnel experiment and found that in general catch efficiency decreased with increasing wind speed and collector height with values as low as 75%. Neff (1977) compared rainfall measurements between standard rain gauges and pit rain gauges and found catch efficiency was as low as 25% for some rain fall events. Thus, collector catch efficiency can have a substantial effect on measured WDEL. Evaporation from the water surface in a collector can be controlled using an evaporation suppressant, but this does not control evaporation from inside surfaces unless the collector is completely filled with the evaporation suppressant. Collector(s) containing a known volume of water are often located outside the microclimate of the sprinklers(s) to adjust for collector evaporation, but this does not account for evaporation from wetted inside collector surfaces. Winward and Hill (2007) investigated collector performance and found that water applied to collector inside surfaces evaporated at a higher rate than standing water. The traditional collector used in measuring water applied by sprinkler irrigation is subject to measurement errors which make it difficult for accurate and reliable measurement of application depth. Unfortunately there is no substitute for collectors in sprinkler evaluation tests but sources of potential measurement error must be recognized and minimized by collector design, installation and use.

Sprinkler WDEL studies focused on measuring evaporation only have used the increase in conservative tracer concentration of water caught in collectors to quantify evaporation of sprinkler droplets in flight (table 1). These studies have reported loss values of 1 to 15%. Using a conservative tracer circumvents measurement errors associated with collector catch efficiency but evaporation from wetted surfaces and water in the collector can result in measurement errors. Kohl et al. (1987) used the conservative tracer technique in combination with air sampling techniques to quantify center pivot sprinkler WDEL. They reported WDEL values of 0.4 to 1.4% for low pressure fixed plate spray sprinklers.

The wide range of sprinkler irrigation WDEL values reported in the literature has lead to misconceptions and confusion as to the amount of water lost to wind drift and evaporation among irrigation experts, irrigation industry personnel and the general public. Undoubtedly,

Table 1. Review of published wind drift and evaporation loss studies.

Investigator	Year	Method	WDEL definition	WDEL range, %
Abo-Ghobar	1992	Collector	Discharge – catch	15 - 36
Christiansen	1941	Collector	Discharge - catch	1 - 42
Frost and Schwalen	1955	Collector	Discharge - catch	3 - 45
George	1955	Collector	Increase in electrical conductivity	2 – 15
Kohl et al.	1987	Collector, air sampling	Increase in K^+ ion and collected K^+ ion mass water equivalent	0.4 – 1.5
Kraus	1966	Collector	Increase in Na^+ ion	3 – 9
Ocampo et al.	2003	Collector	Discharge – catch	0 - 22
Ortíz	2009	Collector	Dicharge – catch	8 - 14
Playán et al.	2005			5 - 15
Robinson	1973	Collector	Increase in electrical conductivity	0.7 – 8
Silva	2006	Collector	Discharge – catch	6 - 36
Sternburg	1967	Collector	Discharge – catch	11 - 25
Till	1957	Collector	Increase in electrical conductivity	0.7 – 2.7
Yazar	1984	Collector	Discharge – catch	2 – 31

some of the reported WDEL values are the result measurement errors. The uncertainty in the magnitude of WDEL with sprinkler irrigation systems has lead to increased scrutiny by environmental regulators on the use of sprinkler irrigation systems, namely center pivot sprinkler systems, for land application of animal and municipal waste water. The objective of this project was to develop and evaluate a methodology for measurement of WDEL from center pivot sprinklers. The evaluation criteria were the magnitude of water volume balance error.

Methods and Materials

The technique employed in this study to measure sprinkler WDEL is based on that of Kohl et al., (1987). Potassium Bromide with the Br^- ion for a conservative tracer was used to account for water evaporation from sprinkler droplets in flight, water evaporation from collectors, and water leaving the wetted pattern of the sprinkler due to aerosolization of small water droplets and drift. The volume balance equation for sprinkler irrigation can be represented as:

$$V_{spr} = V_{ap} + V_{ev} + V_a + V_{dr} \qquad (1)$$

where V_{spr} is the volume of discharge from the sprinkler (L), V_{ap} is the volume of water applied to plant and soil surfaces (L), V_{ev} is the volume of water evaporated from droplets in flight that do not completely evaporate (L), V_a is the volume of water in drops that completely evaporate (aerosolize) (L), and V_{dr} the volume of water that is deposited on downwind plant and soil surfaces that evaporates soon after contact (drift) (L).

