IN-FIELD EVALUATION OF IRRIGATION SYSTEM PERFORMANCE WITHIN THE SUGARCANE INDUSTRY OF THE SOUTH-EAST LOWVELD IN ZIMBABWE

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DISCLAIMER

I wish to certify that the work reported in this dissertation is my own original and unaided work except where specific acknowledgement is made.

Signed:______________________________

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ABSTRACT

The near collapse of the Zimbabwean sugarcane industry in 1991/1992 was concluded to be as a result of critical water shortages. This, combined with the uncertainty in the availability of water and a climate characterised by recurring droughts, strongly motivated the sugarcane industry in the South-East Lowveld to strive for improvements in water management and led to the establishment of the Mobile Irrigation Performance Unit (MIPU) in April 2000.

Following an extensive literature review, evaluation methods and performance parameters were determined for the different irrigation systems currently in use in the sugarcane industry within the Lowveld of Zimbabwe, in relation to international standards. The systems in use included furrow, centre pivot, hand-move sprinkler, static sprinkler and sub-surface drip. The study also resulted in the development of some novel evaluation tools, examples being a simple device to measure the inflow to irrigation furrows and a uniquely shaped nozzle, used to determine operating pressures within the sub-surface drip system. Factors that can affect a system's performance were investigated and a comparison of the different irrigation system's performance parameters was shown. The evaluation results obtained by the Lowveld MIPU were also compared to MIPU results obtained internationally and reported in the literature.

The MIPU evaluations are considered to be of great benefit to the farmer because an extensive database of irrigation system performance has been collated, against which farmers can benchmark their systems in the future. It is also possible that the repetitive nature of certain management and design variables which may be detrimental to system performance under local conditions, can eventually be rendered obsolete, for example, incorrect assumptions in scheduling of irrigation. The evaluation data can also be used to help facilitate objective decisions regarding the selection of irrigation systems to suit particular environments.

The research indicates that the sugarcane industry could derive major benefits in improved irrigation systems performance by ensuring that irrigation system operators have the required calibre of skills and sufficient training. The results reported here should benefit farmers and result in refinements to the crop production system rendering it more cost effective and efficient.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

In South Africa, irrigated agriculture is reportedly the largest user of water resources, using 53% of the total annual amount used (WRC, 1999). In California Pitts *et al.* (1996) noted that irrigated agriculture accounted for more than 80% of all surface water diverted whilst in Zimbabwe, irrigated agriculture has been reported to consume 80% of the recorded water use (GoZ, 1999). Therefore, as pressures increase on the finite global water reserves, and as competition for water increases between the different economic and environmental sectors, the irrigation sector, in particular, is being forced to become more accountable for their water use (Ascough, 2005).

In their conclusions on the effect of the 1991/1992 drought in Zimbabwe, Binnie and Partners (1993) stated that the reason for the near collapse of the sugarcane industry was as a result of critical water shortages. This, combined with the uncertainty in the availability of water and a climate characterised by recurring droughts, strongly motivated the sugarcane industry in the South-East Lowveld of Zimbabwe to strive for improvements in water management (Lecler and Griffiths, 2003). As a consequence, the sugarcane industry in Zimbabwe initiated a Water Management Project (WMP) in 1998 (ZSAES, 1998), which was to be administered from the Zimbabwe Sugar Association Experiment Station (ZSAES).

A Mobile Irrigation Performance Unit (MIPU) was established in April 2000 to, *inter alia*, collect evaluation data that were needed for the field level objective of the WMP, which was to collate and analyse information already available on crop yields, irrigation systems and water use (ZSAES, 2000). The author was tasked to establish and run the MIPU, under the supervision of Dr NL Lecler, who was the manager of the WMP.

The objectives of the research described in this dissertation were to use data collected by the MIPU in order to:

(i) Apply, and/or develop, methodologies suitable for in-field evaluation of irrigation systems in the Zimbabwean sugarcane industry,

(ii) Determine performance parameters of the different irrigation systems in the Zimbabwe sugarcane industry in relation to international standards,

(iii) Define and investigate factors which may affect selected performance parameters within the different irrigation systems, and

(iv) Compare the performance parameters between the different irrigation systems operating within the Zimbabwean sugarcane industry.

Owing to the Zimbabwean governments land reform programme which was started in 2000, one main objective of the MIPU programme was not included in the research, this would have involved follow-up evaluations on the selected private commercial farms and would have helped to determine the effect on an irrigation systems performance, once the written report by the MIPU had been adopted by the farmer.

In the present irrigation market there are a variety of irrigation systems which are accessible to an irrigation farmer. The actual, and not the potential, performance of these systems and the respective management criteria, under specific local conditions, can be major factors in the choice of one system over the other. In addition, the fact that one farmer could achieve higher sugarcane yield per unit of water used compared to another, in the same area, needed investigation. Griffiths and Lecler (2001) state that the reasons for differences in performance could be a combination of environmental conditions, scheduling, system performance/design and management.

Supporting this statement, Solomon (1998) notes that due to the fact that crop yield is related to irrigation uniformity and the efficient use of resources, engineers regard uniformity as an important factor to be considered in the selection, design and management of irrigation systems. In this regard, Fairweather *et al.* (2003) note that techniques for improving the effectiveness of all types of irrigation systems can be found in many agriculture water-related journals with the common thread in most techniques being the management component and, in many cases, the requirement to measure the irrigation event. This measurement of the irrigation event is known as an evaluation.

In order to calculate the in-field distribution of water by the irrigation system, otherwise known as the uniformity, and in order to assess the efficiency as well as to determine how adequately the irrigation system met the irrigation target application, specific evaluation procedures for specific irrigation systems must be followed. An evaluation of an irrigation system involves taking in-field measurements and then using scientific principles to assess these measurements in light of selected performance standards. However, most countries, including Australia and South Africa, are still in the process of finalising these standards. Evaluating an irrigation system should measure and show the effectiveness of existing irrigation practice (Merriam and Keller, 1978), provide remedial measures if necessary, and determine the impact of factors which affect the performance parameters on the overall economic viability of a farmer's production system.

Before this project was instituted there had been limited evaluation of the various irrigation systems in operation within the Zimbabwean sugarcane industry. It was therefore anticipated that this project would contribute towards achieving these goals for local sugarcane farmers.

Currently centre pivot, furrow, hand-move sprinkler, static sprinkler and sub-surface drip irrigation systems are used for irrigating sugarcane in the South-East Lowveld of Zimbabwe. Thus a literature review of the performance parameters and evaluation methodologies currently available for these respective irrigation systems is presented in Chapter 2. Details on the methodologies chosen and used in the evaluations are provided in Chapter 3. The results and analyses of the in-field evaluations are contained in Chapter 4. Additional data and tools from the MIPU evaluations which can be used to enhance an irrigation systems performance are presented in Chapter 5. Discussion of the study, including conclusion and recommendations is contained in Chapter 6, and the references used in the document are contained in Chapter 7.

2. OVERVIEW OF IRRIGATION SYSTEM PERFORMANCE

In order to fully appreciate and understand the performance of an irrigation system, a review of the important performance parameters, evaluation methodologies and results of evaluations undertaken around the world, are presented in this chapter.

2.1 Performance Parameters

The ideal irrigation system applies water at a rate that allows all water to infiltrate and the water to be distributed both in space and time to match crop water requirements in each parcel of the field (Hoffman and Martin, 1993). However, this is for an ideal system which is rarely, if ever, found in practice. Most, if not all, irrigation systems will require some measure of improvement in order to obtain an "ideal" irrigation system. In order to quantify any improvements in irrigation performance obtained from either better management, or through the application of improved technology, Fairweather *et al.* (2003), state that it is important to take appropriate measurements, which can help determine the efficiency of an irrigation system.

In this regard, Lecler (2004) proposed a system whereby the uniformity measures within a field, taken from numerous irrigation events together with water management information, are utilised in an irrigation and yield forecasting model (*ZIMsched 2.0*). Such a model can be used to simulate the effects of management and uniformity on the water budget and yield estimates over an entire growing season and thus allows for the eventual calculation of the efficiency of a farmers production system.

The increasing competition for scarce water resources has motivated researchers and water resource managers to examine more closely the efficiency of water use in agriculture. According to Wichelns (2003), several researchers have defined terms, both old and new, to describe irrigation efficiency in order to enhance the information available when evaluating water policy decisions.

Unfortunately, numerous definitions of efficiency and uniformity have been developed over the years for different objectives and irrigation systems. Attempts at unifying these definitions have not been entirely successful. Some of the difficulties stem from conflicting objectives, while others arise from differences between academic and practitioner needs (Clemmens and Dedrick, 1994). However, in discussions held with various researchers (Strelkoff, 2004; Lecler 2006; Raine, 2006), there is general consensus on the fact that as long as units and measurements are clearly defined, even if certain equations in different studies are slightly different, the information used in the equations can be used to compare/benchmark the performance of irrigation systems, with an acceptable level of accuracy.

The three performance parameters which are important when reporting on the performance of an irrigation system are efficiency, uniformity and adequacy. All of these parameters are interrelated and are discussed in the following sections.

2.1.1 Efficiency

Wolters and Bos (1989) state that efficiency is generally defined as the dimensionless ratio of output divided by input. Fairweather *et al.* (2003) concur with this definition and cite Barrett Purcell and Associates (1999) as correctly pointing out that efficiency is in fact a dimensionless term obtained by dividing values which have the same units. However, in the context of irrigation there is much confusion with respect to the definition of efficiency.

The confusion is due to the fact that efficiency can mean different things to different people. There are publications which document the evolution of efficiency terms and performance concepts used in the irrigation industry (Wolters and Bos, 1989; Fairweather *et al.*, 2003; Ascough, 2004) and a number of publications containing reviews of efficiency terms which the respective authors believe are relevant within the field of irrigation (Heerman *et al.*, 1990; Clemmens *et al.*, 1995; Burt *et al.*, 1997; Pereira, 1999; Purcell and Curry, 2003; Page Bloomer and Associates, 2006).

The "confusion" surrounding the efficiency terms has lead to some countries and international institutions to attempt to clarify and standardise the relevant terms used. One of the most comprehensive initial attempts was carried out by the American Society of Civil Engineering (ASCE) Task Committee on Defining Irrigation Efficiency and Uniformity, which published a variety of papers on the subject, clarifying common points of confusion and proposing methods whereby the accuracy of numerical values of the performance indicators could be assessed (Burt *et al.*, 1997). This committee favoured an irrigation water balance approach, which determines the fate of the various fractions of the total irrigation water applied, by defining terms such as consumptive and non-consumptive use, beneficial and non-beneficial use and also reasonable and non-reasonable use. These terms are expanded on below, based on explanations by Burt *et al.* (1997) and Ascough (2001):

- Consumptive use: Irrigation water that ends up either in the atmosphere, through evaporation and transpiration, or in the harvested plant tissue, with this water considered to be irrecoverable.
- Non-consumptive use: These include any other amounts of water that leave the selected region which can be re-applied elsewhere.
- Beneficial use: Water that supports the production of a crop and which is consumed in order to fulfil an agronomic need.
- Non-beneficial: Any water use that is not beneficially used is, by definition, non-beneficial.
- Reasonable use: All beneficial uses are reasonable uses in the context of irrigation performance.
- Unreasonable use: For the purpose of measuring irrigation performance, unreasonable uses are non-beneficial uses that are not reasonable, i.e. they are without economic, practical, or other justification.

In Australia, a four-stage project titled "Determining a Framework, Terms and Definitions for Water Use Efficiency in Irrigation", was initiated in 1999 by the National Irrigation Efficiency Group (NIEG), which is a sub-committee of the National Program for Irrigation Research and Development (NPIRD). The purpose of the project was to promote the development of consistent irrigation standards (Purcell and Currey, 2003). Linked to this project, Barrett Purcell and Associates (1999) suggest a framework that considers the performance of all aspects involved in an irrigation water balance approach in determining the fractional use of water, as shown in Figure 2.1.

Ascough (2004) notes that in South Africa, definitions for irrigation efficiency have been varied and are not universally applied. In an effort to standardise the definitions a workshop was held in 2002 at the Agricultural Research Council's Institute for Agricultural Engineering (ARC-ILI) in Pretoria,. This led to project K5/1482/4, funded by the Water Research Commission, titled "Standards and Guidelines for Improved Efficiency of Irrigation Water Use From Dam Wall Release to Root Zone Application" (Ascough, 2004). As part of this project, uniformity and efficiency terms within a comprehensive water balance framework have been proposed by Lecler (2005).

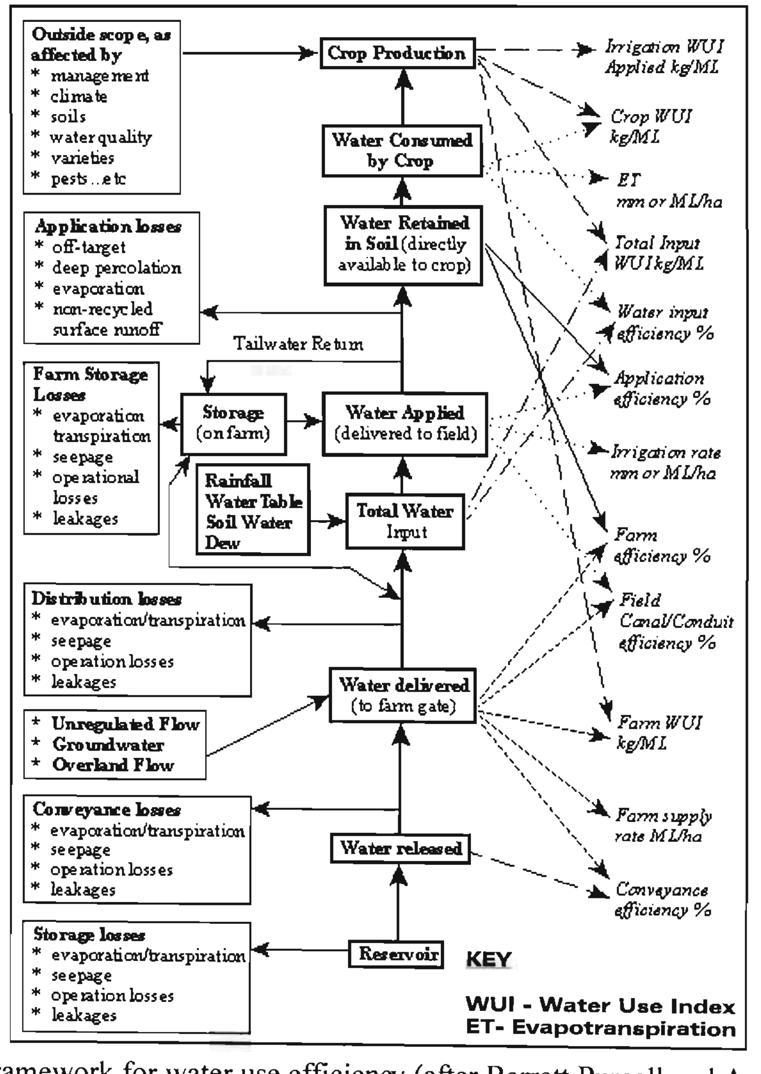

Figure 2.1 Framework for water use efficiency (after Barrett Purcell and Associates, 1999)

The International Commission on Irrigation and Drainage (ICID) is currently drafting a paper titled "Efficient Irrigation; inefficient communication; flawed recommendations", which also seeks to propose a framework on consistent terminology and definitions (ICID, 2006).

Burt *et al.* (1997) state that efficiency terms are, in principle, difficult to evaluate rapidly and require a detailed inventory and quantification of the ultimate destinations and uses of applied irrigation water. In order to overcome this difficulty, an alternative "single event" efficiency is described which enables the performance of an irrigation system in the field to be assessed by how efficiently the system satisfies a perceived need.

This "single event" efficiency is known as the Application Efficiency (AE), and is based on the concept of meeting a target irrigation depth for that event, as interpreted by Burt *et al.* (1997) and also supported by Lecler (2005). Other definitions of AE are proposed by Wolters and Bos (1989). The Burt *et al.* (1997) formulation of AE is given in Equation 2.1. The average depths are given in mm. The target depth chosen can be the soil moisture deficit (SMD), or a smaller amount to supplement rainfall, or it may include a portion of the spray evaporation losses which can be considered to be beneficial (Lecler, 2004). It must be noted that the chosen target depth is also dependent on the type of irrigation system in use.

$$AE = \frac{\text{average depth of irrigation water contributing to TARGET}}{\text{average depth of irrigation water applied}} \times 100\% \qquad (2.1)$$

The first requirement for the efficient operation of an irrigation system is the uniform application of water. Pitts (2001) noted that a highly uniform application of water does not ensure high efficiency, since water can be uniformly under or over-applied. However, in order to achieve good crop yields, both a highly efficient system and uniform application of water are required. Baum *et al.* (2005) explain that irrigation can be uniform and inefficient; however, irrigation cannot be non-uniform and efficient. As a result, irrigation uniformity can be a good indication of potential irrigation efficiency, and is easier to quantify and measure than efficiency.

2.1.2 Uniformity

According to Solomon (1998), the term "irrigation uniformity" refers to the variation, or non-uniformity, in the spatial distribution of the amounts of water applied to locations within the wetted area. Uniformity influences crop yields through the agronomic effects of under and over-watering. Insufficient water leads to high soil moisture tension, plant stress and reduced crop yields.

Excess water may reduce crop yields as a result of leaching of plant nutrients, an anaerobic rooting environment as well as increased disease or failure to stimulate growth of economically valuable parts of the plant (Griffiths and Lecler, 2001).

