University of Southern Queensland

Faculty of Health, Engineering & Sciences

UNIFORMITY PERFORMANCE OF NON-STANDARD OVERLAPPED CENTER PIVOT AND LATERAL MOVE SPRINKLERS

A dissertation submitted by

Mr Matthew J. Green

In fulfilment of the requirements of

Bachelor of Engineering Honours

November 2015

ABSTRACT

Irrigation efficiency is an important area of research for the irrigation industry across the world, to date part-circle sprinklers have not formed part of this research effort. The investigation into the uniformity performance of part-circle sprinkler will help to fill the knowledge gap. This project tested two of the most commonly used part-circle sprinklers under ideal laboratory conditions to assess their performance. Results show that the PC-S3000 model sprinkler performs very well and with some simple improvements could provide uniformity equal to that of a standard sprinkler. The PC-D3000 model was not as impressive with low levels of uniformity even when overlapped with other sprinklers. Modelling of the sprinkler test data determined the optimum orientation and spacing of each sprinkler combination of nozzle size and pressure setting based on a boomback setup of four sprinklers. Further modelling of the PC-S3000 using the test data that produced the best uniformity, revealed that five sprinklers orientated in a specific way provides the best coefficient of uniformity equal to 88.96%. The outcome of this project delivers a sprinkler layout that can be applied to new and existing irrigators and also recommends many areas of future work that needs to be carried out in the future.

University of Southern Queensland

Faculty of Health, Engineering & Science

ENG 4111/2 Research Project

Limitations of Use

The council of the University of Southern Queensland, its Faculty of Health, Engineering & Sciences, and the staff of the University of Southern Queensland, do not accept any responsibility for the truth, accuracy or completeness of material contained within or associated with this dissertation.

Persons using all or any part of this material do at their own risk, and not at the risk of the Counil of the University of Southern Queensland, its Facalty of Health, Engineering & Sciences or the staff at the University of Southern Queensland.

This dissertation reports an educational exercise and has no purpose or validity beyond this exercise. The sole purpose of the course pair entitled "Research Project" is to contribute to the overall education within the student's chosen degree progam. This document, the associated harware, software, drawings, and other material set out in the associated appendices should not be used for any other purpose. If they are so used, it is entirely at the risk of the user.

Dean

Faculty of Health, Engineering & Sciences

University of Southern Queensland

Faculty of Health, Engineering and Sciences

ENG4111/ENG4112 Research Project

Certification of Dissertation

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

Matthew Green

0061032766

ACKNOWLEDGEMENTS

This research was carried out under the principle supervision of Dr Joseph Foley. Without the knowledge and guidance of Dr Joseph Foley this dissertation would not have been possible to complete.

Appreciation is also due to Daniel Eising of the University of Southern Queensland faculty of Engineering for his assistance during the practical phase of this research.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Chapter 1 INTRODUCTION

1.1 Background

Up until approximately ten thousand years ago humans were hunters and gatherers, our ancestors would collect food from plants in the area and would hunt animals using primitive hunting tools. Only in the last ten thousand years have humans learnt to raise crops and tame animals (Mays, 2008). The earliest signs of water control for agricultural purposes were found in Egypt, northern Iraq and Syria (Mays, 2008). Since these early systems the human race has developed an understanding of plants and what is needed to produce food. The term irrigation comes from the Latin word for “moist” or “wet” in modern terms it is defined as the “replenishment of soil water storage in the plant root zone through methods other than natural precipitation” (International Comission on Irrigation and Drainage (ICID), 2012).

Irrigation in early times consisted of channel systems directing water to farm lands from streams, rivers or lakes. Over time these irrigation systems became more complicated giving more control over the water. These early ideas and innovations still form the basis of modern forms of irrigation particularly in third world countries, flood irrigation is the most common form of irrigation and has been around for thousands of years, it involves the application of water through one of three ways, level basin flooding, furrow or boarder strip surface irrigation (International Commission on Irrigation and Drainage (ICID), 2012). As technology has improved so too has the efficiency of modern irrigation, improvements have come about through the development of channel linings and rammed earth channels, but the biggest improvement came about with the invention pumps and sprinklers. The invention of the pump allowed for water to be moved quickly and efficiently around an area without major earthworks, this invention lead to the sprinkler which reduced the amount of water being lost to the environment through evapotranspiration and increased the production of irrigated crops.

As recently as 70 years ago major leaps in irrigation efficiency have been made, in the mid 1940's the centre pivot irrigator was developed by Frank Zybach (Ganzel, 2006) which revolutionised irrigation practices worldwide and continues to improve water efficiency and crop production. In June 1976 the *Scientific American* magazine said the centre pivot irrigator was "perhaps the most significant mechanical innovation in agriculture since the replacement of draft animals by the tractor" (Ganzel, 2006). Within 25 years of the first irrigator being sold there were ten thousand machines in operations in Nebraska alone, it was even said that United States astronauts could clearly pick out north-west Nebraska by the green crop circles spread across the land, this is a testament to how revolutionary these machines really were.

Since the invention of the centre pivot irrigator there have been many improvements made on the original design many around the sprinkler operation though the main structure remains the same. The original systems were high pressure units operating in the vicinity of 80 PSI using large impact sprinklers (Foley, n.d.), by the 1970's low pressure sprinklers had been developed reducing pressure requirements by half. The centre pivot system was later modified to move in a straight line, this is known as the lateral move irrigator.

The centre pivot irrigator was not introduced In Australia until the 1960's where it was quickly taken up by Victorian and South Australian produces particularly in the dairy industry. As technology improved and the lateral move irrigator was developed these machines have risen in popularity amongst broad acre farming enterprises as they have allowed for farming in 'strips' instead of 'circles'. This move from centre pivot to lateral move irrigators has seen a big increase in irrigated land particularly in the Murray – Darling basin, the nature of the lateral move machines is particularly favourable for crops such as cotton.

There have been many efforts by academics and industry leaders to improve on designs and management practices to better manage these machines and to improve the efficiency of water delivery to the crop. A major issue for these machines has always been water application on and around the towers that support the pipe superstructure and drive mechanisms. When the move from high impact sprinklers to low pressure emitters occurred these emitters where suspended below the main delivery pipes which caused issues with water intersecting the towers, which ultimately meant that water was being directed into the wheel tracks of the machine leading to problems with wheel bogging and the development of wheel ruts. The solution to this problem was called the 'part-circle sprinkler' it was designed so that the water would not intersect the tower or the wheel tracks there for eliminating the problems seen when using standard sprinklers.

Although these sprinklers in theory would eliminate the issues with towers they brought their own issues which still have not fully been understood, although these sprinklers where designed to fix an issue through poor implementation and lack of knowledge these sprinklers have not solved the problem. Over time the industry has developed methods to use these devices more accurately, some solutions include the use of boom backs and strategic positioning of emitters so that the wetted radius of the device does not intersect the tower. These methods of management are working to stop rutting and bogging of the machines but through lack of research the pattern of application is still relatively unknown and as a result there are still reductions of crop productivity of up to 10% in some cases (Senninger Irrigation Inc., 2010).

1.2 Research Aim

The aim of this research project is to take a critical look at the most commonly used part-circle irrigation emitters to determine how they perform under ideal conditions. The objective is to determine if there are any way to improve the application of water around the towers without developing issues with wheel rutting and bogging, this will be done through modelling the application patterns and manipulating the orientation and spacing of sprinklers to optimise water delivery to the crops. Particular importance will be placed on the outer edges of the application area in order to understand the exact performance of these devices around the outer edge of the application radius.

The finished product of this project will be a spacing design for a lateral move irrigator that will optimise the water delivery to crops within the desired area around the tower, this research will also shed light on the optimal working radius for these devices.

1.3 Dissertation Outline

Chapter 1

Chapter one is focused on the background of irrigation and touches briefly on some of the issues that are faced by operators using part-circle sprinklers. Section 1.2 explains the research aims of this project and highlights what this project is about.

Chapter 2

Is the results of a literature review on the topic of part circle sprinklers, and explains that there is very little literature on the performance of part-circle irrigation sprinklers in general and even less on their uniformity performance specifically.

Chapter 3

The methodology used during the testing phase of this project is explained in depth in this chapter. The pressure and nozzle combinations used are explained as well as how the data will be collected is explained and outlined in a simple and easy to understand way.

Chapter 4

Chapter four analyses the results of the testing, providing surface mesh and contour maps of the application depth data collected during testing, offering a visual representation of the uniformity of the device.

Chapter 5

Explains the model developed in MatLab and demonstrates the results of the modelling process undertaken. The first stage of modelling involves testing of all test data to determine the most uniform sprinkler, nozzle and pressure combination. The second stage takes the best sprinkler combination to optimise the layout design for the sprinkler and returns a design that is considered to be the best possible solution.

Chapter 6

This is the discussion chapter where all information presented is summarised and discussed, revealing some of the key issues and successes that came from this dissertation.

Chapter 7

Concludes the dissertation relating back to the research aim and describes if the aim was meet, and what future work may need to be completed to bridge the gap of knowledge identified in chapter 2.

(This page is intentionally blank)

Chapter 2 LITERATURE REVIEW

2.1 Part-Circle Sprinkler

2.1.1 Sprinkler models

The Australian Irrigation industry has two main suppliers of part-circle centre pivot and lateral move sprinklers. Nelson Irrigation (Nelson Irrigation, 2015) have the largest range of part-circle irrigation sprinklers with three options, two moving plate models and a static plate model. Senninger Irrigation (Senninger Irrigation, 2015) offers one model which is also a static plate sprinkler.

Figure 0:1 Nelson irrigation PC-D3000

Figure 0:2 Senninger irrigation LDN UP3

Figure 0:1 shows Nelson Irrigation's static plate model the PC-D3000, Figure 0:2 shows the LDN UP3 model sprinkler from Senninger irrigation. Both these are static plate type sprinklers, and both produce streamlets from the blue spray plate, to give a wetted radius of approximately 170°.

The part-circle sprinkler developed by Senninger irrigation is not often used as Senninger is known for their full circle i-Wob series standard sprinklers, and for this reason the LDN will not be tested as part of this project. The PC-D3000 on the other hand is the most commonly used part-circle static plate sprinkler on the Australian market and will be one of two sprinklers tested.

Figure 0:4 Nelson irrigation PC – S3000

Figure 0:3 Nelson irrigation PC-R3000

Figure 0:4 shows the spinning plate model PC-S3000 and Figure 0:4 Nelson irrigation PC – S3000Figure 0:3 is the PC-R3000 rotating plate model both developed by Nelson Irrigation, the difference between the two models are just in the design of the deflection plate. The rotating plate sprinkler is designed for systems operating in high wind areas, while the PC-S3000 is designed to deliver a gentle rain like droplet pattern. Both of these sprinklers are used on machines across the country, for this project the PC-S3000 was chosen as the second sprinkler to be tested.

2.1.2 Sprinkler specifications

The PC-D3000 and PC-S3000 model sprinklers were the two models chosen for testing, both of these devices use Nelson Irrigation's 3TN nozzle system which is used to modify the flow rate of the sprinkler, below is the manufacturer's specifications for the two sprinklers.

PC-D3000 – Static plate

Operating pressure: 10 – 20 PSI

Radius of application: 170 Degrees

Nozzle sizes range: #09 - #50

PC-S3000 – Moving plate

Operating Pressure: 10 – 20 PSI

Radius of application: 190 Degrees

Nozzle size range: #14 - #40

Nelson Irrigation Inc. manufacture both of the part-circle irrigation sprinklers chosen, the specifications listed above are available from their website (Nelson Irrigation , 2015). Each of the sprinklers has a recommended range at which the devices should be operated within. During the testing phase of the project the sprinklers will be tested across the whole range. For each sprinkler 5 3TN nozzles will be used, these nozzles are designed to regulate the volume of water passing through the sprinkler with a low number indicating low flow rates while high numbers mean high flow rate. At the same time as testing with different nozzle sizes, operating pressure will also be tested with each nozzle being tested at both 68.95 KPa or 10 PSI and secondly at 103.4 KPa or 15 PSI.

The reason for testing at different pressure settings is to determine if the sprinkler characteristics, mainly uniformity changes significantly between the different pressures. The application radius is also listed as it is needed for the methodology and will be a discussion point when analysing the results.

It is common on Australian centre pivot and lateral move irrigation machines to position these devices at one of a selection of standard heights above the crop, the most common heights above crops are 1.22 metres and 2.44 metres. The aim is to test each of the sprinklers at both of these heights to compare their uniformity performance and application patterns.

2.2 Wheel Rutting & Bogging

A significant problem with newly installed centre pivot and lateral move irrigation machines is wheel rutting and bogging. A 2011 survey of thirty growers in the Murray-darling basin indicated that 63% of the growers experienced this issue during operation (Wigginton, et al., 2011). Wheel tracks often develop into ruts as a result of excessive water application on the wheel tracks, and the compaction by the tower wheels tracking over the wet soil (Department of Primary Industries Victoria, 2006). As wheel ruts increase in depth over time wheels can slip and bog in the uneven ruts causing the machines fail safe system to engage shutting down the irrigator, regular disruptions from bogging means any labour savings achieved by installing the machine is quickly lost.

As these ruts get deeper they also put added stress on the drivetrains installed in the machines, the added stresses will increase wear on the components resulting in eventual failure (Department of Primary Industries Victoria, 2006) adding to costs of the machine but also lost production waiting for parts.

Several options are available for reducing the water applied to the wheel tracks this dissertation is focusing on part circle sprinklers which are a common solution for this problem. In a report released by Senninger irrigation states that there are several problems encountered while using part circle sprinklers. These issues mainly extend from applying the pressure of a full circle sprinkler to a half circle sprinkler resulting in twice the amount of water being applied to half the area, the increase in applied water has the danger of exceeding the soil infiltration rate and producing runoff, the excess water produced often impacts the wheel tracks (Senninger Irrigation Inc., 2010), recreating the issue of wheel rutting.

The issue of preventing wheel rutting has impacted on the ability for centre pivot and lateral move machines to uniformly irrigate the crops in the immediate vicinity of the towers, this is a significant issue for growers as it is estimated that a centre pivot machine that has approximately 9500 metres of wheel track, will lose 2.6 metres each side of the track due to lack of water which results in lower yields in these areas, this is very significant as this means a loss of approximately 10% of the total irrigated area (Senninger Irrigation Inc., 2010). This loss of crop yield costs growers thousands of dollars annually, this is why the research into this area is very important to the industry, if we can reduce the area of poor application around the towers without effecting wheel ruts this would be a major success for the industry as a whole.

2.3 Testing Standards

The International Organisation of Standardisation is the organisation responsible for developing a set of standards applicable to the testing and analysis of irrigation sprinklers. ISO 15886-3:2012 Agricultural irrigation equipment – Sprinklers – Part 3: Characterisation of distribution and test methods, is the standard that I will be utilising to conduct the testing. ISO 15886 – 3 sets out testing methods relating to indoor testing procedures for standard sprinklers but also contains an annex that touches on testing of part circle sprinklers.

I may also need to refer to ISO 11545 - 2009, Agricultural irrigation equipment – centre pivot and moving lateral irrigation machines with sprayer or sprinkler nozzles – Determination of uniformity of water distribution. I may refer to this international standard when determining the distribution and uniformity of each sprinkler, although this standard is more focused and concerned about testing in the field. Field testing is significantly different to 'lab' tests because you need to account for wind drift, evaporation and elevation of the property, hence why this standard will not be followed religiously.

2.4 Application Uniformity

There are two commonly used coefficients that describe the uniformity of irrigation systems, the first is the 'Distribution Uniformity (DU)' and 'Coefficient of Uniformity (Cu)' there are several different equations proposed for the coefficient of uniformity which will be looked at for this dissertation.

2.4.1 Coefficients of uniformity

Research into the area of irrigation testing the literature speaks about the different 'coefficients of uniformity' that can be used, in this section I will compare some of the methods used to quantify irrigation uniformity.

2.4.2 Heermann and Hein

In 1968 D. F. Heermann and P. R. Hein presented their work on the "performance characteristics of self-propelled centre pivot irrigation systems" which was published in the transactions of ASAE (Hein & Heermann, 1968). A major part of the work these men presented was the development of an equation that can be used to determine the coefficient of uniformity for a centre pivot irrigator. The original equation is shown below

Equation 1 – Heermann and Hein coefficient of uniformity equation

$$C_u = 100\left[1.0 - \frac{\sum\limits_{s} S_s \left| D_s - \frac{\sum\limits_{s} D_s S_s}{\sum\limits_{s} S_s} \right|}{\sum\limits_{s} D_s\, S_s}\right]$$

Equation 1 incorporates the distance from the centre of rotation (S_S) and the total depth of application from a sprinkler at distance S from the centre of rotation (D_S). The significance of this equation was that, the equation gave a weighting to sprinklers that are further from the centre of rotation as these sprinklers are required to have a higher application rate as the area of application increases with the larger radii. The Heermann and Hein coefficient of uniformity is still in use today although it has been refined slightly (Foley & Raine, 2001).

Equation 2 – Revised Heermann and Hein equation

$$C_u = 100\left[1.0 - \frac{\sum\limits_{s} S_s \left| D_s - \overline{D} \right|}{\sum\limits_{s} D_s S_s}\right]$$

This Coefficient is only suitable for use with centre pivot irrigation systems, but it is one of the most common ways of determining the coefficient of uniformity for those machines.

2.4.3 Marek, Undersander & Ebeling

In 1986 the American Society of Agricultural Engineers (ASAE) published "An Areal-Weighted Uniformity Coefficient for centre pivot irrigation Systems" which developed a new more sensitive uniformity coefficient for centre pivot irrigators (Marek, et al., 1986). The equation proposed is shown below

Equation 3 – Areal weighted uniformity coefficient equation

$$C_{WSD} = 100\left[1 - \frac{\sqrt{\dfrac{\sum^{N}\left[r_i x_i - \left(r_i \dfrac{\sum^{N} r_i x_i}{\sum^{N} r_i}\right)\right]^2}{N-1}}}{\dfrac{\sum^{N} r_i x_i}{N}}\right]$$

The work carried out by Marek *et al.* (1986) and also work later carried out by Bremond and Molle (1995) were all around the use of areal-weighted uniformity coefficients specifically for centre pivot machines (Foley & Raine, 2001). Both methods highlight deviations from the mean rather than mean deviations such as the equation presented by Heermann and Hein, The deviations from the mean methods are useful for highlighting areas of inefficiencies in the system such as blocked or poor performing sprinklers. Another drawback for these coefficients is that they are specifically formulated for centre pivot machines and there for cannot be applied to a lateral move irrigation system.

2.4.4 Christiansen coefficient

The Christiansen Coefficient of uniformity (CU) is one of the most common indicators of sprinkler uniformity (ISO 15886-3, 2012), it was first published in a bulletin (670) by the University of California in October 1942 (Christiansen, 1942). Where Christiansen presented his equation as shown below

Equation 4 – Christiansen coefficient of uniformity equation

$$C_u = 100\left(1.0 - \frac{\Sigma x}{mn}\right)$$

Where x is the deviation of individual observations from the mean value of m and n is the number of observations. “An absolutely uniform application is then represented by a uniformity coefficient of 100%; a less uniform application, by some lower percentage” (Christiansen, 1942). Recent publications have used a modified Christiansen coefficient equation that is easier to understand and calculate.

Equation 5 – Modified Christiansen coefficient

$$C_u = 100\left(1.0 - \frac{M}{\bar{x}}\right)$$

Where M is given as the mean absolute deviation of the applied water depths.

Equation 6 – Mean equation

$$M = \frac{\Sigma|x_i - \bar{x}|}{n}$$

$\bar{x}$ Is the mean applied depth, n is the number of measurements taken and x_i is the depth measurement at the place in question.

2.4.5 Industry standards

A generally accepted industry standard for irrigation coefficients of uniformity (CU) is that for modern irrigators the CU should not be less than 90% although it is stated that part-circle sprinklers have a lower CU. A review of centre pivot and lateral move irrigators conducted in 2011 states that the generally accepted standard is CU = 92% (Wigginton, et al., 2011). Other literature goes further to say that CU <70% is not acceptable on modern irrigation equipment, machines below 70% need to be fixed immediately.

2.4.6 Application uniformity summary

All of the methods presented for the calculation of a coefficient of uniformity other than Christiansen's coefficient are all specific to centre pivot irrigators making them not ideal for this project, for the most part this dissertation lateral move irrigators will be the focus. Many irrigation research papers state that they have used Christiansen's coefficient. ISO 15886 – 3 the standard for testing the uniformity of irrigation sprinklers also lists Christiansen's coefficient as one of the methods for determining uniformity. It is for this reason that for this project I will be using Christiansen uniformity coefficient to determine how uniform each sprinkler is, I will endeavour to develop a design that meets the industry standard of CU = 92% during the modelling section of this project.

2.5 Distribution uniformity

The distribution uniformity represents the spatial evenness of the applied water across an area (Howell, 2003). The distribution uniformity is an empirical index that is calculated as a ratio and expressed as a percentage. The percentage represents the mean of the lowest quarter of applied depth and the mean of the total applied depth (Foley & Raine, 2001).

Equation 7 Distribution uniformity equation

$$DU\ (\%) = \frac{\bar{x}_{lower\ quater}}{\bar{x}} * 100$$

The uniformity of application for irrigation sprinklers has traditionally been viewed as being acceptable if the distribution uniformity is calculated at anything greater than 75%. However recent literature from Bremond and Molle (1995), Heermann (1991) and others have suggested the DU below 90% for modern irrigators is unacceptable.

2.6 Application Rate

There are three measures of application rate that are used in the irrigation industry these being, Effective application rate (EAR), Average application rate (AAR) and Instantaneous application rate (IAR). Although these would be important in a field test of any irrigation machine, for this dissertation I will not be considering any of these indicators as they are irrelevant to the overall outcome of the dissertation. The application rate is also specific to the machine setup and operating conditions of the machine. This is irrelevant as the purpose of this research is to determine a generic spacing pattern for any irrigator.

2.7 Current Irrigation Research Topics

This section is designed to highlight the current popular research areas in the field of irrigation science. This section will also highlight areas where research into sprinkler performance can be beneficial to research efforts currently being undertaken. Topics that will be explored include assessment of wind drift effects on irrigation efficiency, droplet size effects, and areas of precision agriculture including site specific variable rate irrigation (SS – VRI) and the value of understanding the soil properties of an irrigated area.

2.7.1 Droplet size distribution

The droplet size from irrigation sprinklers are of interest for two reasons, the first is to do with the susceptibility of drops to wind drift, and the second is to do with the kinetic energy of droplets and the impact they have on the soil surface (Kohl & Deboer, 1984). Investigations into droplet sizes have shown that soil surface crusting and wind drift are two main problems which face irrigation. Wind drift is such a big issue separate research is being done to establish models and to develop methods for mitigation. The kinetic energy developed by larger drop sizes is of great concern to the industry as they will cause soil crusting which reduces the ability for water to penetrate the soil and will inevitably cause runoff (Kohl & Deboer, 1984). Since soil crusting is primarily determined by large drop sizes and the impact energy developed as a result (Kohl & Deboer, 1984), droplet research focuses on just the larger nozzle and sprinkler types including the course plates used to develop these drop sizes.

2.7.2 Wind drift research

Heavily related to droplet size is wind drift, which can have major impacts on irrigation performance. Small droplet sizes are highly susceptible to wind drift, and are linked to high levels of evaporation. Studies regarding wind drift and evaporation have noted that large droplet sizes exceeding 1.5 mm experience low evaporation less than 2% and that drops further to 1% for droplets exceeding 2.5 mm (Molle, et al., 2012). Droplets with a diameter lower than 1 mm with low inertia were exposed for longer and were found to evaporate completely (Molle, et al., 2012). It was found that 30 – 50% of losses were attributed to evaporation while the remaining 50 – 70% can be put down to wind drift pushing the droplets outside of the target zone.

2.7.3 Site specific variable rate application

A major part of the literature available for irrigation is not directed at sprinkler uniformity but rather the application uniformity to the soil, it is widely accepted that irrigation efficiency will be gained through spatially varied irrigation techniques. A study carried out in Germany in 2004 (Al-Kufaishi, et al., 2005) compared Variable Rate Application to Uniform Application testing each at 20, 30 and 40 mm application depths. The study concluded that variable rate application based on soil properties was more efficient at using the water applied, while uniform application lead to higher water losses because of over application of low water storage capacity soils. The study conducted took into account the water storage capacity of the soils and adapted the application rate to the soil types in an effort to reduce water stress on the crops or anaerobic soil conditions (Al-Kufaishi, et al., 2005).

Site specific variable rate irrigation (SS-VRI) technologies are said to be one possible solution for dealing with reducing water availability (Evans, et al., 2013) on farms worldwide. SS – VRI is particularly adaptable to centre pivot and lateral move irrigators due to their high level of automation (Evans, et al., 2013), the types of sprinklers used in these systems include the spinner and static plate sprinklers assessed in this dissertation. The SS – VRI systems are operated to return the average water used by the crops over the past few days as uniformly as possible across the whole field (Evans, et al., 2013), for this system to operate effectively it is important that the sprinklers are managed correctly.

The research being carried out as part of this dissertation will be valuable to the development of SS – VRI systems as it will clearly indicate how part circle sprinklers perform. If the performance of all sprinklers are known it will add another layer of precision increasing the ability to develop precision irrigation practices, increasing crop production with lower water resources.

2.8 Research Summary

It was clear from the literature review undertaken that research in the area of irrigation is focused on developing higher crop yields through precision agriculture. Many other studies are concerned with wind drift and droplet size distributions and how these can be managed on farm to develop higher efficiencies for the conditions in which these machines and devices are operating. The research that I have done has revealed very little on the analysis of irrigation sprinklers as a whole. This may be because it is assumed in industry that all sprinklers, particularly full circle sprinklers work effectively distributing water evenly across 360 degrees.

It was obvious to me after conducting my research into part-circle irrigation sprinklers, that there is very little to no research into the performance of part-circle sprinklers. It is clear that for the industry to utilise these devices correctly then testing and analysis of these devices must take place to improve the usage and efficiencies of these devices in the field. By conducting an in depth analysis of part-circle irrigation sprinkler performance we will be able to better implement strategies for reducing wind drift and evaporation. Much of the current research in the area of irrigation is targeted at getting more from the water currently being used, the information gathered as part of this research will help gain the greater efficiencies the industry is seeking.

Chapter 3 METHODOLOGY

3.1 Objective

The purpose of the testing was to gain insight into the operational characteristics of the two most commonly used part circle centre pivot and lateral move irrigation sprinklers within Australia. This data was then analysed to make recommendations as to how these sprinklers can be more effectively used in the field.

3.2 Outline

The two sprinklers being tested are the Nelson 'spinning plate' style part-circle sprinkler (PC-S3000) and the Nelson 'static plate' part-circle sprinkler (PC-D3000). Five different size 3TN nozzles were selected from the range specified in the manufacturer's specifications for each sprinkler, three low to medium flowrate nozzles will be tested at pressures of 68.95 KPa (10 Psi) and 103.4 KPa (15 Psi) while two high flowrate nozzles will be only tested at 68.95 KPA (10 PSI), the reasons for not conducting a full range of tests using the high flow nozzles will be discussed in a later section. A radial grid was laid out in an open area at approximately 10° increments with a spacing of 0.5 metres, out to a maximum radii of 6.5 meters. At each intersection of the grid a catch can was placed to collect water during the test. The catch cans were then weighed and the weight was converted to millimetres per hour for analysis.

3.3 Resource Requirements

3.3.1 Sprinkler water supply

- 1x 20 mm (female – female) poly elbow
- 1x 20 mm (male – female) poly elbow
- 1x 20 mm rigid poly dropper (450mm long)
- 1x 20 mm poly Tee
- 1x poly reducer 20mm – 8 mm
- 1x 206.85 KPa (30 PSI) pressure gauge
- 1x 20 mm 3 TN nozzle adapter
- 2x Brass ball valve
- 1x 20 mm male threaded joiner
- 1x Thread Tape

Figure 3:1 Sprinkler test setup

These parts are used to develop the testing rig shown in Figure 3:1. Assorted other poly fittings were used to connect to the water supply at the facility, the parts listed above were used to build the system shown. A pump was also used if the flowrate from the mains supply was too low to supply the pressure required to run the test.

3.3.2 Test requirements

- Stop watch
- Thermometer
- Scales accurate to 1 gram
- 450 x 750 mL containers
- Marking tape (Duct Tape)
- 10 Litre bucket
- Tie wire (to mount system to rig)
- PC – S3000 sprinkler & selected nozzle sizes
- PC – D3000 Sprinkler & selected nozzle sizes

A stand was built using timber to support the systems and mount it at the required 1.2 meters, the stand also has the ability to position the sprinkler at 2.44 metres if required.

3.4 Preliminary Test Setup

3.4.1 Building test rig and water supply system

When building the sprinkler and water delivery system it is important to use thread tape to eliminate any water leaks occurring during testing. Once the rig has been setup and the sprinkler system is built measure 1.22 metres from the top of the catch cans to the base of the sprinkler head and mount the sprinkler setup in the correct location. To mount the sprinkler light gauge wire or tie wire was used to secure the device in place this allowed for easy adjustments, other options could include pipe saddles or zip ties. It is important to mount the sprinkler away from the main upright this serves two purposes the first is that it reduces interference meaning no water will impact the upright member, and the second reason is that it allows for the sprinklers to be changed quickly and easily.

An optional extra when testing is the use of a second valve which was used and was found to be very useful. The reason for the second valve is that you can open the second valve completely and then adjust the valve closest to the sprinkler until the required pressure is reached, once this has been done turn the second valve completely off which will stop the water flow, while the valve at the sprinkler will remain in the set position. When it comes to conducting the test the second valve can be opened and the system will then be calibrated for the required pressure, this eliminates the issue of having to make large adjustments to the pressure during the test.

3.4.2 Test area

This process is critical to the success of the testing and has a large impact on the quality of the data produced. For the testing carried out as part of this project and due to the nature of the devices being tested a radial grid catch can layout was used. The grid was dictated heavily by the PC-D3000 static plate device as this device produced individual streamlets from the spray head. This meant that if the catch cans were not in the correct position they would not collect any data. So for this reason the grid I developed was projecting out from the device were 210° semi circles spaced 0.5 metres apart up to 6.5 metres from the sprinklers position. A catch can was placed every 10° of arc on each radii. Although this system worked there are some improvements that needed to be made which are spoken about in Chapter 6.

It should be noted due to the characteristics of these devices, only 170° of area was used for the static plate device, while the spinning plate sprinkler used all of the area (and a bit more). Further to that not every test required the full 6.5 metre radius. The number of catch cans used was dependant on how far the device was throwing the water from the centre.

