HARPER ADAMS UNIVERSITY

Interactions of soil water run-off with overhead (centre-pivot) irrigation and soil cultivations

Ghazwan Husam Tawfeeq Mahmood

M.Sc. Agricultural Sciences. Baghdad University. College of Agriculture.
Agricultural Machines Department. 2001

B.Sc. Agricultural Sciences. Baghdad University. College of Agriculture.
Agricultural Machines Department. 1994-1995

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ربي زدني علما

(rabby zidnee elma)

My Lord, increase me in knowledge

Quran, Taha 114

Abstract

Actual consumption of water was addressed in this thesis by investigating how improved irrigation efficiency and use of appropriate soil cultivations would reduce irrigation water run-off, and thus reduce the actual consumption of water and lead to greater irrigation water use efficiency.

The phenomenon of surface water runoff has begun to have an impact on the productivity of crops in Iraq, especially those that are irrigated by centre pivot sprinkler irrigation systems. Most of these irrigated areas are ploughed with poor tillage operations, and often without consideration of the effect of these operations on soil physical properties and crop responses. The research aims to investigate the effect of different soil tillage practices on the irrigation water runoff potential from the end section of a pre-selected centre pivot system used in Iraq. In addition, an investigation into the sprinkler nozzle outputs was conducted to quantify the uniformity of application and thus it's potential to cause localised runoff. The optimum size of runoff test area suitable for in situ measurement in commercial fields has been identified.

Based on tillage studies on sandy loam soils, subsoiling followed by mouldboard or disc ploughing resulted in higher infiltration rate and soil moisture content, lower shear strength and penetration resistance compared to gang disc harrowing, rigid tine harrowing, rotary harrowing, and no tillage which produced the lower infiltration rate and soil moisture content, higher shear strength and penetration resistance. Therefore, both mouldboard and disc ploughing methods were selected for conducting water runoff experiments. Compared to disc ploughing, mouldboard ploughing produced higher water infiltration rate, lower shear strength and soil bulk density under these experimental conditions.

The results of the effect of three factors of water pressure, nozzle height and type on water distribution uniformity were found to be significant. Water distribution uniformity increased from 51% at 42 kPa (6 psi) to 91% at 103 kPa (15 psi). Similarly, water distribution uniformity increased from 58% at 0.5 m to 84% at 1.5 m nozzle height within normal wind speed.

Water distribution uniformity test results were significantly affected by the rim characteristics of the catch containers and the distance between the cans. Compared with the small circular catch containers at 0.5 m spacing, the close packed larger rectangular shaped catch container produced better resolution of water distribution results under such sprinkler systems.

The effect of water runoff collection sampler size (0.25 m^2, 1 m^2, 4 m^2, and 9 m^2) on the amount of water runoff under an overhead sprinkler system in field conditions was found to be significant. Therefore, for further experimental studies, the water runoff collection sampler selection should be considered so the most representative results of field runoff conditions can be obtained. This study showed that water runoff occurs as a result of several factors including soil preparation in combination with operating conditions of overhead sprinkler system.

Declaration

I declare that all work submitted in this report is my own work and does not involve plagiarism or teamwork other than that authorised.

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1. General introduction

1.1 Brief history of irrigation in Iraq

Ancient hydraulic systems originated in Mesopotamia (Mays. 2008). Argo-environmental systems were set out in that area and closely linked to the presence of water (Ur, 2009). The history of irrigation in Iraq goes back to approximately 4000 BC (Ellickson, and Thorland, 1995) when the Mesopotamians built channels to irrigate lands alongside the southern portion of the Euphrates. Since that time, the region has witnessed the spread of well-designed irrigation systems, including the construction of dams and the creation of irrigation streams (Molle, 2009) and humans have used irrigation to grow crops (Wilkinson, 2000; Denevan, 1995).

The most important water resources for irrigation in these regions are still the Tigris and Euphrates rivers and their tributaries, but include rain water and groundwater (Altinbilek, 2004). Unfortunately, throughout history, salinization has threatened irrigated crops in the central and southern regions of Iraq (Jacobsen and Adams, 1958.) and salinity has been the cause of poor crops for over 3,800 years (Schnepf, 2003; Buringh, 1960). Some studies have suggested that the practice of traditional irrigation methods, such as flood irrigation, has been one of the main causes of these problems (Al-Ansari, 2013; Sama and Hamid, 2012).

1.2 Rivers as an irrigation water source

Based on statistics of the Iraqi Ministry of Water Resources (ASIA, 2013; Perrier and Salkini, 2012), the average annual water resources of the Tigris and Euphrates and their tributaries are around 77 billion m^3 in wet years and 44 billion m^3 in dry years. These rivers without tributaries are around 53 billion m^3 total with 34 billion m^3 from the Tigris and 19 billion m^3 from the Euphrates basins. The area of the Tigris basin is approximately 235 000 km^2, distributed among Turkey (17%), Iran (28.8%), Syria (0.2%) and Iraq (54%). The area of Euphrates basin is approximately 378 000 km^2 distributed among Turkey (33%), Syria (20%) and Iraq (47%). Of the Tigris resources 68% are from outside Iraq, while all the headwaters of the Euphrates are from outside the country, (Cioffi-Revilla, 2001).

In recent years, the water resources of the Euphrates have decreased due to the establishment of big dams in Turkey as well as in Syria. This has led to falling water discharge in Iraq to 9 billion m^3 per year from a previous figure of up to 19 billion m^3. The decrease in water level, in addition to the high evaporation rates, has led to the deterioration of water quality and an increase in concentration of salts. Where salinity ranges from 0.11 S/m (1.1 dS/m) at the entrance of the Euphrates to Iraqi lands, salinity reaches 0.45 S/m (4.5 dS/m) in southern Iraq.

1.3 Precipitation as an irrigation water source

Iraq's climate is generally continental, sub-tropical and semi-arid, while a Mediterranean climate prevails in the northern areas and the north-eastern mountains. The nature of the rainfall is quite seasonal, with rain falling in winter from December to February, except for the north and north-eastern areas where the rainy season extends from November to April. The rate of rainfall is less than 100 mm per annum for more than 60% of the country, especially in central and southern regions. Climate change has been an additional factor to the desertification process (Al-Ansari, 2013); a decrease in rainfall with frequent heat waves, has led to the deterioration of agriculture in these regions. Therefore, it is not possible to employ rainfed agricultural methods in these areas.

1.4 Ground water as an irrigation water source

Studies indicate the existence of good qualities of underground water in the plateau of western Iraq, (west of Mosul area and the upper part of Euphrates). Soluble salts in the groundwater range from 0.078 S/m (0.78 dS/m) to 0.468 S/m (4.68 dS/m). For crop growth Ayers and Westcot (1985) suggest that irrigation water at < 0.75 dS/m cause no problems, 0.75 - 3 dS/m causes increasing problems and > 3.0 dS/m can cause severe crop growth problems. Soil salinity can also decrease water infiltration into the soil (Tanwar, 2003) which can then lead to reduced water availability to the plant and sodium effect increase runoff.

The production rate of wells in the northern regions is approximately 80-400 l/min and in the southern regions 200 l/min; the depth of wells ranges from 50-60 m in the upper part of the Euphrates basin in Iraq to 250-450 m in the south. However, the exploitation of groundwater in Iraq is still limited. The aquifer is estimated in the desert to be 200 billion m^3 yet just one billion m^3 has actually been exploited.

1.5 Irrigation methods used in Iraq

There are many methods of irrigation used in Iraq which are selected depending on land topography, soil texture, duration of irrigation, type of plants to be irrigated and water availability in the area, as well as the availability of labour.

Surface irrigation is the traditional and the most universal method. It delivers water to plants through channels that have been dug up in the ground. These channels may be covered or uncovered. The most obvious advantage of this method is its low cost, making it the most prevalent method used. Despite this, it is an inefficient way to use water and water losses have been estimated to the extent of 60%, according to FAO statistics (Allen *et al.,* 1998). Thus, the Iraqi Ministry of Agriculture was looking to the use of more efficient irrigation methods such as overhead sprinkler types and drip irrigation systems. The sprinkler irrigation method has recently become frequently used among Iraqi farmers, and were used extensively at the beginning of the new millennium with different types of these systems such as solid and mobile.

Centre pivot systems are the most widely used form of sprinkler type irrigation in Iraq, especially in extensive areas near rivers. Despite the existence of high efficiency in water consumption by this method, it is not without limitations with regards to soil and crop growth problems. Surface water runoff is one such problem which can often lead to water and crop loss in addition to the degradation of soil surfaces, where water runoff is the flow of water over the soil surface which cannot be infiltered, (Klocke, 1997; Pereira, 1999; Bjorneberg, *et al.*, 2000). One of the main problem areas for the centre pivot system is from water application from the far end span which travels quickly whilst applying relatively high volumes of water. As a way of addressing the runoff problem there has been much work done on the uniformity of application from these systems and several studies have also focused on changing the soil tillage method to facilitate good irrigation water infiltration into soil from irrigation under mobile sprinkler systems in different environmental conditions (Hasheminia, 1994). These may therefore be areas worthy of further investigation to reduce irrigation water run-off problems under centre pivot systems, (Schneekloth, *et al*, 2005). Janabi, 2010 pointed out that soil in Iraq suffers from erosion problem by rain or wind by 92% of the territory of the country, but to varying degrees. Thereby reducing the efficiency of irrigation systems.

Previously, determining the quantity of water runoff is achieved by large scale purpose-built test areas (Weaver and Noll, 1935). Therefore, to determine the extent of the problem or to investigate problems within specific systems it would be useful to have smaller scale equipment which could be used in situ on the system in its operational environment. Consequently, this research will investigate if a more appropriate small-scale design method of collecting water runoff is possible which still takes account of the sprinkler characteristics, soil texture and the cultivation practices.

2. Literature review

2.1 Irrigation

Irrigation is necessary to supply plants with their needs of water to grow, (Allen *et. al,* 1998) to achieve good yields in dry/arid areas and to avoid root death which can result in early wilting and death of the plant. It should also be applied adequate with plant age or growth stage. Nonetheless, applications should not be applied which increase soil moisture beyond field capacity as this can also reduce yield and produce runoff. Overall, the practice of irrigation can be considered to have three main elements:

1. Water supply: a necessary source of water to irrigate crops must be provided, according to their needs. Water quality plays an important role in crop growth and, so it should be free of polluting substances as well as having an acceptable degree of salinity. The latter being crop specific as some are more/less tolerant.
2. Soil medium: must provide a suitable growing environment as well as physical properties which can store and release adequate quantities of water to plants.
3. Irrigation method: a suitable method selected for irrigation which often comes as a result of options available to farmers, economics and their vision for best management of the field.

With compatibility of the above factors, an irrigation system will be successful, thus obtaining a higher crop yield crop as well as an optimum consumption of water without causing damage to soil or incurring water wastage, (Sojka *et al*., 2007).

Water/irrigation for plant growth could be split into natural and artificial. Natural water/irrigation, is far from human intervention; rainfall or overflowing rivers flooding the ground and providing plants with their need for water, (STYLE, 2005). Artificial irrigation involves human intervention whereby water is collected and stored, abstracted from rivers or groundwater and then transported and distributed to areas of need. In general, there are three types of irrigation: surface, overhead and drip or trickle.

2.1.1 Methods of irrigation and their influence on water runoff

2.1.1.1 Surface irrigation system

Surface irrigation is the oldest irrigation system in use for thousands of years all over the world. It takes various forms and includes a wide range of approaches, which all essentially involve water pouring over the ground's surface and flowing under the influence of gravity into all areas of the field (Bishop, *et al,* 1967; Pereira, 1996).

Surface irrigation is still followed to this day by its various methods such as basin irrigation, furrow irrigation and border irrigation. (Mintesinot*, et al*., 2004. Howell, 2001. Brouwer, *et al*., 1988)

Among the characteristics of this system is the ground topography being used for the distribution of water in the field. It is essential that the water can flow across the whole area without extensive infiltration at the entry to the area but not so quickly that too little water infiltrates at the entry point. Water movement should therefore extend to the extremities of the field and water should infiltrate equally to be utilised by the plant roots, (Harrison, 2009; Bishop, *et al,* 1967).

Regardless of how the water is directed with the various methods, Surface irrigation leads to wastage of water due initially to the extensive surface area and evaporative losses and then secondly the frequent emergence of runoff, especially within the basin system, (Pereira, 1996). Numerous studies in arid and semi-arid regions have confirmed that evaporation of water from the soil surface, after irrigation, also leads to soil sealing and shrinking. This creates a light shallow layer of soil, preventing water infiltration during subsequent irrigation events and hence the subsequent runoff. Numerous studies have been conducted to reduce water runoff by repeating irrigation events with lower amounts of water each time or alternatively by leaving crop residue in the field, (Morison, *et al*, 2008; van Donk and Klocke, 2012). However, these remedial measures only have a minor impact on run-off and evaporation during hot weather conditions in these areas (Casenave, and Valentin, 1992; Deng, *et al,* 2006).

2.1.1.2 Drip/Trickle irrigation system

Drip irrigation systems work by creating a wetted perimeter surrounding the roots only, and maintaining the water content near optimum levels in that root zone, figure (2.1). The wetted area depends on the emitter discharge rate, the soil characteristics and its moisture and permeability rate. Application water quantities are often less than other irrigation methods because there is little direct loss to the atmosphere. Generally, drip irrigation is used to irrigate fruit and vegetable crops, sugar cane and bananas. However, it is not practical for cereal crops, (Sivanappan, 1994; Camp, *et al,* 2000).

Drip irrigation systems consist of a network of main pipes, sub mains and laterals. Emitters are included within the laterals at a specific distance depending on the distance between plants. Emitters differ in the number of water outlets they possess; having either mono or multi-outlets. The latter produces relatively high discharge rates and distributes water to a wider area. However, the emitters' discharge should not exceed 15 litre / hour, (Dhawan, 2000; Dağdelen, *et al,* 2009) because it leads to waterlogging.

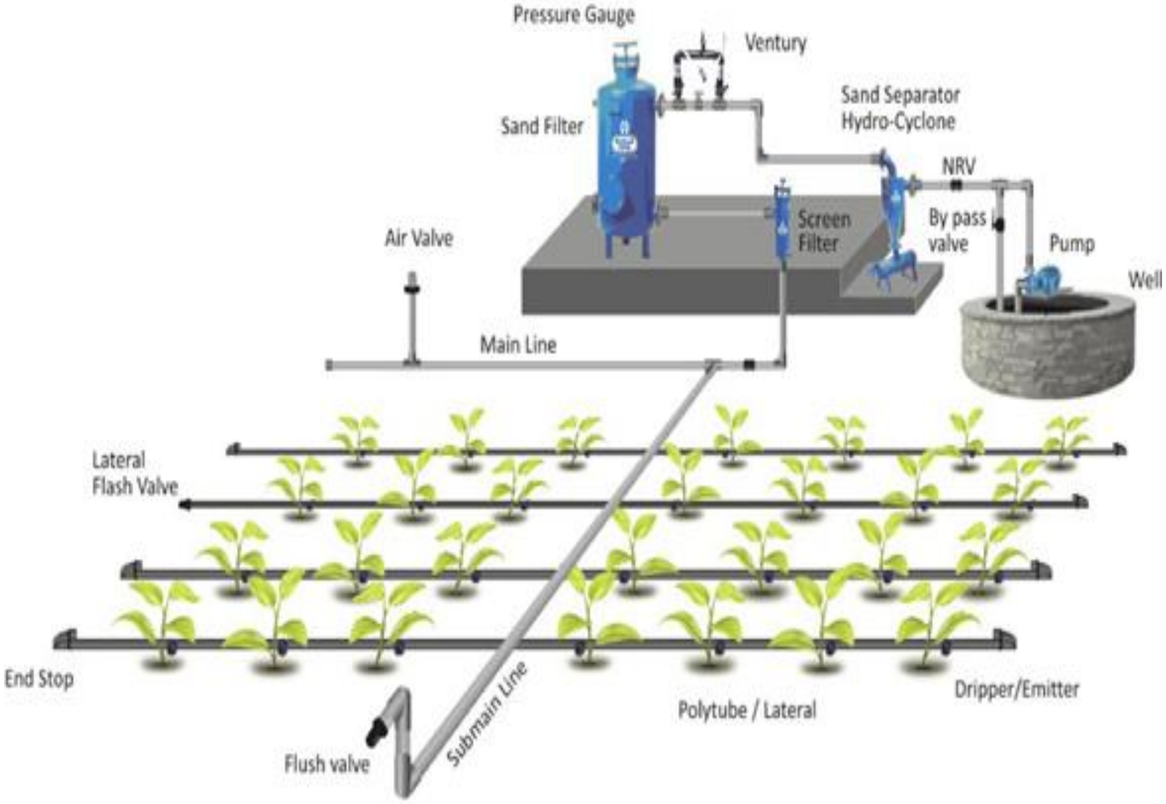


Figure 2. 1 Drip irrigation system (Drip irrigation system, 2017)

This system can work on the flat or slightly sloping land, nonetheless it needs filtration systems to prevent clogging. (Ribeiro *et al*., 2008).

2.1.1.3 Overhead sprinkler irrigation systems

Overhead irrigation and sprinkler irrigation has several forms including rain guns, surface mounted upright sprinklers, the boom types of small scale boom with widths from 12-72m, self-propelled linear move with widths up to 500m and centre pivot with 500m+ radius. For the purpose of this review however only the concept of sprinkler irrigation will be discussed and the development of the centre pivot system as the other types are not a focus of this accompanying research.

The concept of this type of irrigation is based on the idea of natural irrigation by rain (Kincaid, 2005). It is the falling of water from sprinklers in a spray form onto the ground at a rate that creates sufficient moisture content in the root zone with the least amount of deep infiltration. In general, the mechanism of sprinkler irrigation is done by pumping water along a network of pipes to fixed or rotary sprinklers which are attached to outlet points. The pressure forces water into the sprinkler head and is distributed in the form of droplets falling on the ground (Scherer, 2010; Martín-Benito, *et al*, 1992).

Initiated in the 1950s this type of irrigation system became known as solid set systems. This system can be designed to cover the whole field or part of a field whereby the latter requires relocation during the season inside the field, or moved from one field to another at the end of the season. To overcome this problem, a system was developed to have a lateral movement, where wheels are mounted on the pipeline so that the movement of the system would be easier. This method however, known as side-roll sprinklers, is still labour intensive as it needs to be moved every few hours, (Clemmens, and Dedrick, 1994).

In the United States of America in 1940, a variation of the sprinkler system was developed called centre pivot sprinkler irrigation (Koluvek, *et al.*, 1993). It is a self-propelled system, which, by the 1960's, had become the most widely used by farmers. In Iraq, due to low water levels in the Tigris and Euphrates in recent years, centre pivot systems were widely used by farmers, especially in areas adjacent to rivers, their branches or tributaries or irrigation channels. figure 2.2.

Figure 2. 2 A satellite image shows centre pivot system for the upper Euphrates within the area of Aanna in Iraq. (Google earth 2016)

Centre pivot system consists of a long overhead pipeline connected to a central fixed point or pivot and the pipeline moves around the pivot point in a circle, with the pipeline carried on wheeled towers, figures 2.3, 2.6. The source of energy to move the wheels is either electric or hydraulic. This means that the pivot point represents the centre of the circle, while the pipeline represents a radius of the circle. During the movement of the machine, irrigation is applied from the downward facing sprinklers which are distributed at specific intervals along the pipeline to provide a uniform application, figure 2.4.

Figure 2. 3 Centre pivot sprinkler irrigation system (Centre pivot sprinkler irrigation system, 2017)

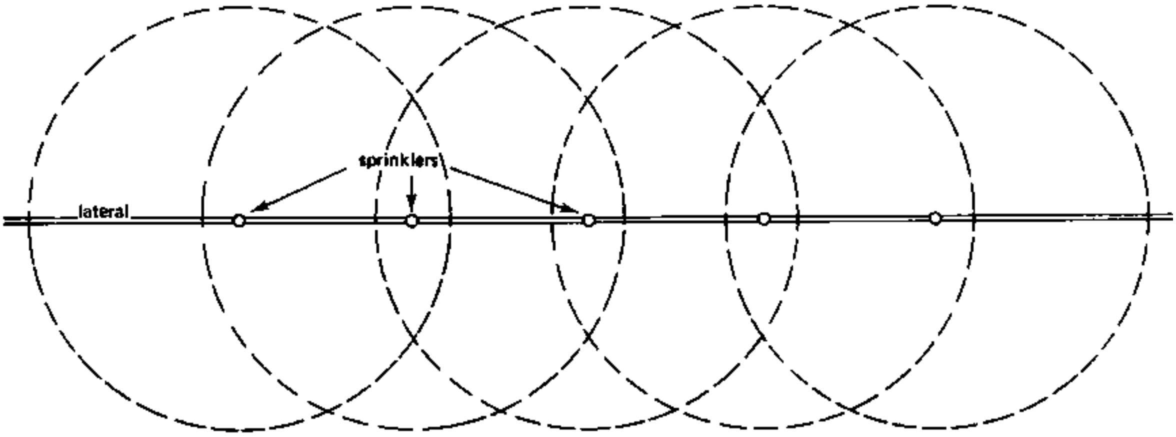


Figure 2. 4 Sprinklers distribution (Sprinkler System Layout, 2017)

A similar type of moveable sprinkler system known as a linear system; is not very different from the centre pivot system in principle, but its movement is characterized by a straight linear path rather than a circular movement, figure 2.5.

Figure 2. 5 linear system (linear sprinkler irrigation system, 2017)

As the sprinkler system`s performance depends on factors such as water pressure, pipe diameter, type and size of nozzles and their spacing, in addition to the speed of movement for movable systems, all elements interact with each other and must be synchronised to obtain the correct water application with the highest efficiency (King and Kincaid, 1997).   If insufficient water is applied the crop will not grow to its potential, however, previous studies have also observed that over application, which exceeds the soil infiltration capacity, leads to surface runoff. This is often due to either an oversize nozzle outlet diameter, incorrect pipeline pressure or incorrect movement speed of the pivot. Alternatively, there may be the lack of compatibility between nozzle spacing, nozzle size, water pressure and/or travelling speed. (Tabuada, 2014; Howell, 2006; New and Fipps, 2000; King and Kincaid, 1997; Howell and Phene, 1983).

The selection of nozzle sizes and distance between nozzles along the lateral has related with water pressure in the lateral, (Huffman, *et al*.,2012). This indicates that there is more than one type of sprinkler package can be chosen. (Huffman, *et al*., 2012) pointed that lateral size is determined by structural strength and the cost of the pipe. Water pressure in the lateral gradually decreases towards the end, therefore it is necessary to increase the size of nozzles in the final parts of the system to ensure uniformity if the distance is fixed between the sprinklers. Otherwise reduce the distance between sprinklers in this part when the size of nozzles is fixed. (Howell, 2006).

2.1.2 Components and operation of the centre pivot system

Centre pivot system consist of an overhead pipeline from which the sprinkler is mounted. One end is fixed to the pivot point and the whole structure revolves around this point. Pivot point, centre pivot or pivot tower are terms given to the metal structure shown in Figure 2.6. Water is pumped from a source to the centre of the pivot tower where it is connected to the main sprinklers pipeline, approximately 3 meters above the soil.

Figure 2. 6 Pivot point (Pivot point, 2017)

The system design allows for a number of towers depending on length of the individual pivot required. The main tower components can be seen, figure 2.6. The distance between the towers ranges from 25 to 75 meters, with the distance being minimized when the length of the pipeline becomes greater, to bear the weight of the larger diameter pipeline required for the greater lengths. Pipeline lengths range from 50 to 1000 meters, according to the considerations of engineering design, it was considered that 400 meters is the typical length of the pipeline (Evans and Sneed, 1996). Common pipeline diameters are between 100 – 250 millimetres (Evans, 2001).

$\pi r^2 = \pi \times 400^2$ Equation 1

$= \pi \times 160.000$

$= 502.400 \text{ m}^2$

$= 50 \text{ ha}$

The wheel mounted towers are operated by an electric motor (0.5 - 1.5 HP) which is installed on each tower and is electrically powered by a generator near to the pivot or from a main line electricity supply installed at the pivot point. Most pivot irrigation systems work with 380-480 volts, 60 Hz, whereas the motion controllers in each tower work with 110 volts.

The pipeline continuously moves around the pivot to irrigate a circular area up to 100 hectares. One rotation may take several hours to several days depending on the rotation speed of the line and the depth of water to be applied. The system can move forward or backward depending on the timer instructions which are setup in the control panel within the structure of the pivot tower. The towers movement starts from the furthest most tower to the nearest to the pivot. The speed of the towers is matched and increases the further away from the pivot point, to ensure straight pipeline movement around the centre. It should be noted that changing the speed of rotation does not affect the spray rates, but affects application depth, i.e. Irrigation depth decreases when the speed of rotation increases (Kranz *et al*., 2005; King and Kincaid, 1997). Kranz, *et al*., (2005) indicated that when determining the movement of the last tower at 50% of the maximum speed, it will move for 30 seconds in one minute and stop the movement 30 seconds. This will double the amount of water to be applied compared to the movement of tower at maximum speed. The lateral speed is determined by the mainboard in the centre pivot.

Distance between sprinklers is a factor affecting application uniformity due to its role associated with sprinkler type, nozzle size and water pressure (Lamm *et al.,* 2006). The sprinklers are installed either direct to the pipeline, or suspended to deliver water droplets close to the soil surface or between plant branches. The latter is to reduce evaporation losses and reduce the impact of wind on water distribution. This sprinkler arrangement is usually adequate for properly designed Low Elevation Spray Application (LESA) figure 2.7.

Figure 2. 7 LESA system (LESA system, 2017)

2.1.3 Water use efficiency in centre pivot sprinkler irrigation systems

Efficient use of water in these systems depends on several factors interacting with each other which include; water pressure inside the sprinkler pipeline, sprinkler type, size and shape of the nozzle, the order of nozzles within the sprinkler package, the distance between sprinklers and their height from the soil surface and / or plant (Heerrmann and Hein, 1968).

These factors are all equally as important and any defect in work or performance of one of them will affect the efficiency of application. Factors that are taken into consideration which are related to the occurrence of water runoff is the operating pressure at which the sprinklers operate, the shape and size of nozzle and the type and position of the sprinklers. However, there is also a significant effect of centre pivot speed relative to the application rate and of soil conditions on infiltration of the applied water and the potential for runoff to occur, this includes the type of soil, quantity of organic matter, soil structure and its stability and the cultivation practices used (Nakawuka et al., 2014; Porter and Marek, 2009; King and Kincaid, 1997).

Recent studies have confirmed that high irrigation efficiency in centre pivot systems arises from large-diameter spray patterns with low operating pressures, which is now named the low energy precision application (LEPA). This type of system is suggested to save water, labour and reduce waterlogging of the crop from poor application efficiency (Lyle and

Bordovsky, 1981; Buchleiter, 1992; Barta *et al.,* 2004). Hudson (1993) has stressed that low uniformity in some sprinklers have led to irrigation runoff.

2.1.3.1 Wetted diameter of a single sprinkler

Knowledge of the wetted diameter of an individual sprinkler is important because it allows for the determination of the overlap requirements for multiple sprinklers to create a suitably uniform application pattern (Perrier and Salkini, 2012; Seginer *et al*., 1991). The wetted diameter for a sprinkler is a straight line starting from the edge of the dry soil which passes through the sprinkler head to the opposite side of the wetted circle figure 2.8. There are several factors affecting the wetted diameter which are: system operating pressure, sprinkler type, sprinkler height from the soil surface and the trajectory of water leaving the sprinkler at an angle relative to horizontal.

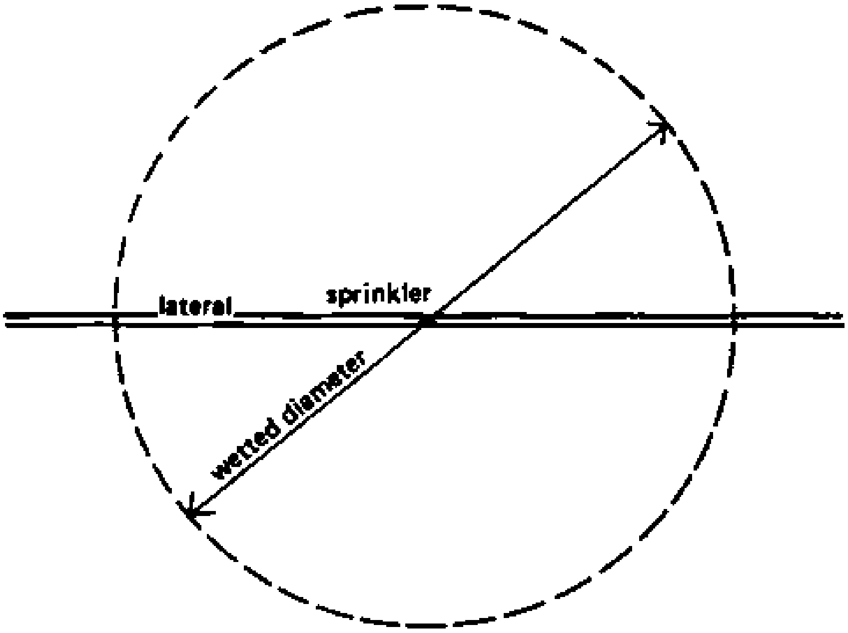


Figure 2. 8 Wetted diameter in the individual sprinkler (Perrier and Salkini, 2012)

2.1.3.2 Irrigation application uniformity

The overall system uniformity could be quantified by investigating the water distribution pattern under the irrigator (Kincaid, 1982; Howell, 2001). This wetted pattern from a single sprinkler becomes a continuous pattern under the irrigator as it travels across the soil.

The work of Christiansen (1942) is central to any discussion of sprinkler uniformity and this in itself is also based on work reported by Staebner (1931). The basic premise is that any irrigation application should provide as regular and uniform an application as possible.

This is to ensure that water is evenly distributed across the application area, with no area receiving more or less than any other thus reducing the potential for wastage and runoff. In order to quantify the application, it is normal for water collectors to be placed at specified points under the irrigation equipment and then the resulting 'caught' quantities are subjected to some type of analysis. The different types of irrigation equipment often require different approaches to the data collection because of their design differences, (Rogers, *et al.,* 2017).

Hansen et al., (1980) produced an equation to measure irrigation uniformity as a coefficient which relied on the equation of Christiansen 1942, equation 2, and was designed for use with several types of ground mounted rotating sprinklers

$$\mathrm{cu} = 100\ (\ 1.0 - \frac{\sum(\mathrm{Xi})}{\mathrm{mn}}) \qquad \text{Equation 2}$$

cu = uniformity coefficient %

xi = deviation from the mean (mm, mL)

m = mean application depth (mm, mL)

n = the number of water containers

This equation uses the mean value of all water caught and the variation from that mean for each individual collector quantity to determine the uniformity as a percentage. There is a broad guide to contextualise the percentage, table 2.1, and possible causes for any poor uniformity results. Although this approach is helpful the overall value gives no indication as to any specific problems especially when it is masked by an acceptable coefficient. The work by Christiansen (1942) and Staebner (1931) however also show graphical representations of the sprinkler patterns which are much more useful to identify problems than the equation alone. This equation is also used for several of the other types of overhead irrigation systems such as rain guns and boom. The coefficient produced is useful but a simple bar chart will often show more detail as to the actual uniformity being achieved, e.g. figure 2.9 adopted from Grove, Unpublished).

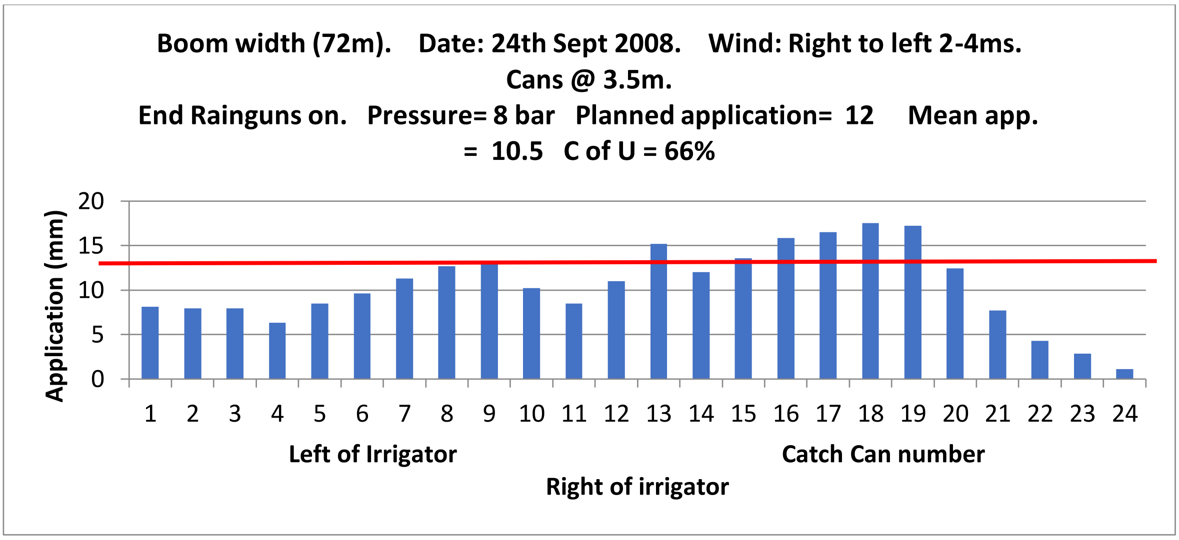
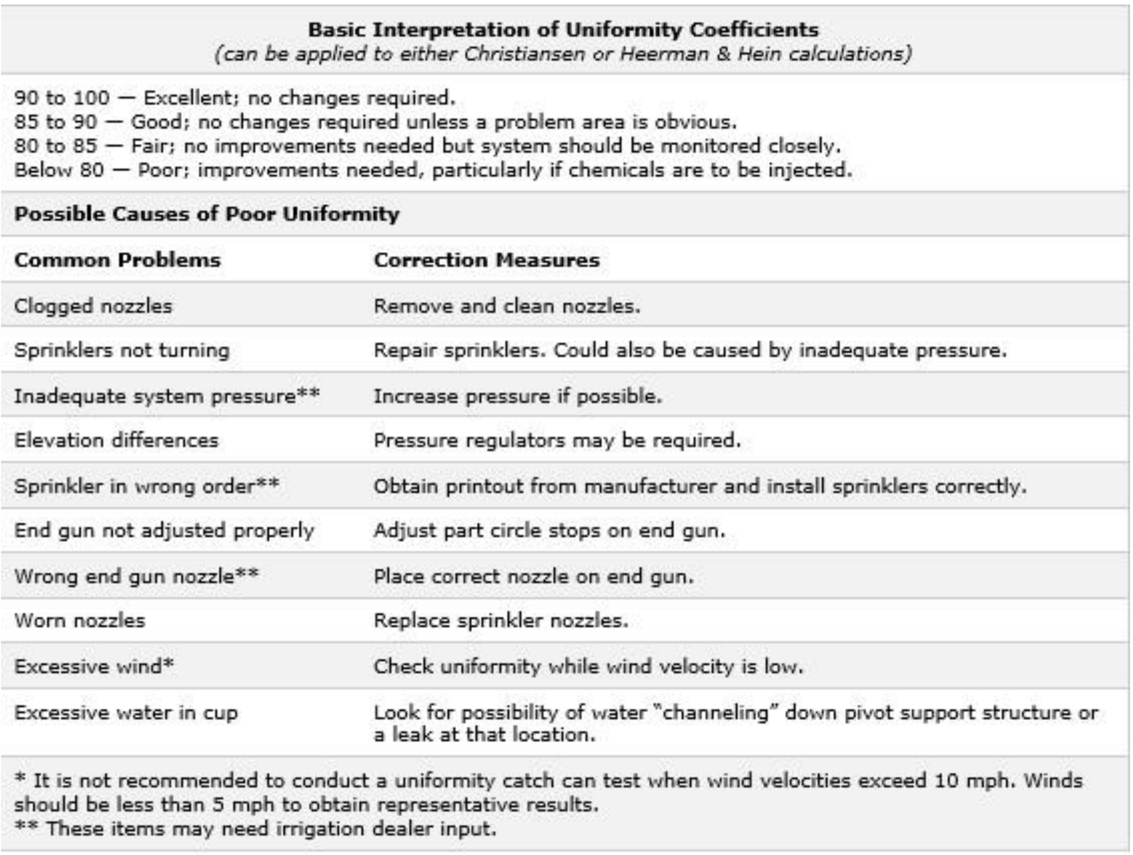


Figure 2. 9 Irrigation uniformity test on a 72m reel and boom (Grove 2008, unpublished)

Table 2. 1 Guide to interpretation of the uniformity coefficient (Harrison and Perry, 2010)



Basic Interpretation of Uniformity Coefficients
(can be applied to either Christiansen or Heerman & Hein calculations)

90 to 100 — Excellent; no changes required.
85 to 90 — Good; no changes required unless a problem area is obvious.
80 to 85 — Fair; no improvements needed but system should be monitored closely.
Below 80 — Poor; improvements needed, particularly if chemicals are to be injected.

Possible Causes of Poor Uniformity

Common Problems	**Correction Measures**
Clogged nozzles	Remove and clean nozzles.
Sprinklers not turning	Repair sprinklers. Could also be caused by inadequate pressure.
Inadequate system pressure**	Increase pressure if possible.
Elevation differences	Pressure regulators may be required.
Sprinkler in wrong order**	Obtain printout from manufacturer and install sprinklers correctly.
End gun not adjusted properly	Adjust part circle stops on end gun.
Wrong end gun nozzle**	Place correct nozzle on end gun.
Worn nozzles	Replace sprinkler nozzles.
Excessive wind*	Check uniformity while wind velocity is low.
Excessive water in cup	Look for possibility of water "channeling" down pivot support structure or a leak at that location.

* It is not recommended to conduct a uniformity catch can test when wind velocities exceed 10 mph. Winds should be less than 5 mph to obtain representative results.
** These items may need irrigation dealer input.

Similarly, Heerrmann and Hein (1968) produced an equation to calculate a uniformity coefficient particularly for centre pivot irrigation systems. These are different to ground mounted sprinklers in that they are moving, have a variety of sprinkler configurations and are mounted on an overhead pipeline with nozzles facing downwards:

$$\mathrm{cu} = 100\ [\ 1.0 - \frac{\sum \mathrm{Ss} \left| \mathrm{Ds} - \frac{\sum \mathrm{Ds\ Ss}}{\sum \mathrm{Ss}} \right|}{\sum \mathrm{Ds\ Ss}}\ ] \qquad \text{Equation 3}$$

Ds = the sum of the absolute value of the deviation of the average catch cup value from each individual catch cup data point.

Ss = the sum of the catch cup observations.

2.1.3.3 Distribution uniformity

As an alternative to the previous two equations the ’distribution uniformity’ (DU) relates to the regularity and consistency of the water delivery along the lateral but generally uses the low quarter DU which measures the average quantity of the lowest quarter of samples divided by the average of all samples. The higher the percentage DU the better the performance of the system (ASABE, 2016).

Distribution uniformity can be expressed as follows:

$$\mathrm{Du} = \frac{\mathrm{acl}\ {}^{1}\!/_{4}}{\mathrm{acs}} * 100 \qquad \text{Equation 4}$$

$$\mathrm{acl}\ {}^{1}\!/_{4} = \frac{\sum \mathrm{cl}{}^{1}\!/_{4}}{\sum \mathrm{pl}{}^{1}\!/_{4}} \qquad \text{Equation 5}$$

$$\mathrm{acs} = \frac{\sum \mathrm{ac}}{\sum \mathrm{pc}} \qquad \text{Equation 6}$$

Du = distribution uniformity (%)

acl = mean of the lowest one-quarter of the measured depths (mm, mL)

acs = overall mean of the catch cup observations (mm, mL)

cl = the sum of the lowest one-quarter from each individual catch cup.

pl = the sum of water accumulation containers.

ac = Average amount of water from all catch cups (mm, mL)

pc = the sum of water accumulation containers.

An evaluation of the main coefficient of Uniformity types can be found in Maroufpoor *et al.* (2010) and Dabbous (1962).

2.1.4 Irrigation water runoff

The process of water passing over the surface of land rather than infiltrating into the soil is known universally as water runoff. Runoff can be seen as a result of single or a combination of factors such as high intensity rainfall onto dry soil or low intensity irrigation onto a saturated soil or crusted soil surface. In relation to the soil pore system itself, infiltration rate will depend on the water transmission characteristics of the soil, the tortuosity of the pores and the ability to maintain a continuous pore system.

One of the benefits of using Low-pressure centre pivot sprinkler irrigation systems is the potential to reduce energy requirements. However, these systems have problems in that they are often accompanied by an increase of water application rates which increases the potential of water runoff, (Kranz and Eisenhauer, 1990). Consequently, it is seldom sufficient to consider irrigation in isolation from the soil which in itself be less or more prone to runoff depending on the crop or soil conditions.

The amount of runoff will be proportional to the amount of precipitation, figure 2.10, but this in itself will also be affected by soil texture, soil structure, soil surface roughness and stability, soil organic matter content, soil water content, slope of the surface, surface cover type and its density.

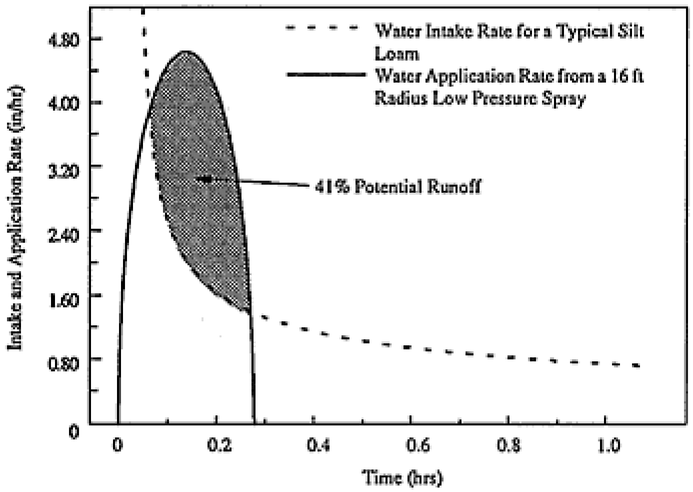


Figure 2. 10 Potential runoff calculated for a low-pressure spray nozzle irrigating a field with silt loam soil (Cahoon *et al*., 1993)

As this research is primarily focused on soil cultivation practices and irrigation from centre pivot irrigators these will be the focus of the factors which affect water runoff.

2.1.5 The effect of sprinkler characteristics and operating pressure on water distribution patterns for centre pivots

2.1.5.1 Sprinkler head and nozzle type

During the past 30 years, the trend has been to produce nozzles which distribute water of large wetted diameters at lower pressures. This is because high-water pressure requires large pumps with high energy requirements, which in turn leads to high fuel cost. However, many sprinkler packages are suitable to operate with centre pivots, (Martin, *et al*., 2012; King, and Kincaid, 1997; Von Bernuth and Gilley, 1985; Gilley, 1984) and these sprinkler packages may contain one of the following types:

1) Impact sprinklers: a device that sprays water through one or two nozzles, it is equipped with an arm to create sprinkler rotation, figure 2.11. Impact sprinklers can work with low water pressure 20 to 40 psi with a wetted diameter of 16.8 to 24.4 meter or with high water pressure, 40 to 80 psi, where the wetted diameter is 18.3 to 45.7 m. The droplet size range is from medium to large for both pressures, where the droplet sizes are 0.00 to 5.08, 5.08 to 7.62, 7.62 to 12.7 mm for small, medium and large respectively, (Kranz *et al.,* 2005).

Figure 2. 11 impact sprinkler (Impact sprinkler, 2017)

2) The spray nozzle: a device that sprays water through one central nozzle. They contain nozzle deflection pads used to distribute water in a half or full circle. These pads are of different types; stationary (fixed and multiple pad), or rotating or oscillating, figures 2.12 a, b, c & d. The parameters are given in table 2.2.

Table 2. 2 Spray nozzle operating types and parameters (Kranz *et al.*, 2005)

Type	Pressure (psi)	Wetted Dia (m)	Droplet size
Rotary pad	15 – 45	12.2 – 22.8	Medium & large
Oscillating	10 – 40	10.7 – 18.3	Medium & large
Fixed stationary	5 – 30	3 – 12	Small & medium
Multiple	5 – 20	3 – 12	Small & medium

Figure 2.12a Fixed pad spray nozzle

Figure 2.12b multiple pad spray nozzle

Figure 2.12c Rotator pad spray nozzle

Figure 2.12d Oscillating pad spray nozzle

Figure 2. 12 Types of nozzle sprinkler head (a, b, c, d)

Consequently, water distribution patterns can vary depending on the sprinkler option. Likewise, as the water pressure inside the centre pivot pipeline decreases the further it travels to the outer most section of the central pivot point a gradual increase in nozzle size is required to compensate for the lower pressure.

As a result, nozzles are arranged sequentially on the pipeline at specific spacing. The order of nozzles within the same package is extremely important and should not be changed when maintaining or replacing damaged nozzles as incorrect nozzles will affect the water distribution pattern along the pipeline, (Heerrmann and Hein, 1968). The irrigation application rate can range between 5 - 75 mm / h along the pipeline when using spray nozzle with the rotating pad, and up to 300 mm / h at the far end of the lateral with nozzles with a stationary pad. Therefore, the potential for water runoff would appear to be greatest at the furthest part of the sprinkler pipeline since the irrigation rate is at its greatest, and the application could be greater than the infiltration rate of the soil. The faster the forward speed, the less water will be added to the soil (Heerrmann and Hein, 1968).

2.1.5.2 Operating pressure

The pressure reduces along the pipeline due to internal friction loss and can vary due to topographical elevation changes of the field where the water pressure decreases with the downstream direction inside the pipe and vice versa (James, 1988). Water pressure can be calculated from;

$$\mathrm{P_d} = \mathrm{P_u} - \mathrm{K}(\mathrm{h_1} \pm \Delta\mathrm{Z}) \quad \text{Equation 7}$$

Where

$\mathrm{P_d}, \mathrm{P_u}$= pressure at down – and upstream positions, respectively (kPa, psi);

h_1= energy loss in pipe between the up – and downstream positions (m, ft.);

ΔZ= difference in elevation between the up – and downstream positions (m, ft.);

K = unit constant (K = 9.81 for P_d, and P_u in kPa, and h_1 and ΔZ in meter. K = 0.43 for P_d, and P_u in kPa, and h_1 and ΔZ in ft.).

Kranz *et al,* (2005) has reported in a laboratory experiment that increases or decreases in the recommended amount of operational pressure within the system leads to small spray diameters and thus a decrease in the uniformity of irrigation application due to droplet mass/velocity. Increasing the operating pressure within the system leads to a decrease in the size of the droplets leaving the spray nozzle as a result of a higher jet velocity which can then influence the kinetic energy of the droplets and their subsequent impact on the soil surface. Small water droplets also do not have enough mass to be projected far from the sprinkler thus reducing the wetted diameter (Rogers *et al*., 2017; Stillmunkes and James, 1982). In contrast decreasing pressure in the system leads to a larger droplet size which then also falls close to the discharge point under the influence of gravity, (Thompson and James, 1985).

The water distribution pattern under a single sprinkler, without overlaps from other sprinklers, have been described as a single or double hump or donut shape due to the water application patterns (Thompson *et al.,* 2000), shown in figure 2.13a-f

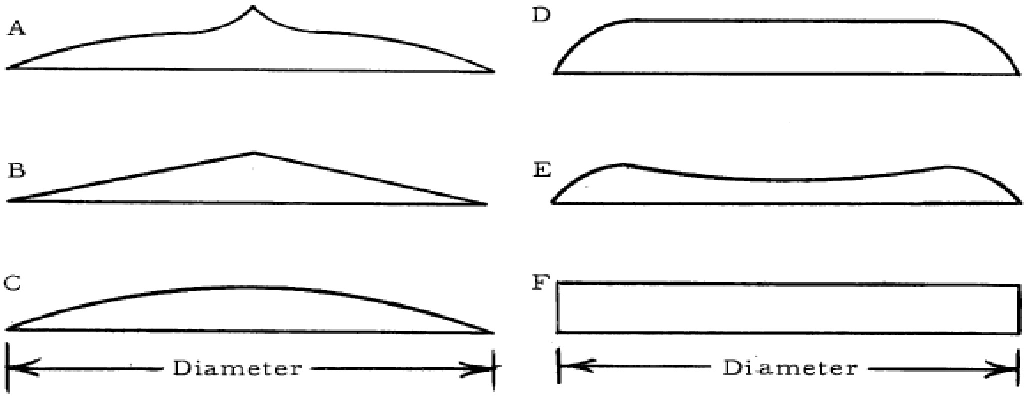


Figure 2. 13 Water distribution patterns from sprinklers (Dabbous, 1962; Christiansen, 1942)

2.1.5.3 Sprinkler position

Lyle and Bordovsky (1981) and Hanson and Orloff (1996) confirmed that irrigation efficiency/uniformity has increased in pivot systems which work with low pressure spray nozzles 69-138 kPa (10-20psi) that were mounted on drop tubes below the sprinkler pipeline.

In practice however, lowering the distance between the spray nozzle and the soil surface simply leads to the reduction of the wetted diameter as the water droplets have less distance to fall (Yan *et al.,* 2010; Rogers *et al*., 1990).

El Wahed *et al*., (2015) investigated the effect of operating pressure, sprinklers spacing and height on the distribution uniformity for fixed spray plate sprinklers. The irrigation system was of five spans centre pivot of 19.6 ha. Water operating pressures were at rate of 200 kPa (29 psi), 400 kPa (58 psi), 600 kPa (87 psi). Sprinklers spacing was varied in each span, 2 m in the third span, 2.5 m in the fourth span, and 3 m in the last span. Fixed spray plate sprinklers were place at 2 m in the third span, 1.75 m in the fourth span, and 1.5 m in the last span.

El Wahed *et al*., (2015) concluded that high values of distribution uniformity DU and uniformity of coefficient CU has obtained when the system operated at high pressures and highest nozzles height. Pressures of 600 and 400 kPa (87 and 58 psi) and nozzle height of 2 m with low sprinklers spacing of 2 m were with high values of DU 93.3 % and CU 94.67% for 600 kPa (87 psi) and 93.93% for 400kPa (58 psi). While the lowest CU and DU average values (66.06% and 61.0%) were with 200 kPa (29 psi) at lowest sprinklers height of 1.5 m, with widest sprinklers spacing of 3 m.

To achieve a greater wetted diameter with low operating pressures, manufacturers have manipulated the sprinkler pad shape to have several grooves to distribute water droplets in a horizontal trajectory with a larger wetted circle.

Results of experiments by Martin *et al.,* (2012) of combined sprinkler package showed that the average droplet sizes were larger with the flat smooth spray plate and decreased for the other devices that were used in the following order: impact sprinkler type straight bore, four-groove Nelson rotator plate, six-groove Senninger wobbler plate, and concave 30-groove Nelson spray plate.

Overhead sprinkler performance can, therefore, have a direct effect on water application and formation of water runoff. Smaller droplet sizes lead to moisten soil surface, but within time a thin layer formed on the surface which leads to runoff (Tarjuelo *et al*., 1999; Thompson *et al.,* 1993). Similarly, the same layer would quickly be formed under the effect of larger droplet sizes.

Consequently, it can be seen that selection of sprinkler type and position must be linked to a suitable operating pressure as they have a large role in the occurrence and reduction of water runoff under centre pivot systems.

2.1.6 Effects of soil factors on water runoff

Soil is a complex porous system, it is the outputs of erosion that has occurred to the mother rocks and influenced by processes of soil formation over time until they reached to the status (Landon, 2014). The Cambridge dictionary (2017) defines soil as, “the material on the surface of the ground in which plants grow”. A more scientific definition is: Soil is the surface layer of the ground in which plant can grow, consisting of organic and non - organic mineral materials and the result of the change of parent material under the influence of climatic factors, macro and micro - organisms for a long period of time, (Brevik, *et al*., 2016).

Soil is composed of three phases: solid, liquid and gaseous. The behaviour of the soil depends on the relationship between these phases, and its properties vary within a single phase in addition to the difference in properties between different phases (Jahn, *et al*., 2006).

The solid phase is more than half the soil volume and more than 75% of its mass, it is often referred to as the soil skeleton or soil matrix. The solid phase contains the mineral particles of sand, silt and clay and includes organic matter which by the process of humifaction produces the adhesive, humus, which binds individual soil particles together to form larger particles called soil aggregates, (Nimmo, 2004)

The gaseous phase: The soil system is constantly in equilibrium with air through the pores between soil particles and is called soil air. The volume of soil air varies from time to time and from place to place within the soil pores, depending on soil moisture and operations performed on the soil, such as cultivations or adding organic fertilisers.

The liquid phase is the water inside the soil pores and on the surfaces of the soil particles (Hillel, 2012). The mixture of the water and soil is known as the soil solution, where it contains different salts present in the soil system or from added fertilizers. The soil solution is ultimately the source of the nutrients needed by plants for their growth. Soil water is critical for plant growth and is linked to precipitation, rainfall and irrigation, and also to the demand from evaporation or evapotranspiration. Soil water which available to be absorbed by roots is in the field capacity limits.