Heermann *et al.* (1990) note that irrigation uniformities for overhead sprinkler irrigation systems can be evaluated by measuring the spatial distribution of application depths with catch cans. For drip systems, the emitter discharge is measured and for surface systems the intake opportunity time, which is the time that water at a particular point takes to infiltrate the soil, is typically used for evaluating irrigation uniformities.

According to Pereira (1999), several parameters are used as indicators of the uniformity of water application to a field. The most commonly used are the Coefficient of Uniformity (CU), Distribution Uniformity (DU) and the Statistical Uniformity Coefficient (SU).

2.1.2.1 Coefficient of Uniformity

One of the first and most common quantitative measures of uniformity is the Christiansen Uniformity Coefficient (CU). This was developed for evaluating sprinkler systems in 1942, and is still the most widely used and accepted measure for uniformity (Ascough and Kiker, 2002). The CU provides a quantitative measure of the average deviation from the mean application depth (King *et al.*, 2000).

The CU can be expressed by (ASAE S436.1, 1998) as

$$CU = 100\left[1 - \frac{\sum_{i-1}^{n} \left|D_i - \overline{D}\right|}{\sum_{i-1}^{n} D_i}\right] \qquad (2.2)$$

where D_i is the catch can depth of the application [mm], $\bar{D}$ is the mean catch can depth [mm], and n is the number of catch cans.

Heermann *et al.* (1990) note that the above definition requires that each can represent the depth applied to equal areas. This is not true for data collected under centre pivot systems. Thus the above equation was modified by Heermann and Hein (1968) to include a term representing the distance from the centre to the catch can, S_i (Ascough, 2004) and changes from CU to CU_{HH}. The CU_{HH} is represented by (ASAE S436.1, 1998) as

$$CU_{HH} = 100\left[1 - \left[\frac{\sum_{i=1}^{n} S_i \left| D_i - \frac{\sum_{i=1}^{n} D_i S_i}{\sum_{i=1}^{n} S_i} \right|}{\sum_{i=1}^{n} D_i S_i}\right]\right] \qquad (2.3)$$

where S_i is the distance from the centre of the pivot to the catch can [m]. There are three important features of the CU formulae which should be recognised and considered when interpreting CU and CU_{HH} values (Zoldoske and Solomon, 1988):

- First, owing to the absolute value used in determining the average absolute deviation from the mean, CU treats over-watering and under-watering equally.
- Secondly, the computation of D assigns penalties in a linear manner. This means that the penalty assigned to each value is in direct proportion to the amount by which it deviates from the mean.
- The third feature of CU is that it is an average measurement. It gives no indication of how severe the deviation may be at a particular location in the field, or how large that critical area might be.

2.1.2.2 Distribution Uniformity

One measure which emphasizes the under-watered area and looks at the critical regions is the Distribution Uniformity (DU). It gives an indication of the magnitude of the unevenness of the distribution and can be defined as the per cent of average application amount in the lowest portion (normally the low quarter) of the field (Rogers *et al.*, 1997).

The lowest quarter fraction, d_{lq} [mm], has been used by the United States Department of Agriculture (USDA) since the 1940s and has proved to be useful in irrigated agriculture. It is defined in Equation 2.4 (Burt *et al.*, 1997):

$$d_{lq} = \frac{\text{vol. accum. in 1/4 total area of elements with smallest depths}}{\text{total area of 1/4 of the total area of elements}} \tag{2.4}$$

From Equation 2.4 the low-quarter distribution uniformity, DU_{lq}, can be defined as:

$$DU_{lq} = \frac{d_{lq}}{d_{avg}} \tag{2.5}$$

$$DU_{lq} = \frac{\text{average low-quarter depth}}{\text{average depth of water accumulated in all elements}} \tag{2.6}$$

where d_{avg} is the total volume accumulated in all elements [mm], divided by total area of all the elements. DU_{lq} is a uniformity term most commonly used in furrow irrigation, but is increasingly being used in other irrigation systems for purposes of comparison.

2.1.2.3 Statistical Uniformity

Ascough and Kiker (2002) state that Statistical Uniformity (SU) is usually used to represent the uniformity of micro-irrigation systems, such as drip irrigation. The main reason is that water is not applied to the whole field area (Koegelenberg and Breedt, 2003).

The SU can be expressed as shown in Equation 2.7 (Pereira, 1999):

$$SU = 100(1 - V_q) = 100\left(1 - \frac{S_q}{q_a}\right) \tag{2.7}$$

where V_q is the coefficient of variation of emitter flow, S_q is the standard deviation of emitter flow [l/h] and q_a is the average emitter flow rate [l/h].

Lecler (2004) noted that the CU, DU_{lq} and SU are all mathematically interrelated, and assuming a normal distribution of data collected in-field, relationships between the three parameters shown in Equations 2.8 and 2.9 may be derived (adapted from Warrick, 1983; Smesrud and Selker, 2001) such that

$$DU_{lq} = 100 - 1.59(100 - CU) \tag{2.8}$$

$$DU_{lq} = 100 - 1.27(100 - SU)\ . \tag{2.9}$$

Clemmens and Solomon (1997) note that the normal distribution represents many irrigation component distributions. Of the three uniformity values, DU_{lq} is the most stringent (Lecler, 2004).

2.1.3 Adequacy

For a single irrigation event it is pertinent to include a parameter which determines how well the required depth of water has been satisfied. In many cases managers and researchers are interested in the low-quarter depth just equalling the required depth. This is termed the low-quarter adequacy (AD_{lq}), and is given by (Burt *et al.*, 1997) as

$$AD_{lq} = \frac{d_{lq}}{d_{req}} \tag{2.10}$$

where d_{req} is the required depth for all beneficial uses [mm]. Ascough (2004) states that with this definition an $AD_{lq} < 1$ indicates under-irrigation, and an $AD_{lq} > 1$ indicates over-irrigation. Figure 2.2 illustrates another form of interpretation of adequacy (English, 2000; King *et al.*, 2000; Magwenzi, 2000), where the graphical concept is defined as the percentage of the field that is fully irrigated. The shape and slope of Figure 2.2 is determined by the uniformity of applied water. The more uniform the application the more level the curve. As more water is applied, more of the curve will be above the irrigation requirement line, and so the adequacy will be higher. This format can be used to examine the relationship between adequacy, efficiency and uniformity (English, 2000). This graphical version of adequacy is denoted by the abbreviation AD.

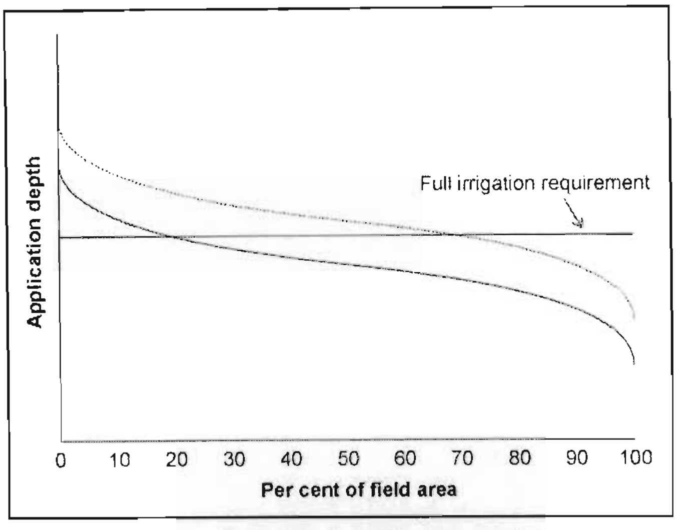

Figure 2.2 Spatial distribution of applied water (after English, 2000)

2.1.4 Relationship between adequacy, efficiency and uniformity

The relationship between adequacy, efficiency and uniformity is best described graphically, with an example taken from English (2000) and shown in Figure 2.3 and 2.4. Figure 2.3 shows two curves, representing two different uniformities, but both applying water at 50% adequacy. The more uniform application results in less excess water applied, and therefore the application efficiency is higher. The more uniform system also results in less under-irrigation. Figure 2.4 shows two curves representing the same uniformity, but different levels of adequacy. This figure illustrates the inverse relationship between adequacy and efficiency, one of the most important, and least understood relationships. As adequacy is increased, the amount of water lost as deep percolation is increased, and therefore efficiency is decreased.

Magwenzi (2000) also notes that there is a limitation in using efficiency as the only measure of irrigation system performance because it does not show the uniformity of distribution or the percentage of the area that was adequately irrigated. Thus, a combination of all the above parameters would be best practice.

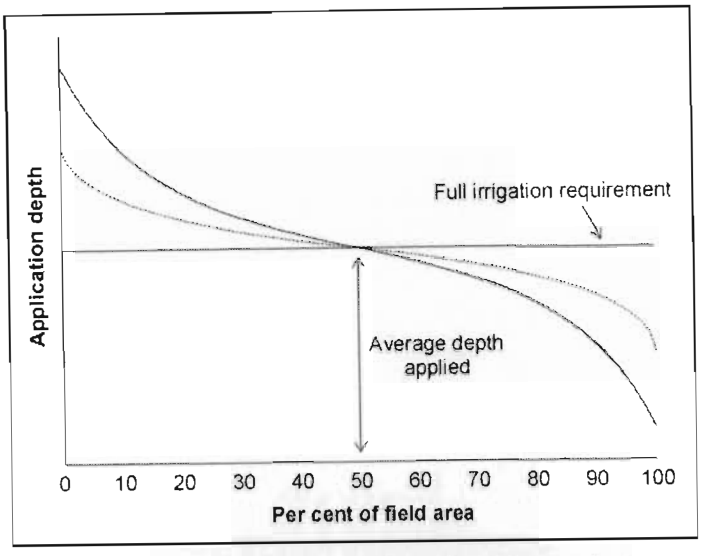

Figure 2.3 Distribution for two irrigation systems having equal adequacy, but different uniformity and application efficiency (after English, 2000)

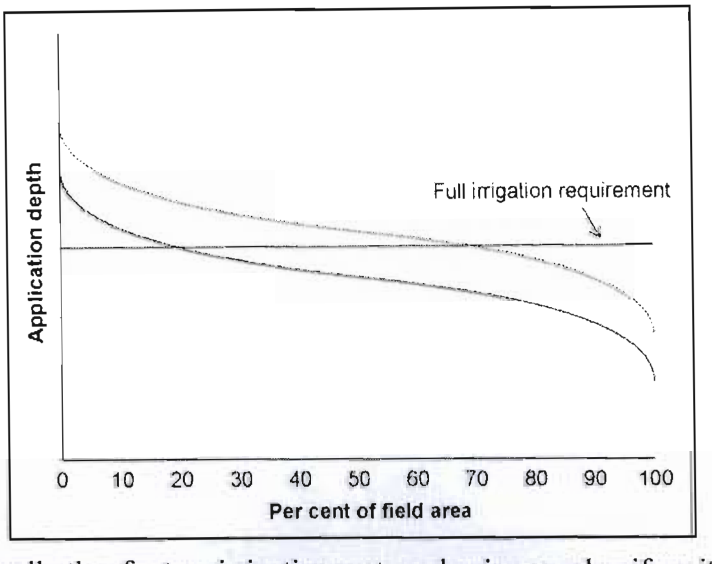

Figure 2.4 Distribution for two irrigation systems having equal uniformity, but different adequacy and application efficiency (after English, 2000)

According to Baum *et al.* (2005) distribution uniformity is often measured as an indicator of potential efficiency. Thus the factors that affect the uniformity must be noted and measured if possible, as they impact on the overall efficiency of a system.

2.1.5 Factors which affect uniformity

The uniformity of each type of irrigation system is influenced by different factors which are detailed by Pereira (1999) and Burt *et al.* (1997). These factors are listed in Tables 2.1 to Table 2.4.

Table 2.1 Examples of components that affect uniformity for furrow irrigation systems (after Burt *et al.*, 1997)

Uniformity component	Factors causing non-uniformity
Opportunity-time differences down a furrow	Extent of ponding Flow rate and duration Slope and roughness Furrow cross-sectional shape Furrow length
Opportunity-time differences between furrows	Different day/night irrigation set times Wheel row compaction/no wheel compaction Different furrow flow rates
Different infiltration characteristics for individual furrows	Different degrees of compaction due to tractor tyres and tillage
Different infiltration characteristics across the field	Different soil types Soil chemical differences Texture differences of soils
Other opportunity time differences throughout a field	Non-uniform land preparation
Difference in day and night intake rates	Viscosity changes due to temperature changes
Infiltration rate differences due to differences in wetted perimeter	Slope changes or restriction to flow along the furrow

Table 2.2 Examples of components that affect uniformity for centre pivot irrigation systems (after Burt *et al.*, 1997)

Uniformity component	Factors causing non-uniformity
Sprinkler (spray head) flow rates not proportional to area served	Poorly controlled sprinkler pressures Elevation changes Pressure regulator differences Nozzle plugging and wear
Sprinkler overlap non-uniformity between adjacent sprinklers	Wind System travel speed variations Elevation of sprinkler (spray head) Crop interface Worn spray plates Spacing
Edge effects	Wind direction changes Soil texture Distance from pivot point Surface conditions (surface ponding, residues) Nozzle angle changes due to topography
Radial arc effects	Activation of end guns and corner swing lateral sections or towers without proper control of flow rates along the pivot length
System flow variation	Engine performance Pump response to different pressure requirements Pressure variations from the source

Table 2.3 Examples of components that affect uniformity for drip/micro irrigation systems (after Burt *et al.*, 1997)

Uniformity component	Factors causing non-uniformity
Difference in discharge between emitters	Pressure differences Plugging of emitters Manufacturing variation Soil differences for buried emitters Temperature differences along a lateral
Volumes applied not proportional to plant area assuming the same plant age	Variations in plant spacing are not matched by emitter spacing or irrigation scheduling. Unequal discharge during start-up and drainage

Table 2.4 Examples of components that affect uniformity for static and hand-move sprinkler irrigation systems (after Burt *et al.*, 1997)

Uniformity component	Factors causing non-uniformity
Flow rate differences between sprinklers	Pressure differences Different nozzle sizes Nozzle wear Nozzle plugging
Sprinkler pattern (catch can) non-uniformity	Spacing Sprinkler design (angle of trajectory, impact-arm interception characteristics) Nozzle size and pressure Wind Vertical orientation of sprinkler head Plant interference around a sprinkler
Unequal application during start-up and shutdown	Pipe diameter and length Duration of set
Edge effects	Inadequate overlap on edges

The condition of an irrigation system will also influence the uniformity of water application and thus the maintenance of the system is important. Thoreson *et al.* (1997) define two types of maintenance:

- Corrective maintenance is any action required to return a system's performance to a desired level, and
- Preventive maintenance is any action required to keep a system's performance at a desired level.

The performance evaluation of in-field irrigation systems can be divided into the two major components of water losses and uniformity of application. Although both components are influenced by system design and management practices, the losses are predominantly a function of management while the uniformity is predominantly a function of the system design characteristics (Raine *et al.*, 2005). Hoffman and Martin (1993) believe that the design of an irrigation system defines the ultimate potential while management of the system dictates the actual level achieved in an irrigation system's performance.

Alvarez *et al.* (2004) note that the general objective of field evaluations is to help farmers detect management and system operation problems. Characterising how the irrigation system performs is a secondary choice. Magwenzi (2000) states that research supports the fact that there is value in evaluating the performance of an irrigation system as an integral part of irrigation management. In trying to improve irrigation efficiencies, it is necessary for irrigators to identify their current efficiencies and the techniques by which improved efficiencies can be achieved, and also be motivated to change (Skewes and Howell, 1998; cited by Raine and Foley, 2002).

2.2 Methodology of Evaluation

Griffiths and Lecler (2001) state that the objectives of evaluating the performance of an irrigation system are:

- to determine if the system is working according to farmer assumptions and design specifications in terms of the amount of water applied, and to thereby provide a basis for improved irrigation scheduling,
- to determine how much variation there is in the amounts of water applied and whether or not the measured variation has a significant impact on crop yields, deep percolation (drainage) and runoff losses, fertiliser use efficiencies and production costs,
- to determine the causes of the variation in applied water and to investigate and recommend cost effective remedial action,
- to assess whether or not the conveyance system is sized within design norms that were based on a fair balance between capital and operating costs,
- to check the efficiency with which power is being used, and
- to produce recommendations to improve on any aspects that would result in the effective use of water and energy.

The information from an evaluation should help a farmer reduce input costs, increase returns and, if necessary, provide motivation for a designer to implement remedial measures if a design was not up to standard (Griffiths and Lecler, 2001).

Merriam and Keller (1978) state that the study of the data from a system evaluation will indicate whether improvements can be made. It would also provide management with a reasoned basis for selecting possible modifications that may be both practical and economical.

There are a number of published evaluation methodologies for the various types of irrigation systems. Describing the details of all of these is beyond the scope of this study. It must also be noted that localised operating conditions may require certain aspects of an evaluation procedure to be adapted to suite the conditions, but should not be drastic enough to affect comparisons.

A generic explanation on what parameters should be measured during an evaluation, followed by references to studies where the various methodologies have been employed, are presented in the following sections.

2.2.1 Furrow

Surface irrigation refers to irrigation systems where water flows over the soil surface under controlled conditions with the purpose of delivering the desired amount of water to infiltrate the soil. In furrow irrigation, water is confined to furrows with the water gradually being absorbed into the bottom and sides of the furrow to wet the soil (Kay, 1993; ARC-ILI, 2004a).

