SIMULATING [illegible]

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Abstract: The uniformity of irrigation systems is important to efficiency, yield, and economics. Wind strongly affects this uniformity. A method is presented for simulating the operation of a sprinkler system in wind. Equations describing the motion of airborne water droplets are shown. The trajectories of water droplets ejected from a sprinkler were numerically computed. Composite results led to predictions of application patterns. Sprinkler droplet size distribution was used to predict the pattern around a sprinkler, and patterns were superimposed to represent a set (not continuously moving) system. Coefficients of uniformity were then computed. The model was validated by comparing predictions with observed application patterns. Individual and multiple sprinkler tests were compared. The simulation system appeared to be an effective predictor of sprinkler performance in wind. Use of this type model can lead to improved sprinkler designs, although variability of the wind vector affects the accuracy of prediction.

Introduction

In many areas of the world, agricultural production depends upon efficient irrigation. If the water necessary for plant growth is not applied uniformly, yields will be adversely affected. Furthermore, in many areas the water available for irrigation is limited, so irrigation systems must apply water so plants can use it efficiently.

Irrigation systems are often designed without adequately considering the effects of wind, and if wind is considered it is only in a very general sense. It has been shown that wind can greatly affect sprinkler performance. If the effect of the magnitude and direction of the wind velocity is not sufficiently considered in the design of a sprinkler irrigation system, the resulting system's performance may be suboptimal. The water jet leaving a sprinkler breaks into individual drops, and thus a ballistics approach may be used to predict the paths of the individual drops. The collective effect of the wind on the individual drops is the effect of the wind on the system.

When an area is subject to a wind of nearly constant magnitude and direction, the wind can be considered in the design of the system. However, the wind velocity is seldom constant. A model that predicts the effect of wind upon the distribution pattern of water from a sprinkler would be a useful tool to aid in the design and efficient operation of irrigation systems. Designs could be tested for their suitability under the prevailing wind conditions for a given area. The model could also be used to analyze existing systems.

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Note.—Discussion open until July 1, 1987. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on April 24, 1986. This paper is part of the *Journal of Irrigation and Drainage Engineering*, Vol. 113, No. 1, February, 1987. ©ASCE, ISSN 0733-9437/87/0001-0119/$01.00. Paper No. 21274.

$$-C_2 V_r V_x = \frac{d^2x}{dt^2} \quad (4b)$$

$$-C_2 V_r V_y = \frac{d^2y}{dt^2} \quad (4c)$$

in which V_x, V_y, V_z = three directional components of the velocity vector; V_r = resultant of the three component velocities; x, y, z = three directional components of drop position; and t = time.

Values of C_2 as a function of drop size were reported by von Bernuth and Gilley (1984). They combined the findings of Laws (1941), Green (1952), and List (1966) to obtain values for drops up to 6 mm in diameter.

The velocities referred to in Eqs. 3 and 4*a–c* are all relative velocities of a drop with respect to the air. If the air is in motion (i.e., a wind is blowing), the directional components of the wind vector can be added to the components of the drop's velocity vector. V_r would then be calculated as the resultant of the relative velocity components.

The velocity of the air moving past a given point is a function of the height above the boundary. Sutton (1953) suggested that in a stable environment, the velocity of the wind at a given height, a, in cm can be approximated by

$$\frac{U_a}{U_*} = \frac{1}{k} \ln\left(\frac{a-d}{Z_0}\right) \quad (5)$$

in which U_a = average air velocity (m/s) at height a; U_* = friction or shear velocity (m/s); k = von Karman constant; d = roughness height (cm); and Z_0 = roughness parameter (cm).

The value of U_* is independent of height for a given adiabatic situation, so the wind velocity U_w (m/s) measured at a reference height w (cm) can be related to the velocity U_a at any other height a by

$$U_a = U_w \frac{\ln\left(\frac{a-d}{Z_0}\right)}{\ln\left(\frac{w-d}{Z_0}\right)} \quad (6)$$

The roughness height, also called the zero-plane displacement, accounts for the shift of the logarithmic curve vertically over a crop canopy. Stanhill (1969) defined the roughness height d in terms of the crop height h (cm) by

$$\log d = 0.9793 \log h - 0.1536 \quad (7)$$

The roughness parameter is a way to describe the ground surface or plant canopy. Tanner and Pelton (1960) related the roughness parameter Z_0 to the crop height h by

$$\log Z_0 = 0.997 \log h - 0.883 \quad (8)$$

Distribution Model

Previous modeling of sprinkler performance in wind was done by Fukui, et al. (1980), who used still air distribution patterns to predict sprinkler performance in windy conditions. Other work involving wind effects on sprinkler patterns was done by Seginer and Kostrinsky (1975).

