BARD

FINAL REPORT

PROJECT NO. US-1001-85

The Effect of Wind on Sprinkler Distribution Patterns

R.D. von Bernuth, I. Seginer

1990

Date: March 16, 1990

BARD

P.O. Box 6

Bet Dagan, ISRAEL

BARD Project No. BARD -US- 1001 - 85

Title

The Effect of Wind on Sprinkler Distribution Patterns

Investigators' Names

(Principal listed first)

Investigators' Institutions

Robert D. von Bernuth

Ido Seginer

University of Tennessee

Technion

Project's starting date: August 1986

Type of Report: 1st Annual ☐ 2nd Annual ☐ Final ☒

Signatures

Principal Investigator

Institution's Authorizing Official

Robert D. von Bernuth

Don O. Richardson

ABSTRACT

This report is a collection of four separate chapters, each representing cooperative work between the U.S. and Israeli investigators. Abstracts of each of the four chapters are presented below.

Chapter 1, An Automated Indoor Apparatus for the Determination of Single-Radius Sprinkler Water-Distribution Patterns.

An automatic apparatus for measuring single-radius sprinkler water distribution patterns was designed and constructed. Unattended tests could be conducted sequentially for a single sprinkler. Operating pressure and riser tilt were changed automatically between test runs. Water heights in the gages were measured sequentially by a single pressure transducer. Computer-controlled solenoid valves were used to connect gages to the transducer and to drain the system.

Comparisons among results were made on the basis of normalized unit patterns. The normalization considered the effect of tilt. The results of more than 200 test provided an estimate of the errors of measurement. The transducer error was less than 1% of the reading, but variation among replications was an order of magnitude larger.

Chapter 2, Wind-Distorted Single-Sprinkler Distribution Patterns

Simulation of water distribution of sprinkler systems under field conditions requires a data base consisting of individual water distribution patterns. These patterns are modified by drift, evaporation, and distortion, caused by wind and evaporative demand. A simple method for adjusting patterns to changing weather conditions, assuming spray loss is distributed proportionally over the pattern was developed.

A set of wind dependent patterns was obtained, which can be used for simulation. These patterns can be interpolated for any desired wind speed, rotated to the required direction and corrected for the spray loss appropriate to the environmental conditions.

Chapter 3, Comparison of Overlapped Wind-Distorted Single-Sprinkler Patterns with Field Measured Overlapped Patterns

Single sprinkler wind-distorted distributions were overlapped for comparison with field measured overlapped patterns. Two measures of similarity were computed. Coefficients of uniformity and normalized sums of squares of differences between the measured and simulated patterns were computed and compared. Both measures indicated that the field patterns could be reasonably well simulated with the interpolation/rotation/overlap technique.

Field measurements of evaporation in the U.S. confirmed earlier results by other researchers and were similar to measurements in Israel. A prediction equation for evaporation was developed.

Chapter 4, Simulation of Wind-Distorted Sprinkler Patterns

Single-sprinkler wind-distorted distribution patterns were simulated, utilizing drop trajectory computations and compared with measured patterns. It was found that the exact formulation of the drag coefficient of single drops is not critical for applications focusing on water distribution. A drag correction factor, k , to account for the effect of the incidence angle between the drag force and the orientation of jet segments was introduced. The agreement between measured and computed patterns was found to improve considerably when the proper value of k is used.

Three measures of similarity were used, with the most comprehensive measure being the normalized sum of squares of differences. The values of k which produce the best agreement seem to be an increasing function of the range of a sprinkler.

Single-patterns computed with the best values of k were used to calculate uniformity coefficients for a realistic spacing of the medium-pressure sprinklers under consideration. The results suggest that the computational method can be used to forecast, with an error of only a few percent the uniformity of application under wind-speeds as high as 8 m/s. Considering the effort involved in field measurements, this seems a viable alternative.

- 28.8 kph

ORIGINAL OBJECTIVES

The original objective of the research was to develop the procedures and techniques required to perform the computations necessary to predict wind-distorted sprinkler patterns. Starting with non-distorted patterns and the laws governing jet ballistics, the wind-distorted patterns of individual and overlapped sprinklers were to be predicted. Input to the prediction model was to come from laboratory testing, and that would entail development of laboratory test procedures capable of providing the information.

DESCRIPTION OF COOPERATION

The cooperation on this project was exceptional. Activities were identified at the inception of the project, and the investigators identified which tasks could be best accomplished by their respective institutions, and were reviewed in personal meetings annually. As the annual reports indicated, each of the investigators worked closely with the other in developing information essential to the next stage of the project, and the final results show that the individual parts fit together for the final result. Four major parts of the project evolved, and they were written as individual chapters. Each part had significant input from both parties.

The indoor apparatus in Chapter 1 was developed at Technion, but results were compared to those obtained in the indoor facility at Tennessee. The patterns developed at Technion (Chapter 2) were the input for the simulation portion of Chapter 3. The field tests and overlap programs in Chapter 3 were developed at Tennessee. Finally, the simulation of wind-distorted sprinkler (Chapter 4) was developed at Technion but used models developed at Tennessee as a reference and starting point. All of the droplet size testing necessary for this chapter was done at Tennessee.

EVALUATION OF RESEARCH ACHIEVEMENTS

We believe that there were three major achievements in this project with several lesser achievements.

1. The automation of an apparatus for measuring single-radius sprinkler water distribution patterns. The facility developed allowed for the unattended collection of sprinkler test data while the operating pressure and riser tilt were being automatically controlled. Data were collected automatically by a computer-controlled sensing system.
2. The ability to take laboratory data and produce wind-distorted sprinkler patterns with some degree of confidence is a first. It is not the first time computer simulation has been used to produce these patterns, but it is the first project to systematically confirm key steps of the process, identify critical problems, and develop methods of coping with those problems. Each critical step of the simulation process was confirmed against laboratory or field tests. The fact that some sprinklers have reduced pattern widths normal to the wind had been discovered before, but the effect that has on uniformity and orientation of the grid had not been investigated. Drop ballistics models used before do not account for this narrowing of the pattern, and a method for doing so was developed. A fast and reasonably accurate method of simulating sprinkler patterns from laboratory data using ballistics theory was developed.
3. Wind and the evaporative demand of air cause the loss of water from the sprinkled area in the form of drift and evaporation. The components of drift and evaporation are difficult to separate,

but bear significantly on the final distribution and net application of a sprinkler system. Field test data were used to quantify the evaporation component and produce a method whereby a sprinkler pattern can be corrected for predicted evaporation.

A realistic approximation of field performance of a sprinkler system can be obtained by using the two developments of this project. Starting with laboratory produced data and ballistics theory, wind-distorted sprinkler patterns corrected for evaporation can be produced, and the expensive, tedious, and often non-representative process of field testing can be virtually eliminated for most cases. This was the objective of the research project.

The benefit to agriculture will take time to appear as the method is adopted and improved, but system designs and use efficiency should be substantially improved.

LIST OF PUBLICATIONS

The publications which will come from this project will come from the individual four chapters. None of them have been submitted for publication yet.

TABLE OF CONTENTS

CHAPTER

Page

I	AN AUTOMATED INDOOR APPARATUS FOR THE DETERMINATION OF SINGLE-RADIUS SPRINKLER WATER DISTRIBUTION PATTERNS	1
	Abstract	1
	Notation	1
	Introduction	2
	Apparatus	3
	1. Water Delivery System	4
	2. Collecting and Measuring System ..	5
	3. Control System	5
	Procedure	5
	Test Program	7
	Results: Discharge	8
	1. Discharge Coefficient	8
	2. Discharge Ratio	8
	Results: Pattern	10
	1. Profiles	10
	2. Moments	12
	Discussion and Conclusions	13
	1. Apparatus	13
	2. Data	14
	Appendix A: The Effect of Riser Tilt on the Precipitation Rate	15
	Appendix B: Derivation of Q_0	17
	References	17
	Acknowledgements	18
	List of Figures	23
II	WIND-DISTORTED SINGLE-SPRINKLER DISTRIBUTION PATTERNS	35
	Abstract	35

1	Notation	35
2		
3	Introduction	36
4		
5	Spray Evaporation	37
6		
7	Proposed Approach	40
8		
9	General	40
10	Analysis Stage	40
11	Synthesis (simulation) Stage	40
12		
13	Experimental Procedure	41
14		
15	Collector Evaporation Correction	42
16		
17	Patterns for Local Summer Conditions	43
18		
19	Corrections for Spray Evaporation and Drift.	45
20		
21	Discussion and Conclusion	47
22		
23	Appendix A: Spray Evaporation As A Function	
24	Of Wet-Bulb Depression	48
25		
26	References	49
27		
28	Acknowledgements	50
29		
30	List of Figures	55
31		
32	III COMPARISON OF OVERLAPPED WIND-DISTORTED SINGLE	
33	SPRINKLER PATTERNS WITH FIELD MEASURED OVERLAPPED	
34	PATTERNS	66
35		
36	Abstract	66
37		
38	Notation	66
39		
40	Introduction	67
41		
42	Pattern Interpolation	67
43		
44	Pattern Rotation	68
45		
46	Overlapping of Patterns	69
47		
48	Field Collected Grid Data	69
49		
50	Comparison of Overlapped Single Sprinkler	
51	Patterns to Field Grid Patterns	69
52		
53	Water Losses in the Field	71
54		
55	Discussion and Conclusions	73

1		
2	References	74
3		
4	Acknowledgements	74
5		
6	List of Figures	77
7		
8	IV SIMULATION OF WIND-DISTORTED SPRINKLER PATTERNS ..	87
9		
10	Abstract	87
11		
12	Notation	87
13		
14	Introduction	88
15		
16	Spray Drag	90
17		
18	Spray Trajectory Computation	91
19		
20	Comparisons with Still-Air Data	93
21		
22	Comparisons with Field Data	95
23		
24	Discussion and Conclusion	98
25		
26	Appendix A: Derivation of Equation (3)	100
27		
28	Appendix B: Outline of Computations	101
29		
30	References	102
31		
32	List of Figures	105
33		
34		
35		
36		

1
2 **AN AUTOMATED INDOOR APPARATUS FOR THE DETERMINATION OF SINGLE-RADIUS**
3 **SPRINKLER WATER-DISTRIBUTION PATTERNS**

4
5 Ido Seginer, Dvora Kantz, Dov Nir
6 Department of Agricultural Engineering, Technion, Haifa 32000, Israel

7
8 R. D. von Bernuth
9 Department of Agricultural Engineering, University of Tennessee,
10 Knoxville, Tennessee

11
12 **ABSTRACT**

13
14 An automatic apparatus for measuring single-radius sprinkler water
15 distribution patterns was designed and constructed. Any number of
16 unattended tests could be conducted sequentially for a single sprinkler.
17 Operating pressure and riser tilt were changed automatically between test
18 runs. Water heights in the gages were measured sequentially by a single
19 pressure transducer. Computer-controlled solenoid valves were used to
20 connect gages to the transducer and to drain the system.

21
22 Comparisons among results were made on the basis of normalized unit
23 patterns. The normalization considered the effect of tilt, since this
24 affects the amount of water collected along the radius.

25
26 About 200 test runs were carried out. These provided an estimate of the
27 errors of measurement. The transducer error was less than 1% of the
28 reading, but variation among replications was an order of magnitude
29 larger.

30
31 **NOTATION**

32		SI units
33	main symbols	
34		
35	A nozzle cross area	m ²
36	b depth of water	m
37	c discharge coefficient	-
38	g gravitational acceleration	m/s ²
39	H pressure head	m
40	L length of nozzle (from axis of riser to tip of nozzle)	m
41	M mean of distribution	m
42	m normalized central statistical moment	-
43	p precipitation (water application) rate	m/s
44	Q sprinkler discharge	m ³ /s
45	q discharge ratio	-
46	R pattern radius	m
47	r radial distance from sprinkler	m
48	t time	s
49	v ordinate of normalized distribution pattern	1/m

1 x, y, z field coordinate system for trajectory calculations m
2 x',y',z' sprinkler cartesian coordinate system m
3
4 α azimuth angle of nozzle in horizontal (field) plane rad
5 θ elevation angle of nozzle relative to sprinkler's equator rad
6 τ angle of riser relative to line of precipitation gages rad
7 σ elevation angle of nozzle relative to horizon (field) rad
8 μ meridian angle of nozzle rad
9

10 subscripts

11
12 g precipitation gages v volumetric method
13

14 superscripts

15
16 ' alternative
17

18 INTRODUCTION

19
20 Sprinkler water distribution patterns are determined for several uses,
21 including the following:
22

- 23 1. Research.
- 24 2. Development of new sprinkler prototypes.
- 25 3. Manufacturers' quality control.
- 26 4. Sprinkler evaluation by consumer organizations.
- 27

28 The point of view of the present paper is closely related to the needs of
29 items 3 and 4, leading to an automatic apparatus, which can routinely
30 test a large number of sprinkler-nozzle-pressure combinations. Since,
31 however, this study grew out of a research project, some space is devoted
32 to testing the effect of tilted risers.
33

34 The water distribution of a sprinkler operating in still air is normally
35 described by the discharge, wetted radius and shape of the radial water
36 pattern. The shape is a characteristic of the normalized (unit area)
37 distribution (Solomon and Bezdek, 1980), and requires several parameters
38 for a satisfactory description. A more complete description of the
39 hydraulic performance would include additional information, in particular
40 information about drop sizes and sprinkler rotation. Direct measurement
41 of drop sizes is possible (Kohl et al., 1985; Hills & Gu, 1989), but
42 cumbersome. Indirect and approximate information can, however, be
43 obtained from knowledge of the water distribution pattern and the
44 operating pressure, either via trajectory calculations (von Bernuth and
45 Gilley, 1984), or from empirical relationships between drop size and
46 distance (Seginer, 1963; Kohl, 1974; Hills & Gu, 1989). The mean rate of
47 revolution, a factor which affects the range reached by drops (Bilanski
48 and Kidder, 1958), can be measured without difficulty, but its uniformity
49 (Farbman and Manor, 1978) is more difficult to obtain. The present paper

1 does not treat direct drop measurements, nor rotation measurements.

2
3 Since the eventual use of most sprinklers is in open fields, the effect
4 of wind cannot be ignored. A sprinkler operating in wind produces a
5 pattern which is no longer radially symmetric. These distorted patterns
6 were traditionally determined by field tests (Seginer and Kostrinsky,
7 1975), but the effort involved in such measurements is often
8 prohibitively large. In recent years new calculational techniques have
9 been developed to produce simulations of wind distorted patterns (Fukui
10 et al., 1980). Such simulation programs require as input only a limited
11 amount of data, namely measured depths of water along a single-radius
12 under indoor conditions. This seems to be an adequate approach, mainly
13 for items 3 and 4 on the uses list opening this section, because those
14 applications require routinely many comparative measurements. An indoor
15 single-radius test apparatus can be readily automated, and the present
16 study is an effort in this direction.

17
18 Attempts to automate sprinkler pattern determinations are not new. First
19 came centralized banks of manometers (Culver and Sinker, 1966), then came
20 camera recording (Farbman and Manor, 1978) and a two-dimensional read-out
21 device (Hermsmeier, 1972), which provided a visual impression of the
22 water distribution. These devices required manual transfer of data from
23 manometers to computer. With the advent of sensitive pressure
24 transducers, the measurement of water levels could be managed by
25 microcomputers, whose task was to turn valves on and off and to record
26 data magnetically. Two examples of this type (Spiess, 1983; Fischer and
27 Wallender, 1988), utilized a single pressure transducer to record
28 sequentially the water levels of all precipitation (water application)
29 gages along a single radius, and solenoid valves to operate the sprinkler
30 and to connect the gages to the transducer.

31
32 The apparatus described below was developed at the Technion, and follows
33 the two examples just quoted. It, too, utilizes a single pressure
34 transducer to serve a computer-controlled array of precipitation gages.
35 In addition, an attempt was made to automate the sprinkler position, so
36 that many consecutive tests could be performed unattended (e.g. during
37 nighttime). The following sections first describe the apparatus, then the
38 measurements performed to-date. Finally the accuracy of the results is
39 discussed and the system is evaluated.

40 41 APPARATUS

42
43 The main function of the Technion apparatus was to produce radial cross-
44 sections of distribution patterns, with emphasis on the relative amount
45 of water along the radius. Absolute discharge was also calculated from
46 the measured patterns, for comparison with results of a standard
47 volumetric method. The main jet could not be measured separately from the
48 secondary jets (produced by interaction with the arm), but this feature
49 can be added later, if necessary. A prototype of a separating device has

1 been developed and tried successfully at the University of Tennessee,
2 Knoxville (UTK). A few data obtained with the UTK apparatus are compared
3 with results obtained with the Technion apparatus. The Technion apparatus
4 in its present form does not measure automatically the rate of rotation,
5 but this, too, can be added if necessary.

6
7 The Technion apparatus (Figures 1 and 2) was assembled and operated in
8 the Civil Engineering Hydraulic Laboratory. It consisted of three main
9 parts:

- 10
11 1. Water delivery system.
12 2. Collecting and measuring system.
13 3. Control system.

- 14
15 1. Water delivery system.

16
17 The source of water was a water tank with fixed water level, 18 m above
18 the floor. A booster pump increased the available pressure from 180 kPa
19 to over 600 kPa. The delivery line was split into 3 parallel pressure
20 regulators, normally set to supply water at 200, 300 and 400 kPa,
21 respectively (Figure 2a). The three lines were joined again before
22 entering the riser on which the sprinkler was mounted. Each one of the 3
23 branches was controlled by a separate solenoid valve. During an
24 unattended test a recording pressure gage was interrogated by the
25 controlling computer at 5 min intervals, to detect any pressure changes.

26
27 The sprinkler to be tested was mounted on a riser, which could be tilted
28 (Figure 2a) in a vertical plane passing through the gages (the plane of
29 the paper in Figure 1). The tilt, which was a requirement of the
30 particular research to be carried out, could be automatically set to any
31 one of 36 positions, separated from one another by 5° (notches on wheel
32 in Figure 2b). The axis of rotation was horizontal through the tip of the
33 nozzle (normal to the plane of Figure 1), and the angle of the riser was
34 measured from the line of precipitation gages. Thus, a riser leaning
35 towards the gages was tagged by a value less than 90° ($\tau < 90^\circ$), while
36 angles larger than 90° described risers leaning 'backwards'. The moving
37 force was a heavy weight (Figure 2b), which pulled the riser towards
38 smaller angles. A pneumatic piston, controlled by the computer, permitted
39 the tilt angle to decrease one increment at a time.

40
41 To protect the surroundings from becoming wet, a semi-circular partition
42 was constructed about 2 m behind the sprinkler (not shown in Figure 2a).
43 The partition was covered with 5 cm thick splash-preventing porous
44 material.

45
46 Every unattended test could consist of an unlimited number of runs, each
47 with its particular pressure and riser tilt. In practice, up to 24
48 thirty-minute runs were performed overnight, consisting of two
49 replications of each of 3x4 pressure-tilt combinations. In a more
50 conventional test application (such as for items 3 and 4 on the list of

uses in the introduction), changing riser tilt may not be required. Instead, changing nozzles or sprinklers may be desirable. In that case the mechanism used to change the tilt could be modified without too much effort to the new requirement.

2. Collecting and measuring system.

Seventeen precipitation gages were placed at 1 meter intervals along a radius, starting at the sprinkler (Figures 1 and 2c). Each gage consisted of a conical plastic funnel, 280 mm in diameter, over a 30 cm long, vertical, 30 mm i.d., brass tube (Figure 2d). The amplification ratio, therefore, was $(280/30)^2 = 87.1$. Each brass tube was connected to a horizontal manifold (Figure 2c) through a 1/2" solenoid valve (Figure 2d). The manifold, which connected the precipitation gages with a single pressure transducer (Schaevitz P-3061), placed at the end of the line, was made of 20 mm i.d. rigid PVC pipe. Care was taken to minimize the opportunity for air bubbles to accumulate. The top of the funnels was 60 cm above the floor and, in this particular study, 50 cm below the nozzle.

In addition to the precipitation gages, three extra vertical tubes were connected via solenoid valves to the manifold (Figure 1): two, which were identical to the other brass tubes, and were used for calibration, plus a short tube, which was used to zero the gages by draining extra water. These three tubes did not have funnels on top, and the two calibration tubes were covered to prevent water from entering during runs.

The pressure transducer was selected to accommodate the pressure range generated by the 30 cm length of the brass tubes. Its full range was 0 to 50 cm water head and its output signal was approximately 1V/10cm[water]. The pressure transducer was sampled about 150 times within 7 seconds, to produce a representative mean.

3. Control system.

The experiments were controlled by an APPLE][+ microcomputer, programmed in BASIC to read input signals, as well as to operate the water delivery system and the collecting and measuring system through the various solenoid valves (Figure 1). To accomplish all this, the original microcomputer was equipped with a clock card, and an A/D card. External to the computer, 26 solid-state relays were used to serve as drivers for the solenoid valves. One of the 26 relays turned the booster pump on and off, 3 operated the pressure regulator valves, 2 were required to operate the pressurized air piston used to tilt the riser, 17 operated the precipitation gage valves, and 3 were used to operate the calibration and drainage tubes. The relays could be activated by the program as well as manually.

PROCEDURE

Three major concerns affected the design and operation of the apparatus:

- 1 1. Air bubbles in the system.
- 2 2. Pressure transducer stability.
- 3 3. Wetting of funnel surface.

4
5 To ensure proper reading, each test (several runs) was preceded by
6 preparations whose aim was to remove bubbles from the system and to
7 recalibrate the pressure transducer. First, air bubbles were removed from
8 the manifold and the transducer by manually flushing with water. Next,
9 the following calibration procedure was applied: After draining all
10 excess water through the drainage tube and closing all valves, the output
11 of the transducer was recorded sequentially for all precipitation gages
12 and for the two calibration tubes. This gave the zero reading for the
13 system. Normally the individual readings were within ± 2.5 mV (± 0.003 mm
14 depth of applied water) of each other, their mean being within ± 25 mV
15 from the long-term mean.