Surface irrigation predates all the other systems in use today, but it is still the most difficult irrigation system to evaluate accurately. The hydraulic performance of furrow irrigation depends on the furrow length, the inflow rate, the cut-off time, the land slope, the spacing and shape of the furrows, the resistance to flow in the furrows, the infiltration characteristics of the soil, and, the in-field variability of all of these factors (Burt, 1995; Jurriens and Lenselink, 2001).

Griffiths and Lecler (2001) note that the process of furrow system evaluation itself is quite simple, but the difficulty is in ensuring that the measurements are accurate. The process can be time consuming when a large number of furrows are selected in order to account for in-field variability. The representativeness of evaluation data can also be questioned when there is a large amount of variation in operator input. Therefore, a large number of evaluations are needed, often repeated on the same field during a season, in order to gain confidence in the results.

The important parameters to measure during an evaluation of a furrow system are as follows. The rate of inflow must be measured using, for example, a calibrated syphon and head measuring device or a calibrated flume/weir. The rates of advance and recession are noted at specific points along the furrow and the time of cut-off is recorded. The outflow, if any, is measured with a calibrated flume. A dumpy level is used for surveying the field slopes. Measurements of the depth and area of water flowing in the furrow are recorded using a flexible tape measure. Evaluation methodologies are detailed in the FAO 45 publication (Walker,1989), Burt (1995) and Koegelenberg and Breedt (2003). The American Society of Agricultural and Biological Engineers (ASABE) have also incorporated a comprehensive procedure for evaluating the performance of furrow irrigation systems in a standards manual (Walker, 2005). In Australia a system has been developed for evaluating surface irrigation systems with "Irrimate^{TM}" tools. These include the patented Irrimate^{TM} tools such as digital siphon flowmeter to determine inflow volume, water advance sensors and a digital in-furrow downstream flume to measure outflow volume (Raine *et al.*, 2005).

After the measurements are taken, the data collected can be used to calculate the infiltration parameters using the 'two-point' method (Elliot and Walker, 1982), the 'advance' technique using Infiltv5 (Durack, 2001) and more recently IPARM (Gillies and Smith, 2005), which uses the outflow data as well as advance data to calculate infiltration parameters.

These parameters can be used in simulation software, e.g. SIRMOD (Walker, 1999) and/or SRFRv3.31 (Strelkoff *et al.*, 1998), in order to calculate the corresponding uniformity and efficiency parameters and simulation errors of less than 5% are possible (Raine, 2006). This software can be used to predict irrigation performance, for example, system uniformity and efficiency for different gradients, soils, field dimensions, in-row or inter-row planting. This prediction capability may facilitate the modification of operational furrow irrigation guidelines and, if necessary, be incorporated in the design and layout so that performance is comparable to the other irrigation systems, such as sprinkler and drip.

Both Tilley and Chapman (1999) and Raine (2006) state that the software which is currently used in Australia (SIRMOD) is used mostly for showing farmers the benefits of management practices and has been very effective in this regard. An area of concern, however, is the accuracy of the calculated infiltration parameters and their representativeness over the field. However, with frequent use, the procedures involved can be refined to give accurate values (Griffiths and Lecler, 2001).

2.2.2 Overhead sprinkler

In the sprinkler method of irrigation, water is applied above the ground surface as a spray resembling rainfall. The spray is developed by the flow of water under pressure through small orifices or nozzles. The pressure is usually obtained by pumping, and the irrigation water is distributed to the field through pipelines (ARC-ILI, 2004b). There are a variety of systems within the overhead sprinkler group, most notably the moving centre pivot, the hand-move impact sprinkler and static floppy sprinkler systems, all of which are discussed in the following sections.

2.2.2.1 Centre pivot

A centre pivot is an automated moving system, consisting of steel frames and pipes which are supported at approximately 50 metre intervals by an A-frame on two wheels, which rotates around a central pivot point. Griffiths and Lecler (2001) recommend that a radial line of rain-gauges be laid out along the entire length of the centre pivot in order to determine the uniformity of the water application. Individual sprinklers are selected and flows are measured, to check against the flow required at those positions for the given system capacity. The water application intensity at the outer edge can also be measured. Time and distance measurements are used to assess the accuracy of the system controller settings.

Kincaid (2002) stated that a key aspect of centre pivot performance is the adequacy with which the application rate of the centre pivot is matched to the infiltration rate of the soil, taking into consideration the effect of soil surface sealing from water droplet impact. This can be measured during an evaluation using a specialised infiltrometer apparatus (ARC-ILI, 1984). This apparatus can also be used to determine and also check design specifications, including:

- the maximum size of a centre pivot, for
- a given wetted bandwidth of the sprinkler,

- soil type, and
- highest daily crop water requirements.

The evaluation procedures used for centre pivot systems are detailed by, *inter alia*, USDA (1997), ASAE S436.1, (1998), Koegelenberg and Breedt (2003) and Page Bloomer and Associates (2006). Software from the International Training and Research Centre (ITRC, 2000) and CpED (Heermann, 2000) can be used to check both design and uniformity, but it is noted that this software requires input in American Imperial (AI) units.

2.2.2.2 Hand-move and static sprinklers

The hand-move sprinkler and in-field static (floppy) systems includes the following hardware: the sprinkler, the standpipe and the lateral pipe. The main difference between the static (floppy) and hand-move systems, is that the lateral pipe for the static is buried while the hand-move system lateral is above ground and moveable. For sprinkler irrigation the design parameters which may affect uniform water application include incorrect spacing and/or orientation of sprinklers, mismatched standing times, flow hydraulics and nozzle wear. Rain-gauges are positioned in a grid system in order to measure the uniformity of water distribution. Pressures need to be measured at the sprinkler, together with the flow rate. Special measurement tools can be used to quantify the wear of the nozzle which, as King *et al.* (2000) state, is extremely important and could result in:

- increases in droplet sizes,
- decreases in the overall system discharge pressures,
- distorted sprinkler spray patterns,
- decreases in the uniformity of water application,
- increases in pipe friction losses,
- changes in the pump operating point and efficiency, and thereby
- contribute to increased pumping costs to the farmer in addition to any reduction in yield.

Griffiths and Lecler (2001) note that the procedures involved in evaluating sprinkler systems are explained adequately in Simpson and Reinders (1999). Koegelenberg and Breedt (2003) and Page

Bloomer and Associates (2006), who used internationally recognised performance standards, also describe evaluation procedures for sprinkler systems. Software that can be used to simulate performance includes Spinkmod (Allen, 2001), which can be used to check the hydraulic design of the scheme, and Catch3D (Allen, 2001) which can be used to calculate the uniformities due to different sprinkler layouts/spacings, wind and operating pressures. Once again it must be noted that the above-mentioned software programs require input in the form of AI units.

2.2.3 Drip systems

Burt and Styles (1999) explain that drip irrigation delivers water directly to small areas adjacent to individual plants through emitters placed along a water delivery line (called a lateral). Typical components for drip systems include a pump, filters, chemical injectors, main and submain lines, laterals and emitters (Griffiths and Lecler, 2001). The emitters have very small flow paths through which water flow and therefore blockages are regularly experienced. Blockages are usually caused by poor water quality and potential problems with clogging should already be identified in the design phase, so that preventative maintenance can be taken (Koegelenberg and Breedt, 2003).

2.2.3.1 Sub-surface drip

There are many variations of drip systems. A variation frequently used is known as sub-surface drip (SSD) irrigation. Magwenzi (2000) notes that this is a system which supplies filtered water and chemicals directly into the soil profile and to the roots of the crop through evenly spaced emitters contained in a lateral drip line, with the laterals buried 0.1 m to 0.2 m below the ground surface. The laterals are evenly spaced along a submain. Within the SSD irrigation system designs utilised in the sugarcane industry there are two different design concepts employed:

- Design A: This keeps the supply submain and the flushing manifold separate.
- Design B: In this case the submain must also serve as the flushing manifold. This is also know as the "ring design".

The evaluation procedure that may be followed is based on the standards in USDA (1997), ASAE EP458 (1998), Burt and Styles (1999), Koegelenberg and Breedt (2003) and Page Bloomer and Associates (2006). Software available from the Irrigation Training and Research Center (ITRC, 2000) can also be used for calculation of system uniformity of the system, if the input values are in AI units.

Griffiths and Lecler (2001) state that pressures and flows are two important aspects in SSD irrigation which can affect uniformity adversely. Up to 30 reference points are chosen in the field, i.e. five emitters along each of six laterals where the emitter flow is measured. If the DU_{lq} is below 80% it is advised that pressures be taken along the lateral (Burt *et al.*, 1998). The pressures on either side of the delivery valve to the field are recorded so as to compare recorded values against design criteria. When the pressure variations down the laterals are combined with the flow variation from emitters, these readings can be used to quantify whether emitter flow variation is due to hydraulics or emitter blockages. If emitter blockages are found to be a major problem, methods to help prevent the situation worsening further are recommended. The causes of the blockages can include poor design leading to inadequate flushing velocities, incorrect filtration, poor water sources and pump intake arrangements, and/or inadequate or inappropriate water treatment and routine maintenance (ASAE EP458, 1998). The flushing velocity is measured using an in-line flowmeter.

Lamm (2006) notes that the ASAE EP458 was actually withdrawn as a standard in 2001 due to there being no consensus over whether the "plugging" issue was being dealt with adequately, and if the standard was being used correctly. However, it is acknowledged that the standard is still in use.

2.2.3.2 Drip water quality

Research conducted by the ARC-ILI in South Africa on the performance of drip irrigation under field conditions, concluded that the quality of water used for drip irrigation was extremely important and suggested that water analysis be conducted annually to identify possible clogging hazards (Anon., 2002). Griffiths and Lecler (2001) also recommend that monthly water samples be submitted for analysis by farmers that use drip irrigation systems. In this way a detailed record can be kept for analysis in order to show in which parts of the year a particular treatment may be more effective than another. Table 2.5 is a collation of international literature which the MIPU used to analyse water quality results, the calculations of which are done by water quality analysis laboratories.

In addition, whenever a chemical is to be added to water used in a drip irrigation system, a "jar test" should first be performed. This involves taking a 2 litre glass coke bottle and filling it with the equivalent concentration of chemical and drip water. The bottle is then left overnight in a dark room. When it is checked the next morning, the bottle is held up against the light and, if any precipitates can be seen, the operator should not go ahead with the chemigation (Burt *et al.*, 1998; Burt and Styles, 1999).

Table 2.5 Water quality analysis for sub-surface drip irrigation (after Anon., 1990; Anon., 1992; Burt *et al.*, 1998; Anon., 1999, cited by Dawes, 1999)

ANALYSIS	REASONING
pH	High values (>7.5) can contribute to the proliferation of iron bacteria, and has an influence on both precipitation of insoluble compounds (especially iron and manganese) and on water treatment conditions. Values higher than 4.5 can encourage growth of sulphur bacteria. A saturation index must be calculated if pH value is above 8.0. If a positive value, then calcium and magnesium carbonates may precipitate.
Conductivity (200μS/cm)	This is an important consideration when deciding the possible applications of a water supply. Saline water may affect the soil, and/or crop (>800μS/cm). Sugarcane has a low tolerance to salinity. Low concentration (<200μS/cm) can lead to permeability problems if sodium concentration is high relative to salinity.
Iron (ppm)	Bacteria feed on ferrous iron (Fe^{2+}) and excrete a sticky red-brown slime (insoluble Fe^{3+} form) which adheres to suspended solids and blocks emitters. Values of above 0.1 ppm can be a risk. Chemical precipitation of insoluble Fe^{3+} can also be a hazard (0.2-1.5 ppm is moderate risk, with pH values ranging from 4 - 8.5).
Manganese (ppm)	Similar to iron, but the reaction is slower and more difficult to deal with. It is a black 'marmite' precipitate. Water with >0.1 ppm can cause clogging.
Calcium (ppm)	Formation of insoluble salts may be a hazard (>250 ppm). Calcium interacts with magnesium. Do not use phosphoric acid for acidification if > 50 ppm, insoluble precipitate will result.
Magnesium (ppm)	Formation of insoluble salts may be a hazard (>25 ppm). Interacts with calcium.

Bicarbonate (ppm)	High concentrations can lead to increased tendency for calcium and magnesium to be precipitated as insoluble carbonates (>90 ppm). If calcium and magnesium are removed there is a potential sodicity hazard.
Sodium (ppm)	This can cause soil structure and permeability problems, especially on clay soils. Sodium Absorption Rate (SAR) >6 is a hazard.
Potassium (ppm)	Not usually a problem. Reduce potassium fertiliser application if >15 ppm.
Chloride (ppm)	Can indirectly affect conductivity. Where 700 ppm is exceeded, poor germination may result due to the toxic chloride levels.
Hydrogen Sulphide (ppm)	Converted by bacteria to elemental sulphur in the presence of small amounts of oxygen and then to white cotton-like balls of slime on emitters (hazard if >0.2 ppm).
Bacteria (count/ml)	If population is greater than 10 000/ml then problems with iron or hydrogen sulphide can be expected.
Langelier Saturation Index (Anon., 2002)	The calculated value must not be a positive number. Otherwise, calcium and magnesium carbonate precipitation can occur.
Suspended and Dissolved Solids (ppm)	In addition to blocking up an emitter due to continual build-up in the emitter pathway, suspended sediments can carry nutrient levels supportive of biological growth which cause sediment binding leading to emitter blockage. Levels of below 40 ppm are considered a low clogging hazard. The 41-80 ppm band is considered moderate, while greater than 81 ppm is high. A value greater than 500 ppm for dissolved solids can be a hazard due to the problem of precipitation at a later stage, either due to aeration or chemigation.

2.3 Review of Results for Irrigation System Performance

It is acknowledged that the results obtained through irrigation system evaluation by different researchers, institutions, and/or organisations, will not always be easily comparable. This may be due to the subtle differences in evaluation methodology, interpretation of performance parameters and calculations.

However, the calculated results will still give a good indication of the relative performance of an irrigation system to a farmer and will help with the selection, management and design of an irrigation system. It is pertinent to have a potential value or benchmark for the performance parameter in question (Clemmens and Dedrick, 1994). In Table 2.6 the potential application efficiencies for well-designed and managed irrigation systems are contained. Potential field uniformity values suggested by Griffiths and Lecler (2001) for moderately well designed and managed irrigation systems are contained in Table 2.7. Selected results of the efficiencies and uniformities values obtained by evaluations of different irrigation systems are reported in the following sections and are summarised in Table 2.8.

Table 2.6 Typical application efficiencies for well designed and managed systems (after Clemmens and Dedrick, 1994)

Irrigation System	Application Efficiency (%)
Furrow	50 - 70
Sub-surface Drip	85 - 90
Centre Pivot	75 - 90
Hand-move Sprinkler	65 - 85
Static (Solid Set) Sprinkler	70 - 85

It must be noted that the AE for sub-surface drip can be quite difficult to determine using standard evaluation methodologies. However, studies have shown that, on average, AE values of over 80% can be regularly attained. This may be attributed to the fact that water can be applied by the system to a specific point for a specific period of time in order to meet demands (Magwenzi, 2000).

Table 2.7 Typical field uniformity values for moderately well designed and managed irrigation systems (after Griffiths and Lecler, 2001)

Irrigation System	Potential Field DU_{lq} (%)	Potential Field CU (%)
Furrow	65 - 87	78 - 91
Sub-surface Drip	86 - 90	-
Centre Pivot	78 - 90	86 - 94
Hand-move Sprinkler	70 - 86	81 - 91
Static (Solid Set) Sprinkler	73 - 86	83 - 91

2.3.1 Furrow

Horst *et al.* (2005) conducted field evaluations in farmer managed fields in Uzbekistan. The DU_{lq} values were generally high, ranging from 65.3% to 94.5%, with an average of 83%, thus indicating appropriate system performance. However the AE values were low, ranging from 36.7% to 80.8%, with an average of less than 50%, thus indicating poor system management. The causes for low AE were found to relate to very long advance times, short intervals between irrigations, and excess water application as a result of the extended cut-off times.

Smith *et al.* (2005) analysed the results from the evaluation of 79 furrow irrigation events conducted by Australian cotton farmers using their usual practices. The AE values were shown to vary widely and, on average, were much lower than desirable, with a mean of 48% and range from 17% to 100%. With the use of SIRMOD it was shown that AE could be increased substantially by the application of simple, inexpensive irrigation management practices involving increased furrow flow rates and reduced irrigation times. After collecting data from 30 commercial irrigators in Australia, Bakker *et al.* (2006) determined that the AE range of 36% to 81%, with a median of 61%, could be improved, with gains up to 20% when using the SIRMOD simulation software

Magwenzi (2000) evaluated fields in the Swaziland sugar industry. DU_{lq} values ranged from 67% to 97% with an average of 84%. AE values ranged from 48% to 74% with a mean of 67%. It was found that the in-row furrow irrigation events had lower AE values. Soil infiltration rate is a major factor affecting AE and uniformity on more permeable soils. Magwenzi (2000) also noted that the computer model SIRMOD is a valuable tool for identifying correct design and operating parameters that maximise AE, such as correct cut-off times and furrow flow rates.

In the western United States of America (California) a project was undertaken which evaluated 385 irrigation systems, 15 of which were furrow systems. DU_{lq} was the primary measure for evaluating performance. Pitts *et al.* (1996) calculated the mean DU_{lq} to be 70% for the furrow systems.