3.4.3 Catch Can labelling

When conducting the testing I used a combined total of 450 catch cans, this was broken up into two sets where they are marked with a specific code that described its position on the grid. This is an important aspect for collecting the catch cans at the conclusion of a test as it allowed for a tests set of catch cans to be collected and weighed while another test is being conducted using the second set of catch cans. If you don’t develop a system for tracking where the containers came from then you will not be able to conduct any testing.

The system I used involved three parts, the first part of the code relates to the angle made from a right angle to the sprinkler i.e. 1 relates to 0 degrees, a right angle to the sprinkler on the right hand side, while 18 is the opposite side or 180° from the right hand side (0 degrees). The second part of the code is a letter which relates to which radial distance the container belonged to i.e. letter ‘A’ relates to 0.5 metres from the sprinkler while letter ‘L’ relates to 6 metres from the sprinkler. The third part of the code simply relates to the set it belongs to.

If the catch can code for example is ‘10C1’ this can is positioned 90° from 0 (right angle to sprinkler on right hand side) or directly in front of the sprinkler (10) and is a radial distance of 1.5 metres from the sprinkler (C) and the can belongs to the first set of catch cans (1). Using this system allowed me to keep track of exactly where each can was. It is vital to the success of this system though that each can is placed in the correct position every time as not to confuse where the container came from.

3.5 Testing Procedure

3.5.1 Testing schedule

Before physical testing can be carried out a plan must be developed which includes how the test will be conducted, which variables will be tested and the conditions of the test outlined. As stated earlier there will be a total of eight tests carried out for each sprinkler, these tests are shown in Table 3:1.

Table 3:1 Sprinkler tests

PC - S3000 Spinning Plate Sprinkler					PC - D3000 Static Plate Sprinkler				
Test No.	**3TN Nozzle**		**Operating Pressure**		**Test No.**	**3TN Nozzle**		**Operating Pressure**	
	Number	**Orifice Dia. (mm)**	**KPa**	**PSI**		**Number**	**Orifice Dia. (mm)**	**KPa**	**PSI**
1	#14	2.78	68.95	10	**1**	#09	1.79	68.95	10
2	#14	2.78	103.4	15	**2**	#09	1.79	103.4	15
3	#20	3.97	68.95	10	**3**	#20	3.97	68.95	10
4	#20	3.97	103.4	15	**4**	#20	3.97	103.4	15
5	#28	5.56	68.95	10	**5**	#30	5.95	68.95	10
6	#28	5.56	103.4	15	**6**	#30	5.95	103.4	15
7	#34	6.75	68.95	10	**7**	#40	7.94	68.95	10
8	#40	7.94	68.95	10	**8**	#50	7.94	68.95	10

The two sprinklers selected were shown to be the most common part – circle sprinklers used on lateral move and centre pivot irrigation machines in Australia.

The nozzle sizes were determined from manufactures specifications, i.e. biggest and smallest recommended nozzles and three chosen at equal intervals between the two extremes. The photos below show the nozzles used during testing.

Figure 3:2 Nozzles used for the spinning plate tests

Figure 3:3 Nozzles used during the static plate test

3.5.2 Test length

Ideally each test should be carried out for one hour this allows for a good representation of how the device works and gives the device time to stabilise to increase the accuracy of the data. In the case of this research time was a major constraint and as a result the decision was made to conduct each test for only half an hour, although this is shorter than the recommended time I was able to verify that no change to the sprinkler discharge occurred after 2-3 minutes indicating that the sprinkler had stabilised giving solid data on its performance.

3.5.3 Testing record

in order to record the weights of the containers used an excel spreadsheet was developed and printed out, this allowed for a hard copy of the data to be filled out at the facility where the testing was carried out, this was then transferred back to the spreadsheet to form a digital copy of the collected data. To complement the recorded weights, photos were also taken as part of the recording process.

3.5.4 Testing procedure

The following is a step by step guide to conducting a test, this process is just replicated for each test, and making sure the preliminary setup was conducted before each new test.

1. Select the nozzle size and corresponding sprinkler head and connect it to the rig setup, making sure that the sprinkler is pointing in the correct direction.

2. Turn on the water and calibrate the system using the valves until the correct pressure is reached, then shut off the water using the second valve. Make sure to note where the water is falling in your grid so the catch cans can be placed in the correct positions.

3. Place out the catch cans in the grid pattern chosen, making sure that each can is in its designated position.

4. Turn on the water and start the timer (30 min test). Make sure to regularly check the pressure gauge to make sure nothing has changed.

5. Take a measurement of the temperature at the beginning and end of the test, and record this with the weight data.

6. While the test is being conducted make observations on how the sprinkler is performing visually and take photos.

7. Once 30 minutes had passed turn off the water and collect all of the catch cans.

8. Using a set of scales record the weight of each container and record it on your sheet making sure to enter the data in the correct grid position relating to the position of the catch can in the grid.

Once the test has been conducted, to speed up the process the catch cans can be placed off to the side away from the sprinklers wetted area. When this is done start at step one again and while the test is underway you can weigh the previous tests samples.

(This page is intentionally blank)

Chapter 4 RESULTS & ANALYSIS

Chapter 4 of the dissertation discusses the results from the practical testing carried out as part of this project. Appendix B provides an example of the data collected from each sprinkler in the form of raw tabulated data. Chapter 4 portraits the test data in a three dimensional surface plot making it easy to visualise the application pattern developed under the part-circle irrigation sprinkler in question (sprinkler is located at the (0,0) coordinate of each figure). All tests were conducted at a height of 1.22 metres from the sprinkler plate to the top of the catch cans.

4.1 PC – S3000 Part-circle sprinkler results

Chapter 3 indicated that each of the two sprinkler tested would be subjected to eight tests each, Table 4:1 show the pressure and nozzle combination selected for each test. The table also indicates a test number assigned to each combination, the test number will be what is used to identify each set of data.

Table 4:1 PC-S3000 Test table

PC – S3000 Part-circle Testing

Test No.	3TN Nozzle		Operating Pressure	
	Number	Orifice Dia. (mm)	KPa	PSI
1	#14	2.78	68.95	10
2	#14	2.78	103.4	15
3	#20	3.97	68.95	10
4	#20	3.97	103.4	15
5	#28	5.56	68.95	10
6	#28	5.56	103.4	15
7	#34	6.75	68.95	10
8	#40	7.94	68.95	10

Each of these tests were carried out under laboratory conditions which eliminated the risk of evaporation and wind drift losses during testing, the temperature of the test environment was also recorded before and after each test, this was found to have no impact on the testing as the temperature never rose more than 1°C during a testing period.

4.1.1 Test 1

Test 1 uses the smallest 3TN nozzle recommended for the PC-S3000 model part-circle sprinkler operating at the lowest recommended pressure of 68.95 KPa (10 PSI).

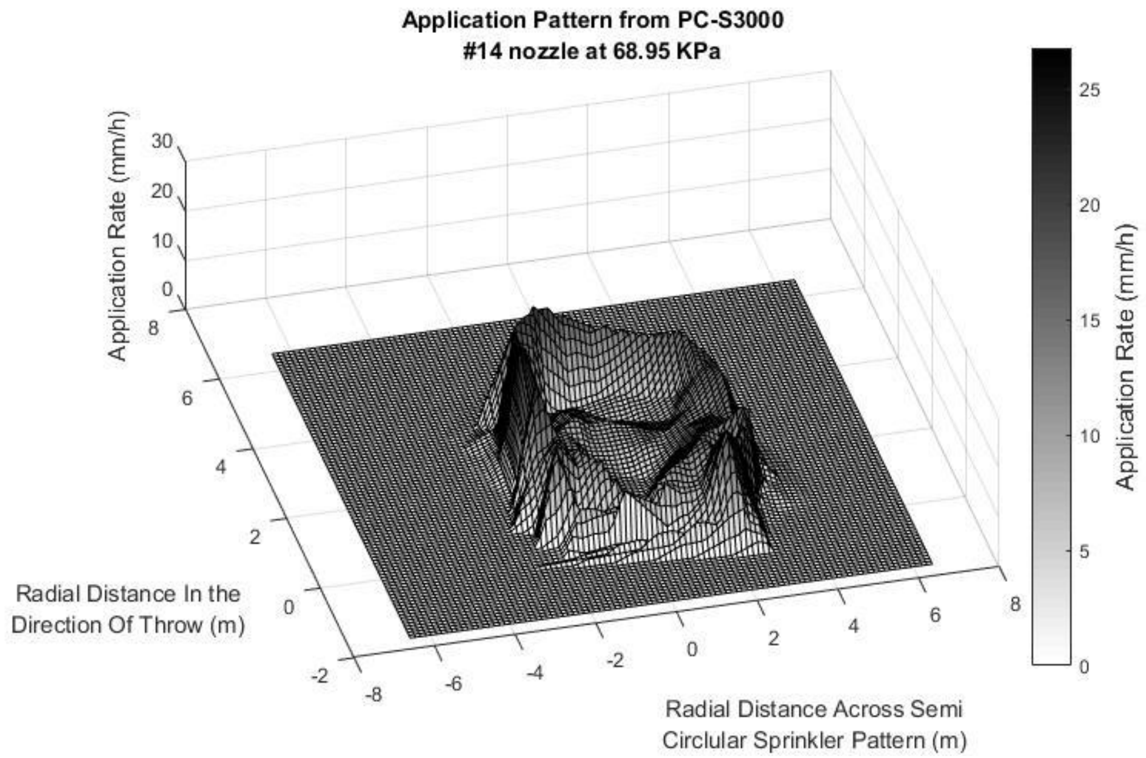

Figure 4:1 Test 1 – Application surface

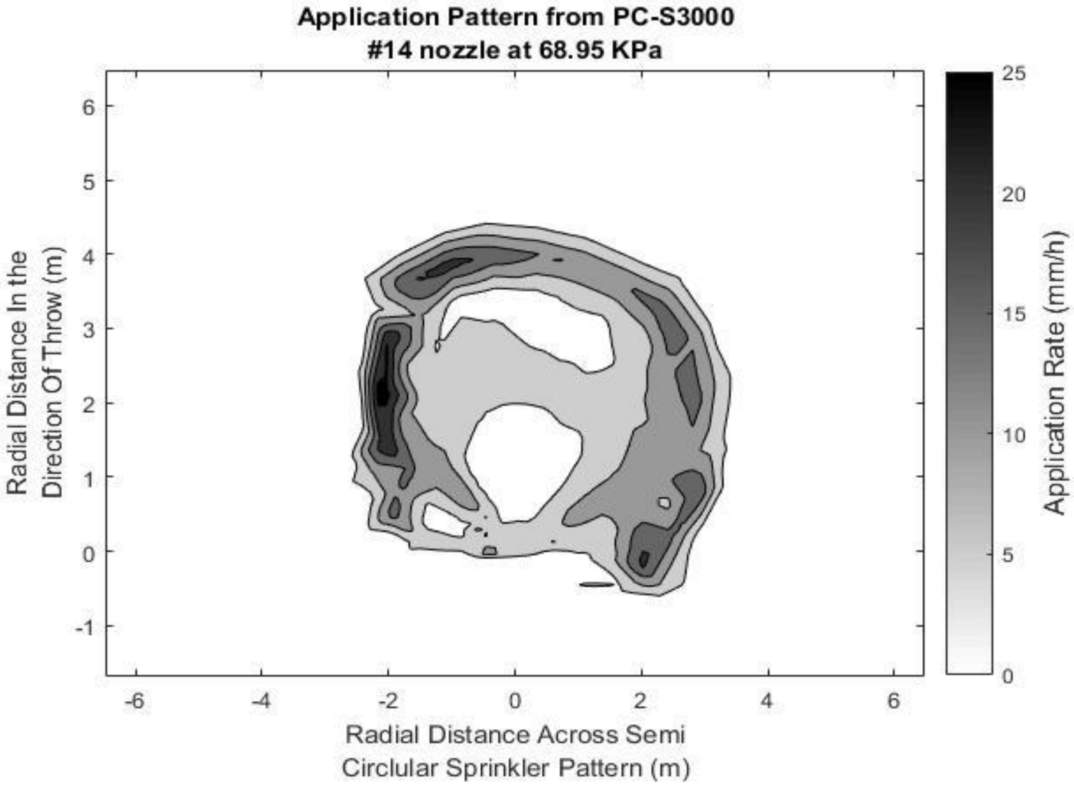

Figure 4:2 Test 1 – Application contour

During the testing of this sprinkler combination it was found that unlike the manufacturer's product specifications the PC-S3000 has a wider application area than the 190° stated, during testing of this device application depths were recorded within a 210° radius. This sprinkler also produced a band of high application depth which is evident in Figure 4:2 indicated by the darker areas of the applied depth contour map. Both Figure 4:1 and Figure 4:2 show that the sprinkler does not apply water in a perfectly circular pattern. Directly in front of the device a throw radius of 4.5 metres could be seen, while to the side of the sprinkler the throw radius reduced down to between 4 – 4.5 metres on the right hand side and 2.5 – 3 metres on the left hand side revealing an inconsistency with the application radius across the wetted perimeter. Due to the design of the sprinklers there was a significant amount of water that fell directly under the sprinkler head, this was recorded to be 69.80 mm/h.

4.1.2 Test 2

Test 2 again used the smallest recommended 3TN nozzle, although conducted the test at a higher pressure of 103.4 KPa (15 PSI).

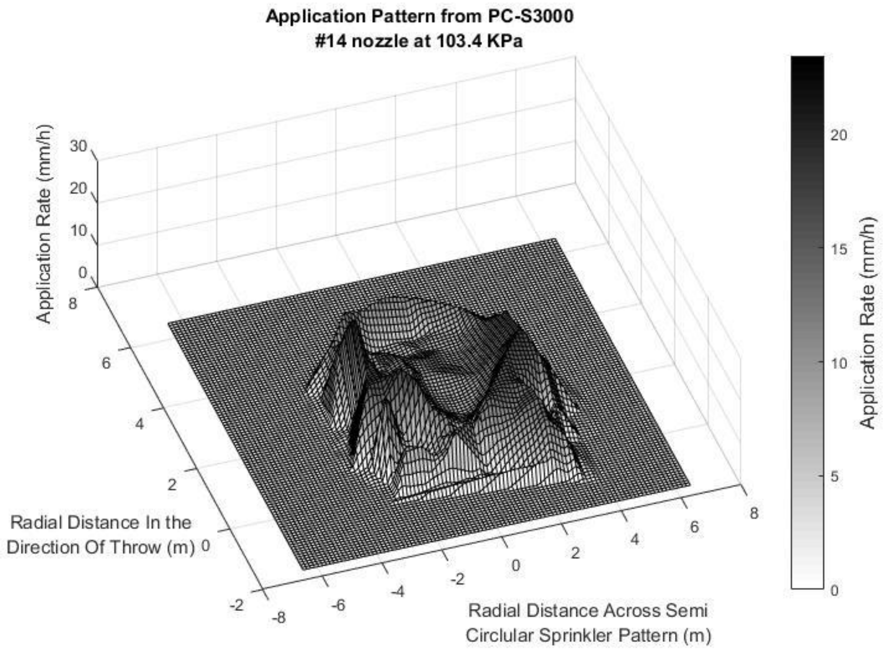

Figure 4:3 Test 2 – Application surface

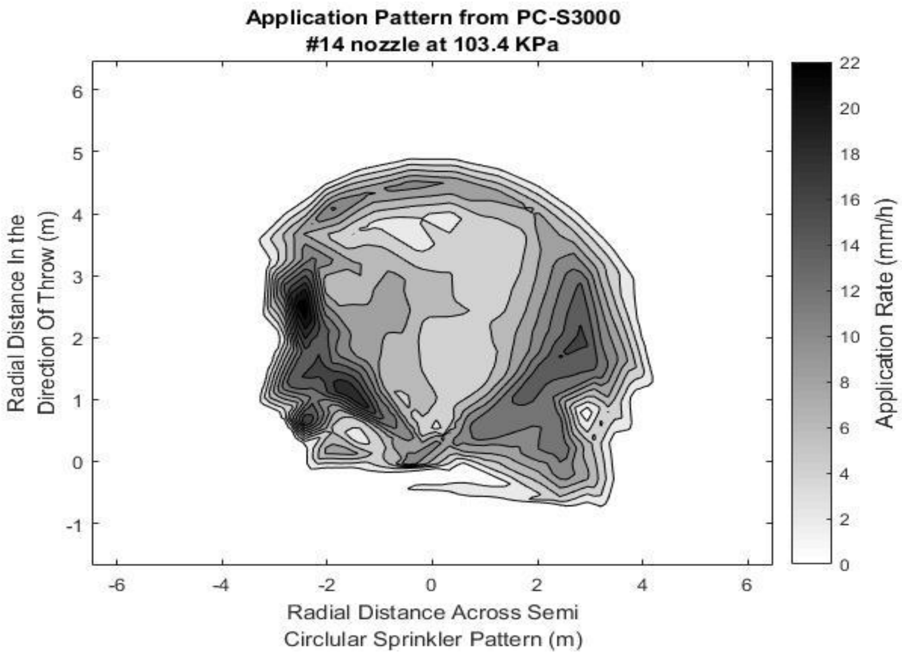

Figure 4:4 Test 2 – Application contour

A consistent trait of these sprinklers throughout all of the testing of the PC-S3000 part-circle sprinkler was that the application radius of the device was 210° opposed to the 190° suggested by the manufacturer of the part-circle sprinkler. From

Figure 4:4 we can see a high variance of application depths across the wetted area, there are also bands of high application shown by the darker colours. The contour map shows that there is an area in the centre of the wetted area that does not get consistent high application rates which has implications for uniformity and crop yields. The increase in pressure has also yielded a larger throw radius directly in front of the device increasing to 5 metres.

Figure 4:4 indicates that there is an inconsistency between application radii on the left and right hand sides, it is unknown why this has developed. On the right hand side of the sprinkler the applied radii is between 4 - 4.5 metres while on the left hand side, application depths were only recorded out to a radius of 2.5 - 3 metres. With the increase in pressure came an increase in the water depth under the sprinkler, 82.96 mm/h was recorded under the sprinkler head.

4.1.3 Test 3

Test 3 is the first test to use the #20 3TN nozzle, this nozzle/sprinkler combination was run at 68.95 KPa (10 PSI) at 1.22 metres above the catch cans.

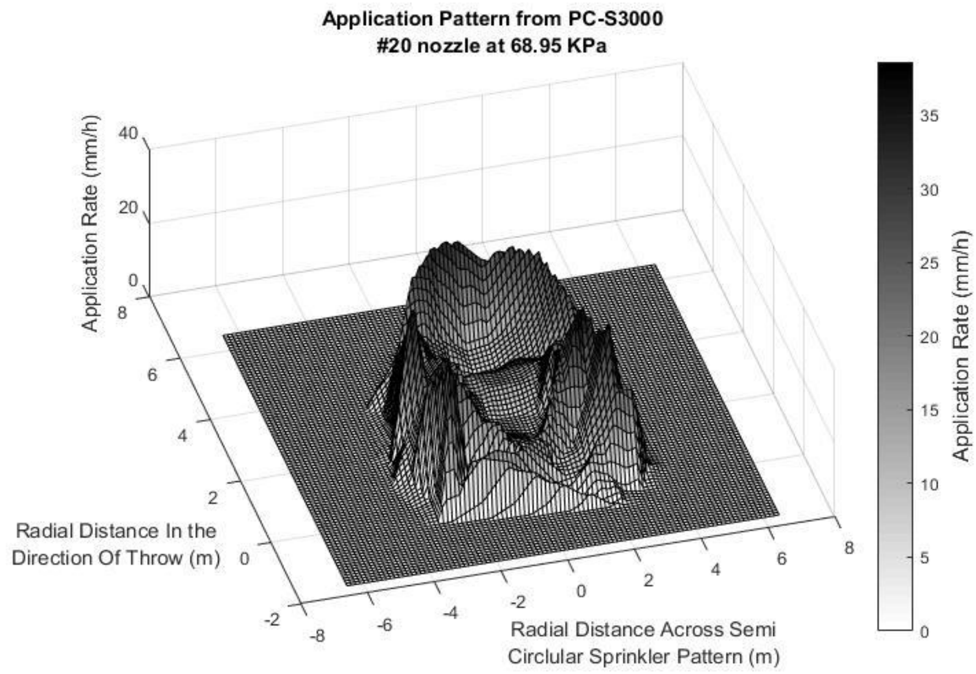

Figure 4:5 Test 3 – Application surface

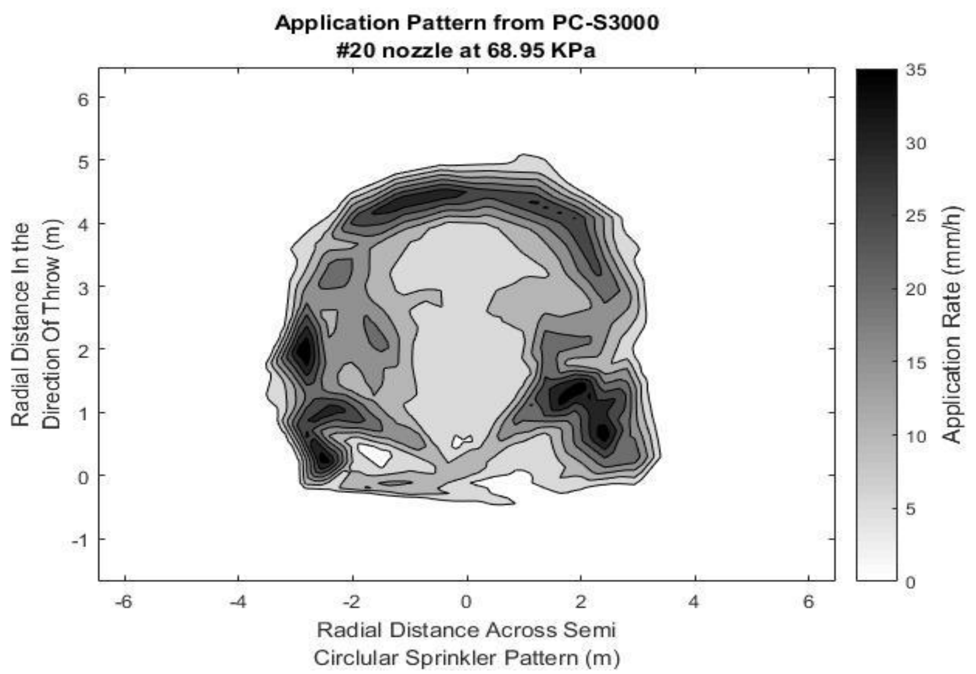

Figure 4:6 Test 3 – Application contour

The larger nozzle size increases the application volume while maintaining the low pressure of 68.95 KPa, the same application characteristics are visible here, and the wider application radius and high application banding are all present in this test as with the previous tests. The application radius in front of the sprinkler is around 5 metres, the issues with inconstant application radii on the right and left hand sides is not an issue with this combination with an application radius of 3 – 4 metres on both sides of the part-circle sprinkler. 92.63 mm/h was the recorded applied depth of water under the sprinkler head during this test, which is higher than the previous tests indicating a relationship between the pressure, volume and losses.

4.1.4 Test 4

Test 4 pairs the #20 3TN nozzle with the PC-S3000 spinning plate model sprinkler at 103.4 KPa (15 PSI).

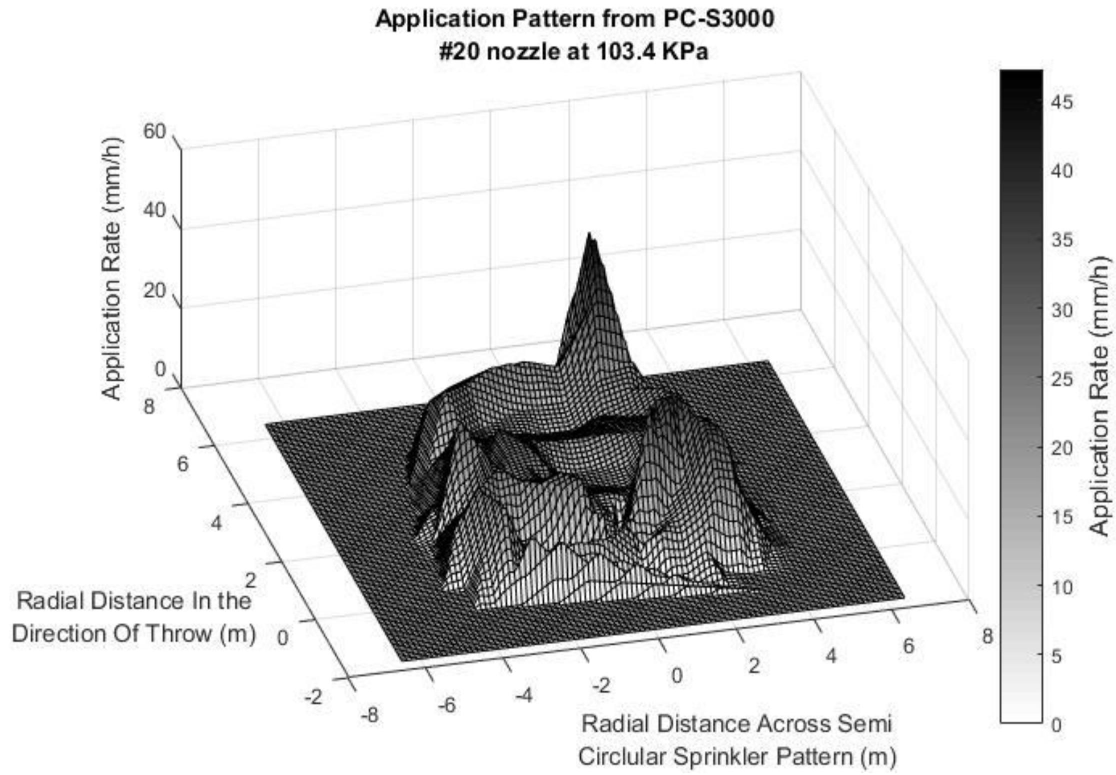

Figure 4:7 Test 4 – Application surface

Figure 4:7 like all of the surface plots really shows the variability of application generated by these devices and makes it easy to understand why research needs to be conducted into the performance of part-circle irrigation sprinklers.

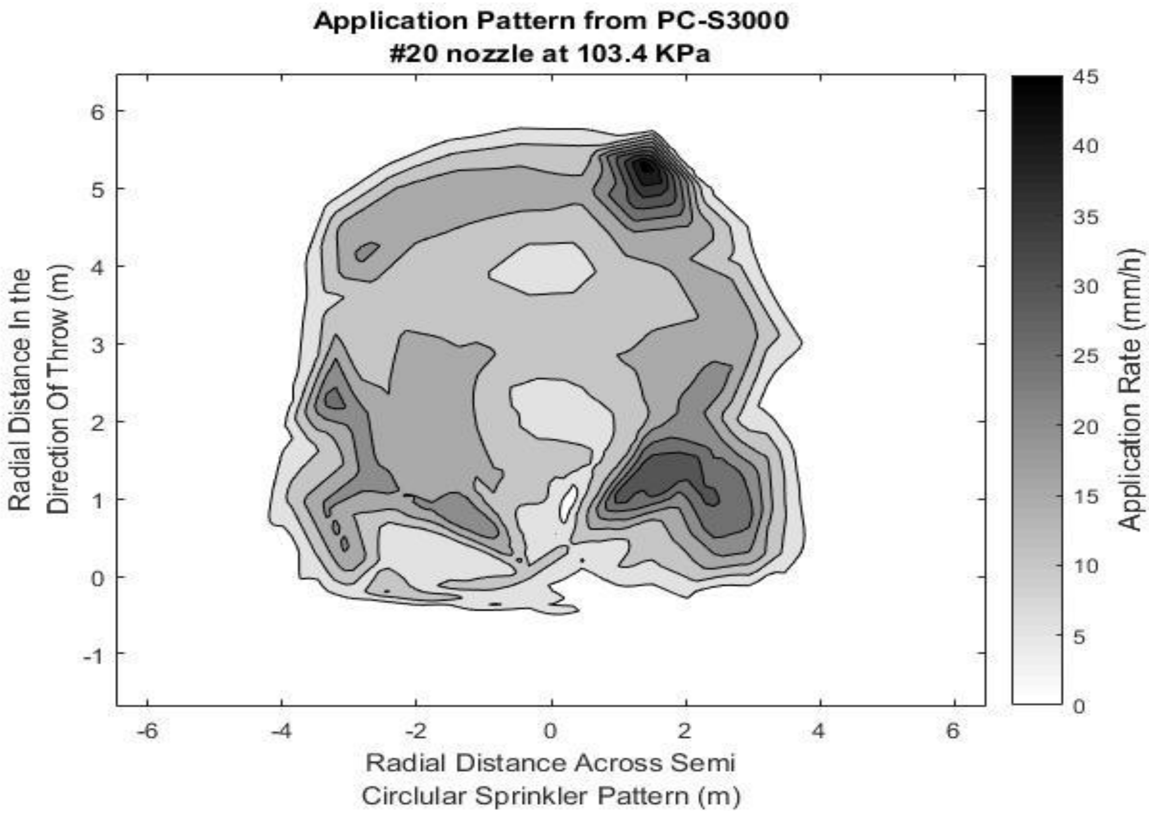

Figure 4:8 Test 4 – Application contour

The increase in pressure leads to a larger throw radius and therefor wetted area, the throw radius of this combination is 6.5 metres directly in front of the sprinkler, and between 4 – 5 metres on the sides. Once again there is an inconsistency between throw radii around the wetted area. The pressure increase also increased the water lost directly below the sprinkler head to 102.57 mm/h, this is an increase of just under 10 mm/h compared to test 3.

4.1.5 Test 5

Test 5 was conducted using the # 28 nozzle at 68.95 KPa (10 Psi). Appendix B contains the raw data for this test.