The inputs to the model described in this paper include water pressure at the nozzle, vertical angle of the nozzle housing, height of the nozzle above the ground, wind speed and direction at a given height, crop height, and the proportions of the total flow in the disturbed and undisturbed streams. The relative volumes of all drop sizes, from 0.2 mm in diameter to the maximum (which varies with the sprinkler and pressure) in 0.1 mm increments are also input. Relative volumes are derived by assuming that all water emitted by the sprinkler can be characterized by one of those specific sizes. Separate size distributions and relative volumes are used for the disturbed (by the arm) and undisturbed streams.

Calculations within the model determine the distance each drop will travel from the sprinkler. The magnitude of the initial velocity vector for the undisturbed stream is calculated using Eq. 1, with a value of 0.98 for c and the pressure that was input. The angle is assumed to be equal to the angle of the housing. The magnitude of the initial velocity vector for the disturbed stream is assumed to be 70% that of the undisturbed. Although drops from the disturbed stream depart approximately normally to the undisturbed stream, that fact was ignored because the effect is inconsequential in a 360° rotation of the sprinkler. The same angle was used for the initial velocity vectors of both streams.

The effect of wind is included in the drag terms of Eq. 4*a–c*, which can be solved using a numerical integration technique such as a fourth order Runge-Kutta (Hornbeck 1975). This method uses the initial location and velocity components, wind components, and drag coefficient. Eqs. 6–8 are used to determine the wind speed at heights other than the given height. The volume of water associated with a drop size is determined by the volume relative frequency of that drop. Drops of the disturbed stream have a different initial velocity vector and origin from the undisturbed, making it necessary to perform the ballistics calculations separately for the disturbed and undisturbed streams. The resulting volume of water at each location is the sum of the volumes of water from all drops that are predicted to land at that location.

In the model, the undisturbed stream is assumed to travel one m along the initial velocity vector before breaking into individual drops, but the water disturbed by the arm is assumed to form individual drops immediately. Although the 1-m distance is arbitrary, von Bernuth and Gilley (1984) reported that it fit their data. To account for the rotation of an actual sprinkler, the initial velocity vector is rotated about the sprinkler in one-degree increments.

The area around the sprinkler is divided into a square grid. The relative volumes of all drops predicted to land within a square are summed. These volumes are made non-dimensional by dividing each volume by the average volume of all squares receiving water. The result is a pattern of relative depths surrounding the sprinkler. The numbers in the grid can be adjusted to represent an actual application of water, or they can be used in statistical calculations without adjustment.

Seginer and Kostrinsky (1975) reported that three factors cause a loss of water between the sprinkler and the collectors: (1) Evaporation; (2)

drift of drops out of the sample area; and (3) splash loss from the collectors. A significant wind would increase all three types of losses. In the model presented in this paper, however, it is assumed that no water is lost.

The squares on the grid surrounding the sprinkler in the model are treated as collectors. Grids are overlapped according to sprinkler spacing to account for the contributions from nearby sprinklers operating in the field, and the appropriate relative depths are summed. The combined contributions of all sprinklers produce repeating blocks of collectors. Formation of repeating blocks requires that all of the contributing sprinklers have identical distribution patterns, which may not be the case in the field. In a well designed system, however, the variation among the patterns of nearby sprinklers should be small. C_u values are calculated from the depths in a repeating block.

Tests Conducted

To satisfy the objectives of this study, model tests were conducted to simulate conditions observed by the USDA Agricultural Research Service in Akron, Colorado. All tests were conducted using a 30 *H* Rainbird (Mention of a brand or trade name is for information purposes only. No endorsement of any product should be herein construed.) impact sprinkler with a 3.57-mm main nozzle and a brass plug in place of the spreader nozzle. Drop size distributions and corresponding relative volumes were estimated with a model developed by von Bernuth and Gilley (1984). That model used data from a single leg test conducted at the University of Tennessee Agricultural Engineering Laboratory under conditions of no wind and high relative humidity. The single leg test was conducted in accordance with ASAE Standard S398T (ASAE 1984).

One set of observed data was from a series of one-hour tests in which water was caught in 96-mm diameter collector cans set upon the ground surface on a 3-m grid around one sprinkler located 2.4 m above the ground. A drop of light viscosity oil was put in each collector to retard evaporation. Catch was measured with a graduated cylinder following each test. Wind velocity and direction were recorded at the 2.4 m height on a strip chart recorder and averaged for the duration of the test. The pressure was measured near the base of the riser during each test and averaged approximately 410 kPa for all of the tests. The tests were conducted during 1983 and 1984.

