AN ABSTRACT OF THE THESIS OF

Michael J. Louie for the degree of Master of Science in Bioresource Engineering and Civil Engineering presented on January 6, 1998. Title: Evaluation of Techniques for On-Farm Monitoring of Percolation and Irrigation System Performance.

Abstract approved: Redacted for Privacy
John S. Selker

Abstract approved: Redacted for Privacy
Jonathan D. Istok

Efficient use of water in agricultural production involves accurate assessment and control of the quantity and spatial uniformity of excess percolation. Passive Capillary Samplers (PCAPS), which sample water from the vadose zone have shown potential to provide superior estimates of soil water flux compared to alternative methods. In a four-year study, 42 PCAPS installed in 21 commercial agricultural fields in Lane County, OR, USA were monitored monthly to evaluate their operational characteristics and ability to estimate soil solution flux. The PCAPS showed little evidence of technical failure, with only two of the 42 installed samplers found to operate inefficiently. Installation of 10 of the 42 samplers in locations susceptible to high or perched water tables resulted in submersion of the samplers, rendering them inoperable. On average, the PCAPS measured soil water flux 25% greater than that obtained from a water balance estimate. This discrepancy was attributed to a possible inaccuracy in water balance evapotranspiration estimates, along with a violation of the PCAPS design assumptions which suggests over-sampling would occur in the presence of high water tables. Analysis of the PCAPS collection ability indicates that

to estimate the mean yearly recharge at each site with a 30% bound on the mean at the 0.05 confidence level, eight PCAPS are required. This number corresponds closely to the results of Brandi-Dohrn et al. (1996a) and is thought to be due to intrinsic variability of percolation.

Spatial uniformity in irrigation water application is essential to reducing excess percolation. Twelve sprinkler irrigation systems used under commercial crop production in Lane County, OR were evaluated for equipment wear and performance. Field measurements of sprinkler nozzle size and discharge rate were recorded for each system and used to estimate water application patterns. New sprinkler nozzles were installed on six of the 12 irrigation systems to compare potential application rate and uniformity with existing system performance. Despite reducing the coefficient of variation in discharge between sprinklers from 10% to 2%, little increase in water application uniformity was attained by replacing the nozzles. A 13% decrease in mean water application rate was documented when new nozzles replaced worn parts. The over-application due to worn or mismatched nozzles gives rise to the potential for increased surface redistribution and deep percolation, resulting in water and nutrient losses.

Evaluation of Techniques for On-Farm Monitoring of Percolation and Irrigation System Performance

by

Michael J. Louie

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Presented January 6, 1998
Commencement June 1998

Master of Science thesis of Michael J. Louie presented on January 6, 1998

APPROVED:

Redacted for Privacy

Co-Major Professor, representing Bioresource Engineering

Redacted for Privacy

Co-Major Professor, representing Civil Engineering

Redacted for Privacy

Head of Department of Bioresource Engineering

Redacted for Privacy

Head of Department of Civil, Construction, and Environmental Engineering

Redacted for Privacy

Dean of Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Redacted for Privacy

Michael J. Louie, Author

ACKNOWLEDGMENT

Special thanks go to my advisor, Dr. John Selker, for giving me the opportunity to join an established project and the freedom to explore my own areas of interest within it. His encouragement, patient demeanor, innovative ideas, and financial support were crucial to the success of this project. I would also like to thank my co-major professor Dr. Jack Istok, and my committee members Dr. Richard Cuenca, Dr. Marshall English, and Dr. Roland De Szoeke. Their teaching, technical support, and encouragement was an immense help during the course of my graduate studies.

Many thanks to my friend and project colleague, Jason Smesrud, with whom I spent many days of field work and fishing. His ideas and direction provided the guidance necessary to make this a successful project.

Thank you to the staff and faculty of the department of Bioresource Engineering and the department of Civil, Construction, and Environmental Engineering. Pursuing a dual major would not have been possible without their cooperation and assistance.

To my family, especially my parents, who supported me in my decision to pursue an advanced degree, and then provided encouragement through word and prayer as I worked to complete my goal.

Finally, and most especially, I express my great appreciation to my fiancée, Erika, for her encouragement, support, patience, and love during our coinciding graduate careers. Her never-ending reassurance has been an invaluable source of support for myself and my dreams.

CONTRIBUTION OF AUTHORS

The chapter 2 manuscript Field Evaluation of Passive Capillary Samplers for Estimating Groundwater Recharge represents the cooperative research efforts of Michael Louie, Patrick Shelby, Jason Smesrud, Lance Gatchell, and Dr. John Selker. Data collection, interpretation, and manuscript writing was performed by Michael Louie. Patrick Shelby, Jason Smesrud, and Lance Gatchell coordinated sampler installation, assisted in data collection, and performed laboratory and field analysis of soil properties. Dr. John Selker served as project director and manuscript editor.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF TABLES

Evaluation of Techniques for On-Farm Monitoring of Percolation and Irrigation System Performance

1. GENERAL INTRODUCTION

Efficient use of water in agricultural production involves accurate assessment and control of the quantity and spatial uniformity of excess percolation. One such tool used to measure the quantity of drainage water is the wick pan lysimeter. Developed in 1986, the wick pan lysimeter, termed the Passive Capillary Sampler (PCAPS), is a relatively new monitoring tool with little information available about its long-term effectiveness. The study reported in chapter 2 summarizes a four-year experiment in using PCAPS to monitor groundwater recharge beneath 21 agricultural fields in Lane County, OR. The study investigates the operational characteristics and accuracy of PCAPS in an agricultural setting for estimating the quantity of groundwater recharge.

Spatial uniformity in irrigation water application is essential to reducing excess percolation. Non-uniform water application results in some areas of the field receiving excess water and other areas experiencing a deficit. Increased irrigation application is required to ensure all areas of the field receive sufficient water. This increased water application causes excess percolation in "wet" areas of the field, resulting in water and nutrient losses that can contribute to groundwater contamination. The study reported in chapter 3 evaluates the current state of sprinkler irrigation systems in Lane County and presents suggestions for improving uniformity of irrigation water application.

Chapter 2

Field Evaluation of Passive Capillary Samplers for Estimating Groundwater Recharge

Michael J. Louie, Patrick M. Shelby, Jason S. Smesrud,
Lance O. Gatchell, and John S. Selker

In preparation for submission to
Water Resources Research

ABSTRACT

Passive capillary samplers (PCAPS), which sample water from the vadose zone via a hanging water column in a fiberglass wick, have shown potential to provide superior estimates of soil water flux compared to alternative methods. The objectives of this study were to evaluate the performance of PCAPS under natural rain-fed conditions concerning (i) their operational characteristics; and (ii) their ability to estimate soil solution flux. Forty-two PCAPS were installed in 21 commercial agricultural fields in Lane County, OR, USA. Monthly measurements of soil water flux and precipitation were recorded at each site for the four-year project duration. Of the 42 installed PCAPS, 12 samplers at six sites were inoperable or did not operate efficiently: Ten samplers were consistently below the water table, which overflowed the collection vessels rendering the samplers inoperable. Only two of the PCAPS exhibited technical failure resulting in unusually low collection efficiencies, thought to be due to a collapse of the collection vessel from over-suction during sample retrieval. On average, the 30 remaining PCAPS measured soil water flux 25% greater than that obtained from a water balance estimate. This discrepancy represents approximately 8% of the total annual precipitation and irrigation each site received. PCAPS collection efficiency was found to be significantly correlated ($R^2 = 0.75$) to the water balance yearly estimated recharge. The difference between PCAPS measured and water balance estimated percolation was attributed to a possible inaccuracy in water balance evapotranspiration estimates, along with a breakdown of the PCAPS design assumptions which suggests over-sampling would occur in the presence of high water tables. To estimate the mean yearly recharge at each site with a 30% bound on the

mean at the 0.05 confidence level, eight PCAPS are required. This number corresponds closely to the results of Brandi-Dohrn et al. (1996a) and is thought to be due to intrinsic variability of percolation.

INTRODUCTION

There is a variety of sampling devices available for monitoring water and solute transport in the vadose zone. These include (i) soil core profile sampling, (ii) vacuum extractors, and (iii) lysimeters. The selection of an appropriate device depends on the project goals, the physical setting of the project, and the available financial resources.

The versatility and low cost of soil coring make it a valuable tool for measuring chemical composition in a given volume of soil. Minimal setup time and the ability to replicate measurements at different depths make soil coring useful for rapid assessment of contaminant spills. However, it is a destructive method that does not allow repetitive measurements at the same point, thus limiting its usefulness when monitoring changes with time. For precise measurements, a large number of samples are required (Rice and Bowman, 1988; Cambardella et al., 1994). Furthermore, since it measures resident concentration, solute flux concentration and amount, if required, must be determined independently of the soil core sampling procedure (Parker and van Genuchten, 1984; Brandi-Dohrn et al., 1996a).

The use of porous ceramic suction cup samplers was introduced by Briggs and McCall (1904) and remains the U.S. Environmental Protection Agency standard for hazardous waste site characterization (U.S. Environmental Protection Agency, 1986).

Low cost and ease of installation and use has resulted in wide use of the suction cup sampler for leachate characterization. However, many problems associated with the use of this sampler have been documented. The sampler provides no estimate of solute flux and the soil volume sampled is not known (England, 1974). Major sources of groundwater recharge such as fingered, preferential, and channeled flow (Kung, 1990; Selker et al., 1992) may not be captured due to non-continuous vacuum during the sampling period or the cross-sectional sampling area being too small (Shaffer et al., 1979; Barbee and Brown, 1986; Boll et al., 1991). This may result in missed contaminant pulses during rainstorms or agrochemical application (Barbee and Brown, 1986; Magid et al., 1992). The soil solution sampled may be unrepresentative of actual leachate when the vacuum applied extracts soil solution at a higher seepage rate than the drainage rate under natural conditions (Severson and Grigal, 1976; Tseng et al., 1995). In most soils, water movement occurs at or near saturated conditions with soil water pressures close to zero. Due to these pressures, a vacuum applied to a suction cup sampler greater than 10 kPa may result in sampling soil solutions that are not subject to leaching (Severson and Grigal, 1976). Barbee and Brown (1986) concluded that applying even small amounts of suction to extract a soil solution sample may cause significantly higher seepage rates, compared with rates under gravity drained conditions. Furthermore, since suction cup samplers predominantly sample resident instead of flux concentration, reported solute concentrations can be ± 100% of true recharge values (Brandi-Dohrn et al., 1996b).

A zero tension lysimeter or pan sampler was designed and introduced by Jordan (1968). Zero-tension pan samplers depend on gravitational drainage to supply soil solution to the sampling reservoir, thus sampling only from a soil matrix with pressure ≥ 0. The soil matrix must build up a capillary fringe prior to sample collection, resulting in a diversion of flow away from the sampler due to the lower pressure of the surrounding soil (Jemison and Fox, 1992). Jemison and Fox (1992) found low collection efficiencies for zero-tension samplers, ranging from 45% to 58%.

The idea of developing a sampler capable of applying tension to the soil water and able to intercept a large flow area led to the introduction of the wick pan lysimeter, termed the Passive Capillary Sampler (PCAPS), by Brown et al. (1986). Passive Capillary Samplers have proven to give superior results to existing soil-water samplers in terms of efficiently collecting soil flux and chemical concentrations (Brown et al., 1986; Holder et al., 1991; Boll et al., 1992; Brandi-Dohrn et al., 1996a). A wetted fiberglass wick acts as a hanging water column that develops suction in the soil water depending on the flux. For minimal disturbance of the native flow regime, the pressure at the top of the wick is matched to the expected pressure in the soil as a function of the flux by applying the design equation of Knutson and Selker (1994). The length and diameter of the wick are adjusted to achieve the closest possible match for the expected pressure/flux conditions.

There have been a limited number of studies on the performance of PCAPS under field conditions. Holder et al. (1991) tested 0.09-m^2 PCAPS in three different textured soils; sand, silt loam, and clay. Since the tests were performed under saturated conditions, the results of the experiments cannot be considered representative of natural vadose zone flow conditions.

Boll et al. (1991) tested two PCAPS in a silt loam and found them to be a significant improvement over zero-tension lysimeters. Under controlled conditions, the collection efficiency as measured with a water balance was 103% for the two PCAPS (C.V. = 25% and 42%) compared to 27% for two zero-tension pan samplers (C.V. = 84% and 91%). Recovery of a Br^- tracer amounted to 63% in the PCAPS and to 6.5% in the zero-tension pan samplers, with the superior performance attributed to the ability of the PCAPS to sample soil-water at low potentials prior to saturation.

Brandi-Dohrn et al. (1996a) installed 32 PCAPS at a depth of 1.2 m in an undisturbed silt loam soil. During a 244-day test period, the authors found the collection efficiency as measured with a water balance to be 80%. During a second 155-day test period, the collection efficiency as measured with a water balance was found to be 66%. The wick matching procedure of Knutson and Selker (1994) suggested the samplers would over-sample on the silt loam soil found in this study. The authors attributed the under-sampling to observed but not quantified runoff and poor air release from the collection bottles. The recovery of a Br^- tracer was low with an average of 29%, which was attributed to plant uptake and lateral water movement due to prominent lateral stratification.

The objectives of this study were to evaluate the performance of PCAPS under natural rain-fed conditions concerning (i) their operational characteristics; and (ii) their ability to estimate soil solution flux.

MATERIALS AND METHODS

Experimental Sites

The experiments were carried out at 21 separate sites located within a 30-km radius throughout northern Lane County, OR. Sixteen original sites were instrumented during the summer of 1993, with an additional five sites instrumented during the fall of 1995. The study includes replicated trials of the major cropping systems employed in the region including perennial rye grass seed, vegetable row crops, peppermint, tree fruits, organic vegetables, and blueberries. Sites were chosen with the cooperation of local farmers and based on 1992 agricultural commodity sales in Lane County.

Soil Description

There are eight soil types represented among the 21 sites. The classification is based on the description of the soil profiles obtained during sampler installation, Lane County soil survey information, and particle size analysis. The soil series, taxonomy, and geologic parent materials for each site are listed in Table 2.1. Soil cores were taken at each site from the 0- to 1-m depth layer and analyzed for bulk density. In situ field saturated hydraulic conductivity, K_{sat}, was measured using the well permeameter method (Elrick and Reynolds, 1992). These basic soil properties are listed for each site in Table 2.2. Particle size distribution (Gee and Bauder, 1986) for each soil series is provided in Appendix A. The pressure-saturation relationship in each soil was obtained by pressure extraction fit to van Genuchten's model (van Genuchten, 1980):

$$S_e = \frac{1}{\left[1 + (-\alpha h)^n\right]^m} \qquad \left(m = 1 - \frac{2}{n}\right) \tag{2.1}$$

with

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \tag{2.2}$$

where S_e is the normalized water content, θ the volumetric water content, with the subscripts r and s denoting residual and saturated, h the pressure (L), and α (L^{-1}), n, and m are empirical parameters. The restriction $m = 1 - 2/n$ was used because it gave the best fit for the critical first 200 cm H_2O of pressure. Least squares fitting was carried out using the RETC code (van Genuchten et al., 1991) (Appendix A).

Table 2.1. Experimental sites, soil series, soil taxonomy, and geologic parent materials

Site	Soil Series	Taxonomic Class	Parent Material
Blueberry #1	Cloquato silt loam	Cumulic Ultic Haploxerolls	recent alluvium
Blueberry #2	Newberg fine sandy loam	Typic Haploxerolls	recent alluvium
Grass Seed #1	Coburg silty clay loam	Pachic Ultic Argixerolls	silty and clayey alluvium
Orchard #1	Newberg fine sandy loam	Typic Haploxerolls	recent alluvium
Orchard #2	Fluvents, nearly level		sediment deposits
Organic #1	Newberg loam	Fluventic Haploxerolls	recent silty alluvium
Organic #2	Malabon silty clay loam	Pachic Ultic Argixerolls	silty and clayey alluvium
Peppermint #1	Newberg loam	Fluventic Haploxerolls	recent silty alluvium
Peppermint #2	Chehalis silty clay loam	Cumulic Ultic Haploxerolls	recent alluvium
Peppermint #3	Newberg fine sandy loam	Typic Haploxerolls	recent alluvium
Peppermint #4	Malabon silty clay loam	Pachic Ultic Argixerolls	silty and clayey alluvium
Peppermint #5	Coburg silty clay loam	Pachic Ultic Argixerolls	silty and clayey alluvium
Peppermint #6	Malabon silty clay loam	Pachic Ultic Argixerolls	silty and clayey alluvium
Peppermint #7	Newberg loam	Fluventic Haploxerolls	recent silty alluvium
Peppermint #8	Malabon silty clay loam	Pachic Ultic Argixerolls	silty and clayey alluvium
Row Crop #1	Newberg fine sandy loam	Typic Haploxerolls	recent alluvium
Row Crop #2	Newberg loam	Fluventic Haploxerolls	recent silty alluvium
Row Crop #3	Malabon silty clay loam	Pachic Ultic Argixerolls	silty and clayey alluvium
Row Crop #4	Malabon silty clay loam	Pachic Ultic Argixerolls	silty and clayey alluvium
Row Crop #5	Malabon silty clay loam	Pachic Ultic Argixerolls	silty and clayey alluvium
Row Crop #6	Newberg loam	Fluventic Haploxerolls	recent silty alluvium

Table 2.2. Mean bulk density and saturated hydraulic conductivity (K_{sat}) of soils at experimental sites for 0- to 1-m depth layer.

Site	Soil Type	Bulk Density Mean	n	K_{sat} Mean	n
		(Mg m^{-3})		(cm hr^{-1})	
Blueberry #1	silt loam	1.49	3	0.76	3
Blueberry #2	fine sandy loam	1.42	3	0.59	3
Grass Seed #1	silty clay loam	1.49	3	1.36	3
Orchard #1	fine sandy loam	1.42	3	10.3	3
Orchard #2	gravelly sand	n/a	n/a	9.29	3
Organic #1	loam	1.05	7	1.73	3
Organic #2	silty clay loam	1.26	7	3.46	3
Peppermint #1	loam	1.26	7	0.58	3
Peppermint #2	silty clay loam	1.36	3	3	3
Peppermint #3	fine sandy loam	1.21	9	1.45	3
Peppermint #4	silty clay loam	1.21	6	1.45	3
Peppermint #5	silty clay loam	1.31	6	0.065	3
Peppermint #6	silty clay loam	1.35	9	1.92	3
Peppermint #7	loam	1.31	7	2.13	3
Peppermint #8	silty clay loam	1.27	7	1.46	3
Row Crop #1	fine sandy loam	1.42	3	8.04	3
Row Crop #2	loam	1.27	6	0.27	3
Row Crop #3	silty clay loam	1.23	6	1.49	3
Row Crop #4	silty clay loam	1.32	6	0.25	3
Row Crop #5	silty clay loam	1.35	6	1.92	3
Row Crop #6	loam	1.31	4	2.13	3

Climate

The climate of Lane County is classified as temperate oceanic, with mild wet winters and warm dry summers. During the cool wet months of November to April, temperatures average 6.6°C with an average monthly precipitation of 142 mm. In contrast, May - October temperatures average 15.8°C with an average monthly precipitation of 39 mm. Climatic data for the region has been recorded for the last 35 years at the Eugene airport. Unfortunately, no evaporation or solar radiation data are collected within Lane County. Little differences in the climate of the Willamette valley can be documented, so data from the U.S. Bureau of Reclamation Northwest Cooperative Agricultural Weather Network, AgriMet, station located in Corvallis, 50 km north of the test site nucleus, were used for the experiments.