Field capacity: It is the moisture content which exists after the drainage of free water, and any moisture remaining is held against gravity at approximately 0.05 bar (0.005 MPa). This is suggested to occur 48 hours after saturation in a free draining soil. The moisture content at field capacity varies depending on the soil texture and structure Field capacity represents the upper limit of soil water suitable for most plants. From field capacity, the soils moisture will be depleted through the processes of evaporation and/or evapotranspiration until all plant available water is used, at which point permanent wilting point (PWP) is reached. The soil moisture at this point is held at approximately 15bar (1.5 MPa). The quantification of PWP is important for irrigation as between FC and PWP the plant available water can be quantified, for runoff however it has little value. Although there is plant available water between FC and PWP it becomes held at greater tensions as the soil dries. The process is not linear, is influenced by soil texture and soil structure and is represented by soil moisture characteristic curves (Williams *et al*., 1983).

However, the volumetric water content of the soil at a given tension of soil moisture is influenced by the process of hysteresis. This means that the water content of a drying soil at a given water potential is greater than the actual water content at the same tension under a wetting front. For capillary water, this is suggested as due to pore space irregularity which in turn affects the soil water tension. For a detailed explanation see (Hillel, 2012). There is some relevance of hysteresis to the process of runoff but mainly to the quantification of soil moisture status for experimental work.

Soil moisture states relative to the tensions they are held at can be demonstrated and quantified using soil moisture characteristic curves, SMCC, figure 2.14.

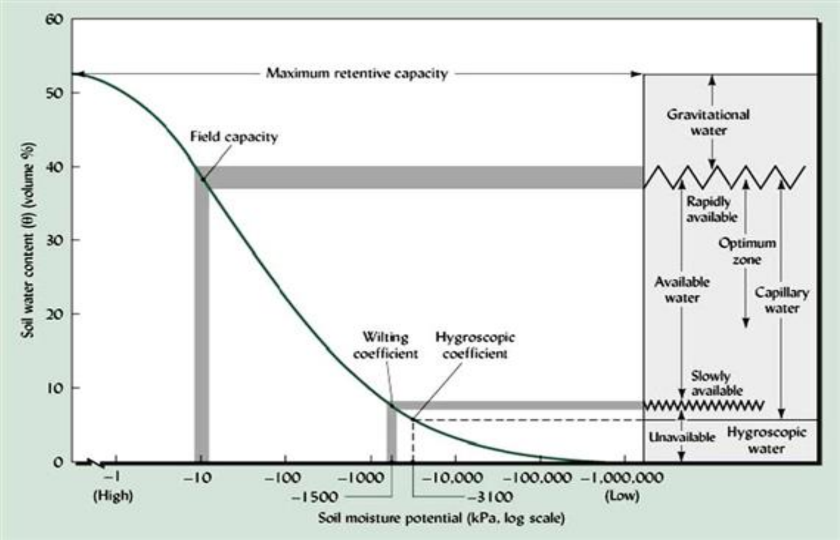


Figure 2. 14 Soil moisture characteristic curves (Brady and Weil, 2008)

2.1.6.1 Soil physical characteristics

1- Soil structure and soil aggregates

Soil structure expresses the degree of combination and arrangement of soil particles and is influenced by the amount of clay and organic matter within the soil, environmental factors and, in agriculture, the type of cropping and cultivation practices used, (Hillel, 1980). Soil particles under normal conditions do not generally exist in an individual form, except for pure sands, as they are connected with each other to form soil aggregates. The importance of soil aggregates for plant growth is both physical for anchorage and root penetration and biologically for access to nutrients and water. Aggregates are also important for soil/water interactions such as the infiltration process and transfer of precipitation and irrigation water within the soil profile. Aggregates also facilitate soil aeration. And increase the activity of the beneficial soil flora and fauna, (Verhulst *et al*., 2010; Fredlund and Rahardjo, 1993).

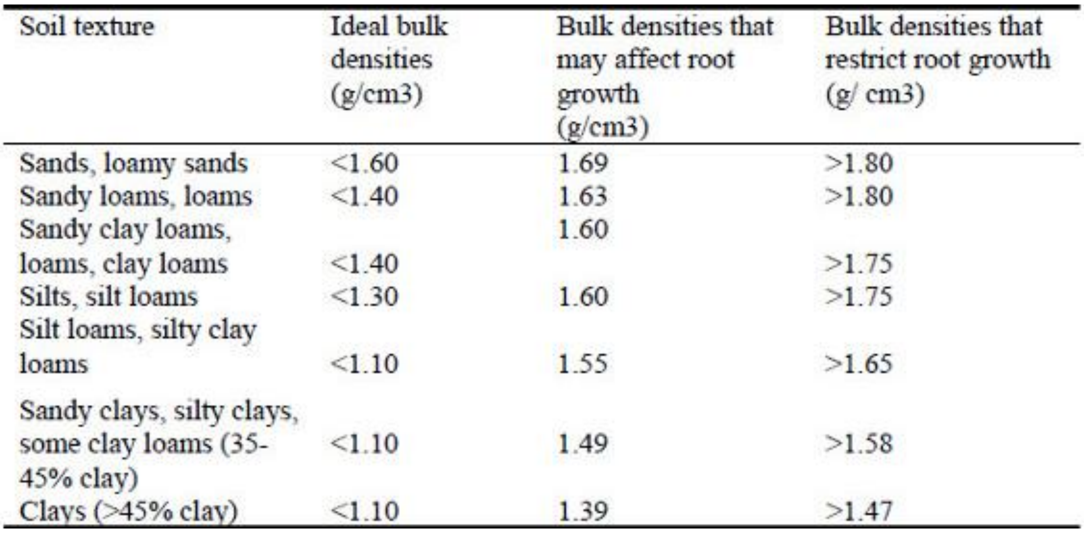
Soil aggregates could be formed by demolition of a uniform soil mass into smaller sizes, or by reunion of small soil aggregates to become larger structures, Hamza and Anderson, (2005), confirmed that the stability of soil aggregates has an active role in maintaining the soil surface against the erosion process. Structural types include granular, blocky (angular and sub-angular), prismatic, platy and massive. Near to the soil surface it is the granular or blocky structures which should dominate to provide a good media for seed growth and infiltration of water into the soil, as opposed to run-off, (McCarthy and McCarthy, 1997). Laboratory, wet methods are used to estimate the structural changes resulting from agricultural operations, since water can facilitate the breakdown of soil aggregates into individual soil particles, thus making them prone to water borne movement in erosion. Particle size range from <0.002 mm for clay, 0.002 to 0.05mm for silt and 0.05 to 2mm for sands under the USDA system (Baillie, 2001). Soils with a large proportion of sand particles are the most prone to erosion. Zhao *et al*., (2011) studied soil erosion and deposition under the effect of rainfall and runoff on particle size distribution in Chinese farms. A laser diffraction was used to determined particle fractions. Soil separates sizes were (0.001– 0.002 mm) for coarse clay, (0.002–0.005 mm) for fine silt, (0.005–0.01 mm) for medium silt, and (0.25-0.5 mm) for sand fractions. The obtained results showed that particle sizes of 0.25–0.5 mm was more exposed to erosion, which led to clay and silt fractions deposited mainly on the topsoil; this in turn increased soil water content. Zhao *et al*., 2011 indicated that distribution patterns of soil particles under the influence of rain, were affected by water distribution and movement. In respect of irrigation, Lamm *et al*., (2012); Lamm *et al*., (2006) confirmed that the application intensity from the LESA system on soil has led to damage of the soil aggregates. This due to in-canopy irrigation system (LESA) produced small sprinkler wetted radius with large volume of water in a short period of irrigation time. In this case, irrigation under high intensity leads to soil erosion in the surface layer. Therefore, a change in the distribution of soil particles will occur; the movement of fine particles with water irrigation will close the pores because of deposition. Thus, increasing the infiltration time and the retention of water for a longer period on the soil surface (Lamm *et al*., 2012).

2- Soil bulk density

This is the oven dried mass of soil sample in a given volume. The bulk density can indicate the proportion of solids and pore spaces within that volume. Nimmo, (2013) confirmed that bulk density reflects the soil pores ratio and the movement of water and air.

Bulk density is often used to identify soil physical attributes such as compaction and impedance to root growth and can indicate the porosity or infiltration capability of the soil. Bulk density varies with the structural condition of the soil, soil type and organic matter content. Bulk densities can be low after soil cultivations such as ploughing but can increase under irrigation due to the movement of soil particles into the soil pores, (Hanks and Lewandowski, 2003). Table 2.3 show bulk density values for various soil types.

Table 2. 3 General relationship of soil bulk density to root growth based on soil texture. (Hanks and Lewandowski, 2003)



Soil texture	Ideal bulk densities (g/cm3)	Bulk densities that may affect root growth (g/cm3)	Bulk densities that restrict root growth (g/ cm3)
Sands, loamy sands	<1.60	1.69	>1.80
Sandy loams, loams	<1.40	1.63	>1.80
Sandy clay loams, loams, clay loams	<1.40	1.60	>1.75
Silts, silt loams	<1.30	1.60	>1.75
Silt loams, silty clay loams	<1.10	1.55	>1.65
Sandy clays, silty clays, some clay loams (35-45% clay)	<1.10	1.49	>1.58
Clays (>45% clay)	<1.10	1.39	>1.47

The bulk density of peat is very variable as there are different types of peat. Chapman, Artz and Pogio (2015) and Paivanen (1969) report a range of 0.04 to 0.34 g cm3.

Bulk density is calculated from the following relation, equation 8:

$$\mathrm{BD}\ (\mathrm{g/cm^3}) = \frac{\text{Mass of dry soil}}{\text{Volume of core}}$$

Equation 8 (Donahue, et al., 1983)

3- Soil porosity

Soil porosity relates to the value of soil voids that can be filled by water or air. It is expressed as a percentage of a volume of soil. There are two elements to soil porosity: the first is the voids between individual soil particles, and the second is the larger voids between soil aggregates. Thus, the overall volume of pores is the sum of small and large voids, (Nimmo, 2013; Hamza and Anderson, 2005).

Pore sizes vary within soils as it is affected by a variety of factors, including: texture, structure, depths, and the amount of organic matter. Irrigation can affect the pore amount as Alhammadi and Al-Shrouf., (2013) confirmed that high infiltration rates could move clay particles to clog pores and accumulate in a layer underneath the soil surface. This layer may then prevent water percolation in deep layers. The overall size of the pores of a sandy soil is less than that for a clay soil, the total volume of pores ranging in sandy soil between the 35 - 50%, while in clay soils 40-60% or more (Alhammadi and Al-Shrouf, 2013). This is due to the physical surface area differences of the particle sizes. Practically, pores size has a significantly greater importance in, clay soils as it contains a higher proportion of small pores which helps to increase its ability to hold water but can also reduce water movement in soil. The pore space can be influential in the infiltration rate which for sandy clay and sandy loam soils range from 40 to 250 mm/h where water moves in all direction under the effect of capillary action, however it is slower than infiltration values in sandy soils which reached up to 4000 mm/h where water moves downward due to the gravitational forces, figure 2.15.

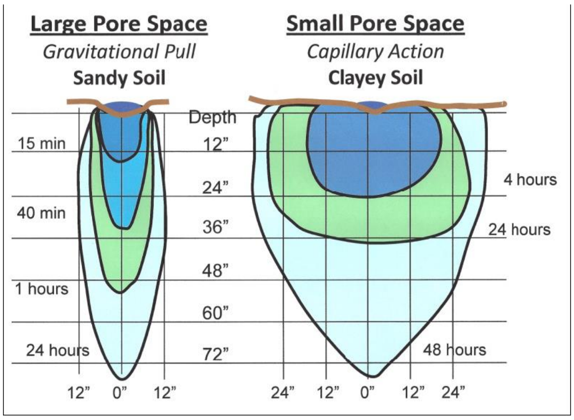


Figure 2. 15 Water movement in sandy and clayey soils (Alhammadi and Al-Shrouf, 2013)

Nimmo (2013) clarified that pore size is also influenced by soil depth. Whenever soil depth increased, the size of pores decreased slightly due to the cohesion or adhesion or merging of particles with each other. This is due to factors of soil compaction by machinery or plant roots, or perhaps the movement of water and fine soil particles leaking down. Accordingly, deep soil porosity ranges between 25% -35%, while in surface layers is more than 60%. Pores have a great importance that they affect and determine drainage and ventilation conditions in the soil.

Porosity is calculated from the following equation 9:

$$\text{porosity (pt)} = \left[1 - \left(\frac{\rho b}{\rho d}\right)\right] * 100 \qquad \text{Equation 9}$$

Where:

ρb= total bulk density

ρd= dry bulk density

In low organic matter soils the pore size can be increased by increasing organic matter, which can occur as plant roots and microorganism’s open channels in the soil, (Dexter, 2004). Porosity can also be affected by agricultural soil cultivation practice, or by removal or retention of the crop residues. This is a balance between increasing the organic matter and therefore improving soil aeration and water movement as well as raising the soil ability to hold water.

4- Soil shear strength and soil penetration properties

There are several factors that affect the stability of aggregates and soil structure, these factors either natural, such as rain and wind or the impact of the machines alternating traffic on soil field (Smith *et al*.; 2012). Rain and wind impact significantly on the soil surface, especially if the vegetation not enough to cover the soil to protect it from erosion, while the impact of the machines effect on surface layer and the layers underneath the surface (Smith *et al*.; 2012).

Yan *et al*., (2011) explained as a result of the effect of the irrigation spray, small-sized soil particles (clay) move down to settle in the pores within the existing structure of the soil. The accumulation of these particles constantly will lead to the creation of a consolidated or compacted layer, thus water and air movement between the higher and lower regions from this layer will stop.

Moreover, the impact of agricultural machinery traffic on the land from preparing the land for farming to the extent of harvest and then preparing the soil for the next crop, compaction of the lower layers of the soil will occur. This compaction will create a layer at a depth of 75 or more than 100 cm from the soil surface, this layer is called the hardpan layer which also stopped the movement of water and air between the higher and lower from this layer (Smith *et al*., 2012; Jadczyszyn, and Niedźwiecki, 2005).

Soil penetration resistance and shear strength or distribution of pore size were used as a function to express soil hardness, soil surface compacting, and soil aeration.

Soil shear resistance is an internal stress between soil particles relative to an applied external stress. Shear strength is reliant on two fundamental forces; internal friction between the surfaces of individual soil particles and on the cohesion strength between particles (Manuwa and Olaiya, 2012). Clay soils usually have high shear resistance compared with sandy soils due to the size of the individual particles and the abundance or lack of cations and electrical forces.

Soil shear resistance is a larger shear stress which can be borne by the soil where it collapses afterwards and gives a clear sliding surface. Under the influence of external load, the pressure at some points can outweigh the inner joints between the soil particles, and slippages arise for some particles. Soil joints can be disrupted in one area, i.e., soil resistance is overcome in that area. While the force of penetration is the ability of soil to be sheared (Batey, T., 2009).

However, Garcia *et al*., (2012) mentioned that soil penetration resistance values are higher when soil moisture content decreased, penetration resistance was 100 kPa when moisture content was 3.7 to 5.6 % for loam sandy soil and bulk density of 1.77 gm/cm^3. Garcia *et al*., (2012) recommended that soil moisture is preferably to be close to field capacity,

Mohr-Coulomb found an equation for resistance soil shearing through a linear relationship between shear stress and vertical stress corresponding to the level of shear, (Salgado, 2013). Shear stress (t) is the result of shear strength (F) divided by the shear area (*A*), namely that:

$$\mathrm{t} = \frac{\mathrm{F}}{\mathrm{A}} \qquad \text{Equation 10}$$

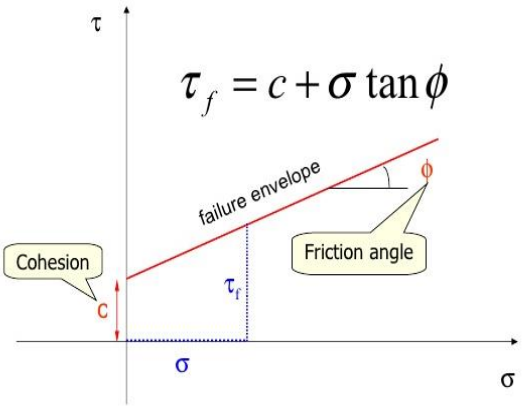
Vertical stress for shear soil (σ) is the result of vertical force (N) divided by surface shear area:

$$\sigma = \frac{\mathrm{N}}{\mathrm{A}} \qquad \text{Equation 11}$$

Therefore, the Coulomb equation for soil shear resistance takes the following linear relationship:

$$\mathrm{t} = \mathrm{c} + \sigma \tan \emptyset \qquad \text{Equation 12}$$

Where (c) symbolizes soil cohesion, and (Φ) represents the angle of internal friction to resist shear. Coulomb equation can be represented, figure 2.16:



τ_f is the maximum shear stress the soil can take without failure, under normal stress of σ.

Figure 2. 16 represents Coulomb equation for soil shear strength, (Cruse and Larson, 1977)

In saturated soil, pressure is equal in all directions, therefore internal friction for particles = 0, and shear resistance be equal to the cohesion, namely that:

$t = c$ Equation 13

In dry sandy soil, resistance to shear depending on the internal friction and lacking cohesion property, and take the following relationship:

$t = \sigma \tan \emptyset$ Equation 14

Consequently, the soil pore ratio plays an important role in determining the shear force resistance. Where the lower the ratio leads to increased soil shear resistance. Which indicates the soil conditions are not suitable for irrigation or to water infiltration to the extent of roots. In other words, water stays on the surface for a long time which means runoff.

Each soil has a certain stress as a result of penetration by different cultivation equipment. Since there are different types of soils which differ in conditions, so there are different values of resistance to shear (Lampurlanés and Cantero-Martinez, 2003).

Hashemi *et al*. (2012) found that in deep ploughing conditions to the depth of 300 mm, shear strength will be less in the lower layer than the upper layers. However, the highest values of shear strength were found with mouldboard plough at a depth of 30 cm.

5- Soil crusting

A soil crust is a layer of soil whose thickness ranges from a few millimetres to a few centimetres. It is created on the soil surface under the influence of water droplets which causes the soil aggregates to breakdown into smaller components. Soil crusts then prevent water infiltration into the soil and results in runoff, (Al – Thobhani 2000).

Cerdan *et al*. (2002) confirmed that water droplets have an energy that breaks down and moves small soil particles of clay and silt. These particles then settle in the spaces/pores between the soil particles thus reducing the pore size or closing them completely.

Twomlow (2000) mentioned that sandy loam soil crusts under natural rainfall, disposed to runoff and thus drought sensitive. Under the influence of high air temperature, the surface soil moisture quickly evaporates shrinking the soil surface and creating cracks that give a final shape of this crusted layer.

Timm *et al*., (1971) remarked that plant growth in the presence of a soil crust depends on the layer thickness; if the thickness at 10 mm, plant stems could penetrate it and grow through. With thicker layers, the stem twists and then breaks through, but with some distortions which will affect the crop growth and ultimate maturity. If the thick layer is up to 5 cm, the plant stem is broken which prevents growth and this will also cause a hole under the crusted layers.

Timm *et al*., (1971) suggested that to address crusting resulting from irrigation, it is possible to establish furrows under the sprinkler irrigation, or to maintain the soil moisture throughout the growing season. It is also suggested that application of gypsum on the soil surface could reduce or prevent the formation of the crust. On the other hand, Doran *et al*., (1999) stressed that soil crusting is sometimes a positive feature as it prevents wind erosion especially with sand and clay soils.

Organic matter reduces soil erosion and runoff. Organic matter is a material mixed with soil and composed of plant and animal residues which have been analysed by the impact of different factors to simpler materials, in addition to the existence of microorganisms. The continuous decomposition of organic matter leads to the production of simpler materials called humus, a dark colour that remains in the soil and gain a lot of fertile (Bot and Benites, 2005).

Lado *et al*., 2004 investigated the effect of soil organic matter content on a seal formation under simulated rainfall with an intensity of 42 mm h^{-1}. Results showed that thick crust of sandy loam soil of low organic matter (2.3%) was developed. On the contrary, soil with high organic matter content (3.5%) was high aggregate stability and limited seal formation. Soil which has low organic matter content that is of a poor structure and less of pore space. Therefore, when it rains or when sprinkling irrigation on this type of soil, soft particles will close the existing pores and thus lead to the formation of a seal that prevents the absorption of water; i.e. the occurrence of surface runoff.

2.1.7 Soil water movement and characteristics

2.1.7.1 Water infiltration into soil

Infiltration is the movement of water from the soil surface to a lower layer. It is a process of water entry into unsaturated soil, (Brouwer *et al*., 1988). Under irrigation, water is added to the soil which alters the distribution of the soil moisture content. After irrigation, soil moisture is distributed within the soil profile which is called the water content profile. This water content profile under centre pivot systems depends on the soil type and structure, soil vegetation, and most importantly on application rates. If the water application rate is higher than the infiltration rate, water runoff will occur, and erosion will take its place. Consequently, anything that disturbs the upper soil layers such as soil cultivation and the deformation of the soil structure or aggregate stability will affect infiltration. As soil cultivation practices have been shown to affect soil infiltration (Al-Ghobari, 2011) soil cultivation method should be selected to be compatible with the type of irrigation system, (Ma *et al*., 2015; Al-Tahan, Y.H., 2007).

Al-Ghobari (2011) reported that water was distributed uniformly in the subsurface layers 12% more than on surface values for centre pivot systems. This suggests that water distribution efficiency for such systems in a root layer have a higher efficiency than that reported for the soil surface. A well-structured of subsurface layers profile after ploughing leads to the uniform distribution of pores. This will result in a preferable distribution of water than it is in the soil surface.

2.1.7.2 Water runoff under centre pivot irrigation

Water runoff appeared with using centre pivot systems type LESA (Low Elevation Spray Application), especially in the wetted area, i.e. in the last part of the system, which has the highest irrigation rate and greater than the rate of absorption due to a limited spray diameter for each nozzle, (Rogers *et al*., 2017; Howell, 2006). The process of runoff usually appears after several irrigations in the growing season suggesting that the problem arises over time.

References showed King and Bjorneberg, (2011); Porter and Marek, (2009); Murray and Grant, (2007) that clay and silty soil are often influenced by irrigation intensity under such systems. However, there is no exemption for sandy soils, (Msibi *et al*., 2014; Skidmore and Layton, 1992) stated that there is an appearance of water runoff when planting crops in sandy loam soils under pivot irrigation systems. Here tillage method plays a role in the formation of a soil structure which is more resistant to erosion or demolition generally. There are some soil physical characteristics which give indications of soil conditions like shear strength and penetration resistance, moisture content and infiltration rate which can identify what causes these problems. In addition, soil crusting and the impact of crop residues in soil can also identify where infiltration problems occur.

2.2. Crop residue and its effect on water runoff

To maintain soil surface under the influence of sprinkler irrigation, Duiker, (2006) indicated that soil with a content of plant residues between 0 to 30% leads to non-scattered soil by 70%. Duiker, (2006) pointed that to reduce soil erosion, selection a best tillage equipment is necessary. Subsoiler is recommended by Duiker (2006) due to the modern design which cause breaking and disturbance of the soil but with leave most residues on the surface.

A study conducted by van Donk *et al*., (2008) to compare corn crop yield in residue-covered (soybean crop) soil, and bare soil; results were significantly ($P < 0.01$) greater with residue-covered areas (12.4 Mg/ha) than bare-soil (10.8 Mg/ha). This was attributed that residue-maintained soil moisture which led to use more water by corn in the growing season.

Mielke (1992) confirmed that the presence of crop residues led to reduced rate of runoff, and in combination with lowering of the irrigation rate centre pivot systems could be used effectively. Crop residues absorb the impact energy of the water droplets, thus reducing soil particle detachment and reduce soil crusting, whilst increasing infiltration rate and decreasing runoff (Nebraska. 2013).

2.3. Tillage

Tillage is considered one of the oldest agricultural operations in history. Ploughing tools made from wood, bone or a carved stone were found in the caves of northern Iraq from 10,000 year ago (Kornfeld, I.E., 2009). Throughout history, tillage is considered as the main key to improving crop production.

Tillage could be expressed as a method of cultivation which uses tilling equipment to prepare a convenient place for seed germination and ensure the success of crop growth. From this concept, tillage equipment and methods have developed technically to cover a wide range of crops in a wide range of soils whilst encompassing many environments and circumstances.

In irrigated agriculture, studies have shown that an agricultural operation success depends on the tillage method compatibility with the method of irrigation. This is because of the link between the irrigation runoff and water runoff. Murray and Grant (2007) confirmed the primary factor in the destruction of soil aggregates after the tillage operation is irrigation. The damaged aggregates ratio varies depending on the soil type, and the proportion of the amount of plant residue and irrigation.

Although centre pivot systems are considered highly efficient in terms of application efficiency of water and use energy they have a significant impact of aggregates damage even if the cultivation was done in good soil conditions.

2.3.1 The effect of tillage type on soil physical properties

Although tillage creates adequate soil aeration and water infiltration in the seed and root zone, it has negative impacts on the stability of soil aggregates and accelerates the process of decomposition of organic matter and oxidization when mixed with the soil, (Ramos *et al*., 2003; Takken *et al*., 2001; Wilhelm *et al*., 1985). The tillage operation reshapes the soil aggregates depending on the shape of the cultivation equipment. However, tillage may be directly destroying aggregates that are exposed to soil compaction. Ploughing processes include cutting, lifting and turning over of a section of soil to a given depth. The turning over process works to break up this section and then re-forms it; the goal is to increase soil porosity, bury surface plant residue and provide a good seedbed for the seeds.

In irrigation conditions however, especially with overhead spraying systems, this process will have a negative impact on the soil and plant (Skidmore and Layton, 1992).

2.3.1.1. Effect of tillage on soil penetration resistance

The type of the cultivation plays an important role in changing some of the physical characteristics of the soil. Hasheminia (1994) found in a field experiment comparing a subsoiler, mouldboard plough, disc plough, rotavator and without ploughing, that soil ploughed by disc plough was less resistant to penetration, equal to 191.0 kPa, while the highest value of penetration was the mouldboard plough, 467.37 kPa at soil depth of 15 cm. This may be related to the different actions and downward pressures achieved by the different system.

Al-Tahan and Al-Ali Khan (2007) found that the penetration values for a loam clay soil ploughed with mouldboard plough were higher than without tilling after a period of 8, 12, and 16 days of irrigation; the values were 600, 1400 and 1800 kPa for mouldboard plough and 400, 600 and 500 kPa for the treatment without tilling, respectively. Which suggest that the untilled soil had better pore structure.

Jabro *et al*. (2010) found that penetration resistance and infiltration rate values were lower in deep tillage to 35 cm than for shallow tillage to 10 cm. Values were 912 kPa and 41.5 mm/hr in deep tillage compared to the surface tillage of 1203 kPa and 30.4 mm /hr. This is suggested as due to an increased soil loosening in the top layer.

2.3.1.2. Effect of tillage on soil shear strength

Manuwa and Olaiya (2012) defined shear strength as the resistance of the soil to the collapse of aggregates or resistance against shear. It was also pointed out that the shear strength decreases with the wet blocks, but it increases when the soil has plastic moisture tension between the particles. i.e., the particles become adjoined and difficult to move. It was noted that the performance of the soil with the ideal shear strength that an addition of water to the mass of dry soil left for a period will lead to increased shear strength due to the movement of particles clogging pores. However, adding water continuously to the upper limit of saturation will lead to a decrease in shear strength. This has been supported by many researchers (Hamza and Anderson, 2005; Hajabbasi and Hemmat, 2000).

Manuwa and Olaiya (2012) found that increasing the water pressure on soil equivalent to 600 kPa led to increased shear strength to the highest extent by 1025 kPa at the soil moisture content of 9.1%. Al Thobhani (2000) explained through a study by USDA (1996) that the shear strength at a depth of 5 cm was close when comparing no-till with mouldboard plough, but the highest values of shear strength were found with mouldboard plough at a depth of 30 cm.

2.3.1.3. The effect of tillage on water infiltration and movement

Investigation of the tillage systems were not limited to roughness and porosity of the soil surface only, but also its impact on the movement of water into the soil, evaporation and drainage, water conductivity and the amount of water remaining in the soil. Soils vary in terms of their ability to retain water, depending on their type, aggregate size after cultivation and organic matter content. This agrees with Da Silva *et al*., (2004).

It is known that the infiltration rate increases in soil with a high percentage of non-capillary pores. Ma *et al*. (2015) observed that sub-soiling followed by rotary tillage gave good results in terms of increased portability of soil water storage for the depths of 20-180 cm after sowing. This led to improved efficiency of water use.

Lindstrom and Onstad (1984) found that the no-till system, when compared with tillage with moldboard and chisel plough, had the highest values of bulk density and lowest values of water conductivity, plus low porosity with surface runoff, under an irrigation intensity of 56 mm / hr.

Due to water scarcity problems in arid and semi-arid regions, tillage techniques had been developed such as reservoir tillage. Reservoir tillage runs between furrows or rows to make small reservoirs in the ground. Dursun and Dursun (2016) pointed that these small reservoirs are hold rain or sprinkler applied water and reduce runoff as well as erosion.

Hasheminia (1994) selected multiple types of nozzles to spray water in different shapes, included spray nozzles on drops (spray drops), spray nozzles on booms (spray booms) and rotator spray nozzles on drops (rotator spray drops) with an operating pressure of 138 kPa, at the outermost spans, where the highest application rates occur; with two types of ploughing; conventional and reservoir tillage. The results showed that reservoir tillage effectively reduced runoff losses to less than 1% of the applied water, also increase the average soil water content by 18% and increased the percentage of available water in the top 65 cm of the root zone of potato plant; but the sprinkler type did not have a significant influence on yield.

Kranz and Eisenhauer (1990) stressed the need for a compatibility between the ploughing system for a particular field with the type of centre pivot irrigation system. Three types of ploughing equipment were tested to improve soil conditions and reduce the probability of runoff. The equipment are chisel shank (subsoiling), small paddles or disk blades (basin) and combine the concepts of a subsoiler and basin tiller (Implanted Reservoir). The results showed that soil conditions were improved when using small paddles.

2.4 Critical review of research gap to be investigated

Water runoff problems under centre pivot irrigation systems still exist due to irrigation intensity which is higher than the water infiltration rate, and not taking into consideration the best cultivation under these systems; this leads to a gradual deterioration of the soil surface. Soil aggregates demolish similarly in flood irrigation and sprinkler irrigation. The only difference is that flood irrigation is direct and demolishes soil aggregates faster than sprinkler irrigation.

This will be required to find the optimum cultivations method to use under centre pivot irrigation. In relation to the work however, the research will focus on equipment currently available to the Iraqi farmers and will not investigate complex equipment available through the world.

2.4.1. Research hypothesis

Varying sprinkler operating parameters alone or in combination with changes in soil cultivation methodology can reduce run-off and improve performance of centre-pivot irrigated crops.

2.4.2. Null hypothesis

Soil cultivation practice and overhead (centre-pivot) irrigation system performance do not influence surface water runoff.

2.4.3. Research aims

The primary aim of this study was to investigate the effect different soil cultivation practices/equipment have on the irrigation water runoff potential from the end section of a pre-selected centre pivot system used in Iraq.

The secondary aims were to (i) investigate the sprinkler nozzle outputs to quantify the uniformity of application and thus it’s potential to cause localised runoff and, (ii) identify an optimum size of runoff test area suitable for in situ measurement in commercial fields.

3. General materials and methods shared between experiments

In this chapter, the general shared research methodology used in the study is described. It includes a description of the method of using the instruments in which samples were taken, in addition to the method of conducting the test, whether field or non-field.

During 2014 - 2016, there were series of field and indoor, protected environment, experiments. Each experiment had distinctive aims and objectives but some of the materials and methods were similar between them. The general materials and methods reported here are applicable to several experiments and are given to prevent unnecessary repetition. These include: infiltration rate, soil shear strength, soil penetration resistance, soil moisture content, and the measurement of water distribution uniformity.

3.1 Infiltration rate

The double ring infiltrometer is a widely-used method to determine the infiltration rate of water into soil. It consists of two metal rings, figure 3.1, which are driven into the soil (Parr and Bertrand, 1960). Several sizes of rings are available, but the ones used in these field experiments were of the larger type, chosen to give the greatest surface area from which to make the assessment. It was felt that due to the nature of the soil disturbance from cultivation equipment the larger diameter rings would provide a better representation of the soil characteristics than smaller rings, the single ring or the mini disc infiltrometer.

3.1.1. Materials

1. Stainless steel double rings with two different diameters, an outer ring with a diameter of 550mm and an inner ring with diameter of 350mm. The height of both rings was 350mm.
2. Wooden piece (timber) to drive the rings into the soil, 1000 mm length, 100 mm width x 100 mm, to prevent damage to the rings whilst being driven into soil
3. Heavy hammer, 5 buckets (5 litre each), ruler 300 mm, measuring jug, stopwatch, perforated metal plate, records data sheet.
4. Water supply capable of supplying sufficient water to the test site.

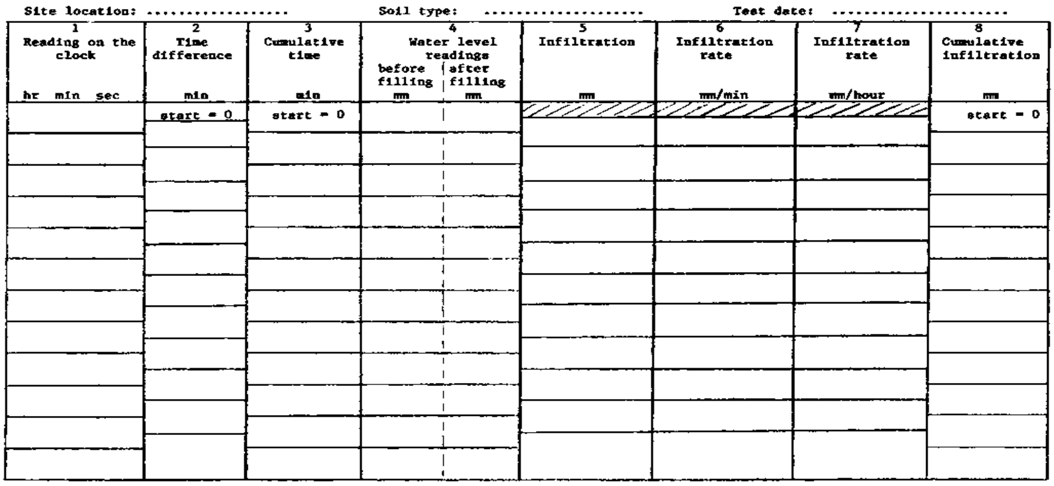
Figure 3. 1 Infiltration rings for double ring infiltrometer

3.1.2. Method of testing the infiltration

1. The areas for the tests were randomly selected in each plot, ensuring that the soil surface had not been compacted in any way after the cultivation.
2. The outer ring was installed firstly into the soil without hammering, then the inner ring was installed in the centre area inside the outer ring.
3. The two rings were then installed at approximately 150 mm into the soil vertically. Timber has been used to protect the ring from damage during hammering and this was moved around the ring to ensure an even installation.
4. The ruler was driven into the soil vertically inside the inner ring to approximately 120 mm depth. The measurement of infiltration was taken in the inner ring.
5. A perforated metal plate was used to cover the soil surface inside the inner ring. This is to avoid the force of the applied water disturbing/compacting the soil surface and to ensure a uniform distribution of water inside the ring.
6. Water had been poured into the outer ring firstly at approximately 70-100 mm depth, to ensure that water from the inner cylinder flows downwards and not laterally.
7. Water is then added to the inner ring at approximately 100 mm depth.
8. From this point, the test has been started. Additional water should be added to the space between the two rings to be in the same depth.
9. The water level and time are recorded when the test begins.
10. The drop-in water level in the inner ring is recorded after two minutes. Then, the water level is brought back to the original level at the start of the test. It should be noted that the water level between the two rings must be similar.
11. The test is continued as the same procedure but depending on the schedule time in the record sheet, table 3.1.
12. Calculations which outlined in the record sheet were done quickly.

13. When two consecutive readings are identical from these calculations, the test should be stopped. This identifies the point that water had reached the basic infiltration rate (Brouwer *et al*., 1988).

Table 3. 1 Infiltration rate sheet (Brouwer *et al.,* 1988)



Site location: .... Soil type: .... Test date: ....

1 Reading on the clock hr min sec	2 Time difference min	3 Cumulative time min	4 Water level readings before filling mm	after filling mm	5 Infiltration mm	6 Infiltration rate mm/min	7 Infiltration rate mm/hour	8 Cumulative infiltration mm
	start = 0	start = 0			▨	▨	▨	start = 0

Where:

Column 1 indicates the readings on the clock in hours, minutes and seconds.

Column 2 indicates the difference in time (in minutes) between two readings.

Column 3 indicates the cumulative time (in minutes); this is the time (in minutes) since the test started.

Column 4 indicates the water level readings (in mm) on the measuring rod: before and after filling.

Column 5 indicates the infiltration (in mm) between two readings; this is the difference in the measured water levels between two readings.

Column 6 indicates the infiltration rate (in mm/minute); this is the infiltration (in mm; column 5) divided by the difference in time (in minutes, column 2).

Column 7 indicates the infiltration rate (in mm/hour); this is the infiltration rate (in mm/minute, column 6) multiplied by 60 (60 minutes in 1 hour).

Column 8 indicates the cumulative infiltration (in mm), (Brouwer *et al.,* 1988).

3.2. Soil shear strength

Soil shear strength is the amount of mechanical strain that a soil volume can withstand before failure by shearing (McCorthy, 1977). The shear strength is a combination of cohesion and friction between soil particles and aggregates and can be affected by soil structural changes and soil moisture (Manuwa, and Olaiya, 2012). In these field experiments soil shear strength was measured by a shear vane (4 blades equi-spaced 8 mm width on 5 mm diameter shaft) with a force gauge (Mecmesin force gauge AFG100N, Slinfold, West Sussex, UK) in units of kg/cm^2 and then the data were converted to kPa, figure 3.2 a and b. Readings were taken at 100, 200 and 300 mm depths from random areas of each plot. The measurements were not taken sequentially from the same spot as the movement of soil at the upper level could impact on the readings taken from subsequent lower depths.

3.2.1. Method

1. The shear vane was pushed down into the soil to the depth of 100 mm then rotated clockwise. The maximum value of torque was recorded in kg/cm$^{2.}$
2. The shear vane was then moved to another position, staying near to the first one and pushed down into the soil to the second depth of 200 mm.
3. The same process repeated with the depth of 200 – 300 mm.
4. This procedure was repeated three times per plot to provide an average value for the plot.

Figure 3. 2 Shear vane (a) and torque meter (b) used for soil shear strength measurements

3.3 Soil penetration

Soil penetration resistance is an indicator of soil compaction and is important in determining the least limiting water range. Soil penetration resistance indicates soil consistency and shear strength. Soil penetration was measured by HUMBOLDT MFG. CO with unit of kg force/ cm^2. Figure 3.3. Readings for soil penetration were taken at a depth of 10, 20, 30 and 40 cm randomly per plot.

3.3.1 Method

1. Set a location in each plot randomly. This area is preferable 0.25 m^2
2. dig down this area to a depth of 50 cm.
3 - Install a ruler on one wall of the hole to know the depth that data would be taken.
4. Push the gauge slowly on the wall of the hole at the required depth.
5. Stop pushing when you feel that the gauge does not push more under the influence of normal hand force.
6. Record the reading.
7. Rewind the gauge to its first position, move to the other depth and follow the same steps as before.

Figure 3. 3 Penetration gauge used for soil penetration measurements

3.4 Soil moisture content

The soil water contents were determined by using Time-Domain Reflectometry TDR (TDR 100, Fieldscout, Spectrum Technologies, Plainfield Illinois, USA) at depths of 100 and 200 mm when measuring infiltration rate and soil shear strength. This provided a volumetric soil moisture content of total water.

3.5. Water distribution uniformity with rectangular cans

As there were many tests and investigations of the sprinkler equipment the basic method used has been reported here. Generally, irrigation uniformity of irrigation sprinklers is carried out using well reported and documented procedures such as Christiansen (1942) and Heerman and Hein (1968). Single sprinklers of the solid set upright type use Christiansen (1942) coefficient of uniformity which is based on water caught in collectors set at pre-defined spacings, as opposed to covering the whole area with collectors. This is different from the type of uniformity measured for moving irrigators which normally collect water in collectors at set spacings, 1-3m apart, in a line underneath the irrigator. For centre pivot irrigators, there is also a separate method and calculation such as that proposed by Heerman and Hein (1968). However, using the standard Christiansen approach of set spacing with small diameter collectors for the detailed sprinkler experiments the graphical interpretation of the data suggested that a more intensive approach was needed. This will be seen in the actual experimental work on Chapter 5. Consequently, to test water distribution uniformity of these sprinklers a revised method was implemented, where 200 rectangular boxes were used to completely cover the area under the sprinkler and thus show where all of the irrigation water was falling onto the area. This more intensive approach was required to determine if any run-off from the cultivation experiments could be exacerbated/explained by the sprinkler output pattern, figure 3.4 and 3.5. These investigations were done in the wind protected environment of the machinery hall at HAU. The actual number of collectors did vary depending on the height of the sprinkler head, 0.5m or 1.5m, the water pressure of the test and the nozzle configuration, as each would affect the spread radius of the water.

3.5.1 Materials

1. Mains water source via a pipe line of 19 mm.
2. Extendable drop leg.
3. Pressure regulators (Nelson High-Flo pressure regulator with square thread. 3/4” FNPT) operated at 42 kPa (6 psi), 69 kPa (10 psi), 103 kPa (15 psi), and 138 kPa (20 psi); water discharge for the regulators are 0.91-3.36 m^3/hr, 0.91-3.36 m^3/hr, 0.45-4.54 m^3/hr, 0.45-4.54 m^3/hr, respectively.
4. Nozzle type: (1) black-33 #21Mustard w/2B, (2) black-33 #44Yellow w/4B and (3) black-33 #42Red w/4B. These nozzles are fitted at the furthest span of the centre pivot system type Valley 15 ha.

5. Catch cans (collectors). Rectangular boxes with external dimensions L 395 mm, W 300 mm and H 270 mm; internal dimensions of box were: L 370 mm, W 270 mm and H 255 mm.
6. Pressure gauge. A Digitron's VAP 445 panel meters' pressure transducers had been used for measurement of water pressure.
7. Weighing scale. A Soehnle 2755 digital scale had been used to weigh the collected amount of water in the boxes.
8. Stopwatch.
9. Recording data sheet.
10. The over-head nozzle height was 1.5 m and 0.5 m above a concrete floor.

3.5.2. Methods

3.5.2.1 Spacing and location of collectors:

There was no space between collectors to cover all the wetted area. Determining the number of boxes to be distributed under each nozzle was based upon the wetted area under each type of nozzle and water pressure, figure 3.5, this was done by:

a. Spraying water for 30 seconds on the ground without having boxes. A wet circle was then formed on the ground, represented the limits of the spraying circle.
b. Four sides surrounding this circle were by permanent line marking paint, so that the painted square includes the wetted circle.
c. The distribution of boxes formed adjacent parallel lines inside this area.
d. It is worth mentioning that the number of boxes was insufficient to cover all the wetted area with 103 and 138 kPa (15 and 20 psi) at the height of 1.5 m and 0.5 m for the red and yellow nozzles, as the wetted area was much larger than the number of boxes available. The boxes were there distributed over a half of the square and the test conducted, then the boxes were transferred to the other half of the square and the test re-run.
e. When a half of the area was used, a line of boxes was positioned at exactly the middle point of the demarcated square, meaning that the line of boxes had span the diameter of the wetted area. This line represented a boundary between the two halves.
f. The test was done on a random basis for nozzles and height.

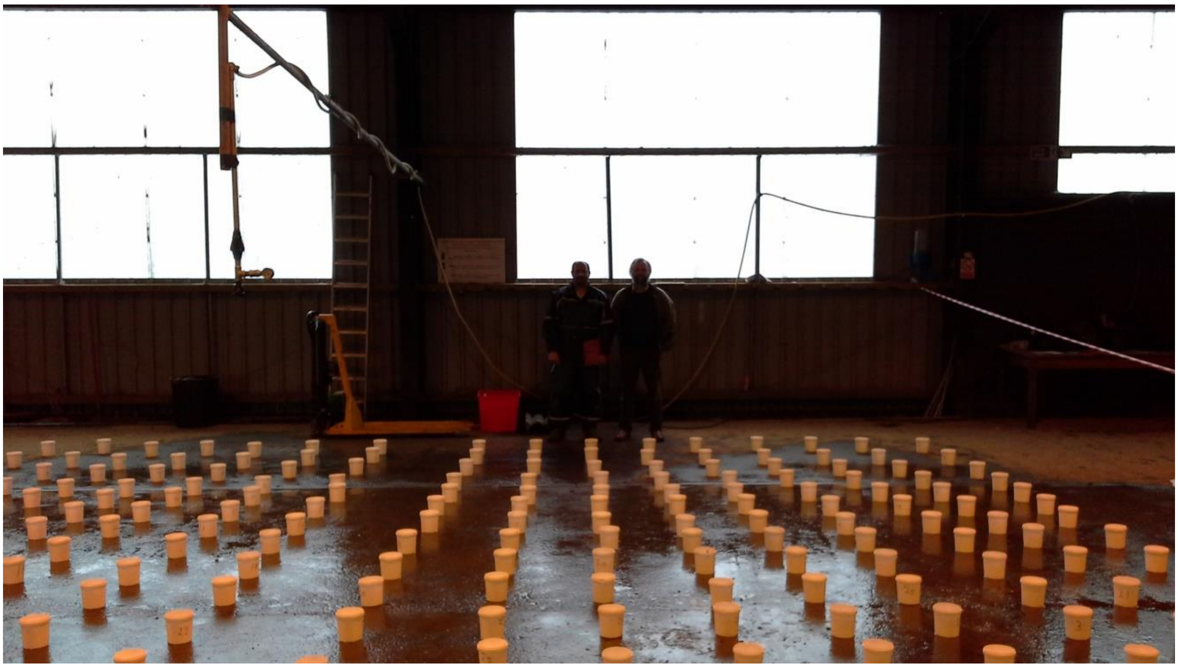


Figure 3. 4 Water distribution uniformity tests of a sprinkler using small circular cans

Figure 3. 5 Water distribution uniformity tests of a sprinkler using rectangular cans

3.5.2.2. Test and procedure

1. Pressure gauge and pressure regulator were installed and adjusted at the bottom of the drop leg. All nozzles were tested in the same position to adjust the wetted pattern for all replicates.
2. Nozzle head was placed at the bottom of the pressure regulator.

3. The height of the nozzle was adjusted firstly to 1.5m from the surface; then the same procedure was used with 0.5m height.
4. Water was applied for 5 minutes.
5. Water caught in the collectors were weighed and recorded directly after turning off the water.
6. The test was repeated four times under varying operating pressures and nozzle type.

3.5.3 Distribution uniformity calculations

There are several formulas for deriving the uniformity of sprinkler output, as discussed in the literature review. For the sprinkler experiments several methods of analysis have been used and these have been described in Chapter 5.

Based on Dukes, 2006, distribution uniformity is expressed as follows:

$$\mathrm{DUlq} = \frac{\overline{\mathrm{V}}_{\mathrm{lq}}}{\overline{\mathrm{V}}_{\mathrm{tot}}} \qquad \text{Equation 15}$$

DUlq = Low Quarter Distribution Uniformity %

$\overline{\mathrm{V}}_{\mathrm{lq}}$= average of the lowest one-fourth of catch-can measurements (mL)

$\overline{\mathrm{V}}_{\mathrm{tot}}$= average depth of application over all catch can measurements (mL)

4. Distribution uniformity of sprinkler irrigation system with Valmont type nozzles

4.1 Introduction

Centre pivot sprinkler irrigation systems were designed to apply water uniformly to all areas within an irrigated field, however, problems will occur if the system applied water under or over application rate (Brouwer *et al*., 1988).

As the core work of this research was to investigate irrigation water runoff under different soil cultivation practices, the uniformity of the applied irrigation also needed to be investigated as it may be a contributory factor. Having a non-uniform application of water could produce water runoff even if only small amounts of water were being applied in small areas. If this is then considered in relation to soil cultivation techniques these areas of intense water application may fall either onto high infiltration zones that could be produced by a tine or subsoiler shank or alternatively fall onto a compressed/consolidated area produced by other soil cultivation equipment.

Irrigation uniformity of centre pivot irrigation is most often measured using the methodology from Heerman and Hein (1968) with the aim to achieve the highest possible practical uniformity coefficients. Irrigation water that is applied at low uniformity is often reported to be responsible for under and overwatering, with the latter resulting in irrigation water runoff and its associated problems. There are several types of irrigation nozzle and packages which have been designed to produce uniform application under varying conditions, e.g. the LESA system as described in chapter 2. Additionally, Solomon *et al*., (1994) mentioned that moving nozzles (drop legs) within the crop canopy significantly affect the uniformity of water applied. Uniformity depends on nozzle spacing, nozzle height and nozzle type (O'Brien *et al*., 2001), and additionally water pressure and wind speed/direction. Barta *et al*. (2004) found that with similar amounts of water applied through above canopy and in-canopy sprinklers, grain yields were equal for crops such as wheat and corn. Although there are losses from air evaporation, drift, and canopy evaporation; these are minor losses compared to runoff, which can be a much greater loss. However, Barta *et al*. (2004) concluded that above canopy irrigation was more efficient at increasing stored soil moisture and reducing runoff as compared to in-canopy irrigation. This may be the result of interference of the uniformity of application from in-canopy applications and thus a more localised application in comparison to above-canopy applications. Barta et al. (2004) also suggested that the reduced runoff from the above canopy irrigation resulted in more stored soil moisture and like slightly more grain yield than in-canopy irrigation. In turn, the water is falling from the above canopy sprinklers flowing from the surface of the leaves to the surface of the soil to be penetrated into the root area.

As the wetted radius of an individual sprinkler head also partially controls the length of time water is applied to a given area of the soil surface, and the sprinkler peak water application rate, these can also affect water runoff. Simply reducing the flow rate of water into the sprinkler system decreases the peak rate at which water is applied to the soil and thus decreases the peak application rate which also reduces the amount of runoff as the application is more likely to be close to the infiltration rate of the soil. However, reducing the system flow rate also reduces the amount of water that can be applied per day and the system flow rate may not can meet the crop water needs (Hanson and Orloff, 1996) and could also significantly affect the application uniformity.

Lowering the nozzle into the canopy and operating at a lower pressure decreases the size of the wetted radius of the sprinkler primarily due to interception by the crop. The reduced size of wetted radius significantly increases the instantaneous application rate per unit area. A higher instantaneous application rate can then lead to runoff if the infiltration rate of the soil is low or reduced by soil cultivation practices. Sprinkler system management should be able to apply as much water as possible during each irrigation event, but only up to the amount where runoff just begins to occur (O'Brien *et al*., 2001; Kranz and Eisenhauer, 1990).

There are several interrelated factors which influence the efficiency of the centre pivot system: the nozzle type, the nozzle height, sprinkler spacing, operating pressure, speed of travel and therefore the application rate.

4.1.1 The nozzle types

The nozzle types are either impact or head spray. The benefits of impact sprays are that they have a large wetting radius and low application rate, which can lead to reduced runoff but does need high to average operating pressure, 414 – 552 kPa (60 – 80 psi). Impact sprinklers are linked directly to the top of the lateral in specific intervals, these sprinklers operate to spray water in high uniformity in line with the circular movement of the lateral. The head sprayers however have lower operating pressures from low to medium 69 – 207 kPa (10 – 30 psi) pressures (Fraisse *et al*., 1995). When buying the irrigator and spray nozzles the low pressure has become a favourite because it needs lower operational energy and is therefore more cost effective (Lamm *et al*., 2006). However, low pressure sprays require attention to the application rate for nozzles and their height above the soil surface to ensure uniformity of application.

Furthermore, when the operating pressure is reduced, the wetting radius will reduce, which leads to an increase in application rate and therefore the appearance of runoff (Hanson and Orloff, 1996). Rogers *et al*., (2017) also noted that originally the water pressures used in the pivot irrigation systems were up 414 – 552 kPa (60 – 80 psi), whereas nowadays the pressure ranges from 69 - 138 kPa (10-20 psi). Consequently, there has been a change in the design of the spray nozzles used in the lateral of the system. High pressure of 414 – 552 kPa (60-80 psi) has a better effect on water dissolution from nozzles and thus get better water distribution (Rogers *et al*., 2017); however, and on the other hand, the use of high pressure at a height of 1.5 m or less leads to shortening the time it takes to drop water drops of high-energy on soil surface. Which leads to soil erosion and the emergence of runoff after a while (Buchleiter, 1992; Brouwer *et al*., 1988).

When pressures of 69 - 138 kPa (10-20 psi) are used, different forms of sprayers are required. One of modified forms is spray sprinkler; Spray sprinklers are mounted on drop tubes extending downwards below the lateral to about 1 – 2.5 m. Each sprinkler consists of a nozzle and different shapes of deflector plates; this is to spray water uniformly. However, uniformity of these nozzles may be less than that of impact sprinklers because of the lower pressure, (Brouwer *et al*., 1988).

An additional sprinkler design named 'rotator' is like the spray sprinkler except that the deflector plate rotates, driven by the nozzle jet of water. A study was conducted by Jiao *et al*., (2017) under low wind conditions to evaluate water distribution patterns of rotating and fixed spray plate sprinklers (Nelson Irrigation Co., Walla Walla, WA, USA). The outlet sizes were of 2.78-, 4.76-, and 6.75-mm, the operating pressure was 103 kPa (15 psi), nozzles height was at 0.8 m. Results showed that rotating spray plate sprinkler produced single-peak patterns, whereas fixed spray plate sprinkler produced double-peak patterns; and the intensive apply area for fixed spray plate sprinkler was located about 2, 3.5 and 4 m away from sprinklers for the three outlet sizes, figure 4.1. Jiao *et al*., (2017) pointed that rotating spray plate sprinkler distributed the most water around the sprinkler, whereas most of the water was distributed on perimeter of the spray circle under fixed spray plate sprinkler.