16
17 Next, 150 cm³ of water were poured into one of the calibration tubes, and
18 a second reading was taken for that tube. This provided another point for
19 the calibration curve, which, based on preliminary checks, was taken to
20 be linear. The calibration coefficient was normally 73.6 ± 0.3 cm³/V
21 (10.4 ± 0.05 cm[water]/V). If it turned out to be significantly different,
22 the test was halted until the malfunction has been rectified. At the end
23 of each test, the two calibration tubes were read again, to check on the
24 stability of the original calibration.

25
26 Following the calibration and initialization of a test, the specified run
27 sequence was started. Before each run, following the automatic setting of
28 pressure and tilt, the sprinkler was operated for 5 min to wet the
29 surface of the funnels. Extra water was drained and the zero for all
30 precipitation gages was read once again before the actual run, which
31 normally lasted for 30 min. At the end of each run the precipitation
32 gages were re-read to determine the radial profile of the distribution
33 pattern.

34
35 Despite the care taken to ensure a valid calibration at all times, the
36 system could produce small errors due to volume changes in the manifold.
37 In principle there should be no movement of water when a valve is opened
38 or closed, since water is practically incompressible and the tubing
39 system is rigid. Furthermore, the valves themselves do not cause any
40 water movement due to opening and closing. Nevertheless, there may be
41 some change of volume due to left-over air bubbles or other
42 imperfections, as is explained below.

43
44 Consider the measurements involved in calibrating the transducer. Just
45 before calibration, all tubes except one are drained and the pressure in
46 the hermetically closed manifold is zero (atmospheric). If there is an
47 air bubble left in the manifold, then, when the valve of the water-
48 holding tube is opened, some of its water may move into the manifold, due
49 to compression of the air bubble. Subsequently, the water level in the
50 tube decreases slightly from its original position. After taking the

1 reading, the valve is closed, but the pressure in the manifold remains as
2 high as it was during the measurement. Opening the valve of any other
3 tube may release the extra pressure and enable the bubble to expand
4 again, forcing some water out of the manifold and into the other tube.

5
6 This scenario suggests that if there is some inadvertent expansive
7 flexibility in the manifold and pressure transducer, there will be a
8 tendency for small amounts of water to flow, via the manifold, from a
9 tube with a high water level to the next sampled low water-level tube.
10 Such movement of water between tubes distorts the true results by tending
11 to reduce the differences between the gages. To eliminate this error,
12 however small, every single pressure measurement was followed by a short
13 drainage period for the manifold. If the expansive flexibility of the
14 system does not change much during a single test (a fact which can be
15 detected by the repeated calibration at the end), this procedure
16 practically eliminates the problem, since the calibration itself is also
17 carried out in the same manner.

18
19 Every single pressure reading, except after drainage, required about 17
20 s. Following the opening of a gage valve, 2 s were provided to quiet down
21 any possible motion in the system. As already mentioned, the next 7 s
22 were used to sample the transducer output 150 times. Subsequently, the
23 gage valve was closed and the manifold drained, as described in the
24 previous paragraph, for a period of 8 s. Consequently, reading all 17
25 precipitation gages required about 5 min. Following the pressure reading
26 sequence, all gages (except calibration gages) were drained for 90 s, in
27 preparation for the next run.

28 29 TEST PROGRAM

30
31 Table 1 provides a summary description of the tests conducted to-date
32 with the apparatus. The experimental design had two objectives: First, to
33 obtain an estimate of the accuracy of the measurements, and second, to
34 produce water distribution data for comparison with simulated patterns.
35 The present paper deals with the first objective only.

36
37 Altogether, 5 series of tests were carried out over a period of 5 months.
38 A total of over 200 run results was obtained, all of which were used for
39 error analysis. Following some preliminary tests, and as more experience
40 had been gained, the number of consecutive runs per (unattended) test was
41 increased to 24, with relatively few malfunctions.

42
43 A single-nozzle wedge-driven impact type sprinkler, Naan 323/92, was
44 selected for the study. It was tested with 3 short circular nozzles of
45 nominal diameter: 2.8, 3.2 and 3.5 mm, under three pressures: 200, 300
46 and 400 kPa and 4 riser angles: 70, 80, 90 and 100 degrees.

47
48 The first series of tests, F, was devised to compare the performance of 5
49 nominally identical sprinklers, mounted on a vertical riser, under three
50 pressures. Each of the 5x3 sprinkler-pressure combinations was repeated

1 at least 3 times. As already explained, all runs within a single test had
2 to be carried out with the same sprinkler, but most of the 3 replicates
3 and all pressures within each test were randomized.

4
5 The other 4 series of tests, A to D, were devised to explore the effect
6 of riser angle at different operating pressures. Each of the series A, B
7 and C was carried out with a different nozzle, while series D was meant
8 to repeat series A, except for the following difference: In Series D the
9 sprinkler was turned a half turn relative to the riser compared to Series
10 A. It should be mentioned that the space, where the tests were carried
11 out, was not air conditioned, and that the weather changed considerably
12 between January and May.

13
14 Before each series of tests, volumetric discharge measurements were
15 taken, using a 100 lit container and a stop-watch.

16 RESULTS: DISCHARGE

17 1. Discharge coefficient

18
19 The results of the volumetric discharge measurements are presented in
20 Figure 3 in terms of the discharge coefficient, c , defined by

$$21 Q_v = cA (2gH)^{1/2}, \quad [1]$$

22
23 where Q_v is the volumetric discharge of the sprinkler, A is the nominal
24 cross-section area of the nozzle, g is the gravitational acceleration,
25 and H is the pressure head. Generally speaking, the coefficient is rather
26 independent of pressure, but varies by about 10% among nozzles. Capital
27 letters refer to the series of tests before which the sprinklers'
28 discharge coefficients were determined. Note that Series F is represented
29 by two calibrations, F1 and F2. Calibration F1 was conducted before
30 series F was started. At some point during the series it became apparent
31 that the pressure gage required an adjustment. Following this adjustment,
32 sprinkler No. 3 was recalibrated, resulting in F2. Since the discharge
33 coefficient, c , was calculated on the basis of nominal pressure, its
34 lower apparent value in F1 means that the operating pressure before the
35 adjustment was too low. From Figure 3 the discharge correction was about
36 3%, which implies a pressure correction of about 7%.

37
38 Representative values of the discharge coefficient were obtained from
39 Figure 3 by averaging and are shown in the penultimate column of Table 1.
40 The coefficient of variation (standard deviation divided by mean) of
41 individual discharge evaluations with the volumetric method (Q_v), is of
42 the order of 1%.

43 2. Discharge ratio

44
45 The amounts of water collected in the precipitation gages were used to

1 calculate an estimate of the sprinkler's discharge. First, voltage
2 differences (before and after sprinkling) were converted to water depths
3 and precipitation (water application) rates (in mm/h) at each of the
4 gages. Then, on the assumption that the pattern is radially symmetric
5 (which it is not for tilted risers) an estimate of the discharge could be
6 calculated by

$$7 \quad Q_g' = 2\pi \int_0^R p r \, dr, \quad [2]$$

10 where Q_g' is the sprinkler's discharge calculated from the gage results,
11 p is the precipitation rate, r is the radial distance from the sprinkler,
12 and R is the radius of the pattern. The ratio between the discharge
13 estimates Q_g' and Q_v is referred to as the discharge ratio

$$16 \quad q' = Q_g' / Q_v. \quad [3]$$

18 This ratio was calculated for every run and turned out to differ among
19 test series and to vary with tilt angle. No significant effect of
20 pressure on the discharge ratio could be detected. Figure 4 shows means
21 of q' (over all pressures and replications, usually 9 runs per point) as
22 a function of riser angle, τ . The standard deviation of individual runs
23 about the mean is about 4%. The shape of all the curves is similar, but
24 the curve for Series D is significantly removed from the others, judging
25 by the standard error, which is only about $\pm 1.5\%$. No experimental error
26 could be detected that would explain the discrepancy (see also Figures 3
27 and 9), and by default this result is blamed on non-uniform rate of
28 rotation (as mentioned earlier, the sprinkler was mounted differently
29 during Series A and D).

31 Let us refer now to the slope and concavity (downward) of the curves of
32 Figure 4. It turns out that these can be explained by the geometry of the
33 system in the following way: Consider a single-nozzle rotary sprinkler on
34 a tilted riser. Water that emerges from the nozzle at a certain point in
35 time, will initially continue to move in the direction of the nozzle's
36 axis. (This initial condition assumes that the angular momentum of the
37 water about the sprinkler's axis is negligible and that the nozzle is
38 radially symmetric.) Once the water is outside the nozzle, the nozzle's
39 continued motion does not affect the trajectory of the jet any longer. In
40 still air, only two forces affect significantly the development of the
41 trajectory: terrestrial gravitation and aerial drag. These forces have a
42 resultant which is confined to the vertical plane through the velocity
43 vector. The water must, therefore, continue to move in this plane, which
44 was defined at the outset by the horizontal azimuth angle of the nozzle,
45 α , at the time of emergence.

47 The analysis in Appendix A shows that a uniform rotation of the sprinkler
48 about its axis, expressed as $d\mu/dt = \text{const}$, does not necessarily result
49 in a uniform azimuthal velocity $d\alpha/dt$. In other words, when the riser is

1 tilted, the radius swept by the jet on the underlying horizontal surface
 2 does not rotate at a uniform rate. If the riser is tilted towards the
 3 precipitation gages ($\tau < 90^\circ$), the sweep is relatively slow and more water
 4 is accumulated in the gages than with a vertical riser. The opposite is
 5 true when the riser is tilted away from the gages. It turns out (Equation
 6 [A23]) that in the direction of the precipitation gages

$$8 \quad q(\tau) = d\mu/d\alpha = \sin(\beta + \tau)/\cos\beta, \quad [4]$$

10 where β is the elevation angle of the nozzle relative to the sprinkler's
 11 equator. The function $q(\tau)$ is the ratio between the quantity of water
 12 collected in the gages when the riser's angle is τ , compared with the
 13 quantity collected under identical conditions but with $\tau = 90^\circ$. This is the
 14 theoretical value of the discharge ratio (Equation [3]). The function
 15 $q(\tau)$ for $\beta = 30^\circ$ is plotted as a dashed curve in Figure 4. It seems to
 16 explain quite well the curvature of the empirical results.

18 In view of Appendix A, Q_g' of Equation [2], which is a function of τ , can
 19 be replaced by

$$21 \quad Q_g = 2\pi \left(d\alpha/d\mu \right) \int_0^R pr \, dr. \quad [5]$$

23 The theoretical value of $q = Q_g/Q_v$ is 1. Relationship [5] can be derived
 24 for a slice of the pattern (which includes the gages) without having to
 25 assume a radially symmetric pattern. The derivation is presented in
 26 Appendix B.

28 The experimental error associated with the determination of Q_g (or Q_g')
 29 is considerably larger than the error associated with Q_v . Replications of
 30 q within each series already exhibit a standard deviation of about 4%.
 31 When comparisons between series of runs are made, the standard deviation
 32 may soar to over 10%. This suggests that the discharge of a sprinkler
 33 should be determined by a volumetric method, while the catch in the
 34 precipitation gages should only be used to determine the shape of the
 35 pattern.

37 RESULTS: PATTERN

39 1. Profiles

41 The shape of a pattern is the information left after normalizing the
 42 original gage data. Solomon and Bezdek (1980) normalized twice: Distance
 43 was measured by r/R and water depth was measured by $p(\pi R^2/Q)$. Our
 44 approach was different for two main reasons.

46 1. Equal quantities collected in different gages along the radius,
 47 represent different quantities of water applied by the sprinkler. This is
 48 clear from Equation [2]. If the data are to be presented in such a way
 49 that equal ordinates represent equal quantities of water, the ordinates

1 should be proportional to pr , not to p .

2
3 2. We wanted to distinguish between patterns that have different wetted
4 radii, R .

5
6 As a result, our standardized patterns retain r as the variable to be
7 plotted along the abscissa, while the variable along the ordinate is

8
9
$$v = p(2\pi r)/Q_g' \quad [6]$$

10
11 The variable v , measured in m^{-1} , assumes the value zero at both ends of
12 the pattern, namely at $r=0$ and $r=R$. The area under the curve is 1
13 (dimensionless). As an example, if v is used to represent the classic
14 triangular pattern (p a linear function of r), the result is a parabola

15
16
$$v = 6r(R - r)/R^3 \quad [7]$$

17
18 Table 2 summarizes the experimental results in terms of distributions of
19 v . Headings over the blocks of numbers provide the nominal information
20 about each block. The first entry in each line within a block is either
21 the sprinkler number (in Series F) or the riser angle (in Series A to D).
22 The second entry is the number of replications over which the pattern
23 shape has been averaged. The other numbers describe the normalized
24 pattern, namely the value of v as a function of r . Each one of these
25 values is a mean over the number of replications, normally 3. The RMS
26 (root mean square) of deviations about these means, namely the standard
27 deviation, is of the order of $4 \times 10^{-3} m^{-1}$ (last column of Table 1). This,
28 divided by a typical value of v (about $0.08 m^{-1}$), corresponds to a
29 coefficient of variation (CV) of 5%. The latter order of magnitude value
30 agrees with the findings of Fischer and Wallender (1988). Their Figure 6
31 shows: 1. That the coefficient of variation for a catch of about $10 cm^3$
32 in a single gage (similar to the catch in the present study) is about 5%.
33 2. That on a log-log plot of CV against volume caught, the slope is
34 approximately -1, which suggests (despite some other evidence) that the
35 standard deviation is roughly constant, as in the present study.

36
37 Altogether there are 63 distinct patterns, some of which are variations
38 on the 36 basic patterns, representing all possible combinations of 3
39 nozzles, 3 pressures and 4 riser angles.

40
41 Figures 5 to 8 show some of these averaged patterns. Figure 5 illustrates
42 the effect of nozzle diameter for operation at 300 kPa. The area under
43 each of the three normalized curves is unity. This elimination of the
44 effect of discharge (a range of about $1/2$ in our case) makes the
45 comparison of shapes more precise. A common feature of the three
46 patterns, as well as of practically all patterns of Table 2, is their bi-
47 modality. Comparison with UTK data in Figure 6 suggests that the peak
48 nearest to the sprinkler is due to the effect of the arm (secondary
49 jets), while the second peak is due to the main jet.

1 In Figure 5, the pattern for the 2.8 mm nozzle has a somewhat shorter
2 wetted radius and a more pronounced bi-modality than the other two
3 patterns. Otherwise, the difference between the patterns is not striking.
4 One would have expected the wetted radius to increase with nozzle
5 diameter, because the ratio of drag to inertia decreases with increasing
6 nozzle diameter. One would also have expected to find a more pronounced
7 second peak (around $r = 8$ to 10 m) for larger nozzle diameters, due to
8 lesser breakup of the main jet. Apparently the range of nozzles was not
9 large enough to show the expected differences.

11 Figure 6 compares several patterns produced by nominally identical
12 setups. Results are means for individual sprinkler heads. There are two
13 UTK patterns, one for the main jet only and another for the unobstructed
14 flow, like that of Series C and F. The difference between the two UTK
15 patterns shows that the main jet delivered about 86% of the total water.
16 The difference between the various patterns of unobstructed flow
17 (excluding the dashed line) is considerably larger than can be explained
18 by the error among replications (last column, Table 1). Generally
19 speaking, the C and UTK patterns envelope the fairly wide cluster of data
20 of Series F. The reason is not clear. The mean discharge during Series C
21 and F seems, from Figure 4, to have been practically equal. The discharge
22 measured at UTK was about 2% higher than the mean Technion-measured Q_g -
23 discharge (Figure 4), but this slight difference by itself cannot explain
24 the variability in Figure 6.

26 Another example of non-repeatable results, this time between series A and
27 D, is presented in Figure 7. The patterns of Series D have a larger
28 wetted radius and a less pronounced first peak. These two series also
29 differed considerably in terms of their Q_g -discharge (Figure 4).

31 Figure 7 also shows the effect of pressure. This effect is regular and
32 intuitively acceptable: As the pressure increases, the two peaks become
33 less pronounced and the water is more uniformly distributed along the
34 radius. The wetted radius, however, is barely affected by the change of
35 pressure. Apparently, the effect of increased pressure is two-fold. On
36 the one hand a higher pressure results in a higher initial velocity, but
37 on the other hand it breaks down the jet into smaller drops. Hence, the
38 increased air resistance at higher pressures seems to compensate for the
39 higher initial emergence velocity.

41 Figure 8 illustrates the effect of riser tilt on the distribution
42 pattern. The maximum range is achieved at $r=90^\circ$ (nozzle elevation
43 $\sigma=8-30^\circ$), while in vacuum $r=105^\circ$ would have been the farthest throwing
44 riser angle. As the riser is tilted towards the precipitation gages
45 (smaller r) both peaks become more pronounced.

47 2. Moments

49 An alternative way to presenting water distribution patterns as profiles
50 of v , is to characterize them in terms of statistical moments of the

distribution. The first four normalized moments, as computed in this study, are as follows:

$$\text{First (relative to radius)} : m_1 = M/R \quad [8]$$

$$\text{Second (coeff. of variation): } m_2 = S/M \quad [9]$$

$$\text{Third (skewness): } m_3 = \left[\int_0^R v(r-M)^3 dr \right] / S^3 \quad [10]$$

$$\text{Fourth (kurtosis): } m_4 = \left[\int_0^R v(r-M)^4 dr \right] / S^4 \quad [11]$$

Where

$$M = \int_0^R v r dr \quad (\text{mean}) \quad [12]$$

$$S = \left[\int_0^R v(r-M)^2 dr \right]^{1/2} \quad (\text{standard deviation}) \quad [13]$$

The wetted radius R and the various moments have been calculated for all the profiles of Table 2. Some of those for $r=90^\circ$ are shown in Figure 9, with emphasis on comparison between series of runs. Some general statements can be made concerning the figure. The most consistent effect of pressure is on the kurtosis (flatness), m_4 , which increases with pressure at the same rate for all nozzles. The larger nozzles are characterized by a larger kurtosis. The pressure has practically no effect on the wetted radius, R , it has a negative effect on the coefficient of variation and conflicting effects on the first and third moments.

The interesting feature of Figure 9 is that pairs of series with identical nozzles, namely (A,D) and (F,C), exhibit similar and characteristic features. The variation within each pair is normally smaller than among series with different nozzles.

DISCUSSION AND CONCLUSIONS

1. Apparatus

At the end of one experimental season the impression obtained of the performance of the equipment is very favorable. Reliability, in terms of unattended operation, was very good, and so was the consistency of the pressure transducer's calibration coefficient. There are still unresolved questions of water clinging to the funnel, perhaps some evaporation, and other undetected problems. The main question, however, is whether the apparatus could be adapted for use in commercial applications for routine work. The answer seems to be positive, because the tilt-changing mechanism can be converted without difficulty to a sprinkler (riser) changing mechanism. This can be envisioned as a circular array of risers arranged around a vertical pivot. A stepping mechanism, similar to that

1 shown in Figure 2b, could rotate the array, switching from one riser to
2 the next by means of computer control. Simultaneously, water supply would
3 also be switched from one riser to the next.

4
5 The proposed apparatus can be modified not only to switch between risers,
6 but also for use with various size sprinklers (including fixed-head
7 sprinklers) and for different water application rates. To make the
8 necessary adjustments it is sufficient to change, respectively, the
9 spacing along the radius and the diameter of the funnels.

10 11 2. Data

12
13 The question of data accuracy can be discussed on several levels. The two
14 main questions are, first, did the apparatus measure properly the amounts
15 of water entering the funnels? and second, were these amounts
16 representative of the tested sprinklers?

17
18 While there were no direct comparisons made between pattern determination
19 by means of the pressure transducer and by means of direct volume
20 measurement, the calibration procedure seems to provide sufficient
21 support to the transducer: The calibration was against a measured volume,
22 the zero of all risers was practically the same and easily repeatable.
23 The calibration coefficient was also very consistent between beginning
24 and end of tests, as well as along the season.

25
26 The question of how representative are the results of a particular run is
27 more difficult to answer. The observed error among replications is
28 considerably larger than that expected from the performance of the
29 transducer and measuring system. It is conceivable, therefore, that the
30 amounts of water entering the funnels were in fact different from run to
31 run as a result of uncontrolled factors.

32
33 Table 1 and results of Series F in Figure 6 show an RMS deviation among
34 replications within a series of about 4.5 km^{-1} , this being of the order
35 of 5% of the ordinates of the pattern (Figure 6). The discrepancy between
36 replications from different series of tests (e.g. A vs D, F vs C) is even
37 larger, as can be seen in Figures 4, 6, 7 and 9. Apparently rather slight
38 differences in sprinkler, orientation, weather and unknown factors are
39 enough to change certain results significantly. In particular let us
40 consider Series A and D (2.8 mm nozzle): The discharge by the volumetric
41 method (Figure 3) was similar for the two series, while the discharge
42 calculated from the gages (Figure 4) was considerably and consistently
43 different. The distribution of water (Figure 7) was again very different,
44 but the difference between Series A and D in terms of moments (Figure 9)
45 was only moderate.

46
47 The results of this study suggest that the accuracy of pressure gage
48 reading is better than 0.1% of full scale, but since a typical reading
49 was about 1/10th of full scale, the accuracy reduced to about 1%. Table 1

1 shows that the coefficient of variation among replicates within series,
2 is of the order of 5% for an individual reading. The coefficient of
3 variation of v among means of nominally identical sprinklers within each
4 series (Series F, Figure 6) is about 10%. When comparisons are made
5 between series, the coefficient of variation may rise to 20%. Usually,
6 measured patterns are smooth, resulting in a shift of water from one
7 region of the pattern to another (e.g. equal-pressure pairs in Figure 7).
8 The resulting error in total discharge, Q_g , due to errors in v is
9 normally less than 5% (Figure 4).