Assuming that bromide mass does not change as water evaporates from droplets in flight, a conservative tracer mass balance between the sprinkler and collector at location *i* can be represented as:

$$V_c^i \cdot C_c^i = \left(V_c^i + V_{evc}^i + V_{ev}^i\right) \cdot C_{iw} \qquad (2)$$

where V_c^i is collector water volume (L), C_c^i is collector Br^- concentration (mg L^{-1}), V_{evc}^i is evaporation from collector (L), V_{ev}^i is droplet evaporation as it travels from the sprinkler to the collector (L), and C_{iw} is Br^- concentration of water in the sprinkler lateral (mg L^{-1}).

Assuming water that enters a collector represents water applied to soil and plant surfaces, V_{ap} at location *i* can be represented as:

$$V_{ap}^i = V_c^i + V_{evc}^i \qquad (3)$$

Substituting eqn. 3 into eqn. 2 and rearranging results in:

$$V_{ap}^i + V_{ev}^i = \frac{V_c^i \cdot C_c^i}{C_{iw}} \qquad (4)$$

For an array of equally spaced collectors, the sum of V_{ap} and V_{ev} (eqn. 1) can be computed as:

$$V_{ap} + V_{ev} = K_c \sum \left(\frac{V_c^i \cdot C_c^i}{C_{iw}} \right) \qquad (5)$$

where K_c is the ratio between the area of the field represented by one collector to its cross-sectional area. Thus, by measuring the volume of water and the concentration of the Br^- ion concentration in the collectors and the irrigation lateral, two of the components of the water balance (eqn. 1) can be determined.

The volume of water in drops that aerosolized was estimated using a vertical array of glass impingers (BioSampler, SKC Inc., Eighty Four, PA) (fig. 1) to capture Br^- ions in the air downwind from the sprinkler. The impingers were mounted at 1, 2, 4, 8, and 12 m above ground level on two towers and operated at a flow rate of 10 to 11 L min^{-1} (Lin et al., 2000)

The volume of aerosolized water droplets passing an impinger, V_{im}^i (L), at a particular vertical location is calculated as:

$$V_{im}^i = \frac{K_{im}^i \cdot M_{im}^i}{C_{iw}} \qquad (6)$$

where M_{im}^i is the mass of Br^- ion captured in the impinger (mg) and K_{im}^i is the ratio between the area of the vertical plane represented by impinger *i* to its cross-sectional area. The total volume of water aerosolized is calculated as:

$$V_a = \sum V_{im}^i = \sum \left(\frac{K_{im}^i \cdot M_{im}^i}{C_{iw}} \right) \qquad (7)$$

The volume of water deposited on downwind plant and soil surfaces that evaporates soon after contact (drift) and cannot be measured using standard collectors was estimated using a horizontal and vertical array of passive samplers (fig. 1). The passive samplers were constructed from light duty scouring pads (USI, Des Plaines, IL) with a dimension of 7.5 cm x 7.5 cm. The volume of drift, V_{dr}^i (L), at a particular passive sampler location *i* is calculated as:

$$V_{dr}^i = \frac{K_{dr}^i \cdot M_{dr}^i}{C_{iw}} \qquad (8)$$

Figure 1. Impinger and passive sampler installed on the tower.

where M_{dr}^{i} is the mass of Br^{-} ion captured on the passive sampler (mg) and K_{dr}^{i} is the ratio between the area of the vertical plane or field area represented by passive sampler *i* to its cross-sectional area. The total volume of drift is calculated as:

$$V_{dr} = \sum V_{dr}^{i} = \sum\left(\frac{K_{dr}^{i} \cdot M_{dr}^{i}}{C_{iw}}\right) \qquad (9)$$

The volume of water applied by a sprinkler, Vspr, is calculated as sprinkler flow rate multiplied by time of application. Volume balance error, VB_{error} (%), used to evaluate the methodology is calculated as:

$$VB_{error} = \left(\frac{V_{spr} - \left(V_{ap} + V_{ev} + V_{a} + V_{dr}\right)}{V_{spr}}\right) \cdot 100 \qquad (10)$$