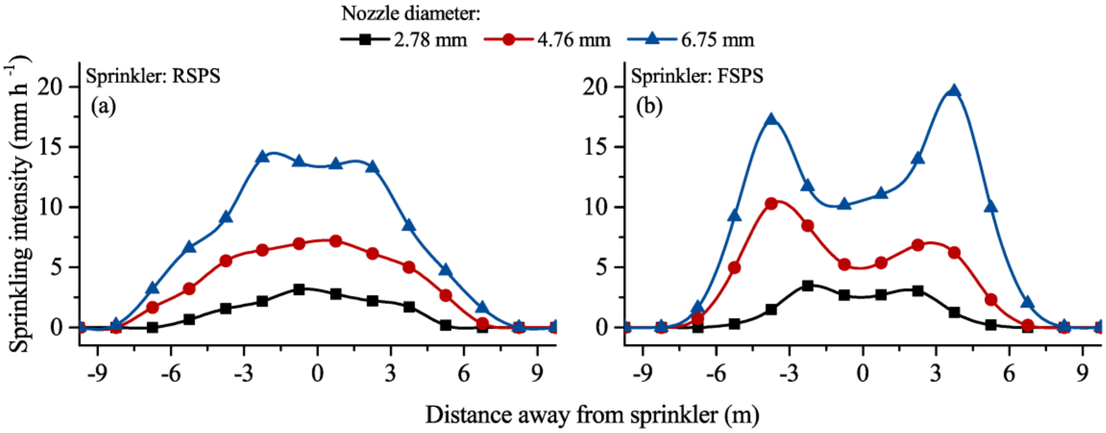


Figure 4. 1 Application intensity for rotating (a) and fixed (b) spray plate sprinklers (Nelson Irrigation Co., Walla Walla, WA, USA), Jiao *et al*., (2017)

The spacing of the sprinklers is very important in relation to the flow rate and operating pressure of the equipment. An individual nozzle will produce a single circle which when moving forward will produce an uneven distribution, figure 4.2. The latter most edge of the centre(x) applying water across the whole diameter whilst the outer edge(y) only applying water at a single non-overlapping point.

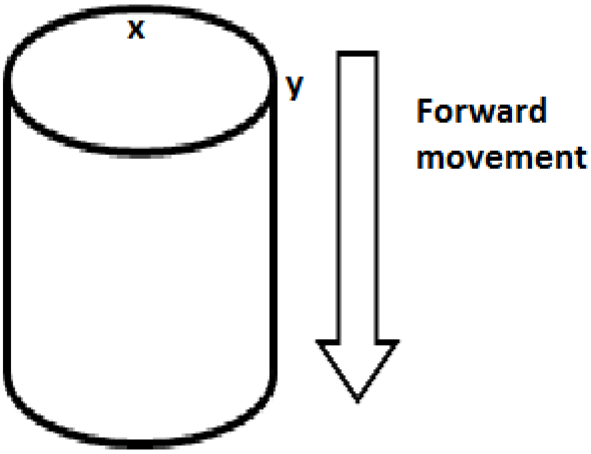


Figure 4. 2 Water application from a single forward moving sprinkler head, with x applying water across the diameter of the circle and y only applying water at the side of the wetted area.

In contrast to this, a series of boom mounted sprinklers will overlap to provide a continuum of water across the whole area, figure 4.3.

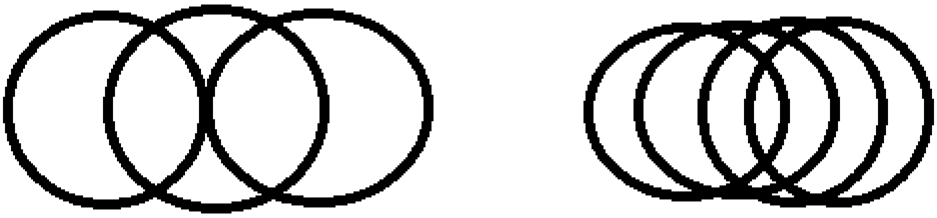


Figure 4. 3 Sprinkler overlap achieved by altering the nozzle spacing on a boom irrigation system.

4.1.2 Operating pressure

Phocaides (2007) pointed out that pivot systems which run on low pressure have become highly efficient in irrigation even if the wind conditions are undesirable. It was also stressed that nozzles operating at low pressure 69-207 kPa (10-30 psi) with low nozzle height give high application rates because of the small wet zone. However, this high rate of irrigation can exceed infiltration rates, leading to runoff.

In addition, the operating pressure also influences the distance between sprinklers where high pressure allows further distances between sprinklers and at the same time maintaining overlap of the wetted area. To get a good irrigation at low pressure, the distance should be close between spray nozzles to maintain the uniformity of overlap in the wetted area (Brouwer *et al*.; 1988), figure 4.3.

4.1.3 Speed of travel

Howell *et al*. (1995) mentioned that a steady speed of the lateral for centre pivot or linear sprinkler systems has an advantage over the solid systems under high wind speed. This is attributable to uniform distribution of the same amount of water to a specific position along the lateral over all the irrigated area. Heermann and Hein (1968) stressed that whenever the lateral speed was low an increase in application rate was observed and when the application rate was higher it resulted in the water runoff. Furthermore, when the speed of the lateral increases, the application depth decreases, but with acceptable uniformity.

The last tower in the system controls the movement of the entire machine. Maximum speed is commonly between 2 to 3 m/min at the outer tower, or 4.3 m/min for special high-speed gear boxes, (Evans *et al*., 1996).

4.1.4 Application rate

Irrigation application time per metre decreases gradually with distance away from the centre point, Heermann and Hein, (1968). This is due to the increasing speed of the lateral and so the irrigation rate needs to also increase gradually at the end part of the system to achieve uniformity both between nozzles and between application areas along the pivot.

If the nozzle height is lowered and the operating pressure decreased the size of the wetted radius also reduces. The reduced size of wetted radius significantly increases the instantaneous application rate. A higher instantaneous application rate can often lead to runoff. Sprinkler system management should be able to apply as much water as possible during each irrigation event, but only up to the amount where runoff just begins to occur (O'Brien *et al*., 2001) (Kranz and Eisenhauer, 1990).

Irrigation rate can be calculated by the accumulated volume of water from sprinkler heads passing though the lateral above a designated area in the field, Dillon et al., (1972).

4.2. Terms and definitions for this section

4.2.1. Sprinkler package:

A collection of sprinklers linked to the spraying lateral whose nozzle sizes vary sequentially along the lateral. It operates under the same operating pressure but differs in discharge. This is in order to ensure water distribution uniformity along the lateral.

4.2.2. Uniformity coefficient

This is a value of irrigation application uniformity as expressed as a percentage of the total application of water. It is designed to give an overall view of how evenly the water is distributed across the application area.

Hansen *et al*., (1980) produced an equation to measure uniformity coefficient which relied on the equation of Christiansen 1942:

$$\mathrm{cu} = 100\ (\ 1.0 - \frac{\sum \mathrm{xi}}{\mathrm{mn}}) \qquad \text{Equation 16}$$

Cu = uniformity coefficient %

xi = standard deviation of total depths of water (mm, mL)

m = Average amount of water (mm, mL)

n = the number of water accumulation containers

However, for centre pivot irrigators a further modified equation was produced by Heerman and Hein (1968) and is the preferred equation for that irrigator type. The uniformity calculations have been covered in more detail in chapter 2 (literature review).

4.2.3 Distribution uniformity

An alternative method to quantify the irrigation uniformity is the ‘distribution uniformity’. This uniformity of distribution relates to the regularity and consistency of the water delivery along the lateral. It is suggested that the more uniform the irrigation, the higher the crop productivity. Distribution uniformity under low wind conditions should be about 75 to 85 percent.

4.2.4 Irrigation rate

Irrigation rate can be calculated by the accumulated volume of water from sprinkler heads passing though the lateral above a designated point in the field.

One of the basic principles of sprinkler irrigation is that irrigation rate should not exceed infiltration rate; otherwise surface runoff problems will appear (Jadczyszyn and Niedzwiecki, 2005).

4.2.5 Wetted diameter:

The wetted dimension of irrigated area perpendicular to the pipeline while the machine is stationary.

4.3 Objective of this research

Valley (Valmont Industries, USA) sprinklers are often used on many of the centre pivot systems found in Iraq. Such systems are commissioned and regularly operated at pressures of 42 kPa (6 psi) (MoA, 2000). Evaluation of specific elements of the Valley sprinklers of a 15ha system was required to ascertain the distribution uniformity and application rate under specific conditions. These provided the baseline characteristics from which variations of sprinkler configuration could be investigated to determine the potential uniformity of water distribution.

The main objective therefore was to characterize the uniformity of specified nozzles and nozzle heights so that this could be considered within the effects of over-head sprinkler irrigation system on soil characteristics for subsequent experimentation within this whole project. This experiment has conducted by modifying a 24m Briggs boom irrigator used by the Crop and Environment Research Centre (CERC), HAU, and using it within a windless environment and in the field. However, the minimum pressure regulated systems available locally operated at 69 kPa (10 psi).

The studied factors were nozzle height at 1.5 and 0.5 m from soil surface; which represents above canopy and in canopy spraying system.

4.4 Materials and methods

Water distribution uniformity evaluation was conducted in both a soil hall (large building with a soil floor) in the Engineering Department, and at a field site at the Crop and Environment Research Centre (CERC), Harper Adams University (HAU), UK, 52°46’27”N 02°25’06’”W. The objective of the experiment under controlled conditions in the soil hall was to determine the performance of the system in a windless environment and identify any potential flaws in the methodology before operating in a field situation. The results of the test under these conditions could then be positively reflected in the operation within the field. This experiment simulated that occurs at the end of a centre pivot.

4.4.1 Materials

1. Boom irrigator, a Briggs R24 boom irrigator connected to an R1/1 hosereel (Briggs Irrigation, Corby, UK)
2. The appropriate last eight nozzles of the outer span (not including the overhang sprayer) of a Valley irrigation 15 ha centre pivot sprinkler irrigation system, see table (4.2).
3. Collectors: polypropylene cans, figure (4.3) with height of 123 mm and 122 mm diameter. The number of cans and their distribution have been explained by the location of each experiment.
4. Nelson 69 kPa (10 psi) (Nelson High-Flo pressure regulator with square thread. 3/4” FNPT) pressure regulators fitted between each outlet and nozzle spray head.
5. Volumetric cylinder, for the measurement of collected water.

4.4.2 Methods

The following steps have been followed in both the soil hall and the field experiments. However, there are some changes in the method of water collectors’ placement which will be explained.

1. Sprinkler heads with nozzles were installed and adjusted on the boom irrigator in a similar way to that found on the centre pivot sprinkler system specification of the Valley 15 ha system. The number of outlets in the Briggs boom was 16 and the distance between any two outlets was 1.5m; the distance between any two spray heads in the latter part of the Valley 15 ha centre pivot system is 3m in the last span. In this test, therefore, the distance between outlets on the Briggs irrigator was set at

3 m by closing of every other outlet, and the number of tested nozzles was then eight; four nozzles for each arm of the boom system.

2. The travel speed of the boom irrigator was adjusted to give an application rate of not less than 12 mm/hr intensity as required by ASAE standards (ANSI/ASAE S436 SEP92).
3. The boom irrigator was then passed over the lines of collectors.
4. Data was recorded by measuring the volume of water caught in the collectors. This was done directly after the irrigation had completed its pass over the collectors.
5. The collectors were uniformly located in a straight line (ANSI/ASAE S436 SEP92) and the spacing between collectors was 0.5 m. The collectors were located along lines parallel to the irrigator pipeline.
6. Wind speed and direction and evaporation records have been obtained from laboratories, HAU, for the field experiment.

4.4.3. Nozzles distribution on the irrigation boom

Table 4.1 shows the distribution of nozzles for the latter part of the Valley 15 ha centre pivot system. As previously mentioned in the General Introduction (chapter 1), water runoff in pivot systems is often in the latter part. Thus, the last eight nozzles of the last tower were selected and according to the sequence in Table 4.2.

Table 4. 1 Sprinkler package of tower 4 (last tower) of 15-hectar centre pivot sprinkler irrigation system type Valley

No.	Sprinkler plate description	Nozzle description
1	black-33	#19Black
2	black-33	#38Grey w/3R
3	black-33	#38Grey w/3R
4	black-33	#40Black w/4B
5	black-33	#40Black w/4B
6	black-33	#40Black w/4B
7	black-33	#40Black w/4B
8	black-33	#40Black w/4B
9	black-33	#42Red w/4B
10	black-33	#37Violet w/3B
11	black-33	#38Grey w/3B
12	black-33	#42Red w/4B
13	black-33	#42Red w/4B
14	black-33	#42Red w/4B
15	black-33	#44Yellow w/4B
16	black-33	#44Yellow w/4B
17	black-33	#42Red w/4B
18	black-33	#44Yellow w/4B
19	black-33	#21Mustard

Table 4. 2 The selected nozzles within the latter package of the Valley 15-hectare centre pivot system.

Nozzle number	Nozzle type
12	black-33 #42Red w/4B
13	black-33 #42Red w/4B
14	black-33 #42Red w/4B
15	black-33 #44Yellow w/4B
16	black-33 #44Yellow w/4B
17	black-33 #42Red w/4B
18	black-33 #44Yellow w/4B
19	black-33 #21Mustard w/2B

The black-33 #21Mustard w/2B (Mustard) is the last nozzle of the package in centre pivot 15-hectare system. The distribution of nozzles was done on the boom system starting with Mustard followed by the rest of the nozzles according to the mentioned sequence in table 4.2.

4.4.4. Catch cans distribution in the soil hall

On 20th June 2015, an experiment was instigated inside the soil hall/Engineering department HAU. The boom irrigation system was operated with all required outlets operating on both sides (arms). Figure 4.4 shows catch cans distributed in soil hall.

Figure 4. 4 Catch cans distribution and water distribution uniformity test in soil hall

(ANSI/ASAE S436 SEP92) standard stated that in order to have water distribution uniformity values, cans should be distributed in one line along the lateral. The distance between one can and another should be 0.5 m. Based on that, the catch cans were distributed at 0.5 m between one collector and another for the line. Thus, the number of collectors reached 21 for each side of the system to be 42 collectors as a total. This to cover all wet area along the arms of the system. The number of lines has been repeated 10 times. The distance between lines was 0.5 m and the total length of the line under each side of the system was 10 meters, whilst the distance between the first and last line was 4.5 meters. The total area of 210 catch can collectors is 45 m^2 under each side. The total area of the test for both sides with the space left between the two sides which is dedicated to the passage of the boom is equal to 103.5 m^2.

4.4.5. Catch cans distribution in the field experiment at CERC

In the field test, collectors were distributed in the same way as they were distributed within the soil hall and for the same distance. However, the 10 collectors' lines were not along the arms of the system, they were separated into two sites of the system sides, figure4.5. This was to allow for full pressurisation of each side of the boom as the results from the soil hall experiment showed a low water distribution rate even though the experiment was conducted under controlled conditions. It was found that the rate of water flow in the system was slightly less than the required limit due to inadequate flow rate from the source. On the field, the same problem was seen with low water pressure and therefore a decision was made to change the method of testing to one boom side at a time and the experiment was repeated with sufficient system water flow.

Water distribution uniformity test in the field was performed for the four nozzles attached to one side of the boom system while closing all outlets of the second side, as in figure 4.5 and 4.6. And then re-doing the test for the second side of the other four nozzles while closing all outlets of the first side.

This test was repeated at nozzle heights of 1.5 m and 0.5 m in order to determine whether there was a difference of distribution uniformity values from the different nozzle heights. Figure 4.6 show the settlement of boom irrigation system in the field with the distribution of the catch can containers. The catch can containers were distributed in 10 lines under left and right sides, each line has 21 catch can. The distance between the two positions was 20 meters.

Catch cans from 1 to 21 contained water from nozzles: black-33 #21Mustard w/2B, black-33 #44Yellow w/4B, black-33 #42Red w/4B and black-33 #44Yellow w/4B; which are the last four nozzles from the centre pivot package, see table 4.2. Therefore, catch cans from 22 to 42 contained water from black-33 #44Yellow w/4B, black-33 #42Red w/4B, black-33 #42Red w/4B and black-33 #42Red w/4B.

Figure 4. 5 Aerial view of the placement of the catch cans for the boom irrigation system in the field (Source: obtained from Grove, 2015)

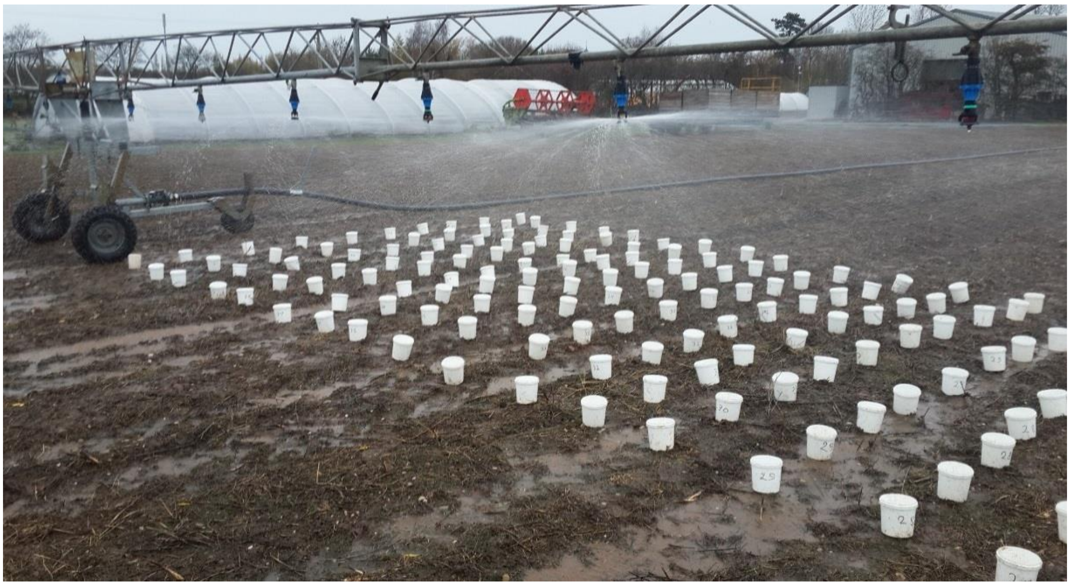


Figure 4. 6 The placement and use of the catch can containers` distribution for one side of the system.

Climatic data for the experiment was taken from the HAU weather station, approximately 250m from the experiment, table 4.3.

Table 4. 3 Climatic data summary for the experimental period (Weather Station, Harper Adams University. Newport, Shropshire, UK. 2015).

Time	Wind Speed m/s	Max Temp ºC	Min Temp ºC	10cm Soil temp ºC	20cm Soil temp ºC	100cm Soil temp ºC	Related humidity %	Precipitation mm
September 2015	1.5	17.7	7.8	13.3	14.2	14.9	88.5	1.2

4.4.6. Statistical analysis

The experiment was arranged with ten replicates. The recorded data was analysed using repeated measures factorial ANOVA using GenStat 16th Edition, VSN International. All differences considered significant at $P \leq 0.05$.

4.5. Results

4.5.1. Soil hall experiment - water distribution uniformity with 1.5 m nozzle height

There were no significant differences between replicates (*P*=0.989). However, the highest uniformity value was 27% and the lowest was 19%. Figure 4.7 shows water distribution for the ten lines which represented the replications of the test. Water distribution uniformity recorded low values for all replicates, the overall rate of all replications was 23%.

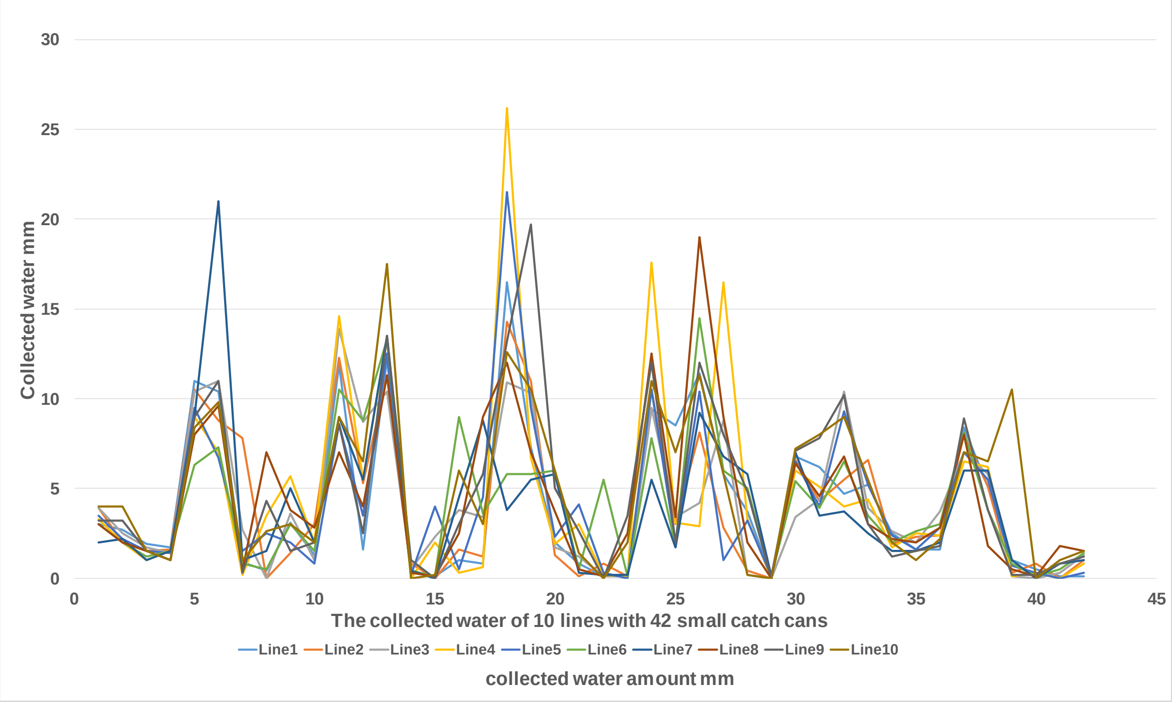


Figure 4. 7 Graphical chart of water distribution for 10 lines (10 replicates) of catch cans along the arm of Boom irrigation system at nozzles height of 1.5 m in the soil hall

Numbers from 1 to 42 at the bottom of the chart represent number of catch can containers distributed on a single line. The nozzles used were shown in table 4.2. The first catch can at the beginning of the system has collected water falling from (42Red w/4B) nozzle. Thus, catch can no. 42 which represents the end of the system, has collected water from (21Mustard w/2B) nozzle.

Water collected from 420 cans was 1829.3 mm. The average was 4.35 mm. Water collected was ranged between 2 to 17 mm at nozzles height of 1.5 m. Figure 4.7 showed that water distribution along the lateral was close to the ten lines. The repetition of catch cans` lines has given a clear picture of the form of water distribution by the system as it passes over the test area, Figure 4.8.

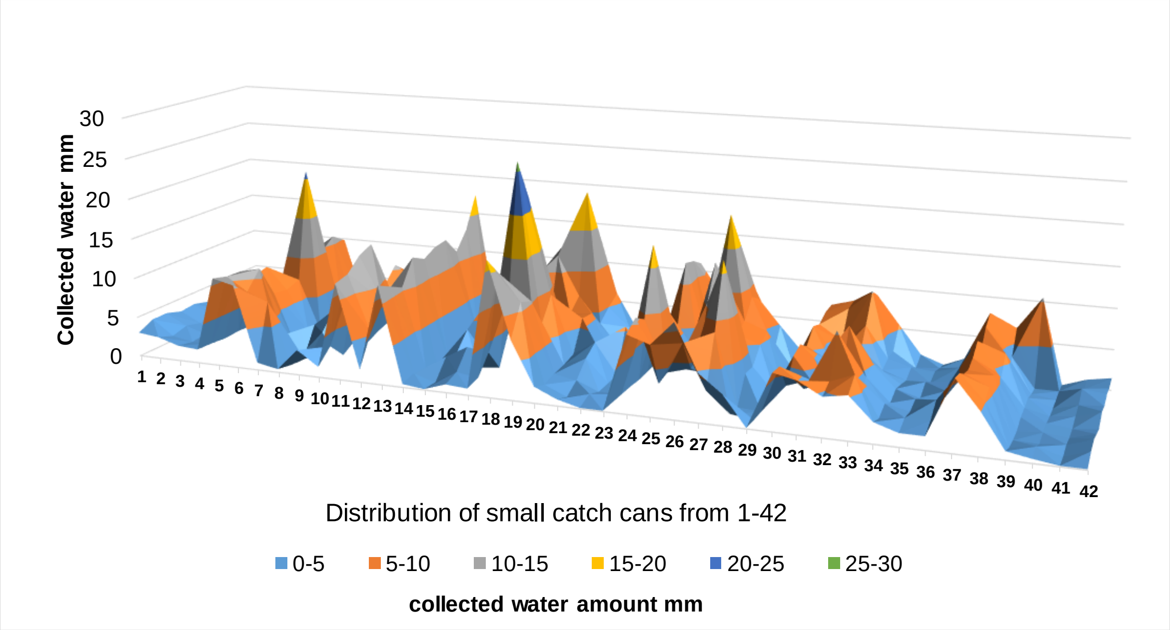


Figure 4. 8 Surface chart of water distribution for 10 lines of catch cans, and distribution uniformity under Boom irrigation system at nozzles height of 1.5 m in the soil hall

4.5.2. Field experiment at CERC, HAU.

Analysis showed significant differences in the values of distribution uniformity (DU %). There was significant nozzle height effect, *P*=<.001, with the distribution uniformity. The means of DU showed increasing in values with nozzle height. Distribution uniformity was 61% at 1.5 m of nozzles height, and 31% with 0.5 m, Figure 4.9.

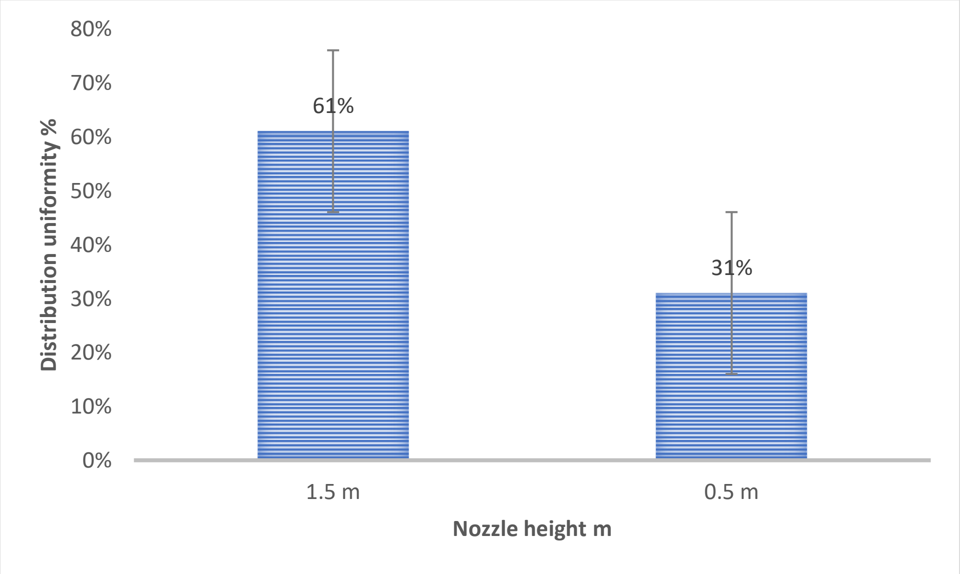


Figure 4. 9 Distribution uniformity% for 1.5 and 0.5 m nozzles height in CERC experiment, *P* < 0.001, s.e.d. = 2.2, CV% = 10.6%

Figure 4.10 and 4.11 show water distribution for the ten lines at height of 1.5 m and 0.5 m of nozzles respectively. The ten lines are representing the replicates of one line of catch cans. Numbers from 1 to 42 at the bottom of the chart represent number of catch can containers distributed on a single line. The first catch can at the beginning of the system has collected water falling from (21Mustard w/2B) nozzle. Thus, catch can no. 42 which represents the end of the system, has collected water from (42Red w/4B) nozzle.

Water collection was 3777.4 mm and 3554.3 mm for 1.5 m and 0.5 m of nozzles height respectively. Number of catch cans was 420, therefore the average of collected water was 8.99 mm and 8.46 mm for 1.5 m and 0.5 m of nozzle height respectively. The highest value was 14.5 mm with 1.5 m nozzle height, and 16.4 mm with 0.5 m, this is due to the regularity of pressure.

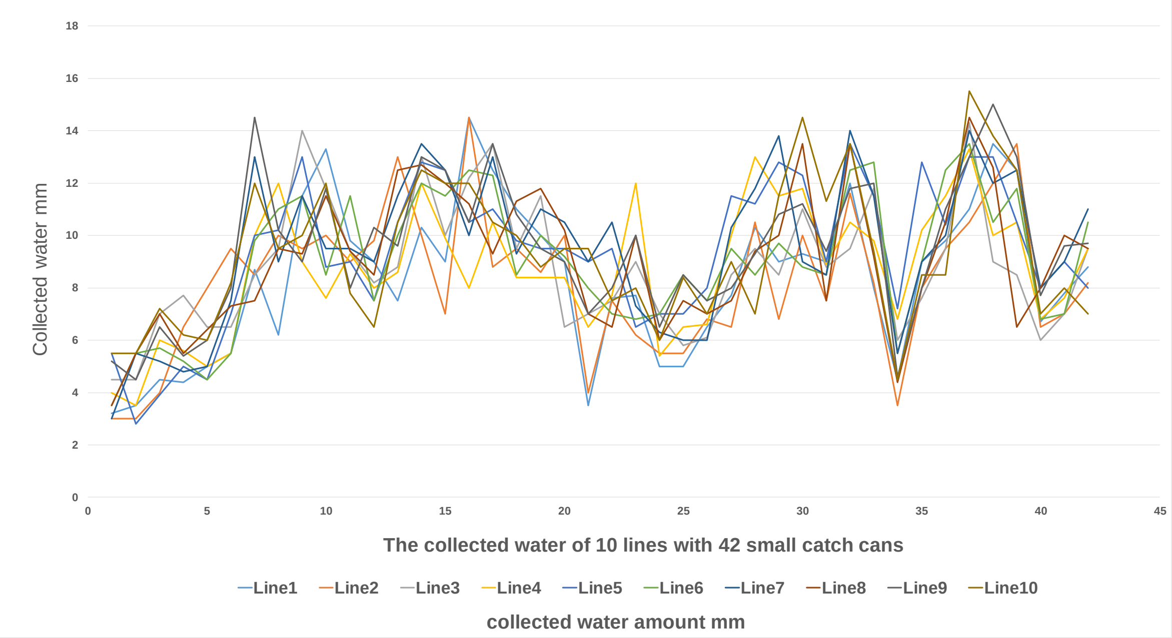


Figure 4. 10 Graphical chart of water distribution for 10 lines (10 replicates) of catch cans along the arm of Boom irrigation system at nozzles height of 1.5 m in the field

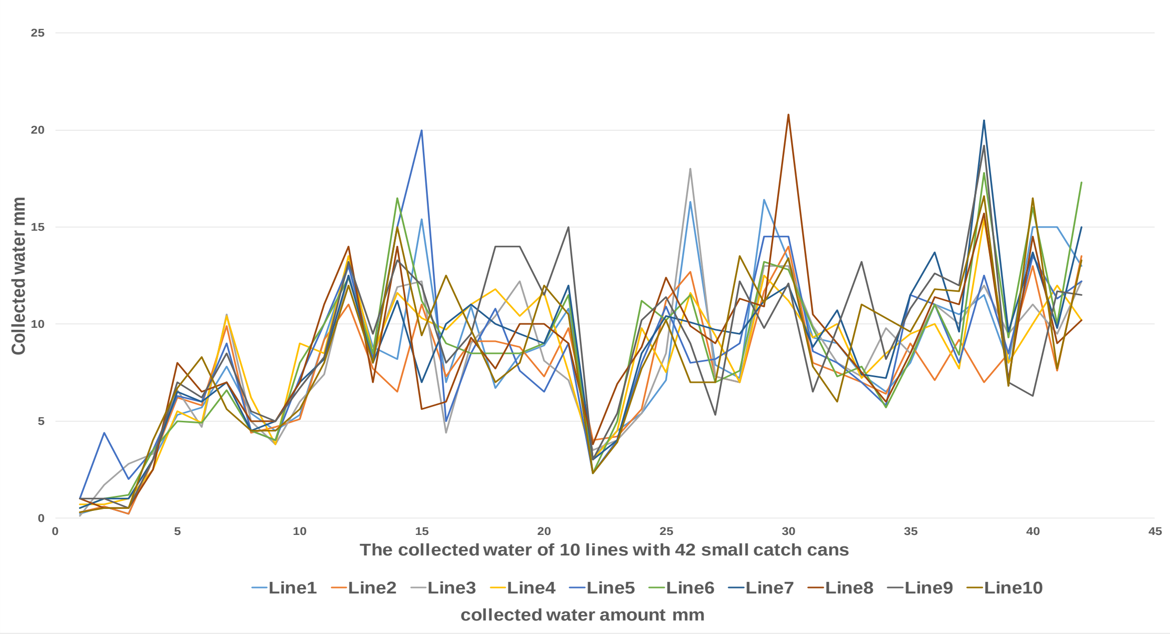
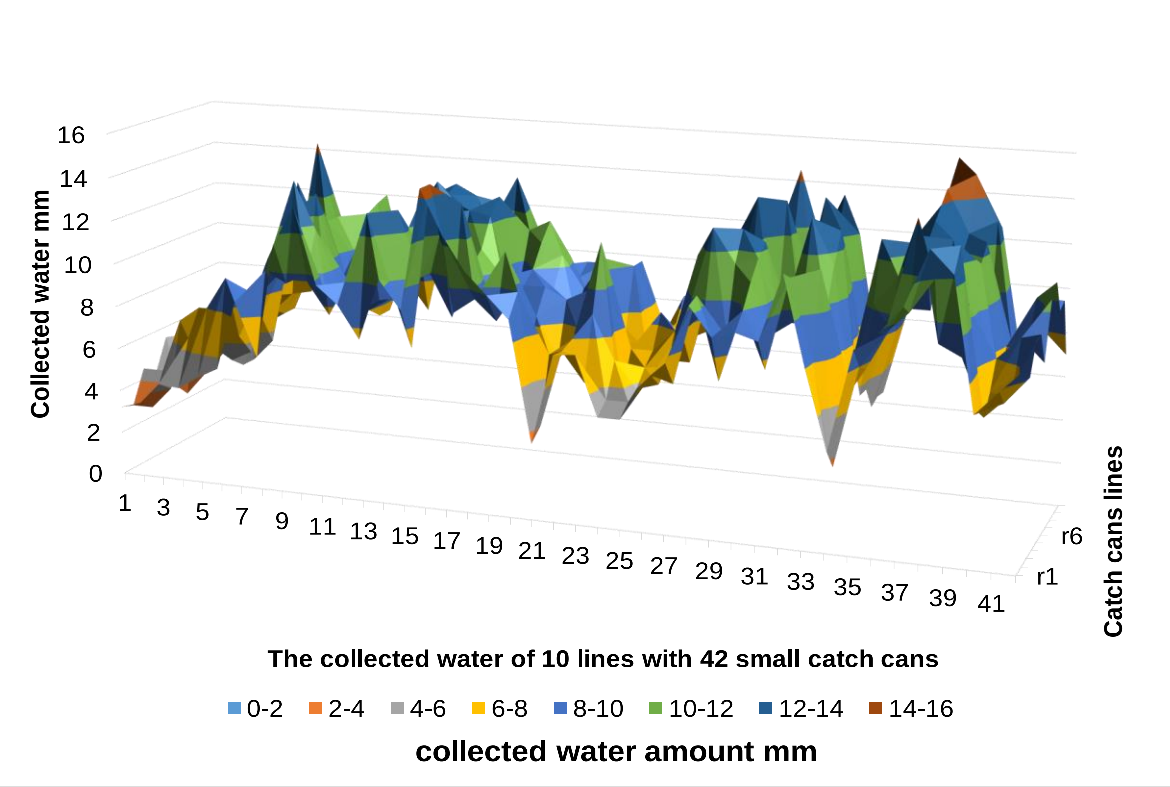
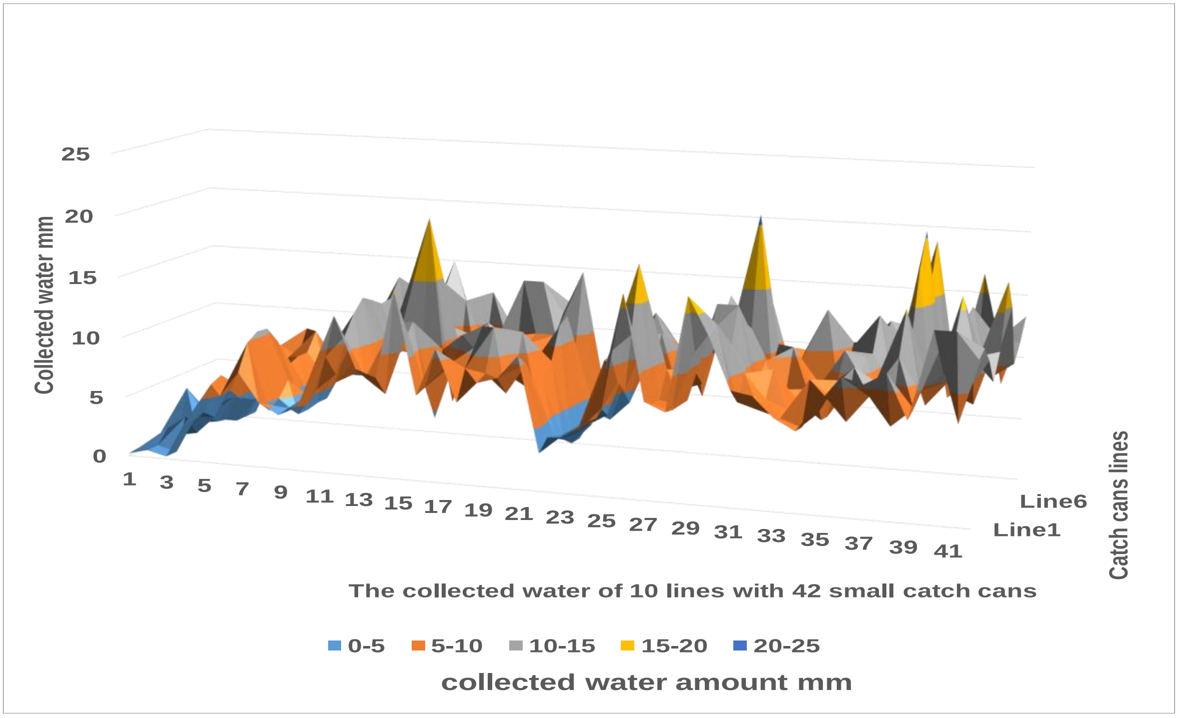


Figure 4. 11 Graphical chart of water distribution for 10 lines (10 replicates) of catch cans along the arm of Boom irrigation system at nozzles height of 0.5 m in the field

Therefore, the water collection at height of 1.5 m was less than at the 0.5 m height. Water collection was ranged approximately between 9 mm to 15 mm and 6 mm to 17 mm at 1.5 m and 0.5 m respectively. Water collection for the two heights was not significant, figure 4.12 a and b.



(a) Nozzles height at 1.5 m



(b) Nozzles height at 0.5 m

Figure 4. 12 Water distribution for a test area at 1.5 m and 0.5 m nozzles height

4.6. Discussion

This experiment investigated the effects of different nozzle heights on water distribution uniformity properties. The experiment was conducted under controlled and field conditions to evaluate the performance of boom spraying system which spraying water through fixed plate-nozzles of the Valley centre pivot system. The test conditions and nozzle height both affected the distribution uniformity values.

4.6.1 Water distribution properties

The results suggest that water distribution is generally greater when nozzles are at 1.5 m height rather than at the 0.5 m height in the field experiment. This suggests that the action of the height of nozzles within the same package led to an increase of the wetted diameter for each nozzle (Solomon *et al*., 1994). This commensurate with King and Kincaid (1997) which stated that application uniformity decreases with sprinkler heights less than 1.5 m. Additionally, nozzles in the outer part of the lateral are in large outlet size, this produce large droplet sizes especially with low pressure of 69 kPa (10 psi) and this will increase application rates and decreases wetted diameter. However, the graphical representation does indicate that there is lack of overlap accuracy, thus leading to low uniformity.

The problem with these systems in Iraq is the lack of application uniformity when using the pressure of 42 kPa (6 psi). Despite following the company's recommendations regarding the distribution of nozzles and controlling the distance between them, in addition to the fact that operating pressure was 69 kPa (10 psi) instead of 42 kPa (6 psi) which is recommended by the company, the results of water distribution were low at both nozzles heights, (King and Kincaid,1997). This may indicate either that the 69 kPa (10 psi) is to be considered low at this part of the sprinkler package, or that nozzles distribution is incorrect. This may be poor water discharge due to the uncontrolled change with nozzles across the boom which is exacerbated within this test to represent the reality of the centre pivot application.

As the nozzle packages are designed for sprinklers to overlap to create a uniform application and pattern, when the height is reduced it is not possible to achieve the full wetted area and thus a lower uniformity occurs. This problem could be overcome at lower heights by reducing the distance between the nozzles and/or increasing the water pressure. However, under both options a greater cost would occur from either a greater number of nozzles or the increased energy cost associated with higher pressure. Reducing the height of nozzles has been shown to lead to a reduction in the distance that droplets of water passed from the nozzle outlet to the surface (Kranz and Eisenhauer, 1990), thus reducing the wetted area under the system. In addition, the droplets of water become closer to the surface and are larger in size which lead to high impact energy that spread and scatter drops into a smaller circular area. While this situation is reduced at higher heights of the nozzle. Unfortunately, the impact energy of the larger drops leads to the dispersion of soil particles which can add to the problem of water runoff by sealing the soil surface or washing away soil. Soil particles mixed with water droplets, which have become wet due to continuous irrigation change the soil surface because of their movement. The uniformity values achieved within the soil hall experiment were substantially lower than expected of only 27% of 1.5 m height. This is below the expected values as shown by Henggeler and Vories, 2009 suggesting that values below 65% are poor. Similarly, Ascough and Kiker (2002) outlined that distribution uniformity for centre pivot system averaged at 81.4%, however, in the CERC field experiment the distribution uniformity of 61% was achieved for a length of 1.5 m but even this is significantly less than expected.

4.6.2. The effect of nozzle height on distribution uniformity

There was significant nozzle height effect, *P*=<.001, with the distribution uniformity. The greater the height of nozzles to 1.5m led to a greater spread and distribution of water within a circle of greater diameter than at lower height of 0.5m. Distribution uniformity was 61% at 1.5 m of nozzles height, and 31% with 0.5 m. However, the amount of water collected was close to both nozzles' heights (8.99 mm and 8.46 mm for 1.5 m and 0.5 m, respectively), this may due to the slow wind speed which did not change the direction of sprinkling water at the highest nozzles height, Barta *et al*., (2004). The reason for the low rates at 0.5 m may due to the lack of sufficient opportunity for spray rings to overlap, (Lamm *et al*.,2006). This is evident in Fig. 4.12 (a and b) which reflects a water distribution compared with the height of 1.5 m.

Regardless of the low rates of uniformity, it should be noted that water collected amount at 0.5m height was like the amount at height of 1.5 m, which means potential soil degradation, (Lamm *et al*.,2012). One of the disadvantages of LESA is water flow at the same rate with a low rise of nozzles compared to the higher heights. This means that application rate may be higher than infiltration rate, which leads to runoff (Lamm *et al*.,2012; Lamm *et al*.,2006; Barta *et al*., (2004).

4.6.3. The effect of test condition on distribution uniformity

The results showed a significant difference of lower distribution uniformity within the soil hall experiment compared to the field experiment. Although all the appropriate conditions were created inside the soil hall to do the water distribution uniformity test, the results would confirm that the pressure achieved were below those required for an adequate test.

Unfortunately, these results of low value but do slow the input of achieving all the application criteria with methodology.

When the methodology was changed to use only one side of the boom at a time, as in the field experiment, the uniformity values were closer to those expected, and as expected, even in the presence of slightly windy conditions, wind speed 1.5 m/s. The height of the nozzles did produce significantly lower uniformity values at the lower height of 0.5m in the field suggesting that when nozzles are lowered to an in-crop position, the uniformity is substantially reduced. This could therefore exacerbate runoff by applying water in small zones and at rates of application which could easily be greater than the infiltration rate of the soil.

Overall of the lower throw anticipated values from the field experiment could be attributed in part to only a small section of the pivot system being evaluated. Consequently, the comparison with other studies could be misleading.

4.7. Conclusions

The conclusions of this experiment can be summarized in the following points:

1. Despite the low flow rates, the height of the nozzle from the soil surface had a significant effect on the distribution uniformity returning higher values at 1.5 m compared to 0.5 m.
2. Mechanical factors in the performance of the simulated irrigation system such as water pressure had a significant effect on irrigation efficiency even if the other test conditions were controlled.
3. Irrigation uniformity was low when testing the latter most nozzles of the Valley 15ha centre pivot sprinkler package in the field. No other test data for just the final centre pivot section was found from which to make comparisons.
4. This experiment was due to be repeated but the outside irrigation pipework is switched of over winter at HAU and the experiment moved into the protected environment of the soil hall. Unfortunately, as the outside irrigation pipework was not switched back on until the next spring the cultivation work took precedence.
5. Further studies are required to accurately determine how the nozzle package would perform both in protected and field environments at optimum water pressures.

5. Performance consistency and water distribution of individual Valmont nozzles

5.1 Consistency evaluation of a Valmont nozzle

5.1.1 Introduction

As part of the nozzle investigation experiments it was necessary to determine the consistency of application between a number of nozzles of the same type and specifications.

As previously explained in the literature review of chapter 2, the problem of water runoff under sprinkler irrigation systems comes from several factors that may sometimes be shared with each other. Some of these factors are related to the technical characteristics of the system. The sprinkler package itself consists of a series of nozzles arranged sequentially along the boom depending on the outlet size of nozzle, with the gradient is larger starting from the centre of the system and ending with the outer part of the last span, (Martin *et al*., 2007). Here the question arises, is the application pattern regular when there is harmony between pressure and system, or there is a defect due to another reason. The runoff problem may result in inconsistencies between the pressure used and the type of nozzle package. In this case, application pattern will be irregular and indicating the lack of uniform distribution of water along the pipeline of the system, (Howell, 2006). As all nozzles are manufactured within quality specifications, performance and output of a product may vary, even if it is very simple, (King and Kincaid, 1997).

In other words, even with nozzles within the same package and the same type and consistency in the outlet size there may still be variability. Any difference in this is then reflected negatively on the application pattern and thus on the overall irrigation efficiency, despite the compatibility between operation pressure and package type, (Martin *et al*., 2007).

5.1.2. Objectives

The purpose of this study is to determine if variability exists between nozzles of the same type.

5.1.3. Hypotheses

Inconsistencies in nozzle manufacture affects the water distribution pattern of the sprinkler.

5.1.4. Null hypotheses

There will be no difference is the pattern of water distribution between irrigator nozzles of the same type from the same manufacturer.

5.1.5 Materials & methods

An experiment was conducted in the machinery hall – Engineering department at Harper Adams University 2016, to find out the presence or absence of performance differences within nozzles of the same configuration. The sprinkler package is Valmont for 15 ha fixed flat nozzle head.

The characteristics from which variations in sprinkler configuration was investigated to determine the reasons leading to the process of water runoff under a centre pivot system. This experiment was conducted utilising nozzle rigs for individual nozzle performance tests.

5.1.6 Water distribution uniformity with a Valmont nozzle experiment

Rectangular catch containers were used in this experiment with no spaces between cans. Rectangular catch containers distribution and collected water procedure were well explained in the general materials and method in chapter 3.

Random selection was made for each of nozzle type, nozzle height and pressure. The experiment was then evaluated four black-33 #44Yellow w/4B nozzle at 10 psi pressure and 0.5 m of nozzle height.

5.1.7 Statistical analysis

The experiment was arranged with six replicates. The recorded data was analysed using one-way ANOVA, using GenStat 17th Edition, VSN International. All differences considered significant at *P* ≤ 0.05.

5.1.8 Test and procedure

1. Since the test uses a combination of four nozzles of the same type with six replications per each, numbering each nozzle was done starting from 1 to 4. A random distribution is produced, according to table 5.1.

Table 5. 1 treatment distribution for consistency evaluation of a Valmont black-33 #44Yellow w/4B nozzle

Sequence of the test	Nozzle to be tested
1	1
2	2
3	3
4	4
5	1
6	2
7	2
8	3
9	4
10	3
11	4
12	4
13	1
14	2
15	3
16	4
17	1
18	2
19	3
20	4
21	1
22	2
23	3
24	1

2. Pressure gauge and pressure regulator was installed and adjusted at the bottom of the drop leg. The sprinkler to be tested was joined directly with the pressure regulator. The positioning of the nozzle, bridge and deflector was maintained in the same orientation when swapping nozzles to ensure that the result from each nozzle was consistent to identify potential moulding differences and performance. Figure 5.6 shows the distribution of the support bars in the sprinkler head. It was adhered to be one of these bars that always be towards the north end of the hall for each test. The measurement time was 5 minutes for each test. Figure 5.1.

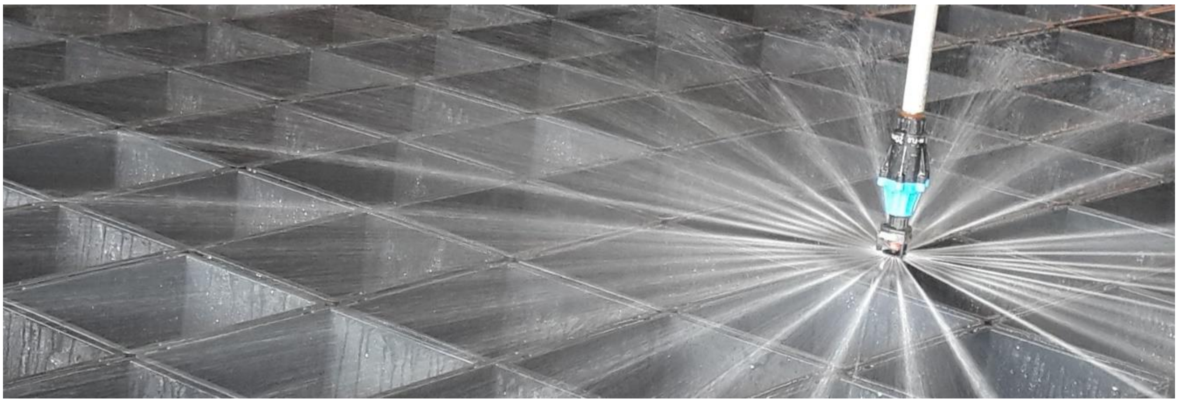


Figure 5. 1 Water distribution uniformity consistency test with a Valmont #44Yellow w/4B nozzle

5.1.9. Results

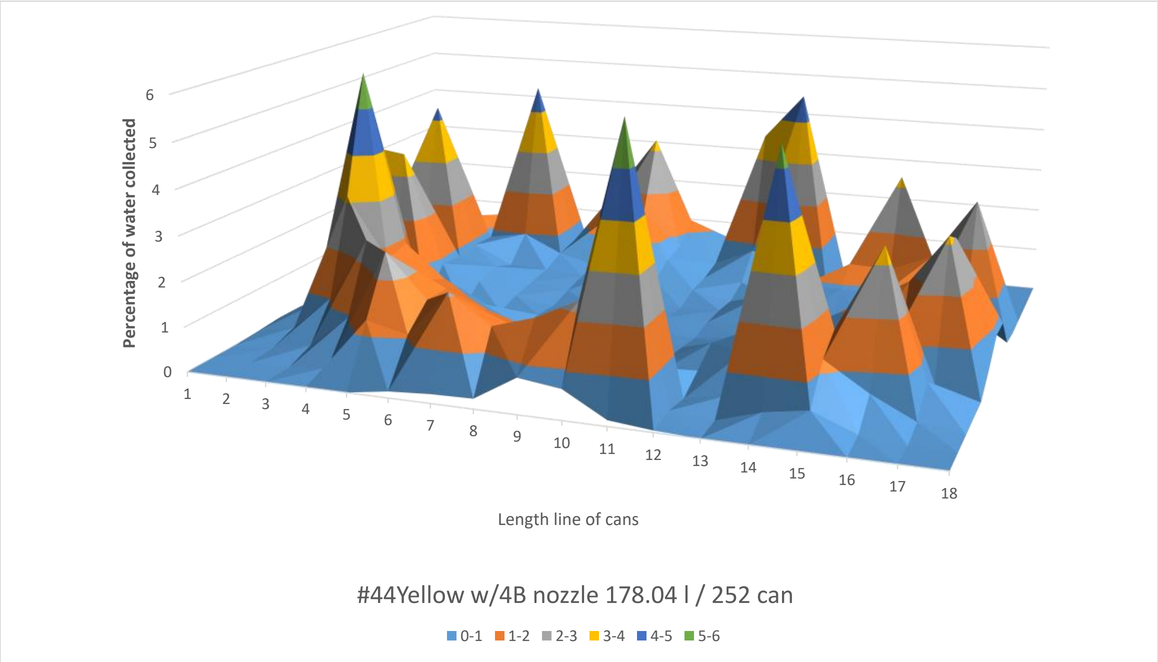
5.1.9.1. Water distribution uniformity with a Valmont nozzle

Consistency evaluation of a Valmont nozzle results are shown in table 5.2. There were no significant differences between treatments *P*=0.649. CV%= 25.9 . When performing statistical calculations, it has not calculated the flow rate coefficient of variation.