10
11 Since the variation of actual water distribution from one test to another
12 is an order of magnitude larger than the measurement error, it may be
13 concluded that the apparatus can be used for single-radius pattern
14 measurements with confidence. On the other hand it seems that several
15 replicated measurements must be taken before a sprinkler can be
16 characterized properly. To obtain a representative average profile may
17 require averaging over several sprinkler heads or at least over several
18 radii of a pattern. The latter can be achieved by turning the riser
19 (automatically) between test runs (by, say, 90° each time). The space in
20 which the tests are to be conducted should be as draft free as possible.

21 22 APPENDIX A: THE EFFECT OF RISER TILT ON THE WATER APPLICATION RATE.

23
24 The natural coordinate system for a rotary sprinkler is spherical, its
25 equatorial plane normal to the riser through the point where the axis of
26 the riser and the axis of the nozzle meet (Figure A1). Let us assume,
27 without loss of generality, that the nozzle is one unit long. In the
28 spherical coordinate system the tip of the nozzle traces a circular
29 trajectory, which may be expressed as follows:

30
31 angular velocity: $d\mu/dt = \text{const.}$ [A1]

32
33 elevation angle : $\beta = \text{const.}$ [A2]

34
35 nozzle length : $L = 1.$ [A3]

36
37 The natural coordinate system for trajectory calculations is different:
38 it must be attached to the field, not to the sprinkler. A convenient
39 arrangement (Figure A2) is to utilize a cartesian system whose z axis
40 points in the vertical direction and its x axis - in the direction of the
41 riser's tilt. In this system the direction of the nozzle can be expressed
42 in terms of (variable) azimuth and elevation angles (Figure A3):

43
44 azimuth angle : $\alpha = \arctan (y/x).$ [A4]

45
46 elevation angle: $\sigma = \arctan [z/\sqrt{(x^2 + y^2)}],$ [A5]

47
48 where x, y and z are the field-coordinates of the nozzle's tip. It is
49 necessary now to express the azimuth and elevation angles in terms of the

angles of the spherical system. This can be done with the help of a second cartesian coordinate system, x', y', z' , which is attached to the spherical system as shown in Figure A1, the x' axis pointing in the direction of the riser's tilt. First let us express x', y' and z' in terms of δ and μ :

$$x' = \cos\delta \cos\mu, \quad [A6]$$

$$y' = \cos\delta \sin\mu, \quad [A7]$$

$$z' = \sin\delta. \quad [A8]$$

Next, let us express x, y and z in terms of x', y' and z' :

$$x = x' \sin r + z' \cos r, \quad [A9]$$

$$y = y', \quad [A10]$$

$$z = z' \sin r - x' \cos r. \quad [A11]$$

Equations [A6] to [A11] yield

$$x = A + B \cos\mu, \quad [A12]$$

$$y = C \sin\mu, \quad [A13]$$

$$z = D - E \cos\mu, \quad [A14]$$

where

$$A = \sin\delta \cos r, \quad [A15]$$

$$B = \cos\delta \sin r, \quad [A16]$$

$$C = \cos\delta, \quad [A17]$$

$$D = \sin\delta \sin r, \quad [A18]$$

$$E = \cos\delta \cos r. \quad [A19]$$

It is now possible to express α and σ in terms of μ and δ , via Equations [A12] to [A14] and [A4] to [A5].

Our particular problem requires the evaluation of $d\alpha/d\mu$. This is done by substituting from Equations [A12] and [A13] into Equation [A4] and differentiating with respect to μ :

$$d\alpha/d\mu = d[\arctan(C \sin\mu/(A + B \cos\mu))]/d\mu, \quad [A20]$$

yielding

$$\frac{d\alpha}{d\mu} = [C(B + A \cos\mu)] / [(B \cos\mu + A)^2 + (C \sin\mu)^2]. \quad [A21]$$

Evaluating this derivative at $\mu=0$ (in the direction of the riser's tilt) yields:

$$(\frac{d\alpha}{d\mu})_{\mu=0} = C/(A + B) = \cos\beta/\sin(\beta+\tau). \quad [A22]$$

Let us consider now the inverse of $(\frac{d\alpha}{d\mu})_{\mu=0}$ as a function of τ

$$q(\tau) = \sin(\beta+\tau)/\cos\beta. \quad [A23]$$

When the riser angle is $\tau = \pi/2$, namely vertical riser, the value of $q(\tau)$ is one. In the neighborhood of $\tau = \pi/2$, $q(\tau)$ increases when τ decreases.

APPENDIX B: DERIVATION OF Q_g

Consider a wedge of water deposited on the horizontal plane, through the openings of the gages, by a single pass of the sweeping jet. The mean shape of such a wedge is shown schematically in Figure B. Note that the pattern need not be radially symmetric. The discharge producing this wedge can be obtained by dividing its volume by the time δt required to sweep the angle $\delta\alpha$:

$$Q_g = \frac{1}{\delta t} \int_0^R b(r\delta\alpha) dr = (\delta\alpha/\delta t) \int_0^R b r dr, \quad [B1]$$

where b is the depth of water. The rate of sweep, $\delta\alpha/\delta t$, may be rewritten as

$$\delta\alpha/\delta t = (\delta\alpha/\delta\mu)(\delta\mu/\delta t). \quad [B2]$$

In one unit of time the sprinkler sweeps the gages n times. Therefore

$$p = nb. \quad [B3]$$

Also

$$\delta\mu/\delta t = \text{const} = 2\pi n. \quad [B4]$$

Substituting in Equation [B1] from Equations [B2] to [B4], yields

$$Q_g = 2\pi (\delta\alpha/\delta\mu) \int_0^R p r dr. \quad [B5]$$

REFERENCES

- Bilanski W.K., Kidder E.H. 1958. Factors that affect the distribution of water from a medium-pressure rotary irrigation sprinkler. Trans ASAE, 1(1):19-23,28.
- Culver R., Sinker R.F. 1966. Rapid assessment of sprinkler performance.

- 1 Journal of the Irrigation and Drainage Division, ASCE 92(IR1):1-17.
2
3 Farbman M., Manor G. 1978. Sprinkler distribution testing facility with
4 central reading. Agric. Eng. Dept., Technion, Haifa, Israel, Publ. No.
5 280. 36 pp. Hebrew with English Abstract.
6
7 Fischer G.R., Wallender W.W. 1988. Collector size and test duration
8 effects on sprinkler water distribution measurements. Trans. ASAE
9 31(2):538-542.
10
11 Fukui Y., Nakanishi K., Okamura S. 1980. Computer evaluation of sprinkler
12 irrigation uniformity. Irrigation Science 2:23-32.
13
14 Hermsmeier L.F. 1972. Sprinkler water distribution testing in a desert
15 environment. Trans. ASAE 15(3):436-439.
16
17 Hills D.J., Gu Y. 1989. Sprinkler volume mean droplet diameter as a
18 function of pressure. Trans. ASAE 32(2):471-476.
19
20 Kohl R.A. 1974. Drop size distribution from medium-sized agricultural
21 sprinklers. Trans. ASAE 17(4):690-693.
22
23 Kohl R.A., von Bernuth R.D., Huebner G. 1985. Drop size distribution
24 measurement problems using a laser unit. Trans. ASAE 28(1):190-192.
25
26 Seginer I. 1963. Water distribution from medium pressure sprinklers.
27 Journal of the Irrigation and Drainage Division, ASCE, 89(IR2):13-30.
28
29 Seginer I., Kostrinsky M. 1975. Wind, sprinkler patterns and system
30 design. Journal of the Irrigation and Drainage Division, ASCE,
31 101(IR4):251-264.
32
33 Solomon K., Bezdek J.C. 1980. Characterizing sprinkler distribution
34 patterns with a clustering algorithm. Trans ASAE 23:899-902,906.
35
36 Spiess M. 1983. Automated catchments for sprinkler testing. Unpublished
37 internal report. Center for Irrigation Technology, California State
38 University at Fresno. 17 pp.
39
40 von Bernuth R.D., Gilley J.R. 1984. Sprinkler droplet size distribution
41 estimation from single leg test data. Trans. ASAE 27(5):1435-1441.
42

43 ACKNOWLEDGEMENTS

44
45 We wish to acknowledge the financial support provided for this study by
46 the US-Israel Binational Agricultural Research and Development Foundation
47 (BARD) and by the Technion Research and Development Foundation.
48

49 We were greatly assisted by Mr. Elisha Baram (senior technician) and Mr.
50 Erez Tsimkhoni (student), who helped to assemble and run the experiment;

by Mr. Avraham Steif, who designed the tilting mechanism, and by the Mechanization Laboratory that built it. The Civil Engineering Hydraulic Laboratory provided the space for the experiment, Mr. Arie Racotch photographed the apparatus and Mrs. Rima Zarkina drew the figures.

Table 1: A summary description of tests, in chronological order.

Sprinkler under test - Naan 323/92.
 Normal duration of a single run - 30 min.
 Nominal pressures used in all runs - 200, 300 and 400 kPa.
 Riser angles in Series A,B,C and D - 70,80,90,100 deg from gage line.
 Riser angle in Series F - 90 deg.

series	dates	number of tests	runs	sprin- kler No.	nomin nozzle diam mm	disch coeff -	RMS among reps km ⁻¹
F	4 to 28 JAN 88	22	50	1 to 5	3.5	0.98	4.6
A	15 to 18 MAR 88	4	37	4	2.8	0.90	4.5
B	3 to 4 MAY 88	3	36	4	3.2	0.96	5.3
C	10 to 12 MAY 88	3	57	4	3.5	0.98	3.4
D	16 to 20 MAY 88	3	36	4	2.8	0.90	4.0
Totals		35	216				

Table 2: Profiles of v averaged over replications. Values of v are given in l/km. Each line sums to 1000.

distance m	1	2	3	4	5	6	7	8	9	10	11	12
------------	---	---	---	---	---	---	---	---	---	----	----	----

sprinkl reps	No.
--------------	-----

Series F / nozzle 3.5 mm / pressure 200 kPa / discharge 0.679 m³/h

1	4	75	84	97	67	57	69	86	102	121	137	98	7
2	3	70	83	91	66	55	72	99	111	131	136	81	5
3	5	61	74	82	63	59	73	92	107	127	141	109	12
4	3	73	96	97	66	58	70	88	111	126	137	76	2
5	3	72	83	96	74	65	76	88	97	120	134	92	3

Series F / nozzle 3.5 mm / pressure 300 kPa / discharge 0.832 m³/h

1	3	61	71	87	81	80	90	97	100	102	104	85	40	2
2	3	62	70	80	75	80	95	113	120	115	104	70	16	
3	4	51	66	74	76	81	92	101	107	109	107	89	45	2
4	3	58	76	85	80	81	92	107	103	115	106	76	21	
5	3	59	74	90	88	87	95	97	98	101	99	80	32	

Series F / nozzle 3.5 mm / pressure 400 kPa / discharge 0.960 m³/h

1	3	46	65	89	96	97	103	104	102	98	92	71	34	3
2	3	47	60	80	91	98	113	122	119	105	87	59	19	
3	4	45	60	72	84	93	104	109	108	107	98	77	39	4
4	3	51	74	88	94	100	111	117	114	104	86	51	10	
5	3	51	69	94	103	103	105	102	98	95	88	64	27	1

1	distance m	1	2	3	4	5	6	7	8	9	10	11	12
2													
3	riser reps												
4	angle												
5	deg												
6													
7	Series A / nozzle 2.8 mm / pressure 200 kPa / discharge 0.399 m ³ /h												
8													
9	70 3	266	131	42	49	98	180	233	1				
10	80 3	206	163	60	40	54	86	129	156	106			
11	90 3	184	167	93	44	45	61	85	115	129	76	1	
12	100 3	178	144	116	61	54	67	87	103	109	74	7	
13													
14	Series A / nozzle 2.8 mm / pressure 300 kPa / discharge 0.489 m ³ /h												
15													
16	70 5	175	90	46	68	108	163	203	147				
17	80 2	129	100	63	62	80	106	131	152	128	41	8	
18	90 3	120	106	82	66	74	91	111	128	128	84	10	
19	100 3	118	98	98	84	85	98	112	124	112	63	8	
20													
21	Series A / nozzle 2.8 mm / pressure 400 kPa / discharge 0.564 m ³ /h												
22													
23	70 3	123	67	48	76	124	168	201	172	21			
24	80 3	111	85	65	78	102	124	142	134	116	38	5	
25	90 3	99	83	77	84	97	111	126	134	117	64	8	
26	100 3	103	89	101	106	108	120	128	122	92	31		
27													
28													
29													
30													
31	Series B / nozzle 3.2 mm / pressure 200 kPa / discharge 0.556 m ³ /h												
32													
33	70 3	166	102	51	50	78	138	233	182				
34	80 3	124	118	68	41	48	71	106	148	189	87		
35	90 3	104	94	84	49	43	55	78	106	139	157	89	2
36	100 3	109	93	94	69	48	55	72	96	122	133	97	12
37													
38	Series B / nozzle 3.2 mm / pressure 300 kPa / discharge 0.681 m ³ /h												
39													
40	70 3	109	79	45	57	87	130	173	196	124			
41	80 3	87	82	61	51	66	89	113	134	147	123	47	
42	90 3	82	68	71	59	63	79	96	114	127	125	90	26
43	100 3	84	68	75	77	73	84	98	113	117	106	79	26
44													
45	Series B / nozzle 3.2 mm / pressure 400 kPa / discharge 0.786 m ³ /h												
46													
47	70 3	95	66	48	72	111	143	171	170	119	5		
48	80 3	76	70	60	65	89	109	122	131	128	104	45	1
49	90 3	74	65	71	74	87	103	113	117	116	100	62	18
50	100 3	74	65	77	87	93	105	111	114	110	92	56	16

1 distance m 1 2 3 4 5 6 7 8 9 10 11 12
2
3 Series C / nozzle 3.5 mm / pressure 200 kPa / discharge 0.679 m³/h
4
5 70 4 141 92 63 72 104 161 198 169
6 80 5 108 104 74 58 67 91 124 138 145 91
7 90 5 87 89 94 66 61 77 97 114 122 116 76 1
8 100 5 80 86 99 88 77 85 100 109 106 100 65 5
9
10 Series C / nozzle 3.5 mm / pressure 300 kPa / discharge 0.832 m³/h
11
12 70 4 106 77 67 89 120 154 159 142 86
13 80 5 91 85 78 77 90 111 128 121 109 82 28
14 90 5 74 78 91 84 88 102 112 113 106 88 54 10
15 100 5 69 85 101 105 103 109 111 107 92 73 40 5
16
17 Series C / nozzle 3.5 mm / pressure 400 kPa / discharge 0.960 m³/h
18
19 70 4 87 67 73 105 134 148 144 125 97 20
20 80 5 73 73 84 96 113 125 124 112 98 72 30
21 90 5 64 73 95 105 110 118 117 106 91 72 41 8
22 100 5 59 75 98 114 114 121 114 102 88 67 36 12
23
24
25
26 Series D / nozzle 2.8 mm / pressure 200 kPa / discharge 0.399 m³/h
27
28 70 3 189 122 47 43 67 110 203 219
29 80 3 148 136 82 43 45 60 86 130 186 84
30 90 2 141 136 110 56 37 40 54 82 121 152 71
31 100 4 124 119 113 68 53 54 66 86 120 139 58
32
33 Series D / nozzle 2.8 mm / pressure 300 kPa / discharge 0.489 m³/h
34
35 70 3 139 95 49 56 86 119 163 206 87
36 80 3 105 96 72 61 72 87 107 129 150 113 8
37 90 3 93 85 86 71 70 79 94 109 126 125 62
38 100 3 103 94 101 90 81 85 94 105 111 97 39
39
40 Series D / nozzle 2.8 mm / pressure 400 kPa / discharge 0.564 m³/h
41
42 70 3 112 82 52 69 108 134 156 174 113
43 80 3 96 85 75 77 96 108 119 127 126 82 9
44 90 3 82 74 86 90 98 105 112 119 117 88 29
45 100 3 82 77 98 112 110 111 114 116 103 64 13
46
47

1 Figure 1: Schematic view of apparatus. CP - centrifugal pump; PT -
2 pressure transducer; COMP - computer.

3
4 Figure 2: Photographs of apparatus components. 2a: Water delivery system.
5 Lower-center: three pressure regulators in parallel. Center: tilting
6 mechanism. Center-right: sprinkler on tilting arm. Center-left: high
7 pressure air to operate pneumatic pistons of tilting mechanism. 2b:
8 Tilting mechanism. Lower-right: weight. Top-left: counter weight for
9 tilting arm. Center: notched wheel and pneumatic piston, which moves
10 right-left to release one notch each time. 2c: Line of precipitation
11 gages. 2d: One precipitation gage mounted on manifold. Water shield
12 lifted to show solenoid valve. Bundle of wires connects the solenoid
13 valves with the computer.

14
15 Figure 3: Discharge coefficients, as a function of operating pressure.

16
17 Figure 4: Unadjusted discharge ratio q' , as a function of riser angle.
18 Dashed line is the theoretical relationship (Equation [4]).

19
20 Figure 5: Comparison of normalized patterns for three different nozzle
21 diameters at operating pressure 300 kPa, and riser angle 90° .

22
23 Figure 6: Comparison of normalized patterns for nominally identical
24 setups: Series C and F and two UTK patterns. Dashed line is for the main
25 jet alone. Nozzle diameter: 3.5 mm, operating pressure: 300 kPa, riser
26 angle: 90° . Each point represents 3 replications. Solid UTK curve is
27 based on 10 replications.

28
29 Figure 7: Effect of pressure on shape of normalized patterns for nozzle
30 diameter 2.8 mm and riser angle 90° . Solid lines are for Series A and
31 dashed lines - for Series D.

32
33 Figure 8: Effect of riser angle on normalized patterns. Series B, nozzle
34 diameter: 3.2 mm, operating pressure: 200 kPa.

35
36 Figure 9: Normalized statistical moments as a function of operating
37 pressure. Riser angle: 90° . Letters in figure indicate Series.

38
39 Figure A: Definition of angles for a sprinkler on a tilted riser.

40
41 Figure B: A wedge of water around precipitation gages.

A1

A2

A3

WIND-DISTORTED SINGLE-SPRINKLER DISTRIBUTION PATTERNS

Ido Seginer, Dvora Kantz, Dov Nir

Department of Agricultural Engineering, Technion, Haifa 32000, Israel

ABSTRACT

Simulation of water distribution of sprinkler systems under field conditions requires a data base consisting of individual water distribution patterns. These patterns are modified by drift, evaporation and distortion, caused by wind and evaporative demand of the air. If it is assumed that spray loss is distributed over the pattern in proportion to the rate of precipitation (water application), a simple method for adjusting these patterns to changing weather conditions is obtained.

Based on experimental results, a set of wind dependent patterns is obtained, which can be used for simulation under conditions similar to those encountered during the experiment. These patterns can be interpolated for any desired wind-speed, rotated to the required direction and corrected for the spray-loss appropriate to the relevant environmental conditions.

The separation of spray loss from collector evaporation requires that collector evaporation be suppressed or corrected for. To avoid the effort associated with evaporation suppression, an approximate correction, based on measured evaporation in peripheral collectors was applied to the data.

NOTATION

main symbols

SI units

C	convective conductance	m/s
c	specific heat of air at constant pressure	J/(kg[air]K)
E	spray evaporation rate	kg[vapor]/(m ² [soil]s)
f	an arbitrary function of wind-speed	kg[vapor]/(m ² [soil]s)
g	an arbitrary function wet bulb depression	-
H	sensible heat flux	W/m ² [soil]
L	discharge ratio Q_E/Q_S	-
M	discharge ratio $(Q_E+Q_D)/Q_S$	-
P	irrigation rate	m/s
Q	water discharge	m ³ /s
q	specific humidity	kg[vapor]/kg[air]
R	ratio of windward to leeward collector loss	-
r	radial distance from sprinkler	m
T	temperature	K
W	wind-speed	m/s
λ	latent heat of vaporization of water	J/kg[vapor]
ρ	air density	kg[air]/m ³

subscripts

1 a dry-bulb E evaporation
2 C collector S sprinkler
3 D drift w wet-bulb
4 d drop

6 INTRODUCTION

8 Simulation by superposition, of water distribution from sprinklers under
9 field conditions, requires information on water distribution patterns and
10 water losses over a range of weather conditions. Usually, the necessary
11 information is obtained from field tests involving either single
12 sprinklers or sets of simultaneously operated sprinklers. Tests of single
13 sprinklers provide the most flexible data base, because the individual
14 patterns can be rotated to any desirable wind direction before they are
15 superimposed.

17 Field distribution patterns differ in at least three respects from
18 laboratory (still air) patterns produced under the same operating
19 pressure:

- 21 1. Some fraction of the water is missing due to drift of small droplets.
- 22 2. Another fraction is missing due to spray evaporation.
- 23 3. The remaining pattern is distorted (no longer radially symmetric).

25 These perturbations of the original patterns depend mainly on the state
26 of the environment (temperature, humidity and wind), but certain
27 interactions with secondary operational conditions, such as sprinkler
28 layout and water temperature may also be important. Obviously, if the
29 final pattern depends on the simultaneous effect of five parameters, as
30 just mentioned, the experimental effort required to produce the necessary
31 data base for even a single sprinkler-pressure combination, becomes
32 formidable. To reduce the problem to manageable proportions,
33 simplifications must be sought, which will produce a modular data
34 structure of relatively independent elements.