Center pivot sprinkler irrigation water application was simulated using a 4-wheel commercial irrigation boom sprinkler system 50 m in length (Briggs Irrigation, Northhamptonshire, UK). The irrigation boom sprinkler system was modified by increasing the boom height 46 cm and adding additional sprinkler outlets along the boom length to provide a sprinkler height of approximately 1.2 m above ground level and a fixed sprinkler spacing of 2.43 to 2.59 m which varied randomly

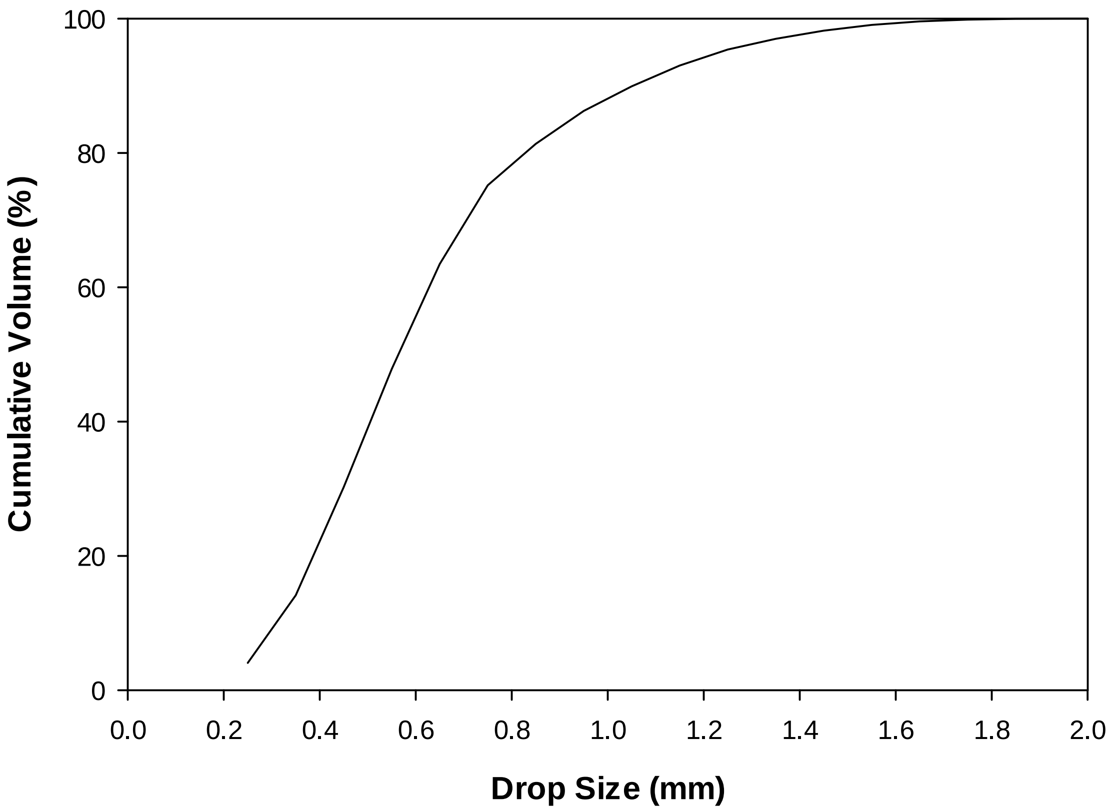

Figure 2. Drop size distribution for sprinkler used in tests.

along the boom. Twenty flat plate spray sprinklers (D3000[1] Nelson Irrigation Corp., Walla Walla, Wash.) equipped with Nelson 138 kPa pressure regulators and 5.1 mm nozzles were installed along the length of boom. The drop size distribution of this sprinkler is shown in figure 2. This sprinkler and pressure combination was selected to maximize wind drift and evaporation due to the relatively small drop size distribution. The stationary sprinkler boom was aligned perpendicular to the prevailing wind direction based on 10 years of hourly wind data at the research site.