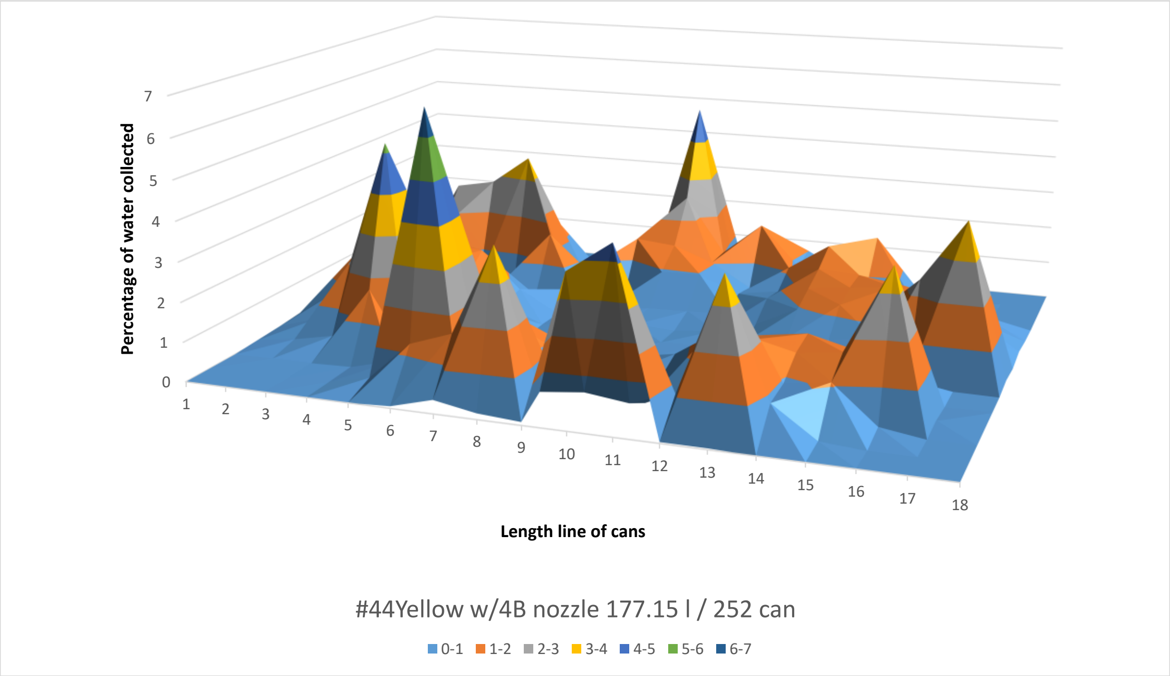
Table 5. 2 water distribution uniformity means of consistency evaluation of a Valmont nozzle

Means: distribution uniformity DU %	#44Yellow w/4B nozzle				Nozzle		
Means Nozzle	1	2	3	4	*P* =	S.E.D	cv %
	71	62	76	69	0.649	10.47	25.9

The amount of water collected in the 252 boxes was 178.04, 177.15, 179.4, and 180.8 litre for four #44Yellow w/4B nozzles respectively, as shown in figure 5.2. a, b, c, d.



5.2 a



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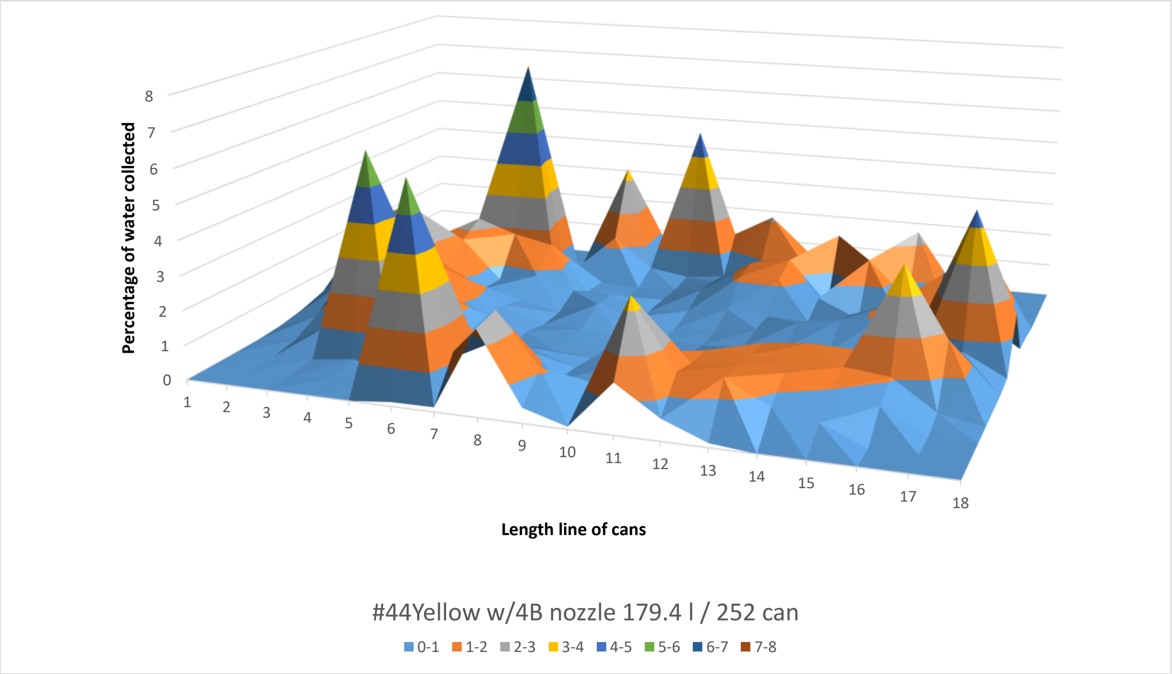
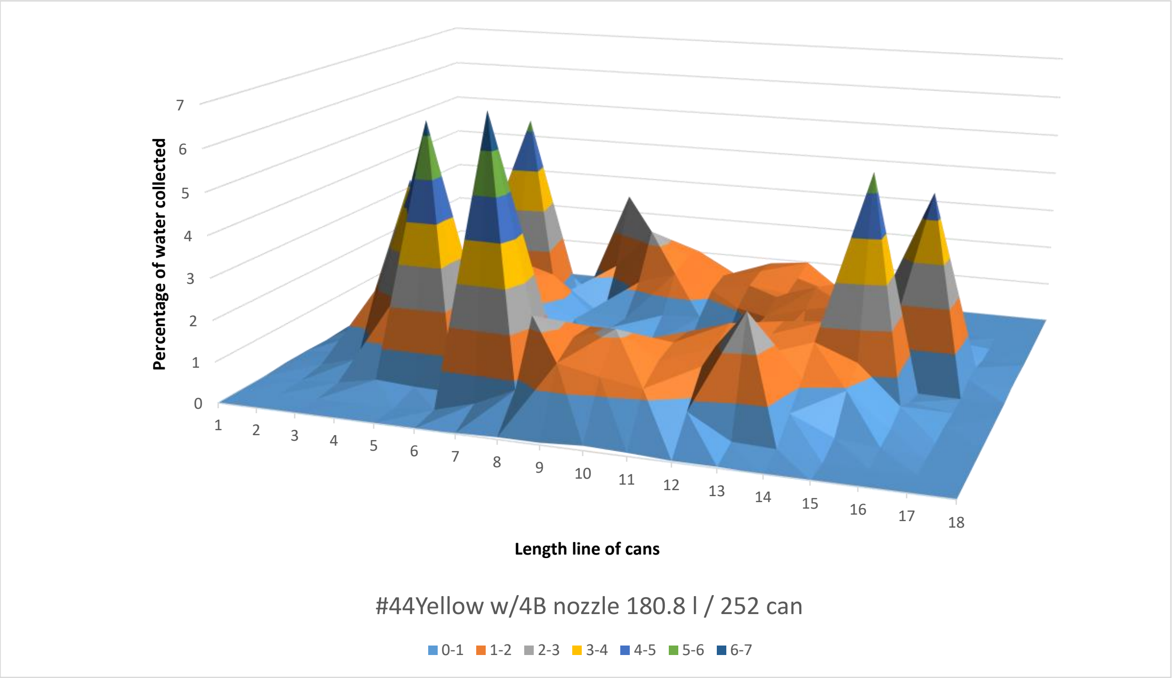


5.2 c



5.2 d

Figure 5. 2 Water distribution % for the four nozzles of #44Yellow w/4B at height of 0.5 m and 69 kPa (10 psi) pressure with rectangular shape catch containers

It can be noted from figure 5.2 that more deposition of water to the left-hand side than the right. This may due to the influence of bars in the sprinkler head, which in turn changes the path of flowing water.

5.1.10. Discussion

An experiment was conducted to measure the consistency of the Valmont centre pivot nozzles of 15 ha, nozzle type was #44Yellow w/4B. Water distribution uniformity test was done separately for one pressure and one nozzle height for several replicates. The results showed no significant difference between the averages, indicating that there is no difference in the water distribution produced from each nozzle.

The accumulated water for each test was similar and distributed to the same number of catch containers. This indicates that irrigation was uniformly distributed if the nozzles of this type are queued one by one, noting that the support bar within the nozzles were in the same direction for all sprinkler head tests.

If this test is conducted by other criteria such as changing pressure or nozzle height therefore it will not affect the test results even if the type of nozzle varies. This indicates that there is no doubt that the problem of runoff is not related to the quality of the product but comes from other technical or operational factors such as pressure variation during irrigation (Howell, 2006) or nozzle overlap characteristics.

Therefore, after studying most of the nozzles characteristics of 15 ha Valmont sprinkler package through the experiments, field experiments to study the effect of irrigation on this type of sprinkler on the soil cultivations and soil conditions is an acceptable progression to determine factors affecting runoff in the field.

5.1.11 Conclusions

Distribution uniformity results were consistent for each of the nozzles evaluated, and this would be suggesting, good quality control standard for this manufacturer. No further work was required to evaluate other nozzles in the package under investigation in this research. Results suggested that as the nozzle variation was minimal the problem of runoff should not arise from variability in individual nozzles.

5.2 Evaluation of the distribution of individual Valmont nozzles

5.2.1 Introduction

Irrigation uniformity is central to optimum application and crop water use.
A crop`s demand for water varies according to its growth stage in order to satisfy plant needs, the less crop losses are seen. Therefore, irrigation systems have to apply water efficiently to avoid water losses, (Ascough and Kiker, 2002). Evaluation of water distribution uniformity for a sprinkler irrigation system is an important performance characteristic. As mentioned in the literature review (chapter 2), there are different types of sprinkler heads for centre pivot irrigation systems, these are chosen and linked to the system by the manufacturers generally or sometimes according to the owner of the system (Harrison, 2009).

Some sprinkler irrigation packages produce larger water droplets such as Fixed-plate and grooved-disk deflector, others produce smaller water droplets such as Spinning-plate and diffuser and wobbling-plate. Alliance (2015) indicated that there are various water application patterns from spray-type sprinklers and impact-type sprinklers and these have met most field conditions. Figure 5.3 shows the differences between fixed and rotator sprays. Impact sprinkler plate produce consistent wetting patterns resulting from the jet disintegration and consistent distribution of water droplets. However, irrigation under field conditions is always subject to the influence of wind and evaporation factors.

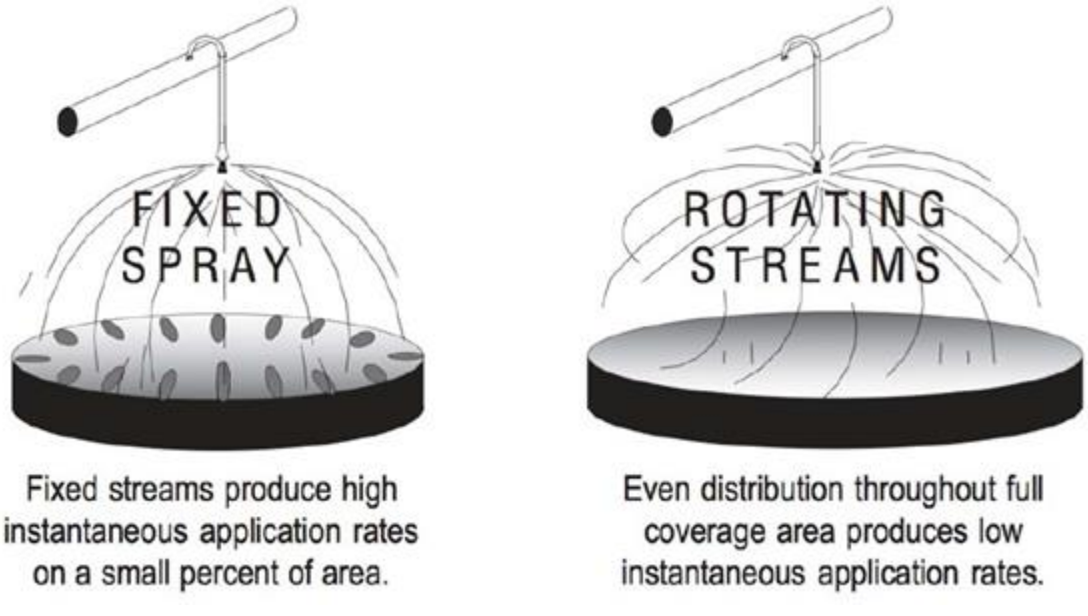


Figure 5. 3 Differences between fixed and rotator sprays (Nelson, 2004)

Jiao *et al*., (2017) evaluated water distribution patterns for rotating and fixed spray plate sprinklers type Nelson (Nelson Irrigation Co., Walla Walla, WA, USA), with three different outlet sizes 2.78-, 4.76-, and 6.75-mm separately. The operating pressure was 103 kPa (15 psi), nozzles height was at 0.8 m. Results showed that rotating spray plate distributed the most water around the sprinkler, whereas most of the water was distributed on perimeter of the spray circle under fixed spray plate sprinkler, figure 5.4. Jiao *et al*., (2017) mentioned that rotating spray plate sprinkler showed better sprinkling performance than fixed spray plate sprinkler under experiment conditions. However, Jiao *et al*., (2017) indicated that selection of sprinklers for centre pivot would depend on soil characteristics and water requirements.

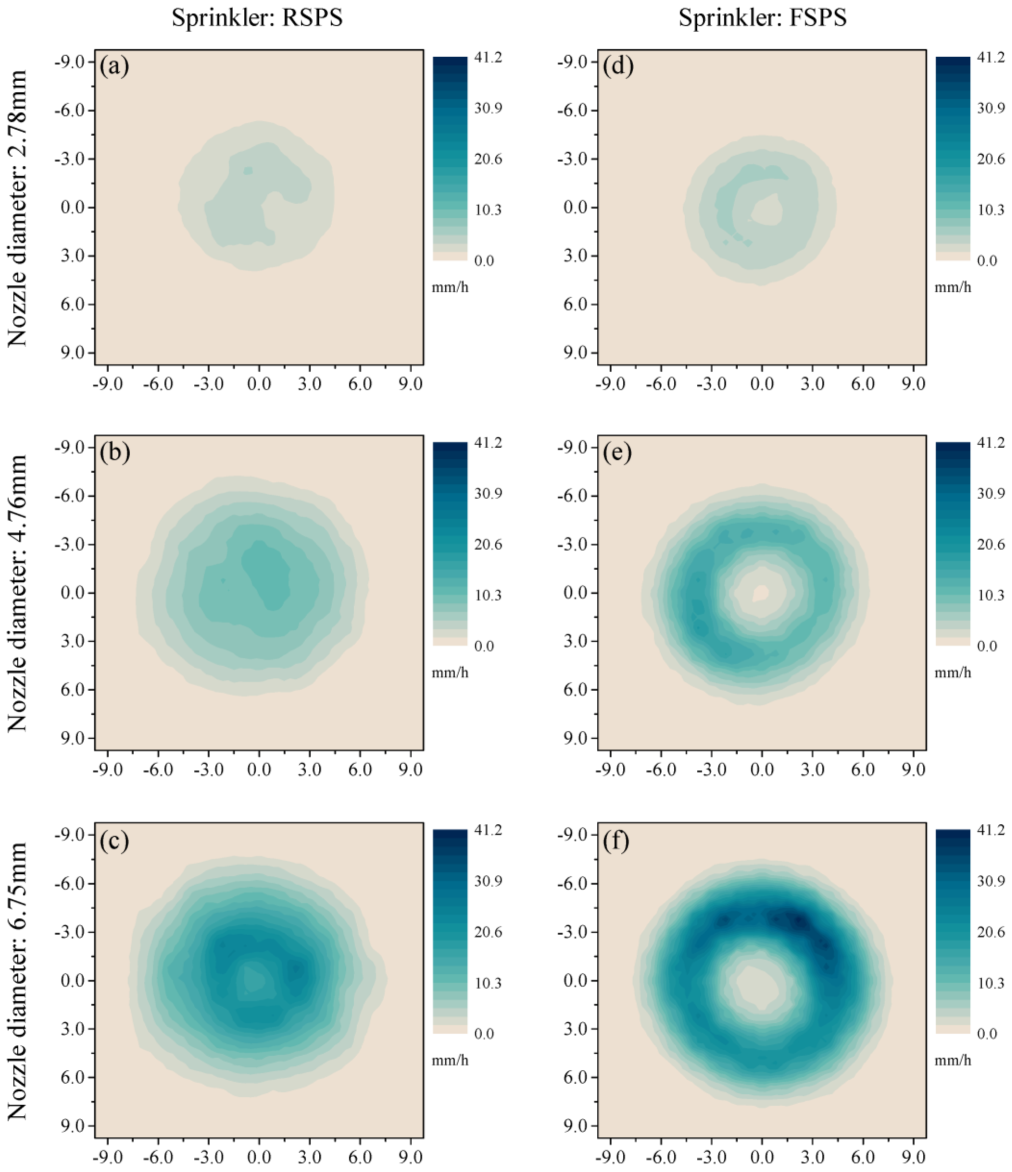


Figure 5. 4 Water distribution patterns of rotating spry plate sprinklers (a, b, c), and fixed spray plate sprinklers (d, e, f) (Jiao *et al*., 2017)

Merriam and Keller (1978) indicated that the evaluation procedure of all types of sprinkler irrigation systems is similar. Water distribution uniformity measurement procedure under sprinkler irrigation systems were established by many researchers, most notably Merriam and Keller (1978) as well as ASAE Standards. The specifications of the catch container in which water is collected as recommended by Merriam and Keller (1978) were 1-quart oil cans or plastic freezer cartons at a spacing of 6.858 m (22.5 feet).

However, the shape and size of cans was more precise with American Society of Agricultural Engineers- ASAE S436.1, (2001). The height of the collectors has to be at least 120 mm. The entrance diameter of the collector has to be one-half to one times its height, but not less than 60 mm. ASAE S436.1, (2001) mentioned the collector spacing along a straight line has to be no more than 3.0 m for spray devices and 50 mm for impact sprinklers. ASAE S436.1, (2001) confirmed that the irrigation system should be operated long enough for the water application pattern to completely cover all collectors.

SWAT Testing Protocol (2015) described the distances between cans in testing protocol being used for spray head sprinkler nozzles to be one-third of the sprinkler spacing for nozzles with a distance of throw less than 4.88 m and one-fourth of the sprinkler spacing for nozzles with a throw equal to or greater than 4.88 m; SWAT Testing Protocol (2015) pointed out that the measurement time should be sufficient to capture a measurable sample.

Clark *et al*., (2006) compared the catch accuracy of IrriGage 100 mm diameter collection devices with a larger diameter (430 mm) collection device (pan) for both fixed-plate and rotating-plate sprinkler irrigation packages. The IrriGage device is a 200 mm long, 102 mm dia. It is a tube and cover made of plastic. The pan collectors had the shallowest depths 100 mm, slightly less than ASAE criteria 120 mm (ASAE S436.1, 2001). Both irrigation packages were operated at 42, 103, and 138 kPa (6, 15, 20 psi) pressure. Sprinkler drops were approximately 1.4 m above the soil surface. Water gross depth was 19 mm with an irrigator travel speed of 24.7 m/h. IrriGage collectors were set up as single, side-by-side, and in-line to evaluate different collectors' arrangements to accurately measure sprinkler irrigation depths and application patterns. PAN collectors had significantly higher ($p < 0.05$) average irrigation depth because the diameter of the PAN collector opening (430 mm) was greater than the IrriGage collectors (100 mm). Irrigation depths from the PAN collector were considered to be more accurate and representative of actual irrigation depths and patterns. The PAN collectors showed a consistent cyclic distribution pattern under the lower pressure 42 kPa (6 psi) sprinklers, and a consistently uniform distribution under the higher pressure 138 kPa (20 psi) sprinklers. Coefficients of uniformity (CU) from IrriGage collectors for fixed-plate sprinkler at 42, 103, and 138 kPa

(6, 15, 20 psi) sprinkler packages averaged 42.3, 79.1, and 80.4%, respectively, while CU values from PAN’s were significantly higher ($p < 0.05$) at 77.5, 90.5, and 92.5%, respectively.

Clark *et al*. (2006) concluded that IrriGage collectors did not reasonably measure irrigation depths or patterns as compared to the PAN collectors. In addition, irrigation application patterns from the IrriGage collectors under the fixed plate sprinkler package with different pressure combinations did not consistently match the PAN results. Clark *et al*. (2006) recommended that the current collector size criteria in the ASAE standard for testing centre pivot and linear move irrigation machines (ASAE S436.1, 2001) need to be reviewed and perhaps revised. They suggested additional research needed to determine an appropriate collector size and shape for the measurement of irrigation depths from centre pivot and linear move irrigation machines with lower pressure sprinkler packages, particularly for fixed plate and coarse-grooved sprinklers.

Since the field experiment described in chapter 4 was assessed by water distribution uniformity using small cans, which had DU 23% in controlled conditions and 61% in the field for nozzles heights of 1.5 m, and based on the above references, an experiment was required to evaluate distribution uniformity of a Valley centre pivot sprinkler system fitted with a15-ha nozzle package with catch cans of two different shapes and sizes.

5.2.2 Research objective

To determine the distribution characteristics of selected irrigation nozzles under controlled conditions with two collector designs.

5.2.3 Research hypothesis

Collector size and placement does not affect irrigation uniformity assessment.

5.2.4 Materials and methods

An experiment was conducted in the Harper Adams University, Engineering department, machinery hall 2016, to evaluate water distribution uniformity test with two different catch can characteristics. The experiment investigated different water pressures and nozzle heights for each nozzle selected from the 15 ha Valley centre pivot sprinkler system nozzle package, namely black-33 #21Mustard w/2B, black-33 #44Yellow w/4B, and black-33 #42Red w/4B

Lines of collectors were used under the wetted area in order to obtain a complete picture of the application pattern.

5.2.4.1 Nozzle installation

Water connection pipes of ¾ inch bore were installed to supply water inside the engineering hall and connected with an extension pipe which connected with the pressure regulator, figure 5.5. Pressure regulators, nominally factory set to supply water at 42, 69, 103, 138 kPa (6, 10, 15, 20 psi) were used. The pipe was joined before entering the pressure regulator with a digital pressure gage to monitor the entry pressure and to detect any pressure changes.

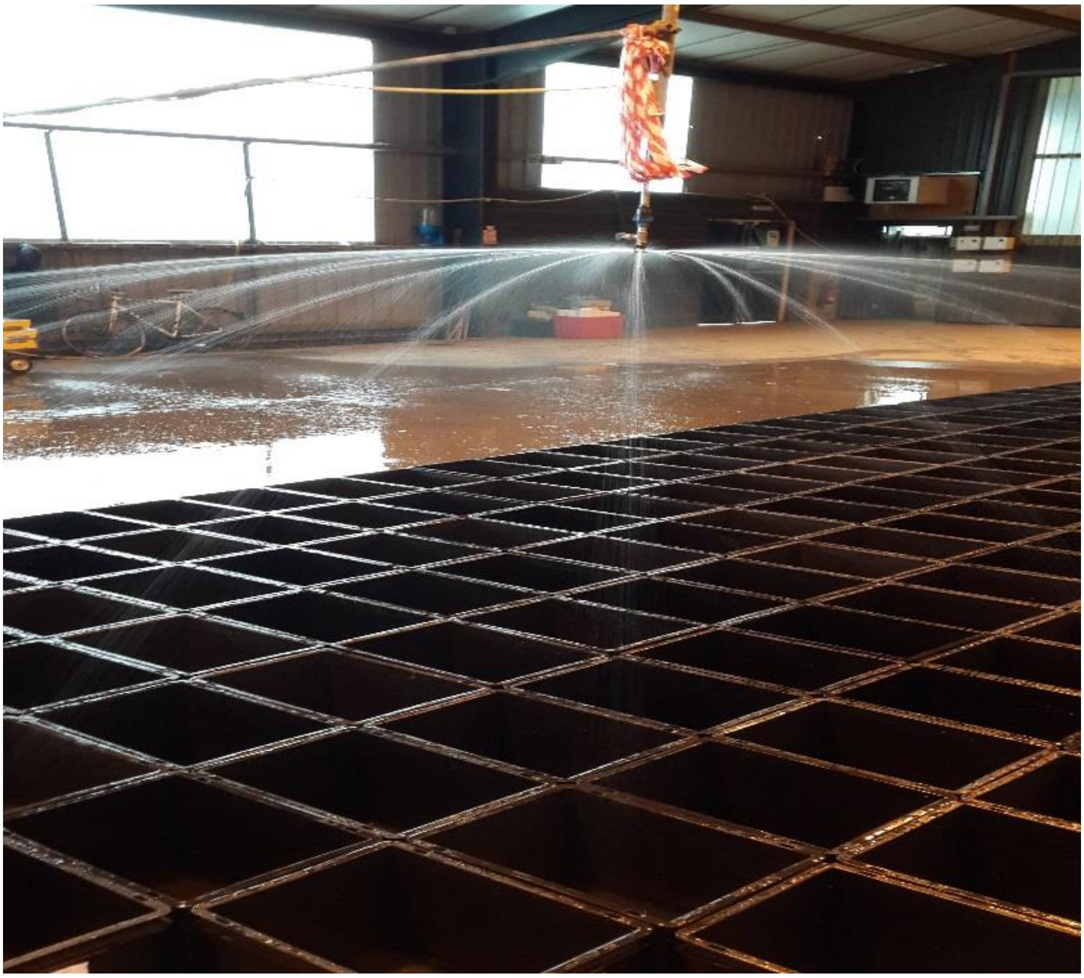


Figure 5. 5 Nozzle set up above collectors in the machinery hall- HAU

The sprinkler to be tested was joined directly with the pressure regulator. The positioning of the nozzle, bridge and deflector was maintained in the same orientation when swapping nozzles to ensure that the result from each nozzle was consistent to identify potential moulding differences and performance, figure 5.6. Water distribution uniformity test was done for two nozzle heights of 1.5 m and 0.5 m. The water application time was 5 minutes for each test.

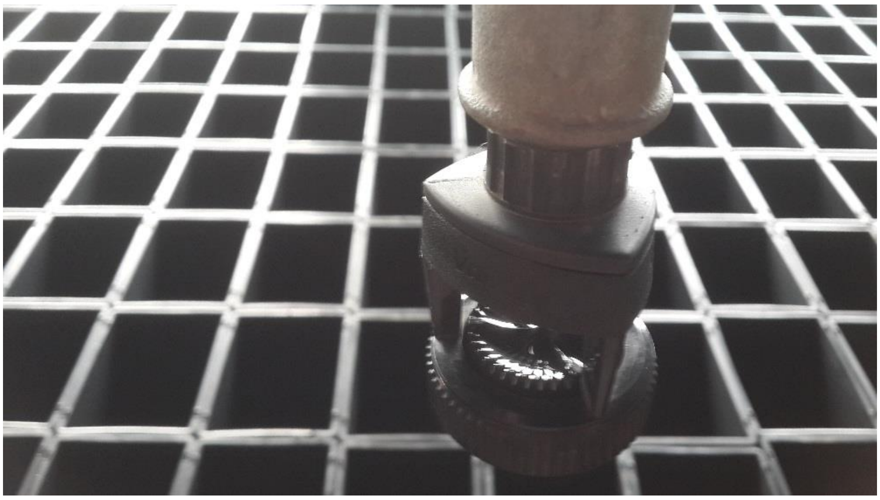


Figure 5. 6 Orientation of the nozzle components which could affect the distribution patterns of the nozzle.   Note the support bars within the nozzle structure.

5.2.4.2 Water pressure

Four different pressure regulators were used when testing with rectangular boxes. They were operated at 42 kPa (6 psi), 69 kPa (10 psi) ,103 kPa (15 psi) and 138 kPa (20 psi). The specifications were mentioned in Chapter 3, 3.5.1

5.2.5 Experimental stages

5.2.5.1 Water distribution uniformity test with small circular catch containers experiment

Polypropylene small size catch containers were used with height of 123 mm and 122 mm diameter, figure 5.7.

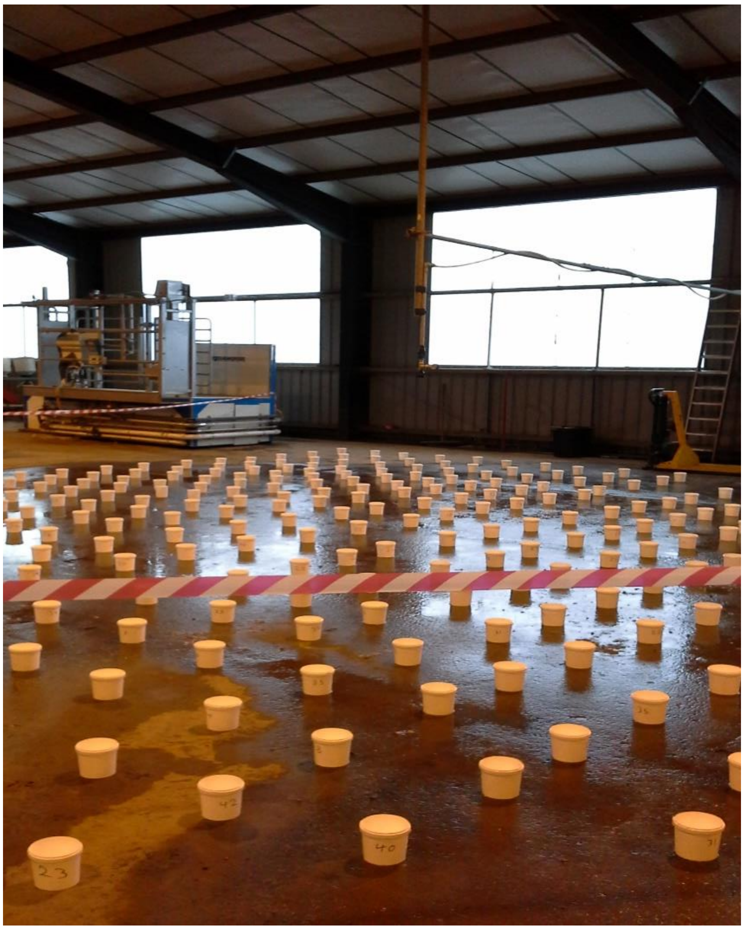


Figure 5. 7 Small size catch containers distribution in the machinery hall- HAU

In order to cover the wetted area by collectors, water was applied for 30 seconds on the ground without the presence of cans. A wet circle then has been formed on the ground, representing the limits of the spraying circle.

Catch containers were then positioned in parallel lines. The distance between the centre of each catch container and its neighbours was equidistant for all tests, 0.5m between lines, so a grid of distributed catch containers has been formed.

For the water distribution tests, water was applied for 5 minutes, then the collected water was measured in each can by volumetric cylinder of 100 ml size directly. This test had been repeated for three replicates with the three nozzles (black-33 #21Mustard w/2B, black-33 #44Yellow w/4B, and black-33 #42Red w/4B). The pressure regulator of 10 psi was used in this test with two heights at 1.5 m and 0.5 m. The pressure regulator selection was random.

5.2.5.2 Water distribution uniformity test with rectangular shape catch containers experiment

Four replicates for water distribution uniformity with rectangular catch containers (boxes) were used. Dimensions of boxes were mentioned in Chapter 3, 3.5.1. There were no spaces between rectangular catch containers when conducting the test, figure 5.8.

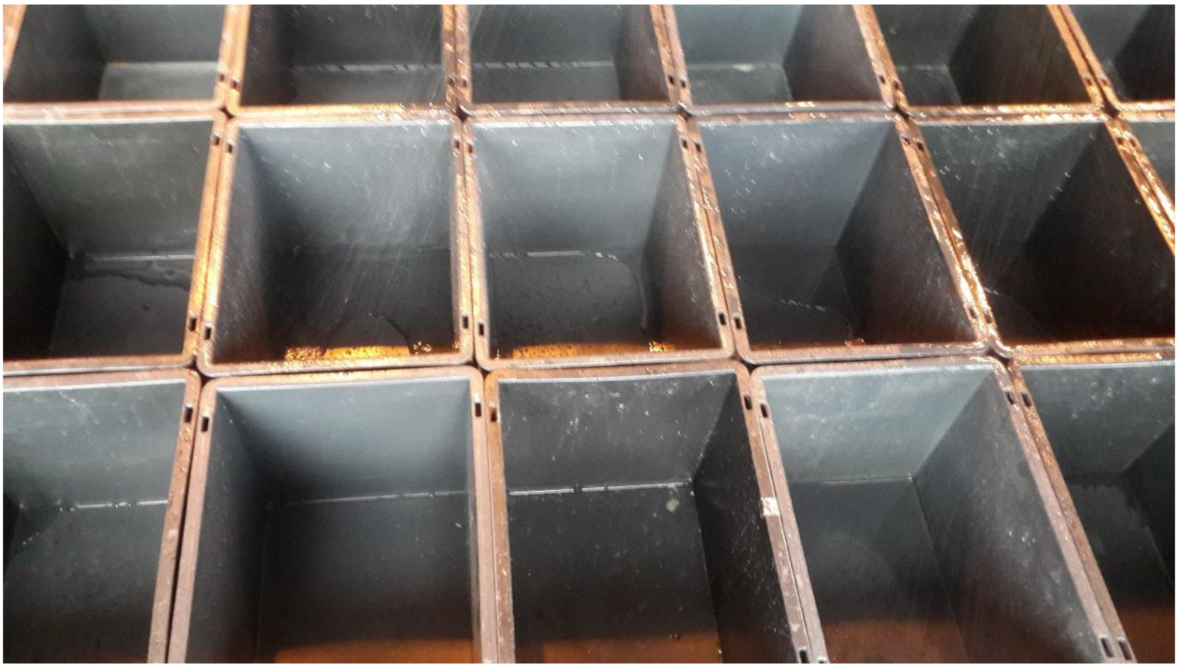


Figure 5. 8 Rectangular shape catch containers distribution

Rectangular shape catches containers distribution and collected water procedure were well explained in the general materials and method in chapter 3.

5.2.6. Statistical analysis

The experiment was arranged with four replicates. The recorded data was analysed using one-way ANOVA for small size catch containers and general ANOVA for rectangular shape catch containers, using GenStat 16th Edition, VSN International. All differences considered significant at $P \leq 0.05$.

5.2.7 Results

The sprinkler distribution patterns appeared different for the different catch cans. DU values under the fixed plate sprinklers of small size catch containers for all test events were lower than rectangular shape catches containers. Generally, water distribution uniformity (DU) from small size catch containers for #21Mustard w/2B, #44Yellow w/4B, #42Red w/4B nozzle averaged 13, 26, and 19%, respectively, while DU values from rectangular shape catch containers were substantially greater at 52, 96, and 66%, respectively.

5.2.7.1 Water distribution uniformity with small size catch containers

Although all distribution uniformity means were low, there were significant differences between treatments. A significant difference was found between the treatment interaction (*P*= 0.006). Water distribution uniformity means were greater at 1.5 m than 0.5 m for all treatments. The highest uniformity of 36% was found at a height of 1.5 m with black-33 #44Yellow w/4B nozzle and least uniformity was with black-33 #21Mustard w/2B nozzle at a height of 0.5 m and was equal to 10%. Table 5.3.

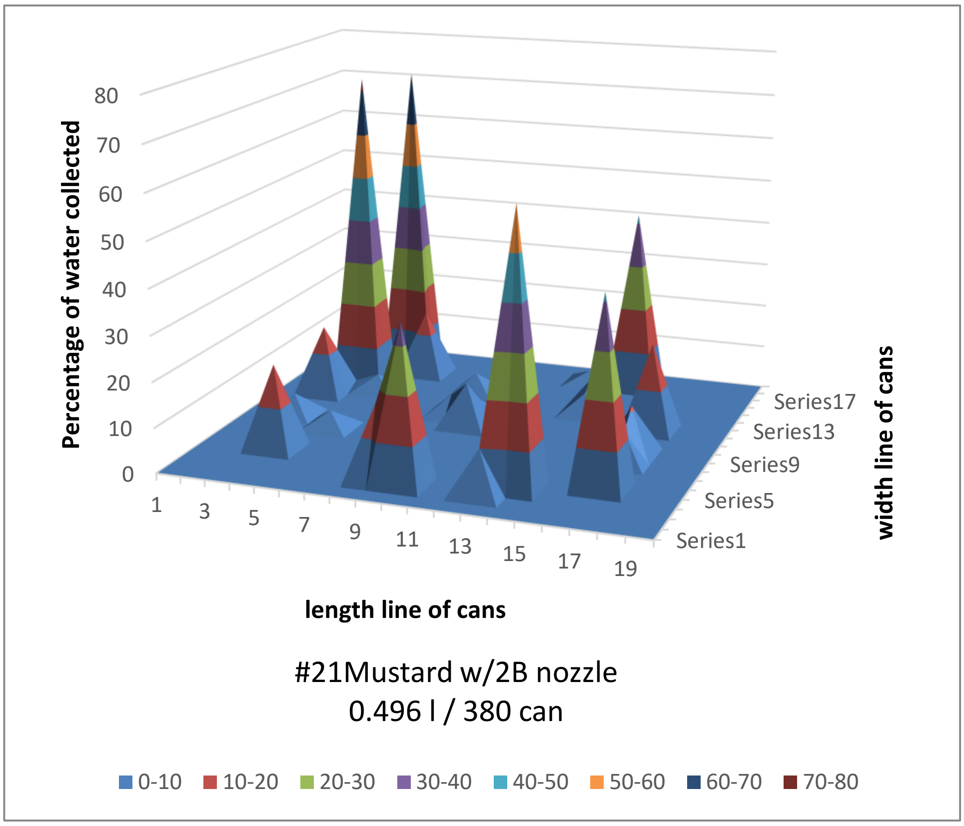
Table 5. 3 Water distribution uniformity means with small size catch containers at two different heights

Means: distribution uniformity DU %		Nozzle type			Height* Nozzle		
Means Height * Nozzle	Height	Mustard	Yellow	Red	*P*	S.E.D	cv %
	1.5 m	16	36	22	0.006	2.632	16.3
	0.5 m	10	16	16			
Means Height effect	1.5 m		0.5 m		<.001	1.519	
	25		14				
Means Nozzle	Mustard	Yellow	Red		<.001	1.861	
	13	26	19				

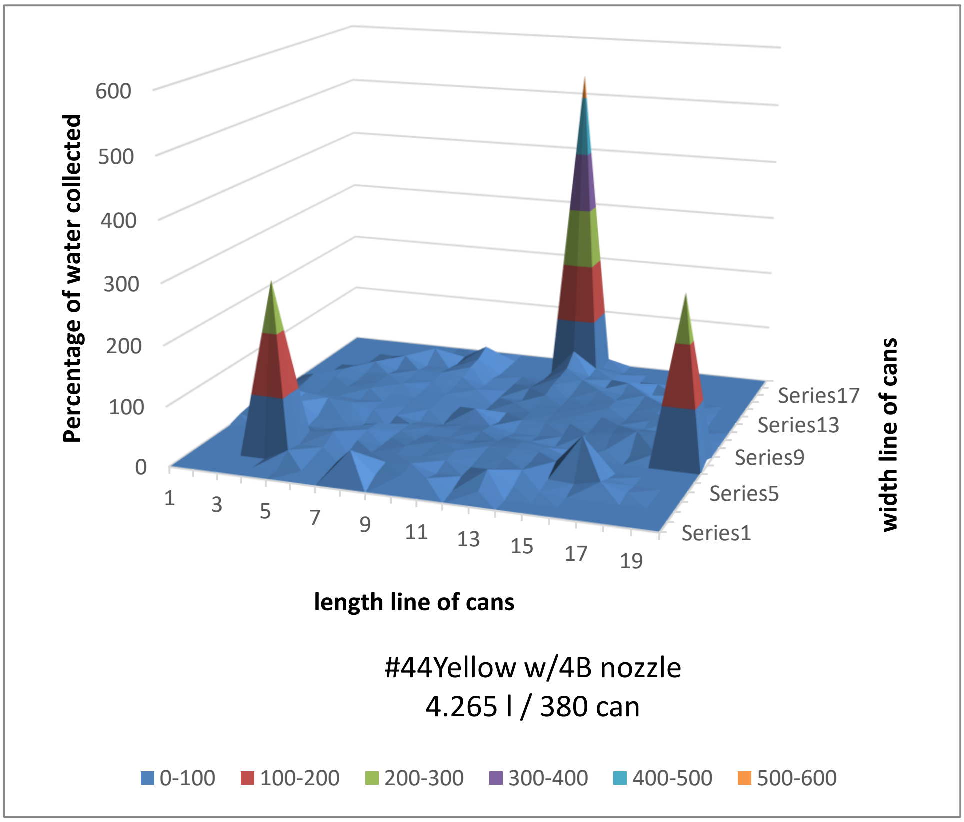
5.2.7.2. The effect of nozzle outlet size on water distribution uniformity

A highly significant difference in water distribution uniformity was recorded for different nozzle outlet size (*P*<.001). Black-33 #44Yellow w/4B nozzle record uniformity of 26% while less uniformity was with 13% of black-33 #21Mustard w/2B nozzle. DU with black-33 #42Red w/4B nozzle was 19%.

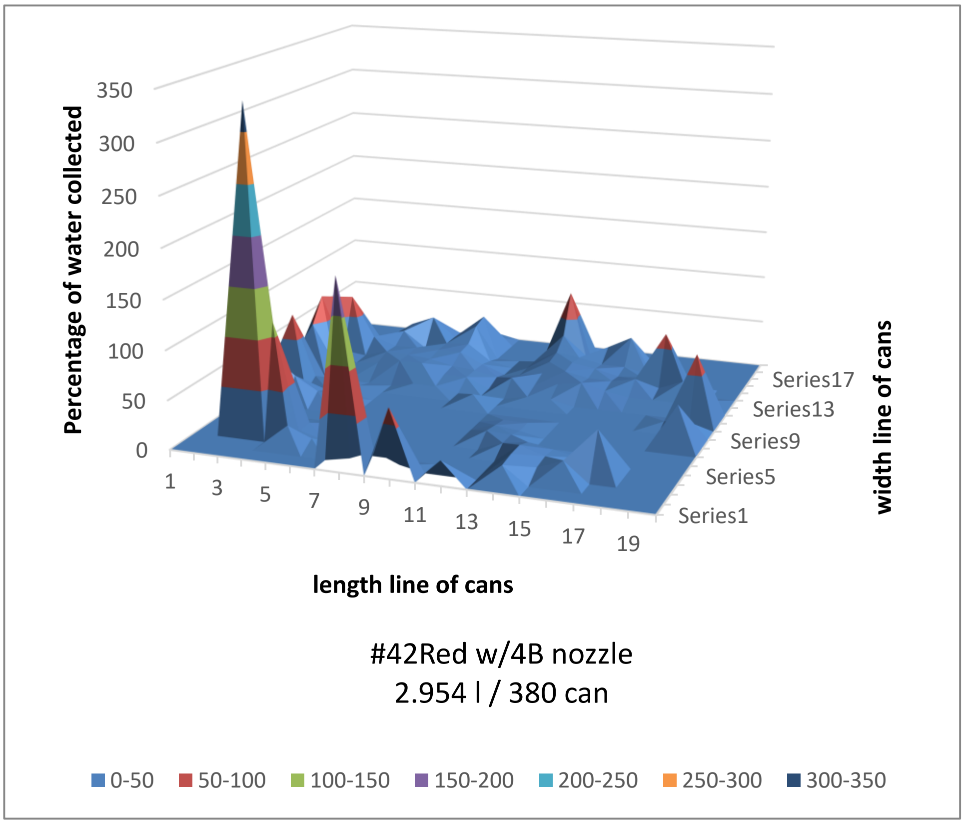
It can be noted from figure 5.9 (a, b, c) that the differences of water distribution for the three-different nozzle outlet size that have been observed.



5.9 a #21Mustard w/2B nozzle



5.9 b #44Yellow w/4B nozzle



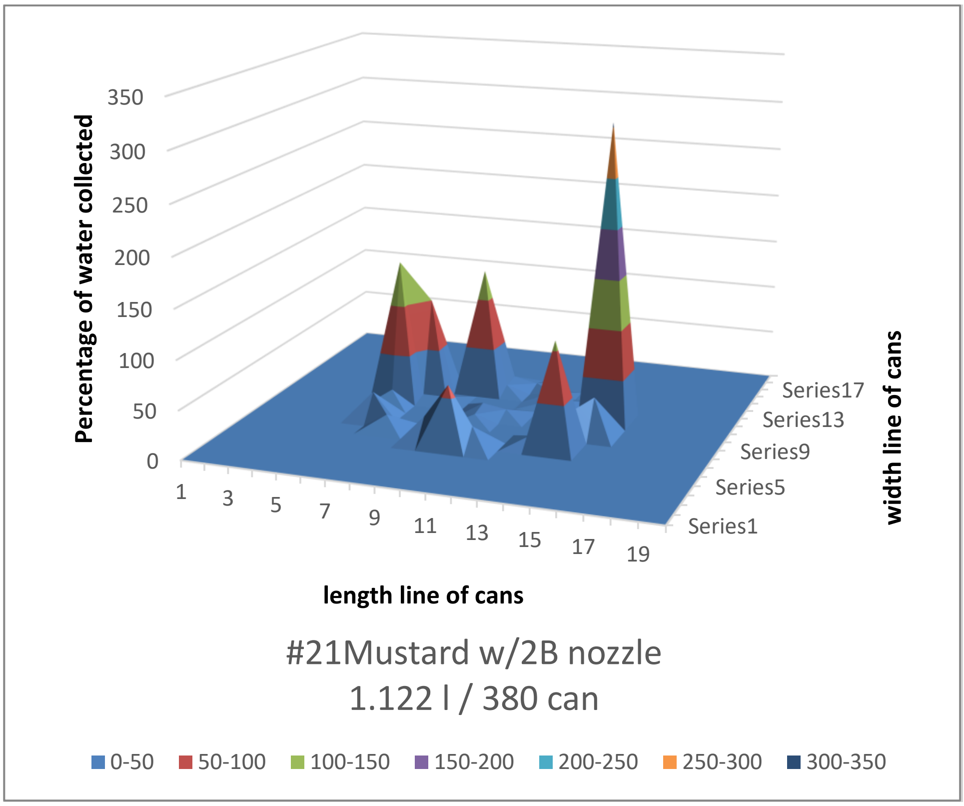
5.9 c #42Red w/4B nozzle

Figure 5. 9 Water distribution for the three different nozzle outlet sizes at height of 1.5 m-10 psi with small size catch containers. a mustard nozzle. b yellow nozzle. c red nozzle

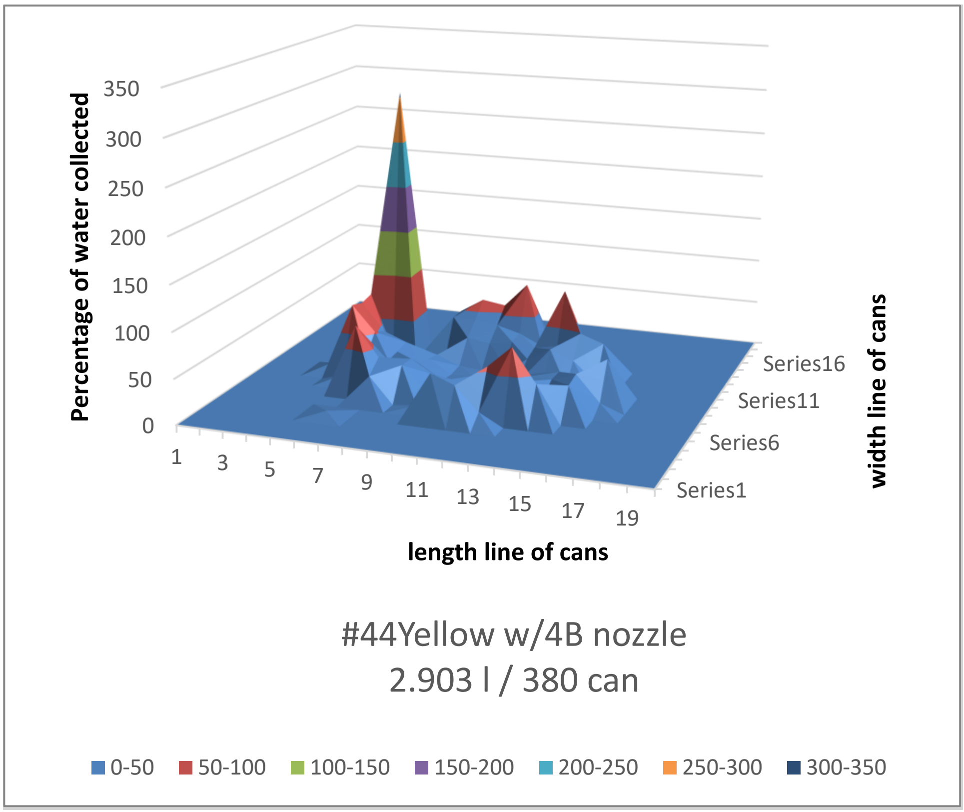
The accumulation of collected water was 0.496, 4.265, 2.954 litre from 380 small size catch containers with #21Mustard w/2B, #44Yellow w/4B, and #42Red w/4B nozzle respectively.

5.2.7.3. The effect of nozzle height on the water distribution uniformity

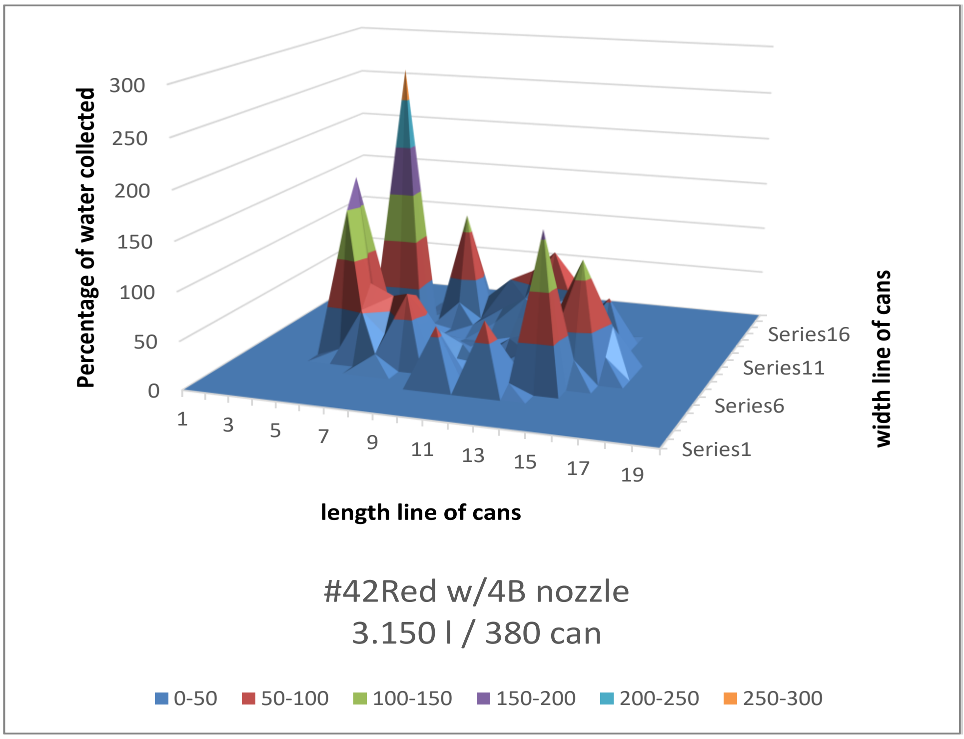
The effect of nozzle height on the water distribution was found to be significant (*P*<.001). Water distribution uniformity was 25% at height of 1.5 m and 14% at 0.5 m, table 5.3. It can be noted from figure 5.10 (a, b, c) that the amount of water collected has changed significantly by changing the nozzle height in addition to the nozzle outlet size. The collected water at height of 0.5 m was significantly lower at 1.122, 2.903, 3.150 litre with #21Mustard w/2B, #44Yellow w/4B, and #42Red w/4B nozzle, respectively.