36 At the present time there seems to be sufficient supporting evidence to
37 the view that total drift (for any given sprinkler-pressure combination)
38 may be formulated as a function of wind-speed alone. Similarly, mean
39 spray evaporation over the whole pattern may be formulated as a function
40 of the wet-bulb depression (or vapor pressure deficit) of the air, and of
41 wind-speed (Yazar, 1984). Thus, the discharge through the sprinkler may
42 be divided into three components

$$44 Q_s = Q_d(W) + Q_e(T_a - T_w, W) + Q_c(T_a - T_w, W), \quad [1]$$

46 where $T_a - T_w$ is wet-bulb depression of the ambient air, W is wind-speed, Q_s
47 is the sprinkler's discharge, Q_d is drift, Q_e is spray evaporation, and Q_c
48 is the discharge reaching the field's surface (or collectors in a test
49 situation). The latter component is usually considered as the net amount

1 of water added to the crop.

2
3 An important special case of Equation [1] occurs when the spray is
4 delivered into saturated air, whose temperature is equal to the
5 temperature of the spray. In this case the vapor pressure gradient
6 between the spray and the air is zero everywhere, and therefore the
7 resulting spray evaporation is zero. There are other situations where the
8 overall evaporation is zero, but only as a net result of evaporation and
9 condensation at different locations in the system. In either case, the
10 bulk equation becomes

$$11 \quad Q_c(W) = Q_s - Q_d(W), \quad [2]$$

12
13 but the distribution patterns may be different in detail.

14
15
16 Let us consider now the question of how the spray evaporation discharge,
17 $Q_E(T_a - T_w, W)$, is distributed over the pattern. While it is possible, in
18 principle, to measure this distribution using existing methods, such
19 information is not readily available. To overcome this lack of
20 information it may be assumed, as a first approximation, that spray
21 evaporation is proportional to local precipitation (water application).
22 With this assumption and information on bulk spray evaporation under a
23 range of environmental conditions, pattern correction for spray
24 evaporation can be undertaken.

25
26 The objective of the present paper is to show an example of how the
27 various loss components can be manipulated to produce a flexible
28 simulation (superposition) program. Following a review of some background
29 material, a field experiment to produce water distribution patterns will
30 be described. The data processing will then lead to a set of patterns,
31 suitable for application under average Israeli summer conditions. A
32 correction procedure for less frequent conditions will also be offered.
33 The proposed method only claims to produce approximate results, since it
34 is based on several crude assumptions.

35 36 SPRAY EVAPORATION

37
38 The standard procedure for determining sprinkler distribution patterns
39 (ASAE, 1988) does not distinguish between spray evaporation and drift.
40 Only the bulk sum of these loss components can be obtained by subtracting
41 $Q_c(T_a - T_w, W)$, based on water accumulated in precipitation collectors, from
42 Q_s , as measured in the supply line. Spray evaporation can be obtained
43 separately, however, by measuring the concentration of a soluble tracer
44 in the collectors, and comparing it with the tracer's original
45 concentration (Till, 1957; Yazar, 1984; Kohl et al., 1987). Since this
46 measurement is carried out separately for each collector, the rate of
47 spray evaporation over the pattern could be mapped. Unfortunately,
48 however, such evaporation maps, if they exist, are not readily available.
49 As a result an approximate approach must be developed to render useful
50 evaporation loss estimates.

Two approaches have been tried in attempts to quantify the dependence of spray loss on environmental parameters: physical and statistical. The physical approach is based on a transfer equation, relating the rate of evaporation to the specific humidity (or vapor pressure) difference between the drops and the surrounding air:

$$E = \rho C (q_d - q_a). \quad [3]$$

In Equation [3] q_d is saturation specific humidity at drop temperature, q_a is specific humidity of the ambient air, ρ is air density, and C is a convective conductance. C depends on the size distribution of the drops, on their air-speed, and on their residence time in the air. Drop size distribution is considered not to be a function of the environmental parameters, but air speed and residence time of individual drops may be a function of wind-speed. Therefore one should consider C as a function of wind-speed (for a given sprinkler-pressure combination).

Equation [3] suggests that, due to the strong dependence of q_d on drop temperature, the evaporation rate is in fact a function of sprinkler water temperature. Fortunately, the normal range of irrigation water temperature is not very wide. Furthermore, due to the high speed of sprinkler drops, their energy balance is dominated by convective fluxes to and from the air. This results in an equilibrium temperature which is equal to the wet-bulb temperature of the ambient air. It has been demonstrated experimentally (Cline et al., 1969; Pair et al., 1969) and by means of computational models (Kincaid and Longley, 1989), that the rate of temperature adjustment, which depends on drop size and speed, is very fast. It turns out that during its 1 to 2 seconds flight, a drop emitted by a medium size sprinkler closes about 80% of the gap between its initial temperature and the wet-bulb temperature. Thus, if the supply water temperature is reasonably close to the wet-bulb temperature, then q_d of Equation [3] may be replaced by the saturation specific humidity at wet-bulb temperature of the ambient air, to yield

$$E \approx \rho C (q_w - q_a). \quad [4]$$

It can be shown (Appendix A) that Equation [4] is equivalent to

$$E \approx \rho C (c/\lambda) (T_a - T_w), \quad [5]$$

where c is specific heat of air at constant pressure and λ is latent heat of vaporization of water.

Investigators using the statistical approach (Frost and Schwalen, 1955; Dylla and Shull, 1983; Yazar, 1984), relate measured bulk evaporation loss to environmental and operational parameters, through empirical formulas. Since the present discussion considers just one sprinkler-pressure combination at a time, the remaining parameters are air temperature, some measure of air humidity and wind. Often, the first two

parameters are replaced by the vapor pressure deficit (vpd) of the air, which is roughly proportional to the wet-bulb depression. The final form of the empirical formulas is usually

$$E = f(W) g(T_a - T_w), \quad [6]$$

a form which is compatible with Equation [5]. Note that $Q_E(T_a - T_w, W)$ could also be reduced to the less general form of Equation [6].

The rate of spray evaporation is also affected by the number of operating sprinklers and their configuration relative to wind direction. The two ends of the spectrum of possibilities are a single sprinkler and an infinite solid set. While the drops of the single sprinkler evaporate into the original, undisturbed environment, the drops of the infinite field (Seginer, 1970) evaporate into a cooler and moister environment (lower T_a and higher T_w), which supports a smaller evaporation rate.

While sprinkling modifies the temperature and humidity of the ambient air, it does not modify the wind field, since extraction of momentum from the air by sprinkler drops is hardly noticeable. Also, the probability of collision between drops emitted by neighboring sprinklers is negligible. These observations lead to the conclusion that the trajectories of droplets, unlike their rate of evaporation, are, to a first approximation, unaffected by sprinkler configuration. There is, however, a complication related to drift: In an infinite field there is, by definition, no drift, while for a single sprinkler it may be a very significant fraction of the total spray loss.

The preceding paragraphs suggest that the utilization of single-sprinkler patterns to simulate sprinkling with other configurations is not simple. For want of better alternatives, however, attempts have been made in the past to utilize single-sprinkler patterns for whole field simulations (Seginer and Kostrinsky, 1975). This still seems to be the most practical approach, if proper adjustments are made to account for the effect of various sprinkler configurations.

Before proceeding to outline the method proposed here for handling evaporation corrections, another possible source of error should be mentioned: According to ASAE Standard No. 330.1 (ASAE, 1988), single-sprinkler patterns are to be measured by an array of collector cans, "such that evaporation [from the cans] is kept to a minimum". Implicitly, the standard suggests the use of an "evaporation suppressant" for this purpose. Since suppression of collector evaporation requires special collectors and a considerable effort (Frost, 1963; Kohl, 1972; Marek et al., 1985), an alternative approach is suggested here: Starting a test with partially filled collectors, makes it possible to delineate the pattern boundary, and to use the cans surrounding the pattern

1 ("peripheral" collectors) to estimate collector evaporation during the
2 test.

3
4 **PROPOSED APPROACH**

5
6 The preceding discussion seems to lead to a pragmatic approach composed
7 of the following elements:

8
9 General

10
11 1. The basic distribution patterns are single-sprinkler patterns, free of
12 collector- and spray-evaporation losses (namely, for conditions where no
13 vapor pressure gradient exists between the spray and the ambient air).
14 They are a function of wind-speed alone (one dimensional set of
15 patterns), and must be evaluated for each sprinkler-pressure combination
16 separately.

17
18 Analysis stage

19
20 2. Collector evaporation is either eliminated by using suppressants, or
21 corrected for, as in the present study, on the basis of evaporation
22 measured in peripheral collectors.

23
24 3. To obtain the evaporation-free patterns, spray evaporation is measured
25 by some tracer technique and the lost amounts are added to the amounts of
26 water which have reached the collectors. In the present study evaporation
27 had to be indirectly estimated.

28
29 4. Bulk spray evaporation losses are related empirically to wind-speed
30 and to wet-bulb depression, for later use in the simulation stage.

31
32 5. Amount of drift is obtained, for each pattern separately, by utilizing
33 Equation [1] to subtract the amount of water which reached the
34 collectors, plus the amount of spray evaporation, from the amount
35 delivered by the sprinkler. As a check on the procedure, drift amounts
36 should be smoothly related to wind-speed. This, too, could not be done
37 with the data of the present study.

38
39 Synthesis (simulation) stage

40
41 6. At each time step the available evaporation-free patterns (item 1) are
42 used to interpolate for the current wind-speed. The resulting pattern is
43 rotated to the specified wind direction.

44
45 7. The resulting pattern is corrected for spray evaporation by removing
46 amounts of water which add up to the appropriate bulk loss for the
47 prevailing ambient conditions (obtained in item 4). The correction is
48 proportional to the evaporation-free depth at each grid point.
49

8. If it is desirable to simulate irrigation by other than single sprinklers (e.g. by a solid-set), the dependence of bulk spray evaporation and of bulk drift on sprinkler configuration, should be available. The basic patterns, namely the evaporation-free single-sprinkler patterns, can then be corrected proportionally for the difference in drift between the single pattern and the other configuration. As an example, the drift loss for an infinite solid-set is zero. Thus the drift obtained in item 5 should be added proportionally to the single-sprinkler pattern, if the distribution from an infinite solid set is to be simulated. The rest of the procedure is as in items 6 and 7, except with the spray-evaporation relationship appropriate for the infinite solid-set.

The approach just described is obviously crude, while still requiring considerable information. Yet it seems as an acceptable compromise at the present time. Eventually, when drop dynamics are better understood, simulations requiring much less empirical information may become reliable enough for common use.

EXPERIMENTAL PROCEDURE

The test setup followed, generally speaking, the guidelines of the ASAE Standard. A 2m by 2m grid of 14 by 14 collectors was used to accumulate water during 1 hour runs in an open field. The sprinkler was supplied by water through a flexible hose. The riser was located mid-way between four neighboring collectors and was moved between runs to convenient locations within the grid, according to wind conditions. White plastic pots, 159 mm in rim diameter and 140 mm high, were used to collect the water. The tip of the sprinkler's nozzle was 50 cm above the collector rims, the same as in the preceding laboratory study (Seginer et al., 1990). The volume of water delivered by the sprinkler during a single run was determined by reading a water-meter.

After setting the empty collectors and re-positioning and levelling the riser, when necessary, each collector was partially filled with an identical volume of water: 67 cm³. Filling the water was done by two people in the following order: Pairs of north-south rows of collectors were filled while moving back and forth along the rows. Filling started at the west, namely the windward edge of the test-field, and required 15 to 20 minutes. Following this operation, water was applied through the sprinkler for 60 minutes, and finally the quantity of water in the collectors was measured volumetrically, again by two people and in the same order as the initial filling. Measuring in this way required 30 to 40 minutes, which means that the collectors on the windward edge were exposed to evaporation for 15 to 20 minutes less than the collectors on the leeward edge of the test-field. Times were recorded to an accuracy of 1 min. After gaining some experience, one test could be completed in about two hours.

Two sets of tests were carried out, one in Megiddo airfield, 35 km inland, south-west of Haifa, and the second in the ICWE Rupin testing ground, 55 km south of Haifa and 5 km inland from the mediterranean coast. The Megiddo tests were carried out from mid-June to mid-July 1988 and the Rupin tests - during the third week of July 1988. The same sprinkler-nozzle-pressure combination, namely Naan 323/92, 3.5 mm diameter, and 300 kPa, was used throughout the study. The mean discharge over all tests was $Q_s = 0.867 \text{ m}^3/\text{h}$. A summary of all the tests used for pattern analysis is presented chronologically in Table 1. Weather data of 12 additional tests were included in the climatic description of Figure 1.

The weather in Israel during June, July and August, is very stable, and is dominated by a fairly strong sea breeze during day-time and a lull during the night. The difference between valley locations at different distances from the coast, in terms of maximum wind-speed and maximum temperature, is considerable. Figure 1a shows the dry-bulb temperature (T_a) and the wet-bulb temperature (T_w), and Figure 1b shows the wind speed (W), all as functions of local (summer) time, for the two locations (Megiddo and Rupin). Each point is the mean for a single run, as presented in Table 1, and the curves are fitted by sight. Superimposed on these data are curves of dry-bulb temperature and wind-speed from Hamadiya, 60 km inland from the coast, roughly on an extension of the line through Haifa and Megiddo (from Seginer and Kostrinsky, 1975).

Figure 1 shows stable diurnal weather patterns with the following characteristics: The day/night amplitudes of dry-bulb temperature and wind-speed, as well as wet bulb depression ($T_a - T_w$), all increase with distance from the coast. The time when the wind maximum occurs is delayed by about 1 h for every 10 km from the coast. When wind-speed is plotted against $T_a - T_w$ in Figure 2, two characteristics of the Israeli summer climate become evident: 1. W and $T_a - T_w$ are fairly well correlated, and 2. The points for Rupin fit well into the pattern for Megiddo. The best proportional fit between the two environmental variables is

$$T_a - T_w = 2.3 W,$$

[7]

the units of the coefficient being in $\text{K}/(\text{m/s})$.

COLLECTOR EVAPORATION CORRECTION

The simplest possible correction for collector evaporation is to assume that the rate of collector evaporation was uniform over the test-field. This makes it equal to the evaporation rate of the peripheral collectors, which can be easily determined. At least two objections can be raised concerning this assumption:

1. Collectors in the inner part of the pattern may evaporate differently than the peripheral collectors. On the one hand evaporation from the

1 wetted field surrounding the inner collectors reduces the evaporative
2 demands from these collectors, compared to the unwetted periphery. On the
3 other hand, water drops clinging to inner collector surfaces may add to
4 the evaporation rate.

5
6 2. Air humidity increases downwind from the leading edge of an irrigated
7 area. As a result, one might expect to find a lesser rate of evaporation
8 in the leeward peripheral collectors than in the windward ones.

9
10 The first argument could not be put to the test in our setup, but the
11 second effect was checked and found to be of negligible magnitude: Figure
12 3 shows R, the ratio of windward to leeward collector loss (corrected for
13 sampling times), as a function of the absolute magnitude of the rate of
14 loss. One observes that the scatter decreases as the absolute loss
15 increases, and that R approaches 1.

16
17 From here on it will be assumed that collector evaporation rate was in
18 fact uniform over the whole test-field. Figure 4, which is a schematic
19 cross-section through the field, reflects this view in a graphical form:
20 Line ABC represents the uniform depth of water deposited in the
21 collectors before the start of a test. If collector evaporation was
22 completely suppressed, then the depth of water at the end of a test would
23 be represented by curve ADC, the area (actually volume) ABCDA
24 representing the precipitation over the field during the sprinkling
25 phase. In reality, a certain collector evaporation, which we assume to be
26 proportional to the exposure time, does take place. This loss, calculated
27 from the water found in the peripheral collectors, is approximated by
28 line EFG. The rate of this loss, expressed in mm/h, is presented in
29 Column 15 of Table 1, which exhibits a wide range of values, from zero at
30 night to about 1.5 mm/h in the afternoon (at Megiddo). Subtracting
31 collector loss, the actual amount of water found in the collectors at the
32 end of a run is represented by the area EFGCDA. The required pattern
33 (area ABCDA) is obtained from the amounts of water found in the
34 collectors at the end of a test, by adding the collector loss and
35 subtracting the initial (uniform) amount of water.

36 37 PATTERNS FOR LOCAL SUMMER CONDITIONS

38
39 Altogether, 33 patterns were corrected for collector evaporation. These
40 corrected patterns were then further analyzed, employing previously
41 developed methods (Seginer, 1969; Seginer and Kostrinsky 1975): First,
42 the location of a pattern's center of gravity was determined. Its
43 distance (shift) and direction from the sprinkler are given in Columns 13
44 and 14 of Table 1. This direction agrees well with the wind direction
45 (Column 12) and the shift is proportional to wind speed. The
46 proportionality coefficient is 0.96 m/(m/s), comparable to the values
47 obtained by Seginer and Kostrinsky (1975) for similar sprinklers.

48
49 The corrected patterns were rotated around the riser, until the pattern's
50 center of gravity lay on the abscissa. This made the abscissa parallel to

1 wind direction, enabling easier comparison between patterns. There is,
2 however, some loss of accuracy due to this process: The rotation involves
3 an interpolation for each of the new grid points. This tends to diffuse
4 the pattern, particularly in regions with strong curvature (points A and
5 C, Figure 4). For the rather coarse grid of 2m by 2m, it resulted in an
6 increased wetted area, which is equivalent to an addition of about 0.4 m
7 to the radius of the pattern. This fringe (like the tails of a Gaussian
8 distribution) is convex and contains only small quantities of water. A
9 correction applied later in the process (utilizing curves such as those
10 of Figure 6), partially corrected for this, as will be seen shortly.

11
12 The length, width and area of the rotated patterns were measured and
13 plotted against wind-speed as dots in Figure 5. These data are rough,
14 since they are based on a 2m by 2m grid. Still, they show a qualitative
15 agreement between the product length-times-width and the area. If the
16 total range of wind-speed is divided in two at about 4 m/s, the following
17 qualitative statements can be made: Between zero and 4 m/s both length
18 and width of the patterns decrease as wind-speed increases. As a result,
19 the wetted area decreases by about 6% for every 1 m/s increase of wind-
20 speed. Beyond 4 m/s the width decreases slightly further, while the
21 length seems to increase again, resulting in an almost constant wetted
22 area between 4 m/s and 8 m/s.

23
24 For each point in the new, wind-direction-oriented coordinate system,
25 water application rate was plotted against wind speed, and a smooth curve
26 was fitted. A few of these curves are shown in Figure 6, all for grid
27 points $\sqrt{50}$ m distant from the sprinkler. The individual data points are
28 for the grid point (7,1), namely 7 m downwind of the sprinkler and 1 m to
29 either side. The scatter is due to the range of wet-bulb depression for
30 any given wind-speed (Figure 2), and to other sources of error. The root-
31 mean-square (RMS) of the deviations about the mean curve (fitted by
32 sight) is 0.2 mm/h.

33
34 Collecting values from such curves for all grid points at the same wind-
35 speed, representative patterns were obtained for wind-speed 0, 2, 4, 6,
36 and 8 m/s (Table 2). The wet-bulb depression associated with each of
37 these patterns may be obtained from Equation [7]. In particular, the wet-
38 bulb depression associated with wind-speed zero, is itself zero,
39 indicating that under these conditions (night-time) there is practically
40 no spray evaporation, nor drift. The length, width and area of the
41 patterns of Table 2 are connected by solid lines in Figure 5. These
42 results are consistently lower than the best fit curve through the
43 points. This is partially a result of the coarseness of the grid (easily
44 demonstrable for the circular pattern associated with zero wind speed)
45 and partially due to elimination of the rotation-generated fringe
46 mentioned earlier.

47
48 The pattern for calm conditions was obtained by extrapolating to zero
49 wind-speed, and since this pattern is radially symmetric, one radial
50 cross-section is sufficient to completely describe it. The mean cross-

1 section, based on data from all grid-points, is shown in Figure 7. The
2 wetted radius of the pattern is approximately 12.9 m, this value having
3 been used to indicate the zero wind-speed value of length, width and area
4 in Figure 5 (note the discrepancies at zero windspeed from the solid
5 line).

6
7 One drawback of Figure 7 is that equal areas on the figure do not
8 represent equal amounts of water. To rectify this, the ordinate was
9 multiplied by $2\pi r$, where r is the radial distance from the sprinkler
10 (following Seginer et al., 1990). The result is a new curve, the area
11 under which represents the sprinkler's discharge. Dividing the new
12 ordinates by the discharge, a unit-area curve is obtained, which is
13 plotted, using a solid line, in Figure 8.

14
15 Figure 8 compares the evaporation-free and distortion-free distribution
16 pattern obtained from the field tests, with patterns measured indoors
17 under nominally identical operating conditions (Seginer et al., 1990).
18 There are two indoor patterns, each representing a separate series of
19 tests, which shows that even under laboratory conditions perfect
20 replications cannot be obtained. In view of this, the difference between
21 the laboratory and field results is not excessive. The field pattern
22 seems to be a somewhat smoothed (diffused) version of the laboratory
23 pattern. At least part of this smoothing is due to the effect of
24 interpolation mentioned above. Another smoothing effect may be due to the
25 fluctuating nature of natural flow. This happens at all wind-speeds and
26 even for apparently zero wind-speed, since a zero mean wind-speed, as
27 well as a zero shift of the pattern's center of gravity may be the result
28 of cancelling effects of changing wind direction during a 60 minutes
29 test.

30
31 Note that the patterns of Table 2 are not the evaporation-free (basic)
32 patterns mentioned earlier. Rather, they are characteristic of Israeli
33 conditions, where wet-bulb depression is highly correlated with wind-
34 speed (Figure 2). They may be used, as is, for general purpose
35 simulations under conditions similar to the conditions of the tests. In
36 the next section a suggestion will be made how to modify these patterns
37 for use under different conditions.