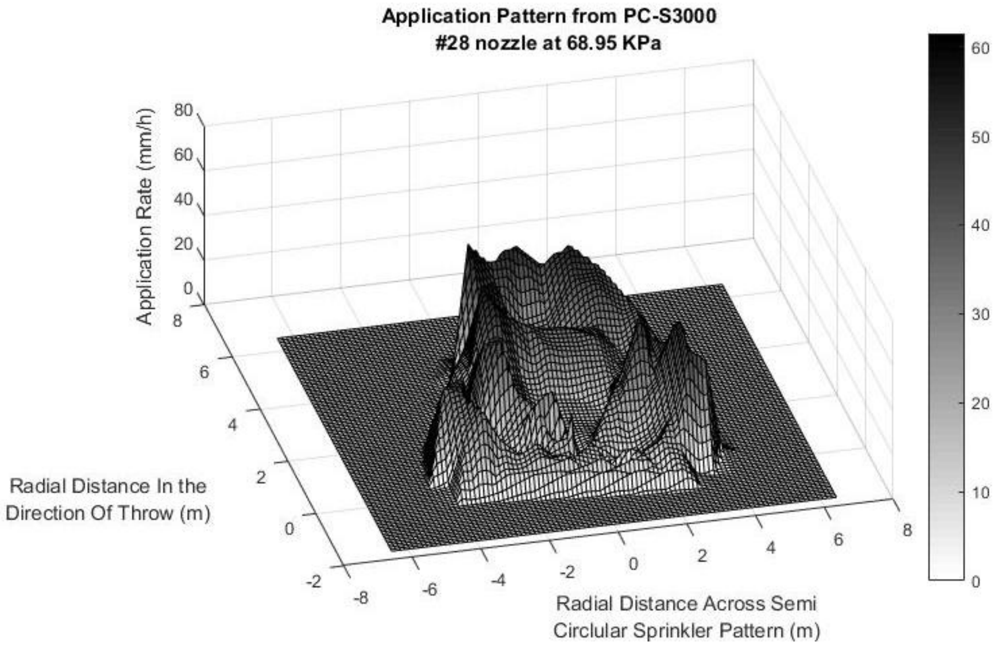

Figure 4:9 Test 5 – Application surface

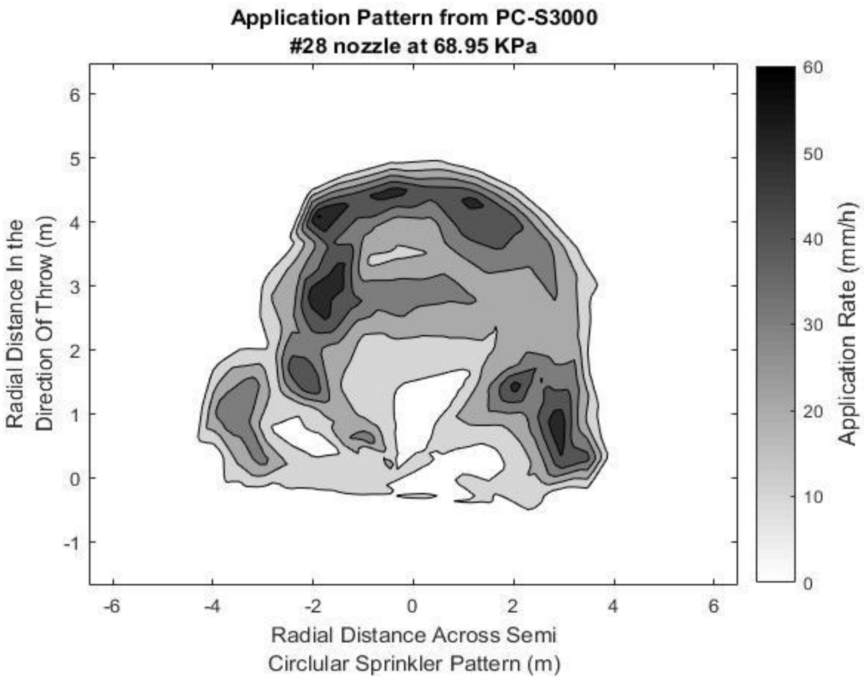

Figure 4:10 Test 5 - Application contour

Figure 4:10 once again indicates that there is a larger throw radius in front of the sprinkler, in this case out to 5 – 5.5 metres. The right hand side has recorded depths out to 3.5 – 4 metres, the left hand side on the other hand has a section with very low to no application represented by the cut out. This cut out section could be caused by the brackets that hold the spinning plate to the top of the sprinkler, these can be seen in Figure 4:10. On the left hand side of the sprinkler, depths were recorded between 4.5 – 5 metres, though this is reduced by over a meter in the cut out area. 82.27 mm/h was the depth recorded under the sprinkler, it is not known why this value is lower than previous tests. One reason that could explain this reduction is that the design of the PC-S3000 part-circle sprinkler is more efficient at distributing the inflow at higher flow rates from the larger nozzles than the lower discharge produced by smaller nozzles. This theory is supported by the high application rate band present directly in front of the sprinkler.

4.1.6 Test 6

Test 6 is the last of the tests conducted at 103.4 KPa (15 PSI), it pairs the PC-S3000 with the #28 3TN nozzle.

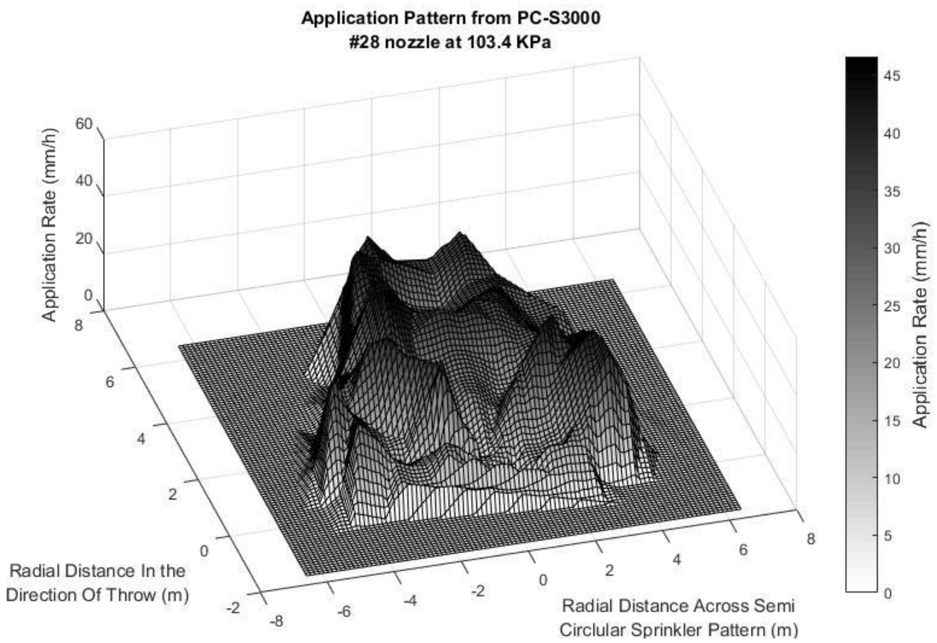

Figure 4:11 Test 6 – Application surface

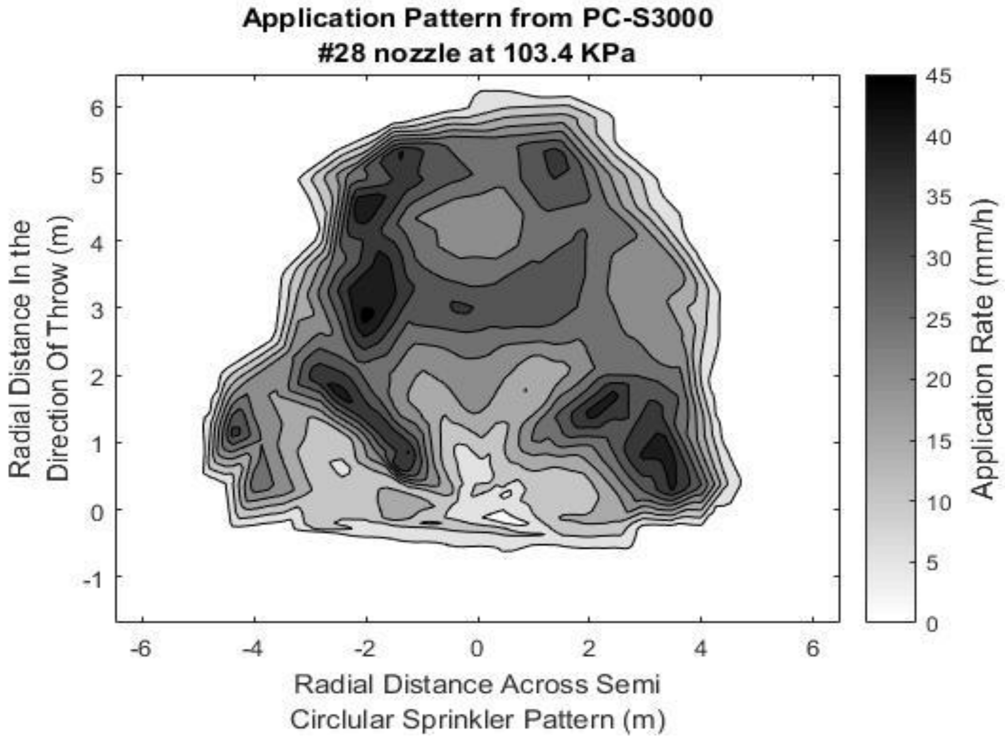

Figure 4:12 Test 6 – Application contour

The application pattern is very similar to that of test 5, This test provides further evidence to support the theory that the higher volumes of water being put through the sprinkler has a significant effect on the sprinklers uniformity. There are two particular sections of Figure 4:12 that are of interest and they are the dark areas around the coordinate points (2, 2) on the right hand side and the long dark band around the coordinate point (-2, 2) on the left. These two dark spots line up with the support structure of the PC-S3000 model sprinkler, it is evident that along these lines the support is having an effect on the water distribution. This theory will be discussed in depth later in this chapter.

We can also determine from the research that with higher flow nozzles fitted the application pattern is becoming more circular with the maximum recorded radius of application being 6.5 metres directly in front, while only reducing to 4.5 – 5 metres on the sides. As with test 5 the trend for reduced losses under the sprinkler head continues with 79.32 mm/h the recorded depth in this test.

4.1.7 Test 7

Test 7 was the only test to use the #34 3TN nozzle, this test was run at 68.95 KPa (10 PSI).

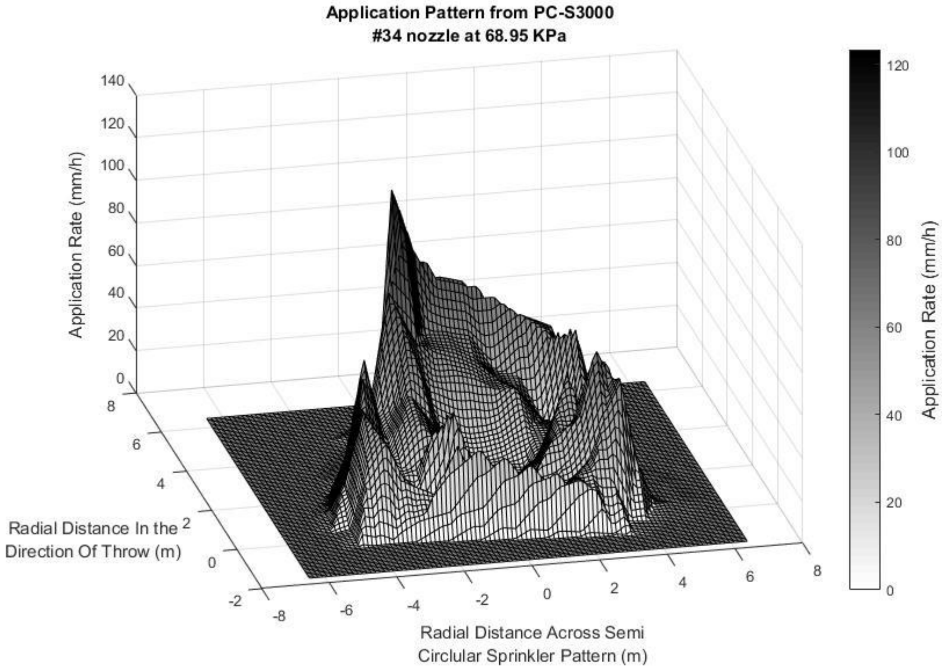

Figure 4:13 Test 7 – Application surface

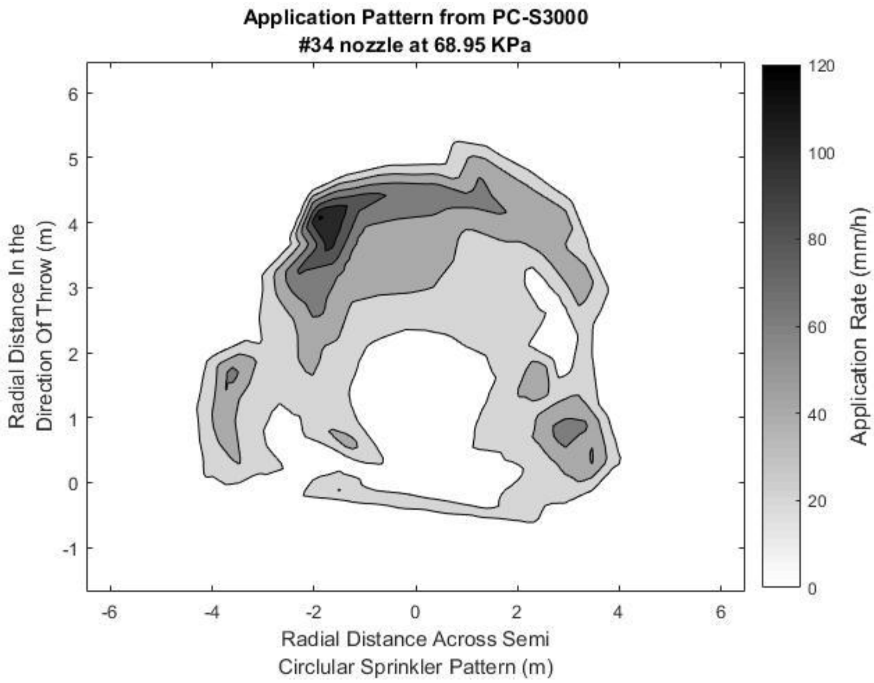

Figure 4:14 Test 7 - Application contour

The previous two tests indicated an anomaly with the application pattern on the left hand side which is also consistent with this test results. 5.5 metres from the sprinkler was the furthest recorded depth from the sprinkler head directly in front while 4.5 metres was the average on the sides. The pattern of reduced losses continues with 65.55 mm/h recorded during this test.

4.1.8 Test 8

Test 8 used the #40 3TN nozzle which is the largest nozzle size recommended by the manufacturer, operating at 68.95 KPa (10 PSI).

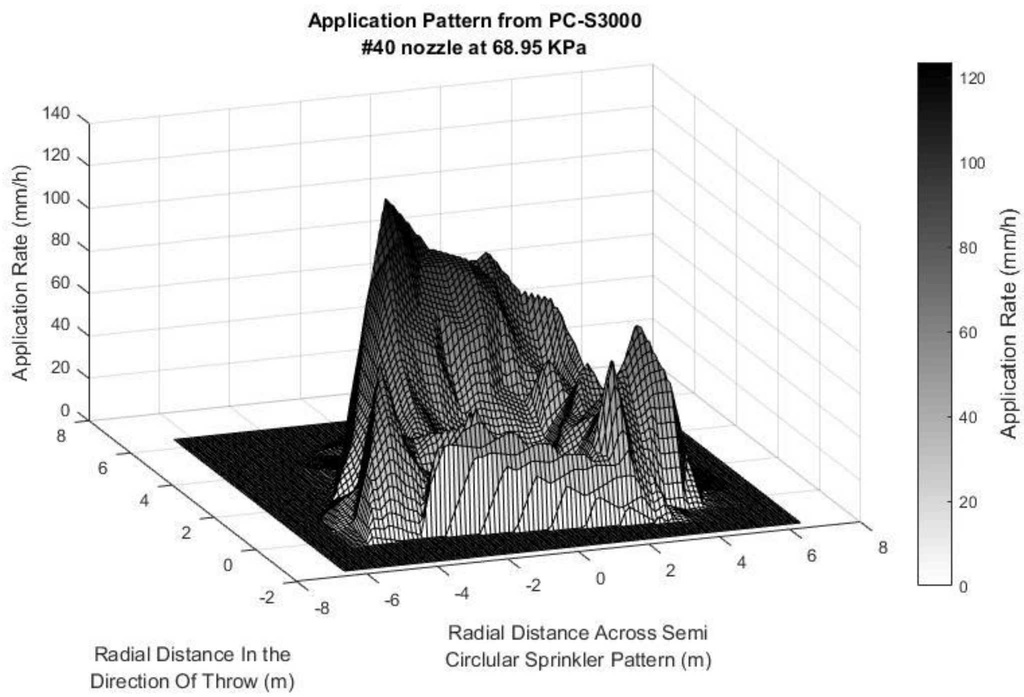

Figure 4:15 Test 8 – Application surface

Figure 4:15 shows that using the largest nozzle size means that there are much greater application rate across the wetted area although this still is not enough to eliminate the ‘horse shoe’ shape pattern generated by these sprinklers.

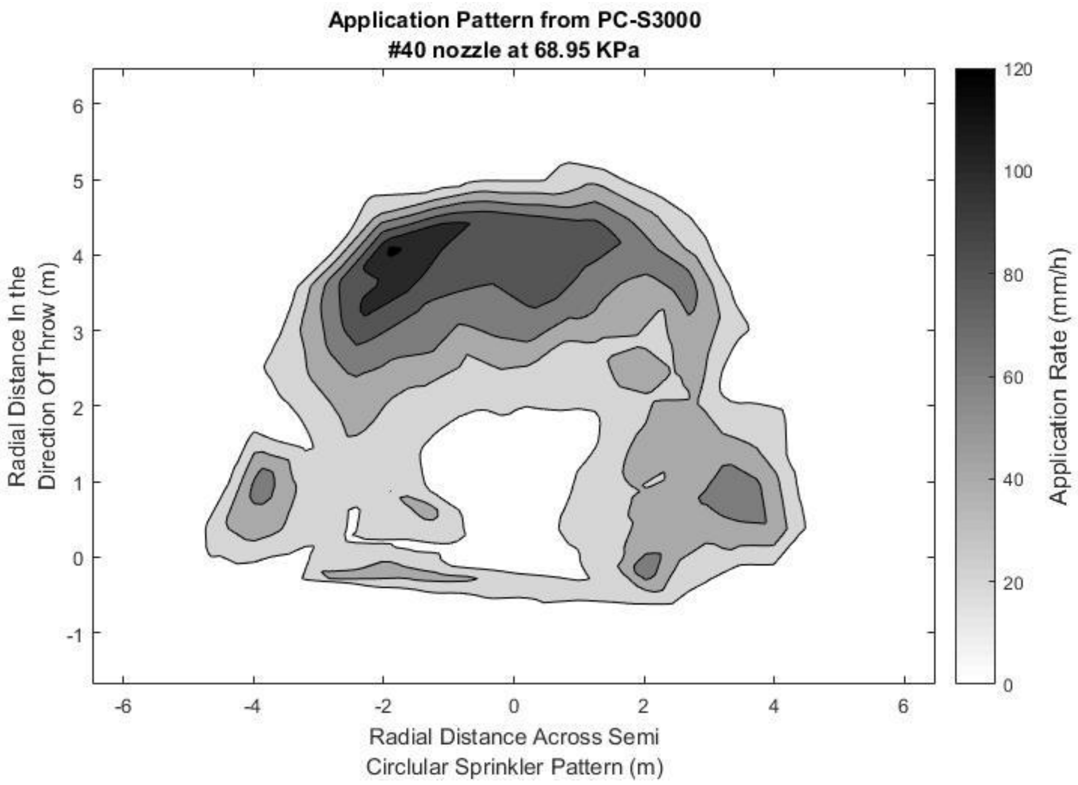

Figure 4:16 Test 8 – Application contour

Figure 4:16 along with previous tests indicates the anomaly on the left hand side of the figure although in this test the anomaly is also seen on the right hand side of the figure. This will also explain the sudden rise in lost water under the sprinkler, 93.48 mm/h which is a significant increase from the 65.55 mm/h seen in the previous test.

4.1.9 PC – S3000 Analysis summary

There were a couple of consistencies seen throughout all eight tests conducted using the PC–S3000 part-circle irrigation sprinkler. The first is that all tests revealed a 'horse shoe' shaped application pattern, which has implications when positioning these sprinklers on an irrigator particularly when all are orientated the same way. When designing the placement patterns of these sprinklers it is important that they are spaced properly to reduce areas of low application, the modelling of these application patterns will reveal optimum spacing for each scenario.

Another disadvantage of these sprinklers is the volume of water being lost under the sprinkler head, the water that is falling below the sprinkler will directly contribute to wheel rutting and bogging issues discussed in section 2.2. The high level of water being lost will cause runoff under the sprinkler head leading to wheel rutting and soil crusting in some cases. Throughout all of the tests using the PC-S3000 model part-circle sprinkler there were sections of the contour plots that show high application rates close to the sprinkler head. This is most likely because of the design of the sprinkler head, the PC-S3000 uses three mounting brackets that connect base plate to the main body of the sprinkler.

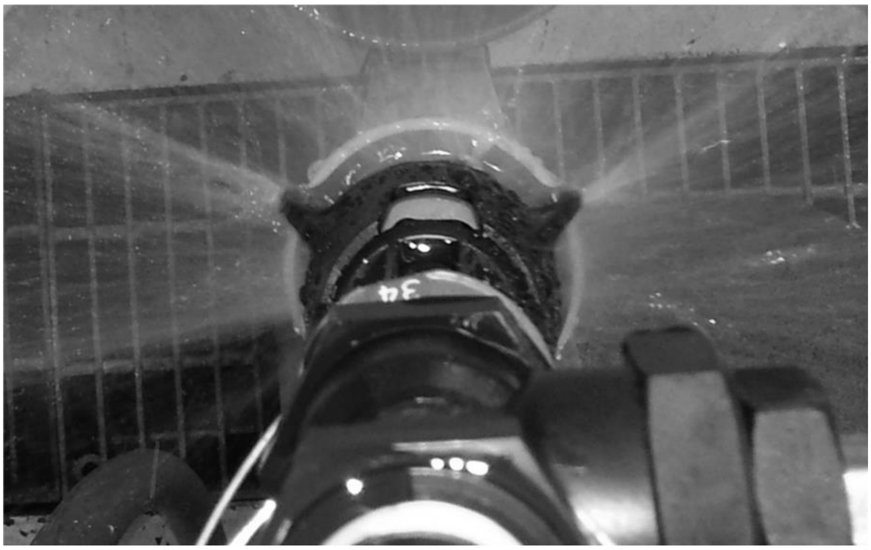

Figure 4:17 Operational sprinkler bracket effect

Figure 4:17 illustrates the brackets position and how the application is affected by the brackets, heavy concentrations of water around the uprights indicate that these brackets are most likely the reason for large loses under the sprinkler head. This is reflected in the data that was collected during testing, the high concentrations close to the sprinkler seen in the contour maps shows that the sprinkler design means that the water is falling much closer to the device in the regions effected compared to the areas where there are no obstructions. It is these obstructions that are causing such a large application rate directly below the device, as water collides with these brackets the droplets are losing all of their energy and subsequently falling down below the device.

4.2 PC - D3000 Part-circle Sprinkler Results

The PC – D3000 model sprinkler was also subjected to 8 tests, this section represents the data collected in the same way shown in the previous section. Table 4:2 shows the combination of pressure and nozzle size used for each test.

Table 4:2 PC-D3000 Static plate tests

PC - D3000 Static Plate Sprinkler

Test No.	3TN Nozzle		Operating Pressure	
	Number	Orifice Dia. (mm)	KPa	PSI
1	#09	1.79	68.95	10
2	#09	1.79	103.4	15
3	#20	3.97	68.95	10
4	#20	3.97	103.4	15
5	#30	5.95	68.95	10
6	#30	5.95	103.4	15
7	#40	7.94	68.95	10
8	#50	7.94	68.95	10

4.2.1 Test 1

As seen from Table 4:2, test 1 paired the PC-D3000 static plate irrigation sprinkler with a #09 3TN nozzles and operated the device at 68.95 KPa (10 PSI).

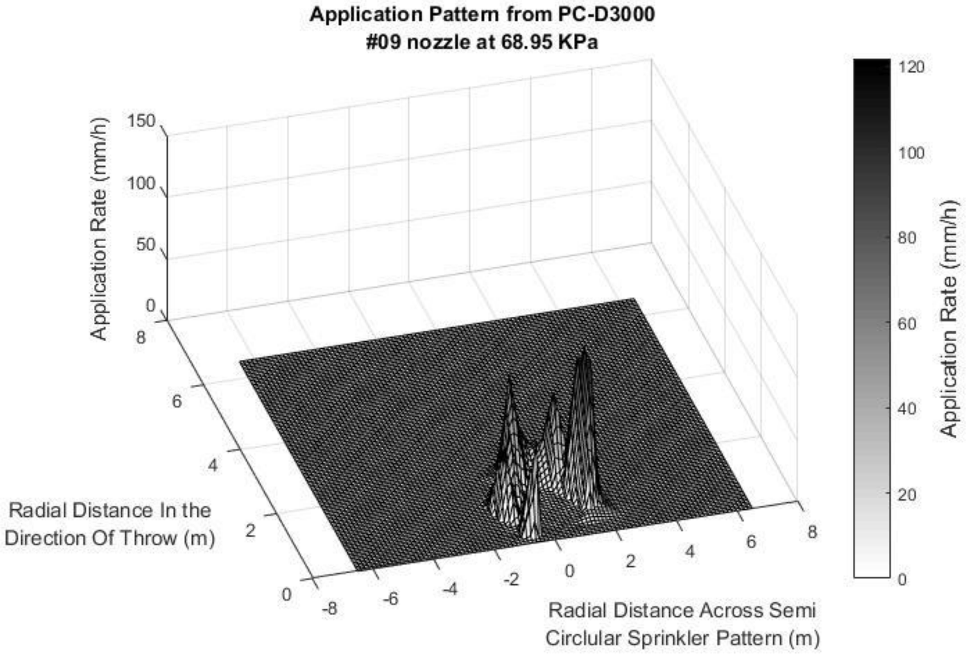

Figure 4:18 Test 1 – Application surface

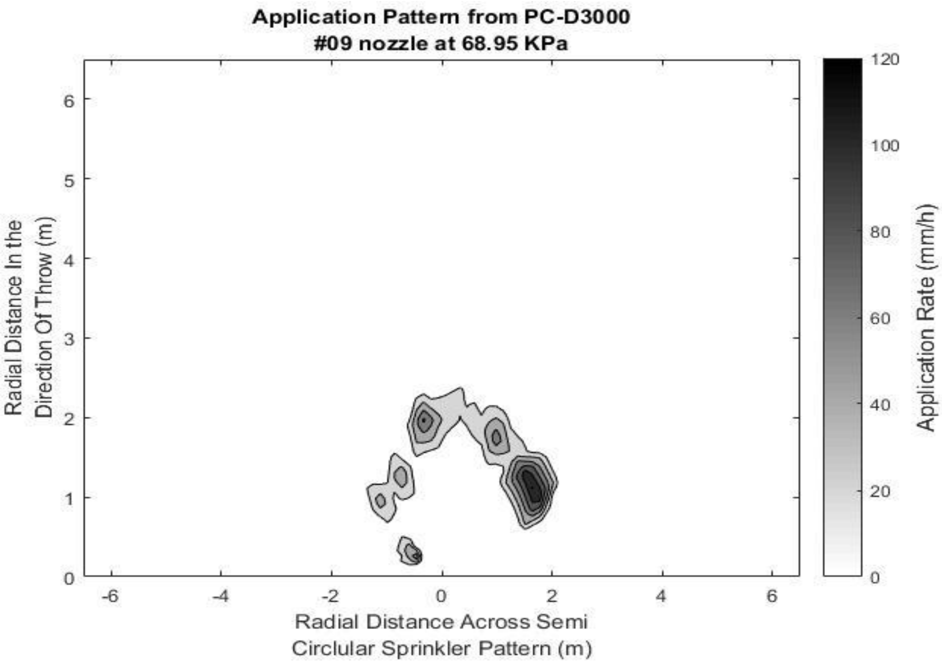

Figure 4:19 Test 1 - Application contour

Due to that static nature of the spray plate of this device the throw radius depends on the volume and pressure of the inflow. Since this test utilises the smallest nozzle specified by the manufacturer with the lowest pressure, the throw radius is small, within 2.5 metres. The design of this device meant that the application radius is only 1.5 – 2.5 metres.

Figure 4:20 provides a look at the operation of the sprinkler and shows how the device spreads the water, this pattern like the PC – S3000 also seems to develop a 'horse shoe' like pattern providing greater application length in front compared to the sides. Losses below the device were down to 10.62 mm/h for this test which is very reasonable.

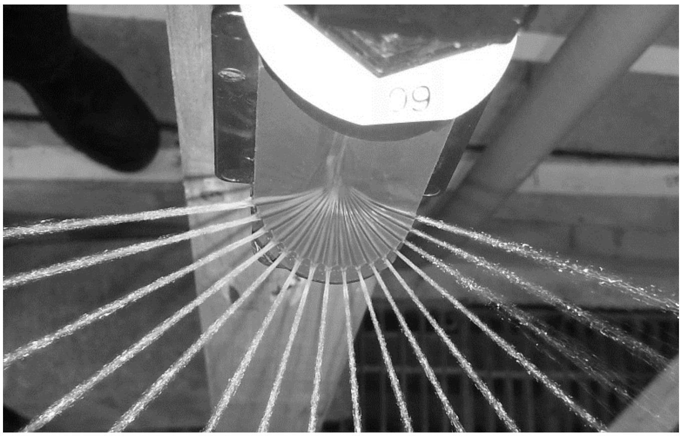

Figure 4:20 Test 1 - Sprinkler pattern

4.2.2 Test 2

Test 2 also used the #09 3TN nozzle, operated at 103.4 KPa (15 PSI).