Percentage of water collected
350
300
250
200
150
100
50
0
1
3
5
7
9
11
13
15
17
19
length line of cans
Series17
Series13
Series9
Series5
Series1
width line of cans
#21Mustard w/2B nozzle
1.122 l / 380 can
0-50
50-100
100-150
150-200
200-250
250-300
300-350

5.10a


Percentage of water collected
350
300
250
200
150
100
50
0
1
3
5
7
9
11
13
15
17
19
length line of cans
Series16
Series11
Series6
Series1
width line of cans
#44Yellow w/4B nozzle
2.903 l / 380 can
0-50
50-100
100-150
150-200
200-250
250-300
300-350

5.10b



5.10c

Figure 5. 10 Water distribution for the three different nozzle outlet sizes at height of 0.5 m-10 psi with small size catch containers. a mustard nozzle. b yellow nozzle. c red nozzle

5.2.8. Water distribution uniformity with rectangular shape catch containers

Significant differences of water distribution uniformity under the effect of nozzle height, water pressure, and nozzle outlet size have been obtained when testing with rectangular shape catch containers (*P*<0.001). There were no significant differences between the interaction between treatment (*P* = 0.081) as shown in Table 5.4.

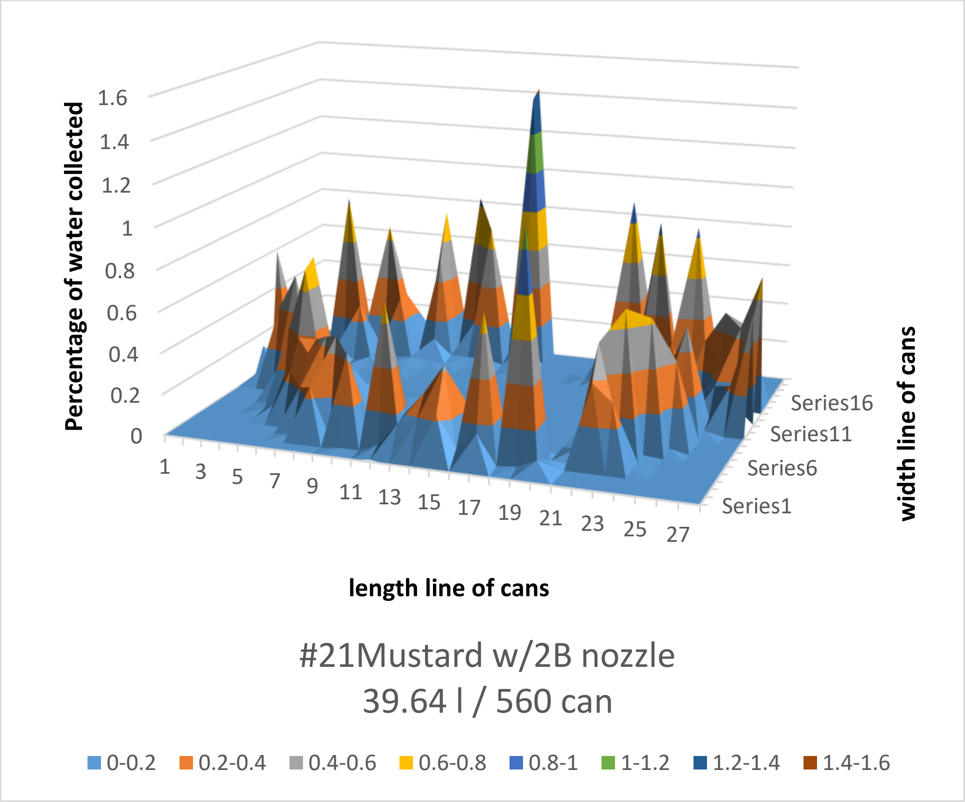
Table 5. 4 Water distribution uniformity (%) results for rectangular shape catch containers under the effect of different nozzle outlet size and height, and water pressure.

Means: distribution uniformity DU %		Nozzle type				Height* Pressure* Nozzle		
Height	Pressure psi	Mustard	Yellow	Red		*P*	S.E.D	cv %
1.5 m	6	69	97	39		0.081	11.78	20.1
	10	59	95	51				
	15	68	148	110				
	20	68	123	87				
0.5 m	6	33	39	28				
	10	32	47	62				
	15	40	103	80				
	20	44	119	71				
Means Height effect	1.5 m		0.5 m			<.001	3.40	
	84		58					
Means Pressure psi	6	10	15	20		<.001	4.81	
	51	57	91	85				
Means Height * Pressure		6	10	15	20	0.106	6.80	
	1.5 m	69	68	109	93			
	0.5 m	34	47	74	78			
Means Nozzle	Mustard		Yellow	Red		<.001	4.16	
	52		96	66				
Means Height * Nozzle		Mustard	Yellow	Red		.007	5.89	
	1.5 m	66	116	72				
	0.5 m	37	77	60				
Means Pressure * Nozzle		Mustard	Yellow	Red		<.001	8.33	
	6 psi	51	68	34				
	10 psi	45	71	56				
	15 psi	54	125	95				
	20 psi	56	121	79				

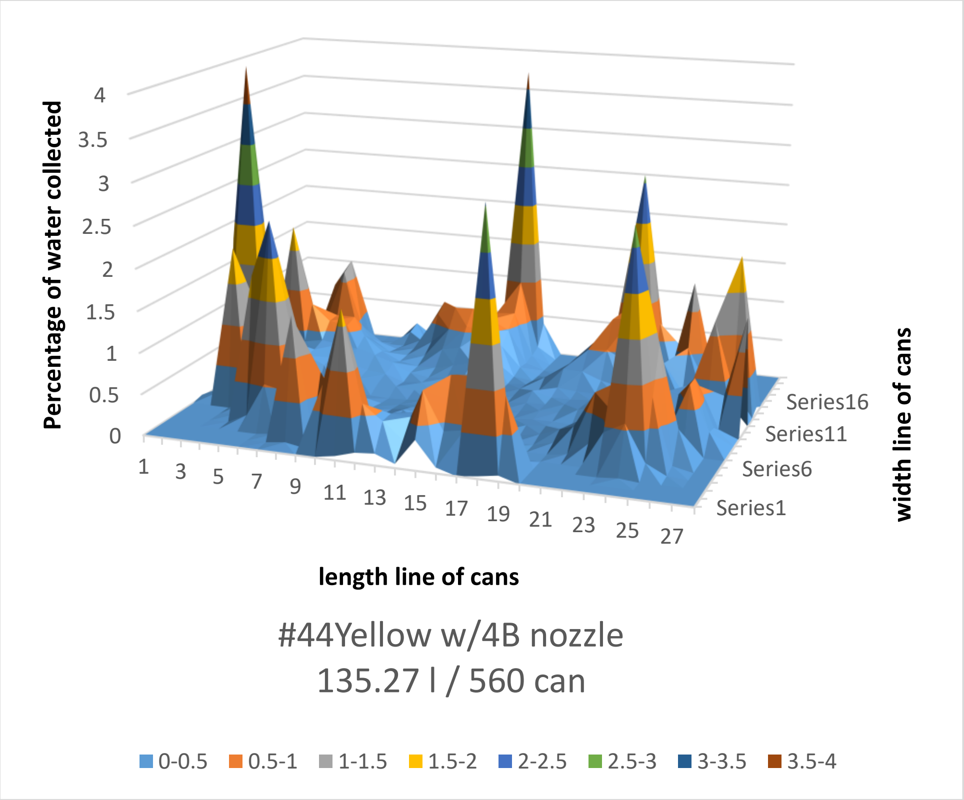
5.2.8.1 The effect of nozzle outlet size on water distribution uniformity %

There were significant differences of water distribution uniformity means under the effect of differences of nozzles outlet size (*p*= <.0010). The black-33 #44Yellow w/4B nozzle had the highest uniformity of 96% and the lowest was obtained by the black-33 #21Mustard w/2B nozzle, DU= 52%. Water distribution uniformity with black-33 #42Red w/4B nozzle was 66%.

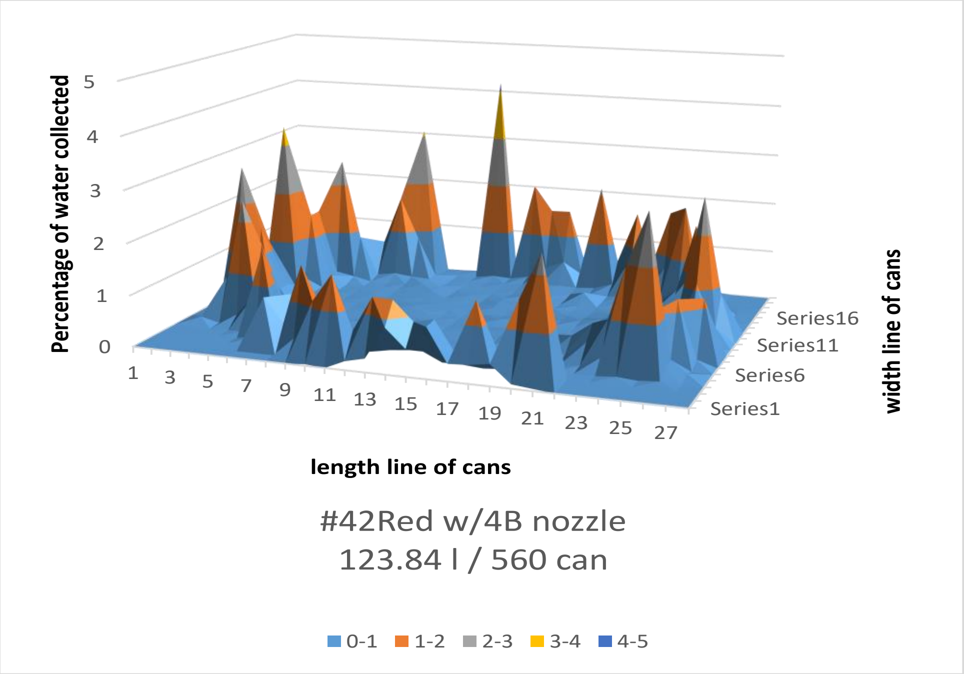
The total amount of water collected in the 560 box was 39.64, 135.27, 123.84 litre for #21Mustard w/2B, #44Yellow w/4B, #42Red w/4B nozzle respectively, as shown in figure 5.11. (a, b, c).



5.11a



5.11b



5.11c

Figure 5. 11 Water distribution % for the three different nozzle outlet sizes at height of 1.5 m and 42 kPa (6 psi) pressure with rectangular shape catch containers. a mustard nozzle. b yellow nozzle. c red nozzle

5.2.8.2 The effect of nozzle height on the water distribution uniformity

There were significant differences of water distribution uniformity means under the effect of differences of nozzles height (P <0.001). Water distribution uniformity was 84% at height 1.5 m and 58% at 0.5 m.

There was significant difference of water distribution uniformity under the effect of interaction between nozzle height and outlet size (P =0.007); showing there was a significant effect on uniformity depending on the height and the actual nozzle used.

Water has been spread over 560 rectangular shape catch containers at a height of 1.5 m when testing the three nozzles separately. The amount of collected water was 39.64, 135.27, 123.53 litre for #21Mustard w/2B, #44Yellow w/4B, #42Red w/4B nozzle respectively. While catch containers number has decreased at a height of 0.5 m due to the reduction of wetted area and became 168, 196, 154 cans with the amount of water collected being 37.12, 134.74, and 123.53 litre for #21Mustard w/2B, #44Yellow w/4B, #42Red w/4B nozzle respectively. Figure 5.12, 5.13 and 5.14 show water distribution for the three nozzles at 6 psi pressure.

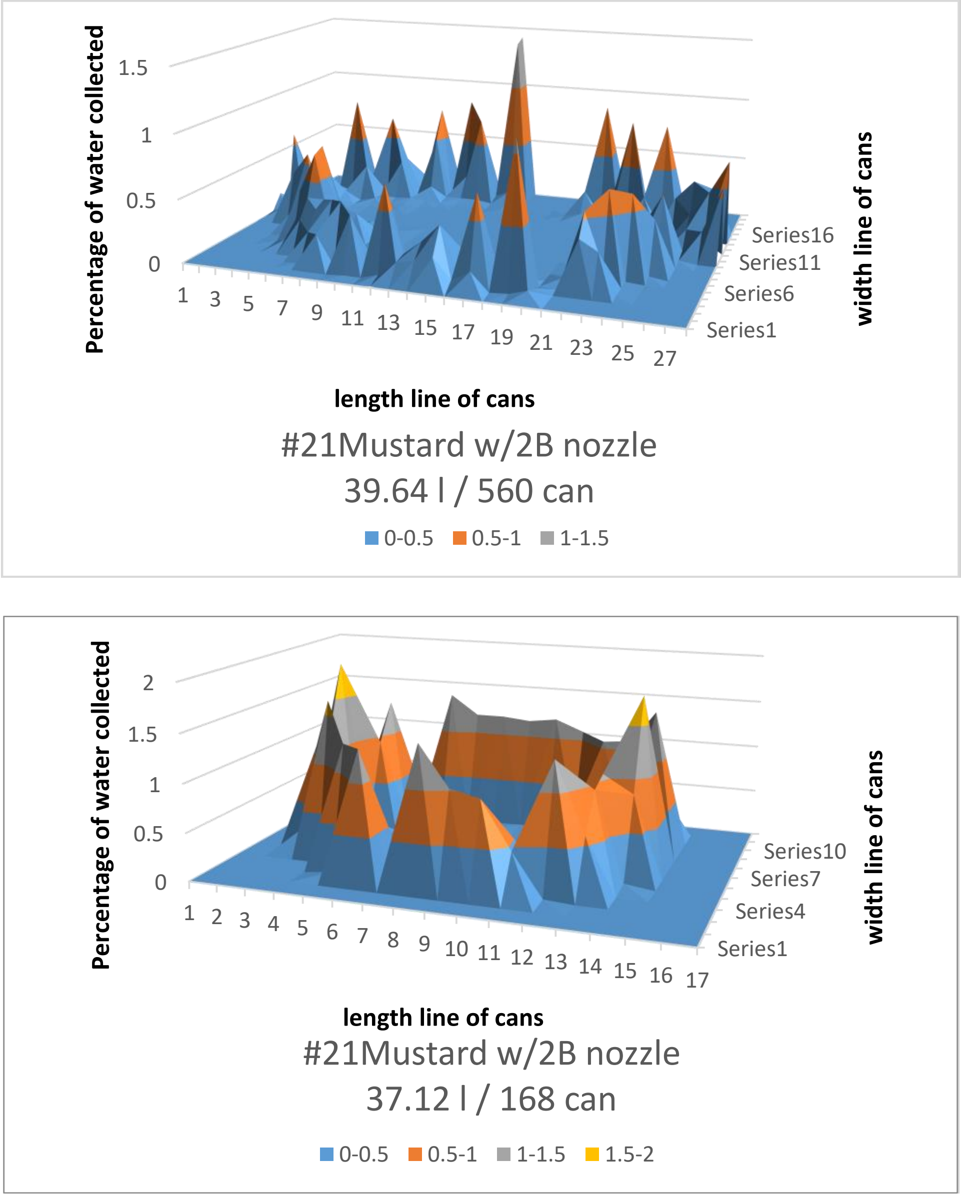
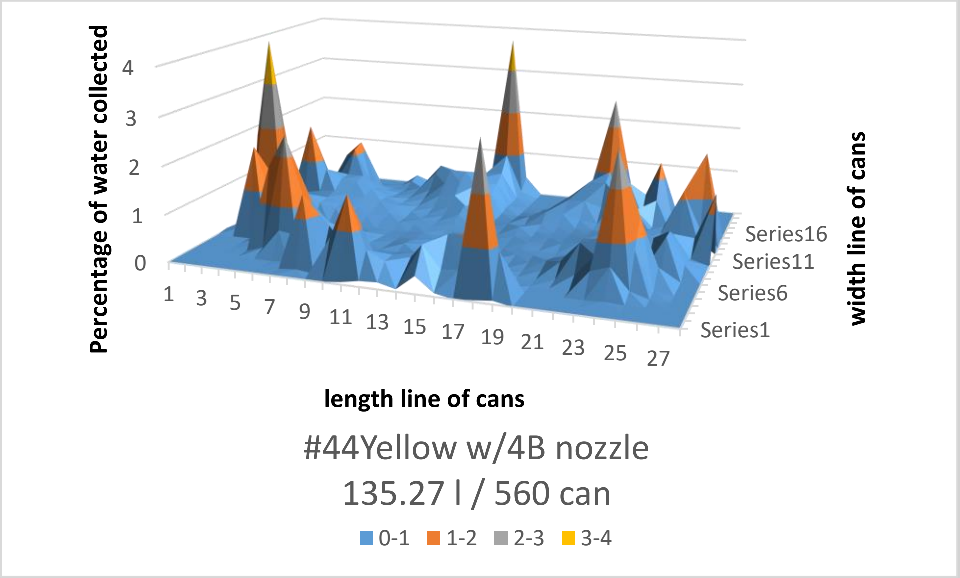


Figure 5. 12 Water distribution for #21Mustard w/2B nozzle at height of 1.5 m (top) and 0.5 m (bottom) at 42 kPa (6 psi) pressure with rectangular shape catch containers



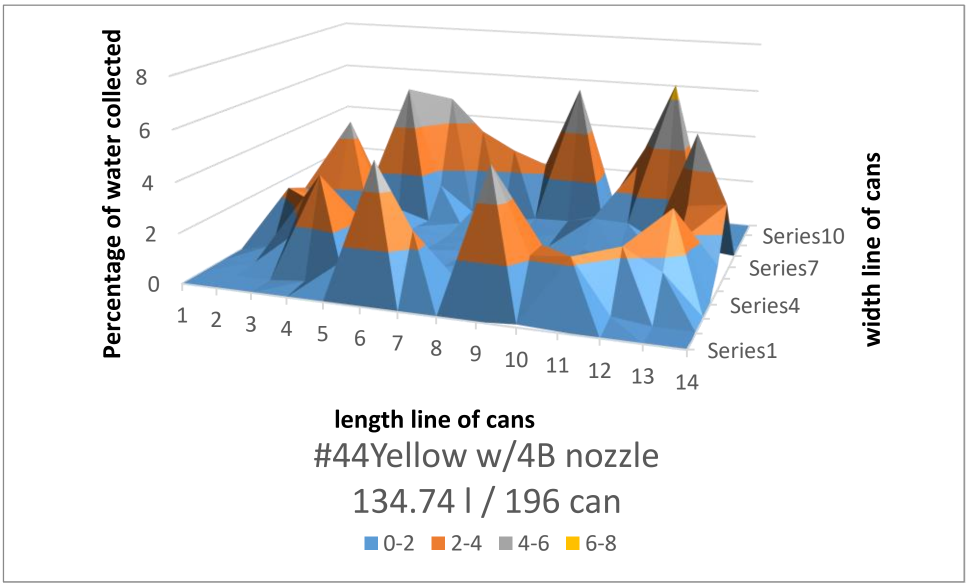
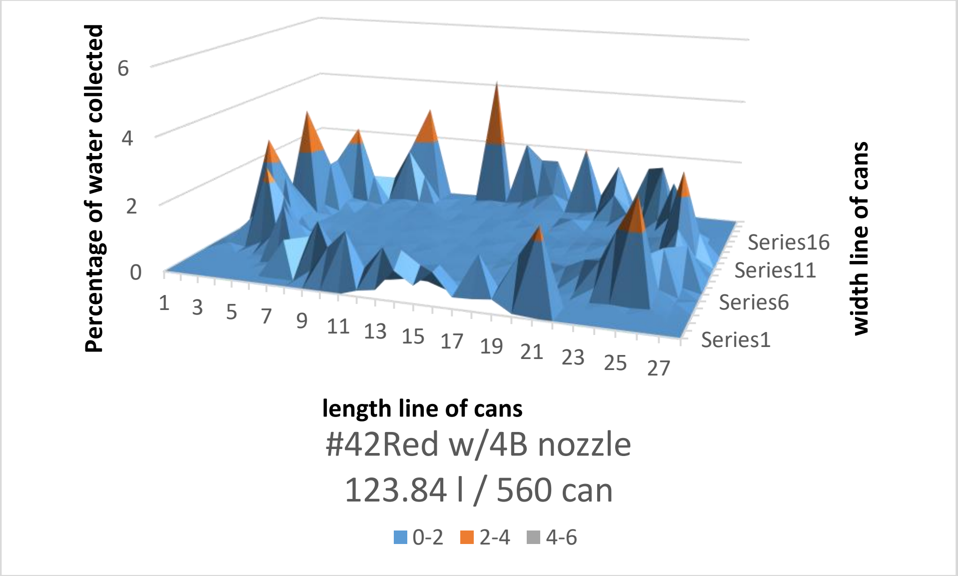


Figure 5. 13 Water distribution for #44Yellow w/4B nozzle at height of 1.5 m (top) and 0.5 m (bottom) and 42 kPa (6 psi) pressure with rectangular shape catch containers



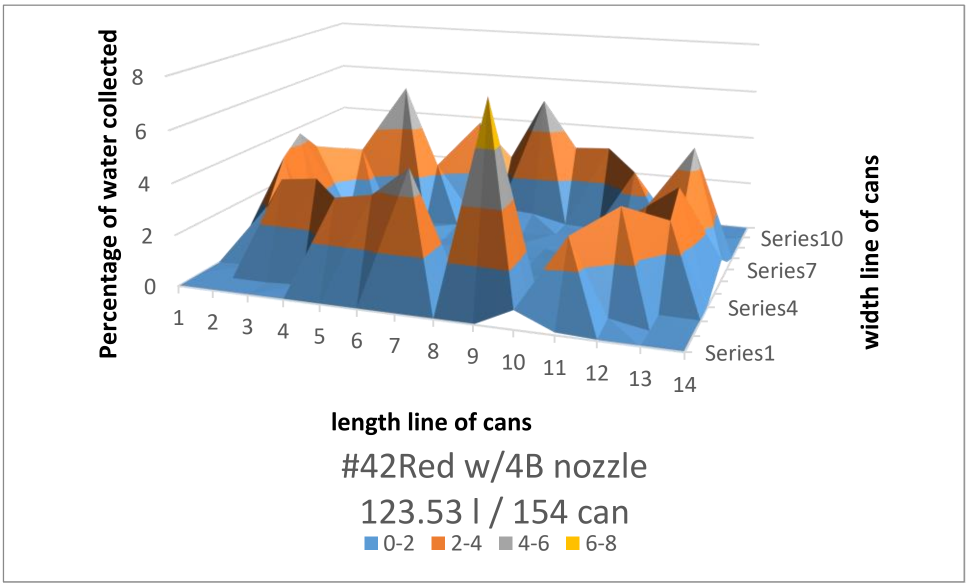


Figure 5. 14 Water distribution for #42Red w/4B nozzle at height of 1.5 m (top) and 0.5 m (bottom) and 42 kPa (6 psi) pressure with rectangular shape catch containers

5.2.8.3 The effect of water pressure on the water distribution uniformity

There were significant differences of water distribution uniformity means under the effect of differences of water pressure (*P*= 0.001). The higher the water pressure, the greater the uniformity of irrigation, except for a small difference between 15 and 20 psi pressure, table 5.4. The distribution uniformity means were 51%, 57%, 91%, and 85% for each of 42, 69, 103, 138 kPa (6, 10, 15, and 20 psi).

There were no significant differences of water distribution uniformity means under the interaction between water pressure and nozzle height (*P*= 0.106).

There were significant differences of water distribution uniformity means under the interaction between water pressure and nozzle type (*P*= 0.001).

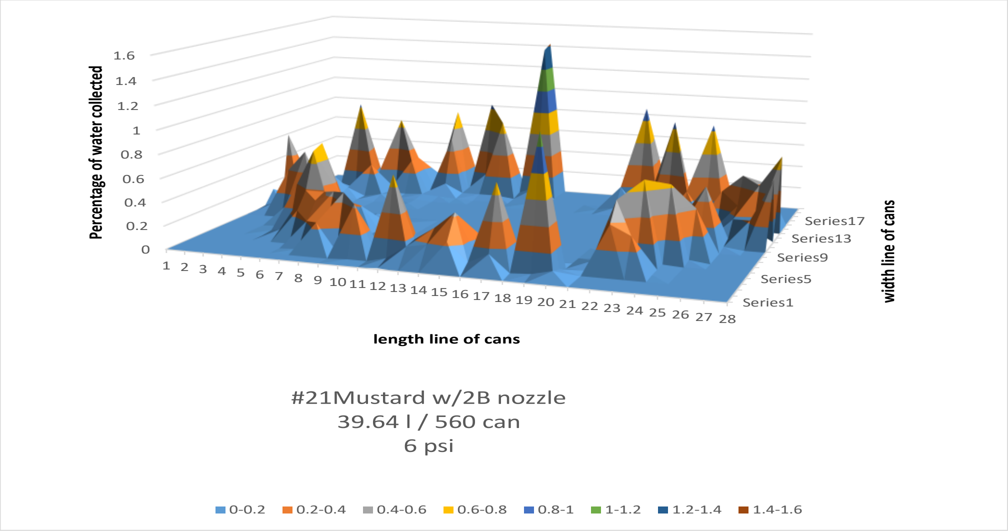
It can be seen from table 5.4 that a significant increase in the distribution uniformity means of all pressures with the #44Yellow w/4B and #42Red w/4B nozzles. It should be noted that the pressure of 103 kPa (15 psi) with these two nozzles was slightly higher than at 138 kPa (20 psi).

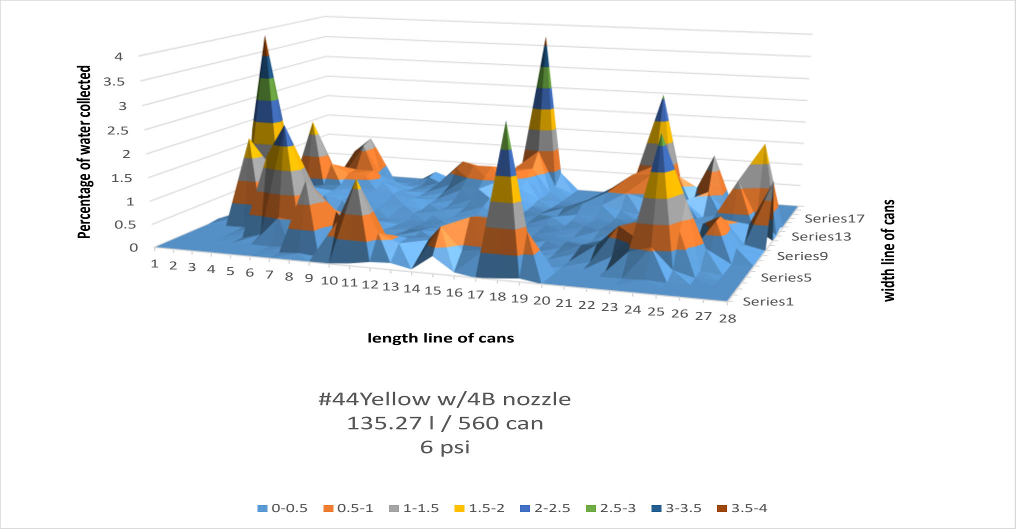
The distribution uniformity means were 125% and 95% at 15 psi, and 121%, 79% at 20 psi for #44Yellow w/4B and #42Red w/4B nozzles, respectively. The distribution uniformity means of #21Mustard w/2B nozzle ranged from 51% to 56% for the used pressures.

The results showed that the applied pressure has a significant effect on the amount of water collected in the cans, in addition to the significant effect that interferes with the type of nozzle. In figures 5.15, 5.16, 5.17 and 5.18 at a height of 1.5 m, there was a significant increase in the amount of water for each nozzle accompanied by an increase in the amount of pressure used. However, amount of water has no relation with distribution uniformity.

#44Yellow w/4B nozzle significantly exceeded the accumulation of the largest quantity of water for all the pressures on the rest of the treatments. It was 135.27, 192.66, 212.07 and 216.48 litres, respectively. Compared with #42Red w/4B nozzle 123.84, 159.11, 185.51, and 211.77 litres, respectively; and #21Mustard w/2B nozzle 39.64, 39.88, 49.21, and 56.14 litres, respectively.

Water collected with rectangular shape catch containers under 10 psi pressure at nozzle height of 1.5 m averaged at 39.88 l / 924 can, 162.66 l / 896 can, and 159.11 l / 924 can for #21Mustard w/2B, #44Yellow w/4B, #42Red w/4B nozzle, respectively. While at nozzle height of 0.5 m it averaged at 38.46 l / 225 can, 172.82 l / 221 can, and 166.07 l / 208 can for the three nozzles, respectively.





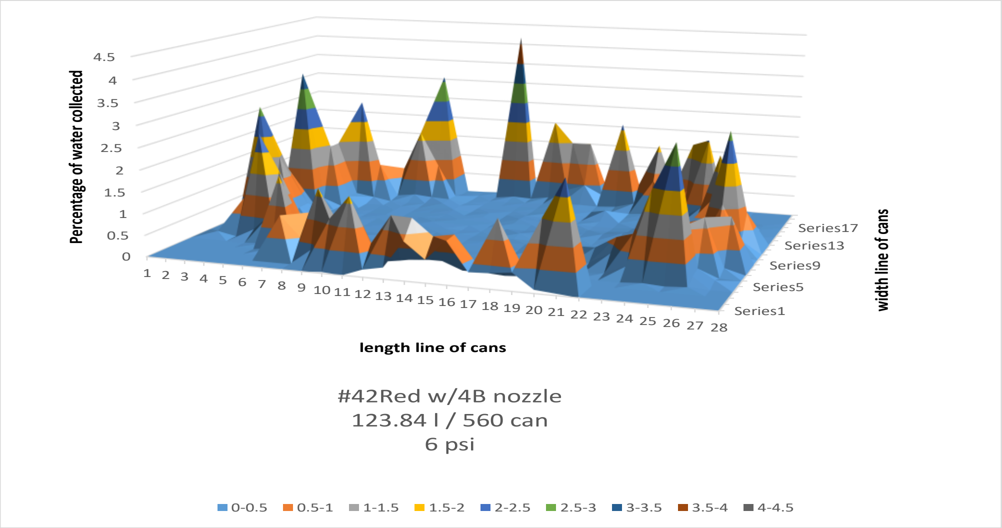
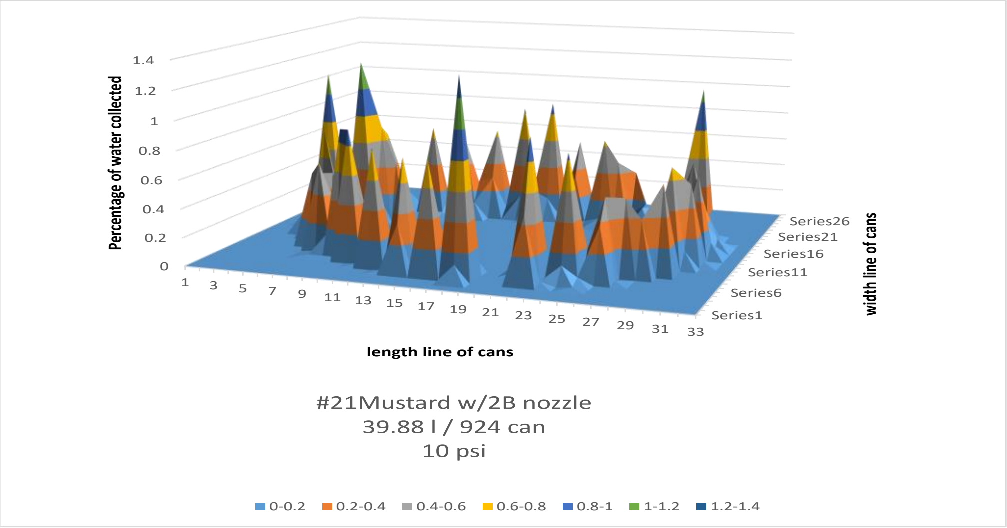
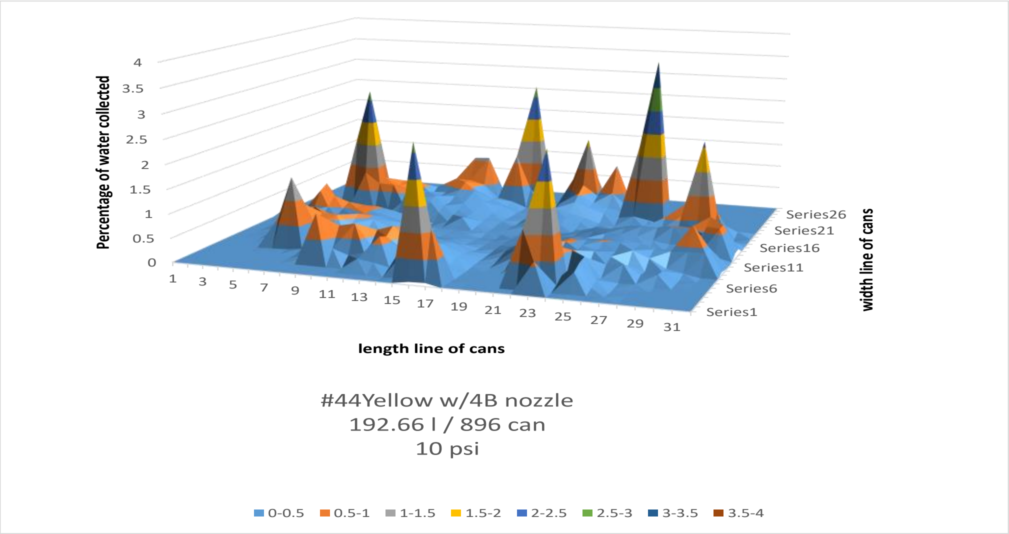


Figure 5. 15 Water distribution (%) for the three different nozzle outlet sizes at height of 1.5 m and 42 kPa (6 psi) pressure with rectangular shape catch containers. a mustard nozzle. b yellow nozzle. c red nozzle





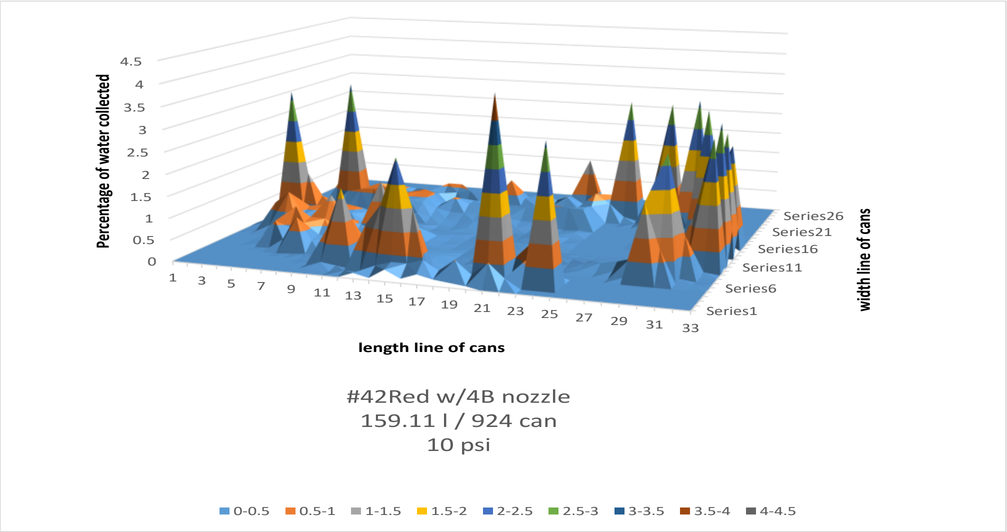


Figure 5. 16 Water distribution for the three-different nozzle outlet size at height of 1.5 m and 69 kPa (10 psi) pressure with rectangular shape catch containers. a mustard nozzle. b yellow nozzle. c red nozzle

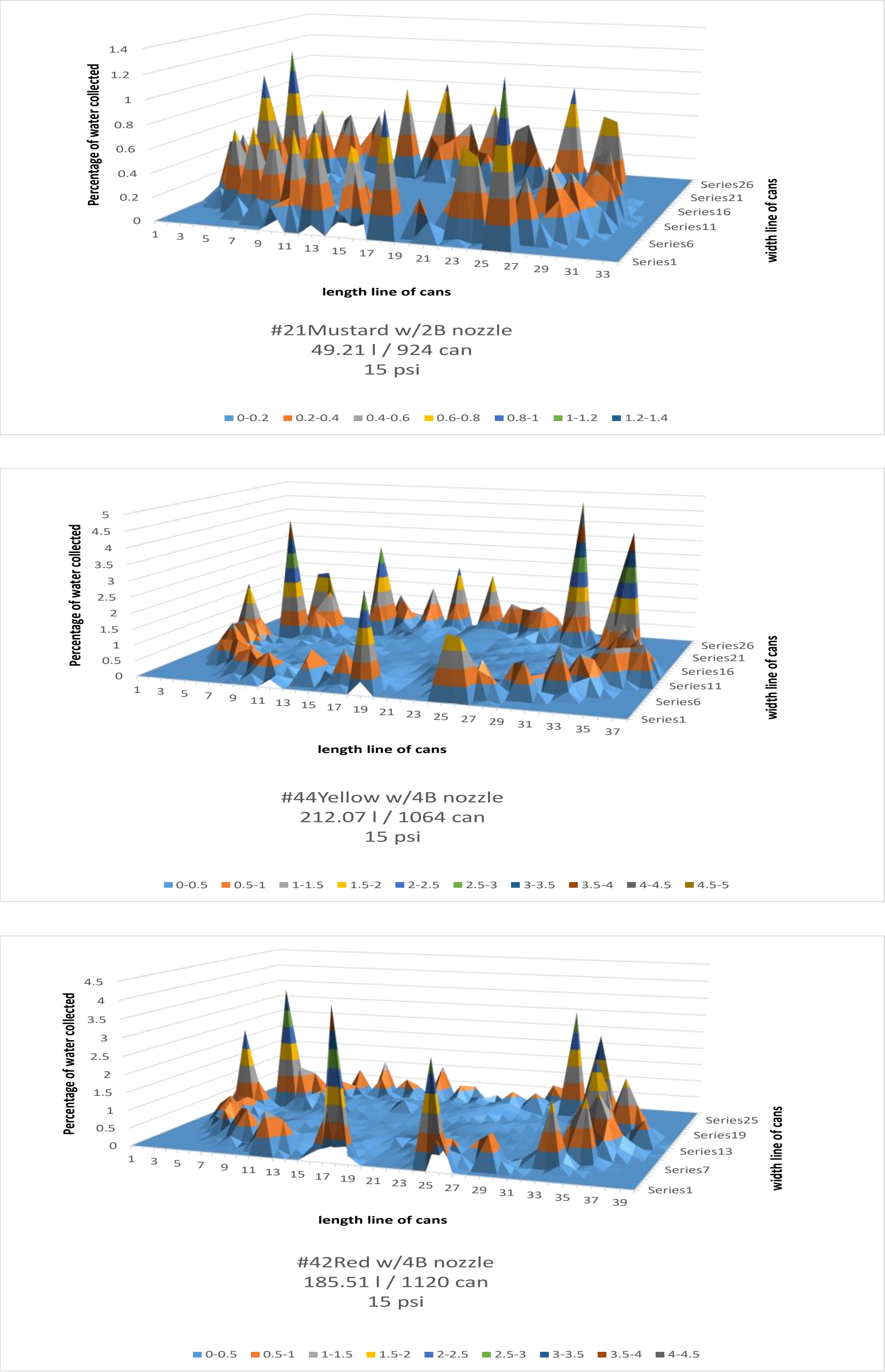


Figure 5. 17 Water distribution (%) for the three different nozzle outlet sizes at height of 1.5 m and 103 kPa (15 psi) pressure with rectangular shape catch containers. a mustard nozzle. b yellow nozzle. c red nozzle

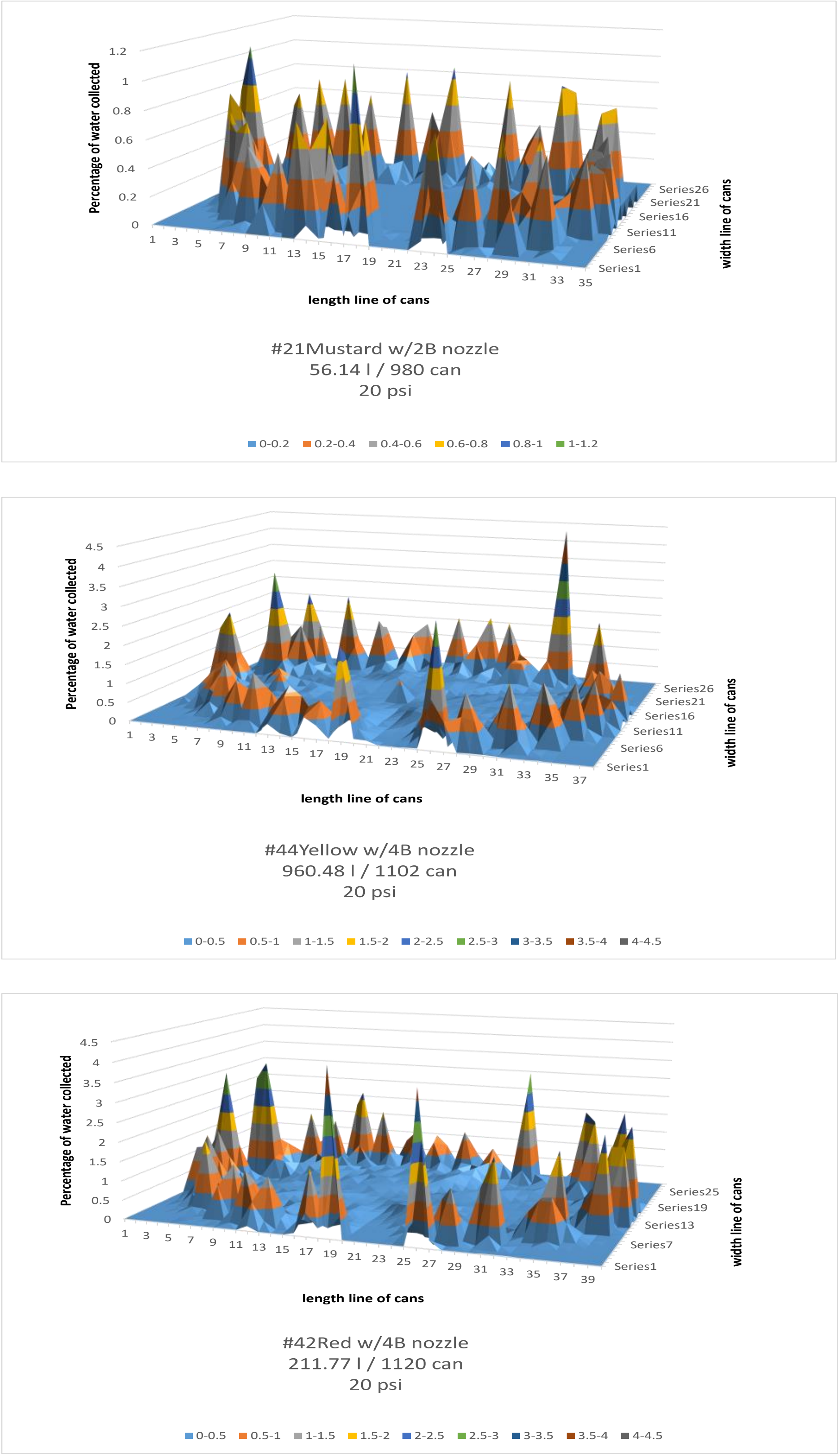


Figure 5. 18 Water distribution (%) for the three different nozzle outlet sizes at height of 1.5 m and 138 kPa (20 psi) pressure with rectangular shape catch containers. a mustard nozzle. b yellow nozzle. c red nozzle

In addition to these results a visual representation of the collection pattern was used by colour coding the values in excel (Microsoft), figure 5.19. This clearly demonstrates the effect of the three supports found in the nozzle as seen in figure 5.6. Figure 5.19 shows the circular pattern of water distribution has cut into three sections and the lack of water collected in the catch cans. The yellow colour represents the non-collection of water in the catch cans.

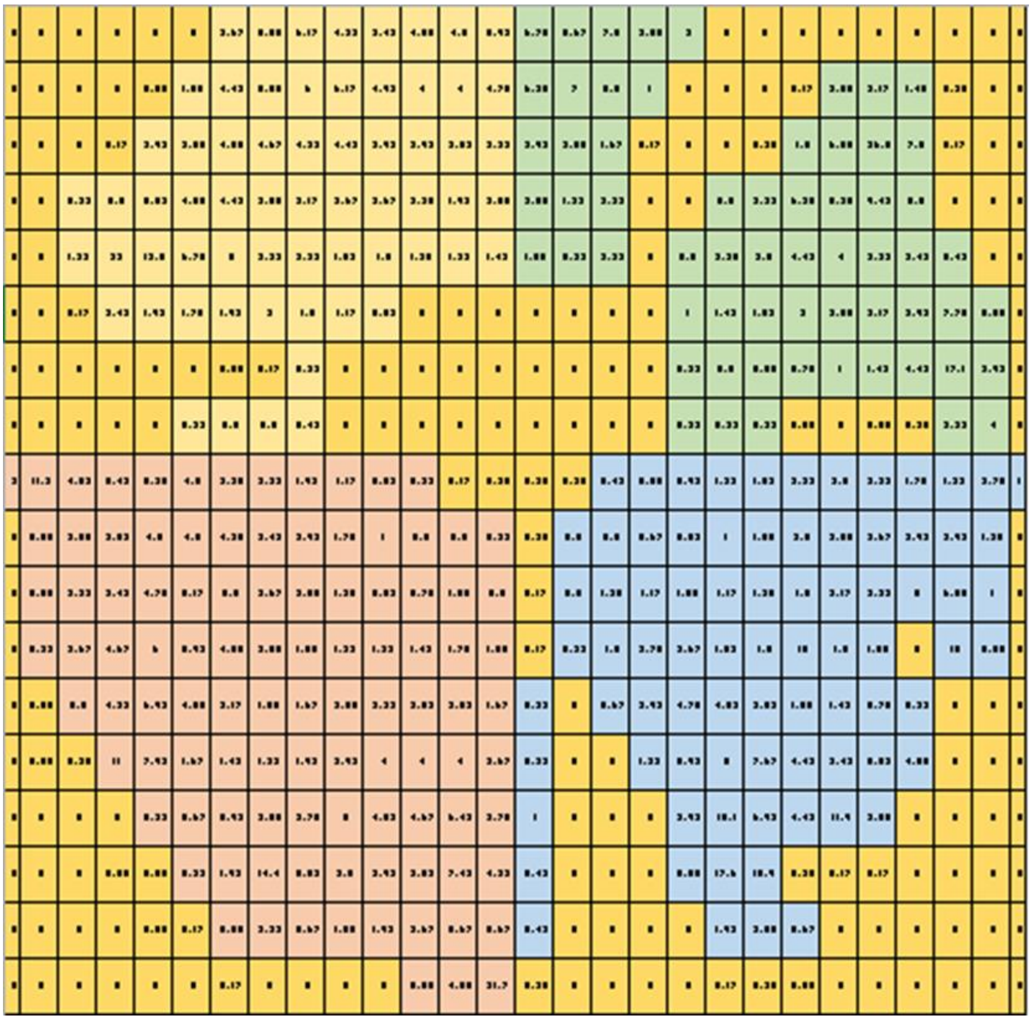


Figure 5. 19 Catch can layout, 8m x 8m, with rectangular collectors in correct proportion, displaying the overall pattern and the 3 distinct lines where no water was collected.

Figure 5.6 is taken from one of the readings obtained during the experiment. The colours distributed around the centre in this model are just an expression of the distribution of water under nozzle. It is not necessarily to know the values of water distribution amount in this figure, but the objective is to know the effect of the presence of the three supports on water distribution.

Further investigation of the pattern was then carried out to determine how the water distribution would be affected if the sprinkler was moving, as it would be once mounted on a travelling boom at 2.5m per minute, figure 5.20. It can be seen that without any overlap from other sprinklers the water application is considerably higher around lines 5, 14 and 23.

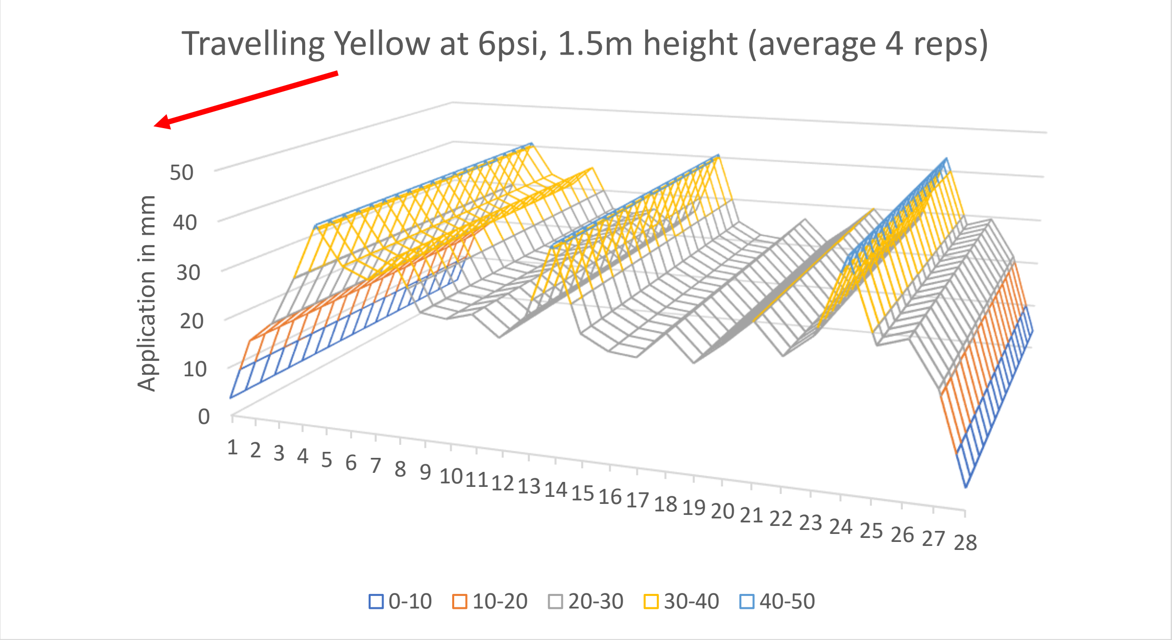


Figure 5. 20 Representation of the effect of a single sprinkler travelling forwards and the areas of overlap which need to occur to provide a uniform application.

A possible alternative analysis to quantify the spatial distribution of the pattern was investigated and could provide an opportunity for further evaluation, Hot spot analysis, figure 5.21. Unfortunately, there was insufficient time to develop this technique and so the figure is shown simply as an opportunity for further research and analysis. Hot spot analysis is a spatial analysis and mapping technique which identifies clustering of spatial phenomena. These spatial phenomena are shown as points or blocks on a map or graph and refer to locations where this clustering occurs. The hot spot depends on the results of z-scores and p-values, z-scores are standard deviations and the p-value is a probability. A significant hot spot is a feature that has a high value and surrounded by high values of features. Spatial clustering of high values is due to high z-score and small p-value. Confidence levels are 90, 95, or 99 percent, if the confidence level within 99% this indicates acceptance of the null hypothesis (Pro, A., 2017).

Figure 5.21 shows hot spot analysis of the yellow nozzle data at 1.5m height and 69 kPa (10 psi) pressure. The upper part shows confidence levels of the distribution pattern. The results showed that confidence level of 99 % is very small, which is in red. The lower part of the figure shows the distribution of confidence levels for the pattern.