Precipitation was measured with a non-recording gauge at the Eugene Weather Center. For the first year of the project, eight of the 16 initial sites were chosen for instrumentation with six non-recording rain gauges. After the first year of the project, all sites were instrumented with at least two non-recording gauges. Measurements have been corrected by +2% to adjust for the systematic error introduced by the average wind speed of 0.8 m s^{-1} measured at the Eugene Weather Center (Larson and Peck, 1974).

Evapotranspiration, required for the water balance, was calculated by applying crop coefficients to daily reference evapotranspiration estimates. Alfalfa reference evapotranspiration was obtained from the U.S. Bureau of Reclamation where climate data from the Corvallis AgriMet station is used in conjunction with the 1982 Kimberly-Penman equation (Wright, 1982) to estimate daily reference evapotranspiration. The 1982 Kimberly-Penman equation is a theoretically based energy balance equation combining net radiation and advective energy transfer. The form of the 1982 Kimberly-Penman equation used in AgriMet crop modeling is as follows (U. S. Bureau of Reclamation, 1995):

$$ET_r = \frac{\Delta}{\Delta + \gamma}\left(R_n - G\right) + \frac{\gamma}{\Delta + \gamma} 6.43 W_f \left(e_s - e_a\right) \qquad (2.3)$$

where ET_r is the alfalfa reference evapotranspiration in MJ m^{-2} d^{-1}, Δ is the slope of the saturation vapor pressure-temperature curve in mb K^{-1}, γ is the psychometric constant in mb K^{-1}, R_n the net radiation in MJ m^{-2} d^{-1}, G the soil heat flux in MJ m^{-2} d^{-1}, 6.43 the constant of proportionality in MJ m^{-2} d^{-1} kPa^{-1}, W_f the dimensionless wind function, and $(e_s - e_a)$ the mean daily vapor pressure deficit in kPa. Compared to lysimeter measured evapotranspiration at 11 locations throughout the Unites States, the 1982 Kimberly-Penman equation has been found to over-estimate alfalfa reference evapotranspiration by an average of 10% (Jensen et al., 1990).

Crop coefficients taken from Selker et al. (1998) were multiplied by daily alfalfa reference evapotranspiration to estimate daily crop evapotranspiration. For crop coefficients based on grass reference evapotranspiration, the Food and Agricultural Organization (FAO) grass crop coefficient (Doorenbos and Pruitt, 1977) was applied in conjunction with the alfalfa reference crop coefficient. During months when the soil surface was bare, a crop coefficient for evaporation based on the number of days between significant rainfall events was computed and applied (El Kayal, 1983; Ryan and Cuenca, 1984):

For $I_f < 4$ days,

$$K_{ci} = (1.286 - 0.27 \ln I_f) \exp[(-0.01 - 0.042 \ln I_f) ET_{ri}] \tag{2.4}$$

For $I_f \geq 4$ days,

$$K_{ci} = 2(I_f)^{-0.49} \exp[(-0.02 - 0.04 \ln I_f) ET_{ri}] \tag{2.5}$$

where K_{ci} is the bare surface grass reference crop coefficient, I_f the interval between significant (> 1 mm) rainfall events in the previous 14 days, and ET_{ri} the average grass reference evapotranspiration over the previous 14 days.

Management

Site management was left entirely up to the land owners, and thus without experimental design. Table 2.3 gives the crop history of each site from 1994 to 1997. Irrigation water, nutrients, and chemicals were applied at the discretion of the owner. All irrigation water was sprinkler applied, with amounts measured by two non-recording rain gauges located directly above the PCAPS at each site.

Table 2.3. Summer crop history of experimental sites

Site	1994	1995	1996	1997
Blueberry #1	Blueberry	Blueberry	Blueberry	Blueberry
Blueberry #2	Blueberry	Blueberry	Blueberry	Blueberry
Grass Seed #1	Rye Grass	Rye Grass	Rye Grass	Rye Grass
Orchard #1	Apple	Apple	Apple	Apple
Orchard #2	Peach	Peach	Peach	Peach
Organic #1	Mixed Veg.	Mixed Veg.	Mixed Veg.	Mixed Veg.
Organic #2	Foenugreek Seed	Lemon Balm	Lemon Balm	Lemon Balm
Peppermint #1	Peppermint	Peppermint	Peppermint	Peppermint
Peppermint #2	Peppermint	Peppermint	Peppermint	Peppermint
Peppermint #3	Peppermint	Peppermint	Peppermint	Peppermint
Peppermint #4	Peppermint	Peppermint	Peppermint	Peppermint
Peppermint #5	Rye Grass	Peppermint	Peppermint	Peppermint
Peppermint #6			Peppermint	Peppermint
Peppermint #7			Peppermint	Peppermint
Peppermint #8			Peppermint	Peppermint
Row Crop #1	Sweet Corn	Sweet Corn	Carrots	Raddish Seed
Row Crop #2	Red Beets	Sweet Corn	Green Beans	Sweet Corn
Row Crop #3	Beet Seed	Wheat	Sweet Corn	Green Beans
Row Crop #4	Sweet Corn	Sweet Corn	Green Beans	Green Beans
Row Crop #5			Sweet Corn	Sweet Corn
Row Crop #6			Green Beans	Carrots

Instrumentation

The PCAPS installed at the 16 original sites during the summer of 1993 were constructed from a custom molded 15-kg epoxy-coated fiberglass box (0.33 by 0.87, 0.62 m deep) which supports a stainless steel panel (1 mm thick, 0.32 by 0.86 m) with a 1.75-cm edge (Figure 2.1). The panel is subdivided into three 0.31- by 0.29-m sections, with one wick at the center of each section. A 31.6-mm I.D. hole was punched in the middle of each section and fitted with an alloy 304 stainless steel pipe. A single 60-L vacuum molded HDPE collection vessel (0.24 by 0.78, 0.32 m deep) was fitted to the bottom interior of the fiberglass box. Silicone sealant and a rubber stopper were used to fit the pipes and HDPE sample access tubing to ensure a waterproof sampler with respect to the collection vessel. As a precaution, a drainage tube was built in to allow removal of water from the fiberglass box.

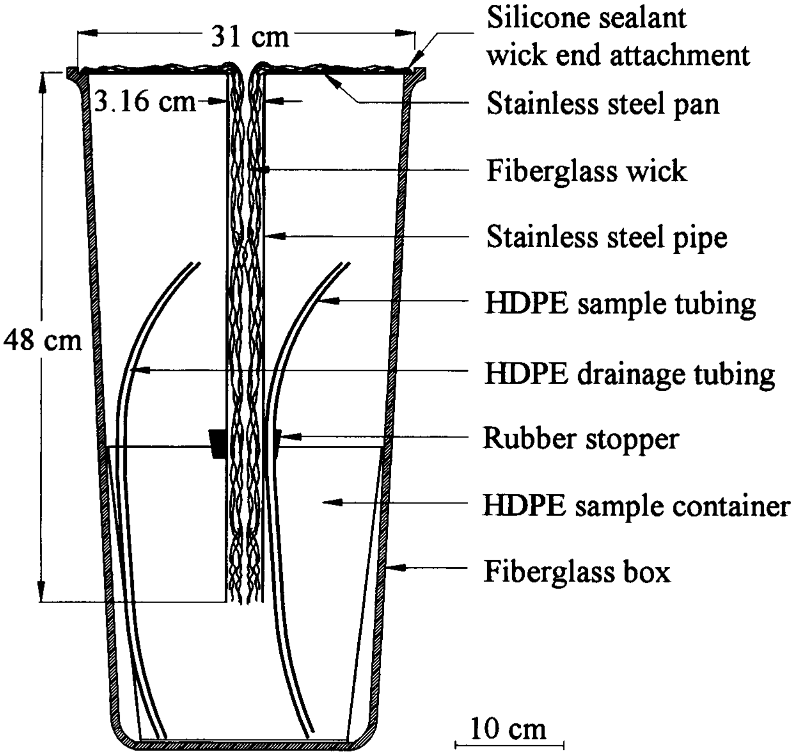

Figure 2.1. Cross-sectional view of PCAPS installed at the 16 original sites (drawn to scale).

The PCAPS installed at the five additional sites during the fall of 1995 were modified to eliminate the need for a separate collection vessel and outer box (Figure 2.2). A custom welded 0.64-cm thick HDPE box (0.35 by 0.85, 0.67 m deep) supports an HDPE top panel (0.64 cm thick, 0.34 by 0.84 m) with a 1.75 cm edge. The top panel is subdivided into three 0.34- by 0.28-m sections, each containing one wick. A 25.4-mm I.D. hole was drilled in the middle of each section for the wicks.

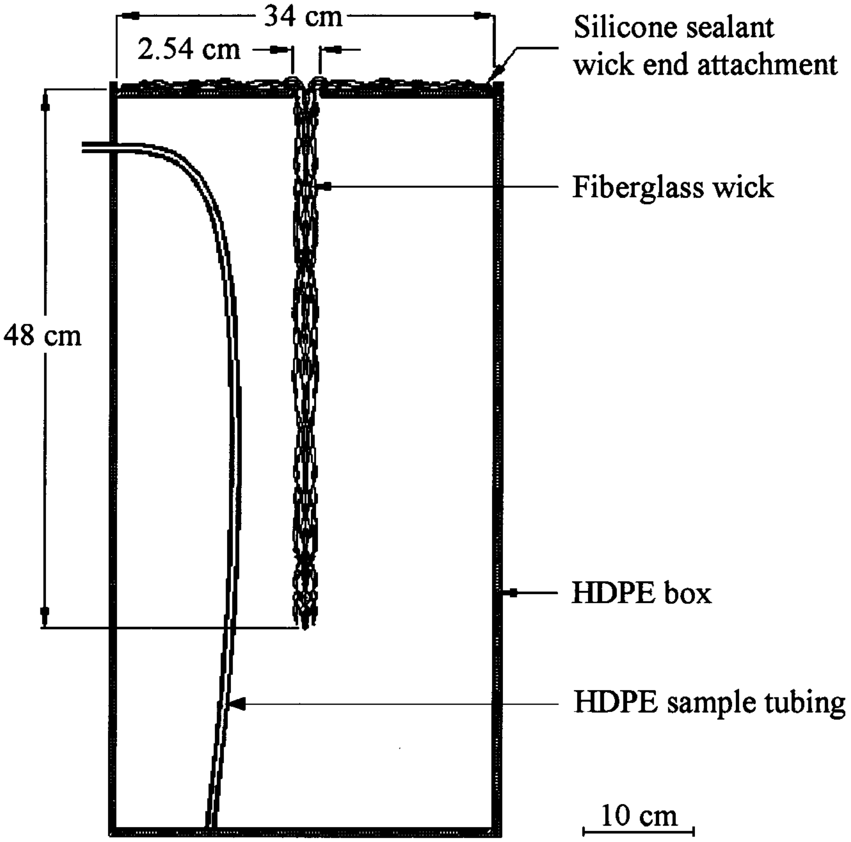

Figure 2.2. Cross-sectional view of PCAPS installed at the five additional sites (drawn to scale).

Two types of wicks were employed; a braided 2.93-cm O.D. medium density and 2.48-cm O.D. high density Amatex fiberglass wicks (no. 10-863KR-08 and no. 10-864KR-08, Amatex Co., Norristown, PA) with a maximum fiber length of 80 cm (Table 2.4). The first 20 cm of the wicks were separated into single strands and cleaned by kiln combustion according to Knutson et al. (1993). The wick filaments were spread out radially on the top panel and the end of each strand glued down with one drop of silicone sealant.

Table 2.4. PCAPS installation parameters for each site.

Site	Soil Type	Wick Type	PCAPS Depth (m)
Blueberry #1	silt loam	medium-density	0.80
Blueberry #2	fine sandy loam	high-density	0.80
Grass Seed #1	silty clay loam	high-density	0.92
Orchard #1	fine sandy loam	medium-density	0.92
Orchard #2	gravelly sand	high-density	0.65
Organic #1	loam	medium-density	0.92
Organic #2	silty clay loam	high-density	0.80
Peppermint #1	loam	medium-density	0.80
Peppermint #2	silty clay loam	high-density	0.92
Peppermint #3	fine sandy loam	high-density	0.92
Peppermint #4	silty clay loam	high-density	0.92
Peppermint #5	silty clay loam	high-density	0.92
Peppermint #6	silty clay loam	high-density	1.00
Peppermint #7	loam	high-density	1.00
Peppermint #8	silty clay loam	high-density	1.00
Row Crop #1	fine sandy loam	medium-density	0.92
Row Crop #2	loam	high-density	0.90
Row Crop #3	silty clay loam	high-density	0.92
Row Crop #4	silty clay loam	high-density	0.92
Row Crop #5	silty clay loam	high-density	1.00
Row Crop #6	loam	high-density	1.00

The sampler is designed to remain in operation for an indefinite time period. Through the use of environmentally stable, non-adsorbing materials (fiberglass, HDPE, stainless steel) (Topp and Smith, 1992) the sampler is well suited for long-term nitrate and pesticide monitoring.

Two PCAPS were installed at each experimental site. Individual farmers designated a section of each field for PCAP placement. Ground penetrating radar (GPR) was used over the designated area to determine ideal sampler locations. Several passes with a Geophysical Survey Systems, Inc. SIR10A GPR with 100 and 500 MHz antennas were made at each site. Reflections caused by differing dielectric constants indicate interfaces between soil layers (Kung et al., 1991). Soil samples along the GPR transects were used to correlate depth of penetration with soil strata. Areas excluded for PCAP placement lacked homogeneous profiles or contained sloping soil interfaces that may divert water away from the samplers.

The PCAPS were installed from a trench 2.4-m long, 1.2 m-wide, and 2.4-m deep dug with a backhoe. A tunnel was dug in the side of the trench for the installation of each PCAPS such that the roof of the tunnel was between 0.65 and 1.0 m below the surface (Table 2.4). The top panel of the PCAPS was filled with slightly compacted native soil with an additional layer above the panel to fill any small gaps. The samplers were elevated with wooden wedges to bring them into firm contact with the tunnel roof. A bentonite seal was used to hydraulically isolate the samplers from the trench. Tubing to collect samples from each PCAPS was run about 10 m to an irrigation box outside the cultivated area of the field. The trenches were back-filled and compacted to avoid any settling or swelling. Installation at the 16 original sites was completed on September 1, 1993 and at the five additional sites on September 22, 1995.

Sampling

Samples were collected once a month beginning in October 1993. During periods of heavy precipitation, samples were collected after every 10 to 15 cm of rainfall, as the maximum PCAP collection volume is 22 cm of percolation. Samples were taken, on average, every 26 days from October 1993 to November 1997. At the five additional sites, sampling began in October 1995. Sampling was discontinued at the Blueberry #2 and Orchard #1 sites in March 1996 and at the Orchard #2 site in April 1996. A vacuum pump was used to extract samples into a 4000-ml glass vacuum flask, and the total collected volume was recorded.

RESULTS AND DISCUSSION

Operational Characteristics

Of the 42 PCAPS installed, 12 samplers at six sites were inoperable or did not operate efficiently. Two samplers at the Peppermint #2 site were deemed inoperable due to the soil type and hydrogeology of the location. During installation, large boulder-sized rocks were encountered along with many abrupt textural changes in the soil profile. Heavy winter rains and intense irrigation kept the site constantly ponded, restricting access to the samplers. The six collection vessels from samplers at the Grass Seed #1, Peppermint #5, and Peppermint #8 sites were overflowing at least 10 out of 12 months during the first two years of sampling. A high or perched water table at these sites kept the sampler submerged and the collection vessels full year-around. The two collection vessels from samplers at the Organic #1 site were overflowing during half of the winter months. During the summer irrigation season, sprinkler laterals drained directly above the two samplers resulting in high collection volumes and no estimate of the depth of water applied at the surface. Two samplers at the Peppermint #1 site collected estimated percolation very inefficiently. The inability of both samplers to estimate percolation was thought to be due to a collapse of the interior collection vessels from over-suction during sample retrieval. These six sites were excluded from estimates of PCAPS collection efficiency.

Two periods of unusually high precipitation occurred during January and February of 1996 and again in November and December of 1996. This extreme precipitation resulted in high or perched water tables that flooded 43% of the PCAPS.

Samplers at these sites remained below the water table for one to three months after the precipitation events.

Wick and Soil Matching

Ideally, the pressure at the top of the wick should match the pressure of the soil for any soil-water flux. Unmatched soil-wick pressure could result in a disturbance of the native flow regime leading to non-representative sampling of the groundwater recharge (Knutson and Selker, 1994; Rimmer et al., 1995). In selecting wicks, the procedure provided by Knutson and Selker (1994) was followed. Gardner (1958) used the exponential conductivity relationship to solve Richards equation for steady-state evaporative flux from a water table:

$$h = \left(\frac{1}{\alpha}\right)\ln\left[\exp(\alpha z)\left(\frac{q}{K_{sat}}+1\right)-\frac{q}{K_{sat}}\right] \tag{2.6}$$

where h is pressure head at elevation z above the water table (negative upward), q is the flux (positive upward), α the exponential constant, and K_{sat} the saturated hydraulic conductivity. If the water table is assumed to be far below the sampler (z is large), then a unit gradient exists in the soil and Eq. (2.6) reduces to:

$$h_{soil} = \frac{1}{\alpha_{soil}}\ln\left[-\frac{q}{K_{sat}}\right] \tag{2.7}$$

where h_{soil} is the pore-water pressure in the soil(negative) for flux q (negative downward), α_{soil} the exponential constant for the soil according to Gardner's unsaturated hydraulic conductivity model (Gardner, 1958), and K_{sat} is the soil's saturated conductivity. It was found that the conductivity-pressure relationship of wicks is very well described by an exponential function, and thus that the pressure at the top of the wick can be predicted using the equation (Knutson and Selker 1994):

$$h_w = \frac{1}{\alpha_w}\ln\left[\exp(\alpha_w z_w)\left(q\frac{A_s}{A_w K_{sat}}+1\right)-\left(q\frac{A_s}{A_w K_{sat}}\right)\right] \tag{2.8}$$

where h_w is the pressure at the top of the wick (negative) for flux q (negative downward), α_w the exponential constant for the wick according to Gardner's unsaturated hydraulic conductivity model (Gardner, 1958), z_w the length of the wick (negative), A_s the sampling area, A_w the cross-sectional area of the wick, and K_{sat} the saturated hydraulic conductivity of the wick. The wick matching procedure for this study was governed by certain practical constraints. The maximum wick fiber length was limited to 80 cm due to the dimensions of the sampling device. This creates the critical constraint that minimum pressure applied by the wick is h_w = -80 cm H_2O. Additional constraints included the sampling area, A_s, was limited to 900 cm^2, and the selection of wicks limited to those commercially available. Wick types were chosen based on their goodness of fit to the soil unsaturated conductivity in the pressure range of –15 to –80 cm H_2O, where most flux occurs.