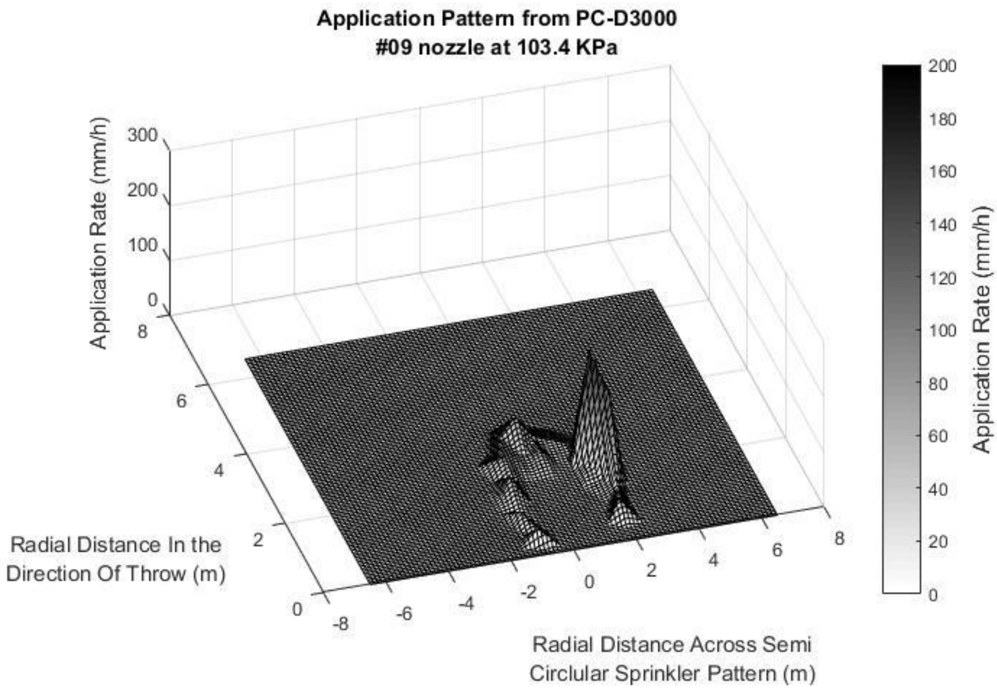

Figure 4:21 Test 2 – Application surface

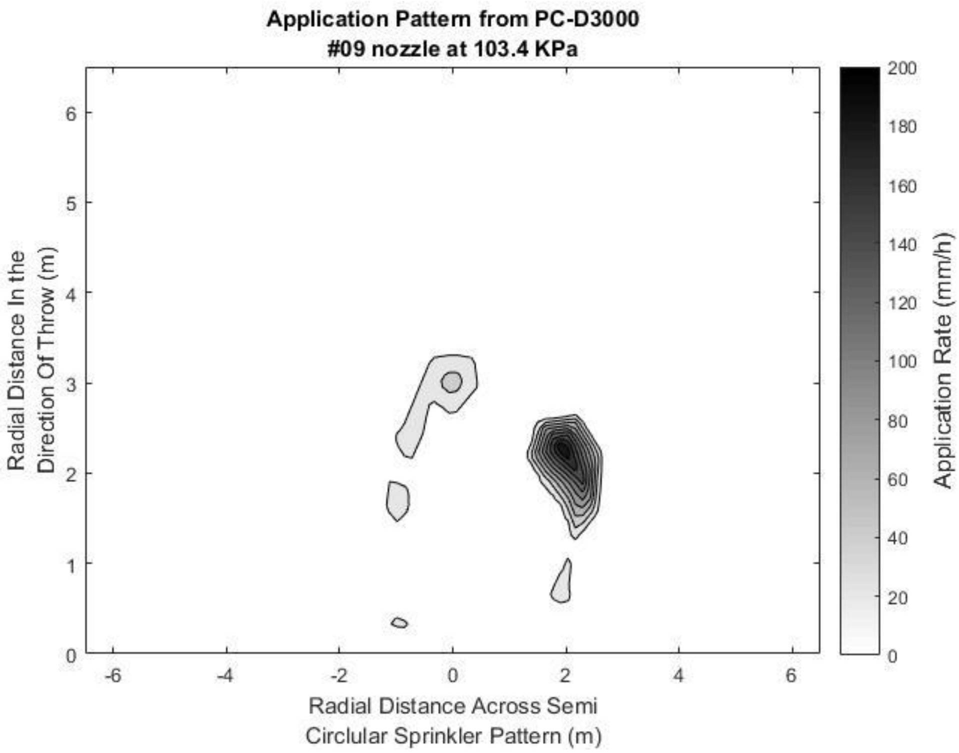

Figure 4:22 Test 2 – Application contour

Figure 4:22 clearly shows an elliptical shape application pattern forms from this sprinkler with the centre recording depths out to 3.5 metres while on the side falls were down to 1 – 1.5 metres on the left hand side, while on the right hand side application depths between 2 – 2.5 metres were present. During this test only 12.68 mm/h was recorded below the sprinkler head, compared to the PC – S3000 these losses are very small.

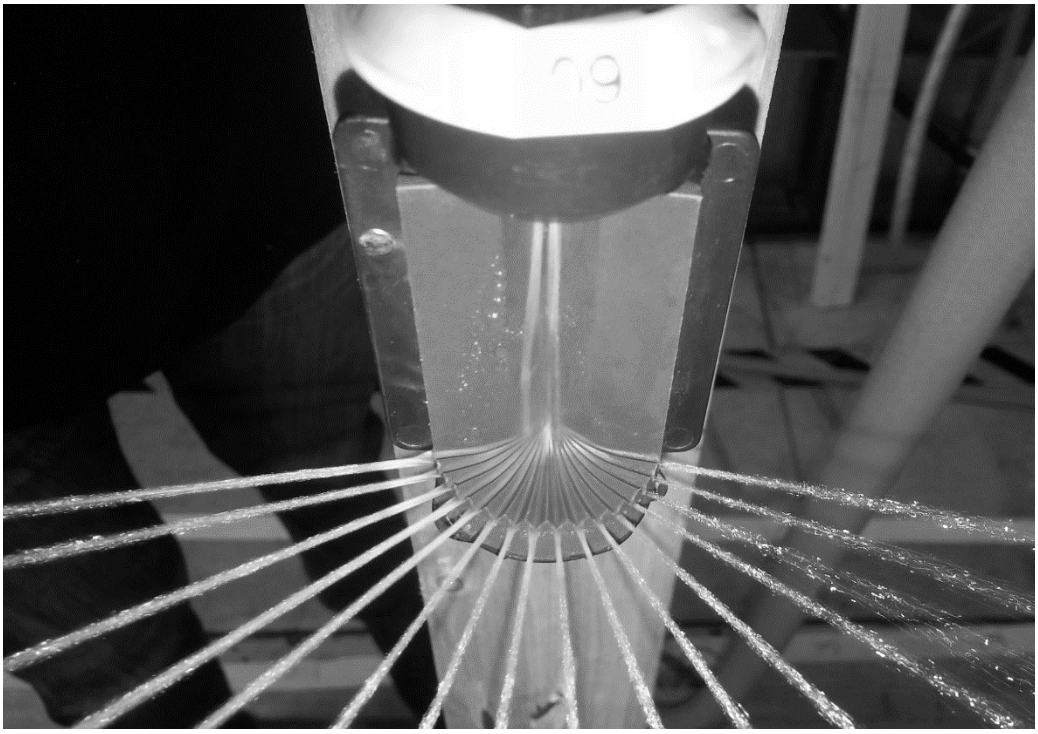

Figure 4:23 Test 2 – Sprinkler pattern

Figure 4:23 shows the part-circle sprinkler working correctly with the inflow being split into streamlets and being directed around the 170° application radius. In this image the catch cans were positioned on the opposite side of the photo, so the right hand side of this image relates to the left hand side of the figures above. In Figure 4:23 the three most right hand streams look to be lighter in volume than the rest which translates directly to the 1 -1.5 metre radius of application seen in Figure 4:22 indicating that this issue is caused by the spray head and nothing else.

4.2.3 Test 3

Test three was conducted using the pressure setting 68.95 KPa (10 PSI) with the #20 3TN nozzle.

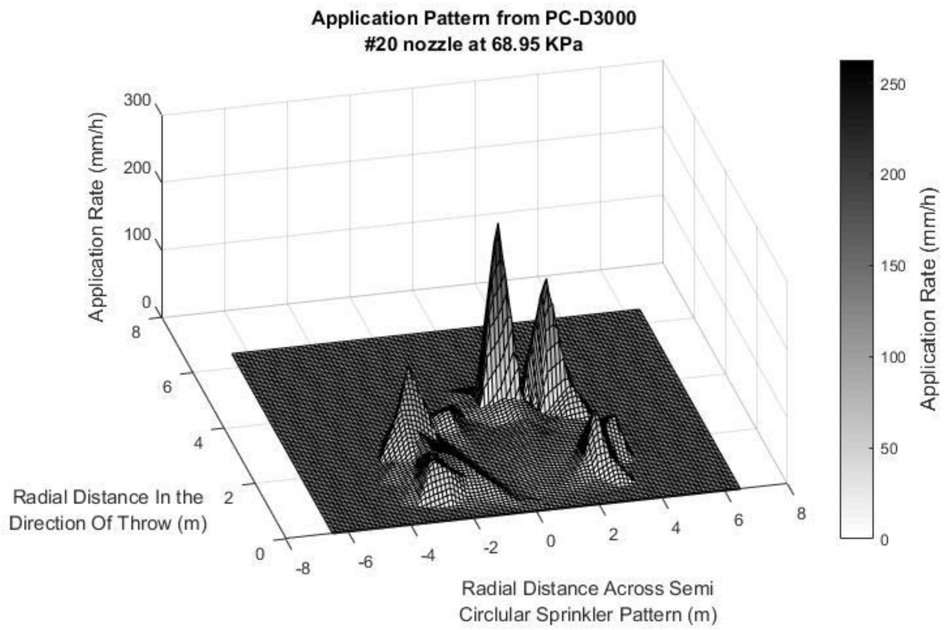

Figure 4:24 Test 3– Application surface

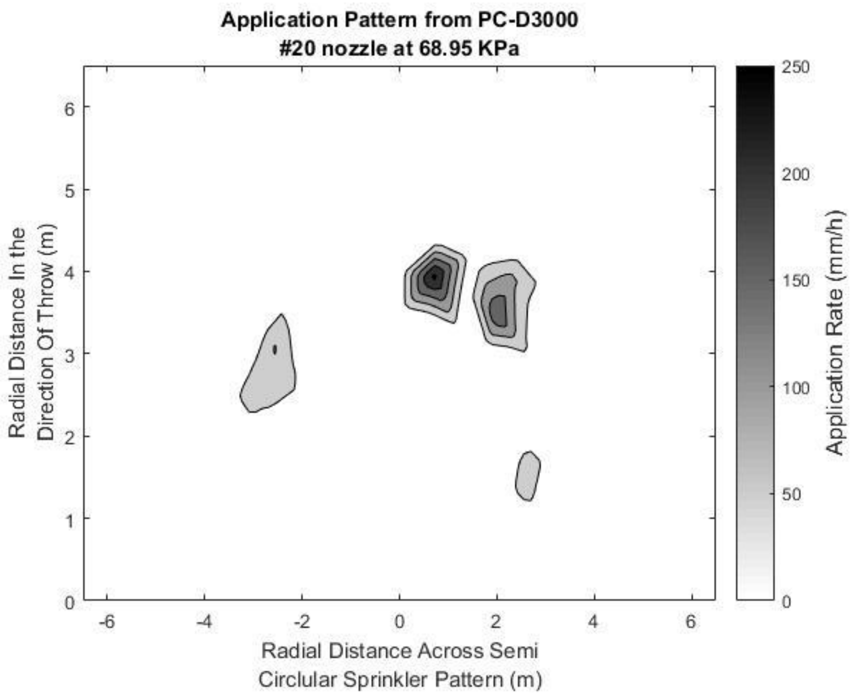

Figure 4:25 Test 3– Application contour

In this test we first encountered the problem of sheeting, this occurs when the inflowing water overtops the small grooves cut into the spray plate to spread the water, this is clearly illustrated in Figure 4:26 where the streams seen in Figure 4:23 have joined together to form almost one stream. This had major effects on the data collected as it created areas of no application depths which is clearly seen from Figure 4:24 and Figure 4:25. This means that in the field when this occurs there is a large variance between application depths and therefor has an effect on crop growth rates under these devices. The losses under the PC-D3000 are still low even with the problem of sheeting with only 14 mm/h being recorded during this test.

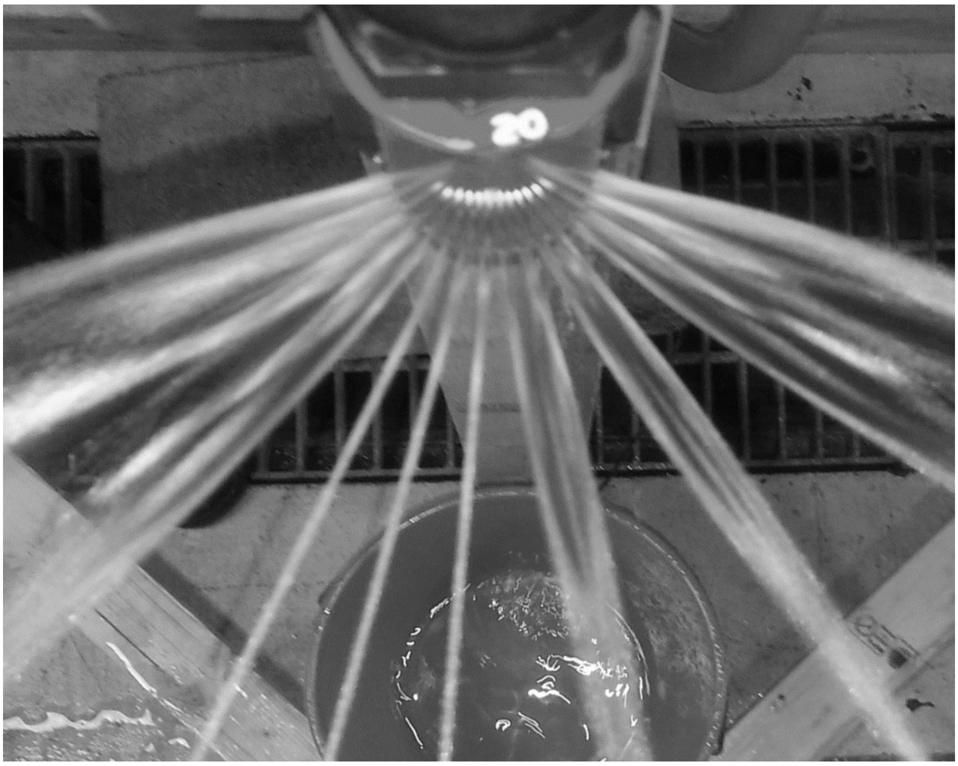

Figure 4:26 Test 3 - Sprinkler pattern

4.2.4 Test 4

Test 4 also used the #20 3TN nozzle with an operational pressure of 103.4 KPa (15 PSI).

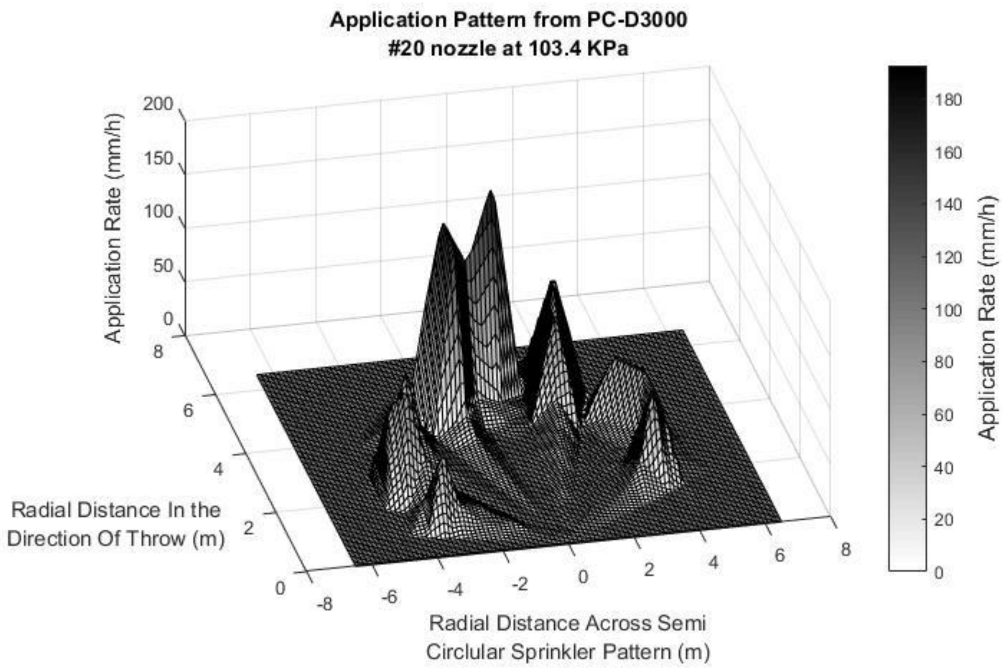

Figure 4:27 Test 4 - Application surface

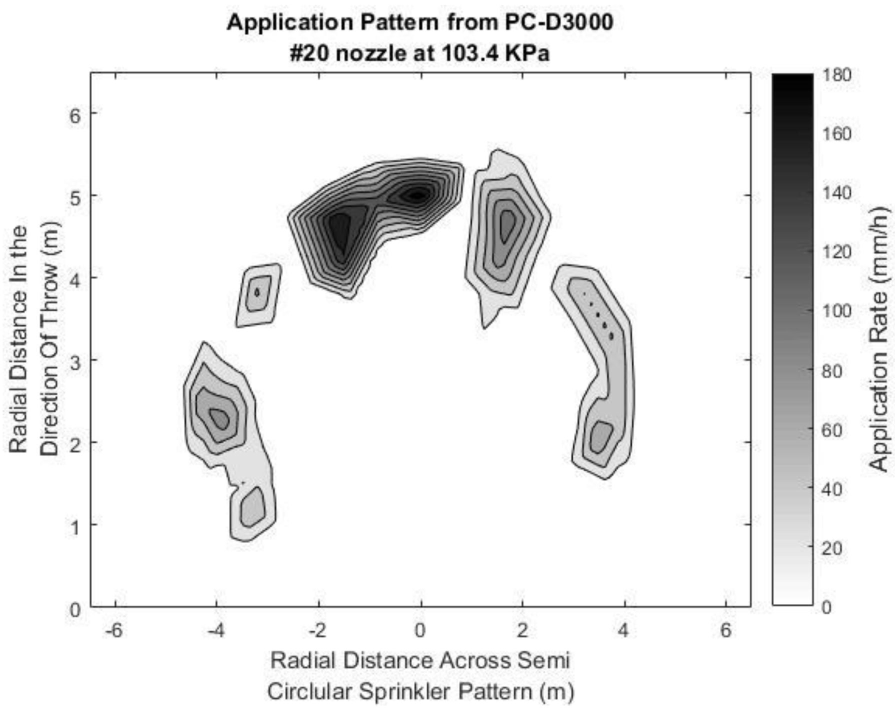

Figure 4:28 Test 4 – Application contour

Figure 4:27 clearly demonstrates how this device works, there are clear lines of application with peaks between 4 – 5.5 metres in front of the sprinkler head and closer in on the edges, one common trait of this sprinkler is that in the centre of the application pattern there is little measurable applied depth, which needs to be considered when applying the technology in the field. 17.82 mm/h was the measured loss below the static plate of the sprinkler which translates to low level losses.

Figure 4:29 Test 4 – Sprinkler pattern

In this test we can see from Figure 4:29 the sheeting effect has increased with the pressure, when analysing the application data recorded during the test it clearly indicates that the sheeting effect has a significant effect on where the water is being applied across the wetted area.

4.2.5 Test 5

This test was conducted using the #30 3TN nozzle running at a pressure of 68.95 KPA (10 PSI).

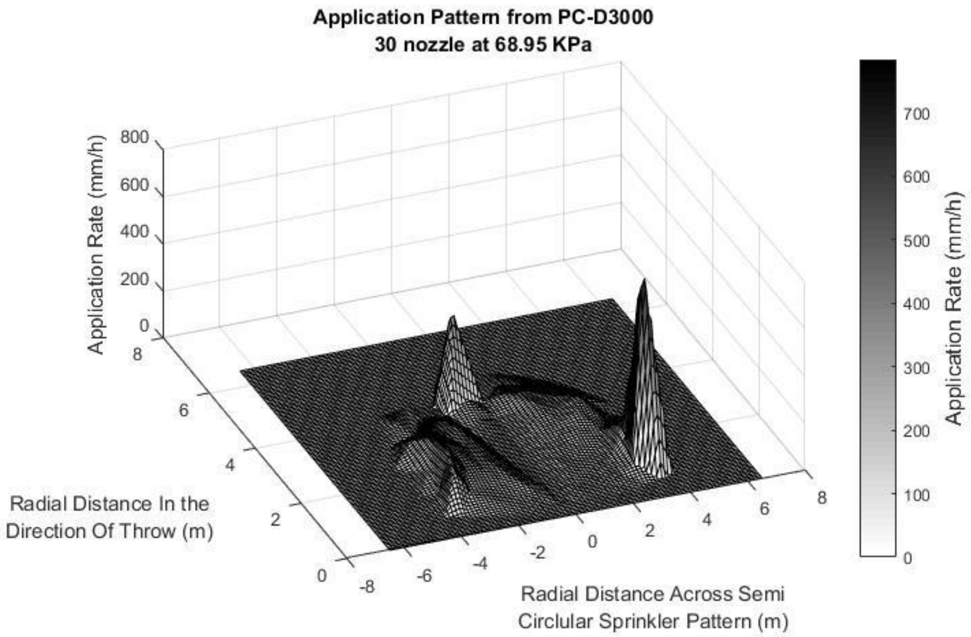

Figure 4:30 Test 5 – Application surface

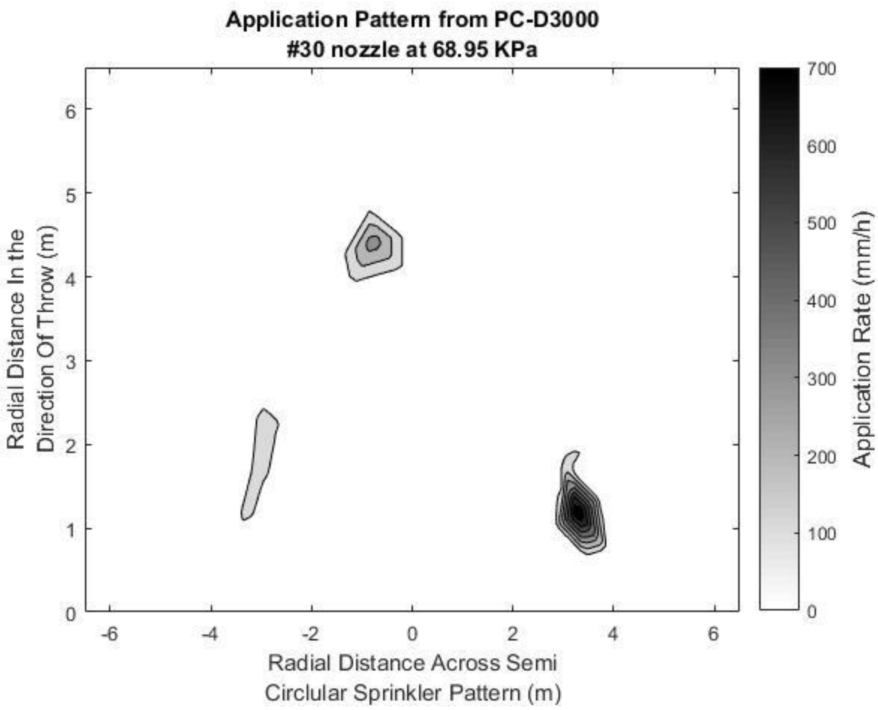

Figure 4:31 Test 5 – Application contour

The figures above are misleading, the figures above are not totally representative of the overall application pattern as in one particular section of the wetted area a very large amount of water was directed to the one spot, which is easy to see. It is unknown why this has occurred and you will see it more with the following tests, this is an anomaly that will have to be assessed further in future testing. This anomaly did not affect the losses below the sprinkler as they were only 22.40 mm/h.

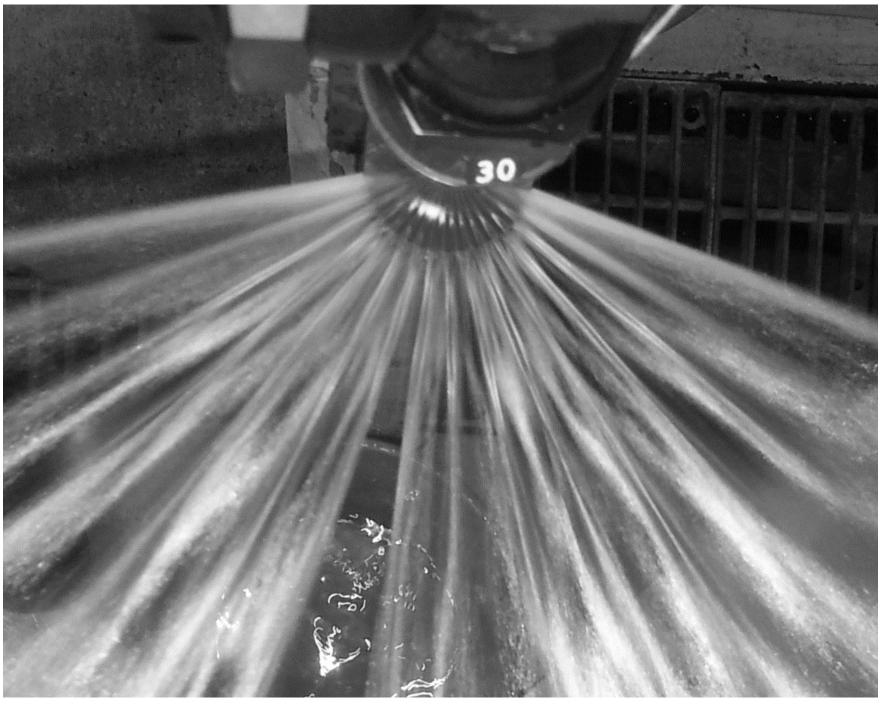

Figure 4:32 Test 5 – Sprinkler pattern

Figure 4:32 supports the theory that the sheeting problem increases with both pressure and volume but does not offer any explanation of the large spot application seen in the tests. Interestingly though it seems that with the increased sheeting comes a more uniform application within the application band.

4.2.6 Test 6

Test 6 used the same 3TN nozzle (#30) as test 5 although with a higher pressure setting of 103.4 KPa (15 PSI).

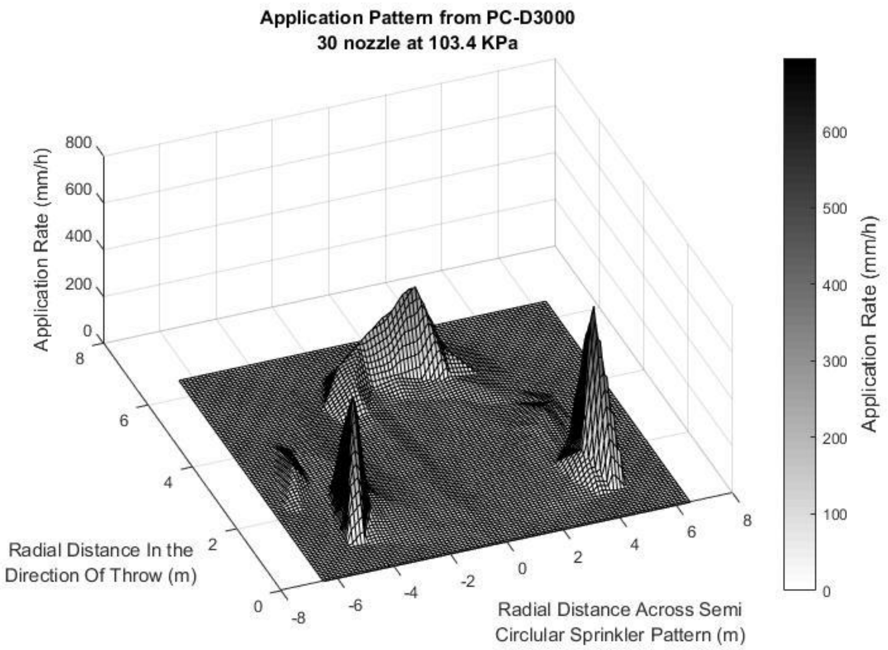

Figure 4:33 Test 6 – Application surface

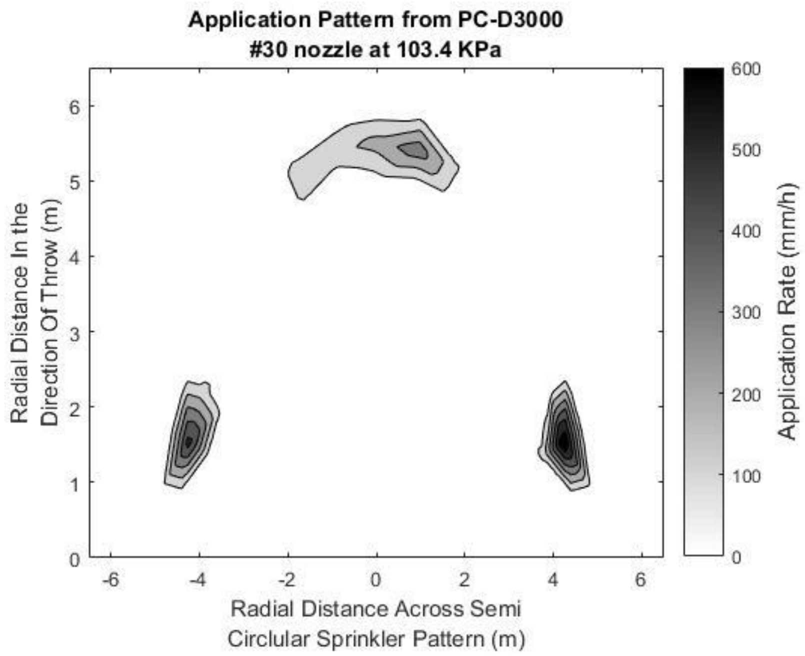

Figure 4:34 Test 6 – Application contour

As with test 6 we see those areas of very large application, which do not give a good representation of what is happening below these peaks. The increase in flow rate and pressure has also increased the losses to 30.09 mm/h, as well as the throw radius which is up to 6 metres directly in front of the sprinkler. Figure 4:35 shows the sheeting occurring on almost all of the streamlets and once again it doesn't offer any explanation as to why the recorded data is showing huge peaks in selected areas around the wetted area.

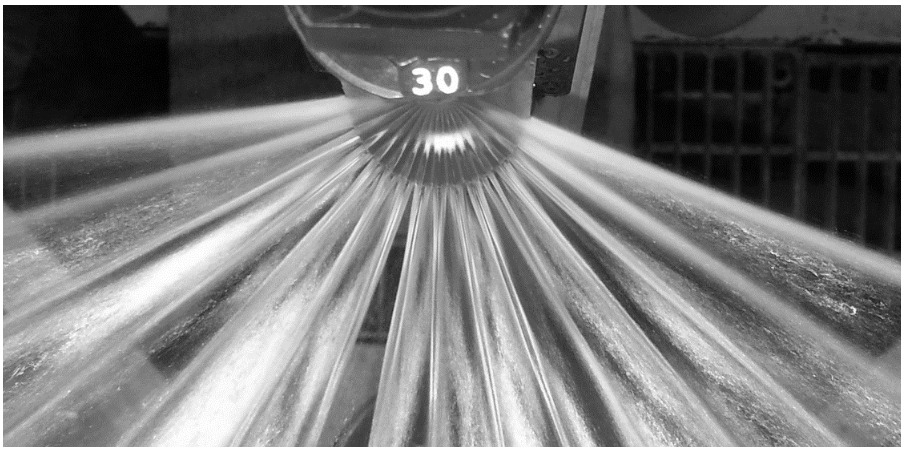

Figure 4:35 Test 6 – Sprinkler pattern

4.2.7 Test 7

Test 7 was conducted at the pressure setting of 68.95 KPa (10 PSI) using the #40 3TN nozzle.