Two adjacent lines of collectors aligned perpendicular to the sprinkler boom with 1 m spacing between collectors in a line were used to measure water applied (fig. 3). Collectors between the two lines were offset ½ spacing to effectively provide 0.5 m collector spacing perpendicular to the sprinkler boom. The collectors used were metal cans measuring 15.2 cm in diameter and 20.3 cm in height. The collectors were placed in pits (holes) excavated below ground level to maximize collector catch efficiency. The pits were lined with metal rings to maintain their integrity between tests and to minimize water entry into the pit causing the collector to float out of position during a test. The collectors were placed in the pits to a depth that positioned the

[1] Mention of trade name, proprietary product, or specific equipment does not constitute a guarantee or warranty by the authors or their institutions and does not imply approval of product to the exclusion of others that may be suitable.

Figure 3. Test site showing layout of collectors relative to sprinkler boom and vertical sampling tower with inset close up view of collector in pit.

collector opening 1 to 2 cm above ground level. The collectors were placed in the pits and leveled immediately before a test. The collectors were rinsed with distilled water between each test. A straw erosion mat was placed around the collector pits to minimize splash into collectors.

The two 12 m tall towers were located 20 m downwind from the sprinkler irrigation boom. The vertical passive samplers were installed at each impinger location, thus a total of 10 impingers and passive samplers were operated simultaneously on the towers. Six passive samplers were also installed on the ground surface between the towers and the extent of the sprinkler wetted radius using 2 m spacing between horizontal passive samplers.

A positive displacement injection pump was used to inject the high concentration KBr solution (~250,000 mg L^{-1}) into the applied water. The injection pump was started the instant water filled the water supply line at the location of injection. Two elbows and 30 m of pipe length insured adequate mixing of the KBr solution with the irrigation water before entering the sprinkler boom.

The duration of the tests was 30 minutes. A transit time ultrasonic flow meter was used to monitor flow rate into the sprinkler irrigation boom during a test. Wind speed and direction were recorded by a weather station within 50 m of the test site. Wind speed, relative humidity and air temperature were recorded every second and logged as 1 min average values. Wind direction was read once every minute and logged. The volume of water in the collectors was measured using a graduated cylinder immediately after a test. A subsample of the collector water was saved for Br^- ion concentration analysis. The impingers and passive samplers were installed immediately before a test and collected immediately after a test.

Bromide ion concentration in the collector water, impinger solution and passive sampler extraction solution was determined using flow injection analysis according to QuickChem method 10-135-21-2-B (Lachate Instruments, Loveland, CO). Bromide ions on the passive samplers were extracted with 60 ml of deionized water.

Results and Discussion

Five wind drift and evaporation tests have been conducted to date over a limited range in wind speeds with the results shown in table 2. The volume balance error for three of the five tests was less than 1.5% while volume balance error for two of the tests was greater than 6.5%. The large volume balance error of the two tests does not appear to be correlated with wind speed as higher wind speeds have resulted in small volume balance errors in the case of the 5/24/12 test. Thus, collector catch efficiency does not appear to be the source of error. The large volume balance errors do appear to be correlated with measured collector water volume (V_{col}, table 2) before adjustment for evaporation of droplets and evaporation from within the collector. The cause of this anomaly is unknown. The most likely explanation is that the sprinkler flow rate was less than estimated. Unfortunately, sprinkler irrigation boom flow rate was not monitored for the two tests with high volume balance errors. Subsequent tests where sprinkler irrigation boom flow rate was monitored did not result in large volume balance errors. Additional tests are needed to eliminate sprinkler flow rate variation as the possible cause of the error rather than some other unobserved element.

Another possible explanation for the large volume balance errors is unstable atmospheric conditions causing the Br^- ion to rapidly rise vertically, bypassing detection by the 12 m high impingers and passive samplers. Based on the solar radiation/delta T method for estimating Pasquill-Gifford stability categories (EPA, 2000), atmospheric stability categories ranged from A (very unstable) to B (unstable) for the five tests, without correlation with volume balance error

Table 2. Climatic conditions and results for tests conducted to date. The volumetric percentage of applied water represented by collector volume without adjustment for collector or droplet evaporation (V_{col}), adjusted for collector and droplet evaporation (V_{ap} + V_{ev}), aerosolized water (V_a), drift (V_{dr}) and water volume balance error (VB_{error}).