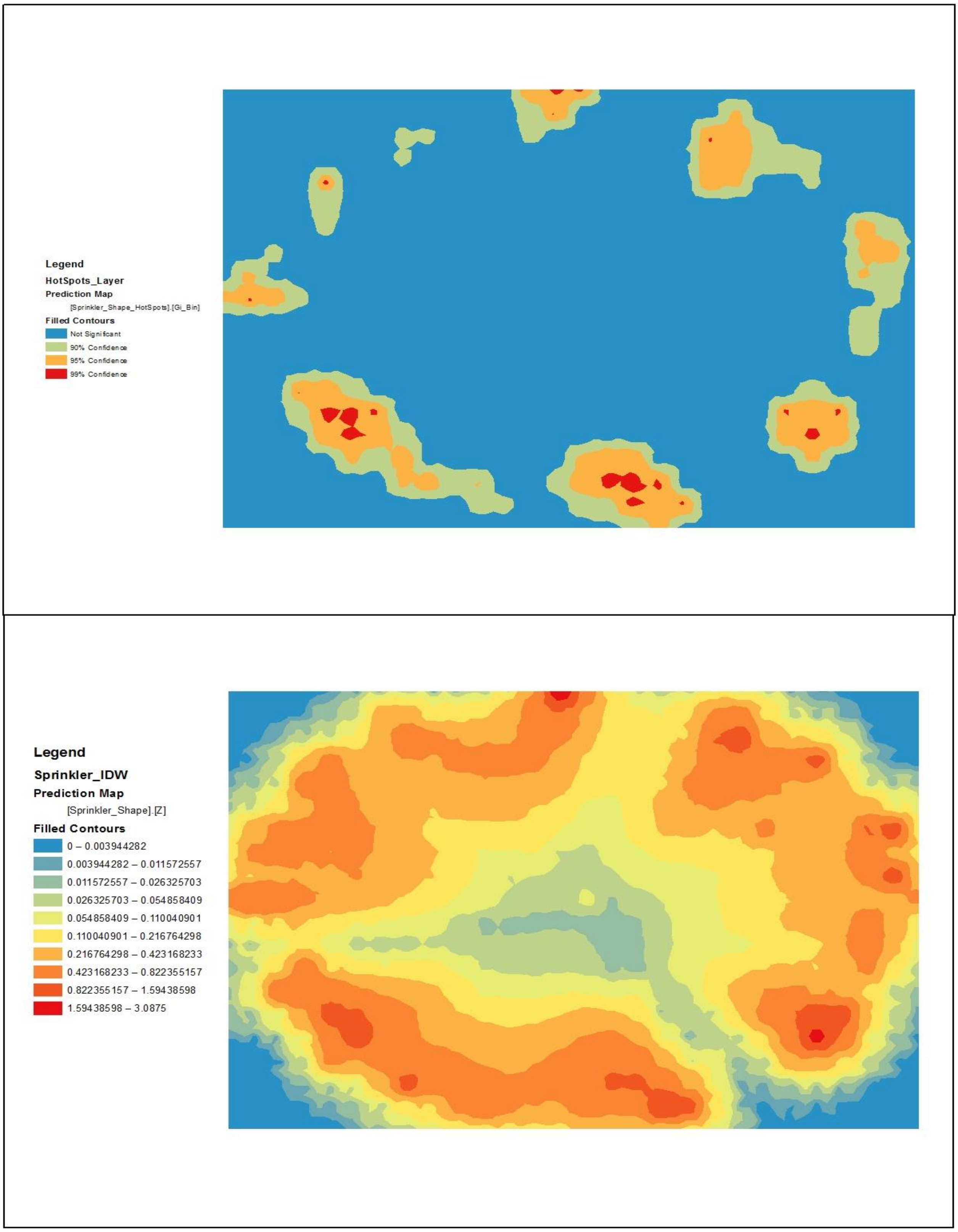


Figure 5. 21 Hot spot analysis of the yellow nozzle data at 1.5m height and 69 kPa (10 psi) pressure (Personal communication with Fabio Veronesi, lecturer/Crop and Environment Sciences department)

5.2.9 Discussion

5.2.9.1. The influence of catch can size and placement on the values of water distribution uniformity

Differences in DU values can be attributed in part to the size of the small size catch containers and the distances between cans relative to the irrigation patterns (Clark *et al*., 2006). Since the test conditions were similar for both types of collectors, the lower distribution uniformity values with small size catch containers were due to small space in which water was collected from top of the cans. In addition, water is not collected in the areas between the cans. The distance between cans led to the failure of catching most of the falling water from the nozzle on the whole test area. Therefore, even if the application was uniform, this type of evaluation may not reflect the reality or true uniformity correctly.

This is the basis for the minimum standards set out by the ASAE to ensure that suitable data and representations are achieved (Clark *et al*., 2006).

The small opening size of collectors plus the distances between them has lost the real visualisation and meaning of the application pattern. Consequently, the decision on distribution uniformity is in doubt when using small catch cans in this manner. Small cans give lower values than may be experienced in the field resulting in runoff.

The distribution of catch cans with larger openings and less distance between cans when measuring water distribution uniformity should therefore provide a better understanding than when the uniformity test is done by traditional cans (Clark *et al*., 2006). It is possible to follow the same traditional method of containers distribution when measuring uniformity, but with larger upper area of the cans in addition to reducing or eliminating the distances between cans if possible.

Accordingly, when comparing water collected rates for both small and rectangular containers under the same test conditions, the results were in high deference. Water collected rate with rectangular containers was more. When data were entered for both tests within the distribution uniformity equation, the results were significantly different between the two tests under the same test conditions. This gives a clear picture of water distribution rate of this type of nozzles which is related to the field conditions. Water collected in the rectangular shape catch containers were considered to be more accurate and representative of true irrigation patterns for each nozzle type as there were no gaps in which to miss applied water under the effect of variation of water pressure and nozzle height.

One of the key elements of these findings is that the patterns from an individual sprinkler is not uniform and so when overlapping nozzles are used there exists a potential for significant variations of distribution uniformity to occur, (Jiao *et al*., 2017).

5.2.9.2. The influence of water pressure and nozzle height on water distribution uniformity

The compatibility between nozzle size and pressure has played an important role in the consistency of application pattern and thus the uniformity rate. This was observed through the results of water pressure of 103 kPa (15 psi) with #44Yellow w/4B nozzle particularly, which has produced good sprinkler distribution patterns which led to production of higher DU values.

DU values under the fixed plate sprinkler with #21Mustard w/2B nozzle were substantially lower than #44Yellow w/4B and #42Red w/4B nozzle. This is typically due to the small outlet size which can result in small application patterns (Jiao *et al*., 2017). Water distribution values were variable but were low with 42 kPa (6 psi) and 69 kPa (10 psi) pressure for all nozzles that were tested. This indicates that this sprinkler package is not suited to work under low pressure.

When the data from the single yellow nozzle at 6 psi is used to mimic the effect of a travelling boom, figure 5.20, the need for good overlapping between nozzles is apparent (Lamm *et al*., 2006).

One of the elements from visual representation of the data also demonstrates how the application is affected by the nozzle supports on the bottom plate, figure 5.18, where the supports interfere with the application.

As the actual pressure regulators are screwed onto the boom outlet there is a potential for this pattern to be achieved in any one of 360° options which would make ideal overlapping between nozzles a variable to consider in relation to the potential for localised runoff. This can be seen in the hot spot results, which can reflect a clear picture of distribution uniformity; and the potential for adjacent hot spots to seed runoff. Unfortunately, it was not possible within the time constraints to set up overlapping nozzles to continue this part of the investigation to determine the range of the effect achieved.

One of the main reasons that lead to water runoff is application rate more than soil infiltration rate (Brouwer *et al*., 1988). It can be observed from the results that water collected with rectangular shape catch containers under 69 kPa (10 psi) pressure at nozzle height of 1.5 m averaged 39.88 l / 924 can (0.04 l/ can), 162.66 l / 896 can (0.18 l/ can), and 159.11 l / 924 can (0.17 l/ can) for #21Mustard w/2B, #44Yellow w/4B, #42Red w/4B nozzle respectively, while at nozzle height of 0.5 m averaged 38.46 l / 225 can (0.17 l/ can), 172.82 l / 221 can (0.78 l/ can), and 166.07 l / 208 can (0.79 l/ can) for the three nozzles, respectively. Which means increase in water collection rate calculated on the basis of number of cans 23% of mustard and yellow nozzles and 21% of red nozzle, at different height of the nozzle.

The decrease in number of cans for each nozzle at a height of 0.5 m compared with 1.5 m, indicates that application rate is more than infiltration rate at height of 0.5 m when applied in the field. This indicates a definite occurrence of runoff, (Lamm *et al*., 2012; Lamm *et al*., 2006)

An analysis of variance showed that DU value differences were not significant within any of the water pressure from the various nozzle heights. However, the reduction in the number of cans under the same rate of discharge gives an indication of the decrease in wetting area, which may mean an increase in the rate of irrigation over the reduced area of application, (Bjorneberg *et al*., 2000; Casenave and Valentin, 1992). This was evident from water collection samples during each test.

It is worth mentioning that the collected water with #21Mustard w/2B nozzle with 6 psi at 0.5 m was slightly higher by 30% than 1.5 m. This probably comes from compatibility between the low pressure and nozzle out let size which has produced compatible application pattern at this height.

As mentioned in materials and methods of chapter 3 for the order of nozzles distribution of 15 ha Valley centre pivot system and according to the obtained results, water application pattern for this sprinkler package has become clear. The positioning of the nozzle, bridge and deflector has been maintained when reassembling and potential differences in performance has been identified. It is therefore possible to obtain the application pattern.

This is however not applied by the farmer and the positioning of the nozzle, bridge and deflector along the boom is generally not considered. This in turn is a new factor added to the known factors causing water runoff.

Although the uniformity and water application patterns were better identified by the use of full surface coverage collectors it should be noted that the data collection using this method was extremely time consuming. Consequently, the amount of investigation which can be done is limited and thus further practical investigation of overlap characteristics between different nozzles and sprinkler packages is required. In the field, the full importance of these findings is all relative to the potential for irrigation water runoff and where this is low the lack of high uniformity is less relevant as the soil itself will even up the application in many cases (Howell, 2006). The investigation of the consistency of application between different nozzles of the same configuration however show that the manufacturing process adds virtually no variation to the output and thus provides a uniform product from which to work.

5.2.10. Conclusions

1. Nozzle performance in terms of application uniformity was not sufficiently well described using the smaller catch cans. The larger collectors gave a good resolution of the water application and identified that the nozzle bridge supports influence the overall uniformity of application.
2. Application patterns under the fixed plate sprinkler with various nozzle outlet sizes produce relatively large amplitude variations which can be difficult to accurately measure with a collector that has a relatively small opening.
3. The rectangular shape catch containers showed a consistent distribution pattern under the lower and higher pressures and low and high elevation of the nozzles.
4. System operating at pressures of 103 or 138 kPa (15 or 20 psi) result in greater uniformity than pressures of 42 and 69 kPa (6 and 10 psi), however, further work in relation to overlap effects between nozzles is needed.
5. An issue of the nozzle bridge orientation of adjacent nozzles was identified as a potential source for water distribution hot spots and the seeding of runoff, again an area for further investigation.

6. The effect of tillage type on soil properties and irrigation water runoff under simulated centre pivot irrigation.

6.1. Introduction

The problem of water runoff under the application of irrigation from centre pivot systems requires a study of the factors leading to it as soil conditions (soil texture, organic matter contain, plant residue), tillage methods and the sprinkler system performance. In this study, it is necessary to carry out field experiments to observe the occurrence of runoff in a range of field conditions.

A large field experiment was carried out in 2014 and two further field experiments were done in 2016. These experiments included investigation of the effect of the type and method of soil cultivation on specific soil characteristics. These cultivator types included soil inversion by mouldboard plough or various types of soil mixing from equipment such as rotary cultivators, gang discs or spring tine equipment. The soil characteristics were investigated before and after the use of sprinkler irrigation.

Water infiltration rate, soil shear strength, and soil penetration resistance before and after sprinkler irrigation was studied in the first experiment. Infiltration rate and shear strength before and after irrigation were also studied in the second experiment. The third experiment measured infiltration rate and soil bulk density before and after irrigation. Soil moisture content was measured for all experiments before and after irrigation. Surface water runoff was measured in both the second and third experiments.

In addition, the actual measurement of water runoff was investigated in this study to determine if run-off measurements could be made using a mobile system rather than a dedicated test facility as is normal (Zhao *et al*., 2014; Römkens *et al*., 2002). The investigation also considered the size of the measurement area to determine if smaller scale assessments could provide a sufficiently accurate measurement of the run-off.

The compatibility between the sprinkler irrigation system and tillage methods has an important role in maintaining soil structure and aggregate stability (Scherer, *et al*., 2013). Therefore, there should be a better understanding of the relationship between irrigation intensity using sprinkler irrigation and the method of soil cultivation.

Much research has been dedicated to the performance of a particular type of tillage on different soil types (Hamid, 2012; Daraghmeh *et al*., 2009; Marques da Silva *et al*., 2004). Daraghmeh et al. (2009) indicated that changing tillage methods as well as the rate of irrigation can have a considerable impact upon soil aggregate stability and in controlling water runoff. Furthermore, the performance of a particular type of tillage varies widely depending on the difference in the soil type. Based on that, the measurements of shear strength and penetration resistance for example will change accordingly, in addition to the impact of the tillage depth factor (Hamid, 2012).

Tillage practices such as mouldboard and disc ploughs and subsoilers have been used to increase soil porosity. In a study by Pagliai *et al*., (2004) on three tillage practices: minimum tillage by harrowing soil with a disc harrow to a depth of 0.1m, conventional deep tillage by mouldboard ploughing to a depth of 0.4 m, and alternative tillage by subsoiling to a depth 0.5 m; on soil porosity and hydraulic conductivity. Pagliai *et al*., (2004) found that with loam soil, a minimum tillage and soil tilled by subsoiling generally have higher macroporosity and more homogeneous distribution, as well as higher hydraulic conductivity through the profile. This has been attributed to soil structure was more open, a larger number of elongated transmission pores, thus allowing better water movement. Pagliai *et al*., (2004) referred that ploughed soil by mouldboard was subjective to surface crusting more than soils cultivated by subsoiler or with minimum tillage. Raper and Sharma (2002) pointed that subsoilers inverting soil while preserving plant residue without cluttering. Pagliai *et al*., (2004) confirmed that adoption subsoiling tillage would enhanced soil conditions.

Raper and Sharma (2002) clarified that decreased sandy loam soil moisture has led to increase soil disruption above ground when subsoiling. This probably will lead to invert more soil at the expense of crop residue, which means the possibility of accelerating soil degradation, especially if irrigation is by sprinkler system.

Aikins and Afuakwa (2012) indicated that disc ploughing followed by disc harrowing treatment presented the lowest soil penetration resistance 117 kPa (17 psi), lowest dry bulk density (ranged 1.26 Mg m^{-3} to 1.43 Mg m^{-3} at depth 0-0.1 m, 1.275 Mg m^{-3} to 1.425 Mg m^{-3} at depth 0.1-0.2 m), highest moisture content, and highest total porosity; this was compared with no tillage treatment.

Muckel and Mausbach, (1996) mentioned that soil crusting is created under the effect of flowing water or drops which may be from rain or sprinkler irrigation. Crusty soil decreased water infiltration, but at the same time it is an upper barrier to the soil prevents the evaporation of water from subsurface layers.

Ploughed soils are more vulnerable to crusting than non-cultivated soils especially when large sprinkler volumes are applied (Cantón *et al*., 2009). The soil aggregates in non-cultivated soil are more stable than those in ploughed soils, leading to the prevention of crusting (Mikha *et al*. 2011; Ramos *et al*., 2003; Al – Thobhani, 2000). However, where soil cultivations are needed careful selection of appropriate soil cultivation of clay soils can increase the efficiency of irrigation (Lipiec *et al*., 2006).

It is notable that most of studies reviewed have used more technical- cultivation techniques to approach the problem of runoff and erosion, for example, the use of implanted reservoirs small indents in the soil surface, or combinations of subsoiler and basin tillage techniques (Kranz and Eisenhauer 1990). This subsoiler/implanter has shanks which shatter the soil profile to a depth of 250 to 300 mm, midway between the crop rows, while large paddle wheels, installed behind each shank, create concave holes in the surface approximately 250 mm in diameter and 200 to 250 mm deep at intervals of approximately 600 mm. These holes collect water and provide time for infiltration which then reduces runoff. However, most Iraqi farmers do not have access to such technical equipment and rely on some basic equipment to cultivate soil such as the mouldboard and disc ploughs.

It can be seen therefore that although there are some technical cultivation answers to some of the irrigated runoff problems, there is little research which considers how combinations of basic equipment can be used alongside regular, almost daily, irrigation to prevent runoff especially from the high output end section of centre pivot irrigation. Therefore, an attention to compatibility of soil cultivation method with sprinkler application rates should be considered.

6.1.1. Aim of the experiment:

To evaluate the effect of selected cultivation equipment on soil physical properties before and after irrigation.

6.1.2. Hypothesis

The type of cultivation equipment used will affect on infiltration rate, soil shear strength and penetration resistance, and therefore controlling water runoff from simulated centre-pivot irrigation systems.

6.1.3. Null hypothesis

The type of cultivation equipment used will not affect soil properties, infiltration rate or runoff from simulated centre-pivot irrigation.

6.1.4 Materials and methods

6.1.4.1. Soil preparations

The experiment was conducted in June – August 2014 at Flatt Nook Field, Harper Adams University, UK, 52°46’27”N 02°25’06’”W. Soil texture analysis was determined (MAFF/ADAS, 1985), and found to be sandy loam soil with average sand, silt and clay content of 60%, 20% and 20%, respectively. Topsoil depth was approximately 350-400 mm at which point the soil becomes a loamy sand turning to bedrock at approximately 0.8m (Beard, 1988). A completely randomized block of eighteen cultivation treatments (table 6.1), which included: mouldboard and disc ploughing to 200mm depth, and gang disc harrowing, rigid tine harrowing and rotary harrowing to 150mm depth. Treatments were replicated four times giving a total of 72 plots, (Appendix 2). For each of these treatments a second factor of subsoiling before cultivation, subsoiling after cultivation or no subsoiling were also used. Subsoiling was carried out to a depth of 450 mm. table 6.2 showed the description of equipment used.

The tractor used was a New Holland T6040 (89.5 kW) with a standard three-point hitch. A Briggs R24 boom irrigator connected to an R1/1 hose reel (Briggs Irrigation, Corby, UK) was used to irrigate the field. Nozzles were 3TN #20, S3000 spinning plates with Nelson pressure regulators operating at 69 kPa at a spacing of 1.5m and a delivery height of 1.35m above the soil, with an application rate of 12 mm/hr. Water to the system was pumped from the mains water supply.

The field was previously planted with maize crop, so it contained plant residues with a density of 0.33 kg/ m^2 of this crop in addition to some weeds.

Table 6. 1 Symbols of the treatments used in the experiment assessing

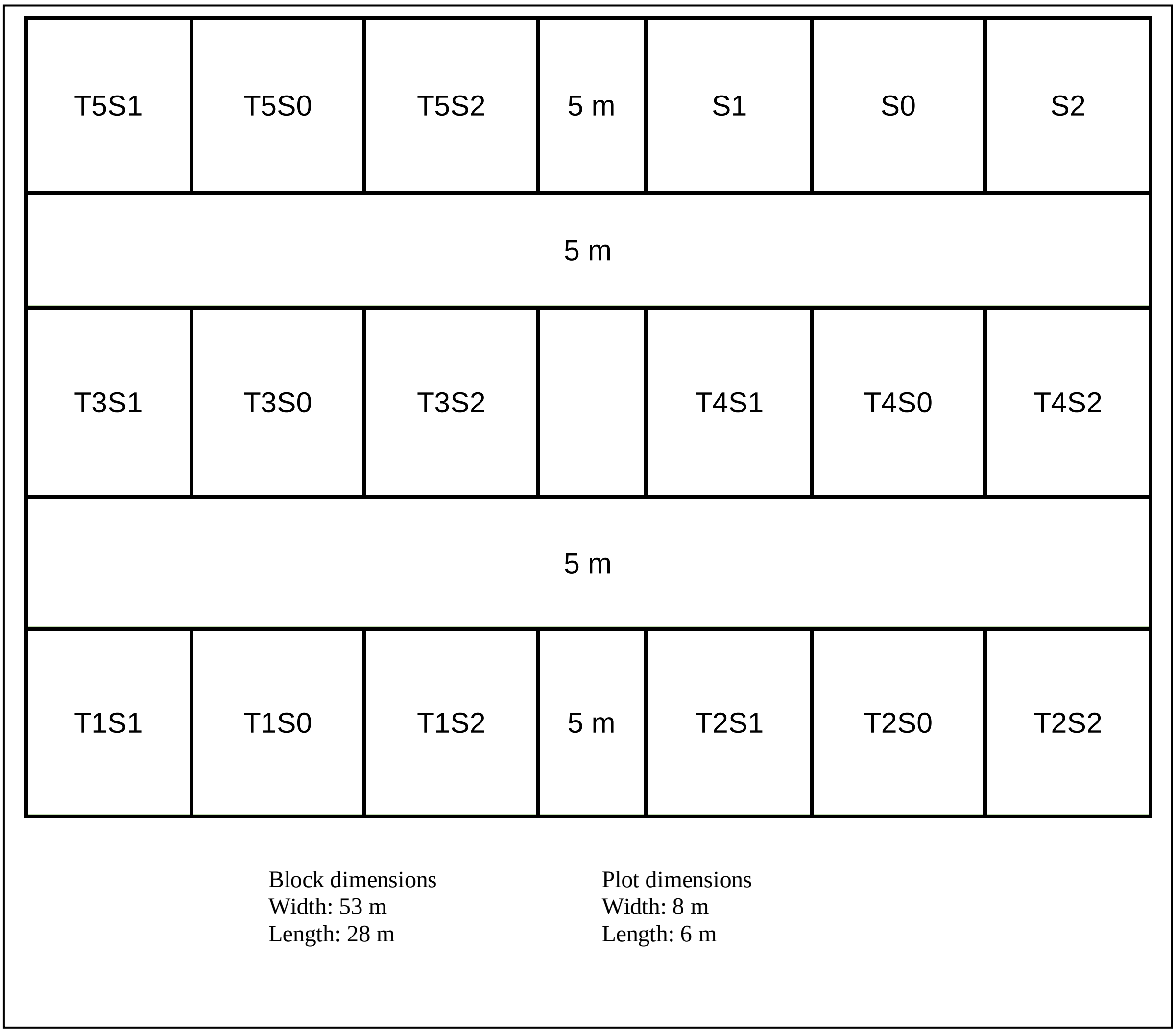
Treatment	Terminology
T1S0	mouldboard ploughing without subsoiling
T1S1	mouldboard ploughing post subsoiling
T1S2	mouldboard ploughing pre-subsoiling
T2S0	disc ploughing without subsoiling
T2S1	disc ploughing post subsoiling
T2S2	disc ploughing pre-subsoiling
T3S0	gang disc harrowing without subsoiling
T3S1	gang disc harrowing post subsoiling
T3S2	gang disc harrowing pre-subsoiling
T4S0	rigid tine harrowing without subsoiling
T4S1	rigid tine harrowing post subsoiling
T4S2	rigid tine harrowing pre-subsoiling
T5S0	rotary harrowing without subsoiling
T5S1	rotary harrowing post subsoiling
T5S2	rotary harrowing pre-subsoiling
S0	No subsoiling
S1	Subsoiling pre-cultivations of mouldboard ploughing, disc ploughing, gang disc harrowing, rigid tine harrowing and rotary harrowing.
S2	Subsoiling post cultivations of mouldboard ploughing, disc ploughing, gang disc harrowing, rigid tine harrowing and rotary harrowing.

Table 6. 2 Equipment configurations for the six treatments used in this study

Treatment number	Treatment name	No. of bodies	Working width (m)	Working depth (mm)
1	Subsoiler plough (MARK ALCOCK)	3 shanks (V shaped)	3	600
2	Mouldboard plough (KVERNELAND)	3 bodies (general body)	0.9 – 1.65 (reversible)	150 – 300
3	Disc plough (HOSKING EQUIPMENT)	2 discs (diameter 52 cm)	0.6 – 1	250 – 300
4	Gang disc harrow (PARMITER)		3.5 – 5	100 – 150
5	Rigid tine harrow (PARMITER)	15 leg (tines with points)	3.6	100 – 200
6	Rotary harrow (CULTIROTOR EL)	24 blades	1.2	150

6.1.4.2. Treatment preparations

Eighteen treatments were investigated in the field. The dimensions of the complete experiment were 111m X 61m, the dimensions of one main plot were (6m X 8m) and 5 m was left as a distance between the treatments. One block is represented in figure 6.1



T5S1	T5S0	T5S2	5 m	S1	S0	S2
5 m						
T3S1	T3S0	T3S2		T4S1	T4S0	T4S2
5 m						
T1S1	T1S0	T1S2	5 m	T2S1	T2S0	T2S2

Block dimensions
Width: 53 m
Length: 28 m

Plot dimensions
Width: 8 m
Length: 6 m

Figure 6. 1 Treatment distribution and plot dimensions for an individual block. See the abbreviation in Table 6.1

Methodology: Initially, the subsoiling for the subsoiling with no cultivation and the pre-cultivation treatment (depth of 450 mm, named S1) was completed along the length of the field (61 m), whereas the subsoiling after cultivating treatment (depth of 450 mm, named S2) was introduced after other cultivations were done. This was repeated for all four blocks. The mouldboard plough (T1), disc plough (T2), gang disc (T3), rigid tine (T4) and rotary harrow (T5) were done perpendicular to the subsoil lines. The plots where there was no subsoiling (named S0) represented the control area.

The irrigator track was positioned to run between block 1 & 2 and also blocks 3 & 4, appendix 2c. The width of the irrigator track was 2m. The plots were positioned such that the boom sprinkler system was directly over the plots. The boom travel speed was 0.97 m min^{-1}. Irrigation application amounts were determined by the application rates and system travel speed. To measure the depth of irrigation, one volumetric gage was placed near each block.

Rainfall and other climatic data for the experiment was taken from the HAU weather station, approximately 650m from the experiment, table 6.3.

Table 6. 3 Climatic data summary for the experimental period (Weather Station, Harper Adams University. Newport, Shropshire, UK. 2014).

Time	Wind Speed m/s	Max Temp ºC	Min Temp ºC	10cm Soil temp ºC	20cm Soil temp ºC	100cm Soil temp ºC	Related humidity %	Precipitation mm
June/July 2014	1.7	22	11.25	17.5	17.9	16.5	78.4	3.7

6.1.4.3 Measurement of crop residue

Crop residue was measured by collecting all material from within a 1m^2 quadrat; and soil moisture was determined by TDR at the same time to a depth of 100 and 200 mm. Crop residue values were taken after ploughing for all treatments and before soil physical measurements.

6.1.5. Statistical analysis

The experiment was arranged in a randomized complete block design (RCBD) with four replicates. The recorded data was analysed using either factorial or with repeated measures factorial ANOVA using Genstat 16th Edition, VSN International. All differences considered significant at $P \leq 0.05$.

6.1.6. Results

Table 6.4 shows crop residue (kg/m^2) for each plot/treatment, and soil moisture content (%) at depths of 100 mm and 200 mm before and after irrigation, (July2014 and August 2014. It could be noted that soil moisture content for most cultivation treatments was higher after irrigation than before irrigation at a depth of 200 mm. However, soil moisture content decreased at this depth with soil harrowing by gang disc harrow and rigid tine harrow without subsoiling. It was 17.58% and 11.62% before irrigation, and 10.4% and 11.5% after irrigation for gang disc harrowing without subsoiling and rigid tine harrowing without subsoiling respectively.

Table 6. 4 Crop residue (kg/m^2) and soil moisture content (%) for different depths before and after irrigation

Treatment	crop residue kg/m^2	soil moisture content vwc % before irrigation		soil moisture content vwc % after irrigation	
		Depth100 mm	Depth200 mm	Depth100 mm	Depth200 mm
T1S0	0.185	5.95	6.18	7.6	15.9
T1S1	0.155	6.72	6.95	6.5	13.7
T1S2	0.2225	6.55	9.00	7.3	15.9
T2S0	0.2825	3.80	7.22	6.5	13.4
T2S1	0.35	4.87	8.37	10.1	17.9
T2S2	0.2575	6.68	10.65	6.2	14.5
T3S0	0.3575	14.65	17.58	4.8	10.4
T3S1	0.365	6.75	10.33	4.8	12.3
T3S2	0.42	9.53	14.13	6.5	11.5
T4S0	0.6075	6.37	11.62	6.8	9.5
T4S1	0.3525	7.30	9.62	9.8	16.8
T4S2	0.3325	7.00	11.58	6.5	14.8
T5S0	0.3125	5.32	9.13	7.6	13.7
T5S1	0.3775	4.62	5.98	10.4	16.5
T5S2	0.305	8.20	10.15	9.5	16.8
S0	0.545	13.23	18.58	12	14.3
S1	0.3575	12.53	12.93	6.2	19.5
S2	0.31	8.43	9.98	9.3	13.2

6.1.6.1. Effect of cultivation/subsoiler treatments on soil infiltration rate (mm/hr-1) before irrigation

There were no significant effects of the mean values for the subsoiler treatments, *P* = 0.433. There were significant main cultivator effects, *P* = 0.003, whereby the rigid tine cultivator achieved mean infiltration rates of 101.1 mm/hr^{-1}, which was significantly greater than the mean for the mouldboard plough at 48.2 mm/hr^{-1} and the rotary harrow at 70.8 mm/hr^{-1}.

There were significant interactions between treatments, *P* = 0.003. The rigid tine cultivator with subsoiler post cultivation achieved the greatest infiltration rate of 120.7 mm/hr^{-1} which was significantly greater than the rotary harrow (60.7 mm/hr^{-1}) and mouldboard plough (42 mm/hr^{-1}) with subsoiler post cultivation, table 6.5.

In individual treatment combinations, the use of a subsoiler did not significantly affect the infiltration of the mouldboard plough, disc plough, gang discs, rigid tine or rotary harrow but subsoiling with no additional cultivation produced significantly greater infiltration than where no subsoiler was used.

Table 6.5 shows infiltration rate values under the influence of subsoil cultivation before irrigation. There were significant differences between the interaction of the treatments after irrigation (*P* =0.002). Subsoiling (S1) resulted in infiltration rates of 84.4 ml / hr compared to the control treatment without subsoiling (S0) which gave 61.6ml / hr. The data in table 6.4 suggests that subsoiling post cultivation significantly reduces the infiltration rate of the soil after the irrigation application. In contrast, the infiltration rate with subsoiling pre-cultivation appears to be unaffected by the irrigation application.

Table 6. 5 Effect of subsoiler and cultivation treatments on the mean infiltration rate (mm/hr) before irrigation

Means: infiltration rate mm/hr before irrigation				Cultivation*Subsoiling		
Subsoiler treatment Main Cultivation Treatment	S0 No subsoiler	S1 Subsoil pre-cultivation	S2 Subsoil post cultivation	*P* =	S.E.D	cv %
Mouldboard plough	69.7	33	42	0.003	21.67	33.6
Disc plough	82.7	103.7	92			
Gang discs	80.7	77.3	83			
Rigid tine	99.3	83.3	120.7			
Rotary harrow	93	58.7	60.7			
No cultivation	17	113	113			
Means of subsoiler effects for main cultivation types	Mouldboard plough	48.2		0.003	12.51	
	Disc plough	93.1				
	Gang discs	80.3				
	Rigid tine	101.1				
	Rotary harrow	70.8				
	No cultivation	81				
Means of main cultivators for each subsoiler	No subsoiler	73.7		0.433	8.85	
	Subsoil pre-cultivation	78.3				
	Subsoil post cultivation	85.2				

There were significant differences between the main treatments (means of all subsoil treatments for each type of cultivator) before irrigation; the highest value for infiltration when using rigid tine harrow = 101.1 ml / hr and lower values when using the mouldboard = 48.2ml / hr, table 6.4. In terms of effect of interaction between the different tillage systems with the subsoiler on the infiltration rate, the results confirmed the presence of significant differences between the treatments before irrigation. It can be noted from table 6.5 that the highest value for infiltration was when using rigid tine before subsoiling = 120.67 ml / hr compared to the control treatment S0 = 17.00ml / hr. Generally, values were lower after irrigation than before irrigation.

6.1.6.2. Effect of cultivation/subsoiler treatments on soil infiltration rate (mm/hr-1) after irrigation

There were no significant main treatment effects, *P* = 0.142. There was a significant effect of the mean of the subsoiler treatments, *P* = 0.002, whereby the subsoiling before cultivation produced significantly greater infiltration than both the no subsoiler and subsoiler post cultivation. There were significant interactions, *P* = 0.014. The main cultivation effects showed only significant effects of the subsoiler for the gang discs, where subsoiler before cultivation gave significantly greater infiltration than subsoiler post cultivation. Not unexpectedly, the subsoiling also significantly increased infiltration rate in the no cultivation treatment, table 6.6. The highest value of infiltration rate after irrigation when using the mouldboard plough after subsoiling = 93.33ml / hr compared to the control treatment S0 = 19.00ml / hr.

The greatest infiltration rate was recorded in the mouldboard plough treatment with subsoiling before ploughing. This was statistically greater than with gang discs with no subsoiler or with subsoiler post disking, rigid tine with subsoiler post cultivation and with no subsoiler or cultivation treatments. This suggests that after irrigation the mouldboard plough, with subsoiling before ploughing, gives the best infiltration and therefore should least runoff from irrigation. Tables 6.6 show infiltration rate values under the influence of subsoil cultivation after irrigation.

With respect to the effect of the irrigation on infiltration rate pre-and post-irrigation, although the rigid tine produced the greatest infiltration on soil pre-irrigation, the irrigation of the soil substantially changed its infiltration from 120 mm/hr^{-1} down to only 48 mm/hr^{-1}. Whereas the infiltration rate of the mouldboard plough improved substantially after irrigation, from only 33 mm/hr^{-1} to 93 mm/hr^{-1}, tables 6.5 and 6.6. However, the combined results were not analysed before and after irrigation.

Table 6. 6 Effect of subsoiler and cultivation treatments on the mean infiltration rate (mm/hr) after irrigation

Means: infiltration rate mm/hr after irrigation				Cultivation*Subsoiling		
Cultivation treatment	S0 No subsoiler	S1 Subsoil pre-cultivation	S2 Subsoil post cultivation	*P* =	S.E.D	cv %
Mouldboard plough	86.0	93.3	66.7	0.014	16.41	28.7
Disc plough	62.7	83.3	76.0			
Gang discs	58.0	86.3	33.0			
Rigid tine	74.7	73.0	48.0			
Rotary harrow	69.3	87.7	74.7			
No cultivation	19.0	85.3	85.3			
Means cultivation effect	Mouldboard plough	82.0		0.142	9.47	
	Disc plough	74.0				
	Gang discs	59.1				
	Rigid tine	65.2				
	Rotary harrow	77.2				
	No cultivation	63.2				
Means subsoiler effect	No subsoiler	61.6		0.002	6.7	
	Subsoil pre-cultivation	84.8				
	Subsoil post cultivation	63.9				

Correlation analysis was used to determine if a relationship existed between the infiltration rate before and after irrigation, Figure 6.2. There was only a weak linear relationship and only a slightly better weak/modest correlation found with a second order polynomial expression. With only 15% of the variation in the post irrigation infiltration rate being explained by the pre-irrigation infiltration rate, there is no real relationship between the two variables. Consequently, the pre-irrigation measurement couldn't be used to predict post irrigation infiltration.

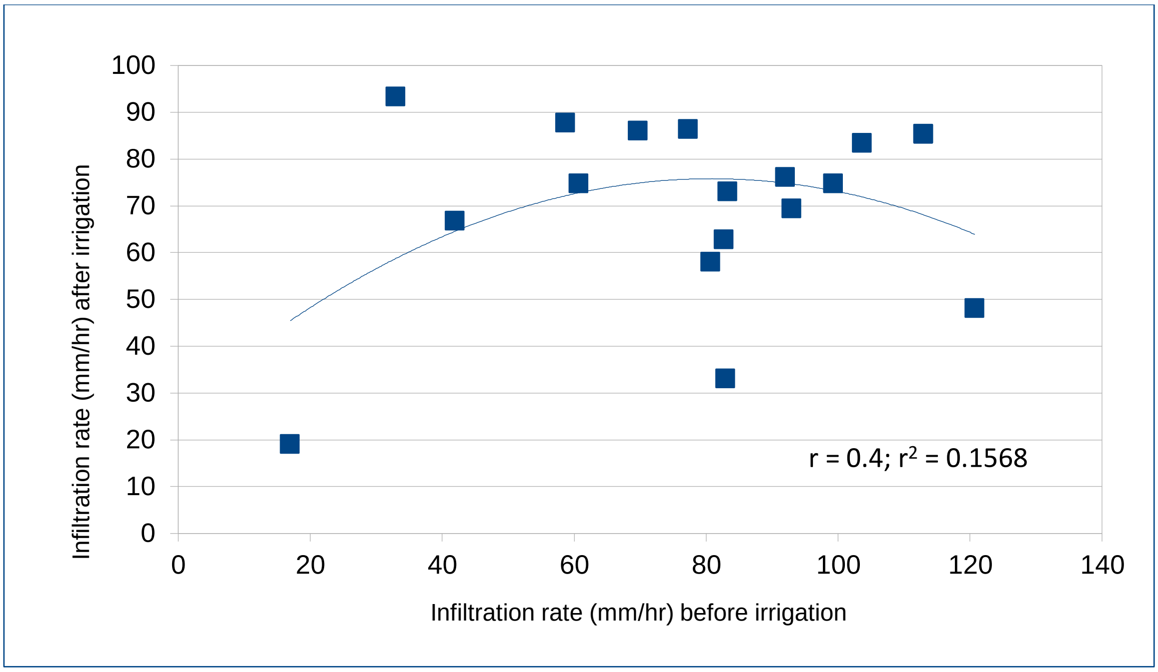


Figure 6. 2 Second order polynomial relationship between infiltration rate before and after irrigation (equation)

6.1.6.3. Effect of cultivation/subsoiler treatments on soil shear strength (KPa) at three depths before irrigation

The greatest soil shear strength of the experiment was seen in the gang disc treatment. There were no significant interactions between subsoiler and depth of the test because all values increased with depth irrespective of the 'no subsoiler' or subsoiler pre-or post-cultivation. Table 6.7 shows soil shear strength values (kPa) under the influence of subsoiler and cultivation treatments at different depths before irrigation.

There were significant interactions for the cultivation and depth of tests but with the exception of the 'no cultivation' main treatment all values increased as depth increased. The 'no cultivation' treatment however showed similar values at 0-10cm of 848 kPa and the 20-30cm value of 850 kPa, whereas the 10-20cm value was significantly lower at only 709 kPa. This suggests that whereas all other cultivation treatments had reduced the shear strength of the 0-10cm layer the upper soil layer in the 'no cultivation' treatment remained largely undisturbed and quite dense. In contrast, the rotary harrow treatment greatly reduced the soil strength at 0-10cm but then increased it to 269 kPa at 10-20cm and then a substantial increase to 674 kPa was seen at 20-30cm. This is not unexpected as the rotary harrow completely destroys soil structure to its working depth of 150mm in this experiment. These results were also similar for the rigid tine and gang disc which also operated at that depth. The disc plough gave the lowest shear strength values at all depths and the mouldboard plough at 0-10 and 10-20cm. The mouldboard plough did increase the shear strength substantially at 20-30cm between the 10-20 and 20-30cm depth, going from 149 kPa to 519 kPa. This would again not be unexpected due to the known compressive effect of the mouldboard plough below the cultivated layer.

The effect of the subsoiler on the main treatments was also significant, $P < 0.001$. Soil shear strength was considerably greater where no subsoiler or cultivation was used (1687 kPa) but was significantly reduced with the use of the subsoiler for both pre-and post-cultivations, table 6.7.

The mouldboard plough showed significantly increased shear strength when subsoiled post cultivation which is in line with the action of the subsoiler which would remove any soil compression resulting from the plough operation.

There were significant overall interactions, $P < 0.001$, but for the ‘no subsoiler’ treatment and post cultivation subsoiler, the trend was generally towards low shear strength values, table 6.7.

Table 6. 7 Effect of subsoiler and cultivation treatments on shear strength (kPa) at different depths before irrigation

Means: soil shear strength kPa before irrigation										Cultivation*Subsoiling*depth		
Cultivation treatment	**S0** **No subsoiler**			**S1** **Subsoil pre-cultivation**			**S2** **Subsoil post cultivation**			***P* =**	**S.E.D**	**cv %**
Depth cm	**10**	**20**	**30**	**10**	**20**	**30**	**10**	**20**	**30**	**<.001**	**121.0**	**35.9**
Mouldboard plough	**116**	**184**	**595**	**94**	**122**	**229**	**122**	**209**	**732**			
Disc plough	**104**	**162**	**270**	**102**	**124**	**264**	**151**	**235**	**345**			
Gang discs	**1007**	**1342**	**1239**	**303**	**487**	**531**	**253**	**550**	**814**			
Rigid tine	**428**	**871**	**1149**	**176**	**172**	**772**	**200**	**324**	**573**			
Rotary harrow	**88**	**448**	**1025**	**70**	**134**	**463**	**161**	**225**	**536**			
No cultivation	**1972**	**1521**	**1569**	**349**	**399**	**564**	**223**	**208**	**418**			

Means cultivation effect	**Mouldboard plough**	**267.3**	**<.001**	**40.3**
	Disc plough	**195.3**		
	Gang discs	**725.0**		
	Rigid tine	**518.3**		
	Rotary harrow	**349.6**		
	No cultivation	**802.3**		

Means subsoiler effect	**No subsoiler**	**782.7**	**<.001**	**28.5**
	Subsoil pre-cultivation	**297.7**		
	Subsoil post cultivation	**349.0**		

Means cultivation* subsoiler effect	**Cultivation**	**No subsoiler**	**Subsoil pre-cultivation**	**Subsoil post cultivation**	**<.001**	**69.8**
	Mouldboard plough	**299.0**	**149**	**354**		
	Disc plough	**179**	**163**	**243**		
	Gang discs	**1196**	**440**	**539**		
	Rigid tine	**816**	**374**	**366**		
	Rotary harrow	**520**	**222**	**307**		
	No cultivation	**1687**	**437**	**283**		

Means Depth	**0-10**	**10-20**	**20-30**	**<.001**	**28.5**
	328.8	**428.8**	**671.3**		

Means Cultivation* Depth effect	**Cultivation**	**0-10**	**10-20**	**20-30**	**<.001**	**69.8**
	Mouldboard plough	**111.0**	**172.0**	**519.0**		
	Disc plough	**119.0**	**174.0**	**293.0**		
	Gang discs	**521.0**	**793.0**	**861.0**		
	Rigid tine	**268.0**	**456.0**	**831.0**		
	Rotary harrow	**106.0**	**269.0**	**674.0**		
	No cultivation	**848.0**	**709.0**	**850.0**		

Means Subsoiler* Depth effect		**0-10**	**10-20**	**20-30**	**0.608**	**49.4**
	No subsoiler	**619.0**	**755.0**	**947.0**		
	Subsoil pre-cultivation	**183.0**	**240.0**	**470.0**		
	Subsoil post cultivation	**185.0**	**292.0**	**570.0**		

6.1.6.4 Effect of cultivation/subsoiler treatments on soil shear strength (KPa) at three depths after irrigation

After irrigation, there were no significant differences for subsoiler means and depth (*P*=0.989), cultivation means and depth (*P*=0.112) or all interactions (*P*=0.066).

Table 6.8. shows soil shear strength values (kPa) under the influence of subsoiler and cultivation treatments at different depths after irrigation.

There were significant differences/interactions between cultivation type and subsoiler treatments (*P*<0.001). All disc plough effects were similar irrespective of subsoiler use. Gang discs showed significantly greater values where no subsoiler was used or when subsoiling was carried out post cultivation. This again supports the beneficial effects of subsoiling before cultivation to avoid compression effects of the cultivation operation. This indicates that the values of soil shear strength are increased when subsoiling post cultivation.

Rigid tine was significantly improved by subsoiling prior to cultivation whereas subsoiling at this point before the mouldboard plough was detrimental to shear strength.

Overall, particularly post irrigation, there is a definite shear strength effect by the combination of pre-or post-subsoiling and the main cultivation type.

For the main cultivation effect means of the three subsoiler timings the gang disc, rigid tine and no cultivation all produced the greatest shear strength values which could indicate increased soil density and thus greater potential for runoff. The rotary harrow and mouldboard plough provided the lowest shear strength values which may be beneficial for water infiltration, but which may also then easily seal the soil surface and create runoff.

Table 6. 8 Effect of subsoiler and cultivation treatments on shear strength (kPa) at different depths after irrigation

Means: soil shear strength kPa after irrigation										**Cultivation*Subsoiling*depth**		
Cultivation treatment	**S0 No subsoiler**			**S1 Subsoil pre-cultivation**			**S2 Subsoil post cultivation**			***P* =**	**S.E.D**	**cv %**
Depth cm	**10**	**20**	**30**	**10**	**20**	**30**	**10**	**20**	**30**	**0.066**	**111.0**	**38.8**
Mouldboard plough	**130**	**152**	**297**	**164**	**412**	**552**	**194**	**230**	**334**			
Disc plough	**212**	**341**	**440**	**341**	**339**	**433**	**137**	**395**	**644**			
Gang discs	**654**	**1047**	**1128**	**182**	**620**	**740**	**135**	**165**	**313**			
Rigid tine	**381**	**641**	**706**	**153**	**270**	**588**	**151**	**626**	**738**			
Rotary harrow	**83**	**200**	**315**	**140**	**315**	**366**	**147**	**221**	**297**			
No cultivation	**663**	**814**	**1127**	**267**	**356**	**550**	**243**	**309**	**468**			

Means cultivation effect	**Mouldboard plough**	**274**	**<.001**	**37.0**
	Disc plough	**365**		
	Gang discs	**554**		
	Rigid tine	**473**		
	Rotary harrow	**232**		
	No cultivation	**533**		

Means subsoiler effect	**No subsoiler**	**518**	**<.001**	**26.2**
	Subsoil pre-cultivation	**377**		
	Subsoil post cultivation	**319**		

	Cultivation	**No subsoiler**	**Subsoil pre-cultivation**	**Subsoil post cultivation**		
Means cultivation* subsoiler effect	**Mouldboard plough**	**193**	**376**	**253**	**<.001**	**64.1**
	Disc plough	**331**	**371**	**392**		
	Gang discs	**943**	**514**	**204**		
	Rigid tine	**576**	**337**	**505**		
	Rotary harrow	**199**	**274**	**221**		
	No cultivation	**868**	**391**	**340**		

Means Depth	**0-10**	**10-20**	**20-30**	**<.001**	**26.2**
	243.3	**413.6**	**557.6**		

	Cultivation	**0-10**	**10-20**	**20-30**		
Means Cultivation* Depth effect	**Mouldboard plough**	**163**	**265**	**394**	**0.112**	**64.1**
	Disc plough	**230**	**358**	**506**		
	Gang discs	**324**	**611**	**727**		
	Rigid tine	**228**	**512**	**677**		
	Rotary harrow	**123**	**245**	**326**		
	No cultivation	**391**	**493**	**715**		

		0-10	**10-20**	**20-30**		
Means Subsoiler* Depth effect	**No subsoiler**	**354**	**532**	**669**	**0.989**	**45.3**
	Subsoil pre-cultivation	**208**	**385**	**538**		
	Subsoil post cultivation	**168**	**324**	**466**		

It can be seen through the table 6.8 that soil shear strength values have decreased after irrigation except for the treatment of tillage by mouldboard and disc plough. The values were 267 and 195 kPa before irrigation and 274 and 365 kPa after irrigation respectively. Unfortunately, it couldn’t be analysed the results before and after irrigation together.

Soil shear strength for the disc plough after irrigation were higher than before irrigation with or without subsoiling. The values before irrigation were 179 without subsoiling, and 163 and 243 kPa for post- and pre-subsoiling respectively. While 331, 371 and 392 kPa after irrigation respectively. It is worth noting that the subsoiler was used without roller and as described in table 6.2.

There were significant differences between soil shear strength values depending on the depth of tillage before and after irrigation. It can be noted from tables 6.7 and 6.8 that the greater the depth, the greater the soil shear strength values. The results also showed that the values after irrigation were less than before irrigation for all depths. However, there were no significant differences of means to the interaction between subsoiling and tillage with depths on soil shear strength after irrigation particularly.

Results show the existence of significant differences in the values of soil shear strength under the effect of interaction between subsoiling and different tillage regimes and tillage depths. There was a significant increase in the values when increasing the depth of tillage for all treatments. Likewise, values increased for all treatment with different tillage regimes without subsoiling.

The soil shear strength values were lower for subsoiling before cultivation, compared to after cultivation, except using gang disc harrow after subsoiling at a depth of 100 mm as well as rigid tine harrow but at a depth of 300 mm.

As for soil shear strength after irrigation, under the effect of interaction between subsoiling and different tillage regimes and tillage depths, there were non-significant values (See tables 6.7 and 6.8).

To determine if a relationship existed between the soil shear strength before irrigation and the soil shear strength post irrigation correlation analysis was used, figure 6.3. There was a very strong positive relationship expressed whereby high shear strength pre-irrigation resulted with lower but commensurate soil shear strength values post irrigation, $r = 0.81$. This suggests that where the cultivation pre-irrigation results in high or low shear strength values these will be merely reduced by irrigation. The r^2 value of 0.649 shows that 65% of the variation in shear values post irrigation can be explained by the shear strength values pre-irrigation. Consequently, it may not be necessary to irrigate cultivated soils to determine the effect of irrigation on their soil shear strength.

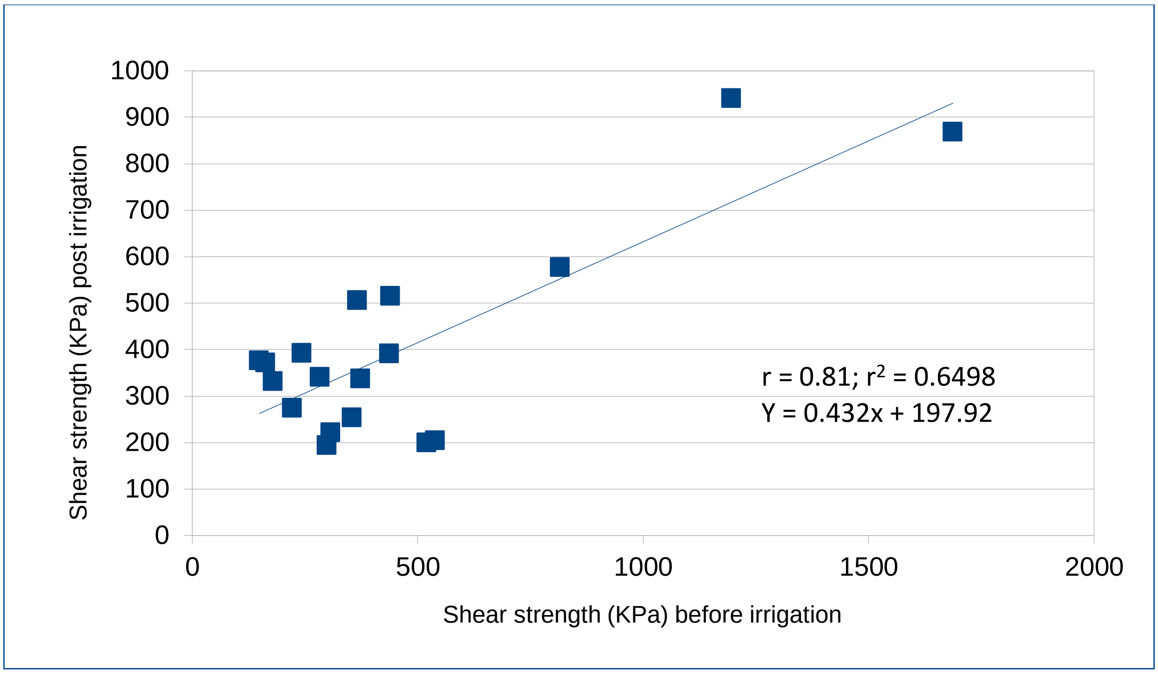


Figure 6. 3 Linear relationship between shear strength before and after irrigation

The correlation in figure 6.3. investigates if a linear relationship exists between the soil shear strength pre-irrigation (post cultivation) and post irrigation and can it be used to predict the soil shear strength post irrigation should the need arise. If the relationship did exist there would be no requirement to test soil shear strength both before and after irrigation and judgement can be made without the need for irrigation within the experiment. This would then reduce the time and cost of the investigation, would allow investigators to make these comparisons in non-irrigated situations and could also be used to suggest the potential for run-off in rain-fed rather than irrigated situation. The correlation coefficient of r = 0.81 is classed as a 'very strong positive' correlation, whereby a high soil strength before irrigation leads to a high soil strength post irrigation under these experimental conditions and treatments. The r^2 of 0.6498 (coefficient of determination), shows that 64% of the variation in post irrigation shear strength can be accounted for by variation in the pre-irrigation soil strength and therefore only 36% of the variation is due to other factors.

6.1.6.5. Effect of cultivation/subsoiler treatments on soil penetration resistance (KPa) at three depths before irrigation

All treatment combinations and analysis showed significant effects, as shown in table 6.9. There were significant subsoiler depth effects, *P*=0.025, with the greatest penetration resistance in the ‘no subsoiler’ treatment. The means of all subsoiler treatments showed increasing resistance with depth.

The means of the main cultivation treatments and depth also showed significant differences, *P*= 0.019. The rotary harrow and both plough types having the lowest penetration resistance in the top 100, 200 and 300 mm. whereas all cultivation treatments had less resistance than none cultivated at 400 mm.

The means of the main treatments and subsoiler interactions showed the reduced resistance with depth for the mouldboard plough, which corresponds to the shear strength values. For all but the disc plough subsoiler either pre-or post-cultivations resulted with lower resistance than where no subsoiler was used. For the disc plough although the pre-cultivation subsoiler resistance was greater (101.1 kPa) than with no subsoiler (88.9kPa) the difference was not statistically significant.

For the mean subsoiler effects the pre-and post-subsoiler means were similar and both had significantly lower, *P*<0.001, resistance than where no subsoiler was used.

For the mean cultivation effects, there was no difference between the penetration resistance between the Mouldboard, disc plough and rotary harrow which were all significantly lower than the resistance for gang discs, rigid tine or no cultivation.

Where the means of all combinations were compared there were significant differences, *P*<0.001.