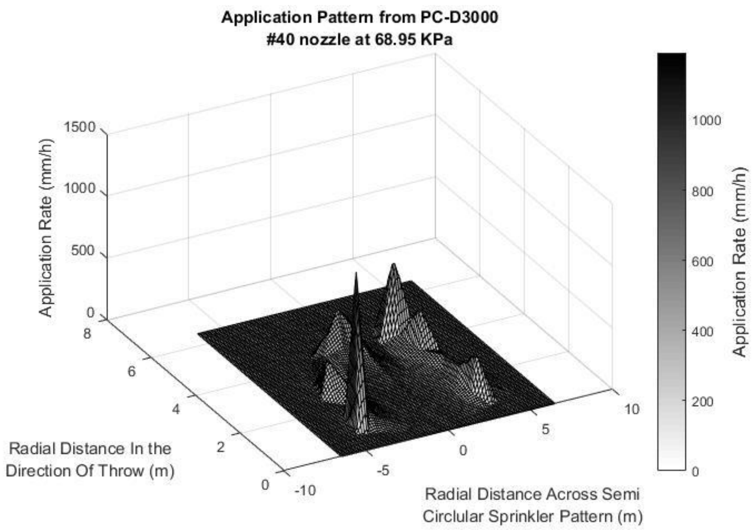

Figure 4:36 Test 7 – Application surface

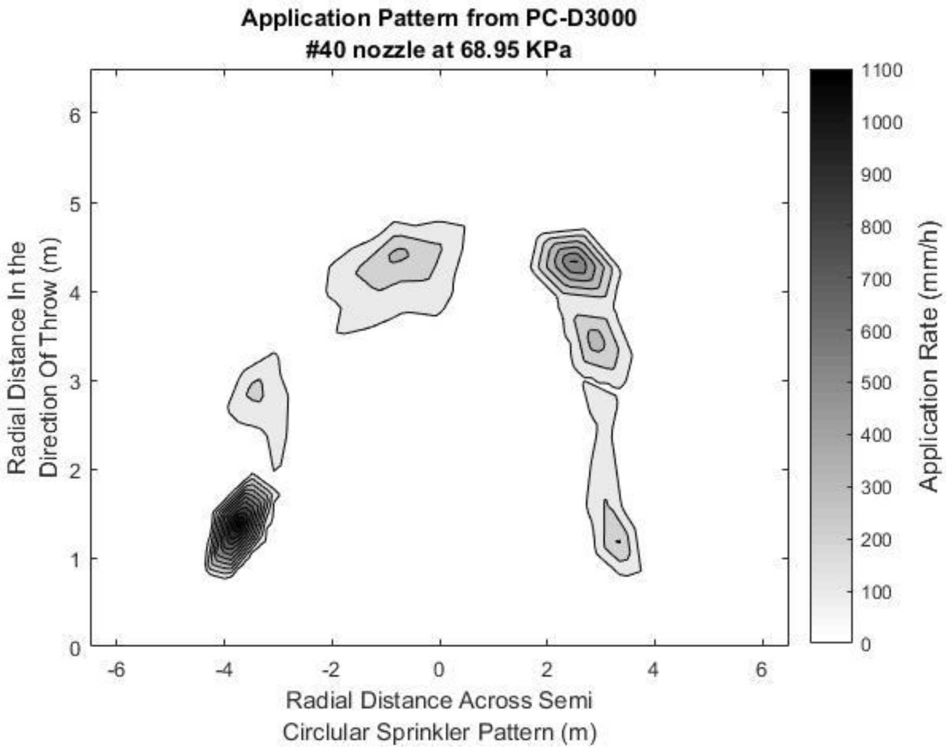

Figure 4:37 Test 7 – Application contour

Test 7 also yielded areas of extremely high application rates even as high as 1219.99 mm/h, the test also showed these spots of high application are occurring more across the wetted area with 5 distinct places for test 7. With the increased volumes of water from the larger 3TN nozzle water losses under the sprinkler also rose to 43.57 mm/h. This combination tested still showed that the centre of the application area gets very little to no water applied while the application band maintained high water application rates. When using the high volume nozzles sheeting occurs across the whole spray plate, as demonstrated by Figure 4:38.

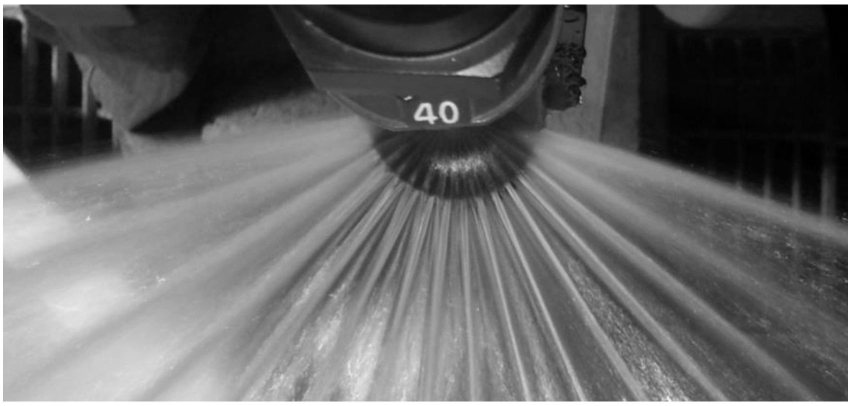

Figure 4:38 Test 7 – Sprinkler pattern

4.2.8 Test 8

This test was the last test conducted with the PC-D3000 static plate part-circle sprinkler using the largest available 3TN nozzle, #50 which was operated at 68.95 KPa (10 PSI).

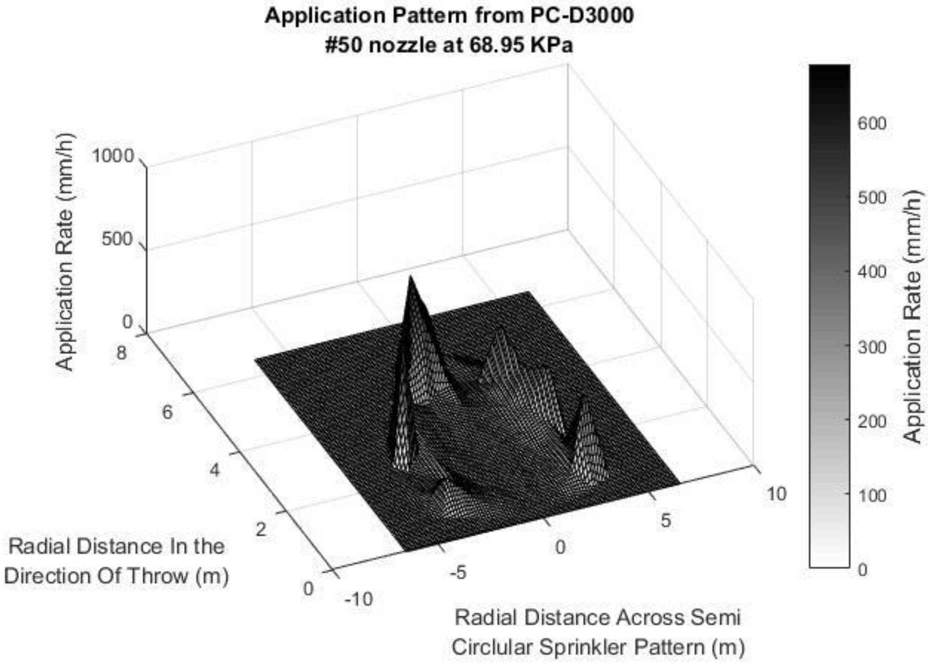

Figure 4:39 Test 8 – Application surface

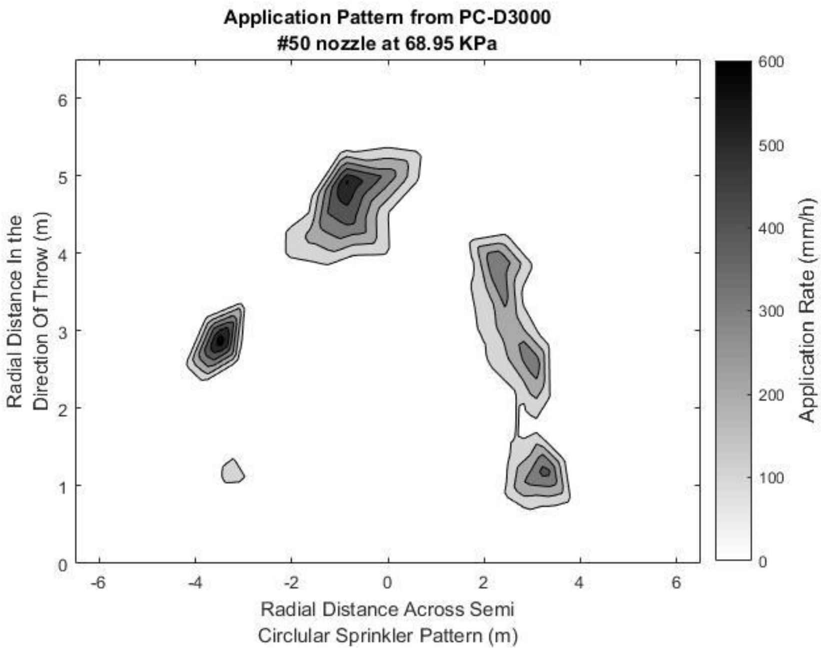

Figure 4:40 Test 8 – Application contour

Test 8 like the previous tests provided areas of high volume application, although the largest recorded application was 712.8 mm/h which was down significantly from test 7. This test also seen an increase in losses with 61.00 mm/h recorded under the sprinkler head. Figure 4:41 again shows the sheeting effects that forms at medium to high volumes passing through the sprinkler, if you look closely around the 3TN nozzle you can also see some water that is directly being lost out the side of the sprinkler head indicating that this large nozzle is overloading the spray head reducing its efficiency.

Figure 4:41 Test 8 – Sprinkler pattern

4.2.9 PC – D3000 Analysis summary

Testing of this part-circle sprinkler revealed several considerations and issues that must be considered when selecting the correct sprinkler for your needs. When operating this device at high volumes and pressures you must expect sheeting to occur. A side effect of sheeting though could translate to wind drift and evaporation losses occurring due to fine mist developing between streamlets. Another consideration is the isolated areas of high application rates which may cause excessive runoff and crusting of the soil in the areas affected. One advantage of the static plate sprinkler is that compared to the spinning plate model, is the low losses, even the biggest nozzle tested had lower losses than the smallest losses recorded in the PC-S3000 model sprinkler tests.

(This page is intentionally blank)

Chapter 5 MODEL DEVELOPMENT AND RESULTS

5.1 Model Development

A major part of this project was to model the results of the testing in an effort to optimise the use of part-circle sprinklers around irrigator towers. MatLab was the program chosen to develop the model with, the script written in MatLab operates by positioning four sprinklers in a Cartesian plain were the sprinkler patterns shown in Chapter 4 can be translated and rotated (Appendix C MatLab Model Code contains an example of the MatLab script). By positioning the applied depths in a Cartesian plain it allowed for the applied depth to be summed in the direction of travel, this produced a line of applied volumes which were used to calculate the Christiansen Coefficient of uniformity described in section 2.4 of the literature review. Figure 5:1 visually illustrates the positioning of the sprinklers in regards to the tower, the most common way to use part-circle sprinklers is to position them behind the towers on a boomback setup.

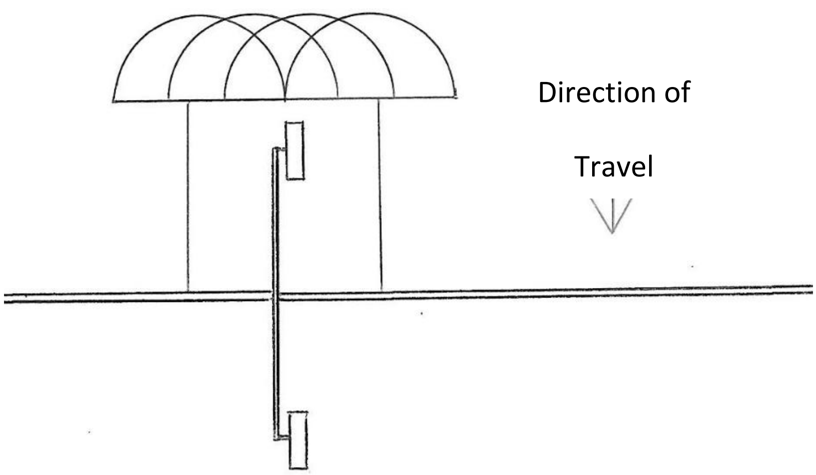

Figure 5:1 Model design diagram

To determine the volume of water applied by a spinkler during a pass over an area, an abitrary speed was assumed to be 100 metres per hour. This speed will not effect the christiansen coefficient, the only effect speed has on the model is with regards to the volume applied under the sprinkler which does not form part of this analysis. Speed was then used to modify the application rate determined from the results data for each sprinkler, this then gave a volume for each catch can per pass. The volume determined was then summed in the direction of travel, as shown by the arrow on Figure 5:1. When the applied volumes were summed it produces a graph like Figure 5:2.

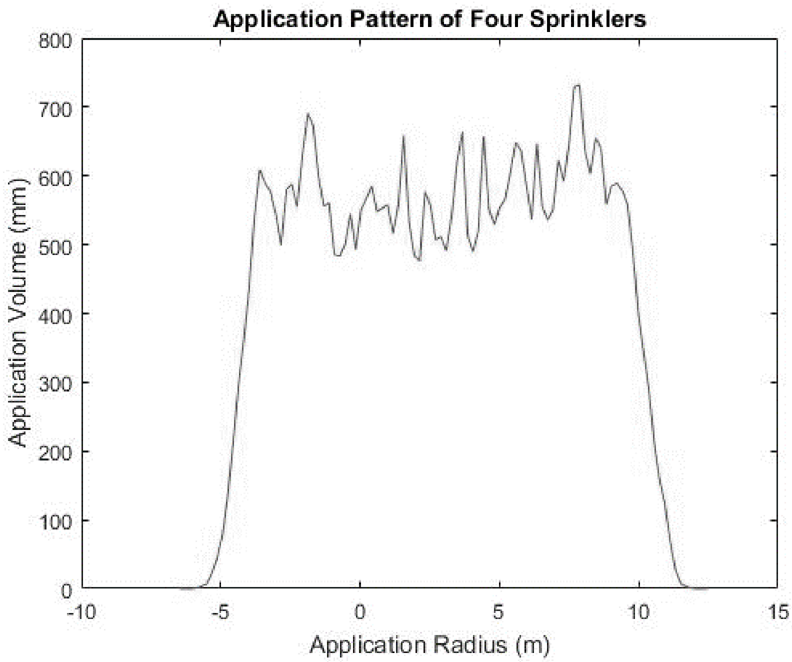

Figure 5:2 Applied volumes example graph

In order to determine the Christiansen Coefficient of Uniformity (CU) the largest 75% of applied volumes was used. The lowest 25% of the application volumes represent areas on the edge of the sprinkler, these values are ignored as the uniformity is calculated for the main wetted area of application and not the outer edges. Once the data set was defined Equation 4 from section 2.4.4 was used to determine the Christiansen coefficient of uniformity (CU). The orientation and spacing of the sprinklers is important to their ability to produce a uniform pattern the first section of the modelling chapter is focused on these two characteristics.

The model was run for all of the tests conducted at spacing distances of 1 metre increments ranging from 1 to 5 metres, at the same time the rotation of the sprinkler was tested ranging from 0° to 90° in increments of 22.5°, this data was then plotted to produce comparison charts. The comparison charts allows for easy identification of optimum spacing and orientation characteristics of the combination in question.

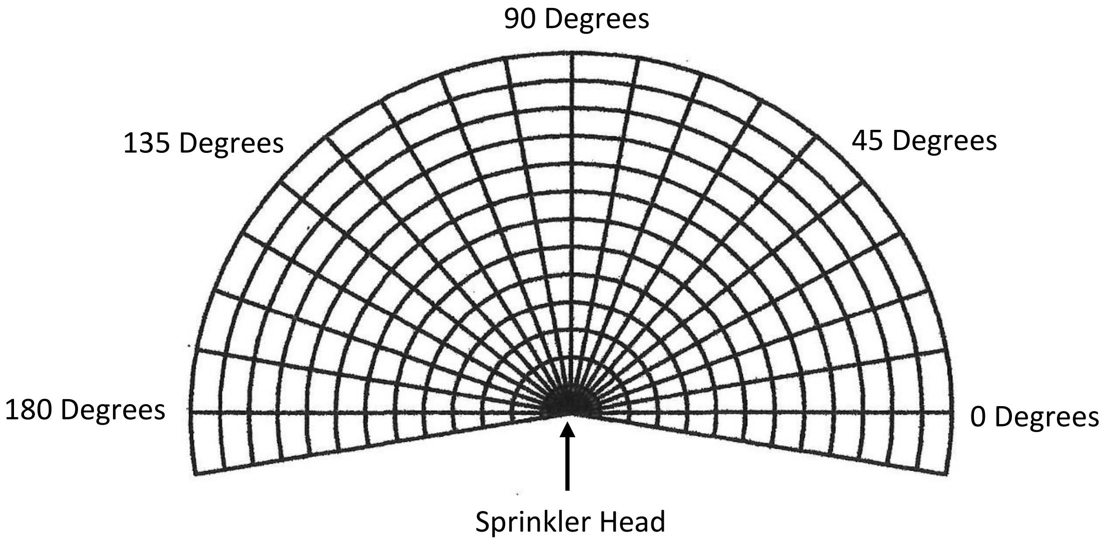

Figure 5:3 Sprinkler orientation diagram

One of the most important parts of this modelling is the orientation of the sprinkler data, and being able to rotate it about the sprinkler head. Figure 5:3 is a guide to explain the angle of the sprinkler. In Figure 5:3 on the right hand side the ‘0 Degree’ mark is where all angles are taken from, the angles are applied to all of the data points to rotate the sprinkler pattern around the sprinkler head seen in the centre. The spacing of the sprinkler is taken from sprinkler head to sprinkler head. For ease of modelling these sprinklers were modelled as if on a lateral move irrigator i.e. moves in a straight line opposed to a circular pattern like a centre pivot. Section 2.4.5 of Chapter 2 looks at the industry standards around the uniformity coefficient, a CU of 92% is generally accepted as the standard that irrigators should be able to achieve. The modelling will aim to meet this standard although part-circle sprinklers are known to perform at a lower level of uniformity compared to full circle sprinkler.

5.2 PC - S3000 Boomback Modelling

5.2.1 Test 1

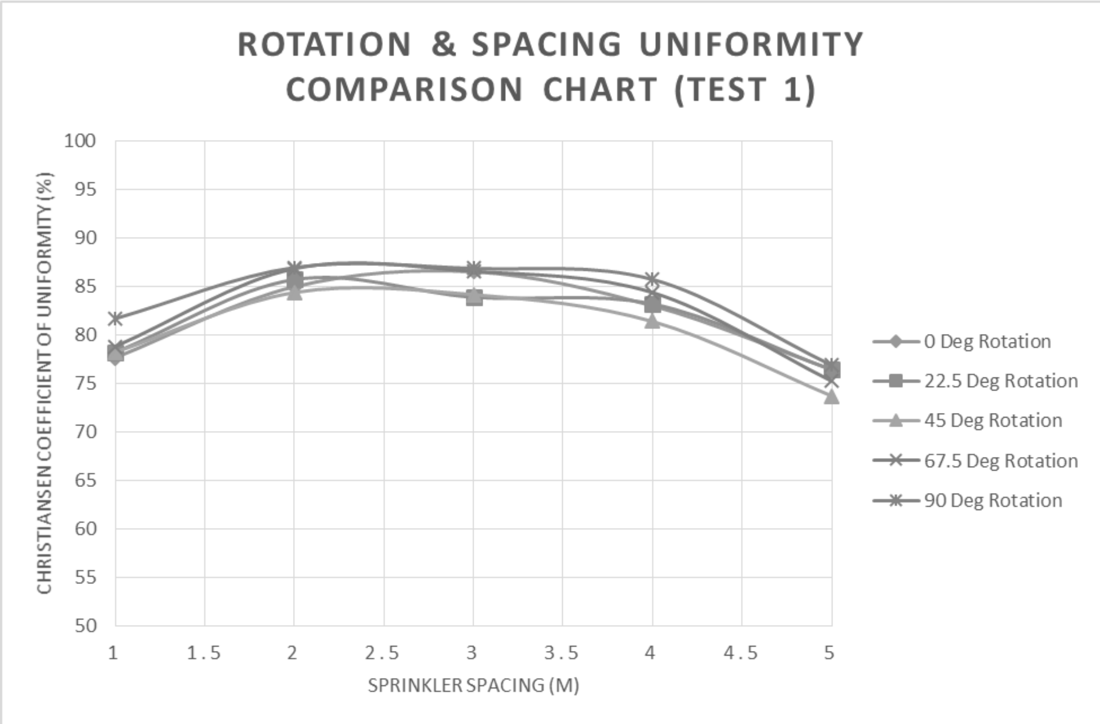

Figure 5:4 Test 1 -Modelling results

A trend can be seen in Figure 5:4, the sprinklers positioned at 1 metre and 5 metre spacing have significantly lower uniformity that those between 2 and 4 metres. The main point to come out of this model is that the combination of 68.95 KPa pressure setting and the number 14 nozzle works best between 2 and 4 metre spacing. The model revealed that the best combination of rotation and spacing is, 90 degrees of rotation spaced 3 metres apart, and this gives a Christiansen coefficient of 86.8% which is just below what is expected of modern irrigation systems. Since the optimum orientation of 90° is impractical in the field it is worth pointing out that the 0° of rotation which is typically of irrigation systems also performs very well with a CU of 86.5% again at the spacing of 3 metres, this indicates that under normal operation the setup modelled will perform adequately.

5.2.2 Test 2

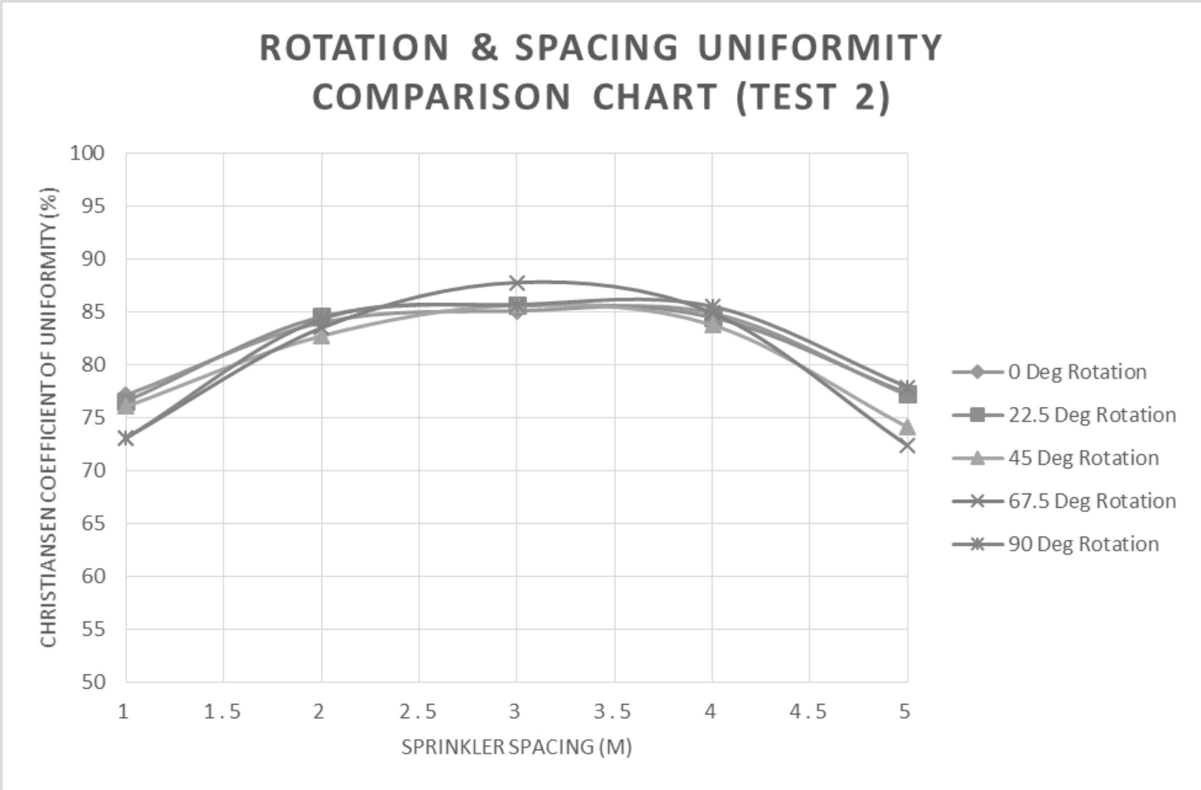

Figure 5:5 Test 2 - Modelling results

Figure 5:5 shows a consistent curve where the close 1 metre spacing and the 5 metre spacing performed poorly. This model clearly has an optimum combination of 3 metre spacing with an orientation of 67.5° which returned a CU of 87.7%. The various other tests show that spacing between 2 metres and 4 metres gives a CU ranged between 83% and 86% this range is acceptable although it is important to remember that this data relates only to ideal conditions, field conditions are very different to the conditions under which these tests were conducted which will have an effect on the coefficient of uniformity.

5.2.3 Test 3

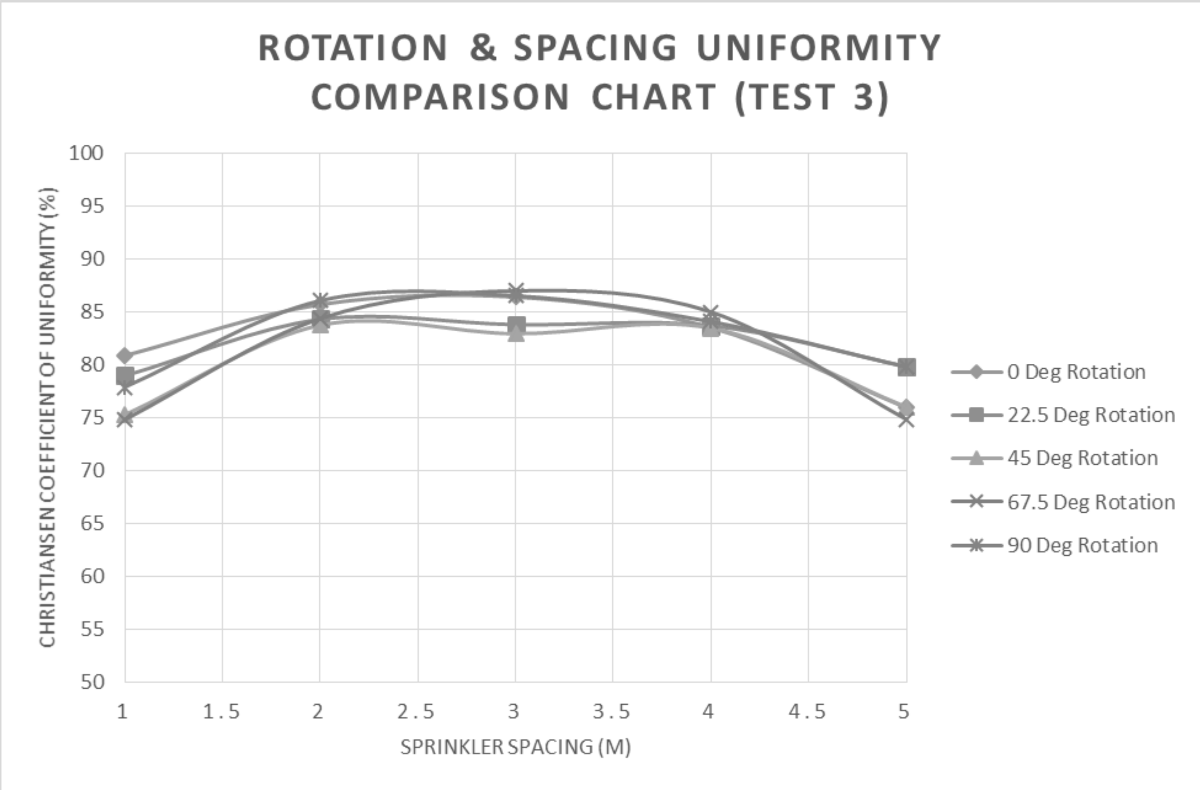

Figure 5:6 Test 3 - Modelling results

There is an ongoing trend this device which is that the outer spacing of 1 metre and 5 metres are significantly lower than the best setup. Any spacing between 2 metres and 4 metres will give reasonable uniformity no matter the orientation of the device itself. As with the previous test the 67.5° orientation is optimum with a CU of 86.9% which only just beats the 90° with a CU of 86.5 % both of these occur at a spacing of 3 metres. Figure 5:6 indicates a reduced CU for orientations of 22.5° and 45° at 3 metre spacing, this is also evident at 2 and 4 metre spacing's although this difference is not as pronounced as that seen at 3 metre spacing.