Another set of data was from a series of multi-hour tests within two laterals operating simultaneously. The spacing between sprinklers on a lateral was 12 m, and rectangular spacing patterns were always used. The spacing between laterals was either 12 m or 18 m, depending upon the test. An average water pressure of approximately 410 kPa was again observed. The sprinkler height was 2.4 m for corn and 1.0 m for grain sorghum. The height of the collectors, 102 mm in diameter, varied from 0.8 m in the sorghum plots to 2.1 m in the corn plots. The tests were conducted at different times during the growing seasons of 1978 and 1979.

Results

A comparison between the model-generated single leg distribution and actual test data is shown in Fig. 2. A cubic spline interpolation routine was used to smooth the observed data. The test was conducted with the same water pressure at the nozzle as the average observed during the field tests in Akron. The curve for predicted values varies somewhat from the one for observed values, but that was expected. The true distribution pattern is the result of the formation of an almost infinite number of drop sizes, each of which travels a unique distance. However, the distribution curve is not nearly as smooth when the process is approximated by fewer drop sizes. If a drop of water lands within a square, the model acts as though the drop landed at the square's center. This leads to cases in which one of the squares receives drops of only one size from the undisturbed jet, while other drop sizes land just outside that square. One square may appear to have too much water, while adjacent squares appear to have too little. When a drop size increment of 0.2 mm was used (as opposed to the current increment of 0.1 mm) the predicted curve was less smooth. Some of the squares received no water from the undisturbed jet, leading to a poorer approximation of the observed single leg curve.

The predicted single leg curve would be smoother if more drop sizes were included in the model. However, computer time and cost precluded using a smaller increment. The model accounts for the entire assumed drop size distribution for a sprinkler along the initial velocity vector. The vector is rotated one degree at a time to account for the rotation of the sprinkler, and the process is repeated. The University of Tennessee's IBM VM 4381-2 mainframe computer requires approximately 15 min of CPU time to produce a full grid around a sprinkler. Doubling the number of drops considered (i.e., halving the increment) would double

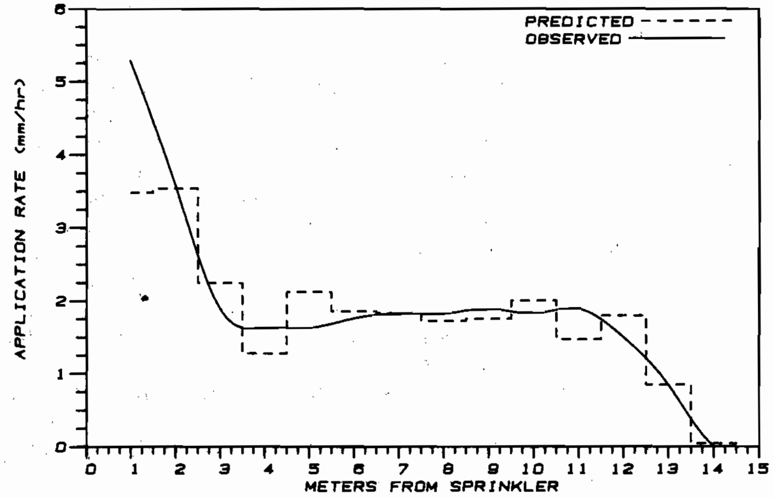

FIG. 2.—Predicted and Observed Single Leg Distribution Curves

the program's execution time. The need for a smoother predicted curve is somewhat reduced, however, because overlapping the grids tends to smooth the peaks and valleys before the uniformity coefficients are calculated.

The data from the single sprinkler tests were studied and nine of the tests were simulated. Wind speeds during the tests ranged from 1.5–4.5 m/s. The predicted and observed water applications were compared by creating contour and three-dimensional plots with the GCONTOUR and G3D procedures, respectively, of SAS/GRAPH (SAS Institute 1981). Examples of the results of the G3D procedure for predicted and observed catches during a 2.5 m/s wind are shown in Figs. 3 and 4.

Statistical comparisons were not performed. The wind speeds and directions reported for the observed tests were averages of conditions that varied during the tests. Because average values were used, the field tests were not exactly duplicated in the simulation. No attempt was made to quantify the error that resulted from this simplified procedure. With accurate wind vector data, more exact duplication is possible, but program execution time would increase proportionately.