2.3.2 Overhead sprinkler

Ascough and Kiker (2002) conducted evaluations on different irrigation systems in the sugar industry in South Africa. Five centre pivot systems were evaluated with an average DU_{lq} of 81.4% and an average AE of 83.6%. Seven hand-move sprinkler systems evaluated resulted in an average DU_{lq} of 56.9% with an average AE of 78.9%. The results from three floppy irrigation systems gave an average DU_{lq} of 67.4%, with an average AE of 76.7%. Irrigation systems that were well maintained and correctly operated generally had a high and acceptable DU_{lq}.

Griffiths and Lecler (2001) conducted seven evaluations on overhead floppy systems in Zimbabwe and found that the average DU_{lq} was 65%, with an average CU of 74%. They established that a direct correlation between pressure and uniformity existed and that well designed and installed floppy systems performed well with average DU_{lq} values of 78% and average CU values of 84%.

Nineteen hand-move systems and eight centre pivot systems were evaluated in the Swaziland sugar industry (Magwenzi 2000). Under moderate wind conditions the DU_{lq} for the hand-move system had an average value of 65%. The AE had a wide range of 49% to 88%. The centre pivots achieved high AEs of 72% to 86% and an average DU_{lq}, of 72%, although run-off losses were not measured which may result in the actual uniformity of the soil and application efficiencies to be lower than those calculated.

Evaluations were conducted on 159 overhead systems in California by Pitts *et al.* (1996) with an average DU_{lq} of 65%. In their study all overhead systems, such as centre pivot, impact sprinkler, and hand-move sprinkler, were combined.

2.3.3 Sub-surface drip

Magwenzi (2000) measured the performance of nine different sub-surface drip (SSD) irrigation fields and found a range of DU_{lq} from a low of 35% to a high of 81%, with an average of 62%. This low average DU_{lq} value was found to be due to poor system design and emitter clogging, which was attributed to water quality and poor maintenance schedules. Of the 23 fields of drip irrigation evaluated by Griffiths and Lecler (2001), the lowest DU_{lq} which was measured was 33%, and the highest was 94%. The average DU_{lq} for all systems was calculated to be 80%. Only 11 systems were above the prescribed DU_{lq} of 86%, which was deemed attainable for moderately well designed and managed drip irrigation systems. It was noted that uniformity does decrease with the age of the system, notably when preventative maintenance was not practised.

The California Polytechnic ITRC evaluated over 500 drip irrigation systems in California, using their mobile laboratories. A fraction of the results, which included 162 systems, were analysed. DU_{lq} values ranging from 44% to 98% were found, with an average DU_{lq} value of 82%. Incorrect design, non-existent water quality checks and poor system maintenance were the main causes of the low DU_{lq} values (ITRC, 2000). The DU_{lq} average for the 174 micro system evaluations, carried out by Pitts *et al.* (1996) was 70%. 75% of the systems had DU_{lq}s below 85%, which implies that the potential water saving benefit of micro-irrigation was not being fully realised. Significant improvement in DU_{lq} was achievable primarily by increased system maintenance such as cleaning of emitters with appropriate chemicals added to the water and regular checks on pressure control valves.

Table 2.8 Summary of the evaluation results from literature

Irrigation System	Average DU_{lq} (%)	Average AE (%)
Furrow	79	57
Centre Pivot	73	86
Static (Floppy) Sprinkler	66	77
Hand-move Sprinkler	72	73
Sub-surface Drip	74	-

2.3.4 Summary

There is a move, internationally, to develop a standardised approach when considering the interpretation and calculation of the performance parameters in irrigation. The idea of a "water balance" within an irrigation system, whether it be furrow, overhead or drip, seems to be universally accepted. Although the South African project K5/1482/4 is not yet concluded, and the fact that it is largely based on the definitions of Burt *et al.* (1997), preliminary results suggest that it will be comprehensive and up-to-date. The update has taken perspectives into consideration and is positioned to provide irrigators with a comprehensive and detailed tool which can be used to enhance productivity.

The concept of including the three terms, i.e. of efficiency, uniformity and adequacy, in reports on irrigation system performance makes considerable sense, as it provides an overall picture of what is actually happening in regard to the amount of water applied and the distribution within a field. There also needs to be a balance between irrigation systems efficiency, uniformity and adequacy, with the economics and suitability of local operating conditions being significant factors in determining the potential values for these parameters.

There are many factors which can affect the uniformity of an irrigation system. Whereas some of these factors cannot be changed, the vast majority can be improved upon. This implies that a farmer can increase the productivity of a cropping system by monitoring the irrigation system. This is the main reason for evaluating an operational irrigation unit. A farmer should derive a benefit from having an installed irrigation system evaluated. This benefit could be realised through immediate remedial work on the system, or through the introduction of well planned maintenance and/or irrigation schedules, thus ensuring a long-term benefit to the farmer.

There are many publications containing methodologies for the evaluation of irrigation systems. The benefit of these publications, is that an evaluator can choose the applicable evaluation methodology which can ensure the collection of accurate and sufficient data under the local operating conditions, in order to calculate selected performance parameters.

Only a limited number of studies contain quantitative results, although there are enough data sets to enable comparisons to be made between the studies. Of the three broader types of irrigation, i.e. drip, flood and overhead, more results are available from flood than the other types of irrigation. However, there is a concerted effort to evaluate and review more of the other types of irrigation systems, as farmers need the information to make comparative decisions.

In making comparisons between the potential and actual DU_{lq} and AE values in Table 2.6, 2.7 and 2.8, it is noted that the AE values of the furrow (57%), centre pivot (86%), hand-move (73%) and static (77%) sprinkler systems were within the potential AE ranges stated. Owing to the difficulty in determining AE for sub-surface drip irrigation systems no credible results were available for a comparison. With regards the DU_{lq} values, only furrow (79%) and hand-move sprinkler (72%) systems were within the design norms, with centre pivot (73%), static sprinkler (66%) and sub-surface drip (74%) being below their respective design norms. Only a limited number of evaluations were conducted on static sprinkler systems, which could have contributed to a skewed and lower DU_{lq} value.

From the review of the above-mentioned studies, various factors have been given as reasons for the AE and DU_{lq} values being below standard/attainable benchmarks. These reasons can be grouped into the following: poor irrigation system design, poor irrigation system management, non-existent or inadequate maintenance schedules, non-existent or inadequate scheduling of irrigation and non-existent water testing procedures. As stated previously, these factors can be dealt with, resulting in the improvement of an irrigation system's performance which will benefit the farmer by providing a more cost effective and efficient crop production system.

The following may be concluded from the review in this Chapter:

- Studies are currently underway to standardise the calculation and interpretation of performance parameters within an irrigation system.
- The adequacy, efficiency and uniformity of irrigation systems should be reported jointly, not as individual parameters.
- Out of the many procedures of evaluation which are available, a method should be chosen which is simple and effective so as to enable the evaluator to accurately attain the information needed in order to calculate the required performance parameters.
- The farmer is the main beneficiary in the evaluation of an irrigation system. Therefore a basic, but comprehensive, report detailing the computed performance parameters in comparison to applicable norms, as well as any remedial measures required to improve performance, applicable maintenance regimes and, if possible, appropriate irrigation scheduling advice should be provided.

3. METHODOLOGY

Evaluations were undertaken within the South-East Lowveld of Zimbabwe, which is situated around the latitude of 21° S an average altitude of 420 metres above sea level (Lecler, 2004). The evaluations were conducted at the sugarcane estates shown in Table 3.1. Also included in Table 3.1 is the approximate area of each estate and the irrigation systems evaluated. The geographic location of each of the respective estates, as assigned by GoogleEarth (2006), are also included in Table 3.1. The estates are

- Hippo Valley Estate (HVE),
- Mkwasine Estate (ME),
- Mwenezana Sugar Estate (MSE), and
- Triangle Group Sugar Estate (TGSE).

Table 3.1 Estates, their areas and the irrigation systems evaluated, together with the geographic location of the respective estates

Estate	Area (Ha)	Systems Evaluated	Latitude (S)	Longitude (E)	Elevation (m)
HVE[1]	12,500	Centre Pivot; In-row and Inter-row Furrow; Static Sprinkler; Sub-surface Drip	21°04'19"	31°38'38"	408
ME[2]	4,700	In-row and Inter-row Furrow	20°50'37"	31°53'06"	462
MSE[3]	2,000	Centre Pivot	21°21'47"	30°37'30"	520
TGSE[4]	13,000	Centre Pivot; In-row Furrow; Hand-move and Static Sprinkler; Sub-surface Drip	21°01'24"	31°26'39"	410

[1] Hippo Valley Estate

[2] Mkwasine Estate

[3] Mwenezana Sugar Estate

[4] Triangle Group Sugar Estate

The other evaluation sites were conducted on private commercial farms located in and around the various sugarcane estates. These will not be assigned as separate sites and shall be referred to as Private Farmers (PF). A map showing the four main evaluation sites in the South-East Lowveld of Zimbabwe is shown below in Figure 3.1. The study area is characterised by hot and dry climatic conditions, and is thus ideally suited to irrigated farming. The water sources for the various estates come from established dams and waterways, as described by Clowes and Breakwell (1998).

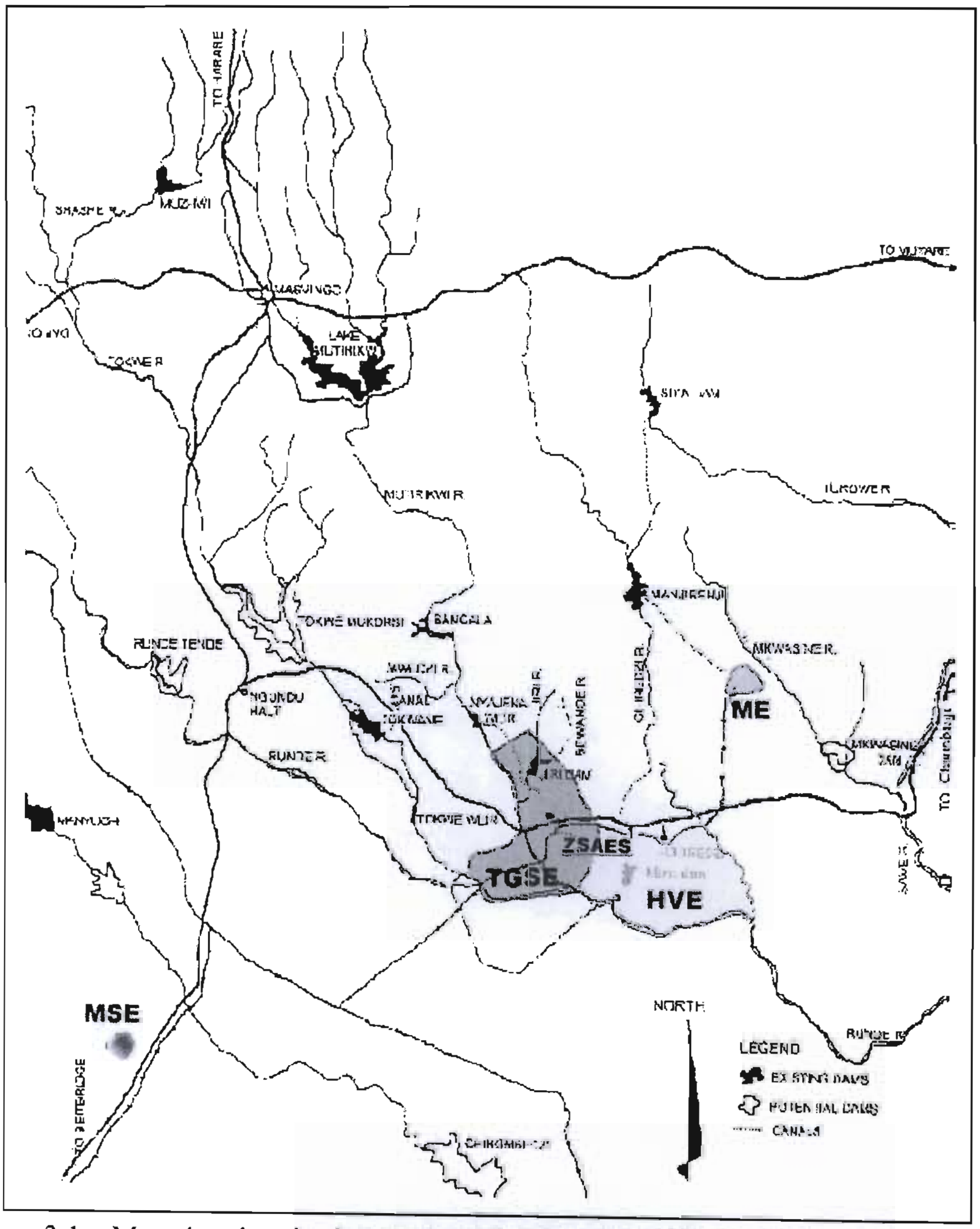

Figure 3.1 Map showing the four main evaluation sites of Hippo Valley Estate (HVE), Mkwasine Estate (ME), Mwenezana Sugar Estate (MSE) and Triangle Group Sugar Estate (TGSE) in the South-East Lowveld of Zimbabwe

It should be noted that the MIPU evaluated the different irrigation systems whilst in operational mode, so as to obtain an indication of how the systems operated under the local management conditions. Thus the evaluation times coincided with the time it took the respective irrigation system to apply the target application amount, as required by the farmer. All evaluation forms used in this research by the MIPU were designed by the author and are included in Appendix A.

3.1 Furrow

The sites used in this dissertation for the furrow irrigation system evaluations were located at Hippo Valley Estate (HVE), Mkwasine Estate (ME) and Triangle Group Sugar Estate (TGSE).

3.1.1 Flow measurement

In order to measure inflow into a furrow the MIPU used syphons and measured the difference in height in the water level between the supply canal and the furrow using a robust and simple instrument shown in Figure 3.2, termed a "Greller". The use of the Greller contributed towards making the evaluation easy, fast and less invasive. Other methods of measuring the inflow into the furrow were considered to be too cumbersome, expensive and time consuming (e.g. setting up of flumes/weirs).

The principle behind the functioning of a Greller is that it measures the driving head for flow in a syphon, to an acceptable level of accuracy. The tube at point A is placed in the supply canal (the feeder), point B is placed in the furrow and is positioned so that it just touches the water in the furrow after the inflow had stabilised.

The difference in water level between the feeder and the furrow water levels was represented by a meniscus in the tube length of area C and was read from a ruler gauge, shown as D in Figure 3.2. For the results used in this study, the Greller-syphon combination method for measuring inflow was used and the Washington State College (WSC) flume was used for measuring outflows.

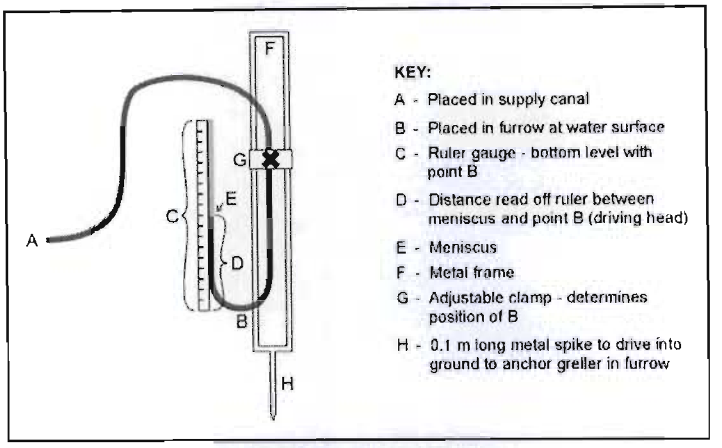

Figure 3.2 The Greller

3.1.2 Evaluation technique

The method used for evaluating furrow irrigation was very similar to the methods described in the Section 2.2.1. For the selected fields, three furrows spaced with a non-evaluation furrow on either side were marked for evaluation. The selected area was deemed to be representative of the entire field. The same evaluation technique was used for in-row and inter-row furrow irrigation. In-row implies that the sugarcane crop is planted in the furrow trench and water is fed down the same furrow. Inter-row implies that the sugarcane crop is planted on the ridges, with the water running down the non-planted furrow trench.

The non-irrigated furrow was placed on either side of the evaluation furrows to ensure that overflow was not introduced from an adjacent furrow, and therefore would not affect the evaluation readings. This was also done so as to make it easier for the evaluators to record data as they would walk down the non-irrigated furrow. Although furrows are not irrigated in this way in practice (i.e. with a non-irrigated furrow either side), it was assumed that the data collected for each individual furrow would still be representative of the majority of furrow irrigation systems in use in the area. Figure 3.3 shows the arrangement of the equipment used in a furrow irrigation evaluation.

Two people were required to complete one furrow evaluation. For ease of explanation, the annotation of a Person A and Person B will be used. The Greller was placed at the top end of the furrow where the feeder canal was situated. Pegs were placed every 10 m down the length of the furrow. For the open-ended furrow the WSC flume was installed in order to measure the water that flowed out at the end of the furrow.

The Greller was primed and the two stopwatches operated by Person A and Person B, who were both positioned at the top end of the furrow when the evaluation began, were started when water was introduced into the furrow. The Greller was adjusted to take measurements at the stabilised water height in the furrow being measured. Readings were taken every 30 seconds by Person A and the time noted when the inflow into the furrow was stopped. This would enable the inflow into the furrow to be calculated. The wetted perimeter and height of water in the furrow was measured using a flexible plastic tape-measure at the top, middle and end of the furrow. The furrow shape, which included measurements of the top, middle and bottom widths and furrow height, was also recorded at these points.