5.2.4 Test 4

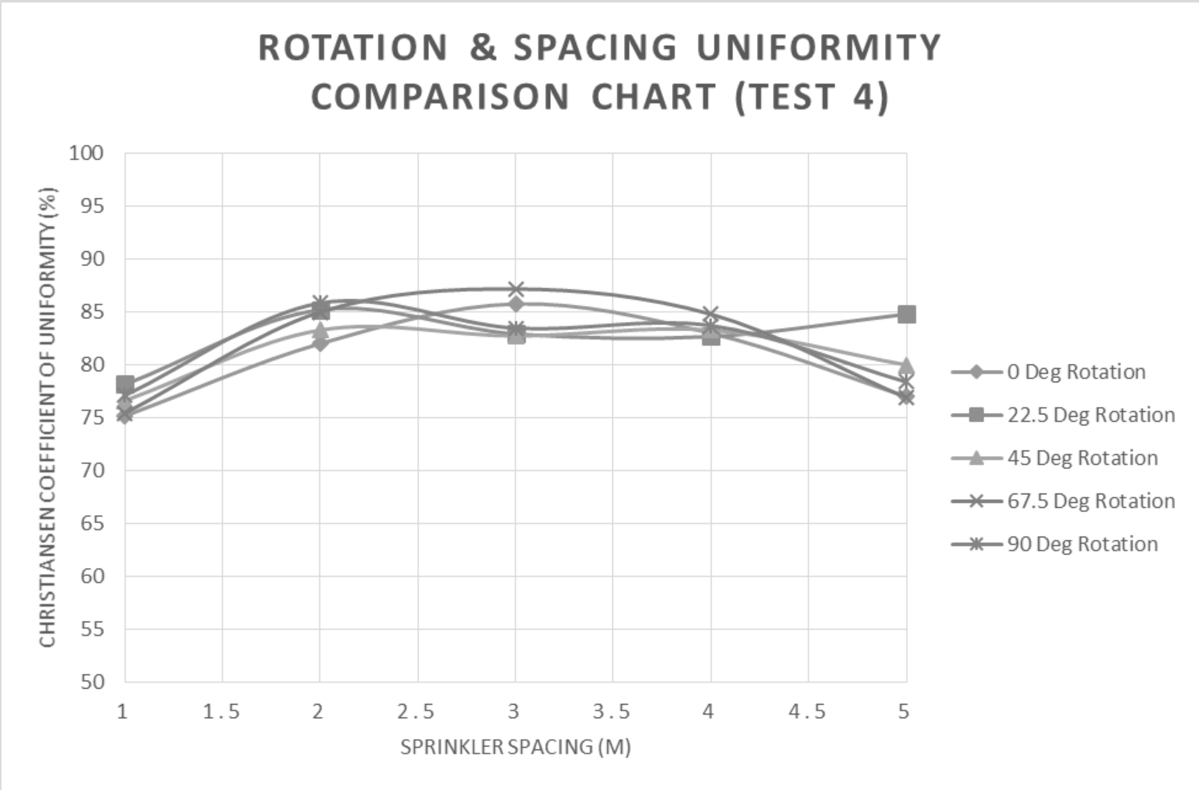

Figure 5:7 Test 4 - Modelling results

Test 4 used the 103.4 KPa pressure setting with the number 20 3TN nozzle, using the results from this test, the results were entered into the model revealing that the optimum position for the sprinkler is at 3 metre centre to centre spacing with an orientation of 67.5° developing a CU equal to 87.1%. An anomaly of this test is the result from the 22.5° orientation spaced at 5 metres test, after several retests the result of CU equal to 84.7% remained. This is significantly higher than the other tests not only with test 4 results but also all other testing results entered into the model. I am unclear as to why this anomaly occurred, it is most likely due to a regular application across a larger area not interfered by the sprinkler positioned alongside it. It should be noted also that if this is the case you would expect to see lower than average application volumes along the length of this design, as the sprinkler patterns would not be overlapping but rather side by side, reducing the applied volume in the line of travel but increasing the coefficient of uniformity.

5.2.5 Test 5

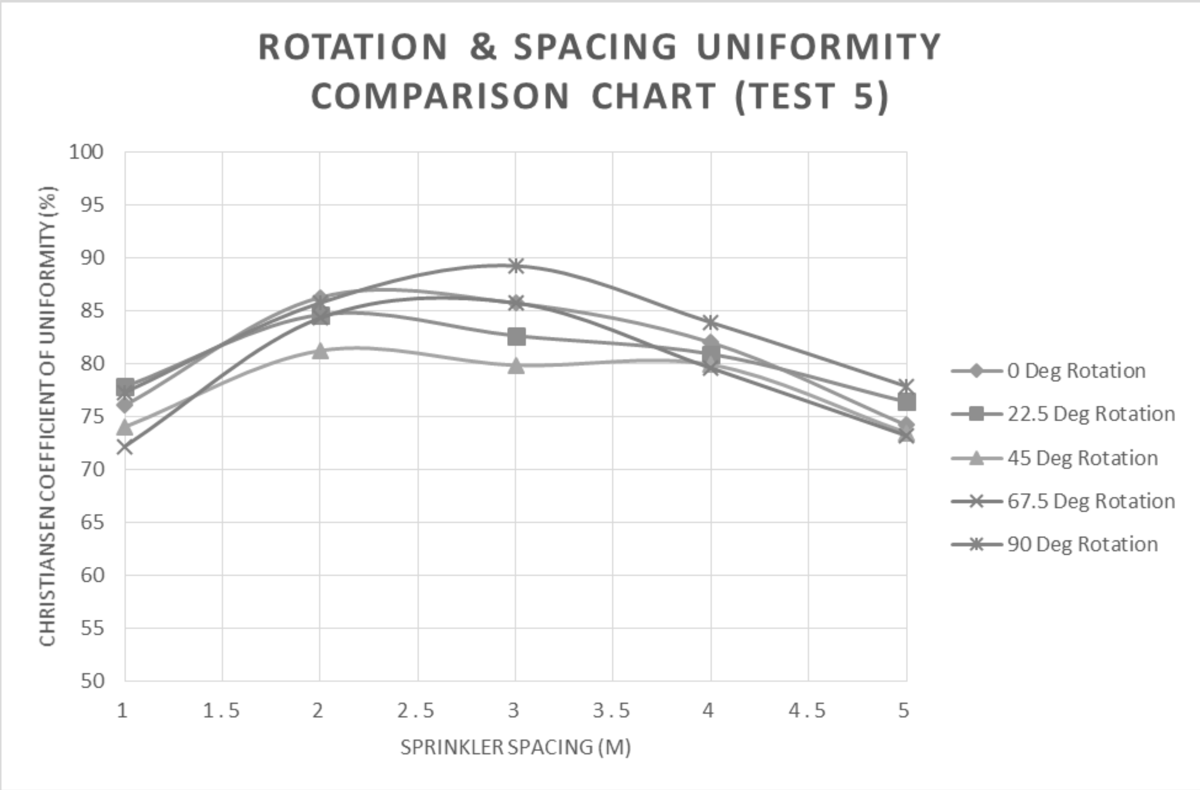

Figure 5:8 Test 5 - Modelling results

The model results for test five show a very promising result of a CU of 89.2% for the 90° orientation seen at a 3 metre spacing. This test indicates a widening gap between different modelled scenarios which would suggest that with larger nozzle sizes the spacing and orientation of the device has a significant effect on the uniformity produced by the PC-S3000 part-circle sprinkler.

A separate note is that the outer edges i.e. 1 metre and 5 metres spacing, the CU calculated is well below the 75% mark which is lower than any other scenarios modelled so far, once again this reinforces the theory that with higher nozzle sizes positioning these devices becomes more critical to the uniformity of the irrigator they are fitted to.

5.2.6 Test 6

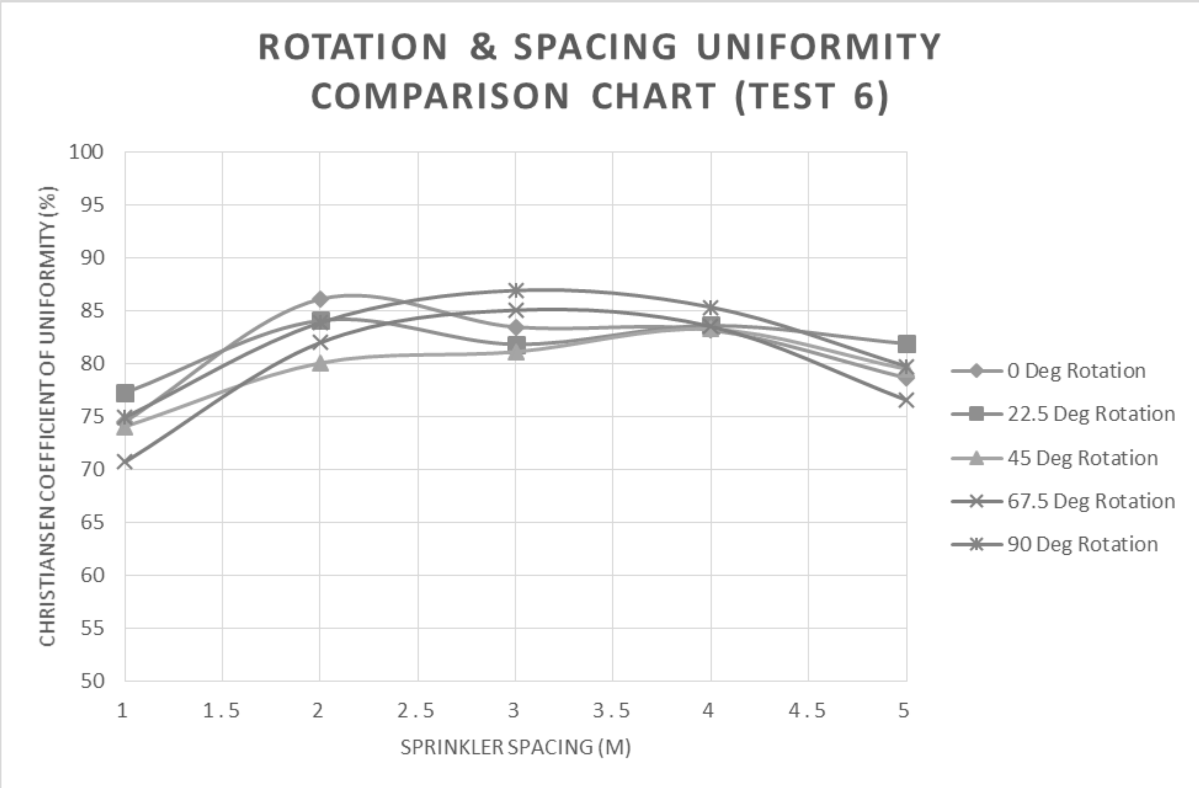

Figure 5:9 Test 6 - Modelling results

As with test 5 the 90° rotation provided the optimum CU of 86.9 % at a 3 metre spacing, not far behind was the 0° rotation spaced at 2 metres with a CU of 86.1%. Figure 5:9 two main patterns, the first is with the 0° and 22.5° models which indicate an optimum spacing of 2 metres before dropping away while on the other end of the scale the 67.5° and 90° models reveal optimum spacing's of 3 metres. The 67.5° model shows that there is a significant change between the best and worst coefficient of uniformity.

5.2.7 Test 7

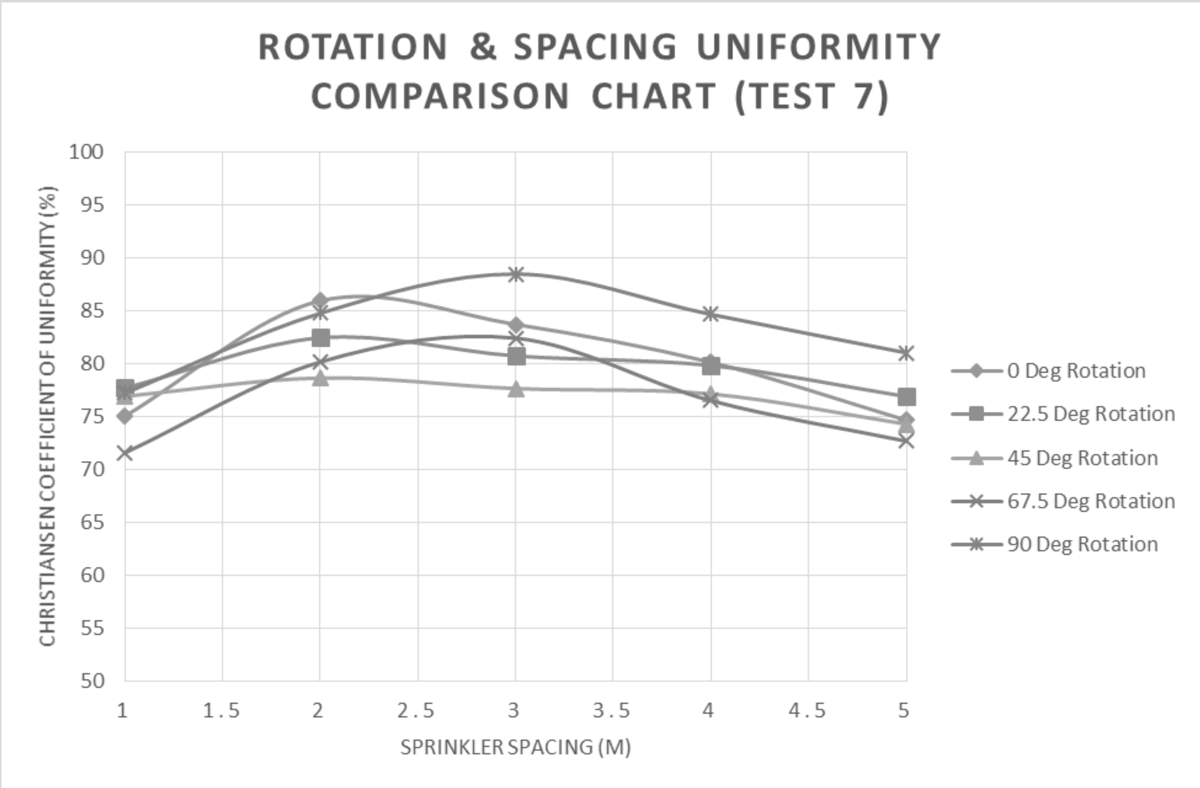

Figure 5:10 Test 7 - Modelling results

The previous two model results shows large variations between sprinkler setups, in this case the 90° rotation at 3 metres again gave the best result of 88.5% CU. It is clear that with higher flow rates these sprinklers become more temperamental with upwards of a 10% difference between the best and worst uniformity seen at the 3 metre spacing. The significant variations between plot lines in Figure 5:10 also backs up the theory that these devices need to be spaced and orientated in a very precise way to achieve optimum uniformity and application volumes.

5.2.8 Test 8

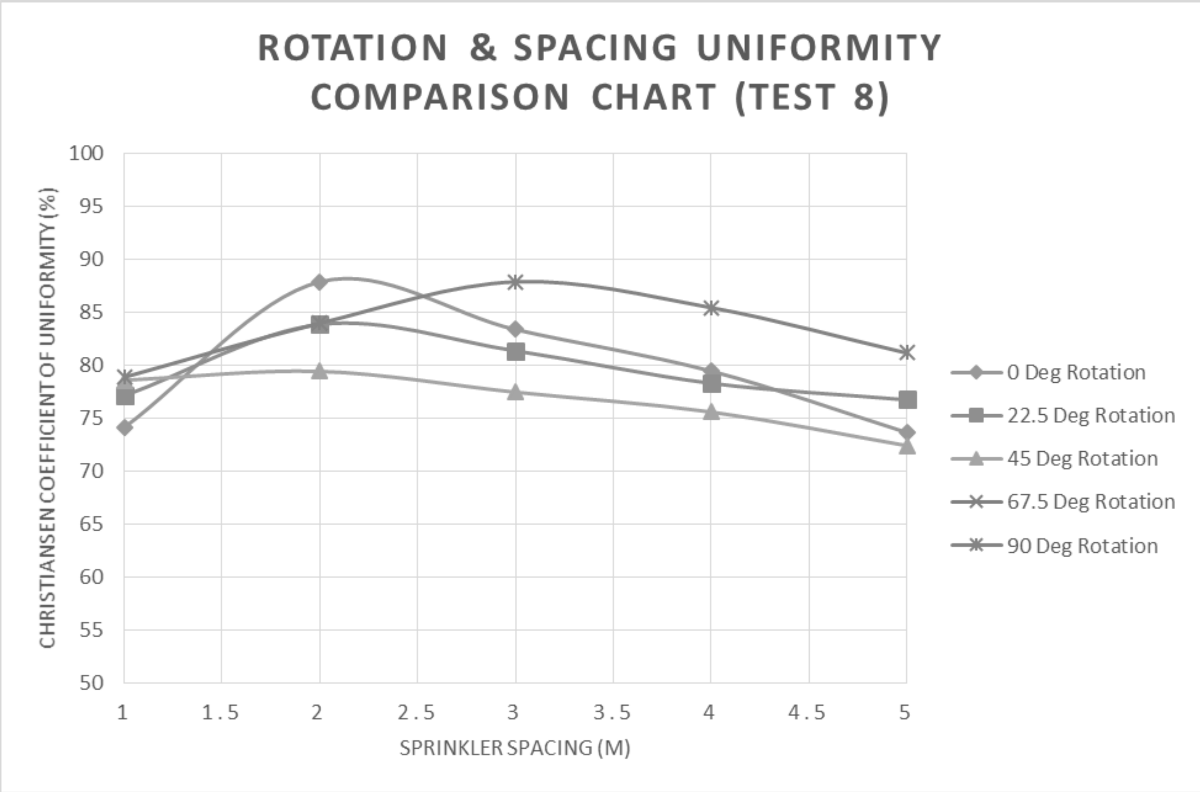

Figure 5:11 Test 8 - Modelling results

Unlike any other model results so far the 0° and 90° models both have virtually the same uniformity coefficient of 87.85% the difference is that the spacing is 2 metres and 3 metres respectively. Once again the large variations between modelled scenarios indicates high levels of variance at large nozzle sizes which follows the trends seen in the testing results for this sprinkler.

5.2.9 PC-S3000 Boomback Summary

The modelling carried out so far on this device unveiled two main trends, the first being the lower nozzle sizes were producing optimum uniformity spaced at 3 metres with an orientation of 67.5°. While at high flow rates the optimum uniformity was being developed by 90° orientation spaced at 3 metres. A third trend that was evident, with lower nozzle sizes the spacing and orientation did not produce huge differences in uniformity, the large nozzles were the opposite of that where spacing and orientation has a significant effect on how well this sprinkler performs.

Table 5:1 Spinning plate model results

PC - S3000 Model Results

Test	Spacing (m)	Orientation (Degrees)	CU (%)
1	3	90	86.6
2	3	67.5	87.7
3	3	67.5	86.9
4	3	67.5	87.1
5	3	90	89.2
6	3	90	86.9
7	3	90	88.5
8	3	90	87.85

Table 5:1 is a summary of the optimum spacing and orientations determined from each test as well as the Christiansen coefficient of uniformity calculated for each test. As indicated earlier test five is the most uniform of all the tests. Table 5:1 also shows that this sprinkler consistently provides the highest uniformity at a spacing of 3 metres and varies between 90 degrees and 67.5 degrees of orientation. All of these sprinkler layouts provide what I would class as a very high level of uniformity, anything above 85% uniformity for a part-circle sprinkler is a good result.

5.3 PC – D3000 Boomback Modelling

5.3.1 Test 1

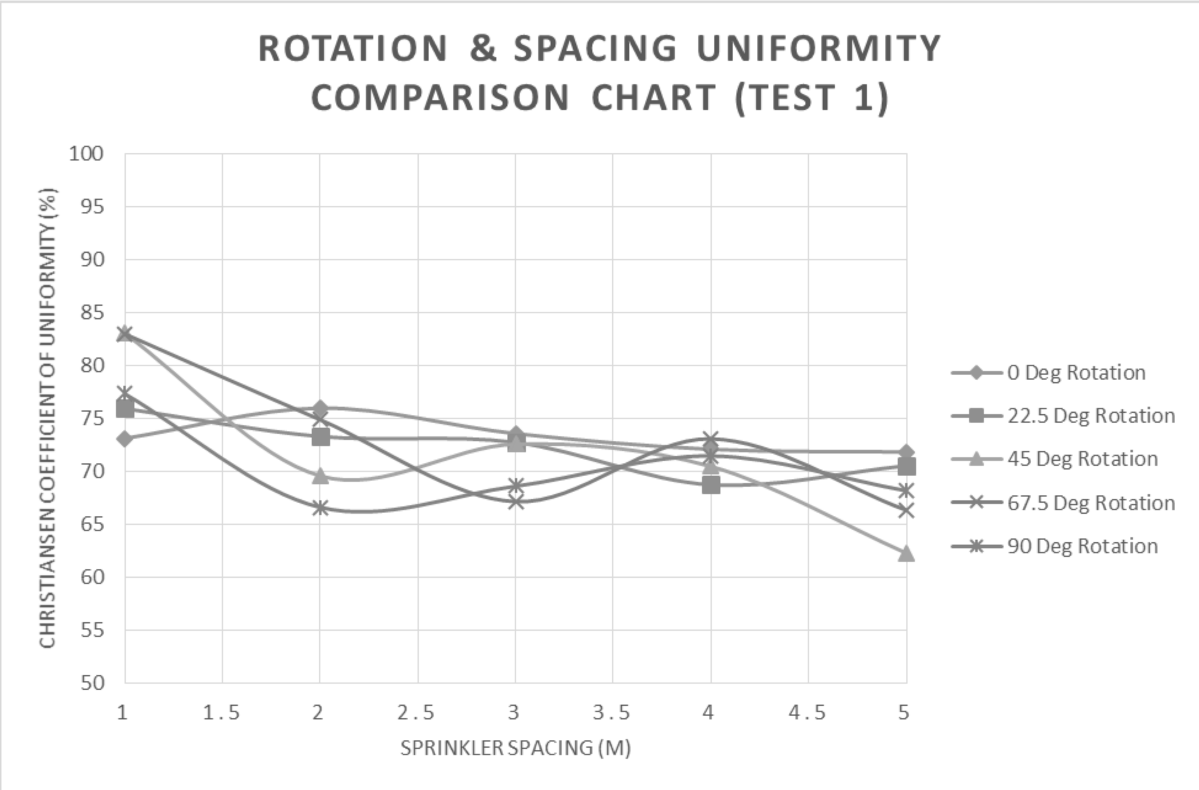

Figure 5:12 Test 1 - Modelling results

Figure 5:12 indicates a different trend than that of the spinning plate sprinkler, the static plate model shows a steady decrease in uniformity as the spacing increases. In this case the 45° orientation setup with a CU equal to 83% only just beats the 90° setup with 82.9% uniformity, both of these were calculated at 1 metre spacing. As stated earlier it is accepted in industry that the Christiansen Coefficient of Uniformity (CU) should not be below 70%, Figure 5:12 indicates that there are several combinations that are below this value and there for should be disregarded when designing a system using this sprinkler.

5.3.2 Test 2

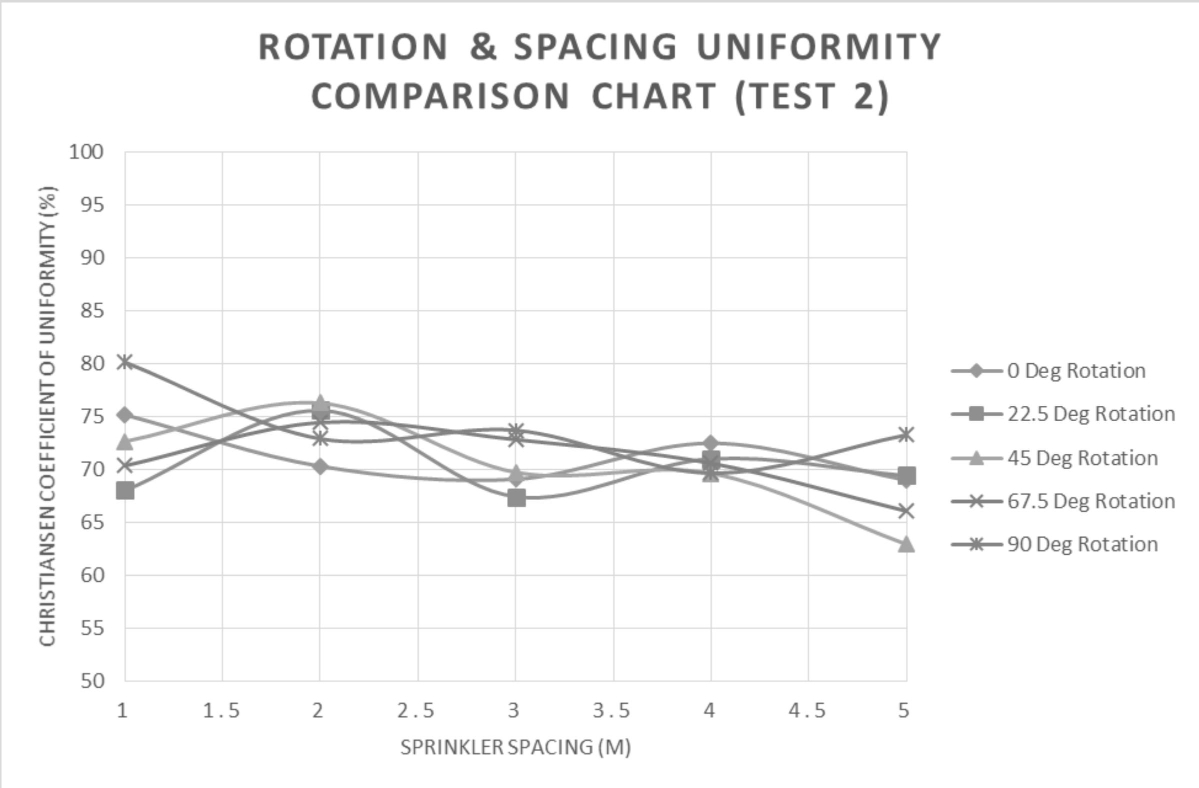

Figure 5:13 Test 2 - Modelling results

As with test 1 there is a declining uniformity with increased spacing, this is caused by the application pattern variability which is easily seen in CHAPTER 4. At a spacing of 1 metre the 90° orientation test is clearly more uniform than any other with a CU of 80.1% which is approximately 5% better than any other at that spacing.

5.3.3 Test 3

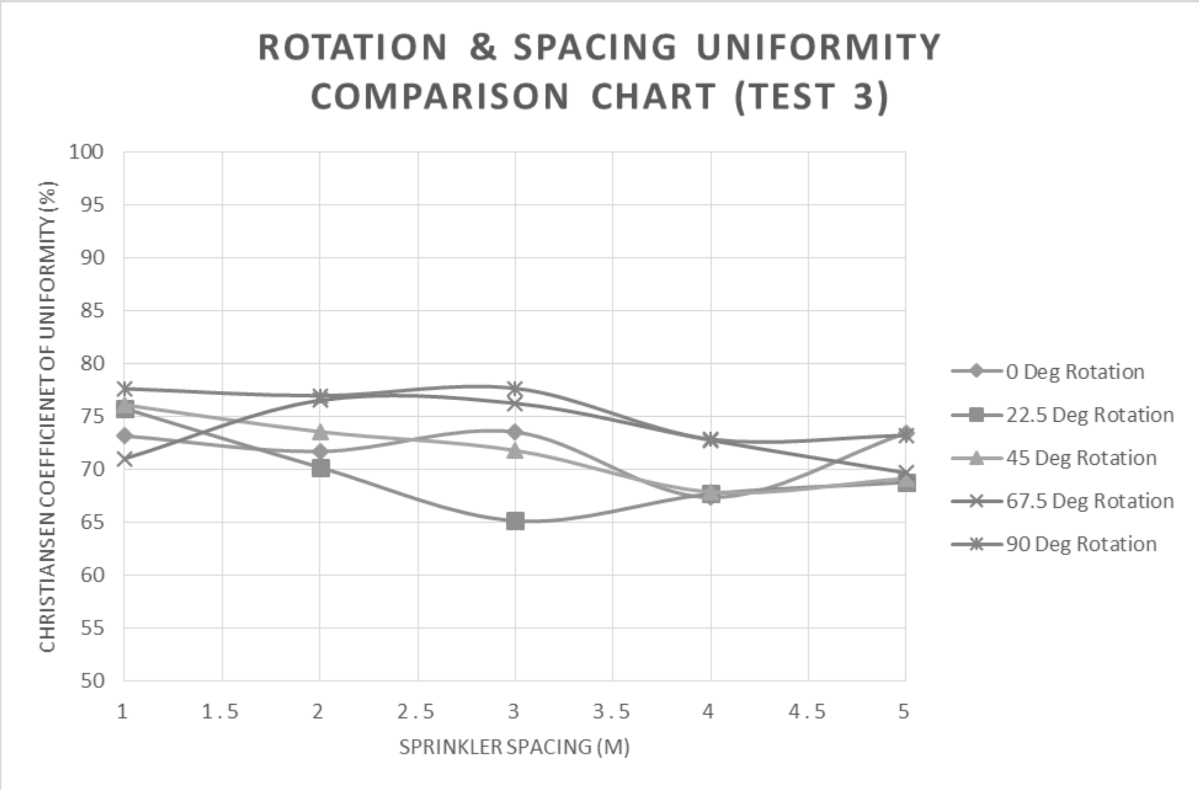

Figure 5:14 Test 3 - Modelling results

This model indicated that the 90° sprinkler orientation was optimum at 3 metre spacing with a CU of 77.7 % while the 1 metre spacing at the same orientation is very close at 77.66%. This would suggest that the sprinkler combination and orientation of 90° can operate at a spacing between 1 metre and 3 metres without changing the uniformity dramatically. Although once again we see large variations of uniformity as the angle changes.

5.3.4 Test 4

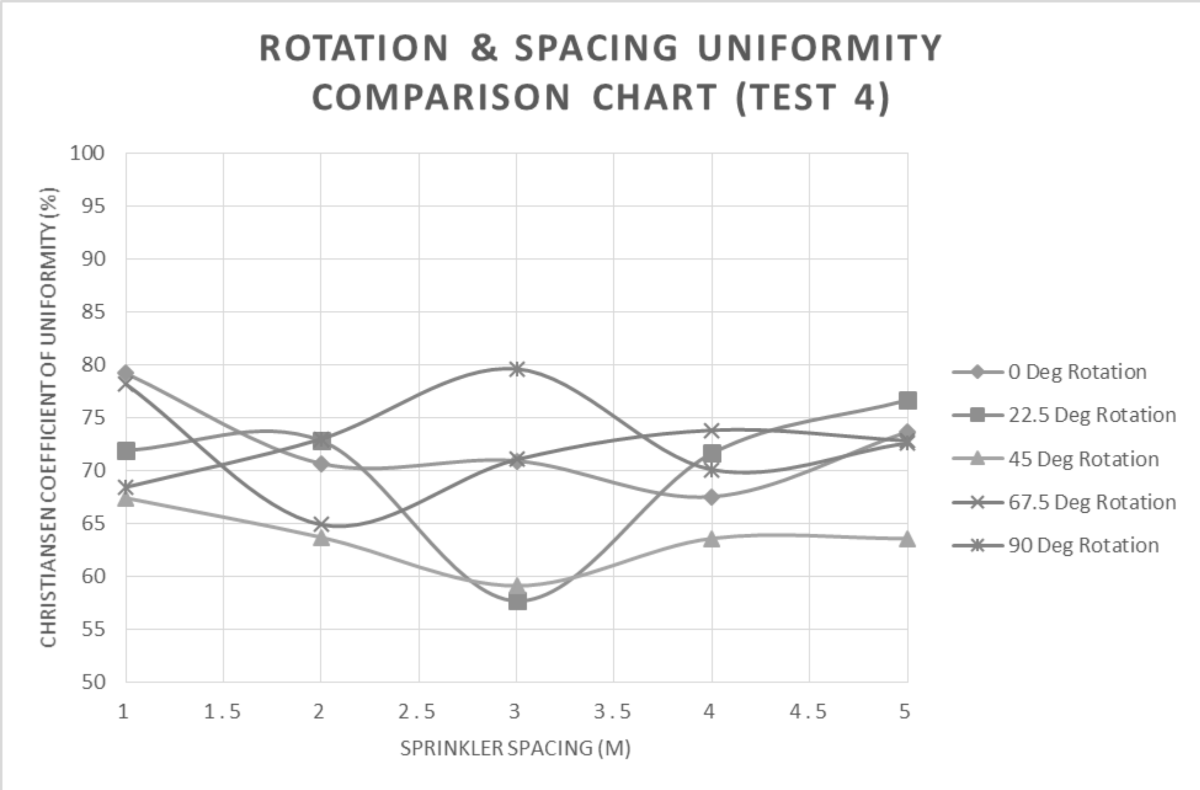

Figure 5:15 Test 4 - Modelling results

Figure 5:15 indicates that this combination of sprinkler, nozzle and pressure is very erratic with no discernible trend between scenarios tested in the model, there is a clear peak at 3 metres spacing for the 90° test this returned a CU of 79.6%, the two orientations close to 80% with a spacing of 1 metre are just below the optimum position noted above. This graph also shows that a lot of the CU values calculated were below the 70% threshold set by the industry which shows how poorly the combination performs when looking at the uniformity.