Collection Efficiency of the PCAPS as Estimated with a Water Balance

To validate soil-water flux measurements obtained by the PCAPS, an annual water balance was computed for each site (Table 2.5). Collection efficiency is defined as the ratio of percolation measured divided by percolation estimated by the water balance. Expected total yearly percolation was calculated as total precipitation and irrigation minus total evapotranspiration. No estimate of changing soil water storage was made between sampling intervals, so it is assumed that soil water storage at the beginning and end of each year are equal. Heavy fall rains in the Pacific Northwest quickly fill available soil water storage, so a water year beginning in December and ending the following November was selected for the annual water balance. It is assumed that surface runoff and lateral subsurface flow are negligible since PCAPS were installed in fields with surface slopes of <3%. Noted in Table 2.5 are the months for which the water balance was computed at each site. Heavy rains during January, February, November, and December of 1996 resulted in the water table at several sites rising above the PCAPS level, flooding the samplers. These months were excluded from the annual water balance. At sites where no measurements of summertime irrigation were made, yearly water balance calculations begin in November and end the following May. Consistent precipitation ensures the soil profile is essentially saturated from November through May.

Table 2.5. Annual water balance and collection efficiency of passive capillary samplers (PCAPS)

Site	Year	Collection Period	Precipitation + Irrigation	Evapo-transpiration	Expected Percolation	Observed Percolation #1	Observed Percolation #2	Collection Efficiency #1	Collection Efficiency #2
		(month/year)	(mm)	(mm)	(mm)	(mm)	(mm)	(%)	(%)
Blueberry #1	1994	12/93 - 11/94	1460	1108	352	463	298	132	84
	1995	12/94 - 11/95	1797	1036	761	530	580	70	76
	1996	12/95 - 5/96	1400	211	1189	1241	963	104	81
	1997	12/96 - 5/97	733	249	484	441	519	91	107
Blueberry #2	1994	12/93 - 5/94	557	288	269	445	690	165	256
	1995	12/94 - 11/95	1563	1037	526	478	875	91	166
	1996	12/95 - 3/96	938	87	851		1176		138
Orchard #1	1994	12/93 - 11/94	1238	934	304	764	721	251	237
	1995	12/94 - 11/95	1215	593	622	704	837	113	135
	1996	12/95 - 3/96	953	87	865	844	922	98	107
Orchard #2	1994	12/93 - 6/94	624	185	439	415	531	95	121
	1995	12/94 - 11/95[i]	783	642	141	219	180	155	127
	1996	12/95 - 4/96	1095	153	943	907	615	96	65
Organic #2	1994	1/94 - 11/94	982	505	477	392	439	82	92
	1995	12/94 - 11/95	1212	822	390	525	460	135	118
	1996	12/95 - 10/96	1684	871	813	1292	677	159	83
	1997	1/97 - 11/97	1130	822	308	319	330	103	107
Peppermint #3	1994	12/93 - 11/94	1305	855	450	556	767	124	170
	1995	12/94 - 11/95	1316	836	480	786	844	164	176
	1996	12/95 - 10/96	1742	758	984	1143	937	116	95
	1997	12/96 - 11/97	1576	724	852	1269	1075	149	126

Table 2.5(continued)

Site	Year	Collection Period	Precipitation + Irrigation	Evapotranspiration	Expected Percolation	Observed Percolation		Collection Efficiency	
						#1	#2	#1	#2
		(month/year)	(mm)	(mm)	(mm)	(mm)	(mm)	(%)	(%)
Peppermint #4	1994	12/93 - 11/94	1404	841	563	1328	1680	236	298
	1995	12/94 - 11/95	1615	821	794	554	944	70	119
	1996	12/95 - 11/96[ii]	2025	766	1258	1009	1085	80	86
	1997	1/97 - 11/97	1258	712	546	607	658	111	121
Peppermint #6	1996	1/96 - 11/96	1937	745	1191	1839	2654	154	223
	1997	12/96 - 11/97	1689	718	971	1310	1329	135	137
Peppermint #7	1996	12/95 - 11/96	2237	771	1466	1367	1849	93	126
	1997	12/96 - 10/97	1500	701	799	440	736	55	92
Row Crop #1	1994	12/93 - 5/94	521	261	260	303	213	116	82
	1995	12/94 - 11/95	1040	854	186	339	126	182	68
	1996	12/95 - 11/96	1928	930	999	743	654	74	65
	1997	12/96 - 11/97	1396	430	966	258	246	27	25
Row Crop #2	1994	12/93 - 6/94	551	329	222	231	294	104	133
	1995	2/95 - 5/95	429	126	304	409	358	135	118
	1996	3/96 - 10/96	854	575	279	239	407	86	146
	1997	2/97 - 11/97	946	699	247	456	572	185	232
Row Crop #3	1994	12/93 - 11/94	953	442	511	592	614	116	120
	1995	12/94 - 11/95	1068	707	361	483	593	134	164
	1996	12/95 - 11/96	1672	744	928	1235	1468	133	158
	1997	12/96 - 11/97	1488	573	916	1019	835	111	91

Table 2.5 (continued)

Site	Year	Collection Period	Precipitation + Irrigation	Evapotranspiration	Expected Percolation	Observed Percolation		Collection Efficiency	
						#1	#2	#1	#2
		(month/year)	(mm)	(mm)	(mm)	(mm)	(mm)	(%)	(%)
Row Crop #4	1994	1/94 - 11/94[iii]	1155	780	375	516	550	137	146
	1995	12/94 - 11/95	1191	780	412	608	610	148	148
	1996	12/95 - 10/96[iv]	1428	618	810	1087	1397	134	172
	1997	2/97 - 11/97	1154	619	535	551	562	103	105
Row Crop #5	1996	12/95 - 11/96	1977	831	1146	1235	1198	108	105
	1997	12/96 - 11/97	1517	726	791	701	789	89	100
Row Crop #6	1996	12/95 - 11/96	1911	633	1278	780	1517	61	119
	1997	12/96 - 11/97	1450	762	688	784	1089	114	158

i - Data from January, February, and March 1995 excluded because PCAPS below water table.

ii - Data from January 1996 excluded because PCAPS below water table.

iii - Data from March 1994 excluded because PCAPS below water table.

iv - Data from January 1996 excluded because PCAPS below water table.

Figure 2.3 depicts the relationship between yearly water balance estimated percolation and yearly PCAPS estimated percolation. A 1:1 line is shown to illustrate the agreement between the samplers and the water balance estimated percolation. A majority of points lie above the 1:1 line, indicating that the PCAPS collected more water than predicted by the water balance for the duration of the study. For all sites, PCAPS annual collection efficiency averaged 125% with a median of 118% (C.V. = 36%). This discrepancy represents approximately 8% of the total annual precipitation and irrigation each site received. Regression analysis revealed a positive correlation between the PCAPS estimated recharge and the water balance recharge ($R^2 = 0.75$), indicating that the PCAPS sample amounts are indicative of environmental variability. A positive correlation coefficient ($\rho = 0.70$) between collection efficiencies of PCAPS #1 and #2 imply that the yearly collection efficiencies of the two samplers at each site tend to increase and decrease together.

Two sources of error have been identified as potential contributors to the PCAPS measured percolation being 25% greater than the water balance estimated percolation. High water tables observed during winter months results in a soil pressure gradient much closer to zero than the unit gradient assumed in the wick matching procedure. In these situations, the wick is applying a greater tension than the surrounding soil, resulting in over-collection. In addition, the 1982 Kimberly-Penman equation has been documented to over-estimate reference evapotranspiration by an average of 10% (Jensen et al., 1990). This will lower water balance estimated percolation values, resulting in increased collection efficiencies.

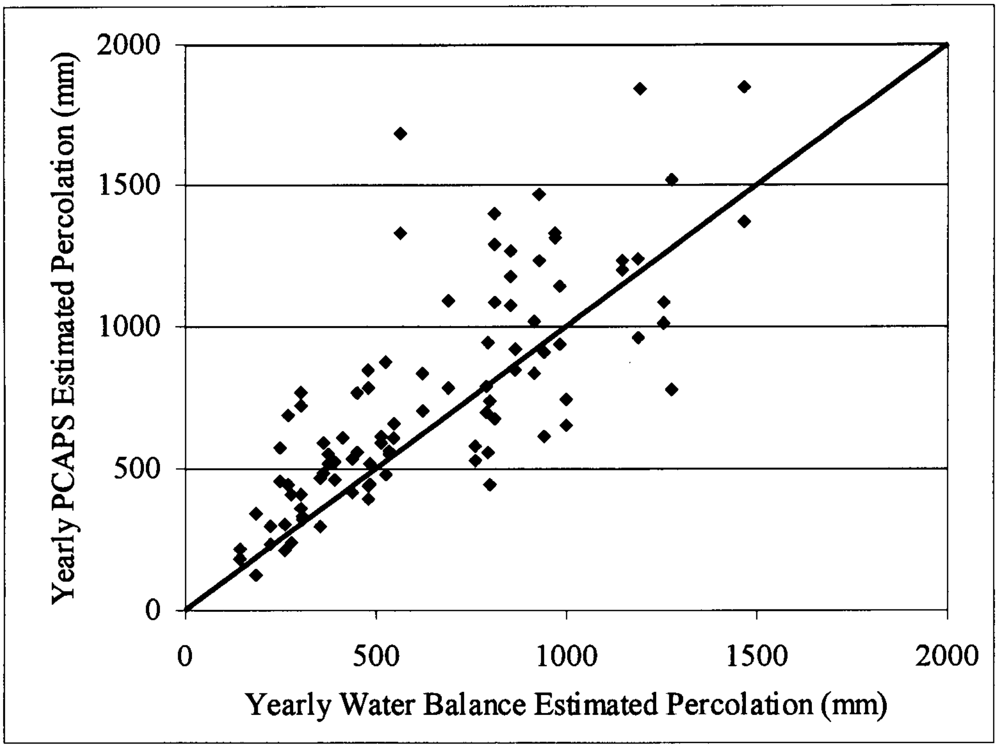

Figure 2.3. Annual water balance estimated percolation, PCAPS estimated percolation,
and 1:1 line.

PCAPS Collection Efficiency as Influenced by Drainage Rate

Water balance estimates provide the best "guess" as to the amount of drainage water which may have leached below the root zone and eventually make it to the ground water. To better understand the PCAPS performance, linear regression was used to determine if a relationship exists between the percolation rate and the PCAPS collection efficiency. Monthly PCAPS collection efficiencies from November through May (months when the soil is assumed to be saturated with no change in soil water storage) for all sites are plotted against water balance estimated percolation rate in

Figure 2.4. Water balance estimated percolation rate was calculated by dividing monthly water balance estimated percolation (precipitation – evapotranspiration) by the number of days since the previous sampling event. Monthly collection efficiencies from November through May averaged 116% (C.V. = 90%) with a median of 93%. A linear regression line developed by minimizing the absolute deviation from the mean indicates that collection efficiency is largely independent of drainage rate (Figure 2.4). Collection efficiencies exhibit the greatest variation during periods of low flux, where the water balance is most sensitive to errors in evapotranspiration estimates. The average November through May monthly collection efficiency of 116% is less than the average yearly collection efficiency of 125%. This deviation supports the premise that an error in the evapotranspiration estimate used in the water balance is the source of the difference between the PCAPS and water balance estimates of percolation. Any over-estimation of crop evapotranspiration by the 1982 Kimberly-Penman equation will lower expected percolation values, resulting in increased collection efficiencies. This will have the greatest impact on collection efficiencies during periods of high evapotranspiration and low flux.

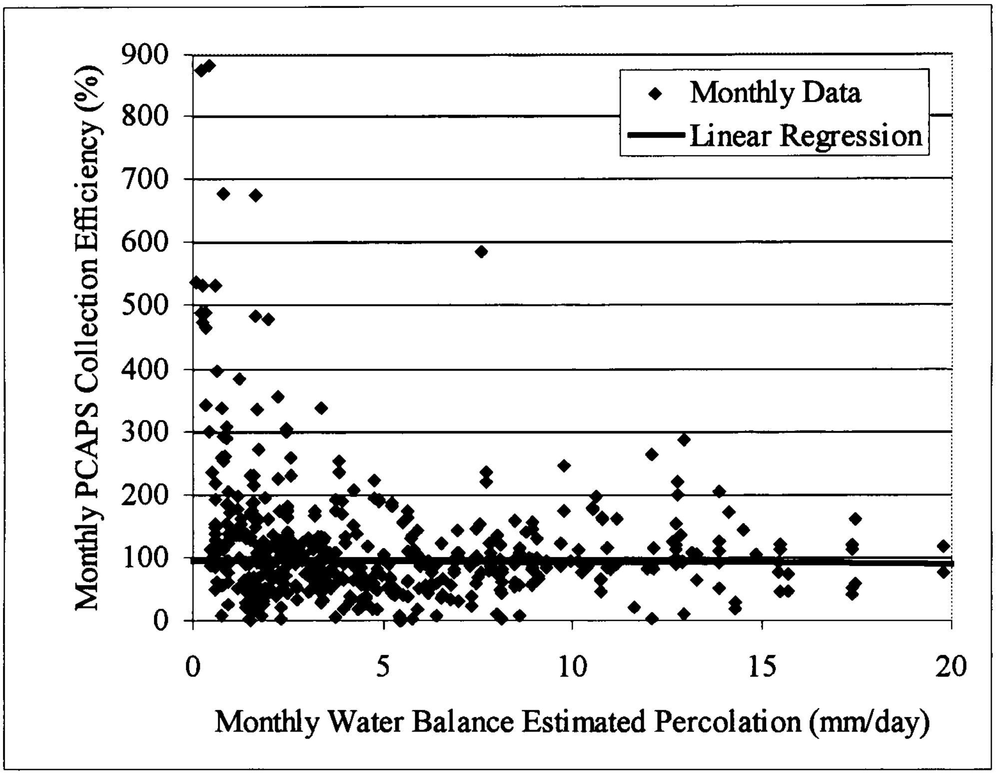

Figure 2.4. Monthly PCAPS collection efficiency as a function of estimated percolation rate.

Number of Samplers Required

The number of PCAPS needed to estimate the annual recharge at each site was determined from the mean collection efficiency confidence interval:

$$\bar{y} \pm t_{\alpha/2,n-1}\left(\frac{s}{\sqrt{n}}\right) \tag{2.9}$$

where $\bar{y}$ is the mean yearly collection efficiency, n the number of samplers, t the t-statistic with n-1 degrees of freedom and a probability of exceedance of $\alpha/2$, and s the sample standard deviation. The sample standard deviation was estimated from the pooled standard deviation of the yearly collection efficiencies for all sites. Therefore, the number of samplers estimate incorporates the variation resulting from the PCAPS, each soil type, and each management system. The minimum number of samplers needed to estimate the mean annual recharge at each site with a 15% bound on the mean and 95% confidence level is 25. A more appropriate bound on the mean may be on the order of 30%, given that the coefficient of variation for the yearly collection efficiencies is 36%. A minimum of eight samplers are needed to estimate the mean annual recharge at each site with a 30% bound on the mean and 95% confidence level. This number corresponds closely to the results of Brandi-Dohrn et al. (1996a) and is thought to be due to intrinsic variability of percolation.

CONCLUSION

The PCAPS showed little evidence of technical failure. Only two of the 42 installed samplers were determined to operate inefficiently, the mechanical failure attributed to an apparent collapse of the interior HDPE sampling box due to over-suction during sample retrieval. Ten of the 42 installed samplers were frequently below the water table, resulting in flooded collection vessels. These PCAPS were installed in locations susceptible to high or perched water tables throughout the year.

PCAPS yearly collection efficiency averaged 125% (C.V. = 36%) in comparison to a water balance estimate. The difference between the estimates of recharge was largely independent of expected percolation. Two likely sources of this discrepancy have been identified. High water tables observed during winter months results in a soil pressure gradient much closer to zero than the unit gradient assumed in the wick matching procedure. In these situations, the wick is applying a greater tension than the surrounding soil, resulting in over-collection. Possible over-estimation of reference evapotranspiration used to compute the water balance percolation will also result in increased collection efficiencies. To estimate the mean annual recharge at each site with a 30% bound on the mean and 95% confidence level, eight samplers are needed. One individual PCAPS may not give an accurate estimate of recharge, but several PCAPS can be used to give a good estimate of actual groundwater recharge.

REFERENCES

Barbee, G. C., and K. W. Brown. 1986. Comparison between suction and free drainage soil solution sampler. Soil Sci. 141(2):149-154.

Boll, J., J. S. Selker, B. M. Nijssen, T. S. Steenhuis, J. van Winkle, and E. Jolles. 1991. Water quality sampling under preferential flow conditions. p. 290-298. *In* R. G. Allen et al. (ed.) Lysimeters for evapotranspiration and environmental measurement. Proc. ASCE Int. Symp. Lysimetry, Honolulu, HI. 23-25 July 1991. Am. Soc. Civ. Eng., New York.

Boll, J., T. S. Steenhuis, and J. S. Selker. 1992. Fiberglass wicks for sampling of water and solutes in the vadose zone. Soil Sci. Soc. Am. J. 56:701-707.

Brandi-Dohrn, F. M., R. P. Dick, M. Hess, and J. S. Selker. 1996a. Field evaluation of passive capillary samplers. Soil Sci. Soc. Am. J. 60:1705-1713.

Brandi-Dohrn, F. M., R. P. Dick, M. Hess, and J. S. Selker. 1996b. Suction cup sampler bias in leaching characterization of an undisturbed field soil. Water Resour. Res. 32(5)1173-1182.

Brown, K. W., J. C. Thomas, and M. W. Holder. 1986. Development of a capillary wick unsaturated zone water sampler. Coop. Agreement CR812316-01-0. U. S. Environ. Protection Agency, Environ. Monit. Syst. Lab., Las Vegas, NV.

Briggs, L. J., and A. G. McCall. 1904. An artificial root for inducing capillary movement of soil moisture. Science (Washington, DC) 20:566-569.

Cambardella, C. A., T. B. Moorman, J. M. Novak, T. B. Parkin, D. L. Karlen, R. F. Turco, and A. E. Konopka. 1994. Field-scale variability of soil properties in central Iowa soils. Soil Sci. Soc. Am. J. 58:1501-1511.

Doorenbos, J., and W. O. Pruitt. 1977. Crop water requirements. Food and Agriculture Organization of the United Nations, Irrigation and Drainage Paper no. 24, revised, Rome, Italy.

El Kayal, A. 1983. Evaluating the design and operation of irrigation canals in Egypt. M.S. Thesis, Department of Civil Engineering, Utah State University, Logan, UT.

Elrick, D. E., and W. D. Reynolds. 1992. Infiltration from constant head well permeameters and infiltrometers. p. 1-24. *In* G. C. Topp et al. (ed.) Advances in measurement of soil physical properties: Bringing theory into practice. SSSA Spec. Publ. 30. SSSA, Madison, WI.