Table 6. 9 Effect of subsoiler and cultivation treatments on soil penetration resistance (kPa) at different depths before irrigation

Means: soil penetration resistance kPa before irrigation													**Cultivation* Subsoiling* Depth**		
Cultivation treatment	**S0** **No subsoiler**				**S1** **Subsoil pre-cultivation**				**S2** **Subsoil post cultivation**				***P* =**	**S.E.D**	**cv %**
Depth cm	**10**	**20**	**30**	**40**	**10**	**20**	**30**	**40**	**10**	**20**	**30**	**40**	**0.01**	**17.71**	**24.9**
Mouldboard plough	**42.9**	**67.4**	**128.7**	**183.9**	**30.6**	**67.4**	**79.7**	**134.8**	**42.9**	**55.2**	**79.7**	**85.8**			
Disc plough	**36.8**	**79.7**	**85.8**	**153.2**	**30.6**	**55.2**	**128.7**	**190.0**	**49.0**	**55.2**	**55.2**	**116.5**			
Gang discs	**79.7**	**153.2**	**159.4**	**196.1**	**49.0**	**85.8**	**85.8**	**141.0**	**61.3**	**98.1**	**122.6**	**128.7**			
Rigid tine	**67.4**	**110.3**	**128.7**	**202.3**	**42.9**	**67.4**	**104.2**	**128.7**	**49.0**	**98.1**	**122.6**	**141.0**			
Rotary harrow	**42.9**	**79.7**	**91.9**	**159.4**	**24.5**	**67.4**	**79.7**	**147.1**	**24.5**	**79.7**	**85.8**	**165.5**			
No cultivation	**104.2**	**171.6**	**165.5**	**226.8**	**61.3**	**91.9**	**110.3**	**202.3**	**49.0**	**85.8**	**98.1**	**183.9**			

Means Cultivation effect	**Mouldboard plough**	**83.3**	**<.001**	**5.11**
	Disc plough	**86.3**		
	Gang discs	**113.4**		
	Rigid tine	**105.2**		
	Rotary harrow	**87.3**		
	No cultivation	**129.2**		

Means Subsoiler effect	**No subsoiler**	**121.6**	**<.001**	**3.62**
	Subsoil pre-cultivation	**91.9**		
	Subsoil post cultivation	**88.9**		

Means Cultivation* Subsoiler effect	**Cultivation**	**No subsoiler**	**Subsoil pre-cultivation**	**Subsoil post cultivation**	**<.001**	**8.86**
	Mouldboard plough	**105.7**	**78.1**	**65.9**		
	Disc plough	**88.9**	**101.1**	**69.0**		
	Gang discs	**147.1**	**90.4**	**102.7**		
	Rigid tine	**127.2**	**85.8**	**102.7**		
	Rotary harrow	**93.5**	**79.7**	**88.9**		
	No cultivation	**167.0**	**116.5**	**104.2**		

Means Depth	**0-10**	**10-20**	**20-30**	**30-40**	**<.001**	**4.17**
	49.4	**87.2**	**106.2**	**160.4**		

Means Cultivation* Depth effect	**Cultivation**	**0-10**	**10-20**	**20-30**	**30-40**	**0.019**	**10.23**
	Mouldboard plough	**38.8**	**63.3**	**96.0**	**134.8**		
	Disc plough	**38.8**	**63.3**	**89.9**	**153.2**		
	Gang discs	**63.3**	**112.4**	**122.6**	**155.3**		
	Rigid tine	**53.1**	**91.9**	**118.5**	**157.3**		
	Rotary harrow	**30.6**	**75.6**	**85.8**	**157.3**		
	No cultivation	**71.5**	**116.5**	**124.6**	**204.3**		

Means Subsoiler* Depth effect		**0-10**	**10-20**	**20-30**	**30-40**	**0.025**	**7.23**
	No subsoiler	**62.3**	**110.3**	**126.7**	**186.9**		
	Subsoil pre-cultivation	**39.8**	**72.5**	**98.1**	**157.3**		
	Subsoil post cultivation	**46.0**	**78.7**	**94.0**	**136.9**		

6.1.6.6 Effect of cultivation/subsoiler treatments on soil penetration resistance (KPa) at three depths after irrigation

Post irrigation all treatments and interactions showed significant differences, as shown in table 6.10. Both the subsoiler means and the cultivation depth means indicated that all penetration values increased with depth. There were significant greater values where no subsoiler or no cultivation was used, *P*<0.001, except at the 300-400 mm depth.

The cultivation subsoiler interaction showed that the depth of operation significantly affected soil penetration resistance. The rotary harrow, gang discs and rigid tine all benefited from subsoiling pre-cultivation whereas the disc plough benefitted more from subsoiling post cultivation. This was emphasised by the means of the subsoiler treatment where subsoil pre-cultivation was significantly lower penetration resistance (116.5 kPa) than subsoiling post cultivation (123.1 kPa). Both were significantly better than the no subsoiler penetration resistance (155.8 kPa).

With the main cultivation means the no cultivation gave the greatest penetration resistance value of 176.2 kPa, which was significantly greater than any of the cultivation treatments. The penetration resistance for the mouldboard plough (98.6 kPa) was significantly lower than all other treatments, *P*<0.001.

There were significant interactions between all treatment combinations, *P*<0.001, table 6.10. The rotary harrow generally produced the lowest penetration resistance at 10cm where no subsoiler was used but once the subsoiler was implemented all other cultivation treatments reduced the penetration resistance in the 0-300 mm zone.

Table 6. 10 Effect of subsoiler and cultivation treatments on soil penetration resistance (kPa) at different depths after irrigation

Means: soil penetration resistance kPa after irrigation													Cultivation* Subsoiling* Depth		
Cultivation treatment	**S0 No subsoiler**				**S1 Subsoil pre-cultivation**				**S2 Subsoil post cultivation**				***P =***	**S.E.D**	**cv %**
Depth cm	**10**	**20**	**30**	**40**	**10**	**20**	**30**	**40**	**10**	**20**	**30**	**40**			**15.9**
Mouldboard plough	**98.1**	**91.9**	**141.0**	**183.9**	**42.9**	**79.7**	**104.2**	**110.3**	**67.4**	**79.7**	**73.5**	**110.3**	**<.001**	**14.78**	
Disc plough	**79.7**	**79.7**	**110.3**	**165.5**	**61.3**	**91.9**	**153.2**	**183.9**	**49.0**	**73.5**	**98.1**	**147.1**			
Gang discs	**122.6**	**147.1**	**177.7**	**239.0**	**30.6**	**110.3**	**153.2**	**214.5**	**98.1**	**122.6**	**159.4**	**220.6**			
Rigid tine	**134.8**	**196.1**	**208.4**	**269.7**	**49.0**	**134.8**	**79.7**	**122.6**	**73.5**	**91.9**	**122.6**	**202.3**			
Rotary harrow	**49.0**	**91.9**	**122.6**	**196.1**	**30.6**	**85.8**	**122.6**	**190.0**	**67.4**	**134.8**	**98.1**	**226.8**			
No cultivation	**171.6**	**183.9**	**208.4**	**269.7**	**116.5**	**147.1**	**171.6**	**208.4**	**116.5**	**147.1**	**171.6**	**202.3**			

Means Cultivation effect	**Mouldboard plough**	**98.6**	**<.001**	**4.27**
	Disc plough	**107.8**		
	Gang discs	**149.7**		
	Rigid tine	**140.5**		
	Rotary harrow	**118.0**		
	No cultivation	**176.2**		

Means Subsoiler effect	**No subsoiler**	**155.8**	**<.001**	**3.48**
	Subsoil pre-cultivation	**116.5**		
	Subsoil post cultivation	**123.1**		

Means Cultivation* Subsoiler effect	**Cultivation**	**No subsoiler**	**Subsoil pre-cultivation**	**Subsoil post cultivation**	**<.001**	**7.39**
	Mouldboard plough	**128.7**	**84.3**	**82.7**		
	Disc plough	**108.8**	**122.6**	**91.9**		
	Gang discs	**171.6**	**127.2**	**150.2**		
	Rigid tine	**202.3**	**96.5**	**122.6**		
	Rotary harrow	**114.9**	**107.3**	**131.8**		
	No cultivation	**208.4**	**160.9**	**159.4**		

Means Depth	**0-10**	**10-20**	**20-30**	**30-40**	**<.001**	**3.48**
	81.0	**116.1**	**137.6**	**192.4**		

Means Cultivation* Depth effect	**Cultivation**	**0-10**	**10-20**	**20-30**	**30-40**	**<.001**
	Mouldboard plough	**69.5**	**83.8**	**106.2**	**134.8**	**8.53**
	Disc plough	**63.3**	**81.7**	**120.5**	**165.5**	
	Gang discs	**83.8**	**126.7**	**163.4**	**224.7**	
	Rigid tine	**85.8**	**141.0**	**136.9**	**198.2**	
	Rotary harrow	**49.0**	**104.2**	**114.4**	**204.3**	
	No cultivation	**134.8**	**159.4**	**183.9**	**226.8**	

Means Subsoiler* Depth effect		**0-10**	**10-20**	**20-30**	**30-40**	**<.001**	**6.03**
	No subsoiler	**109.3**	**131.8**	**161.4**	**220.6**		
	Subsoil pre-cultivation	**55.2**	**108.3**	**130.8**	**171.6**		
	Subsoil post cultivation	**78.7**	**108.3**	**120.5**	**184.9**		

For comparison of before and after irrigation, tables 6.9 and 6.10 show soil penetration resistance values under the influence of different tillage regimes. Soil penetration values were high by approximately 80% when soil was cultivated by either gang disc or rigid tine harrows. There were 113.4 and 105.2 kPa before irrigation, and 149.7 and 140.5 kPa after irrigation respectively. The lowest values were for mouldboard plough and disc plough before and after irrigation, which were 83.3 and 86.3 kPa, and 98.6 and 107.8 kPa respectively.

This is further demonstrated by correlation analysis, figure 6.4, which shows a very strong positive correlation, r = 0.88, between soil penetration resistance before and after irrigation.

This shows that as penetration resistance increases before irrigation a commensurate increase in penetration resistance will occur post irrigation. The r^2 values of 0.77 suggests that 77% of the variation in soil penetration resistance after irrigation can be explained by variation in penetration resistance after irrigation. As with the correlation for soil shear strength before and after irrigation the effect of irrigation on soil penetration resistance can be predicted post irrigation without the need for irrigation.

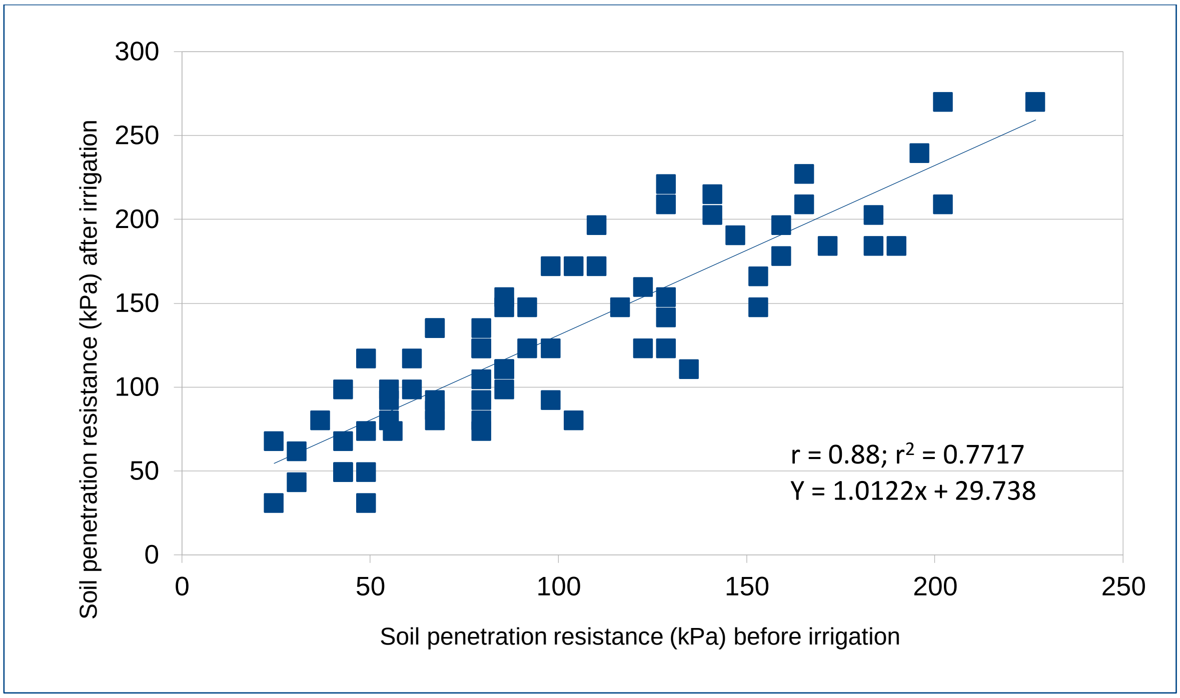


Figure 6. 4 Linear relationship between soil penetration resistance (kPa) before and after irrigation for the cultivation practices in the experiment

The correlation shown in figure 6.4 demonstrates are very strong positive linear relationship, r = 0.88, between soil penetration resistance pre-irrigation and soil penetration resistance post irrigation, whereby a high penetration resistance before irrigation will give a proportionally high penetration resistance post irrigation, and vice versa. This relationship is useful because investigators can predict how soil penetration resistance of similar cultivation treatments, in the absence of irrigation, will influence soil penetration in the presence of irrigation or rainfall. The r^2 of 0.77 shows that 77% of the variation of soil penetration resistance post-irrigation can be accounted for by the variation in soil penetration resistance pre-irrigation and that only 23% is due other factors.

There were significant differences between the treatments with or without subsoiling, especially without subsoiling. Soil penetration for the mouldboard plough before and after irrigation were the lowest values, post- and pre-subsoiling. The values before irrigation were 78.1 kPa post, and 65.9 kPa pre-subsoiling respectively; and 84.3, 82.7 kPa post and pre-subsoiling after irrigation respectively. Mean values after irrigation were higher when subsoiling after cultivation than pre-cultivation; however, soil penetration was less with disc plough when cultivation pre-subsoiling. It was 91.9 kPa when subsoiling post disc ploughing and 122.6 kPa when ploughing post subsoiling, (see table 6.10).

It can be noted that the greater the depth, the greater the soil penetration values. Comparing cultivation treatment with depths, penetration resistance values at a depth of 100 mm were 69.5 and 63.3 kPa for mouldboard and disc ploughs, and 83.8 and 85.8 kPa for gang disc and rigid tine harrows after irrigation respectively. Rotary harrowing recorded the lowest value 30.6 and 49.0 kPa at the same depth before and after irrigation, however, values have increased dramatically as the depth increases.

Further analysis investigated if relationships existed between soil shear strength and infiltration rate before irrigation, figure 6.5, and after irrigation, figure 6.6.

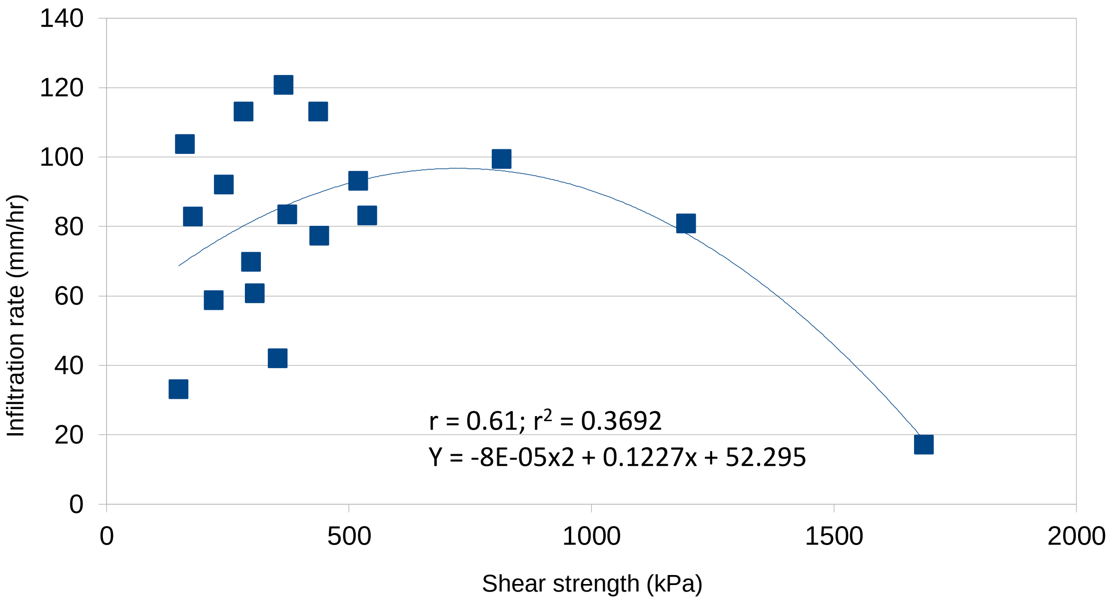


Figure 6. 5 Polynomial (2nd order) relationship between shear strength (before irrigation) and infiltration rate (before irrigation)

Only a weak linear correlation was found but there was a modest 2nd order polynomial correlation between soil shear strength and infiltration rate before irrigation, figure 6.5. The correlation coefficient suggests a modest, $r = 0.61$, relationship between the two variables. This suggests that as soil strength increases initially there is a commensurate increase of infiltration but as the soil strength increases further the infiltration rate then declines. This would be expected as when the soil strength increases the frictional forces increase as the soil pore spaces reduce. The r^2 of only 36% however suggests that there are other factors which may be more influential on infiltration rate than soil shear strength.

When this relationship is investigated post irrigation, figure 6.6, the r value decreases slightly to 0.56, still a modest correlation, and the percentage of variance in infiltration accounted for by the shear strength is only 31%.

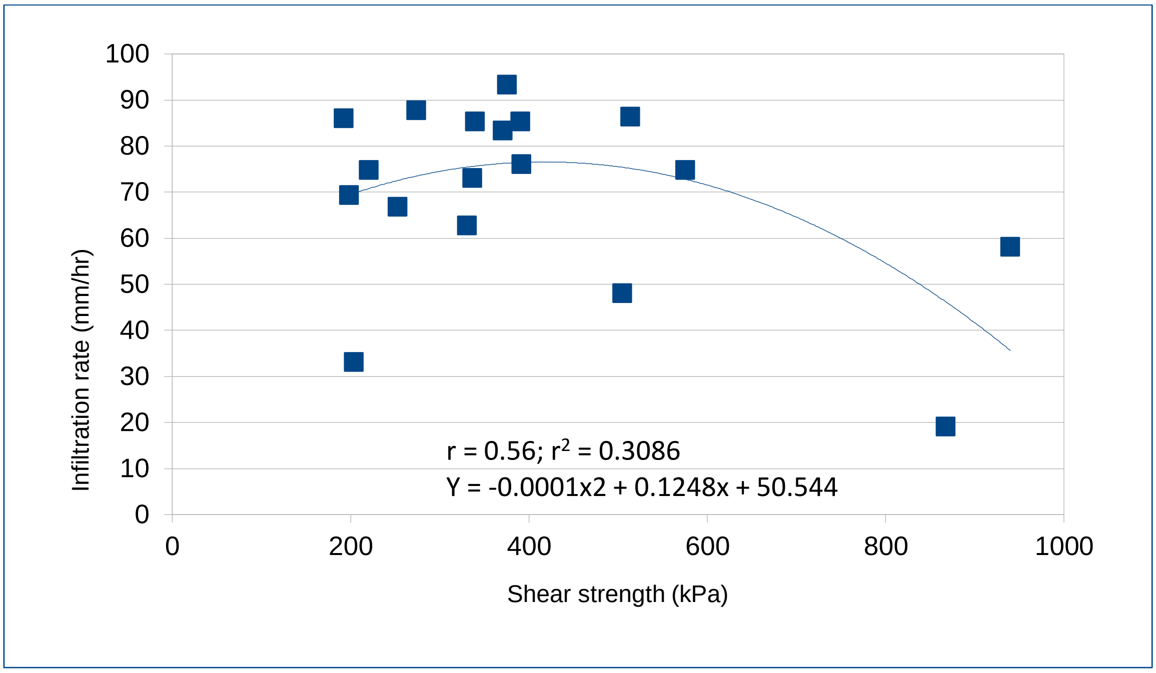


Figure 6. 6 Polynomial (2nd order) relationship between Shear strength (after irrigation) and infiltration rate (after irrigation)

This correlation investigated if a relationship existed between soil shear strength and infiltration rate of the soil post-irrigation. There was no linear relationship, but further investigation revealed that only a 'modest' 2nd order polynomial (quadratic) relationship, $r = 0.56$, existed. This demonstrates that low soil strength, < 400kPa, is detrimental to infiltration, and this is only slightly improved at soil strength around 400kPa where infiltration increases slightly before reducing again between 400 and 1000kPa. This potentially shows therefore that the effects of soil shear strength produced from the cultivation equipment does not greatly affect infiltration rate once the soil has received irrigation and the soil particles and soil structure has been influenced by any irrigation applications. Consequently, soil cultivation equipment which produce these conditions may influence erosion potential before irrigation as shown in figure 6.5, but may be less important once that irrigation, or rainfall, has occurred. The r^2 of 0.309 suggests that only 30% of the variation of infiltration rate is accounted for by variation in the soil shear strength and so 70% of variation is due to unmeasured factors.

6.1.7. Discussion

This experiment investigated the effects of different soil cultivation types on several soil structural properties. The experiment was based on a main treatment of primary cultivation types with the addition of three sub secondary treatments based on the use of pre-cultivation subsoiler, post cultivation subsoiler or no subsoiler. The Subsoiler played an important role in changing soil characteristics and this appears with results for infiltration, soil shear strength and soil penetration resistance.

The results suggest that infiltration rate is generally higher when using a subsoiler pre-cultivation rather than post cultivation. This is with regard to the results of the post-irrigation. As for results before irrigation, there are no significant differences. This suggests that the action of the subsoiler in lifting the soil is changing the porosity or aggregate arrangement of the soil profile and that the effects are increasing after the soil has been irrigated. Initially, pre-irrigation, there is no difference in infiltration rate when using the subsoiler before or after cultivation. After irrigation however, infiltration is significantly better where the subsoiler was used before the main cultivation process. This could be attributed to the result of removal of any underlying soil structural compaction by means of soil shattering as the subsoiler is designed to do (Pagliai, *et al*., 2004; Raper and Sharma, 2002).

However, when operating a subsoiler post cultivation the soil overlying the subsoiler wings would already be potentially loose and would reduce the zone or effect of the subsoiler, potentially causing structural damage rather than improvement. This may then have led to soil slumping, reducing the infiltration rate of the soil profile and a loss in soil aggregate form which in turn leads to greater destruction of soil aggregates (Hasheminia, 1994; Soane *et al*., 1986). The reasons why this effect was not apparent from the infiltration tests before irrigation are not clear but could be due to additional amount of water which increased the movement of smaller particles thus further blocking the soil pores (Alhassoun, 2011; Cerdan *et al*., 2002). This could in part be supported as the penetration resistances after irrigation were greatest for the post cultivation subsoiling whereas they were similar or reversed before irrigation, tables 6.9 and 6.10.

Infiltration rates were low before irrigation when using the mouldboard plough compared to other cultivation equipment. Ploughing by mouldboard plough led to the demolition of soil aggregates unlike other tillage equipment. It’s likely that the movement of small sized soil particles occurred in the water during the measurement of infiltration rate, as claimed by Alhassoun (2011). These particles clogged the pores, especially in the upper 100 mm layer of soil (Cerdan *et al*., 2002).

The success of the germination process first begins with the creation of an appropriate place for the seeds, and secondly, the creation of good soil conditions to extend the roots to the time of harvesting. Here, the process must be carried out according to logic, since soil surface preferably should not be changed after it is ploughed; Therefore, logically the soil should be ploughed to the lower layers first and then ploughed the surface layer (Aikins and Afuakwa, 2012; Manuwa and Olaiya, 2012; Mikha *et al*., 2011). Thus, the results of the study showed that the rate of shear and penetration values were high for subsoiling process was after soil ploughing compared with subsoiling before ploughing.

High values of shear strength were obtained when using a gang disc and rigid tine harrow without subsoiling. The reason that soil was only minimally turned over on a very superficial level was due to the nature of the equipment and its performance efficiency. This was confirmed by both Al-Thobhani (2000) and Jury *et al*.; (1991). However, when using the subsoiler pre-or post-harrowing with gang disc and rigid tine harrows, the shear strength values were also high. This is due to the harrows had a slight effect on soil aggregates at the surface, in addition to the subsoiler shanks only shattering the lower soil layers without affecting the top soil layers (Pagliai *et al*., 2004).

Furthermore, the sprinkler irrigation system had a significant effect on raising shear strength and penetration values when using the gang disc and rigid tine harrows. This was due to the falling water drops leading to a change in the surface soil structure. The water droplets are probably working to move the soft particles of soil that clog the pores in the surface soil layer, especially if the soil is treated with this type of equipment, there is a decrease in infiltration rate resulting in a decrease in moisture content in sub-surface layers. As a result, shear strength values become high (Ramos *et al.,* 2003; Nimmo and Perkins, 2002; Davies and Finney, 2001).

Primary moisture content affected infiltration rate particularly after irrigation. It can be seen that most infiltration values with the treatments were less after irrigation than before irrigation, in keeping with the findings of (Agricultural Irrigation, 2014). Infiltration rates and subsequent depth of the wet layer are influenced by two main factors. These are; the combined effect of droplet impact and tillage which together influence the destruction of soil aggregates (Aikins and Afuakwa, 2012; Sami, 2011). It should be noted that shear strength values were less after irrigation compared to before irrigation, especially when cultivating with the gang disc and rigid tine harrows, post or pre-subsoiling. Crusting of the soil surface from irrigation causes moisture to be trapped under the soil surface, unable to evaporate. This in turn reduces the shear strength values and the soil remains plastic. Action after irrigation causes a reduction in shear strength. It is possible to add this reasoning to the evaluation of differing shear strengths based on interactions between subsoiling and different tillage depths (Raper and Sharma, 2002; Muckel and Mausbach, 1996).

When subsoiling (pre-or post-cultivation) by mouldboard or disc ploughs, the results show that soil shear strength and penetration values were low compared with values obtained without any subsoiling. Understanding the interaction between these ploughing regimes has resulted in improved control of infiltration rate and soil conditions, as claimed by Mikha (2011) and Al-Thobhani (2000). A 200mm tillage depth by mouldboard and disc as well as subsoiling at a depth of 450 mm improved soil characteristics better than cultivation by gang disc and rigid tine harrows (Pagliai *et al*., 2004).

Using a rotary harrow which stirs the soil very quickly and completely destroys the upper soil structure to the working depth; shear strength values were low for the top soil layer especially with subsoiling. However, these values were significantly higher at lower depths. Rotary harrows turn and soften the soil surface (Shippen *et al.,* 1980). Nevertheless, this layer is still subject to the process of surface crusting if irrigated by a sprinkler system, but is more cohesive (Hussain *et al.,* 2013; NRCS, 2006) because less moisture being trapped in sub surface layers as a response to the soil surface being sealed through crusting.

The soil had high porosity and a low penetration resistance when it was cultivated by the mouldboard plough or the rotary harrow in contrast to the cultivation by the gang disc and the rigid tine harrows, this is agreement with Sahu and Reheman (2006). This occurs because the soil is only being minimally turned over on a very superficial level when cultivated by the gang disc and the rigid tine harrows. Through the obtained results, it became clear that there are differences in the performance of all tillage equipment that were used in the experiment. The subsoiler plough played an important role in changing soil characteristics as has been reported in other studies (Pagliai *et al*., 2004; Raper and Sharma, 2002). Subsoiler broken up soil layers at depth below the surface without mixing. This would be decreased soil density and strength and increased porosity which improving water infiltration.

It is well known that the crop residues in the field help to maintain soil surface and aggregate stability. However, gang disc and rigid tine equipment did not invert soil and mix it with crop residue. However, mouldboard plough would invert and bury the crop residues whereas the rotary harrow would increase the breakdown of the residue and incorporate into the soil surface (Donk *et al*., 2008; Duiker, 2006). The disc plough would achieve some incorporation but as it does not fully invert the soil the effects would be variable (Pagliai *et al*., 2004). Therefore, in some treatments this led the soil surface to be protected from water applications and others less so.

The high values of soil shear strength and penetration resistance are in agreement with Al – Thobhani (2000) who discussed the movement of small sized soil particles occurring in the water from the surface layer to the under layers. These particles clogged the pores, especially in the upper 100 mm layer of soil. In addition, soil temperature degrees at depths of 100 mm and 200 mm ranged between 16.8 – 18.7ºC (table 6.3) through the period of the experiment which would lead to the evaporation of large amounts of soil moisture (Mikha *et al*. 2011; Ramos *et al*., 2003). Within these conditions, a thin layer of soil would be created, and which could affect the structure of the soil.

Cultivating the soil by mouldboard and disc plough as well as the rotary harrow post or pre-subsoiling minimized soil aggregates and increased porosity as indicated by shear strength and penetration rate values. This is desirable for root growing but on the other hand, these pores are very susceptible to being clogged by the small particles which would lead to increasing the magnitude of shear strength and penetration resistance (Almehmdy, 2013; Ramos *et al*., 2003; Cerdan *et al*., 2002; Hajabbasi and Hemmat, 2000). When harrowing soil by gang disc or rigid tine, it is noted from the results that using a subsoiler with the above equipment pre-or post-harrowing, led to a decrease in the values in shear strength; This may be due to gang disc and rigid tine harrows failing to cultivate the soil to a suitable degree unless the treatment had been cultivated by the subsoiler, which concurs with Hamid (2012), and Daraghmeh *et al*., (2009).

The results obtained from the first experiment on 2014, suggested clear evidence that cultivation type was very influential on the soil structural properties measured. Thus, meaning that specific equipment needed further investigation and some could be disregarded. The methods chosen for further investigation, (subsoiling followed by mouldboard or disc ploughing) maintained good soil conditions under the effect of sprinkler irrigation. Based on these results, subsequent experiments were then conducted to investigate the effect of frequent sprinkler irrigation which is the problem leading to water runoff (Brouwer *et al*., 1988).

6.1.8 Intermediate conclusion

From these findings, soil surface properties are clearly affected by cultivation type and the use of overhead irrigation. The key findings however are that the rigid tine, gang discs and rotary harrow do not provide good soil structural properties that are suitable for use under irrigation. The disc and mouldboard ploughs however need further investigation. In addition, these cultivation implements are not the only equipment which affect the soil as the action of planting of the crop also uses soil engaging equipment. Consequently, it will be necessary to duplicate some of this initial work and also extend it to include interactions with planting equipment.

6.2. The effect of cultivation type and drilling on some soil properties and irrigation water runoff under simulated centre pivot irrigation

6.2.1 Introduction

Although centre pivot systems achieved high efficiencies of water use compared with flood irrigation methods this was not achieved without some application problems of runoff. This occurs due to high irrigation application rates relative to the infiltration rate of the soil (Neibling *et al*., 2009) and it has become evident that the pump supply system, sprinklers and operating conditions must be designed to prevent runoff and its associated problems of seed displacement and soil crusting (Brouwer, 1985). Crusting is the formation of a thin dense surface layer with no voids which prevents the ingress of water (Lipiec *et al*., 2006). It can develop as a result of rainfall or irrigation which promote aggregate breakdown, movement of clay particles, compression of the fine soil particles, moving them closer together and ultimately loss of pore spaces (Hajabbasi and Hemmat, 2000). Consequently, whenever crusting occurs it leads to reduced infiltration. Soil crusting is a ubiquitous problem worldwide, occurring across a wide range of soils. The thickness of the crust layer can range from a few millimetres to a few centimetres (Al – Thobhani, 2000). There is a significant effect of water droplet impact on the stability of soil-surface aggregates, clay particles were displaced from the surface layer to the lower layers leaving behind sand and silt particles on the surface. This thin soil surface layer reduced infiltration rate and would lead to increasing the volume of shear strength and penetration resistance (Almehmdy, 2013; Ramos *et al*., 2003; Hajabbasi and Hemmat, 2000).

As a result of these issues the average application rate from the sprinklers is now commonly chosen to be less than the soil infiltration rate but even with this approach the run-off is not completely prevented. Run-off is reduced but not eradicated completely (Cantón *et al*., 2009). As the amount of runoff will depend primarily on the amount and rate of water application, soil infiltration rate, field slope, and conditions present at the soil surface (Kranz and Eisenhauer 1990) several areas of concern exist.

Centre pivot systems have the inherent problem that the outer sections of the system travel quite quickly and with soils which have a high percentage of clay, water application rate at the outer extent of the lateral often exceeds the soil infiltration rate due to the greater application quantity needed at the higher speed. And a decrease of the water pressure along the lateral. When the operating pressure is thus reduced, the wetting radius from the sprinkler will also reduce, which then leads to an increase in application rate and therefore the appearance of runoff (Shimabuku *et al*., 2016; Hanson and Orloff, 1996). Cerdan *et al*. (2002) found that the runoff coefficient, the amount of runoff in relation to the amount of precipitation, ranges from zero to more than 60% in direct proportional relationship to the infiltration rate, where application was 30 mm h^{-1} to less than 10 mm h^{-1}.

Previous research has indicated that changing the rate of irrigation as well as following different cultivation practices can have a considerable impact upon water run-off, for example the work of Truman and Nuti (2009). The mouldboard plough works by cutting and lifting soil, which, depending on the mouldboard size and the ploughing depth, turns the soil using torsion with the plough body shape in a continuous manner along the tillage line. The main purpose of ploughing is to fragment the soil, bury the plant residues and prepare a suitable seedbed but by doing so it also impacts on soil physical properties such as water conductivity and bulk density. In contrast although the disc plough also cuts and lifts soil, it does so in a different way than the mouldboard plough. Cutting soils occurs by the edge of the disc penetrating the soil and maintaining a continuous rotating motion, in addition to the linear direction of the machine. Wherefore, a disc plough reduces friction of soil with the plough base. The mouldboard plough inverts the furrow slice much more than disc plough. This occurs because the lower mouldboard plough` section, the frog is forced into the soil, causing soil compression, in contrast to the disc plough which penetrate soil by its weight (Celik *et al*., 2011). This can mean that the soil condition after cultivation by disc plough can be more cloddy than the soil cultivated by mouldboard plough. Additionally, as the mouldboard plough inverts the soil it is effectively burying the surface trash and weeds in contrast to the disc plough which just mixes them within the soil to a greater or lesser extent. One of the primary reasons for using a mouldboard plough is to create a trash free upper soil layer almost ready for planting (Carter, 1996).

Although applying lower volumes of water to prevent the occurrence of surface crusts and runoff is a simple answer, unfortunately, this is not possible without a reduction of crop yield due to the high evapotranspiration rates in the Iraqi climate (Jaradat, 2003). Additionally, studies that evaluate the effective characteristics of a particular cultivation system relative to an irrigation sprinkler effects on infiltration, runoff, and erosion of specific soil types are limited and thus need further research.

In addition to this follow-on work it was also required to investigate how the operation of drilling would further influence runoff and infiltration. The basic drill designs used in Iraq would therefore need to be considered for this work. Most of farmers in Iraq are using mechanical seed drill type S-SC MARIA 250 - 400, (Maschio, 2017).

Currently the quantification of runoff, from rainfall or irrigation, most often utilises purpose build and large scale fixed sites (Nakawuka *et al*., 2014; King and Bjorneberg, 2011). However, it would also be useful if farm/area specific runoff could be quantified wherever the problem occurs or wherever the research is carried out. To this end it was decided to investigate if a simple and low-cost system could be devised and the minimum size that would be required to be representative, whilst carrying out the primary research on cultivation.

6.2.2. Objectives and Hypotheses for the experiments:

1. To find out the influence of overhead sprinkler irrigation with mouldboard plough and disc plough in addition to the use of subsoiler.
2. To find out the effect of mouldboard and disc ploughing with or without the effect of planting equipment on the physical soil properties.
3. To find out the effect of direction of mouldboard ploughing with drill direction on some of soil physical characteristics, under the influence of sprinkler irrigation.

6.2.2.1. Hypotheses for Crabtree leasow experiment:

Soil conditions and surface water runoff does not affected by mouldboard and disc ploughing with or without planting operation, under overhead sprinkler irrigation system.

6.2.2.2. Hypotheses for Flat nook experiment:

Ploughing and drilling direction does not effect on soil conditions and water runoff occur.

6.2.3. Materials and methods

The findings of experiment 1, chapter 6, suggested that the optimum combination of cultivation type to provide the greatest infiltration rate was with the mouldboard plough and disc plough in addition to the use of subsoiler. Therefore, two field experiments were conducted in 2016 to further investigate the interaction of overhead sprinkler irrigation with this equipment and also to compare the effect of mouldboard and disc ploughing with or without the effect of planting equipment on the physical soil properties of infiltration rate and soil shear strength, under the effect of sprinkler irrigation. In addition, an investigation was planned to determine if a simple commercial field scale water-runoff collection sampler could be utilised within these experiments.

The second experiment was intended to compare the effect of direction of mouldboard ploughing with drill direction on some physical characteristics of soil (infiltration rate and soil bulk density) under the influence of sprinkler irrigation.

The first experiment was conducted in Crabtree leasow field, HAU. While the second experiment was in Flatt Nook field, HAU.

6.2.4. Experiment sites and field information

There was a similarity of using some equipment to prepare the field before doing the experiments in terms of the use of tractor and sprinkler system.

The tractor used was a New Holland T6040 (89.5 kW) with a standard three-point hitch. A Briggs R24 boom irrigator connected to an R1/1 hose reel (Briggs Irrigation, Corby, UK) was used to irrigate the field. Nozzles were black-33 #42Red w/4B (red coloured), black-33 #44Yellow w/4B (yellow coloured) and black-33 #21Mustard w/2B fixed plates. These nozzles are those fitted at the furthest span of the most common 15ha centre pivot system used in Iraq at this time. Nelson High-Flo pressure regulator with square thread. 3/4" FNPT operating at 103 kPa (15psi) were fitted above each nozzle. The sprinklers were positioned at a spacing of 3m and a delivery height of 1.35m above the soil, with an application depth of 12 mm (87 mm/hr).

The first sprinkler nozzle was black-33 #42Red w/4B and positioned 3m from the centre of the boom, the yellow and mustard were fitted at 3m distance alternating along the boom.

Water to the system was pumped from the mains water supply. However, as the main water supply volume was inadequate to supply both sides of the boom and maintain adequate pressure, the irrigator was operated with one side of the irrigator boom at a time for each irrigator run. The 24 replicates were split to two lines as shown in table A3.1 and A3.2 in Appendix 3 to allow for this mode of operation.

The irrigator track was positioned therefore between each of the two lines. The width of the irrigator track was 3m. The distance for the irrigator tracking (irrigator line) was 70m long. The plots were positioned such that the boom sprinkler system was directly over the plots. The boom travel speed was 0.97 m min^{-1}. Irrigation application amounts were determined by the application rates and system travel speed. To measure the depth of irrigation, volumetric gages were placed randomly within the plots.

6.2.4.1 Crabtree Leasow field experiment

The experiment was conducted in April 2016 at Crabtree leasow field, Harper Adams University, UK. The field slope is 3%, figure 6.7. A completely randomized set of two tillage treatments – mouldboard and disc ploughing were used at a 200mm depth respectively. These main treatments were compared with a second factor of drilling after cultivation or no drilling. Drilling was carried out to a depth of 30 mm. Treatments were replicated six times giving a total of 24 plots, (see Appendix 3). All plots were cultivated initially by subsoiler at a depth of 450 mm parallel to the field slope. The dimensions of one main plot were (6m X 8m) and 3 m was left as a distance between each treatment plot.

Soil texture analysis was determined (MAFF/ADAS, 1985), and found to be sandy loam soil with average sand, silt and clay content of 40%, 35% and 25%, respectively.

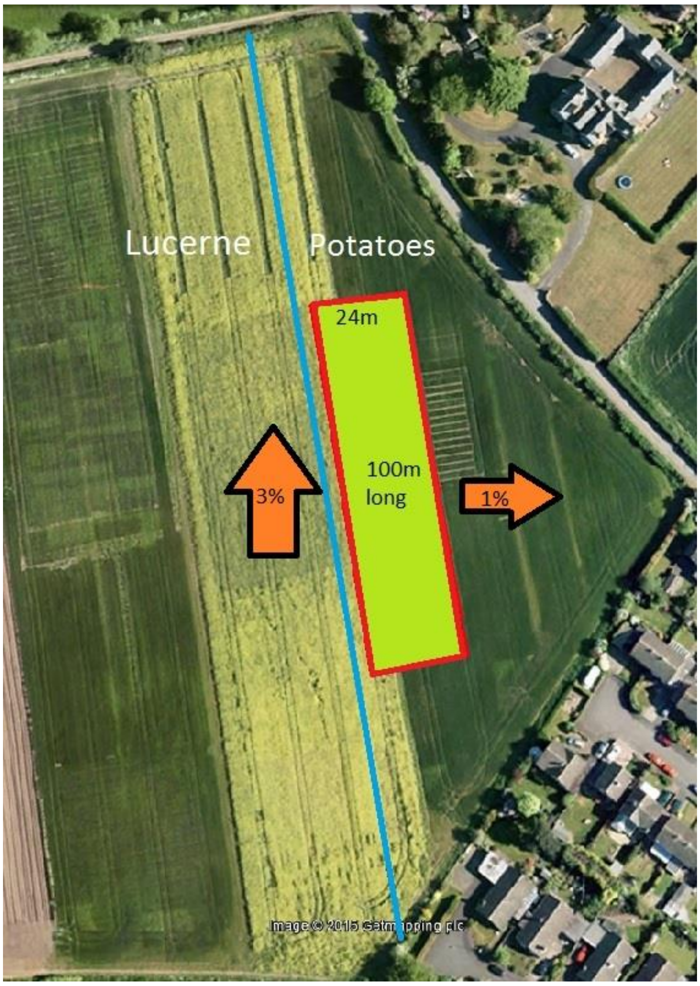


Figure 6. 7 Crabtree leasow site location

6.2.4.2 Flatt Nook field experiment

The experiment was conducted in November 2016 at Flatt Nook field, Harper Adams University, UK. The field slope is 5%. A completely randomized set of two tillage direction treatments of mouldboard plough was used at a 200mm depth. These treatments were compared with a second factor of drilling directions after cultivation, with/without drilling. Drilling was carried out to a depth of 30 mm. Mouldboard ploughing direction was applied parallel (horizontal) (HP) and perpendicular (vertical) (VP) to the field slope, while drilling direction was horizontal (HD), vertical (VD) and 45° (diagonal) (DD) to the field slope. Treatments were replicated four times giving a total of 24 plots, (see Appendix 4). The dimensions of one main plot were (5m X 3m) and 3 m was left as a distance between the treatments.

Soil texture analysis was determined (MAFF/ADAS, 1985), and found to be sandy loam soil with average sand, silt and clay content of 40%, 35% and 25%, respectively.

6.2.5. Measurements of soil physical properties and water infiltration rate

Due to the lack of shear strength probe in the second experiment where it was borrowed by another student, the bulk density was adopted to express soil character before and after water runoff.

Soil shear strength in the first experiment and bulk density in the second experiment were measured for soil physical characteristics, in addition to the measuring of water infiltration rate in the both experiments. Data were collected from within each plot away from the internal water-runoff collectors after preparing the treatments before irrigation and re-doing the same procedure after 24 hrs after water runoff process from area inside collectors randomly.

Soil shear strength and water infiltration rate procedures were explained in detail in chapter 3. Soil bulk density parameter depending on method of coring sample at depths of 50 mm and 100 mm respectively.

6.2.6. Design of water runoff sampler

In order to investigate the water-runoff under sprinkler irrigation system relative to the cultivation method used, several sizes of water-runoff samplers were used to collect the water-runoff, figure 6.8.

6.2.6.1. Runoff collectors

Sheets of compressed wood at thickness of 5 mm and at a height of 250 mm were used to create the frames of the square frame, figure 6.8. The sizes of the frames were: 0.5m x 0.5m (0.25 m^2), 1m x 1m ($1m^2$), 2m x 2m ($4m^2$) and 3m x 3m ($9m^2$). Side panels were cut longer than required so that 5mm cuts (at half the depth of the boards) at appropriate distances to allow for the side panels to be joined simply, and without supplementary fixing materials, in the field, figure 6.9.

1. 0.7m for a frame of 0.5m x 0.5m.
2. 1.2 m for a frame of 1m x 1m.
3. 2.2 m for a frame of 2m x 2m.
4. 3.2 m for a frame of 3m x 3m.

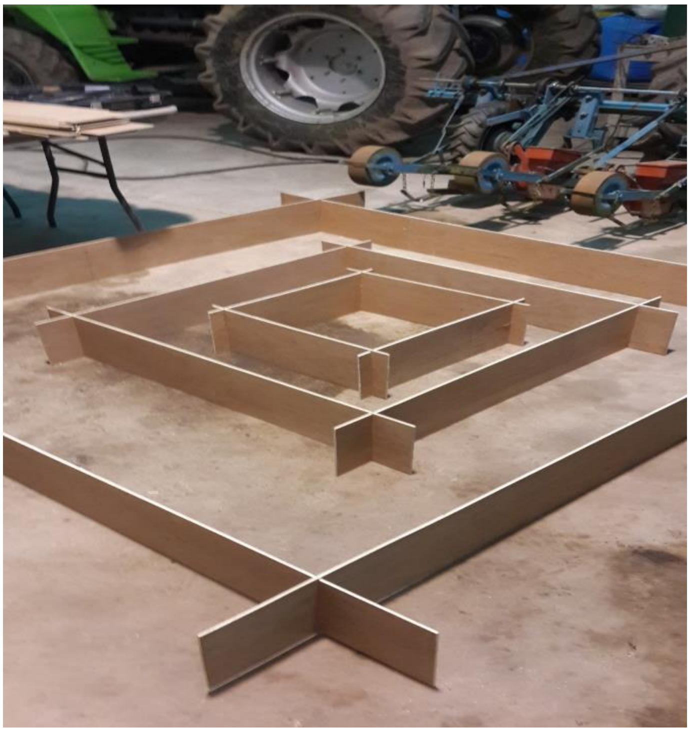


Figure 6. 8 Water-runoff samplers varying in sizes of 0.25 m^2, $1m^2$, $4m^2$,$9m^2$

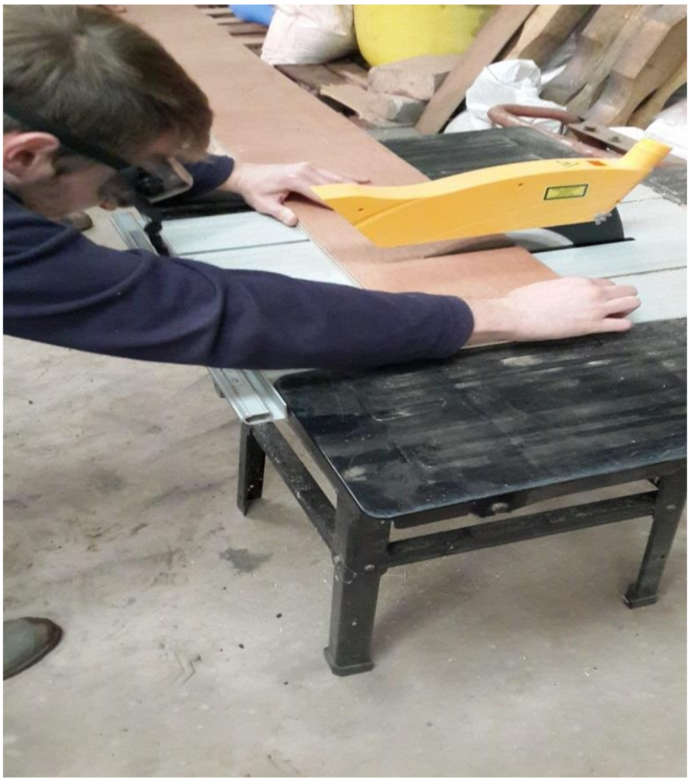


Figure 6. 9 construction of water runoff samplers

6.2.6.2. Distribution of water runoff samplers

Water runoff sampler frames were distributed randomly for all plots, figure 6.10. The frames were compressed into the soil between 0.1– 0.15 m depth, figure 6.11.

Figure 6. 10 Water-runoff samplers’ distribution in Crabtree leasow field experiment

Figure 6. 11 Installation of the frame into the cultivated plots

Rectangular catch cans (containers) were used to collect water runoff, the external dimensions are: L 400 mm, W 300 mm and H 270 mm; and the internal dimensions are: L 37 cm, W 27 cm and H 26 cm. Field slope was known, and it is 5%. Catch containers were distributed on the lowermost corner of the frames. So that one corner of each frame was towards the down end of the slope of the field.

A rectangular tank shape hole was fitted to the dimensions of the catch box container, figure 6.12. The sample area was not levelled before irrigation because this would change the soil surface structure, therefore does not reflect the actual reality of what occurs with soil when irrigating.

All containers were covered firstly, and the rope tightened around the cover to prevent water entering inside the boxes. All plots were then irrigated until water runoff process started, soil moisture content was 30%.

Figure 6. 12 Installation of the collector

Covers were moved directly after the sprayer has crossed the area and let water-runoff move inside the collector. The amount of water collected in each box was weighted by a Soehnle 2755 digital scale and the data recorded.

Figure 6. 13 Sprinkler irrigation process over water-runoff sampler

It is worth mentioning that the direction of the samplers in the second experiment (Flatt Nook field) was settled as a diamond towards the slop of the field, figure 6.14. Rather than set square across the plots.

Figure 6. 14 Water-runoff samplers' distribution in Flatt Nock field experiment

Climatic data for the experiment was taken from the HAU weather station, table 6.11

Table 6. 11 Climatic data summary for the experimental period (Weather Station, Harper Adams University. Newport, Shropshire, UK. 2014).

Time 2016	Wind Speed m/s	Max Temp ºC	Min Temp ºC	10cm Soil temp ºC	20cm Soil temp ºC	100cm Soil temp ºC	Related humidity %	Precipitation mm
April	2.4	12.5	3.0	7.8	8.8	9.3	97.3	2.3
November	1.3	9.3	1.9	5.8	7.0	10.7	92	2.5

6.2.7. Statistical analysis

The first experiment in Crabtree leasow field was arranged in a randomized complete block design (RCBD) with six replicates. The recorded data was analysed using repeated measures factorial ANOVA using Genstat 16th Edition, VSN International. In Flatt Nook field, the experiment was arranged in a randomized complete block design (RCBD) with four replicates. The recorded data was analysed using General Treatment Structure factorial ANOVA using Genstat 16th Edition, VSN International. All differences considered significant at $P \leq 0.05$.

6.2.8. Results

6.2.8.1. Crabtree leasow field experiment soil physical properties

Soil shear strength before irrigation

Table 6.12 shows soil shear strength values (kPa) under the influence of cultivation treatments with or without drilling at different depths before irrigation. There were no significant differences at each of the interaction of treatments means, and drill effect means, and cultivation effect means, and interaction between drill and depth means, and interaction between cultivation and depth means before irrigation.

The results have shown significant differences of soil shear strength values at each of the interaction between drill and cultivation means (P= 0.041), and depth means (P <.001). The higher soil shear strength value was with disc cultivation with drilling 1889 kPa; and the lower was with the same treatment but without drilling 1317 kPa. The mean value of disc cultivation with drilling was higher than mouldboard cultivation with drilling, it was 1889 and 1322 kPa respectively. However, the mean value of mouldboard cultivation without drilling was higher than with drilling 1472 kPa. There were significant differences between soil shear strength values depending on the depth of tillage before irrigation (P =<.001). It can be noted from the table that the greater the depth, the greater the soil shear strength values.

The variation in soil shear strength values at different depths plus the interaction between drill and cultivation before irrigation, resulted in increased coefficient of variance to be 48.8%.

Table 6. 12 Effect of cultivation and drilling treatments on the mean soil shear strength (kPa) before irrigation in Crabtree leasow field (MBP-mouldboard ploughing. DP- disc ploughing)

Means: shear strength kPa		Shear strength depths (cm)			Drill*Cultivation* depths		
Drill/no drill	Cultivation	0-10	10-20	20-30	*P* =	S.E.D	cv %
Drill	MBP	533	1217	2217	0.869	422.5	48.8
	DP	850	1817	3000			
No Drill	MBP	567	1217	2633			
	DP	417	1000	2533			
Means Drill effect	Drill	1606			0.226	172.5	
	No drill	1394					
Means Cultivation	MBP	1397			0.238	172.5	
	DP	1603					
Means Drill * Cultivation		MBP	DP		0.041	243.9	
	Drill	1322	1889				
	No Drill	1472	1317				
Means Depth	0-10		10-20	20-30	<.001	211.2	
	592		1312	2596			
Means Drill * Depth		0-10	10-20	20-30	0.664	298.7	
	Drill	692	1517	2608			
	No Drill	492	1108	2583			
Means Cultivation* Depth		0-10	10-20	20-30	0.829	298.7	
	MBP	550	1217	2425			
	DP	633	1408	2767			

Soil shear strength after water-runoff

Table 6.13 shows soil shear strength values (kPa) under the influence of cultivation treatments with or without drilling at different depths after irrigation and water-runoff. There were no significant differences at each of the interaction of treatments means, and drill effect means, and interaction between drill and depth means, and interaction between cultivation and depth means after water-runoff.

In general, all data means values were substantially lower than before irrigation. The results have shown significant differences of soil shear strength values at each of cultivation effect means (*P* =0.024), and the interaction between drill and cultivation means (*P* = 0.021), and depth means (*P* <.001). The variation in soil shear strength values at different depths plus the interaction between drill and cultivation after irrigation, resulted in increased coefficient of variance to be 32.1%.

The higher soil shear strength value under the effect of cultivation was with disc ploughing treatment 305 kPa. The higher soil shear strength value was with disc cultivation with drilling 344 kPa; and the lower was with the treatment of mouldboard cultivation with drilling 244 kPa. Meanwhile, the mean value of disc cultivation with drilling was higher than mouldboard cultivation with drilling, it was 344 and 244 kPa respectively. However, the mean value of mouldboard cultivation without drilling was higher than with drilling 267 kPa.