5.3.5 Test 5

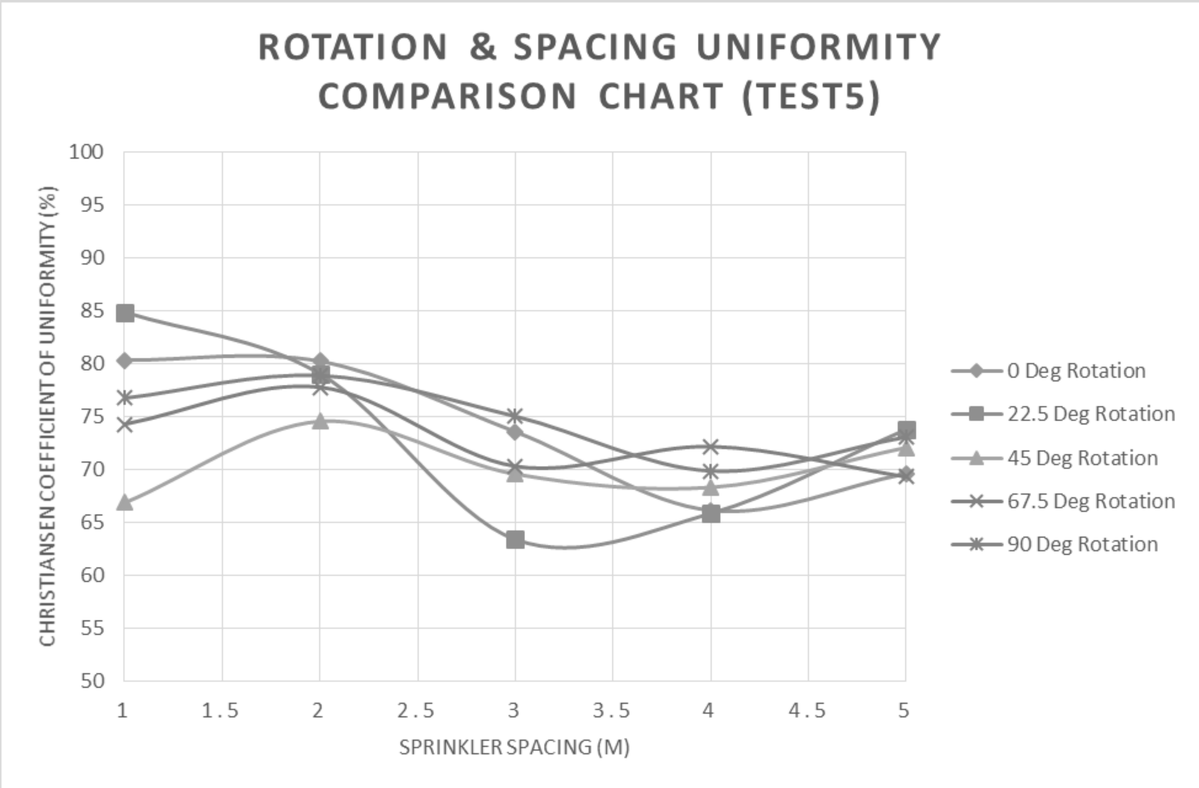

Figure 5:16 Test 5 - Modelling results

Figure 5:16 brings the return of the trend seen in early tests, with the optimum spacing being 1 metre, although surprisingly the optimum orientation is 22.5° which returned a CU of 84.9%. A second point to note about this models results is that there is a convergence of uniformity at the 2 metre spacing, this has not been evident in the previous models results and may be of relevance when designing a sprinkler layout for an irrigator.

5.3.6 Test 6

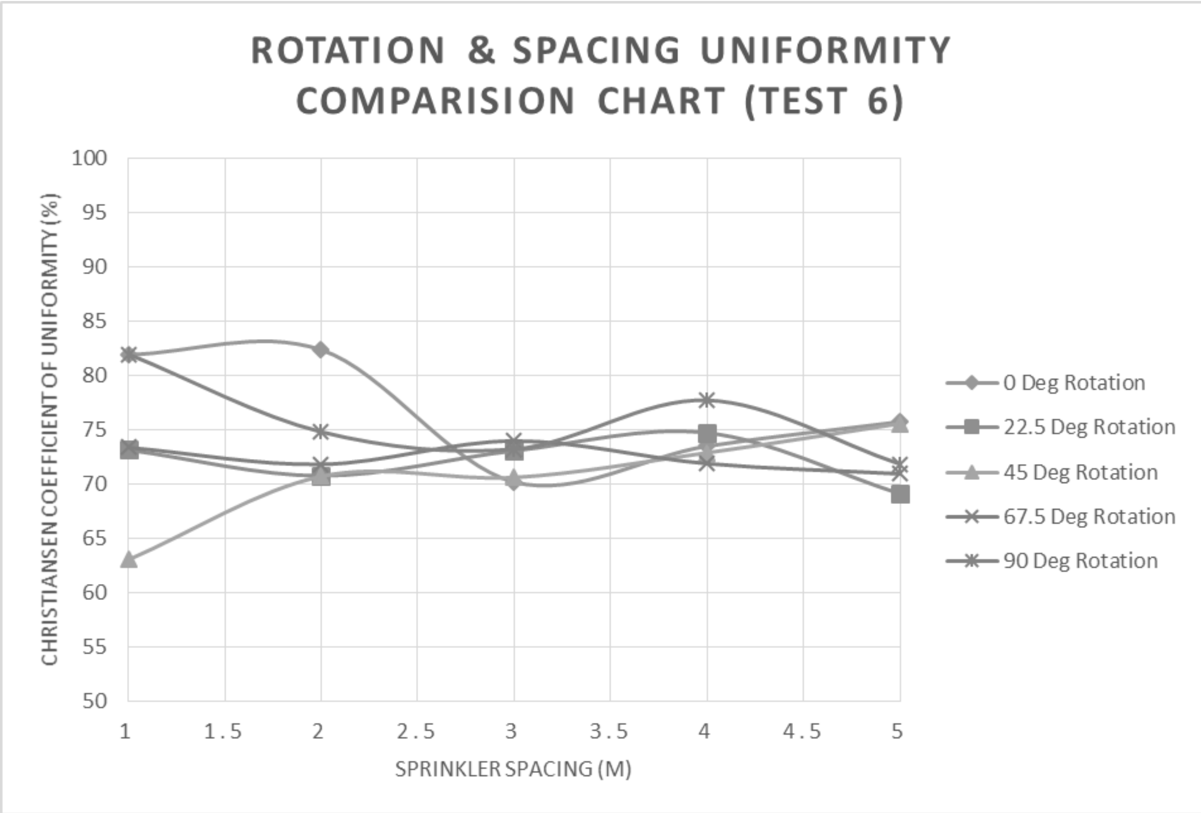

Figure 5:17 Test 6 - Modelling results

In this case a spacing of 2 metres and an orientation of 0° provides the optimum uniformity with a CU of 82.4% which is slightly higher than the 1 metre spacing of 81.9 % for the same orientation. This model shows a convergence of uniformities at the three metre spacing although at a lower uniformity, it is clear that this sprinkler has very inconstant uniformity and this is not changing as the nozzle sizes and pressure settings increase.

5.3.7 Test 7

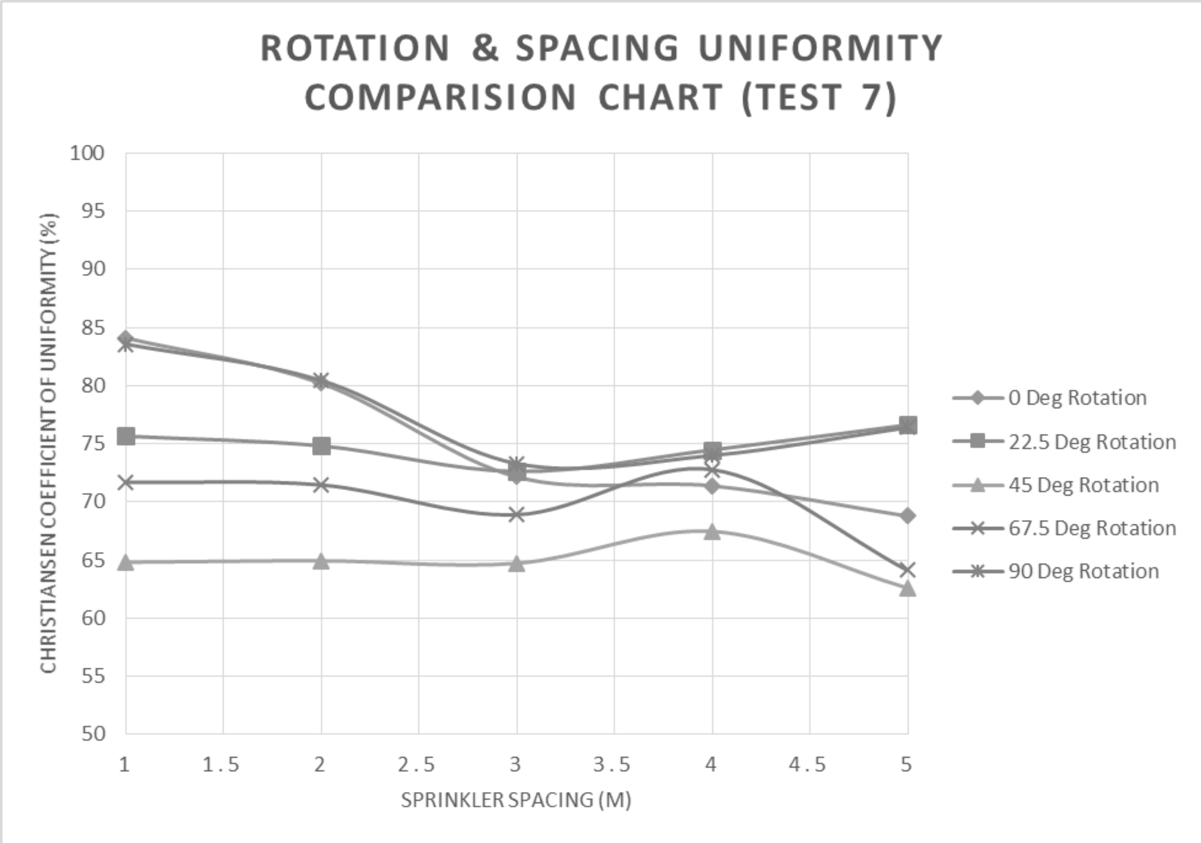

Figure 5:18 Test 7 - Modelling results

Test 7 results shows large differences between model results with the 45° setup performing consistently below the industry threshold of 70%. The largest CU was 84.1% seen at a spacing of 1 metre by the 0° orientation sprinkler. When considering the results of this sprinklers modelling it is very important to consider the results from testing. At higher nozzle sizes we sore large peaks of very high application depths in very precise places around the wetted area and this will have major implications for the modelling. If these large application depths are unique to the sprinkler used in testing then these results may not be representative of the overall performance of these sprinklers, this is a line of enquiry that must be followed up in future.

5.3.8 Test 8

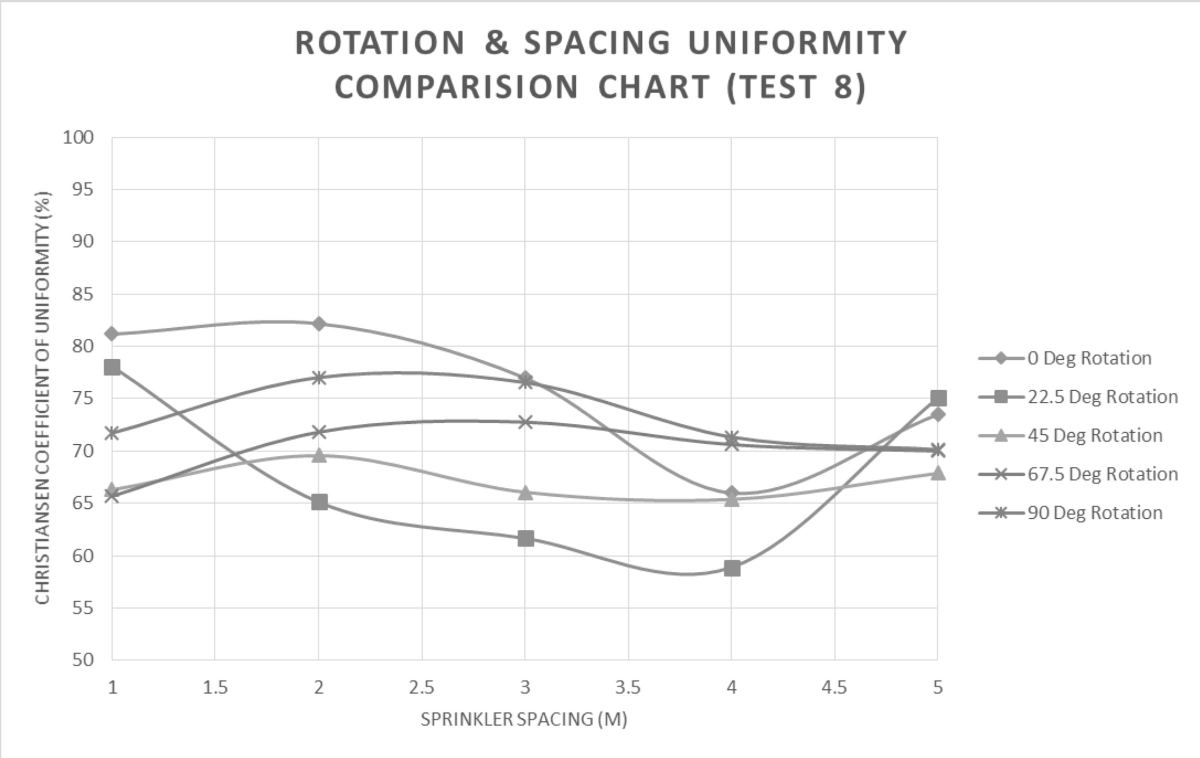

Figure 5:19 Test 8 - Modelling results

The results from this set of modelling show very large differences between results, this would suggest that like the spinning plate model sprinkler at large nozzle sizes the spacing and orientation of the sprinklers has a significant effect on the uniformity of the application. The 0° model results are consistently higher than the others with a CU of 82.2% at 2 metre spacing.

5.3.9 PC – D3000 Boomback summary

The modelling results show that the PC-D3000 performs very poorly in the uniformity test with results significantly lower than expected by industry. We did see a trend in the early test where the uniformity was greater at close spacing's of 1 metre, while at the larger nozzle sizes the uniformity was effected significantly by spacing and orientation angles. As stated earlier, outliers in testing would have affected the modelling results significantly and this must be looked at further before completely disregarding this type of sprinkler.

Table 5:2 Static plate model results

PC - D3000 Model Results

Test	Spacing (m)	Orientation (Degrees)	CU (%)
1	1	45	83
2	1	90	80.1
3	3	90	77.7
4	3	90	79.6
5	1	22.5	84.9
6	2	0	82.4
7	1	0	84.1
8	2	0	82.2

Table 5:2 shows a very different story to the results of the spinning plate sprinkler, the best design for this sprinkler is also test 5 with a uniformity coefficient of 84.9%. Table 5:2 shows just how temperamental this device can be with no obvious optimum spacing or orientation, although 90° or 0° seem to be favoured. Looking at the uniformity coefficients they range from good in tests 5 – 8 and poor for the rest as they have uniformities in the low eighties and late seventies which is considered poor by industry standards.

5.4 Optimisation of Sprinkler Positioning

To optimise the design placement of the part-circle sprinkler around irrigator towers the PC-S3000 model sprinkler setup using test 5 data as seen in Appendix B. Test five was selected because of the high Christiansen Coefficient of uniformity (CU) of 89.25%. Test five was conducted at 68.95KPa (10 PSI) using the number 28 3TN nozzle which is a midrange nozzle, this configuration is an average and common setup applied in the field. The idea of the optimisation was to determine if the uniformity could be increased by manipulating the spacing and orientation of the sprinklers around the tower.

5.4.1 Developing new designs

When looking at developing new designs the model produced for the boomback testing was altered to allow for each sprinkler to be orientated and spaced separately. Once this was completed trials were conducted using different sprinkler spacing and orientations. The information obtained from the boomback modelling was utilised including the optimum spacing and orientation for the sprinkler setup that was chosen.

The layout design is based around the issue of wheel rutting and bogging outlined in Chapter 2. The designs are set out so that no water is applied to the wheel tracks in front and under the towers. The first two designs incorporate two sprinklers on either side of the tower, the main issue with this method is that water is not being applied to the area very close to the tower. All of the designs position the closest sprinkler 1 metre from the tower which means that there is a 2 metre gap under the towers that are not receiving any water, which reduces the ability to grow crops in that area. To combat that issue a fifth sprinkler was employed in designs 3 – 5 which eliminates the issue of low water supply in the area under and around the tower. When reading the tables below the ‘spacing from the tower’ indicates the distance moving out from the tower with a distance of 0 metres indicating it is in line with the tower. All angles are taken from zero degrees on the right hand side of the figure as per Figure 5:3.

5.4.2 Selected designs

5.4.2.1 Design 1

Design one incorporated four sprinklers, the two sprinklers closest to the towers are placed on boombacks to move the application area behind the rear tower which eliminates the issue of wheel rutting and bogging. Table 5:3 indicates the angle the sprinkler must be orientated as well as the distance from the tower that it will be placed.

Table 5:3 Design 1 information

Design 1

Sprinkler	Angle	Spacing from Tower
1	90	-3
2	45	-1
3	315	1
4	250	3

Using the model developed in MatLab this design achieved a coefficient of uniformity (CU) of 83.67%. Figure 5:20 is a visual representation of the design, this gives a greater appreciation of the layout if applied to an irrigator. It is easy to visualise how these sprinklers are positioned to avoid applying water to the tower and wheel tracks.

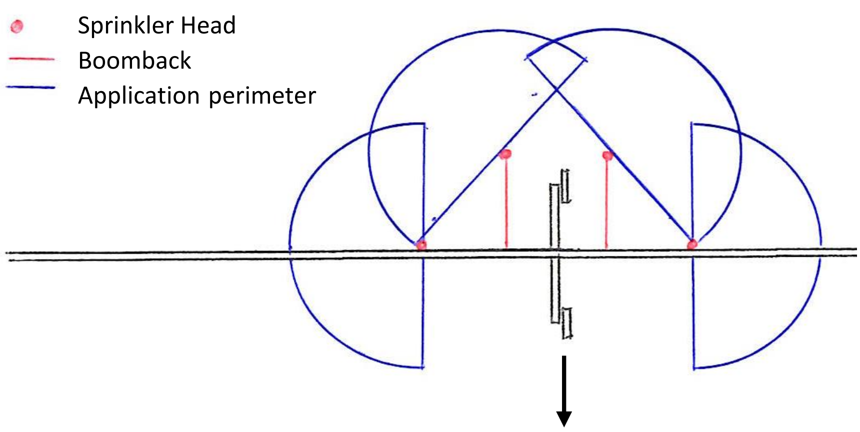

Figure 5:20 Design 1 layout

5.4.2.2 Design 2

Design two improves on the first design while still only using four sprinklers, as with design one, the two closest sprinklers are positioned on boombacks to allow for coverage of the area directly behind the tower.

Table 5:4 Design 2 information

Design 2

Sprinkler	Angle	Spacing from Tower
1	67.5	-3
2	45	-1
3	315	1
4	292.5	3

This design yielded a coefficient of uniformity of 87.47% this is a huge improvement on design one. After manipulating the spacing and orientation of the four sprinklers it was determined that using this model design two was the optimum design using only four sprinklers.

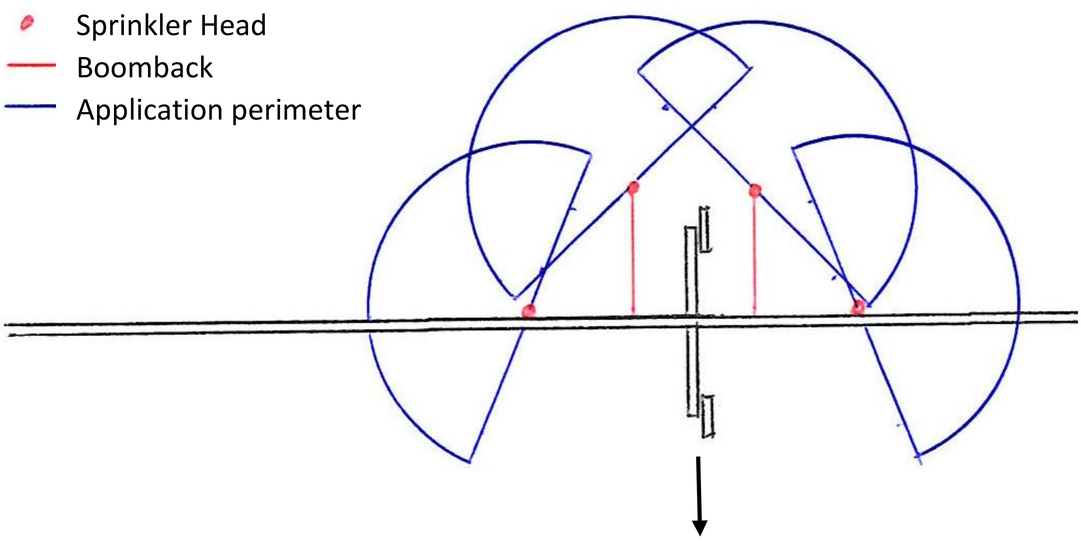

Figure 5:21 Design 2 layout

5.4.2.3 Design 3

After reaching the maximum uniformity with four sprinklers, the next option was to assess how a fifth sprinkler positioned behind the tower would affect the calculated uniformity. This decision lead to higher uniformities but also helped increase application volumes around the towers, which would work to combat the issue of low crop yields around towers. Table 5:5 provides the spacing and orientation of the sprinklers in this design.

Table 5:5 Design 3 information

Design 3

Sprinkler	Angle	Spacing from Tower
1	90	-3
2	45	-1
3	0	0
4	315	1
5	250	3

Figure 5:22 shows the position of sprinkler three behind the tower, sprinklers 2, 3 and 4 are positioned behind the tower wheels with the use of boombacks this allows for the application patters to overlap. The model estimated the uniformity to be equal to 84.99% which is higher than design 1 which has a similar design.

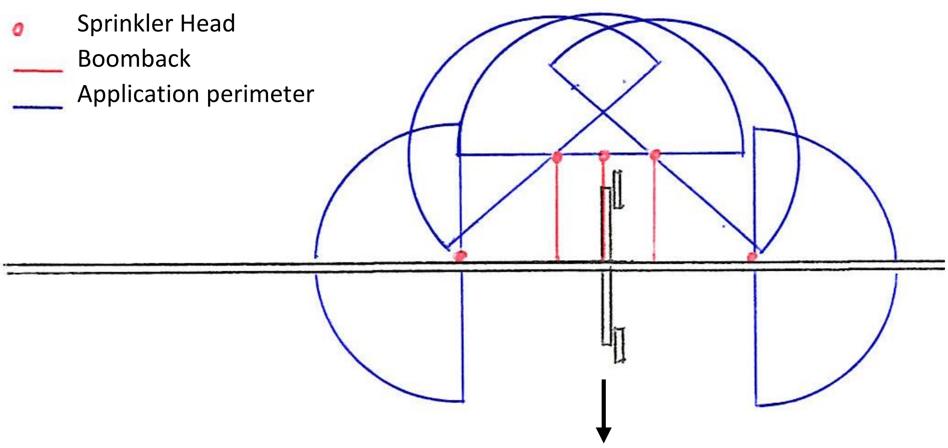

Figure 5:22 Design 3 layout

5.4.2.4 Design 4

Further manipulation of the orientations of the sprinklers lead to design four which is a different design to the previous 3. If the sprinklers are positioned correctly the four sprinklers positioned to the side of the towers will not need boombacks which eliminates a cost when installing the lateral move or centre pivot irrigator.

Table 5:6 Design 4 information

Design 4

Sprinkler	Angle	Spacing from Tower
1	67.5	-3
2	67.5	-1
3	0	0
4	292.5	1
5	292.5	3

The coefficient of uniformity for this design was calculated to be 88.12% which is the highest uniformity of all the designs so far, Figure 5:23 illustrates this unique design.

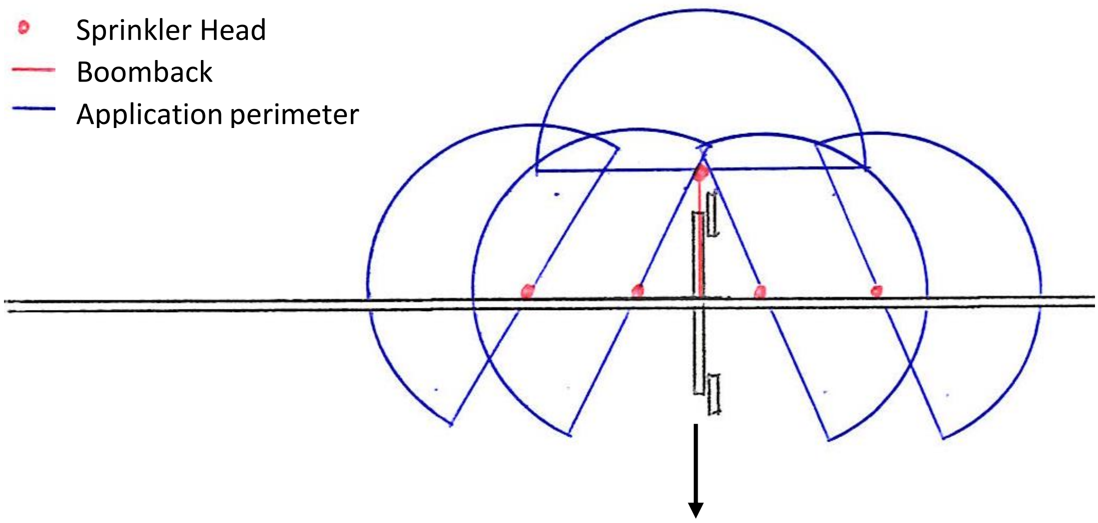

Figure 5:23 Design 4 layout

5.4.2.5 Design 5

Design five incorporates design two's sprinkler orientations and spacing while introducing a fifth sprinkler over the tower to yield the highest coefficient of uniformity with a CU equal to 88.96%. Table 5:7 gives the design parameters needed to produce this design.

Table 5:7 Design 5 information

Design 5

Sprinkler	Angle	Spacing from Tower
1	67.5	-3
2	45	-1
3	0	0
4	315	1
5	292.5	3

Figure 5:24 illustrates the sprinkler layout of this design, the overlap of this design is what produces the great uniformity, it also works to increase the application volume around the tower which will ultimately increase crop yield. The coefficient of uniformity for this design is 88.96% which is less than the 92% standard set by industry, but this result does reinforce the notion that part-circle sprinklers are not able to achieve the high level of unformity that standard sprinklers can.

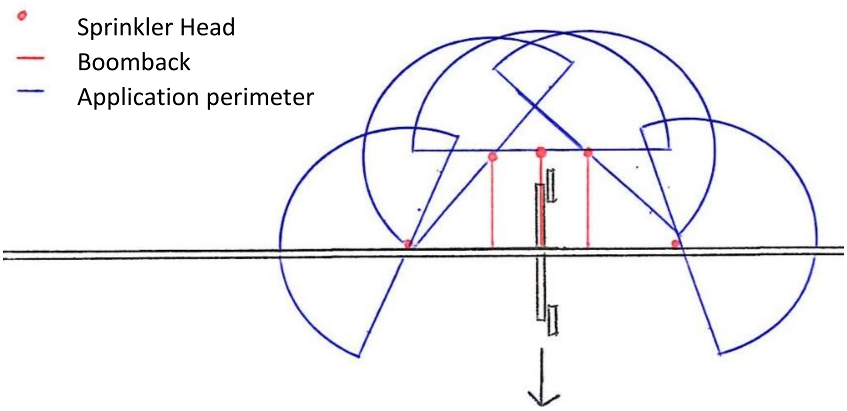

Figure 5:24 Design 5 layout

5.5 Modelling Summary

The purpose of conducting modelling with the data collected as part of the testing phase of this project was to evaluate the uniformity of part-circle sprinklers. In order to assess the uniformity each sprinkler test was evaluated at different spacing and orientation settings, form that data the Christiansen coefficient of uniformity was calculated. The Christiansen's coefficient is considered the standard method for determining uniformity at the end of the modelling, test 5 of the PC-S3000 model sprinkler was selected for its high level of uniformity. This sprinkler was then manipulated to find the optimum position and orientation, the design must be able to be realistically applied to both new and operational lateral move and centre pivot irrigators. A layout incorporating five sprinklers was developed which returned a Christiansen's coefficient of 88.96%, this design can be applied to machines provided a method is determined to easily position the sprinkler heads at the orientation specified. If the problem of ease of application can be fixed this design stands to reduce issues such as low crop yield as well as wheel rutting and bogging.

Chapter 6 DISCUSSION

The purpose of this dissertation is to conduct an investigation into how part-circle irrigation sprinklers perform, mainly looking at their uniformity. During the literature review it became apparent that testing of part-circle sprinklers was a research area that had not been considered in a big way which provided a great opportunity to conduct very meaningful research. The problem with not having research to continue on with is there is no previous studies to base this research off, this meant that there are many areas that can be improved on in future work.

The methodology used to conduct the testing provided many areas of improvement for the next study on this topic. The main improvement that needs to be made moving forward is the amount of data points used in each test needs to be increased, the results and modelling sections touched on the issue of missing areas of applied volumes, particularly with regards to the static plate model sprinkler. By increasing the number of catch cans and also the way they are positioned the uniformity of each sprinkler can be determined with a much higher degree of accuracy. The method by which the catch cans were laid out during testing, while it was a good start needs to be improved. Towards the middle of the wetted area the spacing between the catch cans increased to the point where they could have been missing very important information as to where the water is being applied and also how intense the application is. It is important to note that this does not mean the data collected during testing was not accurate, but rather more information would be beneficial to future studies.

Possibly the biggest limitation of testing for this project was the facility the tests were conducted in, due to the nature of the tests that must be completed a large open area is required to conduct a test.