				% Volume applied by sprinkler				
Date	Wind speed m sec^{-1}	Air temperature ˚C	Relative humidity %	V_{col}	$V_{ap} + V_{ev}$	V_a	V_{dr}	VB_{error} %
9/28/11	3.3	20.0	43.0	96.1	96.8	1.1	0.6	1.5
5/11/12	3.7	15.0	23.0	87.8	90.0	2.3	0.6	7.1
5/24/12	2.5	13.6	35.6	90.2	92.1	0.9	0.5	6.8
6/01/12	2.7	25.4	27.9	96.6	98.9	0.7	0.3	0.1
6/06/12	2.5	9.3	51.6	96.8	99.0	0.0	0.2	0.7

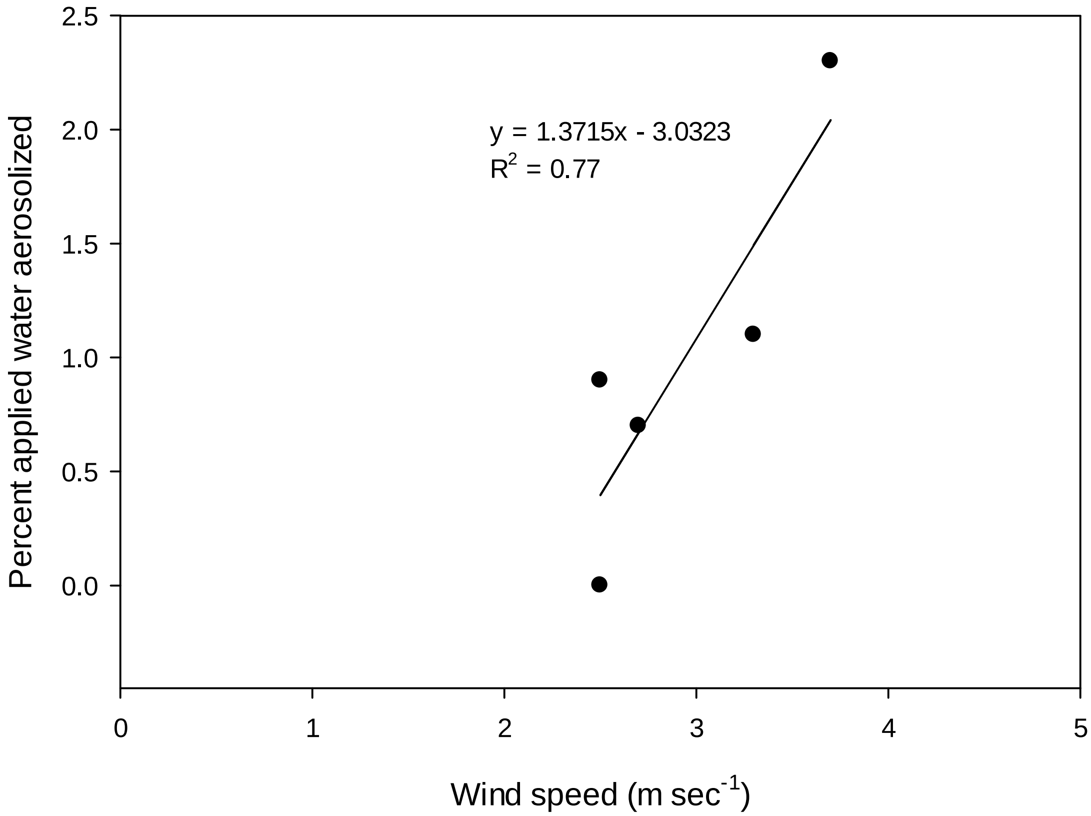

Figure 4. Percent of applied water aerosolized as affected by wind speed.

(data not shown). Thus, instability in atmospheric conditions could certainly play a part in the large volume balance errors on occasions, but not likely in this situation as there is little difference in atmospheric stability between tests.

The percent of applied water aerosolized (V_a, table 2) does appear to be linearly correlated with wind speed, figure 4, which is expected based on underlying physical principles of droplet evaporation in flight. Based on this result, use of the impingers for sampling Br^- ion concentration in the air passing the vertical sampling plane does appear to be appropriate.