Table 6. 13 Effect of cultivation and drilling treatments on the mean soil shear strength (kPa) after water-runoff in Crabtree Leasow field (MBP-mouldboard ploughing. DP- disc ploughing)

Means: shear strength kPa		Shear strength depths (cm)			Drill*Cultivation* depths		
Drill/no drill	Cultivation	0-10	10-20	20-30	*P* =	S.E.D	cv %
Drill	MBP	168	222	343	0.201	519	32.1
	DP	168	365	498			
No Drill	MBP	165	327	308			
	DP	170	293	333			
Means Drill effect	Drill	294			0.191	212	
	No drill	266					
Means Cultivation	MBP	256			0.024	212	
	DP	305					
Means Drill * Cultivation		MBP	DP		0.021	300	
	Drill	244	344				
	No Drill	267	266				
Means Depth	0-10		10-20	20-30	<.001	260	
	168		302	371			
Means Drill * Depth		0-10	10-20	20-30	0.061	367	
	Drill	168	293	421			
	No Drill	168	310	321			
Means Cultivation* Depth		0-10	10-20	20-30	0.246	367	
	MBP	167	274	326			
	DP	169	329	416			

There were significant differences between soil shear strength values depending on the depth of tillage after water-runoff (*P* =<.001). It can be noted from table that the greater the depth, the greater the soil shear strength values.

Table 6.14 shows infiltration rate values under the influence of mouldboard and disc cultivation with or without drilling before and after irrigation. There were significant differences between the interaction of the treatments after irrigation (*P* =0.045). Mouldboard ploughing without drilling (MBP No Drill) resulted in high infiltration rate after runoff of 173.0 ml / hr compared to the treatment disc ploughing without drilling (DP No Drill) which gave 36.0 ml / hr. This follows the behaviour of soil movement with a ploughing method. Infiltration value with mouldboard ploughing without drilling was higher than with drilling after runoff as well as before irrigation, 173.0 ml/hr without drilling, 69.0 ml/hr with drilling after runoff, and 111.0 ml/hr without drilling, 55.0 ml/hr with drilling before irrigation respectively.

It was not set up linear correlations between data before and after irrigation, but in terms of comparing of interaction between the treatments before irrigation and after water-runoff on the infiltration rate, the results confirmed the presence of significant differences between the treatment of disc ploughing without drilling before and after irrigation. It can be noted from table 6.13 that a high value for infiltration was 70.0 ml/hr (DP No Drill) before irrigation to be declined to nearly half of the value after runoff 36.0 ml/hr. It should be noted that although there was no statistically significant difference in the mean values of infiltration rate among cultivation treatment after water-runoff (*P*=0.132), it is possible to point out that the infiltration rate was higher with mouldboard plough 121.0 mm/hr than that of disc plough 63.0 mm/hr.

There were no significant differences between drilling means of infiltration rate before irrigation and after water-runoff.

Table 6. 14 Effect of cultivation and drilling treatments on the mean infiltration rate (ml/hr) before irrigation and after water-runoff in Crabtree Leasow field (MBP-mouldboard ploughing. DP- disc ploughing)

Means: infiltration rate mm/hr		Infiltration rate (mm/hr)	Drill*Cultivation		
Drill/no drill	Cultivation	Before irrigation	*P* =	S.E.D	cv %
Drill	MBP	55.0	0.056	26.11	55.7
	DP	89.0			
No Drill	MBP	111.0			
	DP	70.			
Means Drill effect	Drill	72.0	0.328	18.46	
	No drill	90.5			
Means Cultivation	MBP	83.0	0.852	18.46	
	DP	79.5			
After runoff					
Drill/no drill	Cultivation		*P* =	S.E.D	cv %
Drill	MBP	69.0	0.045	52.4	98.8
	DP	90.0			
No Drill	MBP	173.0			
	DP	36.0			
Means Drill effect	Drill	80.0	0.511	37.1	
	No drill	104.0			
Means Cultivation	MBP	121.0	0.132	37.1	
	DP	63.0			

Water runoff collected amount

Table 6.15 shows water-runoff collected amount means of values (l/m^2) under the influence of mouldboard and disc cultivation treatments with or without drilling at different collector area sizes (m^2). There were no significant differences at each of the interaction of treatments means, and drill effect means, and interaction between drill and cultivation means, and interaction between drill and collector size means, and interaction between cultivation and collector size means.

The results have shown significant differences of water-runoff collected amount means due to the effect of collector size (*P* = 0.003). The mean value of 1x1 m collector size was the higher 4.91 l/m^2 and the lower was with 3x3 m - 1.04 l/m^2. However, the mean values of 0.5x0.5 m and 2x2 m were 3.51 and 2.53 l/m^2 respectively.

Table 6. 15 Effect of cultivation and drilling treatments on the mean water-runoff collected amount (l/m^2) in Crabtree Leasow (MBP-mouldboard ploughing. DP- disc ploughing)

Means: Runoff Litres /m^2		Run off collector area size m^2				Drill*Cultivation* collector size		
Drill/no drill	Cultivation	0.5 x 0.5	1 x 1	2 x 2	3 x 3	*P* =	S.E.D	CV%
Drill	MBP	3.19	2.26	2.02	1.10	0.230	2.046	118.2
	DP	3.52	9.85	2.72	0.61			
No Drill	MBP	4.83	3.09	1.87	0.87			
	DP	2.49	4.45	3.54	1.57			
Means Drill effect	Drill	3.16				0.660	0.723	
	No drill	2.84						
Means Cultivation	MBP	2.40				0.103	0.723	
	DP	3.59						
Means Drill * Cultivation		MBP		DP		0.248	1.023	
	Drill	2.14		4.17				
	No Drill	2.66		3.01				
Means Collector size	0.5 x 0.5	1 x 1	2 x 2	3 x 3		0.003	1.023	
	3.51	4.91	2.53	1.04				
Means Drill * Collector size	Drill	3.35	6.05	2.37	0.86	0.488	1.447	
	No Drill	3.66	3.77	2.70	1.22			
Means Cultivation* Collector size	MBP	4.01	2.67	1.94	0.99	0.053	1.447	
	DP	3.01	7.15	3.13	1.09			

6.2.8.2. Flatt Nook field experiment

Soil bulk density before irrigation and after water-runoff

Table 6.16 and 6.17 shown soil bulk density values (g/cm^3) under the influence of mouldboard ploughing and drilling direction treatments before irrigation and after water-runoff respectively. There were no significant differences for all treatments and their interactions under $P = 0.05$. In general, all means values before irrigation were lower than after water-runoff.

Table 6. 16 Effect of ploughing and drilling direction treatments on the mean soil bulk density (g/cm^3) before irrigation in Flat Nook field (HP-mouldboard horizontal ploughing, VP- mouldboard vertical ploughing, HD- horizontal drilling, VD- vertical drilling, DD- diagonal drilling)

Means: Bulk Density g/cm^3		Bulk density depth (cm)		Drill*Cultivation* depth		
Drill direction	Cultivation direction	0-5	5-10	*P* =	S.E.D	cv %
Horizontal Drill	HP	1.098	1.043	0.574	0.0743	9.7
	VP	1.038	1.138			
Vertical Drill	HP	1.108	1.103			
	VP	1.097	1.092			
Diagonal Drill	HP	1.069	1.069			
	VP	1.023	1.115			
Means Drill direction	HD	1.079		0.701	0.0372	
	VD	1.100				
	DD	1.069				
Means Cultivation	HP	1.082		0.944	0.0303	
	VP	1.084				
Means Drill * Cultivation	HD HP	1.071		0.928	0.0526	
	HD VP	1.088				
	VD HP	1.106				
	VD VP	1.095				
	DD HP	1.069				
	DD VP	1.069				
Means Depth	**0-5**	**5-10**		0.486	0.0303	
	1.072	1.094				
Means Drill * Depth	HD	1.068	1.091	0.791	0.0526	
	VD	1.103	1.098			
	DD	1.046	1.092			
Means Cultivation* Depth		**0-5**	**5-10**	0.185	0.0429	
	HP	1.092	1.072			
	VP	1.053	1.115			

Table 6. 17 Effect of ploughing and drilling direction treatments on the mean soil bulk density (g/cm^3) after water-runoff in Flat Nook field (HP-mouldboard horizontal ploughing, VP- mouldboard vertical ploughing, HD- horizontal drilling, VD- vertical drilling, DD- diagonal drilling)

Means: Bulk Density g/cm^3		Bulk density depth (cm)		Drill*Cultivation* depth		
Drill direction	Cultivation direction	0-5	5-10	*P* =	S.E.D	cv %
Horizontal Drill	HP	1.172	1.263	0.257	0.0771	9.2
	VP	1.158	1.190			
Vertical Drill	HP	1.115	1.102			
	VP	1.091	1.274			
Diagonal Drill	HP	1.186	1.207			
	VP	1.194	1.247			
Means Drill direction	HD	1.196		0.240	0.0386	
	VD	1.146				
	DD	1.208				
Means Cultivation	HP	1.174		0.572	0.0315	
	VP	1.192				
Means Drill * Cultivation	HD HP	1.217		0.323	0.0545	
	HD VP	1.174				
	VD HP	1.109				
	VD VP	1.182				
	DD HP	1.197				
	DD VP	1.220				
Means Depth	0-5		5-10	0.060	0.315	
	1.153		1.214			
Means Drill * Depth	HD	1.165	1.226	0.828	0.0545	
	VD	1.103	1.188			
	DD	1.190	1.227			
Means Cultivation* Depth		0-5	5-10	0.379	0.0445	
	HP	1.158	1.191			
	VP	1.148	1.237			

Water infiltration into cultivated soil

Table 6.18 shows infiltration rate values under the influence of mouldboard ploughing and drilling direction before irrigation and after water-runoff. There were no significant differences for all treatments and their interactions under $P = 0.05$.

Table 6. 18 Effect of ploughing and drilling direction treatments on the mean infiltration rate (mm/hr) before irrigation and after water-runoff in Flat nook field (HP-mouldboard horizontal ploughing, VP- mouldboard vertical ploughing, HD- horizontal drilling, VD- vertical drilling, DD- diagonal drilling)

Means: infiltration rate mm/hr		Infiltration rate (mm/hr)	Drill*Cultivation		
Drill direction	Cultivation direction	Before irrigation	*P* =	S.E.D	cv %
Horizontal Drill	HP	105.0	0.204	32.05	127.7
	VP	20.2			
Vertical Drill	HP	36.0			
	VP	23.2			
Diagonal Drill	HP	19.5			
	VP	9.0			
Means Drill direction	HD	62.6	0.121	22.66	
	VD	29.6			
	DD	14.2			
Means Cultivation	HP	53.5	0.067	18.50	
	VP	17.5			
Drill direction	Cultivation direction	After runoff	*P* =	S.E.D	cv %
Horizontal Drill	HP	10.0	0.173	82.1	212.7
	VP	9.0			
Vertical Drill	HP	30.0			
	VP	142.0			
Diagonal Drill	HP	126.0			
	VP	10.0			
Means Drill direction	HD	10.0	0.407	58.1	
	VD	86.0			
	DD	68.0			
Means Cultivation	HP	56.0	0.971	47.4	
	VP	54.0			

Water runoff

Table 6.19 shows water-runoff collected amount means of values (l/m^2) under the influence of mouldboard ploughing and drilling direction before irrigation and after water-runoff. There were no significant differences at each of the interaction of treatments means, and drill effect means, and interaction between drill and cultivation means, and interaction between drill and collector size means, and interaction between cultivation and collector size means.

The results have shown significant differences of water-runoff collected amount means at the effect of collector size ($P = 0.001$). The mean value of 0.5x0.5 m collector size was the higher 6.62 l/m^2 and the lower was with 2x2 m - 1.10 l/m^2.

Table 6. 19 Effect of ploughing and drilling direction treatments on the mean water-runoff collected amount (l/ m^2) in Flat nook field (HP-mouldboard horizontal ploughing, VP-mouldboard vertical ploughing, HD- horizontal drilling, VD- vertical drilling, DD- diagonal drilling)

Means: Runoff Litres/ m^2		Run off collector area size		Drill*Cultivation* collector size		
Drill direction	Cultivation direction	0.5 x 0.5	2 x 2	*P* =	S.E.D	CV%
Horizontal Drill	HP	7.08	0.70	0.585	3.858	141.3
	VP	13.40	0.63			
Vertical Drill	HP	2.74	0.72			
	VP	4.56	1.09			
Diagonal Drill	HP	6.88	1.86			
	VP	5.06	1.62			
Means Drill direction	HD	5.45		0.271	1.929	
	VD	2.28				
	DD	3.85				
Means Cultivation	HP	3.33		0.504	1.575	
	VP	4.39				
Means Drill * Cultivation	HD HP	3.89		0.565	2.728	
	HD VP	1.73				
	VD HP	4.37				
	VD VP	7.02				
	DD HP	2.83				
	DD VP	3.34				
Means Collector size	0.5 x 0.5		2 x 2	0.001	1.575	
	6.62		1.10			
Means Drill * Collector size	HD	10.24	0.67	0.191	2.728	
	VD	3.65	0.91			
	DD	5.97	1.74			
Means Cultivation* Collector size	HP	5.57	1.09	0.512	2.227	
	VP	7.67	1.12			

6.2.9. Discussion

6.2.9.1 Water runoff

It would appear that the water collection rate was affected by the area of collection. Therefore, it would be expected that the water-runoff rates from the whole collector would be greater for the greater surface area. For this reason, the values shown in table 6.15 are adjusted to runoff per m^2 for all of the samplers, 0.5m x 0.5m, 1m x 1m, 2m x 2m and 3m x 3m. Therefore, as the means of water runoff amount for the collector sizes are significantly much greater for the 1m x 1m collector (4.91 litres) compared to that recorded for the 0.5m x 0.5m collector (3.51 litres).

Within the same irrigation rate, water was distributed over a large area in the larger runoff samplers. Therefore, water depth was less in the large samplers compared with the smaller sizes of runoff samplers. Consequently, water infiltration time in the larger runoff samplers was less than in smaller samplers. Thus, water is more collected in the collection boxes in the 1m x 1m collector samplers. Additionally, it could be suggested that as the smaller sampling size would be less prone to localised cultivation effects and therefore would allow for less infiltration and greater runoff. Thus, all means of values for the plough type and drill for the bigger samplers are low. This was confirmed more clearly by the results of the second experiment, there were high significant differences between the water-runoff collection rate of samplers 0.5m x 0.5m, yielding 6.62 l/ m^2 and 2m x 2m, yielding 1.10 l/ m^2 . It is noted that the 0.5m x 0.5m produced nearly twice the water-runoff in the second experiment compared to the first. Moreover, it can be noted from the second experiment that the collection of water-runoff within a sampler to be adjacent to the field slope has an effect on water-runoff collection rate, where the field slope is 5% In other words, the field slope influences the rate of water-runoff collection when measuring runoff regardless of the sampler size. However, there was no significant effect of drill direction with the type of tillage or sampler size. Based on statistical analysis, it is no more beneficial to enlarge the sampler size above 1m x 1m ($1m^2$).

6.2.9.2. Effect of cultivation and irrigation on the soil properties

Shear strength

In the Crabtree leasow experiment the overall soil shear strength values changed substantially from values ranging from the lowest of 417 to 3000 kPa post cultivation pre-irrigation to 165 to 498 kPa post irrigation to runoff across all depths. There were no statistical differences found between the majority of treatments or interactions but whereas post cultivation values increased from 10 to 20 to 30cm depth the trend was substantially reduced after irrigation to runoff. This may due to soil moisture before irrigation was 15% and after 24 hours of runoff was 28%, which reduced soil shear values (Alhammadi and Al-Shrouf, 2013). As the action of all of the cultivation types is to break down the soil aggregates to a greater or lesser degree, especially on these light sandy soils, there appears to be no difference between the mouldboard ploughing and disc plough irrespective of the use of the drilling operation.

Bulk density

In contrast to this the soil bulk density values from the Flat nook experiment showed an opposite effect whereby the values post cultivation but pre-irrigation were lower (range of 1.023 to 1.138 g/cm^3 than values post irrigation, range from 1.091 to 1.274 g/cm^3. This is as expected as the soil bulk density accounts for the soil mineral content and the pore spaces. Under consistent irrigation the smaller soil particles of silt and clay are washed down into the soil pores as the water breaks up aggregates to release individual particles. As there were no significant effects seen it is sufficient to say that none of the treatment combinations appeared to be more beneficial than any other in maintaining soil pore space and thus potential for better infiltration.

Jan and Kranz (2000) pointed out that drops of water falling from the spray are serving to move fine particles of soil. Soil particles flow with irrigation water on the surface but settle in pores. Continuous irrigation leads to increased soil erosion through particles being taken away in suspension from the sealed soil surface leaving behind only a light surface soil layer. The lack of vegetation, with evaporation factors and the movement of water downwards, leads to an increase in the thickness of this sealed layer. Here the cohesive forces of soil aggregates play their part by maintaining the formation of the ploughed soil.

The various processes of cutting and lifting soil with the vibration of the plough due to direct contact with soil, leads to the fragmentation of soil blocks into smaller pieces to be placed and stacked along the line of ploughing. Therefore, soil that is ploughed by mouldboard plough has a better soil structure when compared with disc ploughing.

This is evident through the second experiment, where the mean values of water-runoff were within the same rate under the influence of mouldboard ploughing for both experiments, regardless of the direction of drilling. The drilling process did not play an important role in reducing the amount of water-runoff, this indicates and confirms that the type of ploughing is the most powerful effect on maintaining soil conditions suitable for plant growth.

6.2.9.3. Effect of soil cultivation on water infiltration into the soil

In the Crabtree leasow experiment the different plough types appeared to interact with the drilling operation differently both before and after irrigation. Where no drilling operation was carried out the mouldboard plough gave the greatest infiltration rates but when a drilling operation was used the disc plough gave the greatest infiltration rates. This suggests that the disc plough provided a soil structure more suited to the subsequent drilling operation than the mouldboard plough. For the Flat nook experiment which then concentrated on the mouldboard plough, due to runoff results, the horizontal drilling (drilled parallel to the field slope) provided the best infiltration rate. Again, this is not unexpected as drilling with the direction of the slope would be conducive to runoff rather than infiltration. However, when looking at the runoff results from the Flat nook experiment it is the drilling diagonally to the slope which appears to create most runoff, although there were no significant differences between any treatments or their interactions.

As mentioned by Celik *et al*., (2011), the shape of soil after mouldboard ploughing is different from disc ploughing. It was found that the plant residue is more mixed with soil when tillage by mouldboard plough compared with disc plough. Accordingly, this would improve water infiltration conditions. All experiment plots were equal in area plus water application was determined to be evenly distributed. However, from other research within this thesis investigating the uniformity of irrigation, there is a possibility that some of the results have been affected by the distribution patterns of either single or overlapping nozzles. However, water distribution uniformity didn`t measured under the boom for both experiments in, Crabtree leasow field and Flatt Nook field. This has been discussed in chapter 5 and together with this work in the general discussions at the end of this thesis. For the purpose of this chapter however the differences between treatments must be considered relative to the type of plough, the direction of ploughing, and the use or direction of the drilling operation (Pagliai *et al*., 2004). For the disc plough the failure to turn the soil completely means the survival of a cloddy soil. This means the percentage of porosity was higher with mouldboard ploughing compared with disc. The cultivated soil has exposure to the effect of sprinkler water droplets which in turn removed the soft soil particles which led to the closure of the pores of the lower soil layer (Hajabbasi and Hemmat, 2000); this means the formation of a superficial layer faster (Lipiec *et al*., 2006). Thus, under the effect of sprinkler irrigation, the percentage of clogged pores was less when ploughing soil by mouldboard. Therefore, water infiltration rate has reduced.

The high CV values for the runoff experiment is a result of widely differing runoff yields. This can be attributed to where in some cases the irrigation rate and infiltration rate are of the same order and depending on individual sampler sites, be either above or below a runoff threshold.

There was some variation between the blocks and this added to the overall variability of the experiment. This variability could have arisen from soil type variation across the site, leading to variable infiltration rate and thus variable run off from the same treatment. There is little opportunity to reduce this problem as each plot needs significant area for machine operation. Consequently, increasing the replicate number would probably have increased the CV% further. Further detailed analysis of the results has shown that considerable variation arose due to the different cultivation methods and the drill or no-drill treatments and thus is a limitation of the experimental design due to the substantially different effects. As this has now been demonstrated any follow-on experiments would need to factor these considerations into experimental design. A different design of experiment such as split plot, could be considered as less ‘turning area’ would be required, but these designs can be less powerful statistically. However, the most likely cause of high CVs is the type and method of runoff collection. An improved design of collecting the run-off and also taking several measurements per plot and averaging them may be beneficial.

6.2.10. Conclusions

Under the conditions of a simulated centre pivot irrigation system;

1. As a result of comparing the different soil conditions produced by the mouldboard and disc ploughs, water infiltration and soil physical properties studied under the effect of the mouldboard plough were improved, and as a result of that water runoff was reduced.
2. The additional soil preparation of drilling had no influence on infiltration and soil physical properties on a sandy loam soil with up to a 3% field slope.
3. The direction of ploughing and drilling with respect to the field slope had no effect on infiltration, water runoff and soil physical properties on a sandy loam soil with up to a 3% field slope.
4. The runoff sampler size had a significant effect on the amount of water collected when the collection area of the sampler is taken into account.

7. General discussion

This research investigated the interaction between cultivation methods and overhead sprinkler system and their effect on water runoff.

The study aims were split with the first study of irrigation nozzle uniformity under the influence of water pressure, height of nozzles and nozzle size. The second was to investigate the effect of soil cultivation with different equipment on irrigation water runoff and the soil physical characteristics which may have influenced this.

As surface runoff often occurs in the last section of centre pivot irrigation systems, due in part to an increase in the nozzles outlet sizes to increase water discharge and the high application rate and travel speed. The nozzles studied in this research focused on the sprinkler package for this section from a Valmont 15ha fixed plate system.
The effect of two nozzle heights of 1.5 and 0.5 m were selected to represent above canopy and in-canopy overhead sprinkler irrigation systems with various water pressure regulators on water distribution uniformity was investigated, results indicated significant effects of nozzle height and water pressure rate on the distribution uniformity properties and water application rate.

Increasing nozzle height from 0.5m to 1.5 m led to increased water distribution. The greater sprinkler height, the greater wetted area and best distribution uniformity values (El Wahed *et al*., 2015; Rogers *et al*., 1997). This was reflected through the results of a field experiment and water distribution uniformity tests by rectangular catch containers. Although water distribution increased with increasing nozzle height from 0.5 m to 1.5 m, water collected amount however, began to reduce with increased nozzles height . This may be due to a larger wetted area has had a lower average application rate (Rogers *et al*., 1997; Heerrmann and Hein, 1968).

Water distribution uniformity values increased with an increased water pressure ascending from 41.4 kPa (6 psi) and 68.9 kPa (10 psi) to 103.4 kPa (15 psi) and 137.9 kPa (20 psi). They were 51%, 57%, 91%, and 85%, respectively. The results of the increasing water distribution uniformity values with the increasing water pressure agree with the finding of (Rogers, 2016; King and Kincaid, 1997; Evans and Sneed, 1996) who reported that, at a given centre pivot system, the greater water pressure, the greater water distribution and irrigation uniformity. This is evident through the results obtained where water distribution uniformity values of 103.4 kPa (15 psi) and 137.9 kPa (20 psi) pressure were higher than values of 41.4 kPa (6 psi) and 68.9 kPa (10 psi). This may due the more compatibility between the type of nozzles package with operating pressure (Martin *et al*., 2012; Almasraf *et al*., 2011; Foley, 2008). In addition, #44Yellow w/4B nozzle and #42Red w/4B nozzle significantly exceeded the accumulation of the largest quantity of water for all the pressures, unlike #21Mustard w/2B nozzle. It was 135.27, 192.66, 212.07 and 216.48 litres, respectively.

Compared with #42Red w/4B nozzle 123.84, 159.11, 185.51, and 211.77 litres, respectively; and #21Mustard w/2B nozzle 39.64, 39.88, 49.21, and 56.14 litres, respectively. This may due to the large outlet size resulted a large application rate (Fipps and New, 2005; King and Kincaid, 1997; Evans, *et al*., 1996). Therefore, water distribution and irrigation uniformity are proportional to operational water pressure.

Moreover, the effect of the interaction of operating pressure and nozzle height on water distribution uniformity was found to be non-significant. This may be due to the fact that the experiment was within controlled conditions within the engineering hall. There may be significant differences in uniformity when conducting a field experiment, especially when the level of the nozzles high.

Regardless of the impact of water pressure and nozzle height, application pattern was influenced by the three supports found in the nozzle. Visual representation of the data showed how the application is affected negatively by the nozzle supports on the bottom plate. Thus, it can be derived, that the pattern from an individual sprinkler is not uniform and so when overlapping nozzles are used there exists a potential for significant variations of distribution uniformity to occur (Hines and County, 2013; Evans, 2001; Kincaid, *et al*., 2000).

The positioning of the nozzle, bridge and deflector had been maintained when reassembling between each nozzle test changeover, and potential differences of performance has been identified. Therefore, distribution uniformity should be high because of the application method used. If this could be applied practically all nozzles on a centre pivot irrigation system, the distribution pattern would probably have been highly uniform because all nozzles were positioned to counteract this problem. In practice, this then requires that on the regular maintenance of the nozzles takes the position of the support bars into account to counteract the effect of distribution uniformity. In addition to that no one is fully aware that the coordination of the placement of nozzles have an impact on irrigation efficiency and the potential reduction for runoff.

The full importance of these findings is all relative to the potential for irrigation water runoff in the field. Where the lack of high uniformity is suggested as less relevant as the soil itself will even up the application in many cases (Darko *et al*., 2017; Ribeiro *et al*., 2013; Foley, 2008), this is probably only true when the soil is well below field capacity before irrigation. When the soil is being irrigated in high volumes at the outer span of a centre pivot and this is above the infiltration rate of soil then poor uniformity could then cause runoff. These findings are all relative to the potential for irrigation water runoff.

The first objective of the project was explored through water distribution tests in the machinery hall at Engineering department in which the effect of water distribution properties on factors that may lead to runoff was evident.

However, to have a comprehensive view of the conditions of water runoff, three experiments were conducted to determine the effect of different cultivation systems on soil physical conditions and water runoff.

The first experiment was conducted to compare the effect of different tillage practices on some selected soil physical properties. The treatments comprised of main treatments of mouldboard ploughing, disc ploughing, gang disc harrowing, and rigid tine harrowing and rotary harrowing; imposed upon these was a second factor of subsoiling before cultivation, subsoiling after cultivation or no subsoiling. The machines selected were the most basic type available or representative of that available to many Iraqi farmers, rather than more complex and expensive equipment also available. The effect of cultivation systems was investigated, and the results indicated significant effects on infiltration rate, soil shear strength and soil penetration resistance.

The Subsoiler played an important role in changing soil characteristics and this appears with results for infiltration, shear strength and penetration. The results confirmed that infiltration rate is higher when using a subsoiler pre-cultivation rather than post cultivation. This may due to the use of the subsoiler post cultivation leading to a loss in soil aggregate form which in turn leads to greater destruction of soil aggregates (Hasheminia, 1994). It may also be the result of a change in the way the soil fracturing would occur when the upper soil layers had been disturbed by cultivation as opposed to the undisturbed soil effect. Subsoilers operate at a critical depth which is based on the ability to shatter soil effectively, after ploughing this critical depth may require revision. Results also confirmed an increased infiltration rate after irrigation than before. The reasons for this are not clear but could be due to the sandy soil not being cohesive when wet, unlike clay soils (Davies *et al*., 2001), and so the infiltration is little affected or even improved once the coarse soil particles are already wet.

Primary moisture content affected infiltration rate particularly after irrigation. Most infiltration values with the treatments were less than before irrigation, in keeping with the findings of (Agricultural Irrigation, 2014). Infiltration rates and subsequent depth of the wet layer is influenced by two main factors. These are; the combined effect of droplet impact and tillage which together influence the destruction of soil aggregates (Aikins and Afuakwa, 2012; Sami, 2011).

Soil shear strength and penetration values were greater by approximately 80% when soil was cultivated by either gang disc or rigid tine, especially without subsoiling, compared with other treatments at the same depth. This is most likely the result of compaction being induced by the gang discs but it is unlikely to be the same reason for the tines. Potentially the soil penetration resistance reading could have been taken in soil between the tines, as the gaps were substantially wider than the tines themselves. In contrast soil had high porosity and low penetration resistance when cultivated by mouldboard or rotary compared with cultivation by gang disc and rigid tine harrows. This may due to soil in the latter only being minimally turned over on a very superficial level, as suggested by Sahu and Reheman (2006).

It is well known that the crop residues in the field maintain soil surface and aggregate stability (Cerdan *et al*., 2002). However, gang disc and rigid tine equipment did not have enough disc or tine sizes to mix the soil with crop residue as well as other treatments. This would also then have led the soil surface to be denser as it was, (Davies and Finney, 2001).

When using the subsoiler to cultivate the soil pre-or post-harrowing, the shear strength and penetration values decreased compared to no-subsoiling but still were higher than for the other treatments. This may due to the subsoiler shattering the lower soil layers to the depth that it reached without affecting soil between the shanks (Kranz and Eisenhauer 1990). The subsoiler design imperatives to shatter the soil surrounding the tines and leaving behind tiny furrows. Soil compaction at lower layers prevent shattering unless the tines pass through it directly, especially with soil at less moisture content (Ma *et al.*, 2015). The results also showed that the greater the depth, the greater the soil shear strength and penetration resistance values after irrigation. This may due to soil particles transformed with water from upper to the underneath layer. Over time and for several irrigation processes, soil will accumulate a component layer that may be difficult to penetrate by roots (Daraghmeh *et al*. 2009; Al-Tahan and Al-Ali Khan, 2007).

Thus, mouldboard ploughing and disc ploughing with subsoiling provides the best soil structural conditions to resist soil surface breakdown under irrigation. If the field conditions suited to ploughing by gang disc and rigid tine harrows rather than other soil equipment, subsoil plough should be used to improve soil conditions and preferring subsoiling before cultivation by harrows. If infiltration rate is lower on the ploughed soil indicates either that soil is saturated or that the irrigation rate is higher than water absorption. Therefore, attention should be paid to the condition of both soil moisture when irrigation in addition to the rate of irrigation under soil conditions, otherwise water runoff is expected to occur.

Therefore, soil physical characteristics are proportional to the soil cultivation methods which have a significant role in the establishment and development of water runoff.

Consequently, to know the effect of water distribution properties studied in the first part of the project on the results of the experiment of cultivation types, in the formation of surface runoff; two field experiments were conducted on this subject. The two experiments investigated some soil properties and water runoff.

Of these the first experiment investigated two tillage treatments – mouldboard and disc ploughing at a 0.2 m depth respectively. These main treatments were compared with a second factor of drilling after cultivation or no drilling. Drilling was carried out to a depth of 0.15 m and used equipment to mimic the drills commonly used in Iraq, often referred to as a cultivator drill.

The second experiment was conducted to investigate two tillage direction treatments of mouldboard plough a 0.2 m depth. These treatments were compared with a second factor of drilling directions after cultivation. Drilling was carried out to a depth of 0.15 m. Mouldboard ploughing direction was applied parallel (horizontal) (HP) and perpendicular (vertical) (VP) to the field slope, while drilling direction was horizontal (HD), vertical (VD) and 45° (diagonal) (DD) to the field slope.

Variation in soil physical conditions depends on the type of soil tillage system. As the action of all the cultivation types is to break down the soil aggregates to a greater or lesser extent. The effect of the water between the soil particles may reduce the frictional forces between individual soil aggregates and soil particles. (Lehrsch and Kincaid, 2006; Silva, 2006).

This may be due to the formation of soil under the influence of the type of plough more than when drilling, especially since the depth of the plough was more than the depth of drilling (Cantón *et al*., 2009). The depth of ploughing to this extent by mouldboard and disc means the formation of soil aggregates at sizes commensurate with the size of the mouldboard or disc. In other words, the chance of the stability of the aggregates by this equipment is more than by drilling or drilling direction. This may be due to drops of water falling from the irrigator are serving to move fine particles of soil. Soil particles flow with irrigation water on the surface but settle in pores. Continuous irrigation leads to increased soil erosion through particles being taken away in suspension from the sealed soil surface leaving behind only a light surface soil layer (Msibi *et al*., 2014; Jan and Kranz, 2000).

Water runoff was identified through proposed samplers and described in Chapter 7. It was found that the use of different size runoff collectors appeared to give different runoff collection efficiencies. The results showed that the amount of water collected in the 1 m^2 sampler is significantly higher than other sampler sizes for reasons attributed to soil and cultivation type, and field slope.

Soil type of both sites where the runoff experiments were conducted was sandy loam soil. Therefore, water runoff was absorbed in a short time especially in larger size samplers.

This gives an indication that the requirements of water runoff testing methods preferably within small areas, and not as it is previously practiced that the experiments are conducted within large areas.

The presence or absence of plant residues has a significant role in the stability of soil against erosion. Thus, the combination of tillage type and soil conditions with application rate of over-head sprinkler system has a large role in the occurrence or non-occurrence of runoff (Kranz and Eisenhauer, 1990).

Therefore, consideration must be given to these conditions. Otherwise, the crop yield will ultimately be negatively affected, plus the waste of water used for agriculture.

8.0 Conclusions

A series of studies investigated the interactions of soil cultivation practice and overhead (centre-pivot) irrigation system performance and their effect on the potential for surface water runoff.

1. Soil preparation by mouldboard plough and disc plough post-subsoiling maintained higher infiltration of surface water under the influence of sprinkler irrigation compared to harrowing systems (gang disc, rigid tine and powered rotary) in this work on sandy loam soils. Leading to the conclusion that the plough is the preferred choice to reduce surface water runoff for the soil type and gradient studied.
2. As a result of comparing the different soil conditions produced by the mouldboard and disc ploughs, water infiltration and soil physical properties studied under the effect of the mouldboard plough were improved generally on a sandy loam soil with up to a 3% field slope and as a result of that surface water runoff reduction was observed, however
    a. The additional soil preparation of drilling had no influence on infiltration and soil physical properties.
    b. The direction of ploughing and drilling with respect to the field slope had no effect on infiltration, water runoff and soil physical.
3. Application uniformity of irrigation in the field improved when operating at 1.5 m above the soil surface, however, water pressure also had a significant influence on distribution uniformity.
4. Rectangular shape catch containers gave a greater resolution of the single nozzle distribution results highlighting the effect of nozzle bridge supports. The issue of the nozzle bridge orientation and its influence on water distribution from adjacent nozzles needs to be further investigated with respect to the initiation of surface runoff.
5. The measured water run-off, l/m^2, was shown to be significantly greater for the smaller sized collectors, 0.5 x 0.5m and 1m x 1m, compared to the larger 2m x 2m and 3m x 3m collectors. The reasons for this cannot be easily related to the differences in infiltration as caused by the different cultivation and drill combinations and so must have arisen due to other factors. One option is that run-off is easier to capture with a small collection area as opposed to a large collection area as there is less area for instant infiltration to occur. A second option is that as the nozzle output patterns demonstrated in the sprinkler uniformity investigation contained high application rate hotspots, and those hotspots were related to the orientation of the nozzle, the nozzle orientation in the field and subsequent hotspot effects may have been more important for smaller collectors than for larger collectors. Further experimental work for run-off effects related to cultivation equipment therefore needs

more research relating to both optimum sized collection system for the area under investigation and a detailed spatial mapping of sprinkler outputs to ensure that the actual uniformity of water application is similar across the irrigated width.

8.1 Recommendations

1. To obtain a better water distribution and avoid water runoff problems, the sprinkler package type fixed plates nozzle head of 15 h Valley systems is preferred to work with pressure of 15 psi with nozzles height up to 1.5 m.
2. To identify best cultivation practice in field conditions, it is recommended that consideration is made to select the most representative water runoff collection sampler size.
3. It is preferable to use full floor coverage of collectors without interstitial distances when measuring water distribution uniformity for individual nozzles.
4. When cultivating, it is recommended to consider using a mouldboard plough on sandy loam soils under centre pivot sprinkler irrigation systems.
5. To improve soil conditions, it is preferable to subsoil the field before cultivation if compaction is identified in the soil profile.

8.2 Further studies

1. Conducting field experiments using other cultivation equipment under the influence of sprinkler systems with different specifications. This would increase the range of scientific solutions available to address the problem of runoff.
2. Investigate how other sprinkler nozzle packages interact with cultivation equipment.
3. Determine the optimum centre pivot speed to prevent runoff for the different type of cultivation packages/systems available.
4. Using advanced computer programs to solve problems of distribution uniformity of centre pivot sprinkler system, as creating a program was not an option in this research. Cranfield University has developed ballistic models, but they are only used in house. For future research, it may be possible to access the software or collaborate, or it may be possible to consider collaboration with the data in order to produce a paper in the longer term.

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Appendix 1 Specifications of the tractor and sprinkler

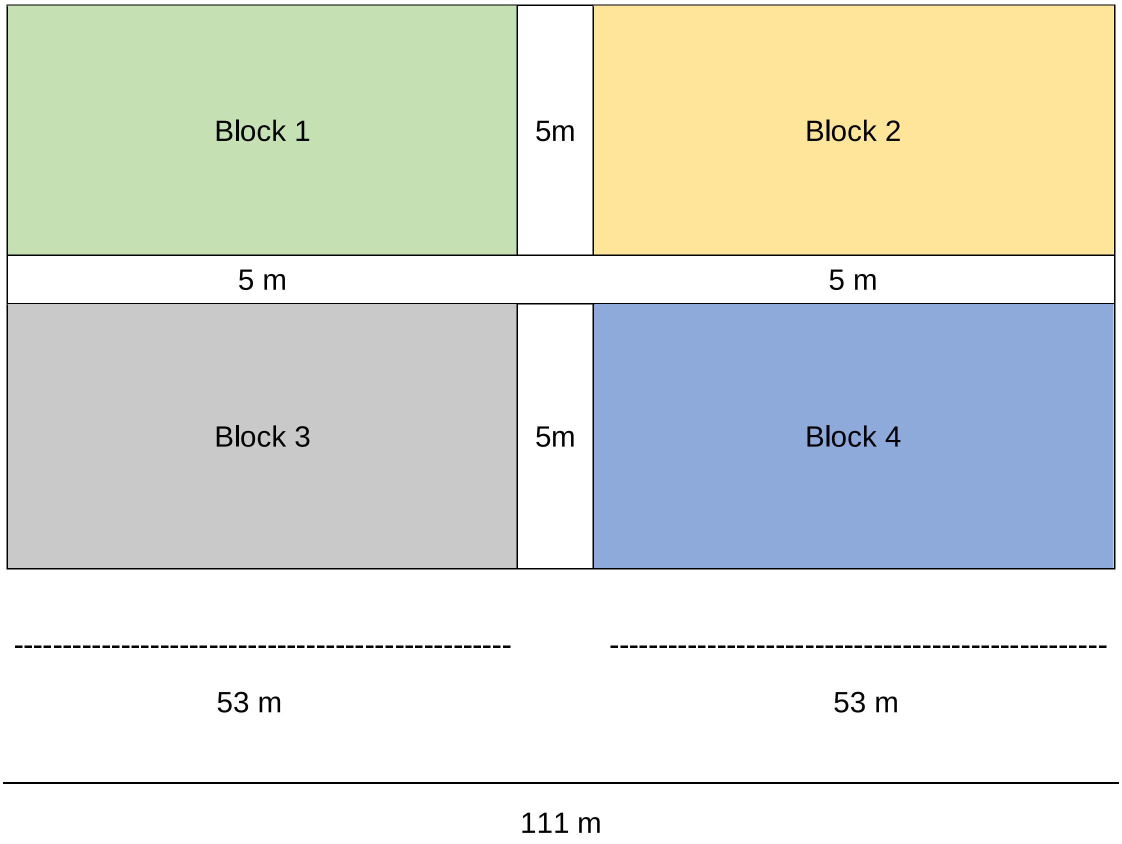
Table A1. 1 Tractor specification

Manufacturer:	New Holland T6040
Factory:	Basildon, England
Engine:	FPT 4.5L 4-cyl diesel
3-Point Hitch:	Rear Type: 2/3N
Control:	electronic lower-link draft control
Rear lift:	12,185 lbs [5527 kg]
Power Take-off (PTO):	Rear PTO: independent
Rear RPM:	540/1000 (1.375)
Engine (gross):	120 hp [89.5 kW]
PTO (claimed):	100 hp [74.6 kW]
Drawbar (tested):	81.0 hp [60.4 kW]
PTO (tested):	117.9 hp [87.9 kW]

Table A1. 2 Sprinkler specification:

Manufacturer:	Briggs
Model:	Boom sprinkler – hose reel mounted R18
Boom length (L):	18 m
Lane spacing (i):	18 – 32 m
Band width (D):	10 – 25 m
Flow:	14-30 m^3/hr (Si110 g/m)
Operating pressure:	1-4 bar (15-60 psi)
Quantity of outlets:	9
Floded length:	5 m
Floded width:	2.8 m
Track width:	1.5 – 4.2 m
Height of nozzle:	1.5 – 2.28 m
Height to top of structure:	2.12 – 2.9 m
Weight:	400 kg

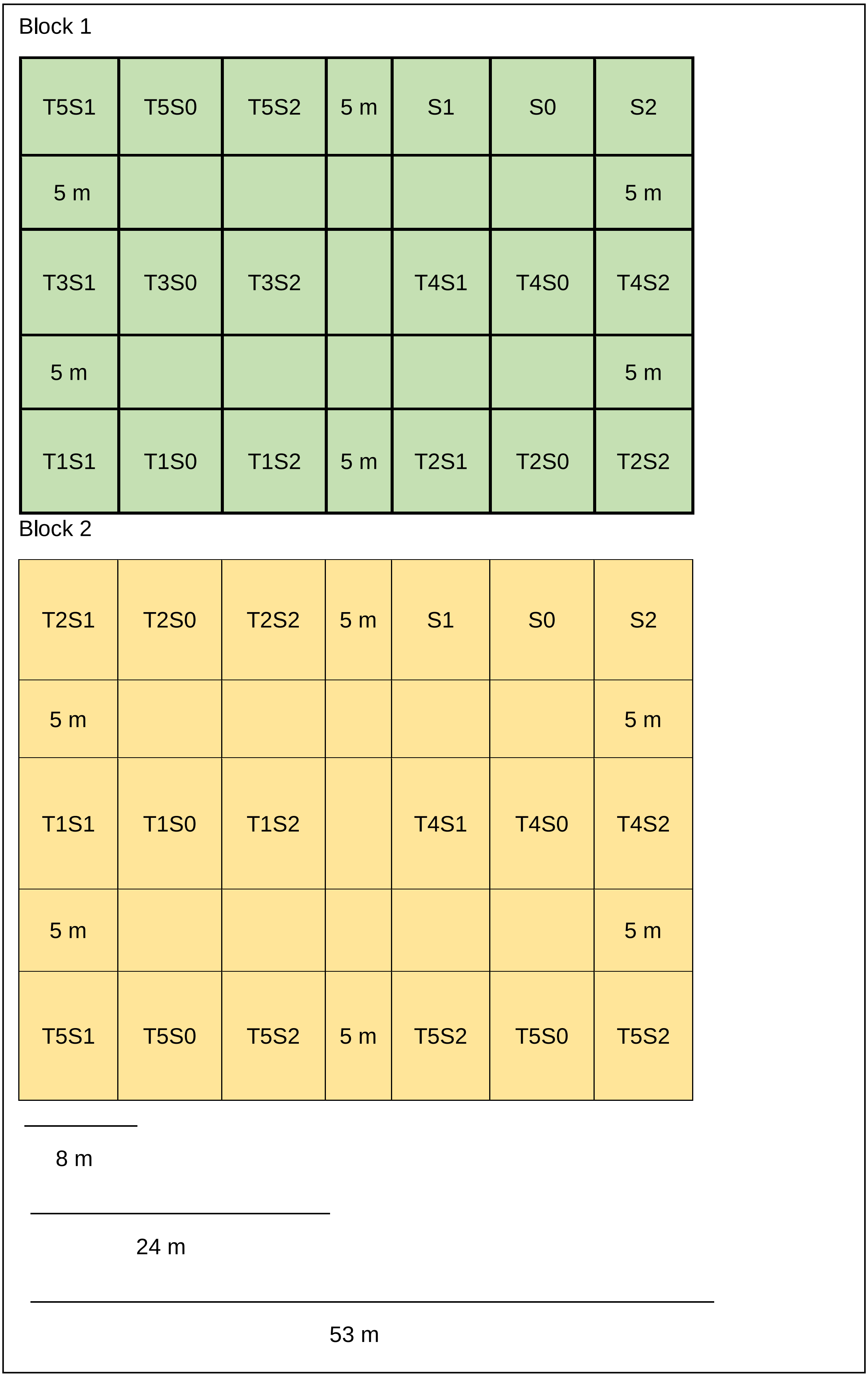
Appendix 2 Experimental blocks and treatment distribution of Flatt Nook field experiment 2014. See the abbreviation in Table 6.1



Field dimensions
Width: 111 m
Length: 61 m

Block dimensions
Width: 53 m
Length: 28 m

Plot dimensions
Width: 8 m
Length: 6 m

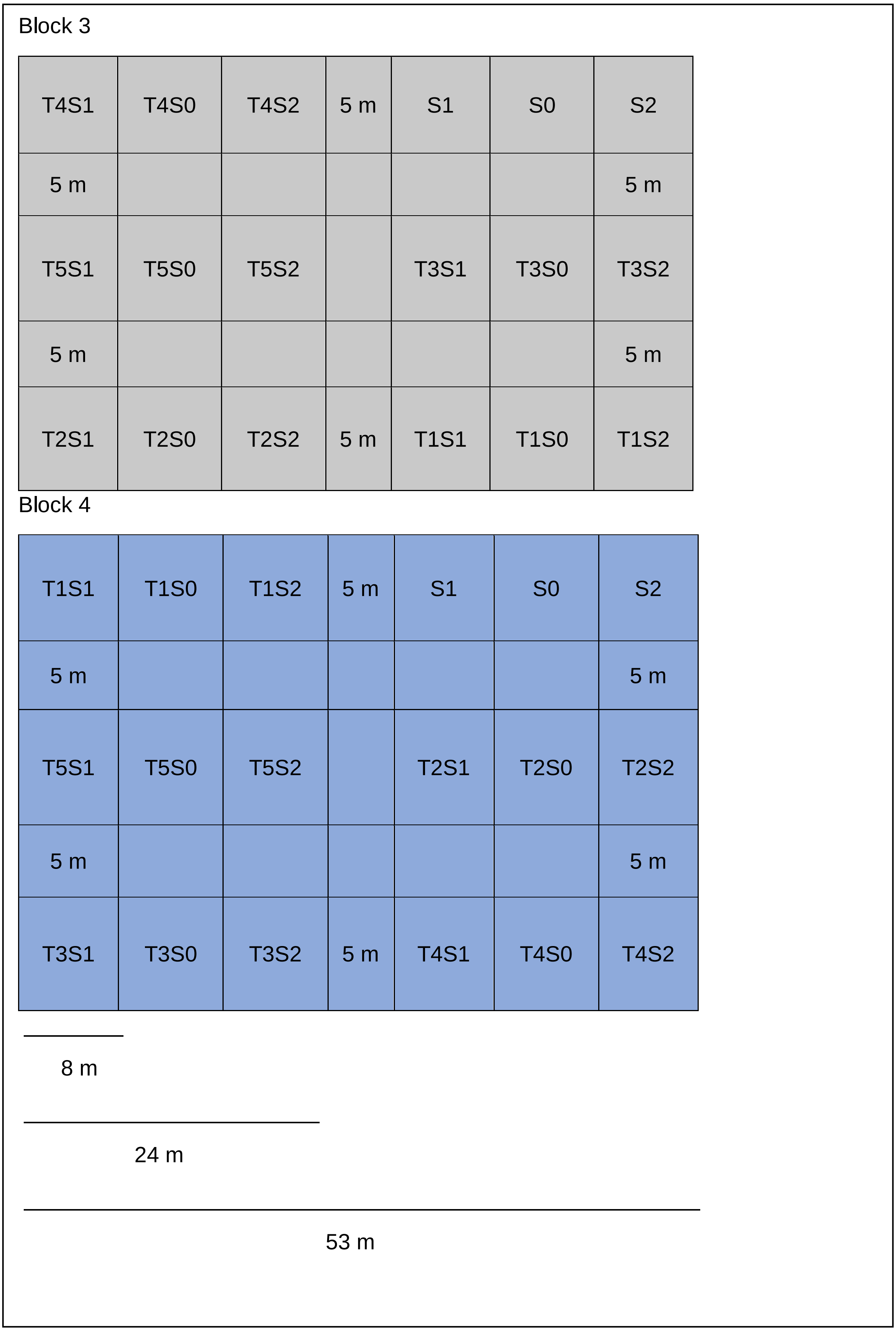


Block 1

T5S1	T5S0	T5S2	5 m	S1	S0	S2
5 m						5 m
T3S1	T3S0	T3S2		T4S1	T4S0	T4S2
5 m						5 m
T1S1	T1S0	T1S2	5 m	T2S1	T2S0	T2S2

Block 2

T2S1	T2S0	T2S2	5 m	S1	S0	S2
5 m						5 m
T1S1	T1S0	T1S2		T4S1	T4S0	T4S2
5 m						5 m
T5S1	T5S0	T5S2	5 m	T5S2	T5S0	T5S2



Block 3

T4S1	T4S0	T4S2	5 m	S1	S0	S2
5 m						5 m
T5S1	T5S0	T5S2		T3S1	T3S0	T3S2
5 m						5 m
T2S1	T2S0	T2S2	5 m	T1S1	T1S0	T1S2

Block 4

T1S1	T1S0	T1S2	5 m	S1	S0	S2
5 m						5 m
T5S1	T5S0	T5S2		T2S1	T2S0	T2S2
5 m						5 m
T3S1	T3S0	T3S2	5 m	T4S1	T4S0	T4S2

Appendix 3 Treatment distribution of Crabtree leasow field experiment April 2016

Left side	8m wide	Sprinkler traction 3m	8m wide	Right side
1	DISC – DRILL	6 m	MB – DRILL	13
	3m guards			
2	MB + DRILL		DISC + DRILL	14
3	DISC + DRILL		MB – DRILL	15
4	MB – DRILL		DISC – DRILL	16
5	MB + DRILL		DISC + DRILL	17
6	DISC – DRILL		MB + DRILL	18
7	MB – DRILL		DISC – DRILL	19
8	DISC + DRILL		MB – DRILL	20
9	MB + DRILL		DISC – DRILL	21
10	DISC + DRILL		MB + DRILL	22
11	DISC – DRILL		MB – DRILL	23
12	MB + DRILL		DISC + DRILL	24

Terminology	
MB	Mouldboard ploughing
DISC	Disc ploughing
+	With drilling
-	Without drilling

Table A3. 1 water-runoff samplers' distribution for each plot of left side of Crabtree leasow field experiment

Left side		Samplers distribution m^2			
1	DISC – DRILL	2*2	0.5*0.5	1*1	3*3
2	MB + DRILL	3*3	2*2	1*1	0.5*0.5
3	DISC + DRILL	3*3	1*1	0.5*0.5	2*2
4	MB – DRILL	0.5*0.5	1*1	2*2	3*3
5	MB + DRILL	1*1	0.5*0.5	3*3	2*2
6	DISC – DRILL	3*3	0.5*0.5	2*2	1*1
7	MB – DRILL	2*2	1*1	0.5*0.5	3*3
8	DISC + DRILL	2*2	0.5*0.5	3*3	1*1
9	MB + DRILL	1*1	3*3	2*2	0.5*0.5
10	DISC + DRILL	3*3	2*2	1*1	0.5*0.5
11	DISC – DRILL	0.5*0.5	1*1	3*3	2*2
12	MB + DRILL	2*2	3*3	1*1	0.5*0.5

Table A3. 2 water-runoff samplers' distribution for each plot of right side of Crabtree leasow field experiment

Right side		Samplers distribution m^2			
13	MB – DRILL	0.5*0.5	1*1	2*2	3*3
14	DISC + DRILL	2*2	3*3	0.5*0.5	1*1
15	MB – DRILL	3*3	0.5*0.5	1*1	2*2
16	DISC – DRILL	1*1	2*2	3*3	0.5*0.5
17	DISC + DRILL	0.5*0.5	3*3	2*2	1*1
18	MB + DRILL	3*3	2*2	1*1	0.5*0.5
19	DISC – DRILL	0.5*0.5	1*1	2*2	3*3
20	MB – DRILL	3*3	0.5*0.5	1*1	2*2
21	DISC – DRILL	2*2	3*3	0.5*0.5	1*1
22	MB + DRILL	1*1	2*2	3*3	0.5*0.5
23	MB – DRILL	0.5*0.5	3*3	2*2	1*1
24	DISC + DRILL	3*3	2*2	1*1	0.5*0.5

Appendix 4 Treatment distribution of Flatt Nook field experiment-November 2016

			Sprinkler traction 3m			
		8m wide		8m wide		
Block 1	1	HP DD	3m	VP HD	13	Block 3
		4m guards				
	2	VP VD		VP DD	14	
	3	HP VD		HP HD	15	
	4	VP HD		HP VD	16	
	5	HP HD		VP VD	17	
	6	VP DD		HP DD	18	
Block 2	7	HP VD		HP VD	19	Block 4
	8	VP DD		VP VD	20	
	9	HP HD		HP HD	21	
	10	HP DD		HP DD	22	
	11	VP VD		VP HD	23	
	12	VP HD		VP DD	24	

Terminology	
HP	Horizontal ploughing
VP	Vertical ploughing
HD	Horizontal Drill
VD	Vertical Drill
DD	Diagonal Drill