Unfortunately the limitation of space meant that testing at higher pressure settings and nozzles sizes could not be conducted. The limitation of space also meant that testing at 2.44 metres (sprinkler height) was not able to be completed as the throw radius would have been too great for the space available. Future work needs to include testing at higher pressures, nozzle sizes and sprinkler heights so that a comparison of uniformity performance can be carried out, giving a much greater ability to optimise the design and placement of part-circle irrigation sprinklers positioned on lateral move and centre pivot irrigators.

A really positive outcome from the spinning plate model (PC-S3000) sprinkler was the overall uniformity of the sprinkler under ideal static conditions. Test results indicated that the device provides a great uniformity and this was backed up with the modelling results although with minor changes to the design of the sprinkler head the uniformity could be increased further. Results also unveiled two issues with the sprinkler, the first is the shape of the application area were applied depth data revealed a 'horse shoe' shaped perimeter rather than a uniform circular pattern as expected. It is important that this is considered when designing sprinkler layouts to be fitted to machines as it does effect uniformity. The second issue is a major problem because these sprinklers lose vast amounts of water directly under the sprinkler head, test results reveal the average loss is 83.57 mm/h under the sprinkler. This is mostly down to the design of the sprinkler head, Figure 4:17 shows how the supports for the spinner plate effect the distribution of water.

The static plate model sprinkler PC-D3000 performed poorly with regards to uniformity, and this was backed up in the modelling stage of the dissertation. Like the spinning plate sprinkler the static plate also produced a 'horse shoe' shaped application pattern, but did not suffer the high level losses that the PC-S3000 model did. The static plate though did have a major issue of its own, this came in the form of extremely high application rates scattered over the wetted area at very specific places. It is unclear if this is an isolated issue specific to the sprinkler used or whether it is an issue for the PC-D3000 model sprinkler, this problem had a major effect on the uniformity of these sprinklers and should be further analysed.

The results section for these tests also highlights an issue of sheeting which occurs when using high flow nozzles it is theorised that the issue of sheeting may actually increase the uniformity of the sprinkler. An increase in catch cans used per test would allow for a more in depth analysis of this idea, the data collected as part of the testing carried out was insufficient to confirm or otherwise comment on the validity of this theory and should be investigated further.

Modelling of the PC-S3000 spinning plate and PC-D3000 static plate model part-circle sprinklers was simple but still yielded very good information. All of the tests carried out were modelled in the same way initially to calculate the Christiansen's coefficient of uniformity which is the industry standard for measuring uniformity of an irrigation system. The coefficient of uniformity test revealed that the spinning plate model sprinkler performed significantly better than the static plate model device, Table 5:1 shows the best results for the PC-S3000 model sprinkler while Table 5:2 gives the best results for the static plate sprinkler. The highest coefficient of uniformity recorded was test 5 of the PC-S3000 sprinkler. This data was then used to develop five designs with a mix of 4 or 5 sprinklers all placed around an irrigation tower in an effort to reduce the risk of water entering the machines wheel tracks. The best design also needed to increase the application depth around the tower to combat a significant issue of low crop yields in the area immediately around a tower.

After many different trials design five was determined to produce the best uniformity with a coefficient of uniformity equal to 88.96% which is a very good result. The industry standard for standard sprinklers is a coefficient of uniformity equal to or higher than 92% although literature states that part-circle sprinklers do not perform to this high standard. The design developed although not meeting industry standards is very promising and not very far off the benchmark standard. This project unfortunately did not test the final design in the field and as a result did not get a chance to validate the model, it is hoped that future work in this area of study will be able to do this and hopefully make adjustments to improve on the design.

(This page is intentionally blank)

Chapter 7 CONCLUSION

Part-circle irrigation sprinklers were designed to solve problems such as wheel rutting and help to fill the areas where standard irrigation sprinklers could not perform. The development of these devices while they have served that initial design brief have also caused issues for manufactures and growers alike. Research into the performance and management strategies for these sprinklers is overdue and this dissertation is just a start at filling the knowledge gap around the performance of these sprinklers. The project has meet the brief of testing and analysing the performance of two of the sprinkler but has posed more questions than answers about how these sprinklers can be operated at the highest efficiency possible. The industry as a whole is looking to optimise the design and operation of centre pivot and lateral move irrigators, and as long as part-circle sprinklers form part of the solution their performance needs to be scrutinised just as the standard sprinklers have been, and the research carried out as part of this dissertation highlights the need for more work to be done.

7.1 Future Work

Throughout this project the sprinklers tested have offered up many areas of future work that needs to be carried out, right from the need to test the other two sprinklers available on the market, to the need to test individual sprinklers more thoroughly to assess the issues highlighted throughout this dissertation. Moving forward with research into this topic should focus on testing the two sprinklers used in this project under field conditions to validate and improve the model that was developed. If a model can be developed that is proven to work then sprinklers that were not tested can be analysed and comparisons can be made between devices. This should lead to the development of a set of design standards or tables that installers can easily use to optimise designs on both new and existing centre pivot, and lateral move irrigation machines both in Australia and around the world.

REFERENCES

Al-Kufaishi, S. A., Blackmore, B. S. & Sourell, H., 2005. The Potential Contribution of Precision Irrigation to Water Conservation. *Precision Agriculture 05,* pp. 943 - 950.

Australian Bureau of Statistics , 2013. *Gross value of irrigated agricultural prodction, 2011 - 12.* [Online]
Available at:
http://www.abs.gov.au/ausstats/abs@.nsf/Lookup/4610.0.55.008main+features42011-12
[Accessed 04 August 2015].

Australian Bureau of Statistics , 2014. *Gross value of irrigated agricultural production 2012-13,* Canberra, Australia: Australian Bureau of Statistics (4610.0.55.008).

Australian Bureau of Statistics, 2014. *Water use on Australian Farms, 2012 - 13.* [Online]
Available at:
http://www.abs.gov.au/AUSSTATS/abs@.nsf/Latestproducts/4618.0Main%20Features32012-13?opendocument&tabname=Summary&prodno=4618.0&issue=2012-13&num=&view=
[Accessed 13 May 2015].

Bremond, B. & Molle, B., 1995. Characterisation of rainfall under centre pivot: influence of measuring procedure. *Journal of Irrigation and Drainage Engineeeing,* 121(September/October), pp. 347 - 353.

Christiansen, J. E., 1942. *Irrigation by Sprinkling,* Berkeley: University of California.

Department of Primary Industries Victoria, 2006. *Centre Pivot Wheel Rutting - AG1261.* [Online]
Available at: http://www.depi.vic.gov.au/agriculture-and-food/farm-management/soil-and-water/irrigation/centre-pivot-wheel-rutting
[Accessed 20 May 2015].

Evans, R. G., LaRue, J., Stone, K. C. & King, B. A., 2013. Adoption of Site Specific Variable Rate Sprinkler Irrigation Systems. *Irrigation Science,* 31(4), pp. 871 - 887.

Foley, J., n.d. Centre Pivot and Lateral Move Machines. In: *WATERpak - a guide for irrigation management in cotton.* s.l.:s.n., pp. 195 - 220.

Foley, J. P. & Raine, S. R., 2001. *Centre pivot and lateral move machines in the Australian cotton indurstry,* Toowoomba: National Centre for Engineering in Agriculture.

Food & Agriculture Organisation of the United Nations, 2010. *Water at a glance - The relationship between water, agriculture, food security and poverty.* [Online]
Available at: http://www.fao.org/documents/card/en/c/1e33db46-60a4-5892-b725-4b9e2ac728ba/
[Accessed 12 May 2015].

Ganzel, B., 2006. *Centre Pivots Take Over.* [Online]
Available at: http://www.livinghistoryfarm.org/farminginthe50s/water_03.html
[Accessed 30 March 2015].

Hein, P. R. & Heermann, D. F., 1968. Performance Characteristics of self propelled pivot sprinkler irrigation system. *Transactions of ASAE,* 11(1), pp. 11 - 15.

Howell, T. A., 2003. *Irrigation Efficiency.* [Online]
Available at: http://www.cprl.ars.usda.gov/pdfs/Howell-Irrig%20Efficiency-Ency%20Water%20Sci.pdf
[Accessed 22 May 2015].

International Comission on Irrigation and Drainage (ICID), 2012. *Irrigation History.* [Online]
Available at: http://www.icid.org/res_irrigation.html
[Accessed 30 March 2015].

International Commission on Irrigation and Drainage (ICID), 2012. *Food Irrigation (Surface Irrigation).* [Online]
Available at: http://www.icid.org/res_irri_flood.html
[Accessed 30 March 2015].

ISO 15886-3, 2012. *Agricultural Irrigation equipment - Sprinklers - Characterisation of Distribution and Test Methods.* s.l.:s.n.

Kincaid, D. C., Solomon, K. H. & Oliphant, J. C., 1996. Drop Size Distributions for Irrigation Sprinklers. *Transactions of the ASAE,* 39(3), pp. 839 - 845.

Kohl, R. A. & Deboer, D. W., 1984. Drop Size Distributions for a Low Pressure Spray Type Agricultural Sprinkler. *Transactions of the ASAE,* pp. 1836 - 1840.

Marek, T. H., Undersander, D. J. & Ebeling, L. L., 1986. An Areal-Weighted Uniformity Coefficient For Centre Pivot Irrigation Systems. *Transactions of ASAE,* 29(6), pp. 1165 - 1667.

Mays, L. W., 2008. *Irrigation Systems, Ancient.* [Online]
Available at: http://www.waterencyclopedia.com/Hy-La/Irrigation-Systems-Ancient.html
[Accessed 16 May 2015].

Molle, B., Tomas, S., Hendawi, M. & Granier, J., 2012. Evaporation and Wind Drift Losses During Sprinkler Irrigation Influenced by Droplet Size Distribution. *Irrigation and Darinage,* 61(2), pp. 240 - 250.

Murray Darling Basin Authority, n.d. *Acid Sulfate Soils.* [Online]
Available at: http://www.mdba.gov.au/what-we-do/research-investigations/acid-sulfate-soils-risk-assessment
[Accessed 05 August 2015].

Murray Darling Basin Authority, n.d. *Blue-Green Algae.* [Online]
Available at: http://www.mdba.gov.au/river-data/water-quality/bga
[Accessed 05 August 2015].

Murray Darling Basin Authority, n.d. *Challanges and Issues: Salinity.* [Online]
Available at: http://www.mdba.gov.au/about-basin/basin-environment/challenges-issues/salinity
[Accessed 05 August 2015].

Murray Darling Basin Authority, n.d. *Hydrology and Landforms.* [Online]
Available at: http://www.mdba.gov.au/about-basin/basin-environment/geography/hydrology
[Accessed 05 August 2015].

Murray Darling Basin Authority, n.d. *Irrigated Agriculture in the Basin - Facts and Figures.* [Online]
Available at: http://www.mdba.gov.au/about-basin/irrigated-agriculture-in-the-basin
[Accessed 05 August 2015].

Murray Darling Basin Authroity, n.d. *Basin Environment.* [Online]
Available at: http://www.mdba.gov.au/about-basin/basin-environment
[Accessed 05 August 2015].

Murray-Darling Basin Authority, n.d. *Irrigated Agriculture in the basin - Facts and figures.* [Online]
Available at: http://www.mdba.gov.au/about-basin/irrigated-agriculture-in-the-basin
[Accessed 04 August 2015].

Nelson Irrigation , 2015. *3000 Series 3TN Nozzle System Metrics,* Walla Walla, WA, USA: Nelson Irrigation Corporation.

Nelson Irrigation Australia, 2015a. *PC - R3000 Part Circle.* [Online]
Available at: http://www.nelsonirrigation.com.au/agriculture/50-nelson-pivot-series/141-pc-r3000-part-circle-pc-r3000-part-circle
[Accessed 20 May 2015].

Nelson Irrigation Australia, 2015b. *PC - S3000.* [Online]
Available at: http://www.nelsonirrigation.com.au/agriculture/50-nelson-pivot-series/140-pc-s3000-part-circle-pc-s3000-part-circle
[Accessed 21 May 2015].

Nelson Irrigation Australia, 2015c. *PC - D3000 Part Circle Sprayhead.* [Online]
Available at: http://www.nelsonirrigation.com.au/agriculture/50-nelson-pivot-series/139-pc-d3000-part-circle-pc-d3000-part-circle
[Accessed 21 May 2015].

Nelson Irrigation, 2015. *Nelson Pivot Series.* [Online]
Available at: http://www.nelsonirrigation.com.au/agriculture/50-nelson-pivot-series

Pacific Institute, 2010. *Freshwater Withdrawal by Country and Sector.* [Online]
Available at:
http://www2.worldwater.org/datav7/data_table_1_total_renewable_freshwater_supply_by_country.pdf
[Accessed 12 May 2015].

Senninger Irrigation Inc., 2010. *Booms, Wheel tracks, and Infiltration Rate.* [Online]
Available at: http://www.senninger.com/booms-wheel-tracks-and-infiltration-rate/
[Accessed 20 May 2015].

Senninger Irrigation Inc., NA. *LDN - Low Drift Nozzle.* [Online]
Available at: http://www.senninger.com/wordpress/wp-content/uploads/2013/04/LDN-UP3-Brochure.pdf
[Accessed 21 May 2015].

Senninger Irrigation, 2015. *LDN UP3.* [Online]
Available at: http://www.senninger.com/pivots-linear-systems/ldn/

South Eastern Australian Climate Initiative, 2012. *Climate and water availablity in south-eastern Australia,* Australia: CSIRO .

The water Cycle in the Murray-Darling Basin. 2005. [Film] Australia: Murray Darling Basin Commission .

Wigginton, D. .., Foley, J. .., Schultz, J. .. & Van Neikerk, R. .., 2011. *Review of Centre Pivot & Lateral Move Installations - in the Queensland Murray Darling Basin,* USQ, Toowoomba: National Centre for Engineering in Agriculture - Publication 1004167/1.

Williams, M., 2014. *What Percentage of Earth is Water?.* [Online]
Available at: http://www.universetoday.com/65588/what-percent-of-earth-is-water/
[Accessed 12 May 2015].

(This page is intentionally blank)

Appendix A Project Specifications

ENG 4111/4112 Research Project – Project Specification

Student: Matthew Green

Topic: Uniformity performance of non-standard overlapped CP & LM sprinklers

Supervisor: Dr Joseph Foley

Enrolment: ENG 4111 – S1 2015

ENG 4112 – S2 2015

Project Aim: Test part-circle irrigation sprinklers under ideal laboratory conditions to determine the sprinkler uniformity. Using these results from testing develop an application model that will be used to determine optimum operating positions around a CP & LM irrigator tower.

Programme:

1. Research background information on the conditions at which these devices operate and the issues surrounding their use in the field.

2. Research testing being carried out in this field and the testing procedures currently implemented.

3. Develop a testing procedure involving the most commonly used part-circle sprinklers operating under two levels of operating pressure.

4. Using the data collected from testing, develop a simple model to show the application pattern of each sprinkler.

5. Using the application patterns developed overlay the results to determine the optimum spacing under various conditions.

6. Evaluate the model predictions of each scenario and analyse the results, and report in a scholarly dissertation.

Appendix B Raw Data

7.2 PC-S3000 test 5 data

PC - S3000 Test 5 Results (mm/h)

Catch can radii	*Radial Distance from Sprinkler head (m)*												
	0.5	**1**	**1.5**	**2**	**2.5**	**3**	**3.5**	**4**	**4.5**	**5**	**5.5**	**6**	**6.5**
350	0.42	0.00	0.00	0.84	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0	1.89	6.10	4.42	6.73	1.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	3.79	10.31	9.05	13.26	19.57	18.94	8.84	1.26	0.00	0.00	0.00	0.00	0.00
20	7.37	9.05	11.57	16.42	28.62	28.41	12.21	1.26	0.00	0.00	0.00	0.00	0.00
30	4.63	8.42	11.79	17.47	31.15	27.99	16.63	4.00	0.42	0.00	0.00	0.00	0.00
40	7.79	13.05	25.25	34.51	34.30	22.52	7.79	1.47	0.42	0.00	0.00	0.00	0.00
50	7.16	19.15	35.57	33.67	25.46	22.94	22.73	18.52	13.47	1.26	0.00	0.00	0.00
60	11.36	16.63	16.42	13.26	14.73	17.47	17.26	15.36	18.94	7.79	0.63	0.00	0.00
70	6.10	10.10	9.68	9.05	10.73	15.57	14.94	12.63	16.42	20.20	5.05	0.00	0.00
80	7.16	0.00	10.94	9.05	10.31	14.73	13.47	12.21	17.26	33.67	49.25	0.00	0.00
90	5.47	8.84	10.94	9.05	9.68	13.89	10.94	8.00	11.15	16.84	11.57	0.00	0.00
100	5.68	10.31	10.73	9.26	9.47	13.89	10.73	8.00	11.36	19.36	12.21	0.00	0.00
110	5.26	10.52	11.57	10.10	9.89	14.94	12.21	10.10	11.36	20.20	13.89	0.00	0.00
120	5.47	9.68	14.94	13.05	13.26	17.26	12.84	10.31	10.94	19.15	15.36	0.00	0.00
130	7.58	9.89	15.78	16.42	19.57	19.78	19.78	13.47	13.05	21.26	15.78	0.00	0.00
140	10.73	13.68	14.10	15.78	18.10	18.52	14.10	10.73	14.52	6.73	0.00	0.00	0.00
150	10.52	22.73	22.73	19.15	17.05	16.20	22.94	28.62	6.10	0.00	0.00	0.00	0.00
160	16.20	18.52	20.41	20.41	20.20	22.73	13.05	8.21	1.26	0.00	0.00	0.00	0.00
170	11.36	7.37	6.10	5.89	8.42	14.31	21.05	11.79	0.00	0.00	0.00	0.00	0.00
180	9.26	5.68	6.73	4.84	8.63	21.26	10.52	0.00	0.00	0.00	0.00	0.00	0.00
190	11.36	13.05	11.57	9.05	16.42	6.52	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Bucket	102.57												

7.3 PC-D3000 test 8 data

PC-D3000 Test 8 Results (mm/h)

Catch Can Radii	Radial Distance From Sprinkler Head (m)												
	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20	0.84	3.79	9.68	27.15	65.45	303.05	462.58	17.89	9.89	2.74	0.00	0.00	0.00
30	1.26	3.58	12.42	22.73	47.56	107.96	74.29	3.79	2.10	1.26	0.00	0.00	0.00
40	2.53	4.42	10.10	17.05	26.31	46.09	104.81	384.08	2.74	1.89	0.00	0.00	0.00
50	2.53	5.05	6.73	13.89	26.31	59.77	122.69	282.22	29.04	17.26	0.00	0.00	0.00
60	2.95	5.68	9.68	15.99	22.10	39.14	72.61	149.84	423.01	23.57	0.00	0.00	0.00
70	1.89	10.73	16.84	17.26	20.20	29.88	40.41	39.14	24.41	25.89	0.00	0.00	0.00
80	7.16	11.36	15.36	15.15	23.15	26.10	35.36	27.36	3.79	1.68	0.00	0.00	0.00
90	1.89	9.26	13.05	14.10	19.57	30.94	53.67	98.28	91.13	368.29	0.00	0.00	0.00
100	5.47	7.37	11.36	11.79	17.89	31.36	51.98	72.82	443.00	615.36	0.00	0.00	0.00
110	1.47	5.68	9.47	10.52	15.99	29.04	45.04	53.67	244.97	7.79	0.00	0.00	0.00
120	2.95	5.89	11.15	13.68	17.26	28.83	47.56	67.98	69.03	5.26	0.00	0.00	0.00
130	1.05	8.84	12.84	18.52	22.52	31.78	55.56	66.92	22.73	4.21	0.00	0.00	0.00
140	3.16	9.26	19.36	16.42	19.36	26.10	55.14	21.68	712.80	8.63	0.00	0.00	0.00
150	1.05	5.05	15.78	25.46	38.72	45.88	14.31	1.05	2.74	1.68	0.00	0.00	0.00
160	1.68	2.74	7.79	20.62	42.93	90.49	136.79	22.31	10.31	0.00	0.00	0.00	0.00
170	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
180	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Bucket	61.00												

Appendix C MatLab Model Code

This code incorporates the section used to plot the result plots seen in chapter 4.

```
clc
clear all
close all

angle = (0:10:200);            % Application Radius
anglerad = angle*(pi/180);     % Convert Application radius to radian angle
dist = (0.5:0.5:6.5);          % Application distance

angleadj = (345*(pi/180));     % Angle adjustment for rotation of results

% Initial zeros matrix for X and Y coordinates
placeX = zeros(length(anglerad),length(dist));
placeY = zeros(length(anglerad),length(dist));

centreX = 0;                    % Translation along X axis
centreY = 0;                    % Translation along Y axis

i = 1;
j = 2;

%  Determines the catch can positions along the X Axis

for i = 1:1:length(dist)

       placeX(1,i) = ((cos(anglerad(1,1)+angleadj))*dist(1,i))+centreX;


       for j = 2:1:length(anglerad)


           placeX(j,i) = ((cos(anglerad(1,j)+angleadj))*dist(1,i)+centreX);


       end

           i = i+1;

           j = j+1;
end

% determines the position of the catch cans along the Y Axis

for i = 1:1:length(dist)

       placeY(1,i) = ((sin(anglerad(1,1)+angleadj))*dist(1,i))+centreY;
```

```
        for j = 2:1:length(anglerad)

            placeY(j,i) = ((sin(anglerad(1,j)+angleadj))*dist(1,i)+centreY);

        end

            i = i+1;

            j = j+1;
end

% Accesses application depth data
Test5 = xlsread('PCS3000_Results.xlsx','Test 5','B31:N51');

% Setup for surface plots

x = placeX.';
y = placeY.';
z = Test5.';

H = ndgrid(x);
O = ndgrid(y);
T = ndgrid(z);

xlin = linspace(min(H),max(H));
ylin = linspace(min(O),max(O));

[X,Y] = meshgrid(xlin,ylin);

F = scatteredInterpolant(H,O,T);
h = F(X,Y);

% Plots application surface and labels plot
figure('Name','Test5 - #28 3TN - 68.95 KPa','NumberTitle','off')
surf(X,Y,h);
xlabel({'Radial Distance Across Semi';'Circlular Sprinkler Pattern (m)'});
ylabel({'Radial Distance In the';'Direction Of Throw (m)'});
zlabel('Application Rate (mm/h)');
title ({'Application Pattern from PC-S3000','#28 nozzle at 68.95
KPa'},'color','k');
c = colorbar;
c.Label.String = 'Application Rate (mm/h)';
c.Label.FontSize = 12;
colormap (flipud(gray));

% Plots the contour map of application depths and labels plot
figure('Name','Test5 - #28 3TN - 68.95 KPa','NumberTitle','off')
contourf(X,Y,h);
xlabel({'Radial Distance Across Semi';'Circlular Sprinkler Pattern (m)'});
ylabel({'Radial Distance In the';'Direction Of Throw (m)'});
zlabel('Application Rate (mm/h)');
title ({'Application Pattern from PC-S3000','#28 nozzle at 68.95
KPa'},'color','k');
```

```
c = colorbar;
c.Label.String = 'Application Rate (mm/h)';
c.Label.FontSize = 12;
colormap(flipud(gray));

%% Start of the Modelling section

Sprinklerangle = 90;              % Orientation of sprinkler 1 (degrees)
sprinklerAngle = 45;              % Orientation of Sprinkler 2 (degrees)
SprinklerAngle = 0;               % Orientation of Sprinkler 3 (degrees)
SprinklerAngleF = 315;            % Orientation of Sprinkler 4 (degrees)
SPRINKLERANGLE = 250;             % Orientation of Sprinkler 5

Angle = (0:10:200)*(pi/180);       % Wetted Radius of Sprinkler (m)
Dist = (0.5:0.5:6.5);              % Length of application (m)
SAngle = Sprinklerangle*(pi/180);  % Radian angle of sprinkler 1
sangle = sprinklerAngle*(pi/180);  % Radian angle of sprinkler 2
SANGLE = SprinklerAngle*(pi/180);  % Radian angle of sprinkler 3
SAngleF = SprinklerAngleF*(pi/180); % Radian angle of sprinkler 4
SANGLEF = SPRINKLERANGLE*(pi/180);  % Radian angle of sprinkler 5

BaseX = zeros(300,300);            % Field of X - values sprinkler 1
BaseY = zeros(300,300);            % Field of Y - values sprinkler 1
BaseZ = zeros(300,300);            % Field of Z - values sprinkler 1

BaseZT = zeros(300,300);           % Field of Z - values sprinkler 2
BaseXT = zeros(300,300);           % Field of X - Values sprinkler 2
BaseYT = zeros(300,300);           % Field of Y - Values sprinkler 2

Basex = zeros(300,300);            % Field of X - values sprinkler 3
Basey = zeros(300,300);            % Field of Y - values sprinkler 3
Basez = zeros(300,300);            % Field of Z - values sprinkler 3

BaseXf = zeros(300,300);           % Field of X - values sprinkler 4
BaseYf = zeros(300,300);           % Field of Y - values sprinkler 4
BaseZf = zeros(300,300);           % Field of Z - values sprinkler 4

BASEXF = zeros(300,300);           % Field of X - values sprinkler 4
BASEYF = zeros(300,300);           % Field of Y - values sprinkler 4
BASEZF = zeros(300,300);           % Field of Z - values sprinkler 4

BASEZ = zeros(300,300);            % Addition of applied depths

xmid = 0;             % Sprinkler head position from (0,0) sprinkler 1
ymid = 0;             % Sprinkler head position from (0,0) sprinkler 1
Xmid = 2;             % Sprinkler head position from (0,0) sprinkler 2
Ymid = 0;             % Sprinkler head position from (0,0) sprinkler 2
xmidT = 4;            % Sprinkler head position from (0,0) sprinkler 3
ymidT = 0;            % Sprinkler head position from (0,0) sprinkler 3
xmidf = 5;            % Sprinkler head position from (0,0) sprinkler 4
ymidf = 0;            % Sprinkler head position from (0,0) sprinkler 4
XMIDF = 7;            % Sprinkler head position from (0,0) sprinkler 5
YMIDF = 0;            % Sprinkler head position from (0,0) sprinkler 5

i = 1;
j = 1;
```

```
data = Test5;

% Determines position of catch can data for each sprinkler
for i = 1:1:length(Dist)

   for j = 1:1:length(Angle)

       % Sprinkler 1 position and application depths
       BaseX((i+ymid),(j+xmid)) =
(((cos(Angle(1,j)+SAngle))*Dist(1,i))+xmid);
       BaseY((i+ymid),(j+xmid)) =
(((sin(Angle(1,j)+SAngle))*Dist(1,i))+ymid);
       BaseZ((i+ymid),(j+xmid)) = data(j,i);
       % Sprinkler 2 position and application depths
       BaseXT((i+Ymid),(j+Xmid)) =
(((cos(Angle(1,j)+sangle))*Dist(1,i))+Xmid);
       BaseYT((i+Ymid),(j+Xmid)) =
(((sin(Angle(1,j)+sangle))*Dist(1,i))+Ymid);
       BaseZT((i+Ymid),(j+Xmid)) = data(j,i);
       % Sprinkler 3 position and application depths
       Basex((i+ymidT),(j+xmidT)) =
(((cos(Angle(1,j)+SANGLE))*Dist(1,i))+xmidT);
       Basey((i+ymidT),(j+xmidT)) =
(((sin(Angle(1,j)+SANGLE))*Dist(1,i))+ymidT);
       Basez((i+ymidT),(j+xmidT)) = data(j,i);
       % Sprinkler 4 position and application depths
       BaseXf((i+ymidf),(j+xmidf)) =
(((cos(Angle(1,j)+SAngleF))*Dist(1,i))+xmidf);
       BaseYf((i+ymidf),(j+xmidf)) =
(((sin(Angle(1,j)+SAngleF))*Dist(1,i))+ymidf);
       BaseZf((i+ymidf),(j+xmidf)) = data(j,i);
       % Sprinkler 5 position and application depths
       BASEXF((i+YMIDF),(j+XMIDF)) =
(((cos(Angle(1,j)+SANGLEF))*Dist(1,i))+XMIDF);
       BASEYF((i+YMIDF),(j+XMIDF)) =
(((sin(Angle(1,j)+SANGLEF))*Dist(1,i))+YMIDF);
       BASEZF((i+YMIDF),(j+XMIDF)) = data(j,i);

  end

   i = i + 1;
   j = j + 1;

end

i = 1;
j = 1;

% Developes Application depth matrix
for i = 1:1:length(BaseZ)

    for j = 1:1:length(BaseZ)

        BASEZ(i,j) = BaseZ(i,j) + BaseZT(i,j) + Basez(i,j) + BaseZf(i,j) +
BASEZF(i,j);

    end
```

```
    i = i + 1;
    j = j + 1;

end

% Plotting setup
x = ndgrid([BaseX.',BaseXT.',Basex.',BaseXf.',BASEXF.']);
y = ndgrid([BaseY.',BaseYT.',Basey.',BaseYf.',BASEYF.']);
z = ndgrid([BASEZ.',BASEZ.',BASEZ.',BASEZ.',BASEZ.']);

xlin = linspace(min(x),max(x));
ylin = linspace(min(y),max(y));

[X,Y] = meshgrid(xlin,ylin);

F = scatteredInterpolant(x,y,z);
h = F(X,Y);

i = 1;
j = 1;

for i = 1:1:length(h)

    for j = 1:1:length(h)

        % Remove negative application rates
        if h(i,j) < 0

            h(i,j) = 0;

        end

      a(1,j) = X(1,j);                  % Define X axis values for plot

    end

    i = i+1;
    j = j+1;

end

% Plots applied volume results
v = ((h/60)*4);         % Application depth over time interval of 4 minutes
s = sum(v,1);           % Sum application volume in the direction of travel
figure
plot(a,s)               % Plot Applied volume in a pass
xlabel('Application Radius (m)');
ylabel('Application Volume (mm)');
title('Application volumes in the direction of travel');

i = 1;
D = (max(s)*0.25);       % Determining the cut off point, bottom 25% is cut

for i = 1:1:length(s)    % Removes the bottom 25% of values
```

```
    if s(1,i) <= D;

        s(1,i) = 0;

    end

 i = 1+i;

end

n = nnz(s);          % Determines the number of non zero cells in the array
xbar = sum(s);       % Sums the values in the array
M = (xbar/n);        % Determines the mean value of s

i = 1;

for i = 1:1:length(s)        % Standard deviations of each reading

    stddev(1,i) = abs((s(1,i)-M));

    if stddev(1,i) == M;

        stddev(1,i) = 0;

    end

      i = i+1;

end

sumx = sum(stddev);                  % Sum standard deviations

christco = (100*(1-(sumx/(M*n))));   % Calculates the chritiansen coeffient

disp('The Christiansen Coefficient of uniformity is (percentage)')
disp(christco)
```