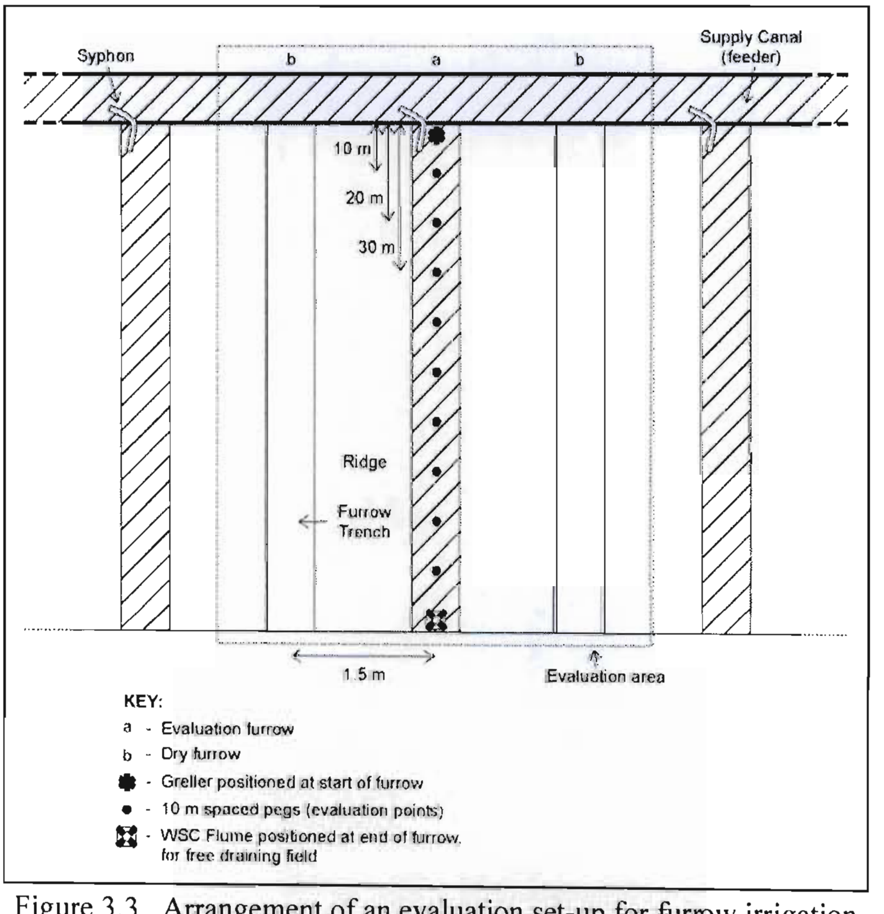

Figure 3.3 Arrangement of an evaluation set-up for furrow irrigation

When the inflow was stopped and the time recorded, Person A then followed the recession front of water, and took the time when the recession front passed the 10 m spaced pegs. The recession front is deemed to have passed a peg when at least 80% of the wetted furrow width at that point had no running water covering it.

The water advancing down the furrow was monitored by Person B. The time when the advance front passed a peg was recorded and water was deemed to have passed the peg when at least 80% of the furrow width was covered with water. This continued down the length of the furrow, until the end of the furrow was reached. There were two options that arose when the end of the furrow was reached. One was when the WSC flume had been installed and the other when the end was blocked. When the WSC flume was installed, readings were taken every 30 seconds, from the time water started flowing through the flume until there was no more water exiting the flume. A builder's level was used to ensure that the flume was installed horizontally. Sheets of plastic were used to ensure no water leaked around the edges of the flume. When the furrow end was blocked, the amount of water that accumulated (ponds) at the end of the furrow was estimated by measuring the length, width and depth of the accumulated body of water. Person A would eventually reach the position of Person B at the furrow end, at which times the watches were stopped. The slope of the furrow was determined after the irrigation application had ceased, and was calculated using a dumpy level and staff.

The MIPU chose the above method of evaluation to ensure that the results could be used in the various furrow simulation models (Strelkoff, 2000; Walker, 2000), from which uniformity down a furrow could be computed. It was initially decided, mainly due to the ease of operation, that the Walker SIRMOD model would be used (Walker, 1999), along with the Australian InfiltV (Durack, 2001) programme. The format of the form which was used in a furrow evaluation is shown in Appendix A.1. Owing to the vast amount of data that had to be collected, trained furrow evaluation teams were organised by the MIPU on each estate. Each team was provided with all the equipment that was necessary to carry out the evaluations.

However, a combination of the unavailability of the SIRMOD software, time-constraints and the large amount of data led to the conclusion that not all the furrow evaluation data could be processed using the simulation programme and that it needed to be processed by another method.

Applying the Koegelenberg and Breedt (2003) method of using the contact times and the relevant performance parameter equations given in Chapter 2, the DU_{lq} was calculated in the same way as for the other irrigation systems. Together with Southey (2007), the AD for furrow was calculated using the Deviation from Target (DT), a parameter which can be easily calculated from the measurements taken and the measured contact times, which gave a robust indication of the system's adequacy. Below is a short summary of the assumptions and the equation used for this calculation.

Let DT be the Deviation from Target application in per cent, C_p be the contact time (the difference in the advance and recession time) at the point p, in seconds, and C be the average contact time, in seconds, across all evaluation points in the furrow. The infiltration (F) for the evaluation point is then given by Equation 3.1:

$$F = (1 + DT) * \frac{C_p}{C} \tag{3.1}$$

The number of all the infiltration points whose infiltration is calculated to be above 1 is divided by the number of evaluation points in the furrow in order to give a rough estimate of the adequacy of the furrow. The calculation makes two assumptions, first, that any point coming into contact with the water flow for the average contact time will have infiltration equal to the amount of water applied relative to the design application, and secondly, that all other points will achieve an infiltration relative to this in proportion to the amount of time they are in contact with the water flow. Thus longer contact will result in higher infiltration. A weakness is that the shape of the infiltration function is curvilinear, thus the above method may exaggerate differences in actual infiltration.

3.2 Overhead Sprinkler

The systems which are described in this category are (i) hand-move sprinkler and (ii) static sprinkler, both of which were evaluated using a similar technique, and (iii) centre pivot irrigation system which requires a different evaluation technique. With all these system evaluations, rain-gauges are used as the water collectors. Thus the depth of water applied by the system is read from the rain-gauge, with the evaluator making certain that the meniscus of the water in the gauge is held at eye level. All rain-gauges were positioned so that the top of the gauge was 0.3 m above the ground level. This was achieved by using a hollow aluminium tube which was cut to the desired length of 0.25 m, thus enabling all gauges to be placed at the same height (the rain-gauge top adds the extra 0.05 m). The tube fitted over the 0.5 m long, 6 mm thick iron rod which was hammered into the ground, and onto which the rain-gauge holder was placed. A point to note is that some evaluators make the mistake of placing the iron rod at the exact grid point, forgetting that the width of the gauge holder has to be taken into account. The exact grid point should be the position of the centre of the rain-gauge. Consequently, the rain-gauges must all be positioned facing the same direction. The MIPU had 60 rain-gauges to use in evaluations.

The MIPU also used a portable Pocket Weather Meter, which enabled the evaluation team to obtain an accurate assessment of the wind conditions on-site. With overhead irrigation, wind speed can be a major factor affecting an irrigation system's performance, as noted from the information contained in Table 2.4. Water losses of 10-20% have been recorded due to wind drift/evaporation (USDA, 1983; Lecler, 2004). Three readings were taken during the course of the evaluation, one at the beginning of the evaluation, one in the middle, and one at the end of the evaluation. These were then combined to obtain an average reading of the wind speed (m/s) during the course of the evaluation.

3.2.1 Centre pivot

Evaluations for the centre pivot irrigation systems were carried out at HVE, MSE and TGSE. A radial line of rain-gauges was placed along the length of the centre pivot. The start of the line was at the point which matched the horizontal positioning of the last sprinkler on the outermost tower. The rest of the gauges were placed 8 m apart in a straight line towards the pivot centre. The distance of 8 m was chosen as it did not interfere with any of the wheel towers, i.e. to ensure that a rain-gauge was never placed in the way of one of the wheels supporting a moving tower. Most of the centre pivots used in the industry are less than 50 ha, so the 60 available rain-gauges were sufficient as a 50 ha centre pivot evaluation would require approximately 50 rain-gauges. Figure 3.4 shows the placement of the rain-gauges. The forms which were used in this type of evaluation are shown in Appendix A.2.

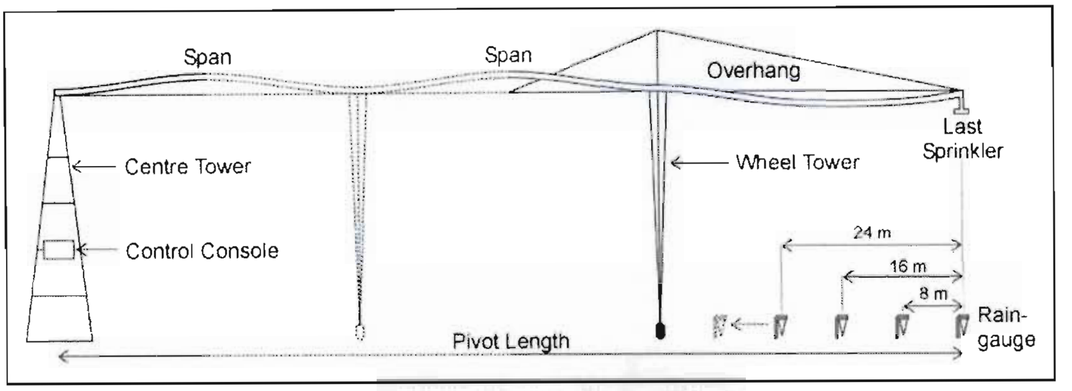

Figure 3.4 Rain-gauge placement for a centre pivot evaluation

3.2.2 Hand-move and static sprinkler

Evaluations were carried out at TGSE for the hand-move irrigation systems, while the static sprinkler evaluations were conducted at HVE and TGSE. The layout used for the hand-move impact sprinkler system in the industry, is 18 m X 18 m. The MIPU used a 3.6 m X 3.6 m grid system of rain-gauges, as shown in Figure 3.5. This grid system translated to the minimum required 25 data points needed when calculating performance parameters, as stipulated by ASAE S436.1 (1998). The reason that a 3 m X 3 m system was not used, which translates to 36 data points, was because of the availability of rain-gauges. As a consequence of the number of evaluations required to be completed on TGSE, two evaluations were carried out at the same time, in different areas, which meant that 50 rain-gauges were used at the same time.

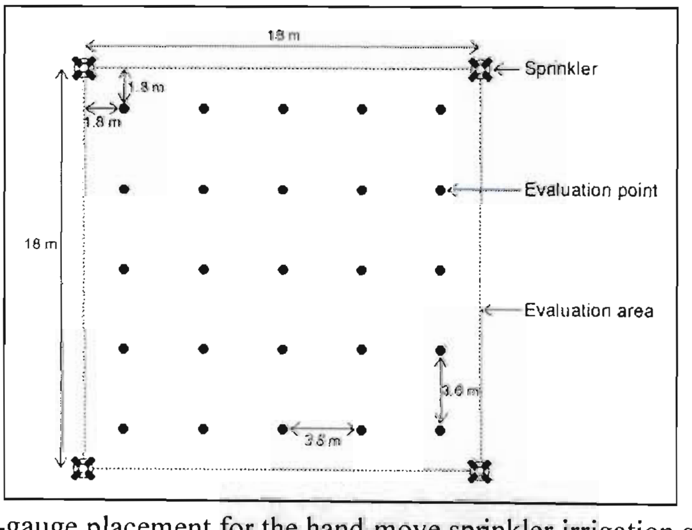

Figure 3.5 Rain-gauge placement for the hand-move sprinkler irrigation system evaluation

The main difference between these two types of sprinkler evaluations is the size of the grid system arrangement of the rain-gauges, which is explained below. The only static sprinkler system used in the sugarcane industry is the "Floppy", which is adequately described in Simpson and Reinders (1999). The design of the system in Zimbabwe uses a 14 m X 12 m triangular spacing. Thus a decision to use a 2 m X 2 m grid system of rain-gauges, as shown Figure 3.6, was made. This translated to 42 gauges being used to collect the water applied by the irrigation system.

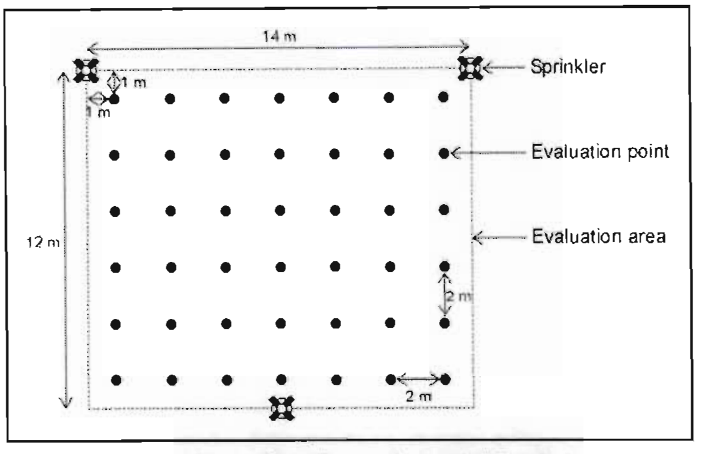

Figure 3.6 Rain-gauge placement for the static sprinkler irrigation system evaluation

The methodology used was similar to that which has been described by Koegelenberg and Breedt (2003). The measurement of flow from the sprinklers on the outside corners of the grid was determined using a hose-pipe, a 25 l bucket and a stopwatch. A needle fitting was fitted to a 500 kPa pressure gauge to measure the pressures at the hydrants for the floppy irrigation sprinkler systems. The procedure for taking the pressures at the sprinkler, for the floppy and hand-move sprinkler was slightly different.

For the floppy system, a specially made standpipe, which had a 500 kPa pressure gauge fitted to the top of the pipe, was used. For the hand-move sprinkler, a pitot tube was fitted to a 500 kPa pressure gauge, with the end of pitot tube being placed in the *vena contracta*, approximately 2 mm from the nozzle. Pressure readings were taken at the sprinklers chosen to represent the evaluation area, and also down the length of the entire line. The specialised fittings are shown in Figure 3.7.

Koegelenberg and Breedt (2003) also mention that the vertical alignment of the risers for both the floppy and hand-move sprinkler can affect the irrigation system's performance. As there is no set evaluation procedure/instrument to quantify this "leaning" affect, the MIPU just commented and marked risers which were not vertical on the evaluation form. The forms used for this type of evaluation are shown in Appendix A.3.

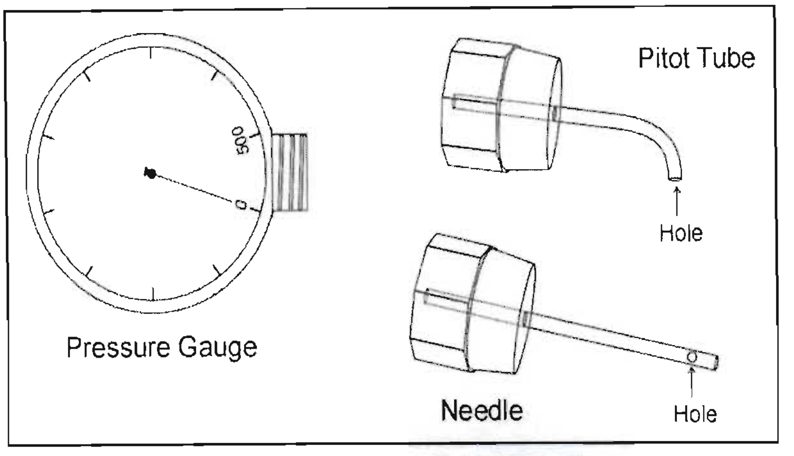

Figure 3.7 Specialised pressure fittings for evaluation of overhead sprinkler system

3.3 Sub-Surface Drip

The MIPU evaluated two types of sub-surface drip systems in the Lowveld, as stipulated in Chapter 2. The same evaluation technique was used for both types. The sites used in the dissertation for sub-surface drip evaluations were situated at HVE, ME and TGSE.

The submain and mainline pressures were recorded using a needle valve and a calibrated 250 kPa pressure gauge, as shown in Figure 3.8. The pressure points were found on either side of the submain control valve. Six laterals were then chosen in the field and five points along these six laterals were selected and evenly spaced holes were dug. Thus there were 30 evaluation points available in total, which were the data points used in the various uniformity calculations. The layout of the collector points can be seen in Figure 3.9.

Reinders (2000) suggested that pressures be taken along the lateral by using an "invasive" technique which required the lateral to be punctured and the needle gauge inserted. The resultant small hole would be plugged with a small plastic screw. The MIPU was not able to source plastic screws and, in addition, farmers did not appreciate the "invasive" nature of the procedure, thus a conical nozzle was designed. This instrument, when attached to the pressure gauge enabled the pressure variation along the submain to be determined by disconnecting the six chosen laterals, one at a time, to take the pressure reading. This instrument, shown in Figure 3.8, was also used to determine the pressure at the other end of the lateral.