Analysis of the nine sets of plots revealed two trends. First, more collectors were predicted to contain water than actually received measurable water in the field. One reason for the greater number of collectors receiving water in the model is the size of the grid. If the model predicted water to land in a 1-m square containing the collector, then the collector was predicted to receive water. It would be possible for water to reach the square in the field without reaching the collector. However, reduction of the model grid to less than 1 m would not be practical. It is also possible that some low calculated values may correspond to immeasurable volumes of water.

Second, predicted depths near the center of the distribution were less than observed depths, while predicted depths further out were greater than observed. The predicted depths exhibited less variation than those observed, probably also due to the grid size. If water reached the 1-m square containing the collector, then all water within the 3-m grid square was assumed caught in the collector. Including all of the water within the grid square probably reduced the effect of less water being caught as distance increased from the center of the distribution. Predictions based on a smaller grid size would show more of the variation seen in the single leg curve (Fig. 2), but should produce better predictions.

Thirteen multiple sprinkler tests were simulated. Wind speeds ranged from 0.5–5.9 m/s. The predicted and observed water applications were compared by calculating Christiansen's C_u for the collectors located between the two operating laterals. For the 12 m × 12 m spacings, 32 collectors were used for each C_u value calculated. For the 12 m × 18 m spacings, 24 collectors were used to calculate each C_u. Table 1 contains the results of the 13 comparisons.

As with the single nozzle comparisons, statistical hypotheses were not tested. However, it is still worthwhile to compare the simulations to results from the field. One of the comparisons (case 7) resulted in considerably more disagreement than the others (i.e., a difference of −13 C_u points). Unfortunately, there is no way to know if the disagreement is due to a problem in the field observations, the simulation, or some com-

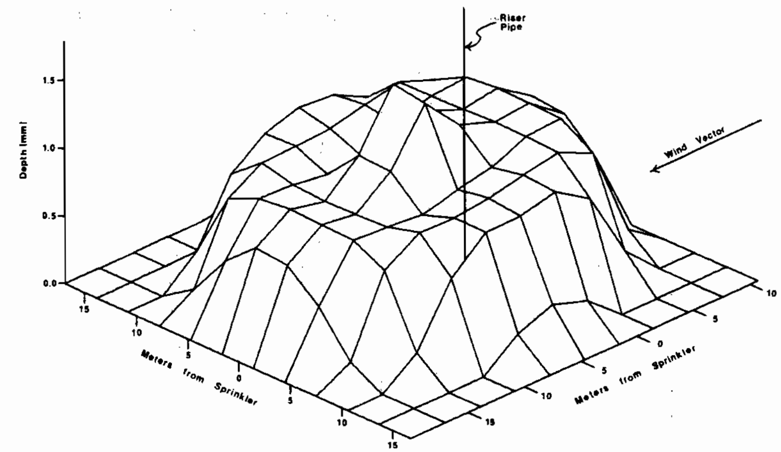

FIG. 3.—Predicted Depths of Water around Sprinkler during 2.5 m/s Wind

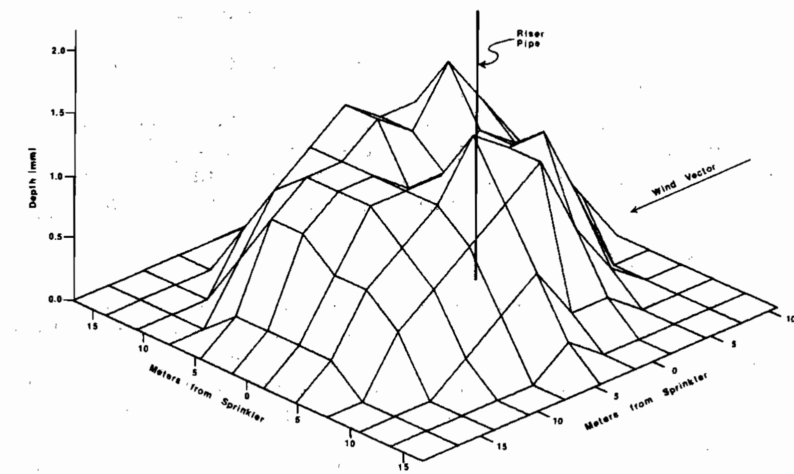

FIG. 4.—Observed Depths of Water around Sprinkler during 2.5 m/s Wind

bination. Even with that worst case included, the average disagreement for the thirteen cases was −2.0 C_u points, or 2.0 points higher for predicted than observed.