38 39 CORRECTIONS FOR SPRAY EVAPORATION AND DRIFT

40
41 Straight-forward reconstruction of evaporation-free patterns is not
42 possible on the basis of the data of this study, since spray evaporation
43 has not been measured separately. Fortunately, spray evaporation of
44 similar sprinklers had been measured by Yazar (1984), except that in his
45 experiment several sprinklers were operated simultaneously. This suggests
46 that the spray evaporation loss in his study was somewhat lower than in
47 the present study.

48
49 To facilitate comparisons with the present study, Yazar's regression was

recalculated with two minor modifications: 1. In the new calculation, wet-bulb depression was used rather than vapor pressure deficit. 2. Non-linear regression of the original variables was replaced by a linear regression of logarithmically transformed variables. Yazar's results, cast in the new form, yield the following prediction equation

$$L = Q_E/Q_S = 0.0087 e^{0.213W} (T_a - T_w)^{0.58}, \quad [8]$$

where W and $T_a - T_w$ are measured in m/s and K respectively. The root-mean-square (RMS) of the differences between the measured and predicted values with this formula is 0.0115, about one percent of the discharge through the sprinkler. A similar analysis to Yazar's could be performed with the spray loss (evaporation plus drift) obtained in this study. The result is

$$M = (Q_E + Q_D)/Q_S = 0.0322 e^{0.075W} (T_a - T_w)^{0.68}, \quad [9]$$

with prediction RMS of 0.0380, about 3 time larger than Yazar's. The increase of the RMS is partially due to the fact that M is about twice as large as L . It should be noted that in contrast to Equation [5], the power of the wet-bulb depression is considerably less than 1 in both formulas. The wind-speed coefficient is considerably smaller in Equation [9] (present study) than in Equation [8]. This, too, does not seem to fit the notion that M , which includes drift, should be more strongly dependent on W than L is. Some of this inconsistency may be due to the relatively high correlation between W and $T_a - T_w$ in the present study (Figure 2), a point to be mentioned again later on.

Values of L from Equation [8] are very roughly 50% of the values calculated by means of Equation [9] for high evaporative conditions. Since this is similar to what Yazar found for the higher wind-speeds in his study, we may, to a first approximation, use Equation [8] to estimate spray evaporation loss in the present study. If it is now assumed that the evaporation loss at each collector is proportional to the amount collected, then each of our patterns could be reconstructed to its evaporation-free form by dividing L proportionally among the collectors.

We have seen that Yazar's (1984) results are similar, in order of magnitude, to the findings of the present study, but considerably different results can also be found in the literature. Figure 9 compares the results of the present study and of Yazar's work, with those of Kohl et al. (1987). The comparison is along the axis of wet-bulb depression and shows L of Yazar's study to be almost 10 times larger than L of Kohl's study. If the effect of wind-speed was also considered, the difference would be even larger. This discrepancy may be partly the result of the difference between sprinklers, and partly an artifact of the measurements.

The information presented up to this point should enable us to extend the use of the distribution patterns of Table 2 to a wider range of applications than at the end of the previous section. One possibility

1 is to assume that spray evaporation loss in the present study and in
2 Yazar's study was approximately the same. Equation [8] could then be used
3 to reconstruct the basic evaporation-free patterns and proceed from there
4 in the manner outlined in section which described the proposed approach.

5
6 Another possibility, restricted to single sprinklers operating in Israeli
7 summer conditions, is to use Equation [9] to modify the patterns.

8 Consider, as an example, the pattern for wind-speed of 4 m/s. This
9 pattern is appropriate for wet-bulb depression $T_a - T_w = 9.2$ K (by Equation
10 [7]). Suppose that one wants to produce a pattern for the same wind-
11 speed, but $T_a - T_w = 5.0$ K. Let us assume now that the loss-fraction M is
12 the same for each of the grid-points. Its values for the standard
13 conditions and the modified conditions (using Equation [9]) are

$$14 \quad M_1 = M(4.0, 9.2) = 0.20 \quad \text{and} \quad M_2 = M(4.0, 5.0) = 0.13,$$

16
17 respectively. The irrigation rates of the modified pattern are obtained
18 from the original ones, using the equation

$$19 \quad P_2 = P_1 (1 - M_2) / (1 - M_1). \quad [10]$$

21
22 The numerical result in the present case is $P_2 = 1.09 P_1$, meaning that
23 more water reaches the ground because the air is more humid.

24
25 If a distribution pattern for an intermediate wind-speed is required, an
26 interpolation between two of the available patterns is performed first,
27 and then a spray-loss correction is applied, if necessary.

28 29 DISCUSSION AND CONCLUSION

30
31 The present study may be viewed as a continuation of a previous one
32 (Seginer and Kostrinsky, 1975). The common concept is that a realistic
33 water distribution map of a whole field, under variable weather
34 conditions, can be obtained through simulation, by superimposing
35 individual water distribution patterns. Unfortunately, these patterns are
36 susceptible to the effect of wind and humidity, so that a complete
37 description for even one sprinkler-pressure combination, consists of a
38 two-dimensional array (distribution pattern) as a function of two
39 independent variables (wind and humidity). The common objective of both
40 studies was to reduce the required basic data to a series of patterns
41 which are a function of wind-speed alone. This was achieved by applying
42 somewhat different spray-loss corrections.

43
44 The field-test methodology of both studies was developed for situations
45 where collector evaporation suppression is impractical. The difference
46 between the two was that in the previous study no estimate of collector
47 evaporation could be obtained. Therefore, a uniform correction, which
48 included collector-loss, spray-evaporation-loss and drift-loss, was
49 applied to all the collectors. This involved a reconstruction of the

1 evaporation-free wetted area (larger than was actually found in the
2 tests), which in the present study could be obtained directly from the
3 data. In the present study, due to the initial deposition of water in the
4 collectors, the pattern of water which reached the surface could be
5 reconstructed with fair accuracy and the spray-loss (evaporation plus
6 drift) could be separated from the collector-loss and determined by
7 subtraction. The spray loss could thus be related to the environmental
8 conditions, a relationship which could later be used for pattern
9 adjustments to a range of weather conditions.

10
11 The assumption that collector evaporation rate was uniform over the test-
12 field could not be validated. Intuitively, the evaporation in the center
13 of the pattern is expected to be smaller than in the periphery (but
14 consider the discussion leading to Figure 3). If this is so, the patterns
15 of Table 2 contain too little water and the spray-loss (Table 1, Column
16 16) is overestimated. The comparison with Yazar's (1984) results
17 suggests, however, that the error is not large. An experiment to compare
18 the use of evaporation suppressants with a correction based on peripheral
19 collectors, may clarify this point.

20
21 Eventually, the individual distribution patterns themselves will be
22 generated by computer from evaporation-, drift- and distortion-free
23 laboratory patterns (Vories et al., 1987; Kincaid and Longley, 1989).
24 Fukui et al. (1980) demonstrated good agreement between measured and
25 computed patterns up to wind-speed of 4.2 m/s. They did not include drop
26 evaporation nor drift in their calculations, yet the agreement with
27 measured data was good. A more rigorous test of the computer generated
28 patterns requires comparisons under high wind-speed and low humidity. The
29 patterns of Table 2 could be used for such tests. In fact, if local spray
30 loss is roughly proportional to local precipitation, Fukui's method could
31 be tested against the measured patterns even without being modified to
32 include drop evaporation and drift.

33
34 For the time being, the results obtained in the present study can be used
35 for approximate simulations of irrigation with single sprinklers, perhaps
36 even with single lines, under the range of weather conditions covered by
37 the experiment. Corrections for conditions deviating from the mean
38 relationship between wind-speed and wet-bulb depression (Equation [7]),
39 can be obtained by using Equations [9] and [10].

40 41 APPENDIX A: SPRAY EVAPORATION AS A FUNCTION OF WET-BULB DEPRESSION

42
43 At equilibrium, the energy balance of a fast moving spray of drops can be
44 approximated by

$$45 \quad H + \lambda E = 0, \quad [A1]$$

46
47
48 where H, the sensible heat flow from the air to the spray, is balanced by
49 λE , the latent heat of vaporization flowing from the spray to the air. H
50 and E may be expressed in terms of temperature and specific humidity

1 differences as follows:

2
3 $H = c\rho C (T_a - T_w),$ [A2]
4

5 $E = \rho C (q_w - q_a),$ [A3]
6

7 where c is specific heat of air at constant pressure, ρ is air density, C
8 is convective conductance to heat and vapor, T_w is spray temperature, T_a
9 is ambient-air temperature, q_w is specific humidity (at saturation) on
10 the surface of the drops, and q_a is specific humidity of the ambient air.

11
12 Substituting in Equation [A1] from Equations [A2] and [A3], one obtains

13
14 $q_w - q_a = (c/\lambda)(T_a - T_w),$ [A4]
15

16 which may be used to substitute for $q_w - q_a$ in Equation [A3], yielding

17
18 $E = \rho C(c/\lambda)(T_a - T_w).$ [A5]
19

20 Equation [A5] shows that for a given sprinkler-pressure combination, the
21 rate of evaporation is approximately proportional to $T_a - T_w$. The three
22 main assumptions are that the effect of radiative fluxes is small, that
23 the drops are at their equilibrium temperature and that C is independent
24 of wind-speed.

25 REFERENCES

- 26
27
28 ASAE. 1988. Procedure for sprinkler distribution testing for research
29 purposes. ASAE standards 1988, Standard No. 330.1, pp 501-503. The
30 Society for Engineering of Food and Agriculture.
31
32 Cline J.F., Wolf M.A., Hungate F.P. 1969. Evaporative cooling of heated
33 irrigation water by sprinkler application. Water Resources Research
34 5(2):401-406.
35
36 Dylla A.S., Shull H. 1983. Estimating losses from a rotating-boom
37 sprinkler. Transactions of the ASAE 26(1):123-125.
38
39 Frost K.R. 1963. Factors affecting evapotranspiration loss during
40 sprinkling. Transactions of the ASAE 6(4):282-283,287.
41
42 Frost K.R., Schwalen H.C. 1955. Sprinkler evaporation loss. Agricultural
43 Engineering 36(8):526-528.
44
45 Fukui Y., Nakanishi K., Okamura S. 1980. Computer evaluation of sprinkler
46 irrigation uniformity. Irrigation Science 2:23-32.
47
48 Kincaid D.C., Longley T.S. 1989. A water droplet evaporation and
49 temperature model. Transactions of the ASAE 32(2):457-463.
50

- 1 Kohl R.A. 1972. Sprinkler precipitation gage errors. Transactions of the
2 ASAE 15(2):264-265,271.
3
4 Kohl K.D., Kohl R.A., DeBoer D.W. 1987. Measurement of low pressure
5 sprinkler evaporation loss. Transactions of the ASAE 30(4):1071-1074.
6
7 Marek T.H., Schneider A.D., Baker S.M., Popham T.W. 1985. Accuracy of
8 three sprinkler collectors. Transactions of the ASAE 28(4):1191-1195.
9
10 Pair C.H., Wright J.L., Jensen M.E. 1969. Sprinkler irrigation spray
11 temperatures. Transactions of the ASAE 12(3):314-315.
12
13 Seginer I. 1969. Wind variation and sprinkler water distribution. Journal
14 of the Irrigation and Drainage Division, ASCE 95(IR2):261-274.
15
16 Seginer I. 1970. A resistance model of evaporation during sprinkling.
17 Agricultural Meteorology 7:487-497.
18
19 Seginer I., Kostrinsky M. 1975. Wind, sprinkler patterns and system
20 design. Journal of the Irrigation and Drainage Division, ASCE
21 101(IR4):251-264.
22
23 Seginer I., Kantz D., Nir D., von Bernuth R.D. 1990. An automated indoor
24 apparatus for the determination of single-radius sprinkler water
25 distribution patterns. BARD Project No. US-1001-85: The effect of wind on
26 sprinkler distribution patterns. Final report, Chapter 1.
27
28 Till M.R. 1957. A method of measuring the evaporation loss from
29 sprinklers. The Journal of the Australian Institute of Agricultural
30 Science. 23:333-334.
31
32 Vories E.D., von Bernuth R.D., Mickelson R.H. 1987. Simulating sprinkler
33 performance in wind. Journal of the Irrigation and Drainage Division,
34 ASCE 113(1):119-130.
35
36 Yazar A. 1984. Evaporation and drift losses from sprinkler irrigation
37 systems under various operating conditions. Agricultural Water Management
38 8:439-449.
39

40 ACKNOWLEDGEMENTS

41
42 We wish to acknowledge the financial support provided for this study by
43 the US-Israel Binational Agricultural Research and Development Foundation
44 (BARD) and by the Technion Research and Development Foundation. We also
45 wish to thank the Israel Center of Waterworks Equipment (ICWE), for
46 permission to use their Rupin test-grounds.
47

48 We were greatly assisted by Mr. Elisha Baram (senior technician) and Mr.
49 Erez Tsimkhoni (student), who helped to assemble and run the experiment.
50

Table 1: Summary of field data and results, summer 1988.

All tests (except as noted) were carried out with sprinkler Naan 323/92, nozzle 3.5 mm, pressure 300 kPa, duration 60 min.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
run	date	time	dis-	rev	im-	temperatures			RH	WS	dir	shift	dir	elect	spray
			mid-run		pact	dry	wet	diff						loss	loss
						T _a	T _w	T _a -T _w							
			lit												
	m-dd-hh:min		h	rpm	cpm	°C	°C	°C	%	m/s	deg	m	deg	mm/h	-
Megiddo.															
11	6-22-12:10		867	4.7	291	29.5	21.8	7.7	50	6.7	255	6.67	253	0.86	0.317
12	6-26-13:02		860	4.8		33.2	22.5	10.7	38	5.0	330	4.76	317	1.16	0.252
13	6-26-16:02		845	4.4		32.5	22.5	10.0	40	7.8	330	7.51	318	1.09	0.224
15	6-27-11:32		862	5.2	296	33.5	22.5	11.0	38	3.1	315	2.75	312	0.90	0.221
16	6-27-13:41		856	4.6	304	36.5	23.0	13.5	30	7.4	315	7.00	314	1.38	0.308
17	6-27-15:45		862	4.9	304	36.0	21.5	14.5	36	8.3	330	7.48	318	1.16	0.339
18	6-28-10:41		873	4.4	298	33.9	21.9	12.0	34	3.3	270	3.53	259	0.74	0.256
19	6-28-12:48		855	4.7		35.0	22.5	12.5	32	6.7	285	6.72	264	1.26	0.299
20	6-28-14:47		882	5.1		35.8	19.8	16.0	20	6.9	285	7.52	274	1.38	0.333
21	6-28-17:30		873	4.9		32.6	18.8	13.8	25	5.6	285	6.50	276	0.93	0.278
22	6-29-14:00		888	4.4		38.5	21.0	17.5	19	5.7	255	4.88	240	1.43	0.356
23	6-29-16:06		855	4.4		40.0	21.0	19.0	16	5.7	255	6.06	253	1.74	0.266
24	6-29-18:20		884	4.9		35.0	22.2	12.8	31	5.3	300	6.09	281	0.86	0.217
25	6-30-05:45		878	4.6	299	24.5	22.2	2.3	83	0.8	225	1.13	218	0.14	0.065
26	6-30-09:22		875	4.6	296	28.6	23.0	5.6	61	3.8	225	3.70	220	0.27	0.185
27	7-01-06:04		872	4.8	297	22.8	21.5	1.3	89	0.6	150	0.69	030	0.21	0.050
28	7-11-20:42		887			28.6	24.0	4.6	68	1.9	315	2.17	274	0.19	0.105
29	7-11-23:23		882	4.7	297	26.2	23.4	2.8	79	1.1	315	2.05	278	0.06	0.046
30	7-12-02:07		841	4.0	303	24.5	22.5	2.0	83	0.6	180	0.61	168	0.01	0.033
31	7-12-04:40		869			23.5	23.0	0.5	95	0.7	225	0.91	207	0.00	0.027
32	7-12-19:30		873	4.5	301	28.5	25.0	3.5	75	3.2	315	4.11	272	0.32	0.148
33	7-12-21:40		867			26.1	23.5	2.6	80	1.4	300	2.27	253	0.06	0.068
34	7-13-00:28		859	4.0	300	24.0	22.5	1.5	88	1.2	315	1.72	253	0.01	0.051
35	7-13-03:19		864	3.8	300	24.0	22.5	1.5	88	0.6	270	1.09	221	0.01	0.012

Rupin

36	7-19-10:55	883	3.8	303	32.0	24.8	7.2	54	2.8	250	2.67	237	0.65	0.186
37	7-19-13:03	876	3.9		32.0	25.0	7.0	56	2.8	270	2.94	236	0.83	0.178
39	7-20-07:16	856	3.7	304	24.3	22.6	1.7	84	1.5	225	1.32	211	0.18	0.071
40	7-20-09:18	859	4.0	304	27.1	23.0	4.1	70	2.1	270	2.31	239	0.34	0.158
41	7-20-11:32	860	4.5	296	29.4	23.5	5.9	60	2.8	270	2.71	246	0.64	0.150
42	7-20-13:30	864	5.2	295	30.6	24.1	6.5	58	2.2	315	2.34	253	0.74	0.152
43	7-20-15:38	862	5.4	296	30.2	23.6	6.6	57	1.8	270	2.11	253	0.63	0.160
44	7-20-17:33	866	5.3	296	28.7	23.5	5.2	60	1.1	270	1.22	255	0.38	0.119
45	7-20-19:28	868	5.0	280	27.5	22.8	4.7	76	0.6	240	1.11	233	0.15	0.098

Column captions: 5 sprinkler revolution, 6 arm impacts, 10 relative humidity, 11 wind-speed, 12 wind direction, 13 center of gravity shift, 14 direction of

23 March 1990

Final Report, BARD US-1001-85

Page 2.52

1 shift, 15 collector evaporation loss, 16 spray evaporation loss.
2

1 Table 2: Water distribution patterns for wind-speeds 0, 2, 4, 6 and 8 m/s
 2 on a 2m by 2m grid. Values in table are in tenths of mm/h. Wind direction
 3 is from left to right. Only upper half of symmetrical pattern is shown.
 4 Sprinkler location is indicated by a "+".

5
 6 m -11 -9 -7 -5 -3 -1 1 3 5 7 9 11
 7

8 W - 0 m/s / $Q_c = 0.866 \text{ m}^3/\text{h}$ / $Q_c/Q_s = 1.00$
 9

10 11 3 6 8 8 6 3
 11 9 6 11 14 15 15 14 11 6
 12 7 6 12 17 19 20 20 19 17 12 6
 13 5 3 11 17 20 24 26 26 24 20 17 11 3
 14 3 6 14 19 24 32 38 38 32 24 19 14 6
 15 1 8 15 20 26 38 63 63 38 26 20 15 8

16 +
 17

18 W - 2 m/s / $Q_c = 0.777 \text{ m}^3/\text{h}$ / $Q_c/Q_s = 0.90$
 19

20 11 1 2 2
 21 9 3 5 6 8 7 5 2
 22 7 3 8 15 20 20 17 14 7 3
 23 5 2 7 18 29 34 32 26 21 15 7 1
 24 3 4 13 31 49 53 43 32 25 19 12 3
 25 1 5 16 40 64 69 53 34 26 22 14 4

26 +
 27

28 W - 4 m/s / $Q_c = 0.687 \text{ m}^3/\text{h}$ / $Q_c/Q_s = 0.79$
 29

30 9 2 3 4 4 2 1
 31 7 4 10 15 14 13 9 5 2
 32 5 4 16 30 34 30 24 16 10 6
 33 3 2 12 31 60 54 40 30 22 16 9 1
 34 1 5 14 52 66 63 42 28 24 18 10 2

35 +
 36

37 W - 6 m/s / $Q_c = 0.597 \text{ m}^3/\text{h}$ / $Q_c/Q_s = 0.69$
 38

39 9 1 2 3 2 2 1
 40 7 2 7 10 11 10 8 4 2 1
 41 5 2 10 22 28 25 18 14 10 5 3 1
 42 3 8 32 51 46 33 24 19 14 9 5 2
 43 1 1 16 51 67 50 33 25 20 16 12 6 2

44 +
 45

46 W - 8 m/s / $Q_c = 0.507 \text{ m}^3/\text{h}$ / $Q_c/Q_s = 0.59$
 47

48 9 1 2 2 1
 49 7 4 8 7 7 5 3 1
 50 5 1 11 20 23 17 13 9 7 4 1
 51 3 1 14 34 51 36 25 17 13 10 7 4 2
 52 1 5 30 58 59 40 24 17 14 11 8 5 2

23 March 1990

Final Report, BARD US-1001-85

Page 2.54

1								+											
2																			
3	m	-11	-9	-7	-5	-3	-1	1	3	5	7	9	11	13	15	17	19	21	

1
2 Figure 1: Meteorological conditions during field tests. June-July 1989.
3 Open symbols - Megiddo, full symbols - Rupin. The finely-dashed curves,
4 not supported here by data points, are for Hamadiya (from Seginer and
5 Kostrinsky, 1975). A: Dry-bulb (circles), and wet-bulb temperature
6 (triangles), as a function of time. B: Wind-speed as a function of time.
7

8 Figure 2: The relationship between wind-speed and wet-bulb depression
9 during the field tests. Open symbols - Megiddo, full symbols - Rupin.
10

11 Figure 3: The ratio R, between windward and leeward collector loss, as a
12 function of the mean collector loss. Data points for collector loss
13 smaller than 0.2 mm/h where not included, due to excessive scatter. Open
14 symbols - Megiddo, full symbols - Rupin.
15

16 Figure 4: A schematic cross-section through the test-field, showing the
17 distribution of water and losses.
18

19 Figure 5: Length, width and area of water distribution patterns as a
20 function of wind-speed (open symbols - Megiddo, full symbols - Rupin).
21 Results for the zero wind-speed pattern (radially symmetric; Figure 7),
22 are indicated by the horizontal dashed lines, and results based on Table
23 2 are connected by solid lines.
24

25 Figure 6: Irrigation rate as a function of wind-speed for grid points
26 located at a distance of $\sqrt{50}$ m from the sprinkler. Results for egative
27 wind-speed at grid-point (i,j), are identical with results of positive
28 wind-speed at grid-point (-i,j).
29

30 Figure 7: Mean radial section through the zero-wind distribution pattern.
31

32 Figure 8: Normalized distribution of water quantity along the radius, for
33 zero-wind conditions. The area under the curve, representing all applied
34 water, is unity. The Laboratory results are from Seginer et al., 1990.
35

36 Figure 9: Total spray loss, M, and spray evaporation loss, L, as a
37 function of wet-bulb depression for three studies: Present study (M) -
38 circles (open symbols - Megiddo, full symbols - Rupin), Yazar's (1984)
39 study (L) - squares, and Kohl et al.'s (1987) study (L) - triangles.