England, C. B. 1974. Comments on "A technique using prorous cups for water sampling at any depth in the unsaturated zone" by Warren W. Wood. Water Resour. Res. 10(5):1049.

Gardner, W. R. 1958. Some steady-state solutions of the unsaturated moisture flow equations with application to evapotranspiration from a water table. Soil Sci. 4:228-232.

Gee, C. W., and J. W. Bauder. 1986. Particle-size analysis. p. 383-411. *In* A. Klute (ed.) Methods of soil analysis. Part 1. 2nd ed. Agron. Monogr. 9. ASA and SSA, Madison, WI.

Jemison, J. M., and R. H. Fox. 1992. Estimation of zero-tension pan lysimeters collection efficiency. Soil Sci. 154:85-94.

Jensen, M. E., R. D. Burman, and R. G. Allen. 1990. Evapotranspiration and irrigation water requirements. ASCE Manuals and Reports on Engineering Practice No. 70. ASCE: New York, NY. pp. 360.

Jordan, C. F. 1968. A simple, tension-free lysimeter. Soil Sci. 105(2):1-86.

Holder, M., K. W. Brown, J. C. Thomas, D. Zabcik, and H. E. Murray. 1991. Capillary-wick unsaturated zone soil pore water sampler. Soil Sci. Soc. Am. J. 55:1195-1202.

Knutson, J. H., S. B. Lee, W. Q. Zhang, and J. S. Selker. 1993. Fiberglass wick preparation for use in passive capillary wick soil pore-water samplers. Soil Sci. Soc. Am. J. 57:1474-1476.

Knutson, J. H., and J. S. Selker. 1994. Unsaturated hydraulic conductivities of fiberglass wicks and designing capillary wick pore-water samplers. Soil Sci. Soc. Am. J. 58:721-729.

Kung, K. –J. S. 1990. Preferential flow in a sandy vadose zone: 2. Mechanisms and implications. Geoderma 46:51-58.

Kung, K. –J. S., J. Boll, J. S. Selker, W. F. Ritter, and T. S. Steenhuis. 1991. Use of ground penetrating radar to improve water quality monitoring in the vadose zone. p. 142-149. *In* Proceedings of the national symposium on preferential flow. Chicago, IL. Dec. 16-17, 1991. ASAE, St. Joseph, MI.

Larson, L. W., and E. L. Peck. 1974. Accuracy of precipitation measurements for hydrologic modeling. Water Resour. Res. 10(4):857-863.

Magid, J., N. Christensen, and H. Nielsen. 1992. Measuring phosphorus fluxes through the root zone of a layered sandy soil: Comparisons between lysimeter and suction cell solution. J. Soil Sci 43:739-747.

Parker, J. C., and M. T. van Genuchten. 1984. Flux-averaged and volume-averaged concentrations in continuum approaches to solute transport. Water Resour. Res. 20(7)866-872.

Rice, R. C. and R. S. Bowman. 1988. Effect of sample size on parameter estimates in solute-transport experiments. Soil Sci. 146:2.

Rimmer, A., T. S. Steenhuis, J. S. Selker, and G. T. Albrecht. 1995. Wick samplers: an evaluation of solute travel times. Soil Sci. 159(4):235-243.

Ryan, P. K., and R. H. Cuenca. 1984. Feasibility and significance of revising consumptive use and net irrigation requirements for Oregon. Project completion report, Department of Agricultural Engineering, Oregon State University, Corvallis, OR.

Selker, J. S., J. –Y. Parlange, and T. Steenhuis. 1992. Fingered flow in two dimensions. 2. Predicting finger moisture profile. Water Resour. Res. 28(9):2523-2528.

Selker, J. S., J. K. Smesrud, and M. Hess. 1998. Western Oregon irrigation guide. Oregon State University Extension Service. *In press.*

Severson, R. C., and D. F. Grigal. 1976. Soil solution concentrations: Effect of extraction time using porous ceramic cups under constant tension. Water Resour. Bull. 12(6):1161-1171.

Shaffer, K. A., D. D. Fritton, and D. E. Baker. 1979. Drainage water sampling in a wet, dual-pore system. J. Environ. Qual. 8(2):241-246.

Topp, E., and W. Smith. 1992. Sorption of the herbicides atrazine and metolachlor to selected plastics and silicone rubber. J. Environ. Qual. 21:316-317.

Tseng, P. –H., M. Th. Van Genuchten, and W. A. Jury. 1995. Simulating the performance of a vacuum solution extraction device for measuring solute flux concentrations in field soils. *In* Proc. of IAHS/IUGG. Denver, CO. July, 1995. pp. 11.

U. S. Bureau of Reclamation. 1995. Agricultural crop water use summary 1988-1994. U. S. Bureau of Reclamation, Pacific Northwest Region, Boise, ID. 25 p.

U. S. Environmental Protection Agency. 1986. Permit guidance manual on unsaturated zone monitoring for hazardous waste treatment units. USEPA Doc. 530-SW-86-040. U. S. Gov. Print. Office, Washington DC.

van Genuchten, M. Th. 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J. 44:892-898.

van Genuchten, M. Th., F. J. Leij, and S. R. Yates. 1991. The RETC code for quantifying the hydraulic functions of unsaturated soils. U. S. Environ. Protection Agency Rep. 600/2-91/065. U. S. Environ. Protection Agency, Ada, OK. 85 p.

Wright, J. L. 1982. New evapotranspiration crop coefficients. J. Irrig. Drainage Div. ASCE 108(IR2):57-74.

Chapter 3

Sprinkler Head Maintenance Effects on Water Application Uniformity

Michael J. Louie and John S. Selker

In preparation for submission to
ASCE Journal of Irrigation and Drainage Engineering

ABSTRACT

The effects of wear on the ability of sprinkler irrigation systems to maintain the designed water application rate and uniformity is of concern in regard to crop performance, water use efficiency, and environmental impact. Twelve sprinkler irrigation systems used under commercial crop production in Lane County, OR, USA, were evaluated for equipment wear and performance. Individual sprinkler nozzle size and discharge rates were measured for each system and used to estimate water application patterns. A computer model was developed to estimate field application rates and uniformity through overlap of individual sprinklers with distinct water distribution patterns. New sprinkler nozzles were installed on six of the 12 irrigation systems to compare potential application rate and uniformity with existing system performance. Despite reducing the coefficient of variation in discharge between sprinklers from 10% to 2%, little increase in water application uniformity was attained by replacing the nozzles. A 13% decrease in mean water application rate was documented when new nozzles replaced worn parts. The over-application due to worn or mismatched nozzles gives rise to the potential for increased surface redistribution and deep percolation, resulting in water and nutrient losses. A management concern is the finding that half of the evaluated irrigation systems were being operated at pressures below manufacturer's recommendations. Even at an optimum pressure, estimates of potential application uniformity fall below recommended levels, predominately due to the widespread use of the 12.2- x 18.3-m sprinkler layout. Adoption of double-nozzle sprinklers appears to be an effective and economical way to increase application uniformity without modifications to sprinkler layout.

INTRODUCTION

Water application uniformity is an increasing concern for sprinkler manufacturers, system designers, and users as energy and water costs rise, environmental protection is emphasized, and water conservation is required. Many factors affect water application uniformity, including sprinkler type, lateral configuration, and environmental conditions. A great deal of research has been conducted on the effects of these factors (e.g., Bilanski and Kidder, 1958; Bean, 1965; Branscheid and Hart, 1968; Seginer and Kostrinsky, 1975; Fukui et al., 1980; Vories and von Bernuth, 1986; Seginer and von Bernuth, 1991; Seginer et al., 1992; Nderitu and Hills, 1993; Li and Kawano, 1996). Effective system design involves sprinkler selection, spacing, and orientation based on trade-offs between equipment costs and yield benefits associated with high application uniformity (Chen and Wallender, 1984). This study extends beyond irrigation system design to investigate the effects of wear as well as inadvertent management changes on the ability of sprinkler systems to maintain the designed water application uniformity.

Irrigation systems were selected for evaluation from commercial farms in the Willamette River alluvial valley of western Oregon, which is used extensively for agricultural production of grass seed, peppermint, orchard, and row crops. The temperate oceanic climate features mild wet winters and warm dry summers. Sprinkler irrigation from surface and groundwater supplies is the predominant method of irrigation water application during the dry growing season from May to September. Other lesser used methods of irrigation throughout western Oregon include center pivot, lateral move, big gun, and trickle.

In western Oregon, agricultural sprinkler irrigation systems are typically designed by an irrigation system specialist working as part of a retail sales organization. After design and installation, system management and maintenance is generally left to the user. Agricultural managers typically overlook the need for routine maintenance on systems that appear functional. Systems are operated and maintained by untrained personnel hired to irrigate fields on a preset schedule. Sprinkler maintenance often consists of replacing inoperable sprinkler heads or components from a stockpile of miscellaneous parts. Unless the entire sprinkler system is examined at regular intervals, this results in a properly designed system becoming an assortment of various sprinkler head models and nozzle sizes that may have little resemblance to the original system. In addition, operators often exceed pumping limitations by simultaneous operation of too many lateral lines, resulting in lower than design pressure.

The objective of this study was to evaluate and analyze existing sprinkler irrigation systems used for commercial agricultural production and determine the impact of simple maintenance procedures in restoring water application uniformity to design standards.

MATERIALS AND METHODS

Characterization of Irrigation Systems

This study was conducted from June 1997 to September 1997 on 12 commercial farms in Lane County, OR. The farms utilize hand-move or side-roll sprinkler irrigation systems with the design parameters listed in Table 3.1.

Table 3.1. Irrigation system parameters for 12 commercial farms selected for evaluation.

Site Number	System Type	Number of Sprinklers on Lateral	Dominant Nozzle Size	Distance Between Heads	Distance Between Laterals	Lateral Diameter
			(mm)	(m)	(m)	(cm)
1	side-roll	19	4.37	12.2	18.3	10.2
2	hand-move	10	4.37	12.2	18.3	7.6
3	hand-move	23	4.37	12.2	18.3	7.6
4	side-roll	36	4.76	12.2	18.3	11.4
5	hand-move	17	4.37	12.2	18.3	7.6
6	side-roll	19	4.37	12.2	18.3	11.4
7	side-roll	33	4.37	12.2	18.3	10.2
8	hand-move	12	4.76	12.2	18.3	7.6
9	side-roll	27	4.76 x 2.38	12.2	18.3	10.2
10	side-roll	44	4.37 x 2.38	12.2	18.3	12.7
11	hand-move	25	4.37	12.2	18.3	7.6
12	hand-move	14	4.37	12.2	18.3	7.6

Field Evaluation

One sprinkler lateral was selected from each of the 12 farms for evaluation. The manufacturer, model number, nominal and actual nozzle size, and riser height were recorded for each sprinkler head on the lateral. Nominal nozzle size was taken from manufacturer labeling and actual nozzle size was measured using a USA standard set of machinists drill bits (Table 3.2). Actual nozzle size was recorded as the largest diameter drill bit that could be fitted into the orifice. Lateral diameter and sprinkler spacing were also noted. During normal operation, measurements of operating pressure and discharge rate were recorded for each individual sprinkler head. Operating pressure was measured using a pressure gauge with pitot attachment, centering the pitot tube in the jet 3 mm from the sprinkler nozzle and recording the highest observed pressure. Discharge rate was measured by recording the volume of water collected during a 30-second interval. A 1-m length of 1.27-cm diameter flexible tubing was fitted around the sprinkler nozzle and directed into a 20-L collection vessel for 30 seconds. For sprinkler models having a rear spreader nozzle, a second piece of tubing was used and the combined discharge rate from the drive and spreader nozzles was measured. New nozzles, with retail cost of $0.45 each, were installed in sprinkler heads on six of the 12 irrigation laterals and the evaluation repeated to compare pre- and post-maintenance sprinkler discharge variations.

Table 3.2. USA standard drill bits

Drill Size	Drill Diameter (mm)
22	3.99
21	4.04
20	4.09
19	4.22
18	4.31
11/64	4.37
17	4.39
16	4.50
15	4.57
14	4.62
13	4.70
3/16	4.76
12	4.80
11	4.85
10	4.91
9	4.98
8	5.05
7	5.11
13/64	5.16
6	5.18
5	5.22

Data Analysis

A computer model was developed to estimate water application uniformity from catch-can tests published for various sprinkler models by the Center for Irrigation Technology (Center for Irrigation Technology, 1996). The model extends beyond commercially available sprinkler software to allow pattern overlap of non-identical sprinkler heads. This was necessary due to the wide variation in sprinkler heads and nozzle sizes observed on a single lateral during system evaluations. In addition, nozzle wear increases the variability in nozzle discharges.

For input, the program requires nominal nozzle size and measured discharge rate for each sprinkler head. Since nozzle wear increases sprinkler discharge rate and changes the water distribution pattern, the model linearly scales up reference single-leg, or radial, catch-can profiles with actual nozzle discharge to generate approximate distribution patterns for each sprinkler. For single-nozzle sprinklers, three single-leg profiles developed at the Center for Irrigation Technology (1996) for Rain Bird 30 series sprinklers operating at 345 kPa with nozzle sizes 3.79, 4.37, and 4.76 mm were used as reference distribution patterns in the model. For double-nozzle sprinklers, two single-leg profiles developed at the Center for Irrigation Technology (1996) for Rain Bird 30 series sprinklers operating at 345 kPa with nozzle sizes 4.37 x 2.38 mm and 4.76 x 3.79 mm were used as reference distribution patterns in the model. Rain Bird 30 series sprinkler patterns were chosen based on the dominant use of this sprinkler model in agricultural irrigation systems of western Oregon. The process of scaling sprinkler patterns up linearly with actual nozzle discharge was validated by estimating the catch from a 4.37-mm nozzle using data from a 3.79-mm nozzle multiplied by the ratio of the sprinkler discharges (Figure 3.1). The estimated catch from the 4.37-mm nozzle closely matched the Center for Irrigation Technology catch-can data (R^2 = 0.86). The validation was confirmed by using scaled data from a 4.37-mm nozzle to approximate the pattern from a 4.76-mm nozzle (R^2 = 0.97) (Figure 3.2). Similar results were found for double-nozzle sprinkler systems using 4.37 x 2.38-mm nozzle data to approximate the pattern from a 4.76 x 2.38-mm nozzle sprinkler (R^2 = 0.93) (Figure 3.3). The model accounts only for the affect of variable sprinkler discharge on water application uniformity, assuming all sprinklers are Rain Bird 30 series operating at 345 kPa.

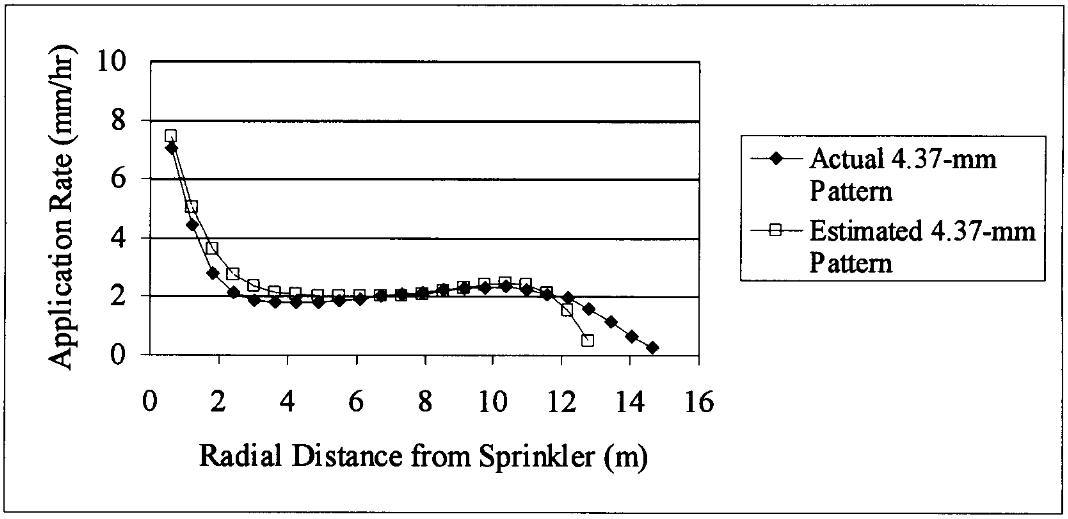

Figure 3.1. Estimated Rain Bird 4.37-mm nozzle water distribution pattern at 345 kPa from 3.79-mm nozzle data scaled by the ratio of sprinkler discharges.

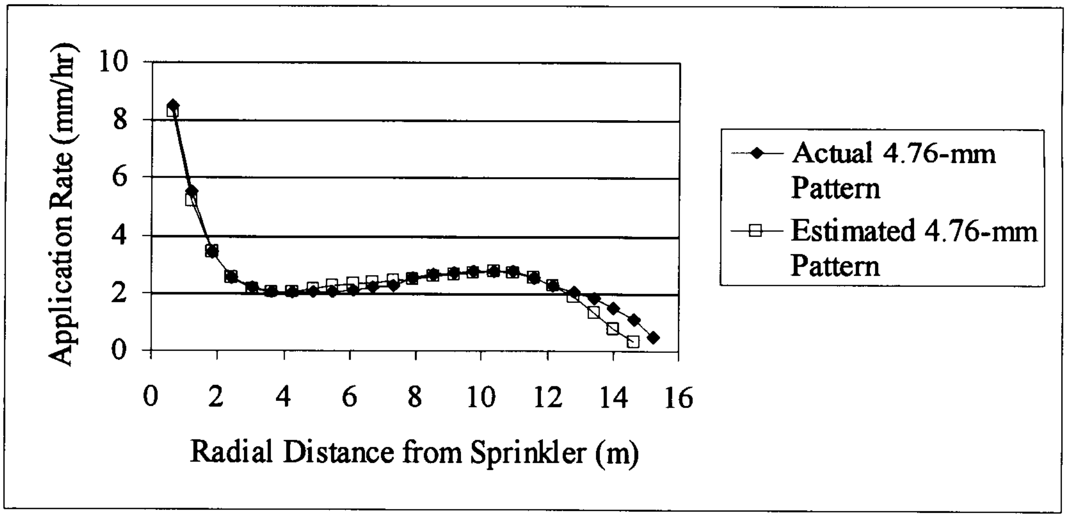

Figure 3.2. Estimated Rain Bird 4.76-mm nozzle water distribution pattern at 345 kPa from 4.37-mm nozzle data scaled by the ratio of sprinkler discharges.