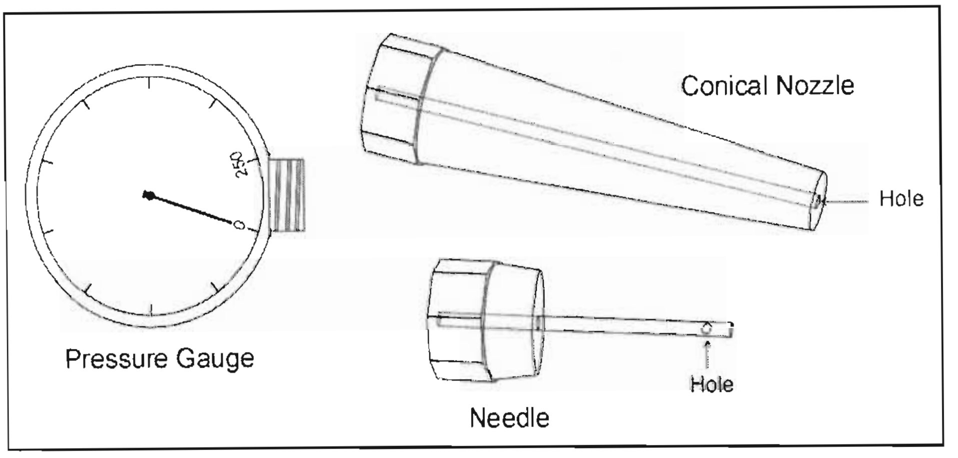

Figure 3.8 Specialised pressure fittings for evaluation of sub-surface drip system

The holes which were dug had to be big enough for the collection containers which were wide brimmed plastic cups with handles. An additional feature that was included was a piece of string which was wound around the dripper tape, on either side of the emitter hole. This was to ensure that water would not run down the tape and hence not be collected, but would instead be "dammed" by the string and drip into the cup. This is a simple, but very effective solution and an inexpensive option. The evaluation time for water to collect in the cup was chosen to be 3 minutes. The time was measured with a stopwatch. The water collected in the cup was measured using a calibrated 25 ml cylinder.

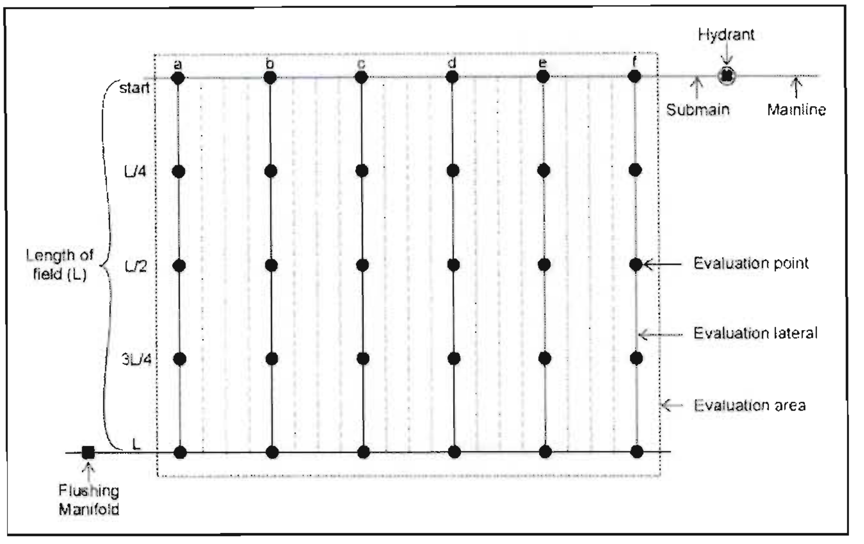

Figure 3.9 Collection container placement for the sub-surface drip irrigation system evaluation

The flushing velocities of the laterals were checked using a portable Arad electric flowmeter (ARAD Flowmeters, 2007). The arrangement of the inlet and outlet piping for the flowmeter is shown in Figure 3.10. End A was attached to the lateral and End B was attached to the blanco pipe which fed into the flushing manifold. The flushing velocity is important as it clears the drip lateral of deposits and precipitates, which may otherwise lead to the blockage of the drip emitters or of the laterals themselves. The forms used for sub-surface drip irrigation evaluation are shown in Appendix A.4.

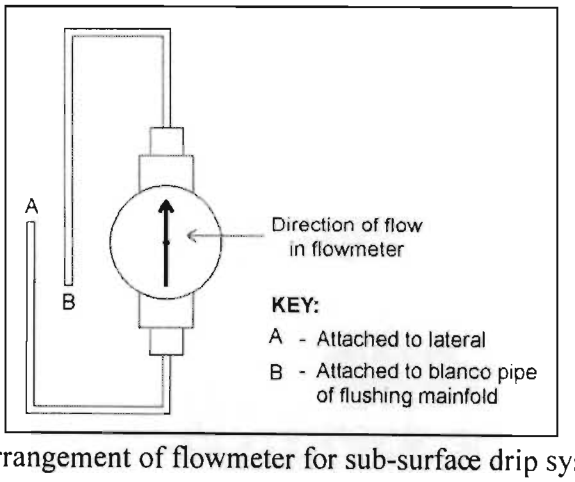

Figure 3.10 Arrangement of flowmeter for sub-surface drip system evaluation

3.4 Calibration of Evaluation Hardware

Certain evaluation hardware had to be calibrated in order to ensure correct data acquisition. The techniques used in calibrating and validating all of the instrumentation mentioned in the preceding chapters are listed below.

3.4.1 The Greller

This device was described in Section 3.1. The accuracy of the Greller was verified using a one metre builder's level and a one metre metal ruler. This was done by measuring the height from the builder's level to the water level in the feeder, represented by C, and on the opposite side of the canal, the height was measured from the builder's level to the water level in the furrow and represented by D . The C value was subtracted from the D value and was compared to the Greller meniscus measurement that was read off the ruler, represented by the E value. This is shown in Figure 3.11. Based on the reading taken, it was decided that the accuracy of the Greller was adequate, as the error margin was consistently under 2 %. An additional correction factor was not added to the "meniscus" reading, as it was felt that it was insignificant.

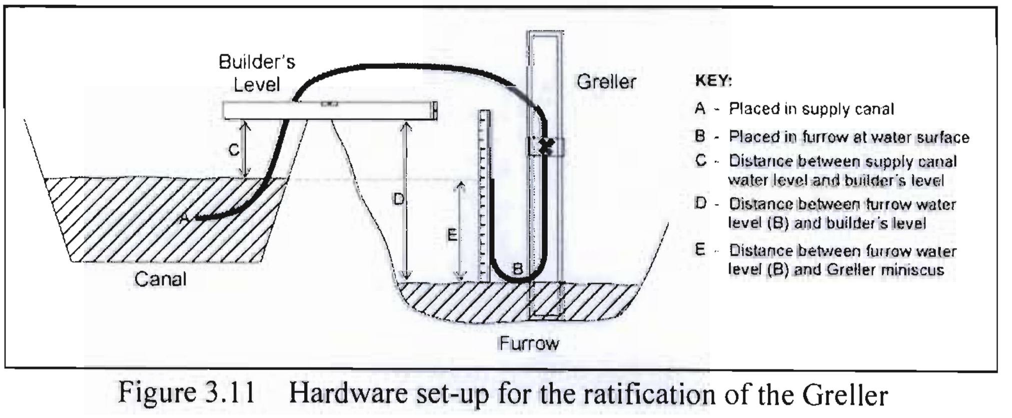

Figure 3.11 Hardware set-up for the ratification of the Greller

3.4.2 Washington State College flume

The outflow from open-ended furrows was measured using a Washington State College (WSC) flume which was calibrated using the setup shown in Figure 3.12. A constant flow of water was introduced at the upstream side of the flume, with a reading taken on the flume gauge, which is located on the side. The water on the downstream side was then collected with a bucket and measured using a two litre calibrated cylinder with a stopwatch to record the time intervals.

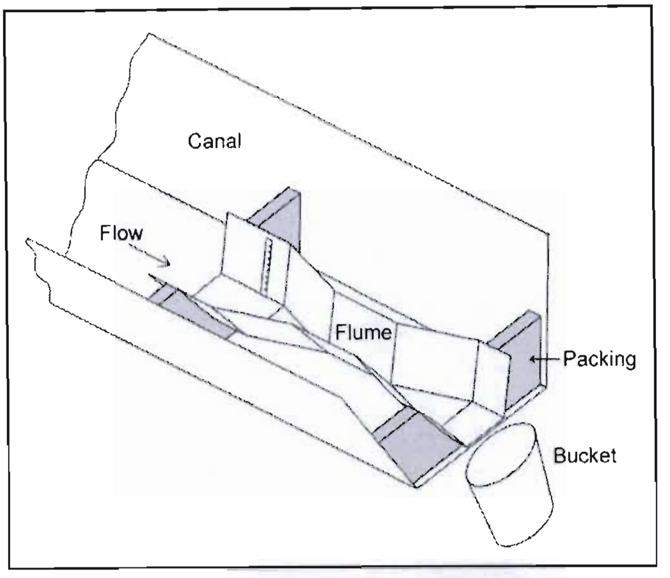

Figure 3.12 Calibrating the WSC flume

A variety of equations to calculate the outflow from a WSC flume are available (Walker and Skogerboe, 1987). However, the gauges that were affixed to the sides of the WSC flumes were simply glued on and it was unclear if these specific flumes were sent from the United States of America in their current condition, or if the gauges had been attached afterwards. Hence, the published calibration equations were considered not to be accurate. Therefore, using the published "TroutPowlus" (Trout, 2000) equation and an equation determined using a Scientific Calculator (48G Hewlard Packard Bell), which was termed "48G1", a best fitting equation, based on the data collected, was determined using a spreadsheet programme (Quattro Pro), as shown in Figure 3.13.

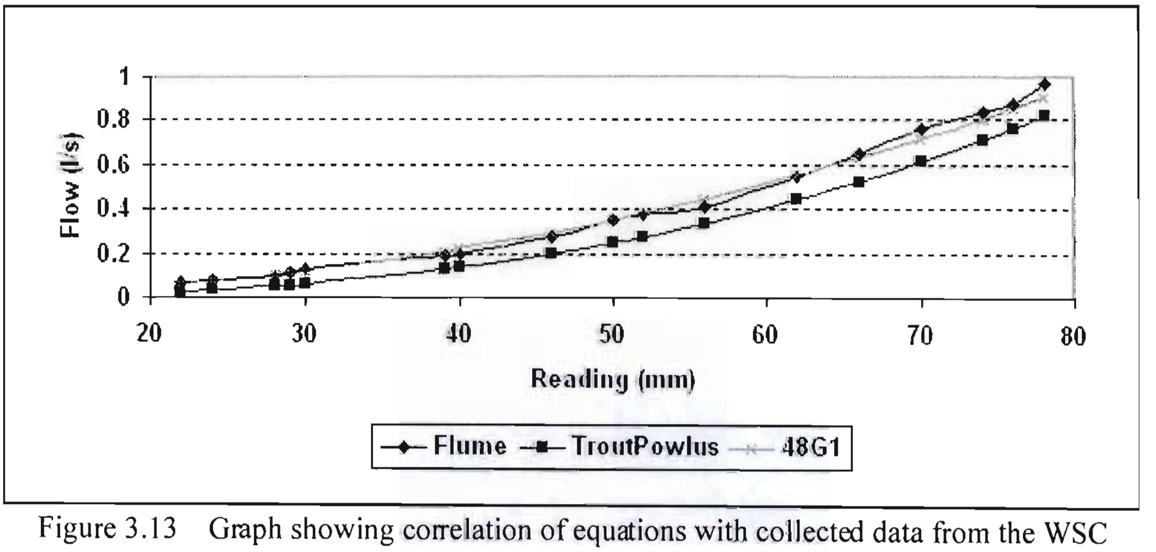

Figure 3.13 Graph showing correlation of equations with collected data from the WSC flume

The equation represented by 48G1 was the best correlation for the outflow of water for the WSC flume, and is given as Equation 3.2.

$$Q = 0.0000882(h - 1.5)^{2.13} \qquad (3.2)$$

where Q is the outflow in [l/s], h is the side gauge reading in [mm], with a 1.5 mm correction for meniscus distortion.

3.4.3 Syphons

The syphons were calibrated using a simple "bucket and stopwatch" technique (Kay, 1993). The hydraulic head was measured using the respective estate Greller set-up, as shown in Figure 3.14. The syphons were calibrated in order to determine the discharge coefficient used in Equation 3.3.

$$Q = CA\sqrt{19.62H} \qquad (3.3)$$

where Q is the measured flow rate [m^3/s], A is the cross-sectional area of the syphon pipe [m^2], H is the measured height difference reading taken from the Greller and C is the discharge coefficient.

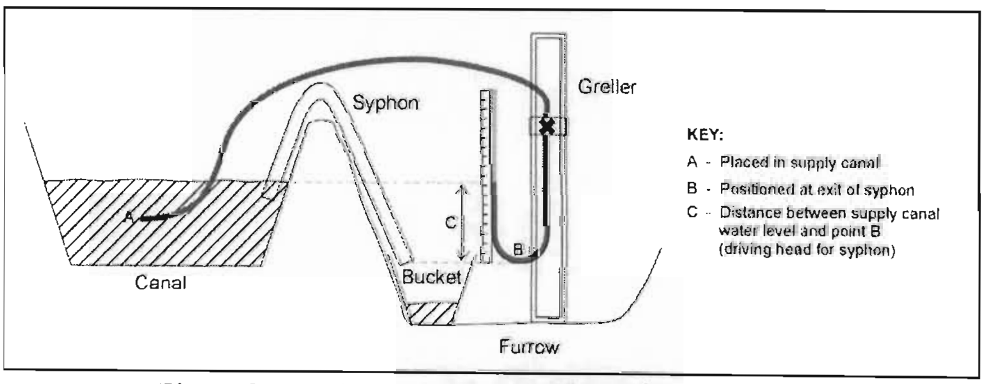

Figure 3.14 Flow measurement for syphon calibration

It must be noted that each estate makes its own syphons by cutting and bending (using hot water) standard PVC 6 m lengths of standard PVC piping. The diameters of the syphons used in the MIPU evaluations are shown in Table 3.2.

Table 3.2 Percentage of predominant syphon sizes used in the MIPU evaluations on various estates

SYPHON SIZE (mm)	PERCENTAGE OF SYPHONS USED IN MIPU EVALUATIONS (%)			
	HVE[1]	ME[2]	TGSE[3]	Total[4]
25	3.6	1.2	0	0.8
40	32.1	12.3	0	10.2
50	17.9	40.7	4.2	13.4
63	7.1	29.7	93.3	64.4
75	35.7	16.1	2.5	10.7
90	3.6	0	0	0.5

[1] Hippo Valley Estate

[2] Mkwasine Estate

[3] Triangle Group Sugar Estate

[4] The per cent of the relevant syphon size with respect to the number of overall syphons used in all the evaluations

The estates submitted samples of the syphons in current use in the field, and these were used in the calibrations. For the purpose of this study the author discarded the evaluations which used the 25 mm and 90 mm syphon sizes as it was felt that the 0.8% and 0.5% values were not representative enough. Table 3.3 contains the calibration coefficients for each of the predominant syphon sizes used by the MIPU evaluation teams at each estate. A value of C = 0.62 is considered the average syphon calibration value by Koegelenberg and Breedt (2003) while the Zimbabwe sugar industry irrigation handbook (Cackett, 1982) suggests a value range of 0.60-0.80. A sample batch of five syphons for each size were used in the calibration tests. Greller heights used in the calibration are 0.05 m, 0.1 m, 0.15 m, 0.2 m and 0.3 m. The calibrated coefficients for each head were averaged for each syphon size.

The average of all the coefficients is 0.65, which the MIPU considered to be a close enough to the 0.62 value given by Koegelenberg and Breedt (2003) to use in the estimation of inflow into a furrow. The predominant syphon diameters used by the estates in the MIPU evaluations was 63 mm syphon, used in 64% of the evaluations, with 50 mm being the next most common syphon diameter used in 13% of the evaluations.

Table 3.3 Calibrated syphon results for the respective estates

ESTATE	SYPHON SIZE (mm)	AVERAGE DISCHARGE COEFFICIENT (C)	PERCENTAGE OF SYPHON SIZE USED IN THE ESTATE MIPU EVALUATIONS (%)
HVE[1]	40	0.67	32.1
	50	0.65	17.9
	63	0.61	7.1
	75	0.69	35.7
ME[2]	40	0.67	12.3
	50	0.63	40.7
	63	0.60	29.7
	75	0.67	16.1
TGSE[3]	40	0.67	0.0
	50	0.65	4.2
	63	0.61	93.3
	75	0.69	2.5

[1] Hippo Valley Estate

[2] Mkwasine Estate

[3] Triangle Group Sugar Estate

3.4.4 Pressure gauges and Arad flowmeter

The 500 kPa and 250 kPa pressure gauges were sent to the TGSE precision instruments laboratory, where specialist equipment was used to accuratelycalibrate the gauges. These gauges were re-calibrated every six months. The Arad flowmeter was calibrated for a range of flows, using the "stopwatch and bucket" technique, whereby the inflow end of the flowmeter was attached to a hose-pipe and the outflow was collected in a bucket, over a predetermined time period and measured using a two litre graduated measuring cylinder. A calibration constant was then calculated which corrected the flowmeter readings to correspond with the actual flow collected. The constant calculated was a value of 1.02.

3.5 Evaluation Toolbox

Table 3.4 contains a list of the required tools for an evaluation and their use, for each respective irrigation system.