A trend observed in the multiple sprinkler comparisons was a tendency to slightly overpredict C_u for lower wind conditions and underpredict C_u for higher wind conditions, which can be seen in Table 1. A probable reason is the variability of the wind vector under field conditions which tends to ameliorate C_u and make the field C_u better than the predicted C_u. Solomon (1979) showed that in order to distinguish small C_u differences (3 points or less) at the 80% C_u level at any reasonable confidence level at least four replications of the field test would be re-

TABLE 1.—Comparison of Observed and Predicted Coefficients of Uniformity

Case (1)	Spacing (m) (2)	Wind speed (m/s) (3)	Nozzle height (m) (4)	Christiansen's Coefficient of Uniformity		
				Observed (5)	Predicted (6)	$O - P$ (7)
1	12×12	1.1	2.4	92	91	1
2	12×12	2.7	2.4	82	81	1
3	12×12	2.5	2.4	83	88	−5
4	12×12	2.2	2.4	86	86	0
5	12×12	1.8	1.0	87	86	1
6	12×12	5.9	1.0	82	85	−3
7	12×12	4.8	1.0	73	86	−13
8	12×18	3.2	2.4	81	83	−2
9	12×18	3.2	2.4	80	82	−2
10	12×18	4.3	2.4	73	80	−7
11	12×18	4.3	2.4	86	87	−1
12	12×18	0.5	2.4	88	84	4
13	12×18	0.5	2.4	87	86	1

Note: Mean $(O - P) = -2.0\%$.

quired. That was not feasible. If case 7 is disregarded, the model predicted field conditions quite well.

It is important to note that during each of the field tests the wind speeds and directions were varying. Furthermore, due to plant height variation the canopy was uneven. The simulation conditions were a constant wind speed from a constant direction over a uniform crop canopy.

Drawbacks to the Model

Although the model discussed in this paper can be quite useful, it does have deficiencies. One problem is that an accurate estimate of the drop size distributions and relative volumes is necessary. The model cannot predict either a radius of throw for a sprinkler or the depths along that radius without a good estimate of the drop size distribution produced by the sprinkler.

Computer time is also a consideration. Simulating a sprinkler irrigation system could be expensive and slow. Personal computers are capable of performing all of the necessary operations, but those computers operate at a much slower rate than the larger mainframe computers. However, computers are constantly being improved and that time difference may become insignificant.

A better understanding of the pertinent aerodynamic processes might improve the model. For example, von Bernuth and Gilley (1984) discuss an envelope of air around the jet of water, with relative velocities between the air and water reduced within that envelope. Furthermore, not enough is known about the breakup of the jet. It seems reasonable that the water may remain as a stream longer downwind than upwind, but the actual relationship is not known.

Finally, most studies on drag forces and the resulting drag coefficients have dealt with drops falling vertically. When the drop is also moving horizontally relative to the air, the drag characteristics may be different. Such motion is more difficult to study because the drop cannot be held in a vertical wind tunnel and observed.

Summary and Conclusions

This study has shown that it is possible to simulate sprinkler operation in windy conditions. The use of such a model can form the basis for evaluating sprinkler designs for field conditions without the need for the extensive field testing that would otherwise be necessary. How well the model simulates actual performance depends on how well actual conditions are described. Variability of the wind vector will affect the accuracy of the model, as will shortcomings that are built into the model due to assumptions. Two key assumptions are: (1) The use of the vertical terminal velocity drag coefficient under all conditions; and (2) the jet breakup at a finite distance from the sprinkler. Nonetheless, the model does predict field performance reasonably well and is seen as a potential tool for irrigation systems analysis.

Appendix I.—References

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Appendix II.—Notation

The following symbols are used in this paper:

a = height of interest for wind;
C = coefficient;
c = nozzle coefficient;
D = aerodynamic drag force;
d = roughness height, or zero-plane displacement;
f = drag acceleration;
g = acceleration due to gravity;
H = pressure head;
h = crop height;
k = von Karman constant;
m = mass of water drop;
N = number of collectors;
t = time;
U = air velocity;
V = water drop velocity;
v = velocity of water through nozzle;
w = reference height for wind;
x = horizontal directional component of position;
$\bar{x}$ = mean collector amount;
x_i = individual collector amount;
y = horizontal directional component of position (perpendicular to x);
Z_0 = roughness parameter;
z = vertical directional component of position;
Σ = summation of N values; and
$| \; |$ = absolute value.

Subscripts

a = at height a;
n = drag (related to exponent n);
r = resultant;
u = uniformity;
w = at reference height w;
x = horizontal direction component;
y = horizontal direction component (perpendicular to x);
z = vertical direction component; and
$*$ = friction or shear.

Superscript

n = drag exponent for velocity.