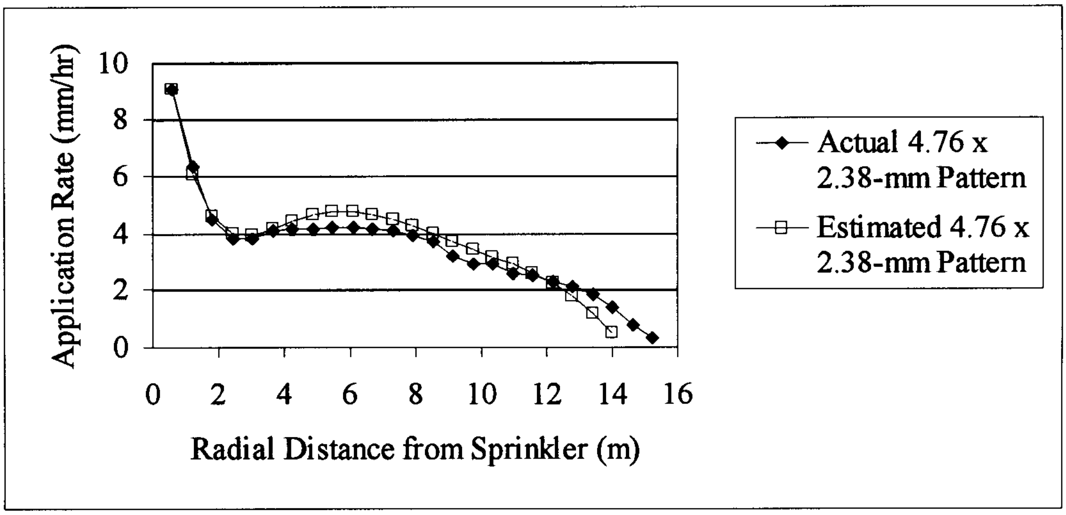

Figure 3.3. Estimated Rain Bird 4.76 x 2.38-mm nozzle water distribution pattern at 345 kPa from 4.37 x 2.38-mm nozzle data scaled by the ratio of sprinkler discharges.

The approximate single-leg catch-can profile for each head is rotated around the sprinkler to generate the traditional single-sprinkler grid (Griffin, 1978). Those grid points not corresponding exactly with the actual distance along the radial leg are linearly interpolated. Sprinkler patterns down the entire lateral are overlapped and contributions from each sprinkler are added to create a spatially varied water-application surface over the area bounded by the sprinklers. Uniformity is then estimated from depths of water calculated at grid points within the enclosed area (Hart, 1963).

The program employs two commonly used methods to quantitatively describe water application uniformity from overlapped sprinklers. Christiansen (1942) defined the water distribution uniformity for a sprinkler system as:

$$UC_c = 1 - \sum_{i=1}^{n} \left[\frac{\left| x_i - \bar{x} \right|}{n\bar{x}} \right] \tag{3.1}$$

where UC_c is the Christiansen uniformity coefficient, x_i is the i^{th} water application depth, and $\bar{x}$ is the mean value of n observations. A statistically based measure introduced for the Hawaiian Sugar Planter's Association (HSPA) is given as:

$$UC_H = 1 - \left(\frac{2}{\pi} \right)^{0.5} \left(\frac{s}{\bar{x}} \right) \tag{3.2}$$

where UC_H is the HSPA uniformity coefficient and s is the standard deviation about the mean (Hart, 1961; Hart and Reynolds, 1965). The HSPA uniformity equation assumes a normal (Gaussian) distribution of sprinkler precipitation over the area. Applying root mean square (RMS) error criteria, Elliott et al. (1980) found the beta probability density function superior to the normal (Gaussian) function for uniformities less than 65, but only slightly superior to the normal distribution function for uniformities greater than 65. Hart (1961) reported UC_c values nearly equal to UC_H for normally distributed sprinkler precipitation data, which is congruent with the findings of Elliot et al. (1980), in which RMS error was similar for UC_c and UC_H over the upper range of uniformities.

Model results for application pattern overlap of identical sprinklers was verified against two commercially available software packages and hand calculations. Single-leg water distribution data from the Center for Irrigation Technology (1996) for a Rain Bird 30H sprinkler equipped with a 4.37-mm nozzle at 345 kPa was overlapped at three common combinations of sprinkler and lateral spacing. Results from the developed model were consistent with those obtained using the Center for Irrigation Technology Space for Windows™ (Oliphant, 1993) and the Utah State University Catch-3D (Allen, 1992) sprinkler overlap programs (Table 3.3). Slight deviations in model results are due to variations in the methods used to convert single-leg catch-can data into grid catch-can data. Model results for application pattern overlap of sprinklers with varying nozzle sizes down a lateral was verified by hand calculation of catch depth at several locations.

Table 3.3. Comparison of three computer model estimates of mean rate and uniformity of water application from overlapped Rain Bird 30H sprinklers equipped with 4.37-mm nozzles operating at 345 kPa.

		Developed Model		Space for Windows™		Catch-3d	
Distance Between Heads	Distance Between Laterals	Mean Application Rate	UC_c	Mean Application Rate	UC_c	Mean Application Rate	UC_c
(m)	(m)	(mm/hr)	(%)	(mm/hr)	(%)	(mm/hr)	(%)
12.2	12.2	8.4	90	8.4	92	8.3	91
12.2	15.2	6.7	80	6.7	82	6.6	81
12.2	18.3	5.6	78	5.6	79	5.5	78

RESULTS AND DISCUSSION

Evaluation of 12 irrigation systems used for commercial crop production in western Oregon was initially performed to better understand the current state of agricultural irrigation in the region. From these evaluations and subsequent discussions with participating farmers, it became apparent that irrigation system maintenance has been given a low priority. In general, irrigation systems left under the management of individual farmers have deteriorated. System surveys revealed nozzle wear resulting in an average increased nozzle diameter of 15% over manufacturer's specifications. This was minor, compared to finding original nozzle sizes ranging from 3.97 to 5.56 mm diameter (100% difference in discharge rate) installed on the same lateral. Two of the laterals surveyed contained combinations of single and double nozzle sprinkler heads. Combined, these factors resulted in an average coefficient of variation, C.V., of 10% in nozzle discharge down the same lateral (Table 3.4). Half of the evaluated systems were being operated at a pressure below the sprinkler manufacturer's recommendations. While correct operating pressure was assumed for computer uniformity calculations, individual farmers were notified of the low-pressure problem.

Table 3.4. Coefficient of variation in sprinkler discharge rates of original system and after new nozzles were installed.

Site	Coefficient of Variation in Nozzle Discharge	
Number	Existing System	System with New Nozzles
	(%)	(%)
1	7	2
2	4	3
3	13	3
4	7	3
5	19	2
6	10	1
7	11	
8	5	
9	11	
10	7	
11	13	
12	18	

To determine the effect of proper system maintenance in reducing variations in sprinkler discharge, new nozzles were installed on six of the 12 evaluated laterals. Re-evaluation of the six systems revealed C.V. in sprinkler discharge dropping from 10% to 2% (Table 3.4). This amount of discharge variation is consistent with that expected due to pressure head loss from friction along the lateral. Data collected during sprinkler evaluations is provided in Appendix B. The dramatic improvement in sprinkler outflow consistency is shown in Figure 3.4 for the six laterals where nozzles were replaced. Figure 3.5 depicts the variation in nozzle discharge of the other six systems originally evaluated. Day-to-day variations in the number of sprinkler laterals simultaneously operating off a given pumping source frequently resulted in different operating pressures from when the systems were originally evaluated to when the systems were re-evaluated with new nozzles. In Figures 3.4 and 3.5, the pressure-corrected discharge rate is a dimensionless quantity computed as follows:

$$\text{Pressure Corrected Discharge Rate} = \left(\frac{Q}{\overline{Q_O}}\right)\left(\frac{\overline{P_O}}{\overline{P}}\right)^{1/2} \qquad (3.3)$$

where Q is the discharge rate of the tested sprinkler, $\overline{P}$ is the average pressure of all tested nozzles on the lateral, $\overline{Q_O}$ is the average discharge rate of sprinklers with the original nozzles installed, and $\overline{P_O}$ is the average pressure during original nozzle tests. The computation of a dimensionless pressure corrected discharge rate removes the influence of a change in operating pressure from when the system was originally evaluated to when the system was re-evaluated with new nozzles, given that nozzle discharge varies with the square root of pressure. The pressure corrected discharge rate is scaled with the average original system discharge rate to allow comparison of discharge rates before and after new nozzles were installed. Referring to Figure 3.4, the trend is for discharge rates to decrease after worn nozzles are replaced with new ones.

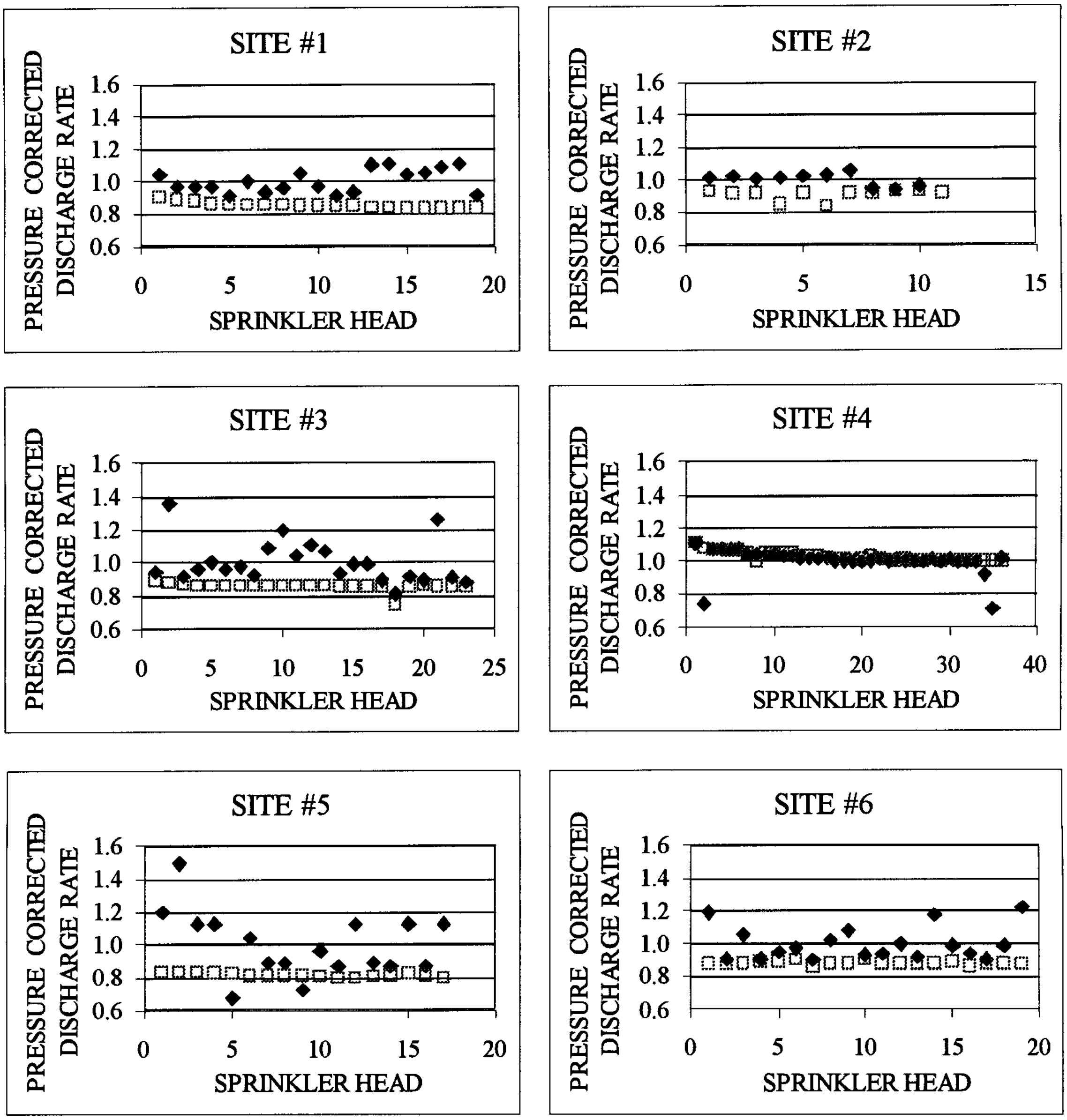

Figure 3.4. Pressure corrected sprinkler discharge rate down six irrigation laterals before nozzle replacement (solid diamonds) and after new nozzles were installed (open squares).

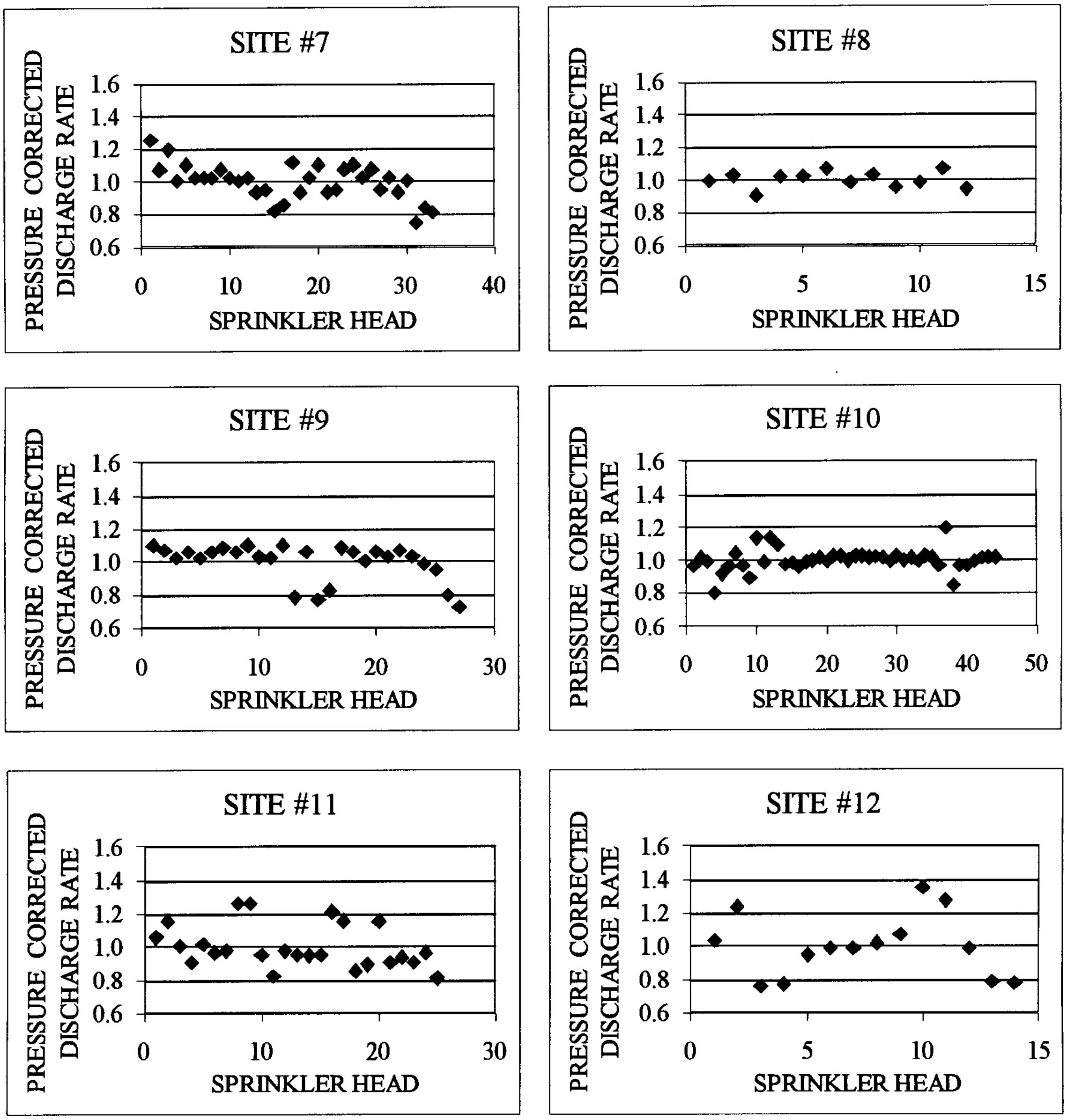

Figure 3.5. Pressure corrected sprinkler discharge rate down six additional irrigation laterals equipped with original nozzles.

The developed model was used to estimate water application uniformity of the irrigation systems before and after installation of new nozzles. In western Oregon, the most common sprinkler spacing is 12.2 m along the lateral with 18.3 m between laterals. This is the only spacing used by participating farmers (Table 3.1). Table 3.5 gives model estimates of mean application rate and water application uniformity for the 12 existing irrigation systems and for the six systems after new nozzles were installed. The Christiansen uniformity coefficient was found to be equal to the HSPA uniformity coefficient for these systems. For the six systems in which new sprinkler nozzles were installed, there was no notable improvement in water application uniformity. This is explained by the overlapping of sprinkler precipitation. At 345 kPa, Rain Bird 30 series sprinklers will distribute water over a radial distance of 12.8 to 15.2 m, depending on nozzle size. For a field irrigated on a 12.2 x 18.3 m spacing, a single location will receive the combined precipitation from the nearest two to four sprinklers. Adjacent sprinklers with widely different discharges are "smoothed out" through overlap to maintain high water application uniformity. This "smoothing" effect is predominant in irrigation systems where sprinkler discharges down the lateral follow a random high-low oscillation. The irrigation system at site 5 deviates from the high-low oscillation pattern with the discharge from the first four sprinklers being higher than the following ones (Figure 3.4). The first 20% of the field is receiving a higher than average irrigation rate. This translates to a comparatively low UC_c of 74 increasing to 78 after new nozzles were installed. The same trend would be expected for site 12, where the UC_c of the existing system is 73 (Figure 3.5). The irrigation systems at sites 9 and 10 generate application uniformities of 87 and 89, despite respective 11% and 7% C.V. in sprinkler discharge rates. These were the only evaluated systems to utilize sprinkler heads with a secondary spreader nozzle in addition to the drive nozzle. Overlapped at a 12.2 x 18.3 m spacing, these double-nozzle systems inherently generate a higher application uniformity than their single-nozzle counterparts.

Table 3.5. Water application rate and uniformity estimated from developed model for 12.2 x 18.3 m spacing at 345-kPa operating pressure.

	Existing System			System with New Nozzles		
Site Number	Mean Application Rate	UC_c	UC_H	Mean Application Rate	UC_c	UC_H
	(mm hr^{-1})	(%)	(%)	(mm hr^{-1})	(%)	(%)
1	6.4	77	77	5.5	78	78
2	6.1	78	78	5.4	78	78
3	6.6	76	76	5.6	78	78
4	7.0	77	77	7.2	77	78
5	6.7	74	74	5.5	78	78
6	6.2	77	77	5.6	78	78
7	6.4	76	76			
8	7.8	77	78			
9[i]	11.1	87	87			
10[i]	9.2	89	89			
11	6.4	76	76			
12	6.0	73	73			

i - Double-nozzle sprinkler heads used on lateral.

The uniformity analysis was repeated to evaluate the influence of nozzle-to-nozzle discharge rate variation on water distribution at sprinkler spacings closer than 12.2 x 18.3 m. Two sprinkler spacings of 12.2 m along the lateral with 15.2 m between laterals (Table 3.6) and 12.2 m along the lateral with 12.2 m between laterals were evaluated (Table 3.7). While uniformities generally increased with closer sprinkler spacing, there was little influence from nozzle-to-nozzle discharge rate variation. In sprinkler systems utilizing single-nozzle heads, sprinkler spacing is the dominant factor influencing potential water application uniformity. For sprinkler systems equipped with double-nozzle heads, sprinkler spacings closer than 12.2 x 18.3 m did not notably increase uniformity.