Table 3.4 Equipment needed to carry out evaluations of irrigation systems

IRRIGATION SYSTEM	EQUIPMENT	USE
General	Stopwatch, Clipboard, Evaluation sheet, Pen/Pencil Pegs, Hammer, Aluminium tube, 100 m tape measure, Water pump pliers	Recording of data Placement of pegs and rain-gauges at correct spacing and height Changing of pressure fittings
Furrow	Dumpy level and staff Builders level 1 m flexi-tape measure Greller, WSC flume	Slope of furrow Installing the WSC flume Furrow shape/Wetted perimeter Inflow and outflow
Hand-move sprinkler and Static (Floppy) sprinkler	250 kPa and 500 kPa calibrated pressure gauge (liquid filled), Pitot fitting, Stand-pipe for floppy Hose pipe and bucket Automatic weather-meter	Pressure readings at points of interest Flow measurement Wind speed
Centre pivot	Automatic rain-gauge Automatic weather-meter Safety harness	Application rate at the outermost sprinkler Wind speed Used when checking sprinkler nozzles
Sub-surface drip	250 kPa calibrated pressure gauge (liquid filled), Needle point fitting, Conical fitting Plastic cup, String, 25 ml graduated cylinder Arad flowmeter	Pressure readings at points of interest Flow measurement Flushing velocity

After all the required data had been collected for the respective irrigation systems, the equations listed in Chapter 2 were used to calculate the DU_{lq} performance parameter. For AD the graphical concept, as described by Figure 2.2, was used for calculating the AD for the overhead sprinkler and sub-surface drip irrigation systems. It must be noted that the centre pivot irrigation system requires the water application readings to be area weighted, as each rain-gauge represents a different area. As stated previously, Equation 3.1 is used to calculate the AD for the furrow irrigation systems.

An additional parameter, which was not described in Chapter 2, was included in this research. This was termed the Deviation from Target (DT). The DT is simply the percentage deviation, either negative (under-watered) or positive (over-watered), from the applied amount that the farmer has calculated/assumed, which is also known as the target application, i.e. if the target application was equal to the application amount that was determined through the evaluation procedure, then the DT = 0%. The equations were entered into a spreadsheet programme (Corel Quattro Pro) to facilitate the process of calculating the vast amount of data collected by the ZSAES and estate MIPUs.

The Application Efficiency (AE) performance parameter was not calculated, as more detailed evaluations are needed, including the use of more specialised and expensive equipment, which was outside the scope of this study. It was felt that the calculation of the AD, DU_{lq} and the DT, were sufficient to compare irrigation systems and to help farmers understand their crop production systems better.

In this Chapter the location of the evaluations carried out in the South-East Lowveld of Zimbabwe and the evaluation techniques for the various irrigation systems found in the area, were described. The calibration of the equipment used in the MIPU evaluations and a listing of this equipment were also discussed. The results obtained by applying the methodology of this Chapter are the subject of Chapter 4.

4. RESULTS

The in-field performance parameters of DU_{lq}, AD and DT for all the systems evaluated in the sugarcane industry, within the Lowveld of Zimbabwe, are presented in this Chapter. The in-field performance parameters will be presented separately for each type of irrigation system and grouped under the categories of furrow, overhead sprinkler and sub-surface drip. The overhead sprinkler category is further subdivided into three categories which are centre pivot, hand-move and static sprinkler. As the calculations were computerised, no sample calculations will be shown.

Owing to the vast amount of data collected the author decided to only consider the uniformity of an irrigation system when investigating possible scatter plot trends caused by factors such as design, maintenance, operation, pressure, water quality and wind for this study. This decision to consider DU_{lq} and not the AD or DT values was based on research which shows that the first requirement for the efficient operation of an irrigation system is uniform water application which will, in turn, contribute towards maximising the return from a farmers crop production system (King *et al.*, 2000; Griffiths and Lecler, 2001). The comparison of the different irrigation systems are presented at the end of this Chapter.

4.1 Furrow

A total of 482 furrow evaluations were analysed, from an initial data set of 511. Approximately 6% (29 furrow measurements) were excluded from the analysis as outliers. The recorded applications in these furrows were so high that the results, especially the mean, would have been severely biased and not representative of the remaining 94% of the fields. Of the 482 data sets, 439 were in-row whilst the remaining 43 were inter-row.

4.1.1 In-field performance parameters

The DU_{lq} histogram and cumulative distribution of all the furrows evaluated by the MIPUs is shown in Figure 4.1. Some explanation is needed for ease of understanding these types of graphs which are used throughout this chapter. Taking the left most bar, it can be seen there is a DU_{lq}

value of 2% associated with the bar. This value is the upper bound of that class boundary. In other words, there was a frequency of four DU_{lq} observations less than or equal to 2%. The next class is greater than 2% but less than or equal to 7% and so on. For the cumulative frequency, if the middle point at the top of the third bar from the right side of the Figure 4.1 is used as an example, this point represents the data which shows that 90% of all the observed DU_{lq} values are equal to 91% and below. Of all the furrow evaluations analysed, 64% were within or above the potential field DU_{lq} range of 65 - 87% reported in the literature. Of this percentage, 65% of the in-row furrow and 49% of the inter-row furrow were within or above the potential field range values. As shown by the data points in the figure, the furrow system could be further improved by concentrating on how to better manage the furrow systems which fall into the DU_{lq} range of 39% to 67%.

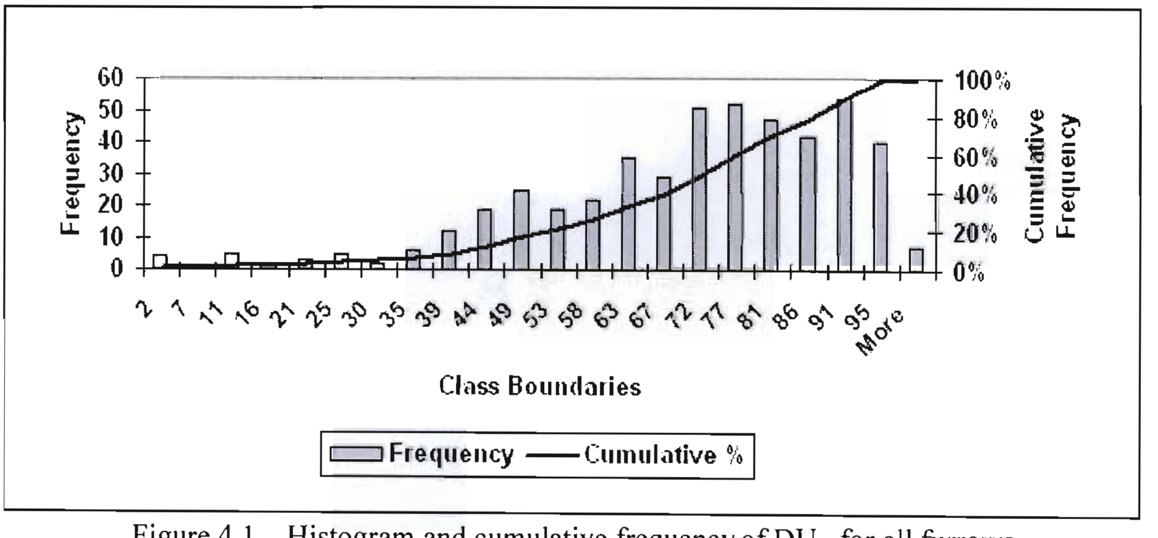

Figure 4.1 Histogram and cumulative frequency of DU_{lq} for all furrows

Although there is no universal range of potential field AD values, USDA (1997) and English (2000) state that for a high value crop, the AD should be a minimum of 80%. For furrow, the target application for HVE, ME and from the fourth TGSE irrigation onwards was 50% of the Total Available Moisture (TAM). For the first three irrigation applications for TGSE the target application (according to TGSE guidelines) was equivalent to 100% TAM. This information is required when determining the AD values for the furrow irrigation systems (cf Chapter 3.1.2). Thus, using AD = 80% as standard, 45% of the in-row evaluations and 12% of the inter-row evaluations had AD values equal to or above the standard. Overall, the furrow system had 41% of the evaluations equal to or above this AD target.

The histogram and cumulative distribution for the AD of all the furrows is shown in Figure 4.2. It can be seen from Figure 4.2 that a high proportion of the furrows, approximately 30%, are not achieving the target application along the entire length of the furrow. This is a mainly due to the management of the irrigations system, and can be rectified through better supervision of the calculations of cut-off times and volume of water application, and the supervision of the operators.

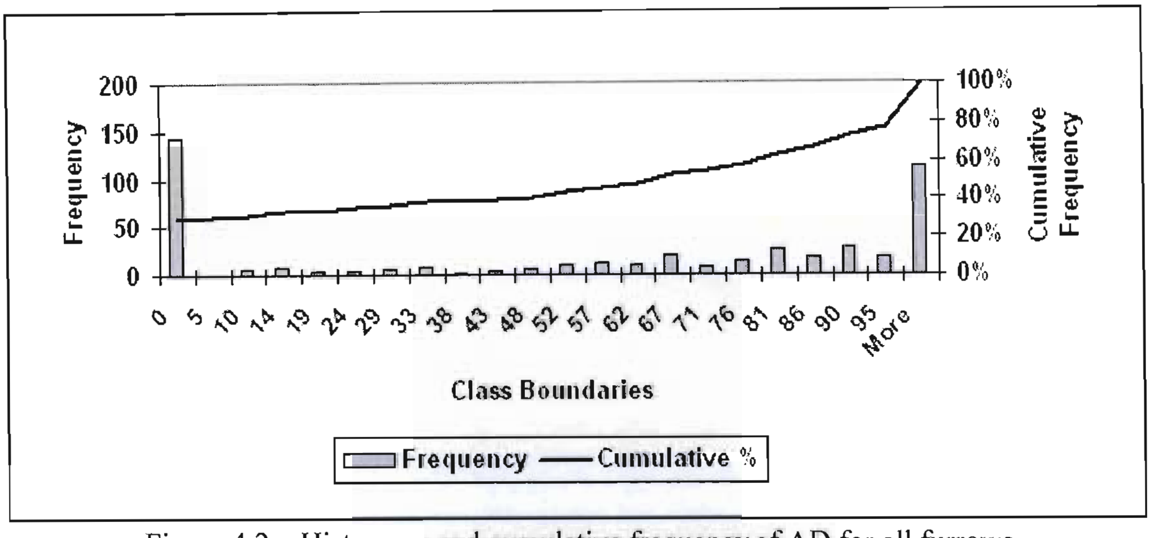

Figure 4.2 Histogram and cumulative frequency of AD for all furrows

Overall, furrow irrigation has a positive DT value of 16%, which indicates that excess water was being applied which could result in the non-beneficial use of water as a consequence of deep drainage and surface run-off. However, the non-beneficial term is relative to field evaluated, as the water may enter another catchment system and be used beneficially for irrigation downstream, although the quality of the water may be compromised due to the possible leaching of fertilisers and salts. On average, nearly 35% more water was being applied using the in-row furrow systems compared to the inter-row furrow systems, with in-row at a positive 19% and inter-row at a negative 15%. It is acknowledged that the sample sizes are not the same and the inter-row values may not be entirely representative, with only 43 tests performed. However, the results are as expected when based on the assumption that inter-row irrigation applies less water than an in-row equivalent, owing to the non-obstruction of water flow by the sugarcane crop for inter-row irrigation and the resultant faster advance front times.

The data contained in Figure 4.3 shows that the water use efficiency could be increased if the number of irrigations indicating gross over application were reduced. Once again, management should play a role in curbing such excesses.

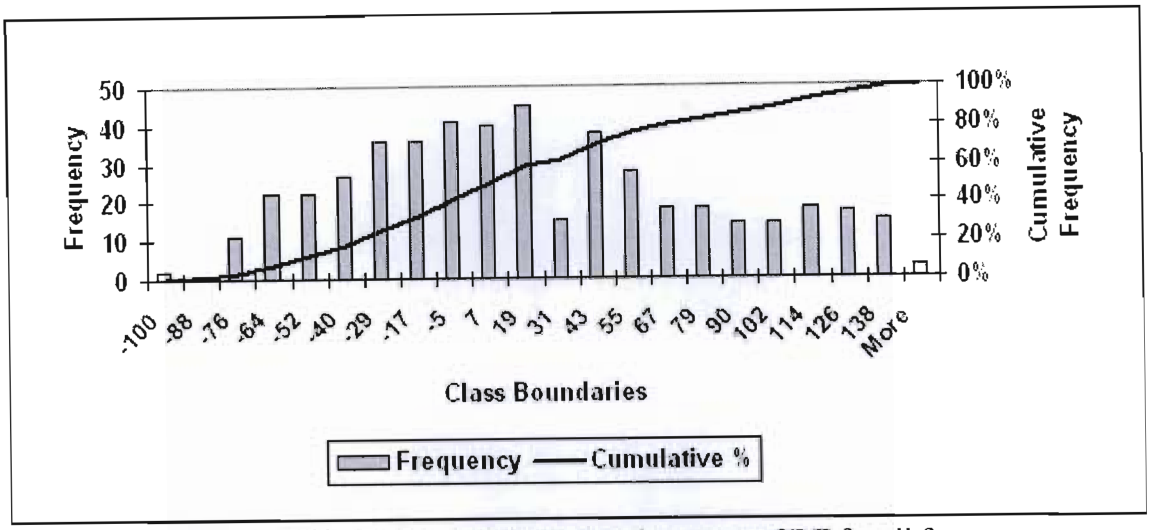

Figure 4.3 Histogram and cumulative frequency of DT for all furrows

4.1.2 Factors which affect uniformity

From the measurements taken during the evaluations, possible trends and factors were investigated, which may have had a direct or indirect impact on the uniformity of the furrow irrigation systems.

4.1.2.1 Irrigation system design, maintenance and operation

It was not the focus of the MIPU to assess the design, hardware, maintenance and management of the irrigation systems in specific detail. However, whenever the MIPU perceived that one of the above-mentioned factors had an impact on an irrigation systems performance, it was recorded. In addition, separating the furrow systems into the different farmer groupings may also help in this regard. To better understand the effects that certain design or operational choices may have on the performance of an irrigation system, the broad categories are sub-divided into the various estates, as shown in Table 4.1. Once this was done, factors which may have affected this type of irrigation system, in the area of design, operation and maintenance, can be investigated. The percentage of evaluations which recorded the DU_{lq} as operating within the design range of 65-

87% were as follows: For in-row furrow, 53% of HVE, 54% of ME, 73% of TGSE (63% for TGSE's first three irrigations and 95% for TGSE's fourth irrigation and onwards) calculations were within or above the design norm. For inter-row furrow, 43% of HVE and 52% of ME measurements were within or above the design norm.

Table 4.1 Measured average distribution uniformity (DU_{lq}), adequacy (AD) and deviation from target (DT) performance parameters and shape, wetted perimeter (WP), slope and length design parameters for the separated furrow irrigation systems

System	Estate	DU_{lq} (%)	AD (%)	DT (%)	Cross-sectional Furrow Shape	WP (mm)	Slope (%)	Length (m)	Number of Evaluations
In-row	HVE[1]	66	58	24	Small border - shallow	930	0.88	104	62
	ME[2]	61	50	15	Parabolic - intermediate	750	0.62	116	112
	TGSE[3]	73	56	19	Parabolic - deep	800	1.10	85	265
Inter-row	HVE	61	43	7	Small border - shallow	960	0.62	170	14
	ME	56	29	-23	Parabolic - intermediate	680	0.65	110	29

[1] Hippo Valley Estate

[2] Mkwasine Estate

[3] Triangle Group Sugar Estate

For AD the in-row evaluations of HVE, ME and TGSE recorded percentages of 42%, 28% and 46% respectively, above the target value of 80% for high value crops, whilst for inter-row HVE and ME recorded 15% and 10% respectively. The in-row furrow irrigation has an average over-application of 24% of the target application, while the inter-row has an average under-application of 14% relative to the target application. Owing to the fact that the inter-row furrow does not have the obstruction to water flow as in-row does, this would be expected, with large inflows and short cut-off times.

The general shape of the furrows, which determine the Wetter Perimeter (WP), were noted by the MIPU and are shown in Figure 4.4. The WP, slope, length and number of irrigations were graphed against DU_{lq} for the in-row and inter-row data collected at each estate. This was done in order to determine if any obvious trends were present between the factors of WP, slope, length, number of irrigations and the uniformity component of DU_{lq}. No obvious trends were noted and the charts are contained in Appendix B.

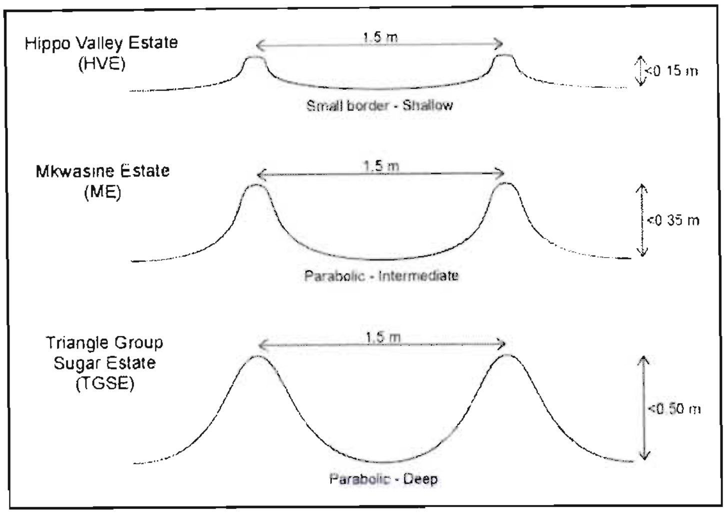

Figure 4.4 Predominant furrow shapes on respective estates

During the course of the furrow evaluations carried out by the ZSAES and estate MIPUs, the author did take note of some practices which might negatively impact on the uniformity of irrigation on the respective estate. One such aspect which the author recommends should be further investigated is the current TGSE scheduling rule. TGSE applies 100% TAM as a target application to the first three irrigations and then 50% TAM to subsequent applications. The estate must assess if irrigating at 100% TAM is really beneficial to both the crop and in the context of the whole crop production system, as water is expensive, especially in terms of its opportunity cost, and if better uniformity could be obtained with an application of 50% of TAM and is managed correctly, the estate could save on the additional cost of water and may attain better yields as a result of the higher irrigation uniformity. Lecler (2004) showed that at TGSE the first three irrigation applications should only be equal in magnitude to 50% of TAM and not 100% TAM, as was the current practice at TGSE.