The percent of applied water measured as drift (V_{dr}, table 2) also appears to be linearly correlated with wind speed, figure 5, which is also expected based on under lying physical principles of sprinkler droplet flight. Based on this result, use of the passive samplers for measuring water volume that evaporates shortly after impact outside the wetted area of the sprinkler system appears to be appropriate.

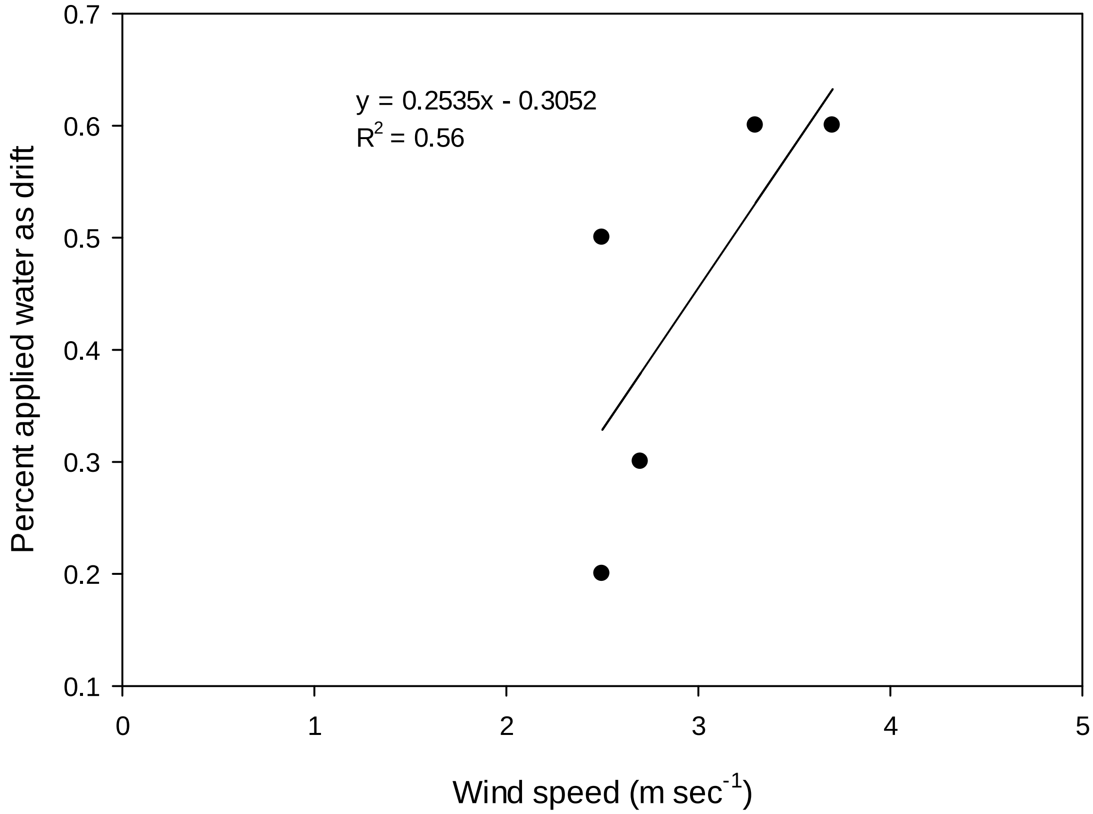

Figure 5. Percent of applied water measured as drift as affected by wind speed.

Overall the limited results from use of the developed methodology to measure WDEL from center pivot sprinklers appears to be feasible. Tests in higher wind speeds are needed to validate the methodology as is determination or at least elimination of the cause for the high volume balance errors.

Conclusion

A methodology for measuring wind drift and evaporation loss from center pivot sprinklers was developed and field tested under limited wind speed conditions. Volume balanced errors have ranged from 0.7 to 7.1%. The cause for the large errors has not yet been determined. The percent of applied water aerosolized and measured as drift was found to be linearly correlated with wind speed. Overall the limited results from use of the methodology to measure WDEL from center pivot sprinklers appears to be feasible. Tests in higher wind speeds are needed to validate the methodology as is determination and elimination of the cause for the high volume balance errors.

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