Table 3.6. Water application rate and uniformity estimated from developed model for 12.2 x 15.2 m spacing at 345-kPa operating pressure.

	Existing System			System with New Nozzles		
Site Number	Mean Application Rate	UC_c	UC_H	Mean Application Rate	UC_c	UC_H
	(mm hr^{-1})	(%)	(%)	(mm hr^{-1})	(%)	(%)
1	7.7	79	80	6.6	80	80
2	7.3	80	80	6.5	80	80
3	7.9	79	79	6.6	80	80
4	8.4	82	81	8.5	83	82
5	8.0	77	77	6.6	80	80
6	7.4	80	80	6.7	80	80
7	7.6	77	78			
8	9.3	83	82			
9[i]	13.3	86	87			
10[i]	11.0	86	87			
11	7.7	78	78			
12	7.2	75	75			

i - Double-nozzle sprinkler heads used on lateral.

Table 3.7. Water application rate and uniformity estimated from developed model for 12.2 x 12.2 m spacing at 345-kPa operating pressure.

	Existing System			System with New Nozzles		
Site Number	Mean Application Rate	UC_c	UC_H	Mean Application Rate	UC_c	UC_H
	(mm hr^{-1})	(%)	(%)	(mm hr^{-1})	(%)	(%)
1	9.7	89	86	8.3	90	88
2	9.3	90	87	8.2	90	87
3	10.0	87	85	8.4	90	88
4	10.6	91	88	10.8	91	88
5	10.1	84	82	8.3	90	88
6	9.4	90	87	8.4	90	88
7	9.6	86	84			
8	11.8	91	88			
9^i	16.7	92	91			
10^i	13.8	91	91			
11	9.7	86	84			
12	9.1	82	80			

i - Double-nozzle sprinkler heads used on lateral.

The data suggest little improvement in water application uniformity is attained by replacing worn or mismatched nozzles on a sprinkler lateral with new nozzles of uniform size. The advantage of properly maintained irrigation systems is increased certainty in estimating the rate at which water is being applied to the field. Farmers operating irrigation systems under the assumption that performance has not changed through lack of maintenance could be inadvertently over-irrigating their crops. The study findings indicate worn or mismatched nozzles increase the water application rate to the field by an average of 13% (Table 3.8). Nozzle wear alone, causing an observed 15% increase in nozzle diameter, should result in a 32% increase in water application rate. Mismatched nozzle sizes on each of the evaluated laterals reduces the impact of nozzle wear to a 13% increase in water application rate. Irrigation systems are typically designed to apply water at a rate just below the soil infiltration rate. An increase in the water application rate may result in ponding and surface redistribution, both undesirables in sprinkler irrigation. If irrigation set times are not adjusted accordingly, there is potential for increased deep percolation resulting in nutrient losses below the root zone.

Table 3.8. Change in mean water application rate of six irrigation systems from deterioration resulting in a worn and mismatched nozzle system.

Site Number	New Nozzle System Mean Application Rate	Existing System Mean Application Rate	Change in Mean Application Rate Between New Nozzle and Existing Systems.
	($mm\ hr^{-1}$)	($mm\ hr^{-1}$)	(%)
1	5.5	6.4	+ 16
2	5.4	6.1	+ 13
3	5.6	6.6	+ 18
4	7.2	7.0	- 3
5	5.5	6.7	+ 22
6	5.6	6.2	+ 11

CONCLUSION

The study shows sprinkler nozzle wear and mismatched nozzle sizes results in an increased water application rate that may not be apparent to the user. Inadvertent over-irrigation results in unnecessary pumping and water costs. In addition, there is potential for increased surface redistribution and deep percolation water loss below the plant root zone. Agricultural nutrients and chemicals carried with these water losses pose a contamination threat to surface and groundwater supplies. Regular maintenance provides the opportunity for inspection and minor repairs to prevent potential system failures.

Sprinkler system evaluations revealed a consistent management oversight when 50% of the tested systems were found to be operating at pressures below manufacturer's recommendations. The impact of low pressure on water application rate and uniformity was not investigated in this study, but agricultural managers should be aware that optimum water droplet distribution is achieved only under correct pressure.

The ten evaluated systems utilizing single-nozzle sprinklers had an average UC_c of 76%. To maintain yields, it is recommended for high-value crops that 90% of the field receive an irrigation depth at or above the irrigation requirement, leaving only 10% of the field in deficit (Cuenca, 1989). Assuming a normal (Gaussian) water distribution and a uniformity of 76%, the over-irrigation necessary to ensure that 90% of the field receives at least the required irrigation depth amounts to 40% of the total applied water. This water is lost to deep percolation below the root zone. Recommended uniformity levels for agricultural systems based on crop value and equipment costs are on the order of 80% for field crops and 85% for specialty crops (Cuenca, 1989). Improving water application uniformity from 76% to 85% reduces the deep percolation losses from 40% to 25% of the total applied water. The two evaluated irrigation systems using double-nozzle sprinklers had an average UC_c of 88% at the 12.2- x 18.3-m spacing. Model results indicate that uniformity levels approach 90% for single-nozzle systems operated at the closer 12.2- x 12.2-m spacing.

Agricultural managers might consider adopting double-nozzle sprinklers, if infiltration rates allow, as a way to increase uniformity without having to change from the widespread 12.2- x 18.3-m sprinkler spacing. Another alternative would be to modify the irrigation layout to accommodate a closer 12.2- x 12.2-m spacing.

One surprise finding from this study is the extent to which sprinkler pattern overlap reduces the impact of nozzle-to-nozzle discharge rate variation such that water application uniformity is not adversely affected. Operated under adequate pressure, the use of worn or mismatched sprinkler nozzles has little impact on water application uniformity compared to new nozzles of uniform size.

REFERENCES

Allen, R.G. 1992. Catch-3D sprinkler pattern analysis software. User's manual. Department of Biological and Irrigation Engineering. Utah State University, Logan, UT 84322-4105. 25 p.

Bean, A. G. M. 1965. Water distribution by irrigation sprinklers. J. Agricultural Engineering Research 10:314-321.

Bilanski, W. K., and E. H. Kidder. 1958. Factors that affect the distribution of water from a medium-pressure rotary irrigation sprinkler. Trans. ASAE 1(1):19-28.

Branscheid, V. O., and W. E. Hart. 1968. Predicting field distributions of a sprinkler system. Trans. ASAE 11(6):801-803, 808.

Center for Irrigation Technology. 1996. Irrigation equipment performance index. Center for Irrigation Technology, California State University at Fresno. CATI Publ. 960801.

Chen, D., and W. W. Wallender. 1984. Economic sprinkler selection, spacing, and orientation. Trans. ASAE 27(3):737-743.

Christiansen, J. E. 1942. Irrigation by sprinkling. University of California, Berkeley. Agric. Exp. Stn. Bull. 670.

Cuenca, R. H. 1989. Irrigation system design – an engineering approach. Prentice-Hall, Englewood Cliffs, New Jersey. 552 p.

Elliott, R. L., J. D. Nelson, J. C. Loftis, and W. E. Hart. 1980. Comparison of sprinkler uniformity models. J. Irrig. Drainage Div. ASCE 106(IR4):321-330.

Fukui, Y., K. Nakanishi, and S. Okamura. 1980. Computer evaluation of sprinkler irrigation uniformity. Irrig. Sci. 2(1):23-32.

Griffin, S. G. 1978. Computer programming solid set systems. ASAE Paper No. 78-2012, ASAE, St. Joseph, MI.

Hart, W. E. 1961. Overhead irrigation pattern parameters. Agricultural Engineering 42(7):354-355.

Hart, W. E. 1963. Sprinkler distribution analysis with a digital computer. Trans. ASAE 6(2):206-208.

Hart, W. E., and W. N. Reynolds. 1965. Analytical design of sprinkler systems. Trans. ASAE 7(4):83-85, 89.

Li, J., and H. Kawano. 1996. Sprinkler rotation nonuniformity and water distribution. Trans. ASAE 39(6):2027-2031.

Nderitu, S. M., and D. J. Hills. 1993. Sprinkler uniformity as affected by riser characteristics. Applied Engineering in Agriculture 9(6):515-521.

Oliphant, J. C. 1993. SPACE for Windows™. Software update. Center for Irrigation Technology, California State University at Fresno. CATI Publ. 930403.

Seginer, I., D. Kantz, D. Nir, and R. D. von Bernuth. 1992. Indoor measurement of single-radius sprinkler patterns. Trans. ASAE 35(2):523-533.

Seginer, I., and M. Kostrinsky. 1975. Wind, sprinkler patterns and system design. J. Irrig. Drainage Div. ASCE 101(IR4):251-264.

Seginer, I., D. Nir, and R. D. von Bernuth. 1991. Simulation of wind distorted sprinkler patterns. J. Irrig. Drainage Eng. ASCE 117(2):285-306.

Vories, E. D., and R. D. von Bernuth. 1986. Single nozzle sprinkler performance in wind. Trans. ASAE 29(5):1325-1330.

4. GENERAL CONCLUSION

Passive Capillary Samplers (PCAPS) were found to be superior estimators of groundwater recharge in comparison to other currently available technologies. The PCAPS showed little evidence of technical failure, with only two of the 42 installed samplers found to operate inefficiently. Installation of 10 of the 42 samplers in locations susceptible to high or perched water tables resulted in submersion of the samplers, rendering them inoperable. On average, the 30 remaining PCAPS measured soil water flux 25% greater than that obtained from a water balance estimate. Two sources of this discrepancy have been identified. High water tables observed during winter months results in a soil pressure gradient much closer to zero than the unit gradient assumed in the wick matching procedure. In these situations, the wick is applying a greater tension than the surrounding soil, resulting in over-collection. Possible over-estimation of reference evapotranspiration used to compute the water balance percolation will also result in increased collection efficiencies. Due to soil variability, eight or more samplers are required per site to obtain a precise measurement of groundwater recharge.

Sprinkler irrigation system evaluations in Lane County, OR, revealed significant nozzle-to-nozzle discharge rate variation due to worn or mismatched nozzles. Surprisingly, sprinkler pattern overlap reduces the impact of this discharge rate variation resulting in little effect on the spatial uniformity of water application. In sprinkler systems employing single-nozzle heads, the common 12.2 x 18.3-m spacing was the predominant cause of documented low water application uniformities. Modifying sprinkler irrigation systems to utilize double-nozzle sprinkler heads or reducing the spacing to 12.2 x 12.2 m would increase water application uniformities to recommended levels. The study results indicate that agricultural managers need to be increasingly aware of correct sprinkler operating pressure and the potential for nozzle wear to result in increased water application rates.

BIBLIOGRAPHY

Allen, R.G. 1992. Catch-3D sprinkler pattern analysis software. User's manual. Department of Biological and Irrigation Engineering. Utah State University, Logan, UT 84322-4105. 25 p.

Barbee, G. C., and K. W. Brown. 1986. Comparison between suction and free drainage soil solution sampler. Soil Sci. 141(2):149-154.

Bean, A. G. M. 1965. Water distribution by irrigation sprinklers. J. Agricultural Engineering Research 10:314-321.

Bilanski, W. K., and E. H. Kidder. 1958. Factors that affect the distribution of water from a medium-pressure rotary irrigation sprinkler. Trans. ASAE 1(1):19-28.

Boll, J., J. S. Selker, B. M. Nijssen, T. S. Steenhuis, J. van Winkle, and E. Jolles. 1991. Water quality sampling under preferential flow conditions. p. 290-298. *In* R. G. Allen et al. (ed.) Lysimeters for evapotranspiration and environmental measurement. Proc. ASCE Int. Symp. Lysimetry, Honolulu, HI. 23-25 July 1991. Am. Soc. Civ. Eng., New York.

Boll, J., T. S. Steenhuis, and J. S. Selker. 1992. Fiberglass wicks for sampling of water and solutes in the vadose zone. Soil Sci. Soc. Am. J. 56:701-707.

Brandi-Dohrn, F. M., R. P. Dick, M. Hess, and J. S. Selker. 1996a. Field evaluation of passive capillary samplers. Soil Sci. Soc. Am. J. 60:1705-1713.

Brandi-Dohrn, F. M., R. P. Dick, M. Hess, and J. S. Selker. 1996b. Suction cup sampler bias in leaching characterization of an undisturbed field soil. Water Resour. Res. 32(5)1173-1182.

Branscheid, V. O., and W. E. Hart. 1968. Predicting field distributions of a sprinkler system. Trans. ASAE 11(6):801-803, 808.

Brown, K. W., J. C. Thomas, and M. W. Holder. 1986. Development of a capillary wick unsaturated zone water sampler. Coop. Agreement CR812316-01-0. U. S. Environ. Protection Agency, Environ. Monit. Syst. Lab., Las Vegas, NV.

Briggs, L. J., and A. G. McCall. 1904. An artificial root for inducing capillary movement of soil moisture. Science (Washington, DC) 20:566-569.

Cambardella, C. A., T. B. Moorman, J. M. Novak, T. B. Parkin, D. L. Karlen, R. F. Turco, and A. E. Konopka. 1994. Field-scale variability of soil properties in central Iowa soils. Soil Sci. Soc. Am. J. 58:1501-1511.

Center for Irrigation Technology. 1996. Irrigation equipment performance index. Center for Irrigation Technology, California State University at Fresno. CATI Publ. 960801.

Chen, D., and W. W. Wallender. 1984. Economic sprinkler selection, spacing, and orientation. Trans. ASAE 27(3):737-743.

Christiansen, J. E. 1942. Irrigation by sprinkling. University of California, Berkeley. Agric. Exp. Stn. Bull. 670.

Cuenca, R. H. 1989. Irrigation system design – an engineering approach. Prentice-Hall, Englewood Cliffs, New Jersey. 552 p.

Doorenbos, J., and W. O. Pruitt. 1977. Crop water requirements. Food and Agriculture Organization of the United Nations, Irrigation and Drainage Paper no. 24, revised, Rome, Italy.

El Kayal, A. 1983. Evaluating the design and operation of irrigation canals in Egypt. M.S. Thesis, Department of Civil Engineering, Utah State University, Logan, UT.

Elliott, R. L., J. D. Nelson, J. C. Loftis, and W. E. Hart. 1980. Comparison of sprinkler uniformity models. J. Irrig. Drainage Div. ASCE 106(IR4):321-330.

Elrick, D. E., and W. D. Reynolds. 1992. Infiltration from constant head well permeameters and infiltrometers. p. 1-24. *In* G. C. Topp et al. (ed.) Advances in measurement of soil physical properties: Bringing theory into practice. SSSA Spec. Publ. 30. SSSA, Madison, WI.

England, C. B. 1974. Comments on "A technique using prorous cups for water sampling at any depth in the unsaturated zone" by Warren W. Wood. Water Resour. Res. 10(5):1049.

Fukui, Y., K. Nakanishi, and S. Okamura. 1980. Computer evaluation of sprinkler irrigation uniformity. Irrig. Sci. 2(1):23-32.

Gardner, W. R. 1958. Some steady-state solutions of the unsaturated moisture flow equations with application to evapotranspiration from a water table. Soil Sci. 4:228-232.

Gee, C. W., and J. W. Bauder. 1986. Particle-size analysis. p. 383-411. *In* A. Klute (ed.) Methods of soil analysis. Part 1. 2nd ed. Agron. Monogr. 9. ASA and SSA, Madison, WI.

Griffin, S. G. 1978. Computer programming solid set systems. ASAE Paper No. 78-2012, ASAE, St. Joseph, MI.

Hart, W. E. 1961. Overhead irrigation pattern parameters. Agricultural Engineering 42(7):354-355.

Hart, W. E. 1963. Sprinkler distribution analysis with a digital computer. Trans. ASAE 6(2):206-208.

Hart, W. E., and W. N. Reynolds. 1965. Analytical design of sprinkler systems. Trans. ASAE 7(4):83-85, 89.

Jemison, J. M., and R. H. Fox. 1992. Estimation of zero-tension pan lysimeters collection efficiency. Soil Sci. 154:85-94.

Jensen, M. E., R. D. Burman, and R. G. Allen. 1990. Evapotranspiration and irrigation water requirements. ASCE Manuals and Reports on Engineering Practice No. 70. ASCE: New York, NY. pp. 360.

Jordan, C. F. 1968. A simple, tension-free lysimeter. Soil Sci. 105(2):1-86.

Holder, M., K. W. Brown, J. C. Thomas, D. Zabcik, and H. E. Murray. 1991. Capillary-wick unsaturated zone soil pore water sampler. Soil Sci. Soc. Am. J. 55:1195-1202.

Knutson, J. H., S. B. Lee, W. Q. Zhang, and J. S. Selker. 1993. Fiberglass wick preparation for use in passive capillary wick soil pore-water samplers. Soil Sci. Soc. Am. J. 57:1474-1476.

Knutson, J. H., and J. S. Selker. 1994. Unsaturated hydraulic conductivities of fiberglass wicks and designing capillary wick pore-water samplers. Soil Sci. Soc. Am. J. 58:721-729.

Kung, K. –J. S. 1990. Preferential flow in a sandy vadose zone: 2. Mechanisms and implications. Geoderma 46:51-58.

Kung, K. –J. S., J. Boll, J. S. Selker, W. F. Ritter, and T. S. Steenhuis. 1991. Use of ground penetrating radar to improve water quality monitoring in the vadose zone. p. 142-149. *In* Proceedings of the national symposium on preferential flow. Chicago, IL. Dec. 16-17, 1991. ASAE, St. Joseph, MI.

Larson, L. W., and E. L. Peck. 1974. Accuracy of precipitation measurements for hydrologic modeling. Water Resour. Res. 10(4):857-863.

Li, J., and H. Kawano. 1996. Sprinkler rotation nonuniformity and water distribution. Trans. ASAE 39(6):2027-2031.

Magid, J., N. Christensen, and H. Nielsen. 1992. Measuring phosphorus fluxes through the root zone of a layered sandy soil: Comparisons between lysimeter and suction cell solution. J. Soil Sci 43:739-747.

Nderitu, S. M., and D. J. Hills. 1993. Sprinkler uniformity as affected by riser characteristics. Applied Engineering in Agriculture 9(6):515-521.

Oliphant, J. C. 1993. SPACE for Windows™. Software update. Center for Irrigation Technology, California State University at Fresno. CATI Publ. 930403.

Parker, J. C., and M. T. van Genuchten. 1984. Flux-averaged and volume-averaged concentrations in continuum approaches to solute transport. Water Resour. Res. 20(7)866-872.

Rice, R. C. and R. S. Bowman. 1988. Effect of sample size on parameter estimates in solute-transport experiments. Soil Sci. 146:2.

Rimmer, A., T. S. Steenhuis, J. S. Selker, and G. T. Albrecht. 1995. Wick samplers: an evaluation of solute travel times. Soil Sci. 159(4):235-243.

Ryan, P. K., and R. H. Cuenca. 1984. Feasibility and significance of revising consumptive use and net irrigation requirements for Oregon. Project completion report, Department of Agricultural Engineering, Oregon State University, Corvallis, OR.