1
2 COMPARISON OF OVERLAPPED WIND-DISTORTED SINGLE SPRINKLER PATTERNS WITH
3 FIELD MEASURED OVERLAPPED PATTERNS
4

5 R. D. von Bernuth, Del Baird

6 Department of Agricultural Engineering, University of Tennessee

7 Knoxville, Tennessee
8

9 Ido Seginer, Dov Nir

10 Department of Agricultural Engineering, Technion, Haifa 32000, Israel
11

12 ABSTRACT
13

14 Single sprinkler wind-distorted distribution patterns were overlapped for
15 comparison with field measured overlapped patterns. For each of the field
16 measured set of conditions (wind speed and wind direction relative to the
17 grid) an interpolated (for wind speed) and rotated (for direction) pattern
18 was produced from measured representative single sprinkler patterns. These
19 patterns were overlapped to produce a grid to be compared to the field
20 measured overlapped patterns.
21

22 Two measures of similarity were computed. Coefficients of uniformity were
23 computed for each pair of matching conditions and those coefficients were
24 compared. Those values compared favorably considering the difficulties
25 encountered in field measurements. The second measure of similarity
26 computed was the normalized sum of squares of differences between the
27 measured and computed (from overlapped single-sprinkler field data) denoted
28 by σ .
29

30 Water losses for the field data were computed and a relationship was
31 developed to predict evaporation. That relationship compared favorably
32 with both the field data and with previous work by Yazar (1984).
33

34
35 NOTATION
36

37 Main Symbols
38
39

40 C_v coefficient of variation, s/m.....-
41 L water loss ratio.....-
42 m mean.....-
43 p water application rate.....m/s
44 q flow rate.....m³/s
45 Q collector can catch.....ml
46 R ratio-
47 s standard deviation-
48 T temperature.....°C
49 x, y field coordinate system for depth location.....m
50 α angle of rotation.....rad

σ normalized root-mean sum of squares.....-

superscripts

* rotated value

subscripts

a air

c field collected value

d water depth

i interpolated value

q water flow

l lower bracketing value

s simulated value or sprinkler value

u upper bracketing value

w wet-bulb

INTRODUCTION

The uniformity of water distribution by sprinklers is an important design factor which affects crop yield, water use efficiency and leaching of nutrients. The distribution pattern of a sprinkler system is greatly affected by wind, and the knowledge of how a design would be affected before its installation would greatly enhance design. The effects of wind on sprinkler distribution have been traditionally considered by using guidelines for spacing reduction to account for reduced uniformity based on rather sparse field data collected by a variety of sources. (Christiansen, 1942; Redditt, 1965; Strong, 1972; Fry and Gray, 1972; Solomon, 1978). For particularly sensitive installations, field tests at the proposed or similar site have been conducted to estimate the effect of wind. These tests are time consuming, expensive, and often not representative.

The concept of measuring the distorted pattern of a single sprinkler in wind and superimposing the patterns of a grid was used by Seginer and Kostrinsky (1975) and Hart and Heermann (1978). Seginer and Kostrinsky (1975) developed a method for interpolating and rotating, but the method presented here is a significant improvement over theirs. A set of wind-distorted single sprinkler distribution patterns was developed by Seginer, et al (1990) that lends itself well to the interpolation and rotation for overlapping at any windspeed or orientation.

PATTERN INTERPOLATION

The set of wind-distorted single sprinkler distribution patterns developed by Seginer, et al includes patterns for wind speeds of 0 to 8 m/s at 2 m/s increments. The pattern for any wind speed between 0 and 8 m/s can be obtained by interpolation between the adjacent two speed patterns. The

desired wind speed is first bracketed by the adjacent available two winds speeds at the 2 m/s increments. The depths (or application rates) for a grid location relative to the sprinkler are used to determine the interpolated depth (rate) in the following fashion

$$p_i(x,y) = [(V-V_1)]/2(p_u(x,y)) + [(V_u-V)/2](p_l(x,y)) \quad (1)$$

where V is the desired wind speed, V_1 is the lower bracketing wind speed, V_u is the upper bracketing wind speed and $p_j(x,y)$ are the respective interpolated value (i), upper (u), and lower (l) application rates for the subscript (j). The difference between V_u and V_1 is 2 because 2 m/s increments were used.

PATTERN ROTATION

Rotation of a grid of depths (surface) is relatively simple. Rotating a point, (x,y) through an angle α leads to the transformed point with co-ordinates

$$x^* = x \cos \alpha - y \sin \alpha, \text{ and} \quad (2)$$

$$y^* = x \sin \alpha + y \cos \alpha. \quad (3)$$

The procedure for rotating a matrix was used to rotate the individual grid point (x,y) within the matrix, to the transformed point (x^*,y^*) . The transformed point will not correspond exactly to a grid point on the original grid, so the depth corresponding to the rotated grid point is found by interpolation. The adjacent four points on the rotated grid are located and the depth is interpolated using the co-ordinates and depths of the surrounding four points according to the following scheme.

The interpolation for the rotated grid was based the method used by Seginer (1969) as follows,

$$p(x^*,y^*) = \alpha x^* + \beta y^* + \gamma x^* y^* + \delta. \quad (4)$$

where α , β , γ , and δ are constant coefficients determined from x,y and p of the four surrounding original nodes.

The effect of rotating the grid is to have rotated the pattern through the negative of the angle the grid was rotated.

An example of an interpolated/rotated pattern is shown in Figure 1 for 3.8 m/s wind interpolated from Table 2 of Seginer et al. (1990) oriented 78° of counter-clockwise rotation from horizontal.

OVERLAPPING OF PATTERNS

The individual interpolated/rotated patterns can then be superimposed (overlapped) at any desired grid spacing to reproduce an actual field condition. Consequently, the effect of any wind speed at any orientation relative to any grid spacing can be simulated using the set of programs developed. The approach of overlapping wind-distorted single sprinkler patterns is to test the validity of the interpolation/rotation/overlap procedure against field collected data.

FIELD COLLECTED GRID DATA

A series of tests was conducted at the Agricultural Research Service Station in Bushland, Texas during the first week of June, 1989. During that time the winds varied from 1.1 m/s to 6.8 m/s and the orientation of the wind relative to the grid varied through 270 degrees. Wind speed and direction, relative humidity, and temperature were recorded every minute for each of the 15 one-hour tests conducted, and the depths of water caught at each point of a 2m X 2m grid (80 total collectors) were recorded. Each collector was prefilled with 20 ml of water in order to estimate the effect of evaporation using the method described by Seginer, et al 1990.

An estimate of the evaporation can be obtained by comparing the water caught with the discharge of the sprinkler. A discharge ratio can be computed by dividing the average catch rate, q_c by the discharge rate, q_s .

$$R_q = q_c/q_s \quad (5)$$

The discharge ratio can be compared to the wet bulb depression.

COMPARISON OF OVERLAPPED SINGLE SPRINKLER PATTERNS TO FIELD GRID PATTERNS

An average wind speed and direction for each of the grid tests was computed, and the respective interpolations, rotations, and overlaps were computed for each of the 15 field tests. For each of the tests, two measures of similarity were computed. The first was the coefficient of uniformity by the HSPA (Hart, 1961) method where:

$$CU=100(1-.798(C_v)) \quad (6)$$

where C_v is the coefficient of variation equal to the standard deviation of the depths of water caught divided by the mean of the depths caught.

The second measure of similarity used was the sum of squares of differences between the two patterns. The raw sum of squares is given by

$$S^2 = \sum (p_c(x,y) - p_m(x,y))^2 \quad (7)$$

This value is divided by the number of grid points involved, N. The square root of the result is divided by the average application depth, m. Thus the normalized statistic σ is found:

$$\sigma = (\sqrt{S^2/N})/m \quad (8)$$

The values of the coefficients of uniformity and normalized sums of squares of differences are given in Table 1. The greatest difference between the CU's is 12 and the greatest σ is 0.869. While these differences indicate that the correspondence between the simulated data and the field collected data are not exact, the correspondence is quite good considering the error introduced in field data collection. For example placement of the grid exactly the same as the simulation is difficult due to uneven terrain and exactness of the grid. The mislocation of a collector by a few centimeters can radically affect the amount of water collected as can be seen in Figure 1. Furthermore, the simulation is not an exact reproduction of the wind direction and speed, because an average of the hourly readings was used in the simulation. If sixty individual interpolation/rotations were averaged for the simulation the accuracy would be significantly improved. For example, during Test 1 on June 3, 1989 the average wind speed was 1.1 m/s and the average direction was 17° rotation relative to the grid. However, for about 20 minutes of the 60 minute test the wind was calm and the directional vane did not move. Simulating the test with three 20 minute test segments (a rather coarse approximation) of 0.0, 1.1, and 2.2 m/s wind speed segments reduced the CU difference from 8.6 to 2 points. All indications are that if sufficiently small increments of time were chosen for the simulation, the differences between simulation and field results would be eliminated.

The correlation between field measured CU and simulation CU is not exactly one-to-one as is shown in Figure 2. As pointed out earlier, variation in the field in wind speed and angle of the wind relative to the grid both affect the quality of the simulation. Generally speaking, variation in either wind speed or direction will tend to increase the CU. The simulation process tends to overpredict CU when the greatest amount of interpolation is required. That is to be expected as the more the raw numbers are manipulated, the more they tend toward the mean. The same is true of rotating the data set. The effect of increasing CU with interpolation can be seen in Figure 3 where multiple runs of the simulation process were used to produce CU as a function of wind for several different rotations. For the even wind speeds where no interpolation was necessary, the values of CU fall on a smooth curve as would be expected. For the odd wind speeds where maximum interpolation was necessary, the CU values are consistent but high. Also shown in Figure 3 for comparison purposes are field data from Solomon (1978) for a similar sprinkler.

One would expect a strong correlation between differences between simulation CU and field CU and σ if there existed a systematic problem in the simulation process. However, there is no correlation. That indicates

1 that the differences are due to random sources inadequately described in
2 the simulation. The strongest source of random error certainly is the
3 random variation in field wind speed and direction. The overprediction
4 tendency of the simulation due to interpolation is systematic but can be
5 seen in Figure 3 to be less than 2 points.
6

7 Another source of systematic error that merits investigation is the
8 possibility of either of the measures of similarity being related to wind.
9 The CU difference is plotted in Figure 4 against wind, and there is no
10 correlation. The normalized sum of squares, σ , is plotted against wind in
11 Figure 5, and there is strong correlation. However, that correlation can
12 be explained at least in part by the correlation of simulation CU and σ as
13 shown in Figure 6. CU as calculated by equation (6) is a linear function
14 of C_v . As CU values increase, the variance of the values must decrease,
15 and so must the variance between the simulated and field values.
16 Therefore, the relationship between CU and σ should be expected. Since CU
17 is a function of wind speed, it is expected that σ would therefore be
18 strongly correlated with wind speed.
19
20
21

22 WATER LOSSES IN THE FIELD

23
24 Seginer et al (1990) discussed field water losses at length. The two major
25 components of field water loss are spray evaporation and wind drift. The
26 data collected in the field at Bushland, Texas in this study was from the
27 center of a sprinkler system 5 sprinklers by 5 sprinklers. It is
28 reasonable to assume that the drift losses around the center sprinkler of a
29 25 sprinkler grid are small, and therefore evaporation is the major source
30 of loss. The field conditions during the week of testing (May 29 through
31 June 3, 1989) were highly variable due to a stagnated frontal system in the
32 area. Conditions for the first three days were hot and windy with high
33 wet-bulb depressions. The latter three days were rainy and cool for the
34 area and wind was calm at dawn building to about 7 m/s by dusk. During the
35 course of the day, it was common for the wind to shift 180°. A summary of
36 the weather conditions and water caught is shown in Table 2.
37

38 All catch data were corrected for evaporation in the manner described by
39 Seginer et al. (1990). The average evaporation from the check cans around
40 the perimeter which had been prefilled, were plotted against wet bulb
41 depression (Figure 7). A very strong correlation with an intercept of
42 0.005 a slope of 0.027 [loss] per K depression. It would be expected that
43 a linear relationship with a zero intercept would exist, and the results
44 are very close to that.
45

46 The actual water caught in the collectors, Q_c , compared to the discharged
47 water from the sprinklers, Q_s , yields a catch ratio R_d ($R_d = Q_c/Q_s$) which
48 should relate to wind and wet bulb depression in the manner described by
49 Yazar (1984) and Seginer et al. (1990). The best fit relationship for R_d
50 is

$$R_d = 1.014e^{-0.014W}(T_a - T_w)^{-0.055} \quad (9)$$

where W is the wind speed in m/s and $(T_a - T_w)$ is the wet bulb depression. The very small exponents and the leading coefficient indicate that the values of R_d did not vary much from 1. This relationship has an RMS error of 0.041 compared to the actual measured value of R_d . Both Yazar and Seginer related the loss rather than the catch to wind and wet bulb depression, and the best fit relationship for loss due to evaporation and wind drift ($L - 1 - R_d$) in this study is

$$L = 0.0046e^{0.38W}(T_a - T_w)^{0.75} \quad (10)$$

Seginer et al. (1990) found a similar equation of

$$L = 0.0322e^{0.075W}(T_a - T_w)^{0.69} \quad (11)$$

Seginer rewrote Yazar's equation as follows

$$L = 0.0087e^{0.213W}(T_a - T_w)^{0.58} \quad (12)$$

Seginer et al. (1990) found an RMS of 0.038. A source of error in the data collected in this study was due to the inability to accurately control the sprinkler discharge, so it is not surprising that the RMS error is somewhat larger. However, there is very little difference between the two RMS errors.

The best prediction for loss can be obtained by subtracting the catch equation (9) from one

$$L = 1 - R_d \quad (13)$$

This equation results in a RMS of 0.041.

The power of the wet-bulb depression is greater than that found by Seginer and more nearly 1 as would be theoretically expected. The wind-speed coefficient is much larger than Seginer found. Seginer reasoned that the power of the wind coefficient should be greater, or at least greater than that found by Yazar (0.58) for evaporation only. He also reasoned that the reason that a stronger relationship was not found was due to the correlation between wind and wet-bulb depression in his study. In this study there was no correlation between wind and wet-bulb depression although many of the readings were at low depressions. A plot of wind versus wet-bulb depression is shown in Figure 8.

The assumption that drift loss in this study was small compared to evaporation may be reasonably good. Comparing the loss prediction equation (10) with Yazar's equation (12) for the conditions of this study, a very close agreement is found. The values are very nearly the same except for

1 the first two tests where the wind was 3.6 and 6.0 m/s respectively and the
2 wet-bulb depression was 13.3 and 9.7 respectively. The losses predicted
3 using Yazar's equation and equation (10) are plotted against actual losses
4 in Figure 9. All values of evaporation, both measured and predicted, are
5 less than 25%.

8 DISCUSSION AND CONCLUSIONS

10 Results of this study indicate that field sprinkler patterns can be
11 reasonably simulated using single-sprinkler wind distorted patterns by
12 interpolating for the desired wind speed and rotating the pattern for the
13 proper orientation of the wind to the grid. Excessive manipulation of the
14 data tends to spread and smooth the data, so for examples tested where
15 maximum interpolation was necessary, the simulation method tended to
16 overpredict uniformity. Since field conditions are rarely constant, the
17 quality of a simulation can be improved by simulating intervals and summing
18 those intervals. Results of this study also confirm the decrease in
19 uniformity with wind, and the uniformities are consistent with those found
20 by other researchers.

22 Orientation of the grid relative to the wind is a significant part of
23 designing a sprinkler system. The sprinkler used in this study
24 demonstrated a narrowing of the pattern normal to the wind which resulted
25 in a lesser uniformity when the longer leg of a rectangular spacing was
26 placed normal to the wind (see Figure 3). That is contrasted to earlier
27 studies of field data and simulation where better uniformities were found
28 with longer leg normal to the wind (Vories and von Bernuth, 1986). The
29 major difference is whether the pattern area is reduced in wind, and in
30 particular whether the pattern is narrowed normal to the wind. Not all
31 sprinklers demonstrate that effect.

33 Quantification of evaporation and wind drift are also important in
34 sprinkler system evaluation. Field data collected in this study, in the
35 center of a rather large system, eliminated most of the wind drift, so the
36 evaporation component could be evaluated. Evaporation from the collector
37 cans followed theoretical values, and evaporation from the sprinkler
38 pattern was quantified with an empirical equation in wind speed and wet-
39 bulb depression, which was similar to that found previously by Yazar (1984)
40 and produced results quite similar to his.

1 REFERENCES

- 2
3 Christiansen, J.E. 1942. Irrigation by Sprinkling. California
4 Agricultural Experiment Station Research Bulletin #670. Berkeley, CA.
5
6 Fry, A.W. and A.S. Gray. 1972. Sprinkler Irrigation Handbook. RainBird
7 Sprinkler Mfg. Corp., Glendora, CA 43 pp.
8
9 Hart, W.E. 1961. Overhead Irrigation Pattern Parameters. Agricultural
10 Engineering 42(7):354-355.
11
12 Hart, W.E. and D.F. Heermann. 1978. Evaluating Water Distributions of
13 Sprinkler Irrigation Systems. Colorado State Experiment Station Technical
14 Bulletin # 128.
15
16 Redditt, W.M. 1965. Factors affecting sprinkler uniformity. In:Hawaii
17 Sugar Planters Association, Sprinkler Irrigation Engineering Manual.
18 Hawaii Sugar Planters Association, Hawaii, pp 10-22.
19
20 Seginer, I.D. and M. Kostrinsky. 1975. Wind, Sprinkler Patterns, and
21 System Design. Proc. ASCE 101(IR4):251-264.
22
23 Seginer, I., D. Kantz., and D. Nir. 1990. Wind-Distorted Single-
24 Distribution Patterns. BARD Project No. US-1001-85: The Effect of Wind on
25 Sprinkler Distribution Patterns. Final Report, Chapter 2.
26
27 Solomon, K. H. 1978. Irrigation Uniformity; Significance and
28 Measurement. Unpublished Report, Lyntone Engineering. Glendora, CA.
29
30 Strong, W.C. 1972. Sprinkler Irrigation Manual. General Sprinkler Corp.
31 Fresno, CA. 27 pp.
32
33 Vories, E.D. and R. D. von Bernuth. 1986. Single Nozzle Sprinkler
34 Performance in Wind. TRANSACTIONS of the ASAE 29(5):1325-1330.
35
36 Yazar, A. 1984. Evaporation and Drift Losses from Sprinkler Irrigation
37 Systems under Various Operating Conditions. Agricultural Water Management
38 8:439-449.
39

41 ACKNOWLEDGEMENTS

42
43 We wish to acknowledge the financial support provided for this study by the
44 US-Israel Binational Agricultural Research and Development Fund (BARD) and
45 the Tennessee Agricultural Experiment Station.

Table 1
Comparisons of Overlapped Single Sprinkler
Wind Distorted Patterns to Field Test

Test#	Wind °	Wind m/s	Field CU	Sim CU	CU Dif	σ^*
1.531 ¹	-74.1	3.6	62.6	54.0	8.6	0.672
2.531 ¹	-22.6	6.0	53.7	56.4	-2.7	0.741
3.531 ¹	-12.2	5.9	47.3	57.4	-10.1	0.823
1.601 ¹	-19.8	6.2	49.5	56.6	-7.1	0.806
5.601	63.6	5.0	54.9	66.7	-11.8	0.704
1.602	-58.9	1.4	74.7	81.3	-6.6	0.402
3.602	-86.7	6.2	57.2	59.1	-1.9	0.748
4.602	-74.6	6.8	61.8	58.4	3.4	0.869
1.603	-16.6	1.1	76.0	84.6	-8.6	0.203
2.603	64.0	1.8	78.5	77.9	0.6	0.181
3.603	-77.5	3.8	70.3	67.5	2.8	0.353
4.603	-78.0	2.9	76.3	72.9	3.4	0.200
5.603	86.4	2.7	78.0	73.8	4.2	0.175
6.603	00.7	5.3	60.2	69.4	-9.2	0.492

¹ 12m x 18m spacing. All others are 12m x 15m.

* normalized root-mean sum of squares statistic

Table 2
Weather Conditions and Water Caught
for Field Test at Bushland, Texas
May 29 to June 3, 1989

Test#	Wind °	Wind m/s	T _a °C	T _w °C	T _a -T _w K	Q _c /Q _s
1.531	-74.1	3.6	33.3	22.0	13.3	0.82
2.531	-22.6	6.0	35.2	25.5	9.7	0.91
3.531	-12.2	5.9	37.0	26.9	10.1	0.79
1.601	-19.8	6.2	16.7	16.3	0.4	1.02
5.601	63.6	5.0	21.5	20.8	0.7	*,**
1.602	-58.9	1.4	18.3	17.2	1.1	1.06
3.602	-86.7	6.2	25.2	21.0	4.2	0.85
4.602	-74.6	6.8	21.7	19.8	1.9	0.85
1.603	-16.6	1.1	16.1	15.1	1.0	1.02
2.603	64.0	1.8	18.0	16.5	1.5	0.88
3.603	-77.5	3.8	18.3	17.2	1.1	0.96
4.603	-78.0	2.9	18.9	18.0	0.9	0.98
5.603	86.4	2.7	19.5	18.6	0.9	0.98
6.603	00.7	5.3	19.5	18.6	0.9	0.90

*,** No data

1 LIST OF FIGURES

2
3 Figure 1. Interpolated/ rotated pattern for a 3.8 m/s wind rotated 78°
4 counter-clockwise. Based on patterns produced by Seginer et al. (1990).
5 Grid is 1m x 1m.