Seginer, I., D. Kantz, D. Nir, and R. D. von Bernuth. 1992. Indoor measurement of single-radius sprinkler patterns. Trans. ASAE 35(2):523-533.

Seginer, I., and M. Kostrinsky. 1975. Wind, sprinkler patterns and system design. J. Irrig. Drainage Div. ASCE 101(IR4):251-264.

Seginer, I., D. Nir, and R. D. von Bernuth. 1991. Simulation of wind distorted sprinkler patterns. J. Irrig. Drainage Eng. ASCE 117(2):285-306.

Selker, J. S., J. –Y. Parlange, and T. Steenhuis. 1992. Fingered flow in two dimensions. 2. Predicting finger moisture profile. Water Resour. Res. 28(9):2523-2528.

Selker, J. S., J. K. Smesrud, and M. Hess. 1998. Western Oregon irrigation guide. Oregon State University Extension Service. *In press.*

Severson, R. C., and D. F. Grigal. 1976. Soil solution concentrations: Effect of extraction time using porous ceramic cups under constant tension. Water Resour. Bull. 12(6):1161-1171.

Shaffer, K. A., D. D. Fritton, and D. E. Baker. 1979. Drainage water sampling in a wet, dual-pore system. J. Environ. Qual. 8(2):241-246.

Topp, E., and W. Smith. 1992. Sorption of the herbicides atrazine and metolachlor to selected plastics and silicone rubber. J. Environ. Qual. 21:316-317.

Tseng, P. –H., M. Th. Van Genuchten, and W. A. Jury. 1995. Simulating the performance of a vacuum solution extraction device for measuring solute flux concentrations in field soils. *In* Proc. of IAHS/IUGG. Denver, CO. July, 1995. pp. 11.

U. S. Bureau of Reclamation. 1995. Agricultural crop water use summary 1988-1994. U. S. Bureau of Reclamation, Pacific Northwest Region, Boise, ID. 25 p.

U. S. Environmental Protection Agency. 1986. Permit guidance manual on unsaturated zone monitoring for hazardous waste treatment units. USEPA Doc. 530-SW-86-040. U. S. Gov. Print. Office, Washington DC.

van Genuchten, M. Th. 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J. 44:892-898.

van Genuchten, M. Th., F. J. Leij, and S. R. Yates. 1991. The RETC code for quantifying the hydraulic functions of unsaturated soils. U. S. Environ. Protection Agency Rep. 600/2-91/065. U. S. Environ. Protection Agency, Ada, OK. 85 p.

Vories, E. D., and R. D. von Bernuth. 1986. Single nozzle sprinkler performance in wind. Trans. ASAE 29(5):1325-1330.

Wright, J. L. 1982. New evapotranspiration crop coefficients. J. Irrig. Drainage Div. ASCE 108(IR2):57-74.

APPENDICES

Appendix A: Soil Properties

Particle size distribution of each soil series present at experimental sites.

		K_{sat}		
Soil	Depth	Clay	Silt	Sand
	(cm)	(%)	(%)	(%)
Awbrig silty clay loam	17	30	55	15
	70	53	27	20
	114	55	20	25
Chehalis silty clay loam	16	35	50	15
	86	30	55	15
	120	20	30	40
Cloquato silt loam	17	5	75	20
	65	10	65	25
	115	3	17	70
Coburg silty clay loam	20	38	20	42
	62	53	17	30
	118	20	30	50
Fluvents	15	2	12	41
(Dredging soils, significant gravel content)	68	3	15	40
Malabon silty clay loam	15	33	42	25
	67	37	43	20
	118	11	29	60
Newberg fine sandy loam	18	10	12	78
	46	5	34	61
	110	10	24	66
Newberg loam	18	15	40	45
	65	10	19	71
	108	13	6	81

Water Retention Parameters from van Genuchten (1980) RETC code

Site	Depth	Saturated Water Content[i]	Residual Water Content[ii]	α	n	R^2
	(cm)	$m^3 m^{-3}$	$m^3 m^{-3}$	cm^{-1}		
Organic #1	15	0.60	0.15	0.0401	2.171	0.89
	46	0.63	0.13	0.1665	2.187	0.96
Organic #2	15	0.49	0.15	0.0135	2.194	0.91
	46	0.49	0.18	0.0087	2.192	0.91
Peppermint #1	15	0.44	0.09	0.0252	2.212	0.93
	46	0.52	0.05	0.1903	2.216	0.86
Peppermint #3	15	0.43	0.14	0.0175	2.179	0.91
	46	0.53	0.12	0.0366	2.194	0.92
Peppermint #4	15	0.47	0.16	0.0084	2.192	0.86
	46	0.54	0.16	0.0175	2.168	0.82
Peppermint #5	15	0.46	0.13	0.0099	2.220	0.93
	46	0.45	0.17	0.0204	2.143	0.91
Peppermint #6	15	0.42	0.13	0.0230	2.182	0.88
	46	0.45	0.15	0.0397	2.160	0.77
Peppermint #7	15	0.49	0.11	0.0191	2.206	0.88
	46	0.45	0.18	0.0207	2.145	0.90
Peppermint #8	15	0.42	0.16	0.0124	2.169	0.91
	46	0.45	0.18	0.0207	2.145	0.90
Row Crop #1	15	0.47	0.16	0.0044	2.214	0.84
	46	0.52	0.09	0.0131	2.256	0.91
Row Crop #2	15	0.45	0.11	0.0102	2.232	0.90
	46	0.53	0.12	0.0103	2.245	0.93
Row Crop #3	15	0.52	0.16	0.0293	2.162	0.86
	46	0.51	0.17	0.0211	2.164	0.93
Row Crop #4	15	0.40	0.16	0.0051	2.216	0.96
	46	0.48	0.13	0.0133	2.213	0.92
Row Crop #5	15	0.46	0.18	0.0728	2.133	0.92
	46	0.48	0.20	0.1204	2.118	0.80
Row Crop #6	15	0.45	0.08	0.0234	2.220	0.86
	46	0.54	0.07	0.0224	2.262	0.90

i - Taken at 0.3 kPa tension.

ii - Taken at 1500 kPa tension and given a low weighting coefficient, since the goodness of fit in this region is of no concern.

Appendix B: Irrigation System Evaluation Data

Site #1 Side Roll
Existing Test Date: 6/25/97
Sprinkler Spacing: 12.2 m
Lateral Spacing: 18.3 m
Lateral Diameter: 10.2 cm

Modified Test Date: 8/21/97
Replacement Drive Nozzle Size: 4.37 mm
Replacement Spreader Nozzle Size: n/a

Sprinkler Model	Drive Nozzle Nominal Diameter (mm)	Drive Nozzle Actual Diameter (mm)	Spreader Nozzle Nominal Diameter (mm)	Spreader Nozzle Actual Diameter (mm)	Original Operating Pressure (kPa)	Original Sprinkler Outflow (L/s)	Modified Operating Pressure (kPa)	Modified Sprinkler Outflow (L/s)	Notes
Nelson F33	4.37	4.62	n/a	n/a	396	0.50	348	0.39	Line Source - North End of Field
Rain Bird 30H	4.37	4.50	n/a	n/a	400	0.47	341	0.38	
Rain Bird 30H	4.37	4.39	n/a	n/a	407	0.47	338	0.38	
Rain Bird 30H	4.37	4.50	n/a	n/a	410	0.47	334	0.37	
Rain Bird 30H	4.37	4.50	n/a	n/a	403	0.44	331	0.37	
Rain Bird 30H	4.37	4.50	n/a	n/a	396	0.48	328	0.37	
Rain Bird 30H	4.37	4.57	n/a	n/a	396	0.45	324	0.37	
Rain Bird 30H	4.37	4.50	n/a	n/a	396	0.46	324	0.37	
Rain Bird 30H	4.37	4.50	n/a	n/a	396	0.51	324	0.37	
Rain Bird 30H	4.37	4.57	n/a	n/a	393	0.47	321	0.37	
Rain Bird 30H	4.37	4.50	n/a	n/a	393	0.44	317	0.37	
Rain Bird 30WS	3.97	4.22	n/a	n/a	396	0.45	314	0.37	
Rain Bird 30WS	4.37	4.62	n/a	n/a	393	0.53	310	0.36	
Rain Bird 30C	4.37	4.70	n/a	n/a	393	0.53	307	0.36	
Rain Bird 30WS	4.37	4.62	n/a	n/a	393	0.50	307	0.36	
Rain Bird 30WS	4.37	4.62	n/a	n/a	396	0.51	303	0.36	
Rain Bird 30WS	4.37	4.62	n/a	n/a	400	0.53	303	0.36	
Rain Bird 30WS	4.37	4.57	n/a	n/a	400	0.53	303	0.36	
Walla Walla P35	4.37	4.39	n/a	n/a	400	0.44	300	0.36	Line End - South End of Field

Site #2 Hand Move
Existing Test Date: 6/25/97
Sprinkler Spacing: 12.2 m
Lateral Spacing: 18.3 m
Lateral Diameter: 7.6 cm

Modified Test Date: 8/21/97
Replacement Drive Nozzle Size: 4.37 mm
Replacement Spreader Nozzle Size: n/a

Sprinkler Model	Drive Nozzle Nominal Diameter	Drive Nozzle Actual Diameter	Spreader Nozzle Nominal Diameter	Spreader Nozzle Actual Diameter	Original Operating Pressure	Original Sprinkler Outflow	Modified Operating Pressure	Modified Sprinkler Outflow	Notes
	(mm)	(mm)	(mm)	(mm)	(kPa)	(L/s)	(kPa)	(L/s)	
Rain Bird 30	4.37	-	plugged off		403	0.46	362	0.21	Line Source - South End of Field
Rain Bird 30H	4.37	4.39	n/a	n/a	403	0.47	359	0.21	
Rain Bird 30H	4.37	4.39	n/a	n/a	403	0.46	359	0.21	
Rain Bird 30H	4.37	4.39	n/a	n/a	407	0.46	365	0.20	
Rain Bird 30WS	4.37	4.39	n/a	n/a	407	0.47	369	0.21	
Nelson F33	4.37	4.39	plugged off		410	0.47	369	0.19	
Rain Bird 30WS	4.37	4.50	n/a	n/a	410	0.48	369	0.21	
Rain Bird 30H	4.37	4.39	n/a	n/a	410	0.43	369	0.21	
Rain Bird 30H	4.37	4.39	n/a	n/a	403	0.43	372	0.21	
Rain Bird 30H	4.37	4.39	n/a	n/a	403	0.44	383	0.21	
Nelson F33	3.97	3.99	2.38	2.38	-	-	379	0.21	Line End - North end of Field

Site #3	Hand Move
Existing Test Date:	9/4/97
Sprinkler Spacing:	12.2 m
Lateral Spacing:	18.3 m
Lateral Diameter:	7.6 cm

Modified Test Date:	9/5/97
Replacement Drive Nozzle Size:	4.37 mm
Replacement Spreader Nozzle Size:	n/a

Sprinkler Model	Drive Nozzle Nominal Diameter (mm)	Drive Nozzle Actual Diameter (mm)	Spreader Nozzle Nominal Diameter (mm)	Spreader Nozzle Actual Diameter (mm)	Original Operating Pressure (kPa)	Original Sprinkler Outflow (L/s)	Modified Operating Pressure (kPa)	Modified Sprinkler Outflow (L/s)	Notes
Rain Bird 30H	4.37	4.39	n/a	n/a	286	0.38	317	0.38	Line End - West End of Field
Rain Bird 30H	5.16	5.22	n/a	n/a	286	0.55	317	0.37	
Rain Bird 30H	4.37	4.39	n/a	n/a	286	0.37	321	0.37	
Rain Bird 30H	4.37	4.39	n/a	n/a	286	0.39	317	0.37	
Rain Bird 30WS	4.37	4.39	n/a	n/a	286	0.40	314	0.37	
Rain Bird 30H	4.37	4.39	n/a	n/a	286	0.39	314	0.37	
Rain Bird 30H	4.37	4.39	n/a	n/a	290	0.39	314	0.37	
Rain Bird 30H	4.37	4.39	n/a	n/a	290	0.37	314	0.37	Line Source
Rain Bird 30	4.76	4.91	plugged off		290	0.44	314	0.37	Tail of Oscillator Cut-Off
Rain Bird 30	4.76	4.91	plugged off		283	0.48	314	0.37	
Rain Bird 30WS	4.37	4.50	n/a	n/a	279	0.42	314	0.37	
Rain Bird 30	4.76	4.91	plugged off		279	0.45	310	0.37	Tail of Oscillator Cut-Off
Rain Bird 30	4.37	4.50	plugged off		276	0.43	310	0.37	
Rain Bird 30H	4.37	4.39	n/a	n/a	272	0.38	303	0.36	
Rain Bird 30WS	4.37	4.39	n/a	n/a	272	0.40	303	0.36	
Rain Bird 30WS	4.37	4.39	n/a	n/a	272	0.40	303	0.36	
Rain Bird 30H	4.37	4.39	n/a	n/a	269	0.36	303	0.36	
Rain Bird 30H	4.37	4.39	n/a	n/a	265	0.33	296	0.32	
Rain Bird 30H	4.37	4.39	n/a	n/a	265	0.37	296	0.36	
Rain Bird 30H	4.37	4.39	n/a	n/a	265	0.36	296	0.37	
Rain Bird 30H	5.16	-	n/a	n/a	265	0.51	296	0.36	
Rain Bird 30H	4.37	4.39	n/a	n/a	265	0.37	296	0.36	
West Ag S2000	4.37	4.39	plugged off		269	0.35	293	0.36	Line End - East End of Field

Site #4 Side Roll
Existing Test Date: 8/18/97
Sprinkler Spacing: 12.2 m
Lateral Spacing: 18.3 m
Lateral Diameter: 11.4 cm

Modified Test Date: 9/3/97
Replacement Drive Nozzle Size: 4.76 mm
Replacement Spreader Nozzle Size: n/a

Sprinkler Model	Drive Nozzle Nominal Diameter	Drive Nozzle Actual Diameter	Spreader Nozzle Nominal Diameter	Spreader Nozzle Actual Diameter	Original Operating Pressure	Original Sprinkler Outflow	Modified Operating Pressure	Modified Sprinkler Outflow	Notes
	(mm)	(mm)	(mm)	(mm)	(kPa)	(L/s)	(kPa)	(L/s)	
Rain Bird 30H	4.76	4.76	n/a	n/a	365	0.48	359	0.48	Line Source - North End of Field
Rain Bird 30H	3.97	3.99	plugged off		359	0.32	352	0.47	
Rain Bird 30H	4.76	4.39	n/a	n/a	352	0.47	345	0.46	
Rain Bird 30H	4.76	4.76	n/a	n/a	348	0.47	345	0.46	
Rain Bird 30H	4.76	4.76	n/a	n/a	345	0.47	341	0.46	
Rain Bird 30H	4.76	4.76	n/a	n/a	345	0.47	341	0.46	
Rain Bird 30H	4.76	3.99	n/a	n/a	345	0.45	338	0.45	
Rain Bird 30H	4.76	4.76	n/a	n/a	341	0.45	338	0.43	
Rain Bird 30H	4.76	4.76	n/a	n/a	338	0.45	334	0.46	
Rain Bird 30H	4.76	4.76	n/a	n/a	338	0.45	334	0.45	
Rain Bird 30H	4.76	4.76	n/a	n/a	334	0.45	334	0.45	
Rain Bird 30H	4.76	4.76	n/a	n/a	331	0.45	334	0.46	
Rain Bird 30H	4.76	4.76	n/a	n/a	328	0.44	331	0.45	
Rain Bird 30H	4.76	4.76	n/a	n/a	324	0.44	328	0.45	
Rain Bird 30H	4.76	4.76	n/a	n/a	324	0.44	324	0.45	
Rain Bird 30H	4.76	4.76	n/a	n/a	321	0.44	324	0.44	
Rain Bird 30H	4.76	4.76	n/a	n/a	321	0.44	324	0.44	
Rain Bird 30H	4.76	4.76	n/a	n/a	321	0.44	321	0.44	
Rain Bird 30H	4.76	4.76	n/a	n/a	321	0.43	321	0.44	
Rain Bird 30H	4.76	4.76	n/a	n/a	321	0.43	317	0.44	
Rain Bird 30H	4.76	4.76	n/a	n/a	321	0.44	317	0.45	

Site #4 (continued)

Rain Bird 30H	4.76	4.76	n/a	n/a	321	0.44	314	0.44	
Rain Bird 30H	4.76	4.76	n/a	n/a	317	0.44	314	0.44	
Rain Bird 30H	4.76	4.76	n/a	n/a	317	0.44	314	0.43	
Rain Bird 30H	4.76	4.76	n/a	n/a	317	0.44	314	0.44	
Rain Bird 30H	4.76	4.76	n/a	n/a	317	0.44	314	0.43	
Rain Bird 30H	4.76	4.76	n/a	n/a	317	0.43	310	0.43	
Rain Bird 30H	4.76	4.76	n/a	n/a	317	0.44	310	0.44	
Rain Bird 30H	4.76	4.76	n/a	n/a	317	0.43	310	0.43	
Rain Bird 30H	4.76	4.76	plugged off		317	0.44	310	0.44	
Rain Bird 30H	4.76	4.76	n/a	n/a	314	0.43	310	0.43	
Rain Bird 30H	4.76	4.76	n/a	n/a	314	0.43	310	0.43	
Rain Bird 30H	4.76	4.76	n/a	n/a	314	0.43	310	0.43	
Rain Bird 30WSH	4.37	4.37	n/a	n/a	310	0.40	307	0.43	
Rain Bird 30H	3.97	3.97	n/a	n/a	310	0.31	307	0.43	
Rain Bird 30H	4.76	4.76	n/a	n/a	314	0.44	310	0.43	Line End - South End of Field

Site #5 Hand Move
Existing Test Date: 9/4/97
Sprinkler Spacing: 12.2 m
Lateral Spacing: 18.3 m
Lateral Diameter: 7.6 cm

Modified Test Date: 9/5/97
Replacement Drive Nozzle Size: 4.37 mm
Replacement Spreader Nozzle Size: n/a

Sprinkler Model	Drive Nozzle Nominal Diameter (mm)	Drive Nozzle Actual Diameter (mm)	Spreader Nozzle Nominal Diameter (mm)	Spreader Nozzle Actual Diameter (mm)	Original Operating Pressure (kPa)	Original Sprinkler Outflow (L/s)	Modified Operating Pressure (kPa)	Modified Sprinkler Outflow (L/s)	Notes
Rain Bird 30WS	4.76	4.91	n/a	n/a	290	0.50	317	0.37	Line Source - North End of Field
Rain Bird 30WS	5.56	-	n/a	n/a	283	0.62	314	0.37	
Rain Bird 30H	4.76	4.85	n/a	n/a	279	0.47	310	0.37	
Nelson F33	4.76	4.85	n/a	n/a	276	0.47	303	0.36	
Rain Bird 30H	3.97	4.09	n/a	n/a	272	0.28	303	0.36	
Rain Bird 30	4.76	4.91	plugged off		269	0.43	300	0.36	
Rain Bird 30H	4.37	4.39	n/a	n/a	269	0.37	300	0.36	
Rain Bird 30H	4.37	4.39	n/a	n/a	265	0.37	300	0.36	
Rain Bird 30	3.97	4.09	plugged off		262	0.30	296	0.36	
Rain Bird 30WS	4.37	4.57	n/a	n/a	255	0.40	293	0.35	
Rain Bird 30H	4.37	4.39	n/a	n/a	255	0.36	290	0.35	
Royal Coach 500467	4.76	4.91	n/a	n/a	259	0.46	290	0.35	
Rain Bird 30H	4.37	4.39	n/a	n/a	262	0.37	296	0.35	
Rain Bird 30H	4.37	4.39	n/a	n/a	262	0.36	300	0.36	
Rain Bird 30	4.76	4.91	plugged off		265	0.47	300	0.36	
Nelson F33	4.37	4.39	n/a	n/a	262	0.36	296	0.36	
Royal Coach 500312	4.76	4.98	plugged off		259	0.47	296	0.35	Line End - South End of Field

Site #6 Side Roll
Existing Test Date: 9/9/97
Sprinkler Spacing: 12.2 m
Lateral Spacing: 18.3 m
Lateral Diameter: 11.4 cm

Modified Test Date: 9/10/97
Replacement Drive Nozzle Size: 4.37 mm
Replacement Spreader Nozzle Size: n/a

Sprinkler Model	Drive Nozzle Nominal Diameter (mm)	Drive Nozzle Actual Diameter (mm)	Spreader Nozzle Nominal Diameter (mm)	Spreader Nozzle Actual Diameter (mm)	Original Operating Pressure (kPa)	Original Sprinkler Outflow (L/s)	Modified Operating Pressure (kPa)	Modified Sprinkler Outflow (L/s)	Notes
Rain Bird 30WS	4.76	4.85	n/a	n/a	303	0.48	221	0.30	Line Source - North End of Field
Rain Bird 30	4.37	4.39	n/a	n/a	303	0.37	217	0.30	
Rain Bird 30	4.37	4.39	plugged off		300	0.43	214	0.30	Tail of Oscillator Cut-Off
Rain Bird 30H	4.37	4.39	plugged off		300	0.37	214	0.30	
Rain Bird 30H	4.37	4.39	n/a	n/a	300	0.38	214	0.30	
Rain Bird 30H	4.37	4.57	n/a	n/a	300	0.39	214	0.31	
Rain Bird 30H	4.37	4.39	n/a	n/a	296	0.36	210	0.29	
Rain Bird 30H	4.37	4.39	n/a	n/a	296	0.41	210	0.30	
Rain Bird 30WS	4.76	4.85	n/a	n/a	296	0.44	210	0.30	
Rain Bird 30	4.37	4.39	plugged off		293	0.38	207	0.31	Tail of Oscillator Cut-Off
Rain Bird 30H	4.37	4.39	n/a	n/a	293	0.38	207	0.30	
Rain Bird 30	4.37	4.62	plugged off		293	0.40	207	0.30	
Rain Bird 30H	4.37	4.39	n/a	n/a	293	0.37	210	0.30	
Rain Bird 30	4.76	4.91	plugged off		290	0.47	210	0.30	
Rain Bird 30	4.37	4.57	plugged off		293	0.40	210	0.30	
Rain Bird 30H	4.37	4.39	n/a	n/a	296	0.38	207	0.29	
West Ag S2000	4.37	4.37	plugged off		296	0.37	207	0.30	
Rain Bird 30H	4.37	4.39	n/a	n/a	293	0.40	203	0.30	
Rain Bird 30WS	4.76	4.91	n/a	n/a	293	0.49	207	0.30	Line End - South End of Field

Site #7 Side Roll
Existing Test Date: 6/24/97
Sprinkler Spacing: 12.2 m
Lateral Spacing: 18.3 m
Lateral Diameter: 10.2 cm

Sprinkler Model	Drive Nozzle Nominal Diameter (mm)	Drive Nozzle Actual Diameter (mm)	Spreader Nozzle Nominal Diameter (mm)	Spreader Nozzle Actual Diameter (mm)	Original Operating Pressure (kPa)	Original Sprinkler Outflow (L/s)	Notes
Rain Bird 30WS	4.76	4.80	n/a	n/a	245	0.45	Line Source - West End of Field
Rain Bird 30WS	4.37	4.57	n/a	n/a	241	0.38	
Rain Bird 30WS	4.37	4.50	n/a	n/a	238	0.43	
Rain Bird 30WS	4.37	4.39	n/a	n/a	234	0.36	
Rain Bird 30WS	4.37	4.50	n/a	n/a	231	0.39	
Rain Bird 30WS	4.37	4.39	n/a	n/a	231	0.37	
Rain Bird 30WS	4.37	4.57	n/a	n/a	231	0.37	
Rain Bird 30WS	4.37	4.39	n/a	n/a	231	0.37	
Rain Bird 30WS	4.37	4.50	n/a	n/a	231	0.38	
Rain Bird 30WS	4.37	4.39	n/a	n/a	231	0.37	
Rain Bird 30WS	4.37	4.57	n/a	n/a	231	0.36	
Rain Bird 30WS	4.37	4.39	n/a	n/a	231	0.37	
Rain Bird 30WS	4.37	4.39	n/a	n/a	231	0.33	
Rain Bird 30WS	4.37	4.39	n/a	n/a	228	0.34	
Rain Bird 30WS	3.97	3.99	n/a	n/a	228	0.29	
Rain Bird 30WS	3.97	4.09	n/a	n/a	221	0.31	Tail of Oscillator Cut-Off
Weather Tec 1030	4.37	4.57	n/a	n/a	221	0.40	
Rain Bird 30WS	3.97	4.09	n/a	n/a	221	0.33	
Rain Bird 30WS	3.97	4.22	n/a	n/a	221	0.37	
Rain Bird 30WS	4.37	4.70	n/a	n/a	221	0.39	
Rain Bird 30WS	3.97	4.09	n/a	n/a	217	0.33	

Site #7 (continued)

Rain Bird 30	4.37	4.39	plugged off		207	0.34	Tail of Oscillator Cut-Off
Weather Tec 1030	3.97	4.09	2.38	2.44	200	0.38	
Rain Bird 30WS	4.37	4.39	n/a	n/a	207	0.39	
Rain Bird 30WS	4.37	4.39	n/a	n/a	207	0.37	
Rain Bird 30WS	4.37	4.57	n/a	n/a	207	0.38	
Rain Bird 30WS	3.97	4.09	n/a	n/a	207	0.34	
Rain Bird 30WS	4.37	4.39	n/a	n/a	207	0.37	
Rain Bird 30WS	4.37	4.57	n/a	n/a	207	0.33	
Weather Tec 1030	4.37	4.39	n/a	n/a	203	0.36	
Royal Coach 500212	3.97	4.09	plugged off		203	0.27	
Rain Bird 30WS	3.97	4.09	n/a	n/a	203	0.30	
Rain Bird 30WS	3.97	4.09	n/a	n/a	200	0.29	Line End - East End of Field

Site #8	Hand Move
Existing Test Date:	6/26/97
Sprinkler Spacing:	12.2 m
Lateral Spacing:	18.3 m
Lateral Diameter:	7.6 cm

Sprinkler Model	Drive Nozzle Nominal Diameter (mm)	Drive Nozzle Actual Diameter (mm)	Spreader Nozzle Nominal Diameter (mm)	Spreader Nozzle Actual Diameter (mm)	Original Operating Pressure (kPa)	Original Sprinkler Outflow (L/s)	Notes
Rain Bird 30	4.76	4.80	n/a	n/a	372	0.51	Line Source - South End of Field
Nelson F33	4.76	4.80	n/a	n/a	369	0.53	
Nelson F33	4.76	4.80	n/a	n/a	365	0.47	
Rain Bird 30WS	4.76	4.80	n/a	n/a	369	0.53	
Rain Bird 30	4.76	4.80	n/a	n/a	369	0.53	
Rain Bird 30WS	4.76	4.85	n/a	n/a	372	0.55	
Rain Bird 40B	4.76	4.85	n/a	n/a	372	0.51	
Rain Bird 40B	4.76	4.85	n/a	n/a	369	0.53	
Rain Bird 30	4.76	4.80	n/a	n/a	369	0.49	
Rain Bird 30H	4.76	4.80	n/a	n/a	372	0.51	
Rain Bird 30	4.76	4.85	n/a	n/a	372	0.55	
Rain Bird 30E	4.76	4.76	n/a	n/a	369	0.49	Line End - North End of Field

Site #9	Side Roll
Existing Test Date:	8/14/97
Sprinkler Spacing:	12.2 m
Lateral Spacing:	18.3 m
Lateral Diameter:	10.2 cm

Sprinkler Model	Drive Nozzle Nominal Diameter (mm)	Drive Nozzle Actual Diameter (mm)	Spreader Nozzle Nominal Diameter (mm)	Spreader Nozzle Actual Diameter (mm)	Original Operating Pressure (kPa)	Original Sprinkler Outflow (L/s)	Notes
Rain Bird 30	4.76	5.05	2.38	2.59	310	0.70	Line Source - South End of Field
Rain Bird 30	4.76	5.22	2.38	2.59	303	0.68	
Rain Bird 30	4.76	5.05	2.38	2.59	303	0.65	
Rain Bird 30	4.76	5.05	2.38	2.59	300	0.68	
Rain Bird 30	4.76	5.05	2.38	2.64	293	0.65	
Rain Bird 30	4.76	5.05	2.38	2.59	293	0.68	
Rain Bird 30	4.76	5.05	2.38	2.59	290	0.69	
Rain Bird 30	4.76	5.05	2.38	2.59	290	0.68	
Rain Bird 30	4.76	5.05	2.38	2.44	290	0.70	
Rain Bird 30	4.76	5.05	2.38	2.59	283	0.66	
Rain Bird 30	4.76	5.05	2.38	2.59	286	0.65	
Rain Bird 30	4.76	5.05	2.38	0.25	283	0.70	
Rain Bird 30	4.76	5.05	plugged off		286	0.50	
Rain Bird 30	4.76	5.05	2.38	2.59	286	0.68	
Nelson F33	4.76	4.98	n/a	n/a	286	0.49	
Nelson F33	4.76	4.98	n/a	n/a	286	0.53	
Rain Bird 30	4.76	5.05	2.38	2.49	286	0.69	
Rain Bird 30	4.76	5.05	2.38	2.59	286	0.68	
Rain Bird 30	4.76	4.98	2.38	2.59	283	0.64	
Rain Bird 30	4.76	5.05	2.38	0.25	283	0.68	
Rain Bird 30	4.76	5.05	2.38	0.25	283	0.66	

Site #9 (continued)

Rain Bird 30	4.76	5.05	2.38	2.64	283	0.68	
Rain Bird 30	4.76	5.05	2.38	2.59	279	0.66	
Rain Bird 30	4.76	5.05	2.38	2.64	283	0.63	
Rain Bird 30	4.76	4.91	2.38	2.38	286	0.61	
Rain Bird 30H	4.76	4.98	n/a	n/a	290	0.51	
Rain Bird 30WS	4.76	4.80	n/a	n/a	293	0.46	Line End - North End of Field

Site #10 Side Roll
Existing Test Date: 6/26/97
Sprinkler Spacing: 12.2 m
Lateral Spacing: 18.3 m
Lateral Diameter: 12.7 cm

Sprinkler Model	Drive Nozzle Nominal Diameter (mm)	Drive Nozzle Actual Diameter (mm)	Spreader Nozzle Nominal Diameter (mm)	Spreader Nozzle Actual Diameter (mm)	Original Operating Pressure (kPa)	Original Sprinkler Outflow (L/s)	Notes
Rain Bird 30	4.76	4.85	2.38	2.72	290	0.53	Line End - East End of Field
Rain Bird 30H	4.76	4.80	2.38	3.28	290	0.56	
Rain Bird 30H	4.37	4.50	2.38	3.28	290	0.55	
Rain Bird 30H	4.37	4.50	2.38	3.66	293	0.44	
Rain Bird 30H	4.37	4.50	2.38	3.05	290	0.51	
Rain Bird 30H	4.37	4.50	2.38	3.05	290	0.53	
Rain Bird 30	4.76	4.80	2.38	3.58	290	0.58	
Rain Bird 30H	4.37	4.50	2.38	3.28	293	0.53	
Rain Bird 30H	4.37	4.50	2.38	3.05	293	0.49	
Rain Bird 30	4.76	4.91	2.38	2.95	293	0.63	
Rain Bird 30H	4.37	4.50	2.38	3.58	296	0.55	
Rain Bird 30H	4.76	4.91	2.38	3.28	296	0.63	
Rain Bird 30H	4.76	4.91	2.38	3.28	296	0.60	
Rain Bird 30H	4.37	4.50	2.38	2.95	303	0.54	
Rain Bird 30H	4.37	4.50	2.38	3.05	310	0.54	
Rain Bird 30H	4.37	4.39	2.38	3.28	314	0.53	
Rain Bird 30H	4.37	4.50	2.38	3.28	317	0.55	
Rain Bird 30H	4.37	4.50	2.38	3.05	317	0.55	
Rain Bird 30H	4.37	4.50	2.38	3.45	321	0.56	
Nelson F33	4.76	4.76	2.38	2.82	321	0.55	
Nelson F33	4.76	4.80	2.38	3.05	321	0.57	

Site #10 (continued)

Nelson F33	4.76	4.80	2.38	2.87	321	0.57	
Nelson F33	4.76	4.76	2.38	2.82	321	0.55	
Nelson F33	4.76	4.80	2.38	3.58	328	0.57	Line Source
Nelson F33	4.76	4.76	2.38	2.95	321	0.57	
Nelson F33	4.76	4.80	2.38	2.87	317	0.56	
Nelson F33	4.76	4.80	2.38	2.79	321	0.56	
Nelson F33	4.76	4.80	2.38	3.05	321	0.56	
Nelson F33	4.76	4.80	2.38	2.95	321	0.55	
Nelson F33	4.76	4.76	2.38	2.82	317	0.57	
Rain Bird 30H	4.37	4.50	2.38	3.28	321	0.55	
Rain Bird 30H	4.37	4.50	2.38	3.28	321	0.56	
Rain Bird 30H	4.37	4.50	2.38	3.05	317	0.55	
Rain Bird 30H	4.37	4.50	2.38	2.95	317	0.57	
Rain Bird 30H	4.37	4.57	2.38	3.28	317	0.56	
Rain Bird 30H	4.37	4.50	2.38	2.95	317	0.53	
Rain Bird 30	4.76	4.91	2.38	2.95	310	0.66	
Rain Bird 30H	4.37	4.39	2.38	3.58	317	0.47	
Rain Bird 30H	4.37	4.50	2.38	2.95	307	0.53	
Rain Bird 30H	4.37	4.39	2.38	3.28	310	0.53	
Rain Bird 30H	4.37	4.50	2.38	2.95	310	0.55	
Rain Bird 30H	4.37	4.50	2.38	3.28	314	0.56	
Rain Bird 30H	4.37	4.57	2.38	3.28	317	0.56	
Rain Bird 30H	4.37	4.39	2.38	3.86	321	0.56	Line End - West End of Field

Site #11 Hand Move
Existing Test Date: 8/7/97
Sprinkler Spacing: 12.2 m
Lateral Spacing: 18.3 m
Lateral Diameter: 7.6 cm

Sprinkler Model	Drive Nozzle Nominal Diameter	Drive Nozzle Actual Diameter	Spreader Nozzle Nominal Diameter	Spreader Nozzle Actual Diameter	Original Operating Pressure	Original Sprinkler Outflow	Notes
	(mm)	(mm)	(mm)	(mm)	(kPa)	(L/s)	
Rain Bird 30H	4.37	-	n/a	n/a	234	0.35	Line Source - North End of Field
Rain Bird 30H	4.37	-	n/a	n/a	228	0.38	
Nelson F33	4.37	-	n/a	n/a	221	0.33	
Rain Bird 30H	4.37	-	n/a	n/a	207	0.30	
Rain Bird 30E	4.37	-	plugged off		207	0.34	
West Ag S2000	4.37	-	plugged off		210	0.32	
Rain Bird 30H	4.37	-	n/a	n/a	207	0.32	
Rain Bird 30	4.76	-	plugged off		200	0.42	
Rain Bird 30	4.76	-	plugged off		200	0.42	
Rain Bird 30H	4.37	-	n/a	n/a	193	0.32	
Rain Bird 30H	3.97	-	n/a	n/a	193	0.27	
Rain Bird 30H	4.37	-	n/a	n/a	190	0.32	
West Ag S2000	4.37	-	plugged off		186	0.32	
Rain Bird 30	4.37	-	plugged off		186	0.31	
West Ag S2000	4.37	-	plugged off		186	0.32	
Rain Bird 30WS	4.76	-	n/a	n/a	186	0.40	
Rain Bird 30H	4.76	-	n/a	n/a	186	0.38	
Rain Bird 30H	4.37	-	n/a	n/a	183	0.28	
West Ag S2000	-	-	n/a	n/a	186	0.30	
Rain Bird 30	4.76	-	plugged off		183	0.38	
Buckner 860	4.37	-	n/a	n/a	186	0.30	

Site #11 (continued)

Rain Bird 30WS	4.37	-	n/a	n/a	186	0.31	
Rain Bird 30	3.97	-	plugged off		193	0.30	
Rain Bird 30H	4.37	-	n/a	n/a	190	0.32	
Rain Bird 30H	-	-	n/a	n/a	190	0.27	Line End - South End of Field

Site #12 Hand Move
Existing Test Date: 8/7/97
Sprinkler Spacing: 12.2 m
Lateral Spacing: 18.3 m
Lateral Diameter: 7.6 cm

Sprinkler Model	Drive Nozzle Nominal Diameter	Drive Nozzle Actual Diameter	Spreader Nozzle Nominal Diameter	Spreader Nozzle Actual Diameter	Original Operating Pressure	Original Sprinkler Outflow	Notes
	(mm)	(mm)	(mm)	(mm)	(kPa)	(L/s)	
Weather Tec 10-30	4.37	-	plugged off		345	0.42	Line Source - East End of Field
Rain Bird 30WS	4.76	-	n/a	n/a	345	0.50	
Rain Bird 30WS	3.97	-	n/a	n/a	345	0.31	
Rain Bird 30WS	3.97	-	n/a	n/a	345	0.31	
Rain Bird 30H	4.37	-	n/a	n/a	345	0.38	
Rain Bird 30WS	4.37	-	n/a	n/a	341	0.40	
West Ag S2000	4.37	-	plugged off		338	0.40	
Rain Bird 30H	4.37	-	n/a	n/a	331	0.41	
Rain Bird 30H	4.37	-	n/a	n/a	328	0.43	
Rain Bird 30H	5.16	-	n/a	n/a	328	0.55	
Rain Bird 30WS	4.76	-	n/a	n/a	328	0.52	
Rain Bird 30H	4.37	-	n/a	n/a	328	0.40	
Rain Bird 30H	3.97	-	n/a	n/a	324	0.32	
Rain Bird 30H	3.97	-	n/a	n/a	338	0.32	Line End - West End of Field