6
7 Figure 2. Simulated uniformity coefficient versus field measured
8 uniformity for 14 tests at Bushland, Texas 29 May 1989 to 3 June 1989.
9 Sprinkler spacings were 12m x 18m and 12m x 15m.

10
11 Figure 3. Uniformity as a function of wind from overlapped wind-distorted
12 single sprinkler patterns with various wind orientations relative to the
13 grid for a 12m x 15m spacing. 0 rotation is with the 12m side normal to
14 the wind. Solomon (1978) data is for a similar sprinkler with unknown
15 orientation.

16
17 Figure 4. Difference in uniformity between simulated and measured patterns
18 as a function of wind speed.

19
20 Figure 5. Normalized mean sum of squares statistic as a function of wind.

21
22 Figure 6. Normalized mean sum of squares statistic as a function of
23 uniformity for the simulated patterns.

24
25 Figure 7. Check can evaporation loss as a function of wet-bulb depression.

26
27 Figure 8. Relationship between wet-bulb depression and wind.

28
29 Figure 9. Predicted evaporation loss by Yazar (1984) and prediction
30 equation (Von Bernuth) compared to measured loss.
31
32
33

SIMULATION OF WIND-DISTORTED SPRINKLER PATTERNS

Ido Seginer, Dov Nir

Department of Agricultural Engineering, Technion, Haifa 32000, Israel

R. D. von Bernuth

Department of Agricultural Engineering, University of Tennessee,

Knoxville, Tennessee

ABSTRACT

Single-sprinkler wind-distorted distribution patterns were simulated utilizing drop trajectory computations, and compared with measured patterns. It was found that the exact formulation of the drag coefficient of single drops is not critical for applications focusing on water distribution. A drag correction factor, k , to account for the effect of the incidence angle between the drag force and the orientation of jet segments, was introduced. The agreement between measured and computed patterns was found to improve considerably when the proper value of k is used.

Three measures of similarity of computed to measured single patterns were suggested. The most comprehensive measure is a normalized sum of squares of differences between the measured and computed local application rates, denoted by σ . The values of k which produce the best agreement in terms of σ , seem to be an increasing function of the range of a sprinkler.

Single-patterns computed with the best values of k were used to calculate uniformity coefficients for a realistic spacing of the medium-pressure sprinklers under consideration. The results suggest that the computational method can be used to forecast, with an error of only a few percent, the uniformity of application under wind-speeds as high as 8 m/s. Considering the effort involved in field measurements, this seems a viable alternative.

NOTATION

main symbols

SI units

A	area	m^2
C	drag coefficient	-
C_2	modified drag coefficient	m^{-1}
CU	Christiansen's uniformity coefficient	-
D	drop diameter	m
d	displacement height	m
E	error in uniformity coefficient	-
F	drag force	N
f	a function relating application rate to surface coordinates	m/s

1	g	gravitational acceleration	m/s^2
2	h	a function relating specific discharge to drop size ...	$m^3/(s \cdot m)$
3	k	drag correction factor	-
4	L	distance of center of mass of pattern from sprinkler	m
5	m	a function relating drop diameter to surface coordinates	m
6	$\underline{m}$	inverse of m	m^{-1}
7	N	number of grid nodes in pattern	-
8	P	operating pressure	Pa
9	p	water application rate	m/s
10	Q	sprinkler discharge	m^3/s
11	q	specific discharge per drop diameter	$m^3/(s \cdot m)$
12	Re	Reynolds Number	-
13	r	radial distance from sprinkler	m
14	S^2	sum of squares of differences of application rate	$(m/s)^2$
15	s	length of coherent jet	m
16	t	time	s
17	U	velocity relative to ground	m/s
18	V	velocity relative to air	m/s
19	W	wind velocity	m/s
20	w	wind velocity component	m/s
21	x,y,z	Cartesian coordinates of field space	m
22	z_o	roughness length	m
23			
24	α	coefficient of interpolation	s^{-1}
25	β	coefficient of interpolation	s^{-1}
26	γ	coefficient of interpolation	$(s \cdot m)^{-1}$
27	δ	coefficient of interpolation	m/s
28	ϵ	normalized difference between distances to center of mass	m
29	η	incidence angle of drag force	rad
30	θ	azimuth angle of nozzle	rad
31	ν	kinematic viscosity of air	m^2/s
32	ρ	density	kg/m^3
33	σ	normalized root-mean sum of squares	-
34	ϕ	measure of overlap	-
35			
36	subscripts		
37			
38	0	zero wind-speed	f field, non-zero wind
39	a	air	r reference height
40	c	computed	x x component
41	i	indoor	y y component
42	m	measured	w water
43			
44	superscripts		
45			
46	'	corrected value	
47			
48	INTRODUCTION		
49			

1 The uniformity of water distribution by irrigation is an important design
2 factor, which affects crop yield, water use efficiency and leaching of
3 fertilizers. When water is applied by sprinklers, the distribution
4 pattern, and hence the uniformity of application, are strongly affected
5 by wind. The traditional approach to assessing the effect of wind on the
6 uniformity was to measure water distribution under field conditions and
7 catalogue the resulting uniformities. Unfortunately, the number of
8 effectively different combinations of wind-speed and direction with
9 sprinkler spacing is immense. Therefore emphasis has shifted to measuring
10 single-sprinkler patterns, which could later be superimposed for various
11 wind directions and spacings. This approach still requires a significant
12 amount of field work (e.g. Seginer and Kostrinsky, 1975), and therefore
13 is not being routinely used.

14
15 Recent attempts to simulate sprinkler spray trajectories (Fukui et al.,
16 1980; von Bernuth and Gilley, 1984), opened up a new alternative, whose
17 outline is as follows: The radial water distribution of a given
18 sprinkler-pressure combination can be conveniently and efficiently
19 measured indoors in still air (Seginer et al., 1990a). The outcome can be
20 expressed by the function

$$21 \quad p_i = f_i(r), \quad [1]$$

22
23
24 where p is the rate of water application at distance r from the sprinkler
25 and the subscript i indicates indoor conditions. Using trajectory
26 simulations it should be possible to calculate, for any given test
27 conditions, the effective size of drops reaching a certain distance from
28 the sprinkler:

$$29 \quad D = m_i(r), \quad [2]$$

30
31
32 where D is effective drop diameter. As shown in Appendix A, the functions
33 f and m can be used to determine the function

$$34 \quad q = h(D), \quad [3]$$

35
36
37 where q is the specific discharge of water at drop size D . It will now be
38 assumed that $h(D)$, whose form depends on the sprinkler (type and nozzle)
39 and the operating pressure, is independent of the environmental
40 conditions. If so, this distribution function can be used as the basis
41 for pattern simulation under wind conditions. To obtain the water
42 distribution under wind conditions, the procedure as outlined above is
43 reversed: First, the distance reached by drops of size D is obtained
44 through trajectory simulations and expressed as

$$45 \quad D = m_f(x,y), \quad [4]$$

46
47
48 where the subscript f indicates field conditions. Then, the relationships
49 of Equations [3] and [4] are used to determine the application rate

1 $P_f = f_f(x,y)$

[5]

2
3 at any point in the field.

4
5 Previous attempts to test this approach were limited to wind-speeds of up
6 to about 4 m/s (Fukui et al., 1980; Vories et al., 1987). The number of
7 field observations was limited, and Vories et al. indicated that the
8 simulated wetted areas were consistently larger than the measured ones.
9 Since this approach seems to hold much promise for practical application
10 by manufacturers of sprinklers and by consumer organizations, a more
11 comprehensive test seemed justified. The present study used a new set of
12 field data (Seginer et al., 1990b) as well as older data (Seginer and
13 Kostrinsky, 1975), and explored several drag coefficient formulations.
14 Results for wind-speeds up to 8 m/s are presented and the applicability
15 of the method is discussed.

16 17 SPRAY DRAG

18
19 The rotation of impact sprinklers may be approximated by a step function.
20 As a result, the main jet is cut into segments, which move through the
21 air almost independently of each other. The rear-part of a jet-segment
22 encounters less air resistance than the forepart, since the surrounding
23 air has already been set in motion by that forepart. If the sprinkler is
24 prevented from rotating, all segments move along the same path, thus
25 experiencing reduced drag. The result is an increased range, which
26 Bilanski and Kidder (1958) and Seginer (1963) showed to be significant.

27
28 Each one of the jet-segments disintegrates along its trajectory into
29 drops of various sizes. The larger drops tend to fall to the ground
30 further away from the sprinkler (Frost and Schwalen, 1955; Schleusener
31 and Kidder, 1960; Seginer, 1965; Kohl, 1974), because the ratio of drag
32 to inertia forces is smaller for these drops. Each drop starts its way as
33 an element of a continuous jet, and normally ends up completely
34 separated. From this point of view one would expect the effective drag
35 coefficient of jet-elements to increase along their trajectory.

36
37 Since this complex behavior is difficult to model, present trajectory
38 simulation studies tend to utilize simplified descriptions of the
39 process: The spray is viewed as a collection of drops, each moving in the
40 air independently of the others, with a drag coefficient which is either
41 constant (Seginer, 1965; von Bernuth and Gilley, 1984) or a function of
42 the Reynolds Number of spherical drops (Fukui et al., 1980). Either
43 assumption is a gross simplification, since, as already mentioned, the
44 association of a drop with its neighbors changes along the trajectory. In
45 addition, large water drops deform in flight, resulting in drag forces
46 considerably larger than for equivalent spheres. Values derived from
47 observation of water drops by Laws (1941) and by Gunn and Kinzer (1949),
48 are presented, respectively, by Seginer (1965) and by Park et al. (1983).

1 Uncertainty concerning the actual variation of drag coefficients along
2 the trajectory, prompted von Bernuth and Gilley (1984) to divide the
3 trajectory into two sections. They reasoned that the jet emerging from a
4 nozzle is initially coherent for some distance, thus encountering little
5 air resistance. They therefore took the drag coefficient to be zero up to
6 a certain distance, s , while from this point on, each drop moves
7 according to a drag coefficient which only depends on the drop diameter.
8 They set the length of the first section of the main jet to $s = 1$ m, in
9 order to match Kohl's (1974) experimental data. They did not apply this
10 correction to the 10% of the water which was affected by the impact arm.
11 This approach can be further elaborated, by assigning each drop-size a
12 different first section, so that a better match can be obtained between
13 the average (mean or median) drop size actually reaching a certain
14 distance and the (uniform) drop size reaching the same distance by
15 trajectory simulation.

16
17 Whatever the drag formulation is, to be useful it should be invariant
18 under a wide range of operating conditions external to the sprinkler. In
19 other words, once a given jet emerges from the nozzle, the same
20 computational scheme should provide acceptable results for different
21 riser heights and tilts, different land slopes and different wind
22 conditions. The inherent (but implicit and vague) assumption in this
23 approach is that the disintegration of a given jet, and thus the change
24 of effective drag coefficient, is only a function of the distance
25 travelled (or time of travel) through the air.

26 27 SPRAY TRAJECTORY COMPUTATION

28
29 Two forces act on a jet-element (or drop) in flight: gravity, in the
30 vertical direction, and drag, in a direction opposite to the element's
31 motion relative to the air. In the absence of wind the trajectory of an
32 element is confined to a vertical plane, but in general the trajectories
33 are three dimensional. Under steady wind conditions, which will be
34 assumed here throughout, the rear-part of a jet-segment traces exactly
35 the same trajectory as its forepart. Hence, the orientation of each jet-
36 segment is parallel to its velocity relative to the ground. In still air
37 the ground-velocity, U , of a jet-element is equal to its air-velocity, V ,
38 but in general, as shown in Figure 1,

$$39 \quad V = U - W,$$

[6]

41
42 where W is the wind vector (relative to the ground). The air-velocity V ,
43 and therefore the drag force, F , are in general not parallel to the jet-
44 segment. This suggests that the drag coefficient may be a function of the
45 incidence angle η , with a minimum when $\eta = \pi/2$ and a maximum when $\eta = 0$.

46
47 The equations of motion for a jet-element, or a drop, (Fukui et al.,
48 1980) are as follows:
49

$$d^2x/dt^2 = -\frac{1}{2}(\rho_a/\rho_w)(C/D)V(dx/dt-w_x) \quad [7]$$

$$d^2y/dt^2 = -\frac{1}{2}(\rho_a/\rho_w)(C/D)V(dy/dt-w_y) \quad [8]$$

$$d^2z/dt^2 = -\frac{1}{2}(\rho_a/\rho_w)(C/D)V dz/dt - g, \quad [9]$$

where x, y and z are the Cartesian distances (referenced to the field) with origin at the sprinkler and with z pointing up; dx/dt, dy/dt and dz/dt are the components of U; V is the air-speed of the element (absolute value of V); t is time; ρ_a and ρ_w are air and water densities, respectively; D is nominal drop diameter, and C is drag coefficient, defined on the basis of a single drop by

$$F = (1/8)\rho_a C \pi D^2 V^2. \quad [10]$$

Traditionally C is given as a function of the Reynolds Number, but authors who consider C to be a function of drop size alone often collect terms and define

$$C_2(D) = \frac{1}{2}(\rho_a/\rho_w)(C/D). \quad [11]$$

To start a simulation, the velocity of the emerging jet should be known. The absolute value of this velocity is proportional to the square root of the operating pressure, with a proportionality factor which is similar for most range nozzles.

The drag coefficient, C, can be formulated in various ways, as already mentioned. Three different formulations were examined in this study:

1. After Fukui et al. (1980), henceforth denoted FUKUI (slightly modified from the original to match segments of the function):

$$\begin{aligned} \text{if } Re \leq 128 & \quad \text{then } C(Re) = 33.3/Re - 0.0033Re + 1.2 \\ \text{if } 128 < Re \leq 1440 & \quad \text{then } C(Re) = 72.2/Re - 0.0000556Re + 0.48 \\ \text{if } 1440 < Re & \quad \text{then } C(Re) = 0.45, \end{aligned} \quad [12]$$

where the Reynolds Number is defined for a nominal drop diameter

$$Re = VD/\nu. \quad [13]$$

2. After von Bernuth and Gilley (1984), henceforth denoted BERNUTH, using the $C_2(D)$ data plotted in their Figure 2.

3. After Hills and Gu (1989), henceforth denoted HILLS:

$$C_2(D) = 0.4671 D^{-0.9859} \quad [14]$$

The first formulation makes C strictly a function of Re, while the other

formulations make it strictly a function of D . It should be evident at this point that for a given value of $C_2(D)$, formulations 2 and 3 produce exactly the same trajectory, except that it may be tagged by a different nominal drop diameter.

The effect of the angle of incidence of the drag force was introduced in this study through a somewhat arbitrary correction of the form

$$C' = C(1 + k |\cos \eta|) \quad [15]$$

where the correction factor k is to be determined by best fit to the experimental data. Since in still air $\eta = \pi/2$ at all points along the trajectory, for such conditions $C' = C$. The correction increases with wind-speed (through its effect on η) and with k .

Wind-speed over an infinite plane is usually assumed to vary logarithmically in the vertical direction

$$W(z) = W_r \frac{\ln[(z-d)/z_0]}{\ln[(z_r-d)/z_0]} \quad [16]$$

where W is wind-speed (absolute value of W), W_r is a reference wind-speed determined at a reference height z_r above ground, and d and z_0 are parameters normally related to crop height. The displacement height d and the roughness length z_0 were estimated to be $d=6.4$ cm and $z_0=1.3$ cm, based on an estimated 10 cm height of the stubble in the field surrounding the test plot. The nominal wind-speed as reported herein refers to a reference height $z_r=2$ m.

COMPARISONS WITH STILL-AIR DATA

Two sets of recent data, relating average drop diameter to the distance from the emitting sprinkler, were used. One set was based on Figure 1 of Hills and Gu (1989) and the other was obtained in the present study. The results for operating-pressure 300 kPa and riser height 1 m are compared in Figure 2 with the relationships predicted by using the three drag formulations mentioned in the previous section. Other comparisons yielded the same general behavior. The agreement among the experimental data is very good throughout most of the range. It should be emphasized that nozzle diameter does not seem to affect considerably the function $D=m(r)$, this being in accord with the assumptions of the model. It may, however, affect the function $q=h(D)$ and thus the size of the largest drops. The largest mean drop diameter actually observed was about 3.2 mm.

The drag formulation which best fits the experimental data is FUKUI. This is probably not the result of a physically superior model, since all of the formulations are crude approximation of the real process. The decision which formulation to use is, however, not critical for the

1 present application, as is illustrated by the next figure.

2
3 Figure 3 shows 3 pairs of relationships $D=m(r)$, one for each of the wind-
4 speeds -6, 0 and 6 m/s (the speed is taken as positive when it is in the
5 direction of the jet). The differences between FUKUI and BERNUTH within
6 each pair is quite significant for the large drop sizes, but consider the
7 following question: What will be the distance reached by drops that in
8 still-air fall 13 m from the sprinkler, when the sprinkler is operated at
9 a wind-speed of 6 m/s or -6 m/s? Using FUKUI we find that the drops
10 reaching the ground at 13 m in still air have a nominal diameter $D=3.55$
11 mm, while BERNUTH labels the same drops as $D=6.0$ mm. This seems a big
12 difference, but when the reverse operation is applied, it turns out that
13 FUKUI's 3.55 mm drops hit the ground almost exactly where BERNUTH's 6.0
14 mm drops fall for practically all wind-speeds (at $r=18.5$ m for $W=6$ m/s
15 and at $r=5.5$ m for $W=-6$ m/s).

16
17 The back-and-forth computation removed most of the absolute error
18 inherent in the two drag formulations and made it unnecessary to know
19 what the drop diameter actually is. Whenever the absolute sizes of the
20 drops are not required, all drag formulations of the form $C_2=C_2(D)$, in
21 our case BERNUTH and HILLS, are exactly equivalent. FUKUI, where $C=C(Re)$,
22 happens to produce a similar result in our case. At this point FUKUI was
23 selected as the drag formulation for the rest of the study.

24
25
26 The next question was the usefulness of dividing the jet into two
27 sections. Figure 2 suggests that, if at all helpful, the length of the
28 first section, s , will be quite small for the available data. Observation
29 of the jet during the experiments also suggested that there is no
30 significant coherent jet in the present case. A computational test was
31 run, nevertheless, with the data given by Seginer et al. (1990a, Table
32 2). These data (their Series A,B and C) show the fraction of water
33 reaching various distances from the sprinkler in still-air for a range of
34 riser tilts. The data can be used to test the hypothesis made in the
35 introduction, that $q=h(D)$ is only a function of the sprinkler and the
36 operating pressure. In other words, the same function $q=h(D)$ should be
37 obtained from test runs that differ from each other in riser tilt alone.
38 At the same time the parameter s could be varied until a best fit is
39 found.

40
41 Some of the results of this test (using FUKUI) are shown in Figure 4. The
42 results shown are for the intermediate nozzle diameter, 3.5 mm, the same
43 nozzle as used in the field experiments reported by Seginer et al.
44 (1990b), and which will be later used for comparisons in this paper. It
45 turns out that the best value of s , for which Figure 4 is drawn, is about
46 $s=0$. The scatter in the figure is rather small (standard deviation of the
47 order of $0.02 \text{ m}^3/(h \cdot \text{mm})$), and the result seems to justify the hypothesis
48 that $q=h(D)$ is invariant with tilt angle, at least for the limited range
49 tested.

Based on the preliminary comparisons reported in this section, a simulation of complete wind-distorted patterns was attempted, using the FUKUI drag formulation with $s=0$. An appropriate value for the drag correction factor k is yet to be determined.

COMPARISONS WITH FIELD DATA

The ultimate test of the proposed approach is the comparison between measured and computed single patterns distorted by wind. Measured patterns suitable for this purpose are given by Seginer & Kostrinsky (1975, Table 2) and by Seginer et al. (1990b, Table 2). There is a slight difference between the methods used to obtain the data in these two studies, the latter probably delineating better the wetted area. There is also a difference in the way the data were presented in the two studies: While in the first study the patterns were corrected for spray loss, this was not done in the second study. To bring all the data to the same standard, a proportional spray correction was applied to the later set of data.

Altogether, five patterns (for wind-speeds $W=0, 2, 4, 6$ and 8 m/s) were available for each of three sprinklers. Table 1 gives the relevant specifications of the 3 sprinkler-pressure combinations. All sprinklers were of the impact type and utilized a single nozzle.

The computations leading to patterns which can be readily compared to the measured patterns, are described briefly in Appendix B. Calculations were carried out for comparisons with all 15 (3 sprinklers by 5 wind-speeds) available measured patterns. The FUKUI drag formulation with the correction introduced in Equation [15] were used throughout. At least five values of the correction factor k were used for each pattern: 0, 0.3, 0.6, 0.9 and 1.2. Sometimes $k=1.5$ was also used, but normally the best value of k was found to lie between 0 and 1.2.

Several comparisons were made between the measured and computed patterns in an attempt to assess the success of the simulations. For each pair of patterns three measures of similarity were computed. These are listed below in an order related to their information content. They may be viewed as representing 1, 2 and 3 dimensional measures of similarity.

1. Distance of the center of mass of a pattern from the sprinkler. The difference between the computed and measured distances, divided by the measured distance, will be denoted by ϵ :

$$\epsilon = (L_c - L_m)/L_m \quad [17]$$

2. Area covered by a pattern. Let us denote the measured wetted-area by A_m and the computed wetted-area by A_c (Figure 5). Dividing the intersection of these areas by their union yields a measure of the overlap of the two areas:

$$\phi = A_m \cap A_c / A_m \cup A_c. \quad [18]$$

This ratio is 1 for a perfect overlap and 0 for no overlap at all.

3. Sum of squares of differences between patterns. First, the raw sum of squares

$$S^2 = \sum (p_c(x,y) - p_m(x,y))^2 \quad [19]$$

is calculated. This is divided by the number of grid points involved, N , and the square root of the result is further divided by the average application rate over the wetted area Q/A . The values for indoors conditions, namely N_0 and A_0 , were used. Thus

$$\sigma = \sqrt{(S^2/N_0)/(Q/A_0)}. \quad [20]$$

The normalized statistic σ is zero for a perfect match. $\sigma=0$ implies $\phi=1$ and $\epsilon=0$, but not vice versa.

It turns out that the computed location of the center of mass, L_c , is barely dependent on the drag correction factor k . Therefore, the results plotted in Figure 6 are means over the range of k values from 0 to 1.2. The figure shows that on the average $\epsilon=0$ for Sprinkler C, in contrast with the results for sprinklers A and B, where the mean discrepancy is $\epsilon=0.16$. This may be a result of the different measurement methods employed to obtain the data.

The effect of k on the computed wetted area, and thus on ϕ , is considerable, unlike its minor effect on L_c . Figure 7 shows a sample result for Sprinkler C at wind-speed of 6 m/s. The dots in this half-pattern indicate locations where the measured application rate is non-zero. The curves show the computed pattern circumference for various values of k . The best fit seems to be between $k=0.6$ and $k=1.2$. Figure 8 shows the measure of overlap, ϕ , as a function of k for Sprinkler C, when operated under a range of wind-speeds. The figure shows that for the best value of k , which is not the same for all wind-speeds, $\phi > 0.9$. The best k values range from 0.75 to 1.15. The best values of ϕ for Sprinklers A and B (not shown) are somewhat lower, but with one exception are above 0.8.

Figure 9 presents sample results (Sprinkler C) of the third measure of similarity, namely σ . These results show that, generally speaking, the deviation from similarity increases with wind-speed (this trend is even more systematic for sprinklers A and B; not shown). The results for wind-speed zero should have been $\sigma=0$ (independent of k) if there were no computational errors. The discrepancy, to the amount of 0.1, is due to the coarseness of the computational grid.

The values of k for which σ attains a minimum are tabulated in Table 2,

1 which suggests the following three observations:

- 2
- 3 1. The values of k differ among sprinklers more than within sprinklers
- 4 (Sprinkler C performs in this respect less well than the other two).
- 5
- 6 2. The value of k seems to correlate positively with the wetted radius:
- 7 The larger the radius, the larger the correction factor needs to be. This
- 8 is illustrated in Figure 10, but should be taken as a preliminary result,
- 9 pertaining to the class of sprinklers under study.
- 10
- 11 3. While k values which maximize ϕ are different from those which
- 12 minimize σ , they, too, increase with increasing wetted radius.
- 13
- 14

15 The evidence to this point does not relate directly to the eventual use
16 of the simulation method, which is the prediction of the uniformity of
17 water distribution in the field. Since there is practically an unlimited
18 number of wind-by-spacing combinations, only an example could be worked
19 out: A 12m by 12m spacing, with wind blowing parallel to the grid, was
20 selected for all sprinklers, and Christiansen's uniformity coefficient,
21 CU (Christiansen, 1942), was calculated for all available patterns. The
22 results for Sprinkler C are shown in Figure 11, which suggests the
23 following:

- 24
- 25 1. The uniformity deteriorates with wind-speed, as expected.
- 26
- 27 2. The uniformity based on simulated patterns decreases as k increases.
- 28 This is directly related to the reduction of the wetted area with
- 29 increasing k (Figure 7).
- 30
- 31 3. There is a value of k for which the uniformity based on the measured
- 32 patterns (reflecting the true process) matches the uniformity based on
- 33 the simulated patterns.
- 34
- 35 4. The error resulting from a deviation from the best value of k is
- 36 roughly proportional to $1 - CU$, where CU is based on the measured pattern.
- 37

38 The vertical dashed line through Figure 11 shows the value of the mean
39 value of k which minimizes σ . If this value was selected, errors of about
40 0.04 in CU would have been incurred. A summary of these errors, E , for
41 all sprinklers is shown in Figure 12, where they are plotted against the
42 uniformity coefficient based on the measured patterns. The scatter in the
43 figure does not suggest a relationship between the error and CU that can
44 be used to correct the results. Nevertheless, two observations may be
45 made:

- 46
- 47 1. The error associated with zero wind-speed is not negligible. This
- 48 error, of the order of 0.02, is a result of using coarse computational
- 49 grids and may be reduced in the future. The results for non-zero wind-

speeds also contain this error.

2. Errors at high CU values cannot be as high as for low CU values (due to the upper bound $CU=1$, Figure 11). Therefore, an envelope of the errors may look like the two radiating lines in Figure 12. At present one may expect the error, E , to be restricted by

$$|E| < 0.3 (1 - CU)$$

[21]

DISCUSSION AND CONCLUSION

The objective of this study was to explore the possibility of replacing measured water distribution patterns by simulated ones. As it stands now, the proposed procedure is as follows:

1. Obtain measured radial distribution pattern ($p_{im}=f_{im}(r)$) for indoor conditions.
2. Use the computational procedure outlined in Appendix B, with a drag correction factor, k , from Figure 10, to obtain wind-distorted patterns on a square grid ($p_{fc}=f_{fc}(x,y)$).
3. Rotate and superimpose these patterns as required, and determine the pertinent uniformity coefficient.

Since the proposed procedure is imperfect, the pros and cons of adapting it for use should be considered. First, however, the possible sources of the errors, such as shown in Figure 12, should be identified. These can be divided into three groups:

1. Field measurement errors. Despite the extensive field work which was used to produce the data-bases utilized in this study, there are inevitable errors due to wind variation and uncertain spray losses, as well as measurement errors. Figure 9 shows an irregularity of the results (lower curve for 6 m/s than for 4 m/s), which can only be attributed to the measured patterns. This particular irregularity does not appear in the data for the other sprinklers, but there are other irregularities in those.

Particular care has been taken by Seginer et al. (1990b), to delineate properly the perimeter of the wetted area. This seems to have paid off in terms of ϕ values (Figure 8) and perhaps also in terms of ϵ (Figure 6), but spray losses (confounded in reality with wind-speed) were still crudely estimated rather than measured in detail.

It is difficult to estimate the magnitude of the field measurement errors, but they can be somewhat reduced with time as more data become available.

2. Computational errors. These are mainly due to the coarseness of the

1 spider-web grid (Appendix B; every $\pi/8$ in θ and 0.5 mm in D). An estimate
2 of these error components in terms of the final CU can be obtained from
3 results for wind-speed zero. Figure 12 contains three such results, two
4 of which have an error of slightly over 0.02. It should be possible to
5 eliminate much of this error with more computing power.

6
7 3. Modelling errors. These errors are intrinsic to the present approach
8 and are suspected to contribute most to the total error. There seem to be
9 two main sources for these errors:

10
11 3.1 The drag formulation in this study, even with the correction factor
12 added, is still very crude and does not reflect the changes along the jet
13 (see section "spray drag coefficients" above). The model predicts a one-
14 to-one relationship between drop diameter and impingement distance,
15 contrary to observation.

16
17 3.2 The simulation considered only water emitted at a velocity
18 corresponding to the operating pressure and at the elevation angle of the
19 nozzle. The water intercepted by the impact arm, although only about 15%
20 of the total (Seginer et al., 1990a), should have been simulated with
21 different initial conditions (lower initial speed and perhaps different
22 elevation angle).

23
24 It may now be asked if with these errors in mind, the proposed approach
25 can be further improved? As already mentioned, the errors due to the
26 first two sources may be somewhat reduced, but the deficiencies of the
27 model are probably not easy to rectify. The analysis in the previous
28 sections brought up certain strong and weak elements of the method:

29
30 First, it has been shown (Figure 3) that for the intended uses of the
31 method, the exact drag coefficient formulation of individual drops is not
32 critical. This is convenient.

33
34 Second, the parameter s , which turned out to be about zero in this study,
35 may be non-zero for other sprinkler-pressure combinations. Its value can
36 be obtained from auxiliary indoor tests which involve changing riser tilt
37 (Figure 4) or riser height. Such tests, when automated (Seginer et al.
38 1990a), are inexpensive to perform.

39
40 On the other hand, the present study suggests that a drag correction
41 factor is required in order to prevent excessively large errors from
42 occurring (Figure 11). Previous studies (Fukui et al., 1980; Vories et
43 al., 1987) seem to have obtained good agreement between measured and
44 computed patterns (or uniformity coefficients) without recourse to such a
45 correction. The latter reference mentioned, however, the difference in
46 wetted area between measured and computed patterns. The correction factor
47 as used in the present study managed to reduce this area discrepancy to a
48 minimum (Figure 7).

While the drag correction factor was given a semi-physical justification, its role is no more than that of an empirical parameter, which, unlike the parameter s , cannot be obtained indoors for lack of wind. At this point in time k does not seem too well behaved. The tentative relationship of Figure 10 is still tenuous and while the increase of k with the wetted radius seems reasonable, more work is required to substantiate (or perhaps refute) it.

Finally, let us consider the alternatives for treating the effect of wind on sprinkler water distribution. There seem to be three alternatives:

1. Disregard the effect of wind, or use the already empirically-established relationships as far as possible. This may be a reasonable attitude for the short term or for a mature technology (in this case sprinkling) on its way out. At present this seems to be the prevailing attitude, partly because in certain cases (especially with center-pivots) wind is not considered a major factor, while in other cases irrigation is confined to the low-wind hours. This attitude is also supported by the prohibitively high cost of field measurements.

2. Rely on field measurements. In addition to the drawback of being expensive, this alternative suffers from the inaccuracy inherent in short-term field measurements (as discussed earlier).

3. Transfer to simulation. While improvement of this approach is still required, it is in a state which enables its application. Once the automatic indoors setup is available (this is required in any case for routine checks as well as for developmental purposes), the cost of runs and computations becomes minimal. The results can be occasionally checked by field tests of solid-set configurations, which require considerably less effort than tests of individual sprinklers. In addition, the correction for spray losses in solid-set tests is less critical. These occasional field data can be used to check on the best value of k (Figure 11) and gain more understanding of its behavior.

APPENDIX A: DERIVATION OF EQUATION [3]

Note: numbers on the left indicate source equations. Numbers on the right enumerate the resulting equations.

$$[1] \quad p_i = f_i(r), \quad [A1]$$

$$[2] \quad D = m_i(r), \quad [A2]$$

$$[A2] \quad r = \underline{m}_i(D) \quad [A3]$$

where $\underline{m}_i$ is the inverse of the function m_i .

$$[A1][A3] \quad p_i = f_i(\underline{m}_i(D)) \quad [A4]$$

$$Q = 2\pi \int p_1 r \, dr \quad [A5]$$

$$[A4][A5] \quad Q(D) = 2\pi \int f_1(m_1(D)) r \, dr \quad [A6]$$

$$[A6] \quad q = dQ(D)/dD = h(D) \quad [A7]$$

Equation [A7] is identical to Equation [3].

APPENDIX B: OUTLINE OF COMPUTATIONS

The trajectory equations (Equations [7] to [9]) were solved numerically, using the Runge-Kutta forth-order integration scheme. The results were not very sensitive to the time step, except when very high drag coefficients were involved (e.g. the BERNUTH formulation for small drops). Normally a time step of 0.02 s was used (a typical flight time in this study was between 1 and 2 s).

Once the trajectory calculations are completed, the results must be compared with the experimental data. The measured patterns are given in terms of water application rates on a square, 2m by 2m grid, while trajectory calculations produce impingement points, which, when connected, resemble spider-web configurations. Figure B1 shows an example of these two grid arrangements. The sprinkler (heavy cross in the figure) is located at the origin of the field coordinate system, equidistant from 4 surrounding square-grid nodes. Computed web nodes are indicated by circles, and identified by the azimuth angle of the nozzle when the water emerged, θ , and by drop size, D (in this study trajectories were computed for every $\pi/8$ in θ and 0.5 mm in D). The largest drop size is associated with the boundary of the pattern, namely with application rate $p=0$. Unlike the example in Figure B1, the largest drop diameter is usually not a round number. The central node of the web pattern (presumably where drops of zero diameter hit the ground), is obtained by interpolation. The four-sided areas with corners at grid nodes will be referred to as grid-cells.

To assign an application rate value to a web-grid node, the still-air function $p_1 = f_1(r)$ for the particular sprinkler-pressure under consideration must be available. This function can be evaluated at web-grid nodes over a still-air pattern where the $M=\text{const}$ curves are circles, the $\theta=\text{const}$ are straight radii and the center of the pattern coincides with the location of the sprinkler. A node may be considered to represent the area surrounding it ($\frac{1}{4}$ of the area of the four cells surrounding the node). The hatched octagon in Figure B1, surrounding node $(3\pi/8, 2)$, is a schematic representation of such an area. If the corresponding areas for a still-air and a wind-affected patterns are, respectively, A_1 and A_f , then

$$p_f/p_1 = A_1/A_f. \quad [B1]$$

The application rate at the center point of the pattern (square node in

Figure B1) has to be averaged over the different values obtained by considering the various triangles which share this node.

Next, the problem is to compare distribution patterns given on two different grids. More specifically, the web-grid application rates $p_{fc}(\theta, M)$ (p_f in Equation [B1]), are first used to find the square-grid values, $p_{fc}(x, y)$. Then the square-grid values are compared with the measured values $p_{fm}(x, y)$. To obtain $p_{fc}(x, y)$, two steps must be taken:

1. Finding the web-grid cell which contains a particular square-grid node.
2. Interpolating from the 4 nodes of the web-grid cell to the square-grid node.

There are several ways of finding if a point is inside a convex polygon (web-grid cells are assumed to be convex). Here the following approach was used: If a point is connected by straight lines to the vertexes of a polygon, the sum of the angles subtended by the sides of the polygon is 2π (Figure B2). If the point is internal (Point I in the figure), each angle equals at most π . If the point is external (Point E), one angle must be greater than π .

The interpolation formula for the second step was an adaptation of the one proposed by Seginer (1969), namely

$$p(x, y) = \alpha x + \beta y + \gamma xy + \delta, \quad [B2]$$

where α , β , γ , and δ are constant coefficients, determined from x, y and p of the four surrounding web-grid nodes. When these four nodes are not arranged on an x - y rectangular grid, the surface of Equation [B2] may sometimes yield unreasonable results. To remedy this problem, the web-grid cell was first mapped into a unit square cell parallel to the x - y grid. Then the interpolation was performed on the mapped cell with the aid of Equation [B2] and the results mapped back again to the original cell.

The web-grid triangular cells near the center of the pattern (Figure B1) were treated in a similar manner. Here a plane through the three surrounding nodes was used for interpolation (i.e. in Equation [B2] $\gamma=0$), and there was no need for mapping and inverse mapping.

REFERENCES

- Bilanski W.K., Kidder E.H. 1958. Factors that affect the distribution of water from a medium-pressure rotary irrigation sprinkler. Trans ASAE, 1(1):19-23, 28.
- Christiansen J.E. 1942. Irrigation by sprinkling. University of California Agricultural Experiment Station Bulletin No. 670.

- 1 Frost K.R., Schwalen H.C. 1955. Sprinkler evaporation loss. *Agricultural*
2 *Engineering* 36(8):526-528.
3
- 4 Fukui Y., Nakanishi K., Okamura S. 1980. Computer evaluation of sprinkler
5 irrigation uniformity. *Irrigation Science* 2:23-32.
6
- 7 Gunn R., Kinzer G.D. 1949. Terminal velocity of water droplets in
8 stagnant air. *J. Meteorology*. 6(4):243-248.
9
- 10 Hills D.J., Gu Y. 1989. Sprinkler volume mean droplet diameter as a
11 function of pressure. *Trans. ASAE* 32(2):471-476.
12
- 13 Kohl R.A. 1974. Drop size distribution from medium-sized agricultural
14 sprinklers. *Trans. ASAE* 17(4):690-693.
15
- 16 Laws J.O. 1941. Measurement of fall velocity of water drops and
17 raindrops. *Trans. American Geophysical Union* 22:709-721.
18
- 19 Park S.W., Mitchell J.K., Bubenzer G.D. 1983. Rainfall characteristics
20 and their relation to splash erosion. *Transactions of the ASAE* 26(3):795-
21 804.
22
- 23 Schleusener P.E., Kidder E.H. 1960. Energy of falling drops from medium-
24 pressure irrigation sprinkler. *Agricultural Engineering* 41(2):100-102.
25
- 26 Seginer I. 1963. Water distribution from medium pressure sprinklers.
27 *Journal of the Irrigation and Drainage Division, ASCE*, 89(IR2):13-30.
28
- 29 Seginer I. 1965. Tangential velocity of sprinkler drops. *Transaction of*
30 *the ASAE* 8(1):90-93.
31
- 32 Seginer I. 1969. Wind variation and sprinkler water distribution. *Journal*
33 *of the Irrigation and Drainage Division, ASCE* 95(IR2):261-274.
34
- 35 Seginer I., Kostinsky M. 1975. Wind, sprinkler patterns and system
36 design. *Journal of the Irrigation and Drainage Division, ASCE*,
37 101(IR4):251-264.
38
- 39 Seginer I., Kantz D., Nir D., von Bernuth R.D. 1990a. An automated indoor
40 apparatus for the determination of single-radius sprinkler water
41 distribution patterns. BARD Project No. US-1001-85: The effect of wind on
42 sprinkler distribution patterns. Final report, Chapter 1.
43
- 44 Seginer I., Kantz D., Nir D. 1990b. Wind-distorted single-sprinkler
45 distribution patterns. BARD Project No. US-1001-85: The effect of wind on
46 sprinkler distribution patterns. Final report, Chapter 2.
47
- 48 von Bernuth R.D., Gilley J.R. 1984. Sprinkler droplet size distribution
49 estimation from single leg data. *Transactions of the ASAE* 27(5):1435-
50 1441.

Vories E.D., von Bernuth R.D., Mickelson R.H. 1987. Simulating sprinkler performance in wind. Journal of the Irrigation and Drainage Division, ASCE 113(1):119-130.

Table 1: Characteristics of the sprinklers whose measured distribution patterns were used for comparison with computed patterns.

sprinkler	model	nozzle diameter	pressure	wetted radius	source
		mm	kPa	m	
A	Na'an 323/92	4.0	250	12.1	Seginer & Kostrinsky (1975)
B	Na'an 233/92	5.0	300	15.4	Seginer & Kostrinsky (1975)
C	Na'an 323/92	3.5	300	12.9	Seginer et al. (1990b)

Table 2: Optimal values of the drag correction factor k.

sprinkler	k values which minimize σ					mean k to maxi- mize ϕ	wetted radius (m)
	wind speed (m/s)						
	2	4	6	8			
A	0.48	0.45	0.45	0.42	0.45	0.80	12.1
B	1.05	1.10	1.08	1.04	1.07	1.00	15.4
C	0.81	0.68	0.68	0.42	0.65	0.95	12.9

1 LIST OF FIGURES

2
3 Figure 1: A schematic representation of the geometry and velocities for a
4 jet-segment. U is the ground-velocity of the element, V is its air-
5 velocity, W is wind velocity and η is the incidence angle of the drag
6 force.

7
8 Figure 2: Measured and computed distances reached by drops of various
9 sizes. Operating pressure 300 kPa; Riser height 1.0 m. Curves show
10 computed values.

11
12 Figure 3: Computed distances reached by drops according to two drag
13 formulations.

14
15 Figure 4: Drop size distributions for a range of riser tilts at three
16 operating pressures. Sprinkler C; nozzle diameter 3.5 mm.

17
18 Figure 5: A schematic representation of measured (A_m) and computed (A_c)
19 wetted-areas produced by a single sprinkler.

20
21 Figure 6: Comparison of measured (L_m) and computed (L_c) distances from
22 the sprinkler to the center of mass of corresponding distribution
23 patterns. ϵ is the normalized difference between the two distances.

24
25 Figure 7: The contracting effect of the drag correction factor, k , on the
26 computed perimeter of a distribution pattern. Sprinkler C. Wind-speed is
27 6 m/s. Dots indicate locations where the measured application rate is
28 non-zero. Higher values of k result in more elongated patterns.

29
30 Figure 8: The variation with k of the measure of overlap of measured and
31 computed pattern area, ϕ . Data are for Sprinkler C over a range of wind-
32 speeds W .

33
34 Figure 9: The effect of the drag correction, k , on the normalized root-
35 mean-square (RMS) of differences between measured and computed patterns,
36 σ . Data are for Sprinkler C over a range of wind-speeds W .

37
38 Figure 10: The increase of the σ -minimizing value of k with the range of
39 a sprinkler. Data of Table 2.

40
41 Figure 11: Uniformity coefficients for Sprinkler C spaced on a 12m by 12m
42 grid as a function of k which minimizes σ . Wind, W , is parallel to the
43 spacing-grid. Horizontal dashed lines are based on measured patterns and
44 solid lines are based on computed patterns. The vertical dashed line
45 shows the mean value of k from Table 2.

46
47 Figure 12: Errors in the uniformity coefficient CU for the computed
48 patterns, assuming that the measured patterns are correct. The error is
49 related to CU based on the measured patterns. Numbers indicate wind-speed

1 in m/s.

2

3 Figure B1: A schematic spider-web grid over a background of a 2m by 2m
4 square grid. D is the nominal drop diameter and θ is the azimuth angle of
5 the nozzle. Wind direction is in the positive direction of the x-axis.

6

7 Figure B2: A schematic presentation of the geometry of points internal,
8 I, and external, E, to a convex four-sided polygon.