The MIPU at ME conducted follow-through evaluations on the same 10 in-row furrows, with the evaluations spaced throughout the growing season. The design application for all the furrows was 50 mm, which was equivalent to 50% of the TAM values for all fields. The change in application amounts throughout the season as the sugarcane crop is growing, is shown in Figure 4.5. The scatter plot indicates there may be a slight trend, however, there is additional unexplained variation. The trend shows an increase in water application as the growing season lengthens, which would be expected with continued growth, and in some instances, lodging of the sugarcane crop which would impede the flow of water down the furrow, thus creating longer contact times which, on average, would result in more water infiltrating the furrow (Clowes and Breakwell, 1998).

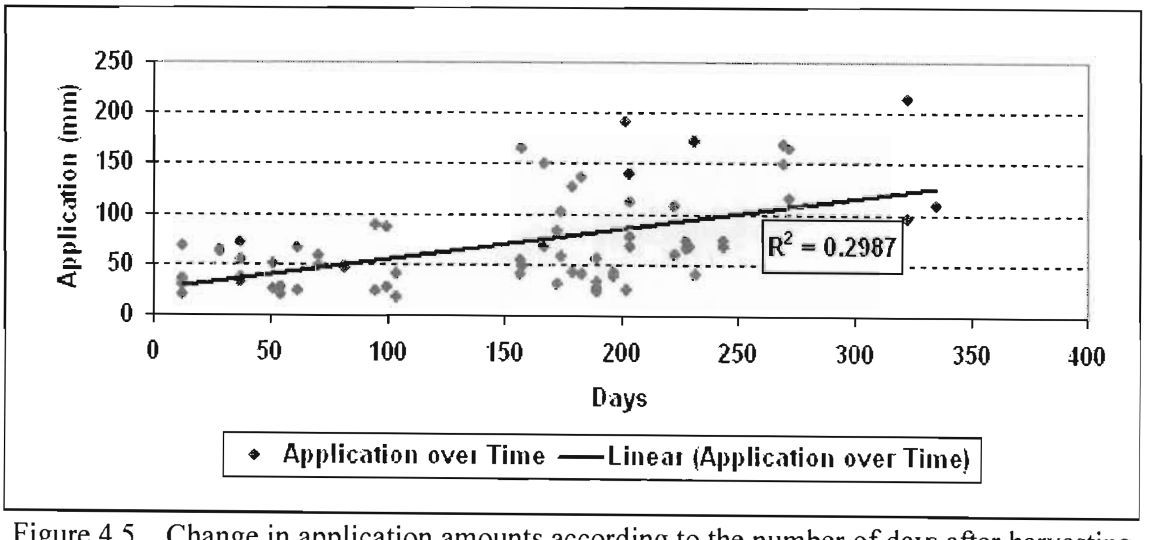

Figure 4.5 Change in application amounts according to the number of days after harvesting or planting for ME furrows

When these data are separated into an average application amount per quarter of the year, as shown in Figure 4.6, it is evident that there is a large increase in the application amount by quarter. It is recommended that the management at ME should try to control this by considering a change in the furrow system type to in-row which would result in less impediment to water flow, except in the instance of lodging, or possibly by increasing the flowrate into the furrow, with a shorter contact time.

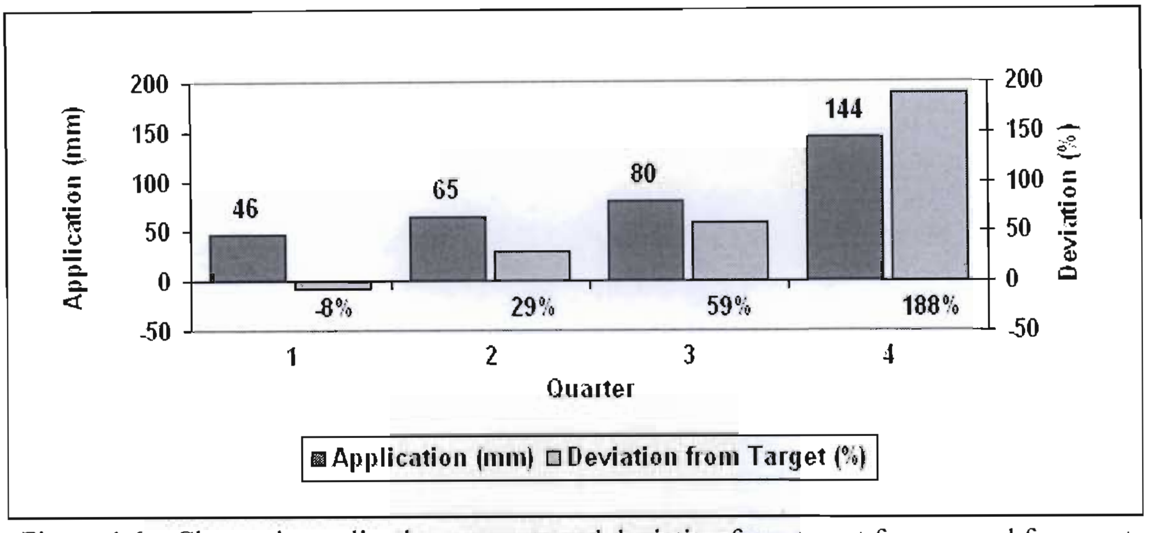

Figure 4.6 Change in application amounts and deviation from target for seasonal furrow at ME

The furrow simulation software, such as SIRMOD could be used by ME to assist with making management decisions in this regard. The above results indicate that the change in infiltration times, as a result of the increased obstruction in the furrow which is usually attributed to either the increase in the sugarcane ratoon size in the furrow or additional debris and lodging, were resulting in increasing over-irrigation as the season progressed.

An indication of the increases in advance time, down a particular furrow at ME, over a number of irrigation events during the growing season is shown in Figure 4.7. The increase in the recession time is shown in Figure 4.8. Whilst these times are expected to increase as a result of factors such as impediment of water flow as a result of the growth of the sugarcane crop, the increase in the contact times should not be increasing at such a rate and should be controlled by the management of the inflow rate and cut-off time for the furrow.

The DU_{lq} was also calculated for each of these evaluations, using the contact times and the methods explained by Koegelenberg and Breedt (2003). Listing the evaluation number with the respective uniformity, it can be seen that the uniformity decreases significantly over the season as shown in Table 4.2.

Table 4.2 Changes in the average distribution uniformity (DU_{lq}) values with the number of the irrigation event evaluated for furrow irrigation at Mkwasine Estate (ME)

Evaluation (Number)	2	3	4	5	7	8
DU_{lq} (%)	72	68	68	48	41	23

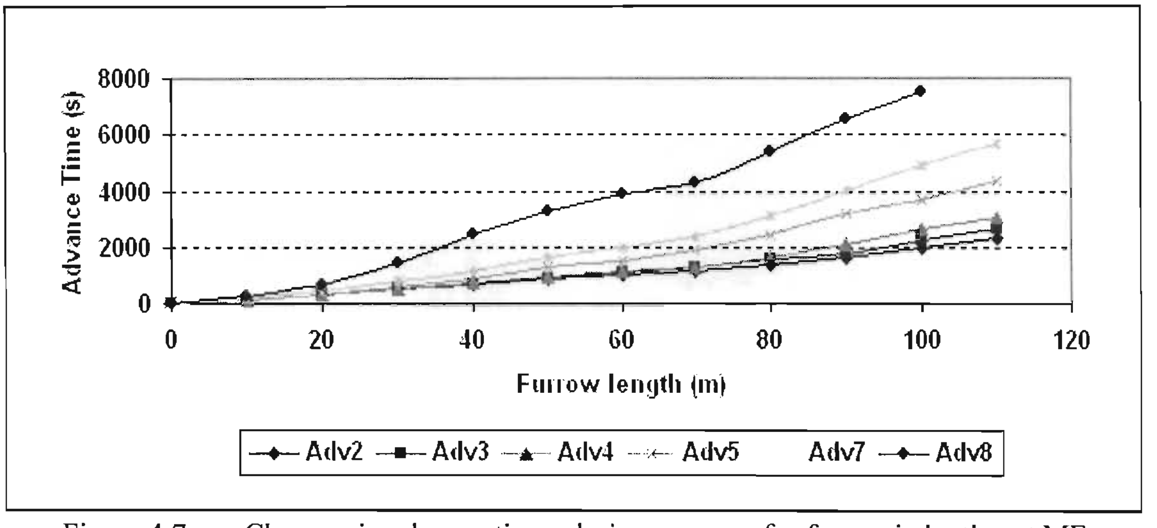

Figure 4.7 Changes in advance times during a season for furrow irrigation at ME

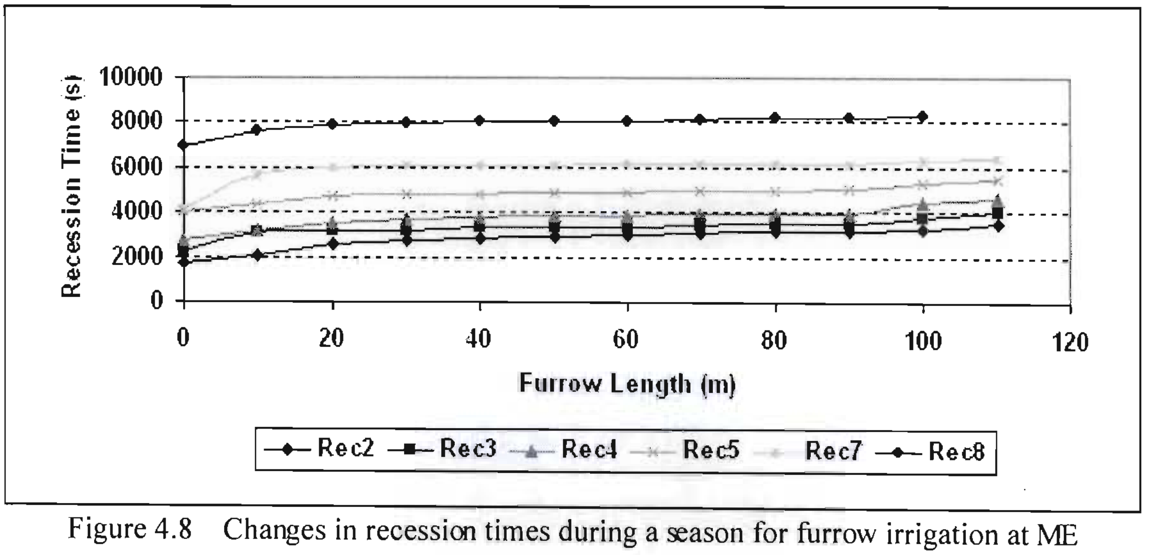

Figure 4.8 Changes in recession times during a season for furrow irrigation at ME

While carrying out evaluations on the estates, the MIPU noticed that the quality of the furrow ridges do decrease with time, and the furrow shape used by HVE seemed to be especially susceptible to collapse, thereby allowing water from adjacent furrows to mix, thus decreasing the uniformity of the irrigation event. HVE uses machinery called a "metfab", which is pulled behind a tractor and which works like a scraper down the length of the furrow, after every harvest. Although this practice reconstitutes the furrow shape, it could lead to wheel track compaction in the field. The other estates use disk ridgers, which are only placed in-field when deemed necessary, usually after three years. There is scope for additional research to determine if the different machinery used, may affect the in-field uniformity of water application.

Another "hardware" aspect that could affect irrigation perfomance, is the quality of the syphons. Cracks and "short" syphons which are more sensitive to height of water in the feeder canal, can affect the volume of water applied. On a number of occasions, the MIPU teams also noted that syphons had actually stopped syphoning owing to blockage of the syphon by debris/large stones in the feeder canal, or the "whirlpool" affect which leads to the sucking in of air into the syphon owing to the fact that the syphon end which was placed in the feeder canal is too short, and thus too close to the water surface. A pro-active preventative maintenance programme for the furrow irrigation systems on the estates was not evident, including maintenance on the feeder canal systems, syphons and furrow ridges. However, there are corrective maintenance measures that are carried out by the estates, such as fixing of badly leaking feeder canals, re-ridging in certain field portions and replacement of badly damaged syphons. In poorly designed fields, TGSE re-designs furrow irrigated fields at re-planting of the sugarcane crop, and reshapes fields to attain more uniform slopes and furrow lengths. TGSE have also incorporated new drainage, where deemed necessary, in the re-design process.

4.2 Overhead Sprinkler

Thirty three centre pivot, 66 hand-move and 14 static sprinkler evaluations were conducted by the ZSAES MIPU during the course of this research.

4.2.1 In-field performance parameters

The DU_{lq}, AD and DT values for the centre pivot, hand-move and static sprinkler irrigation systems are included in this section. The DU_{lq} results are shown in Figures 4.9 through to 4.11 respectively.

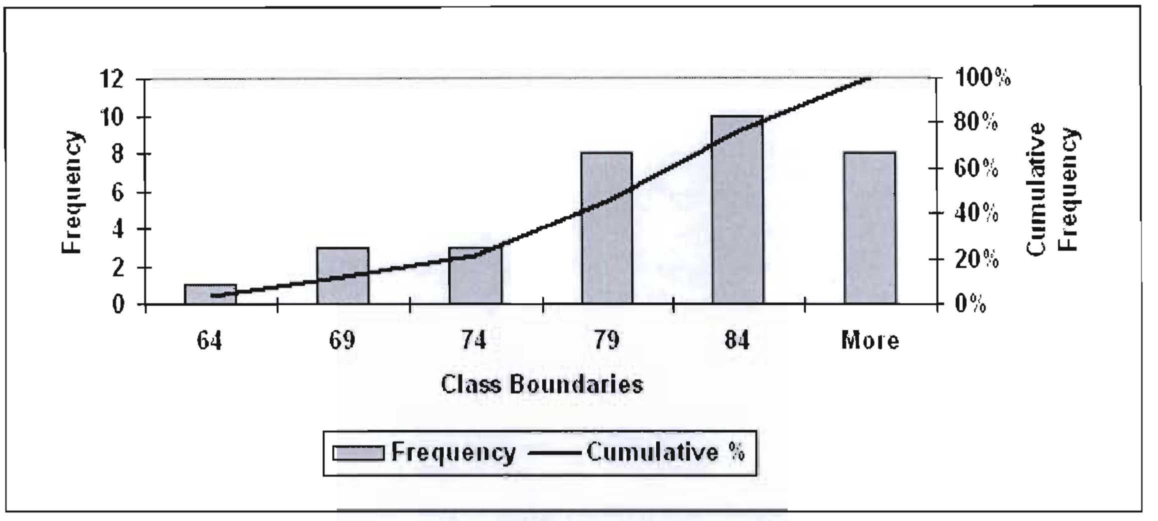

Figure 4.9 Histogram and cumulative frequency of DU_{lq} for centre pivot

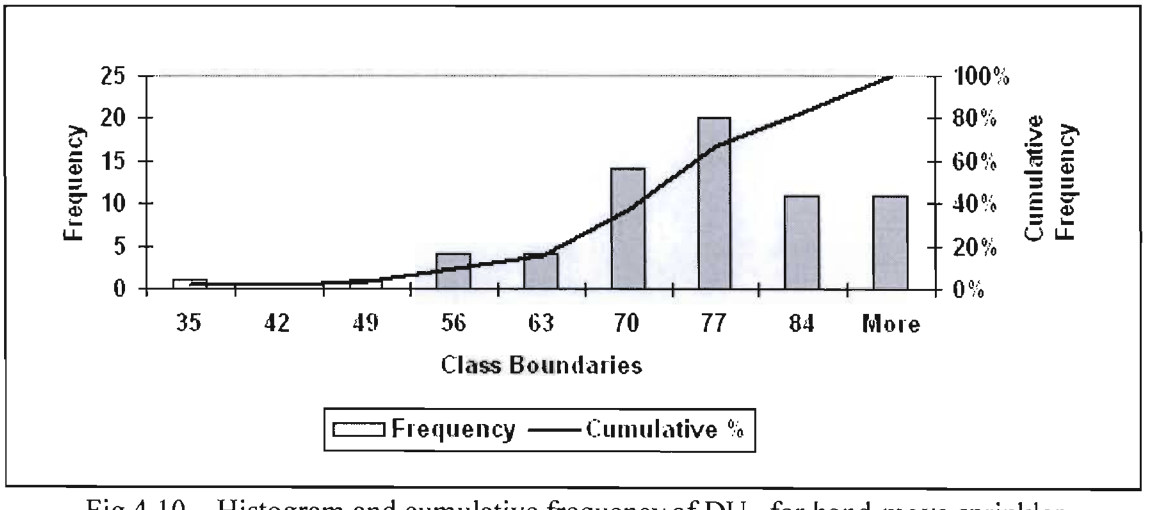

Fig 4.10 Histogram and cumulative frequency of DU_{lq} for hand-move sprinkler

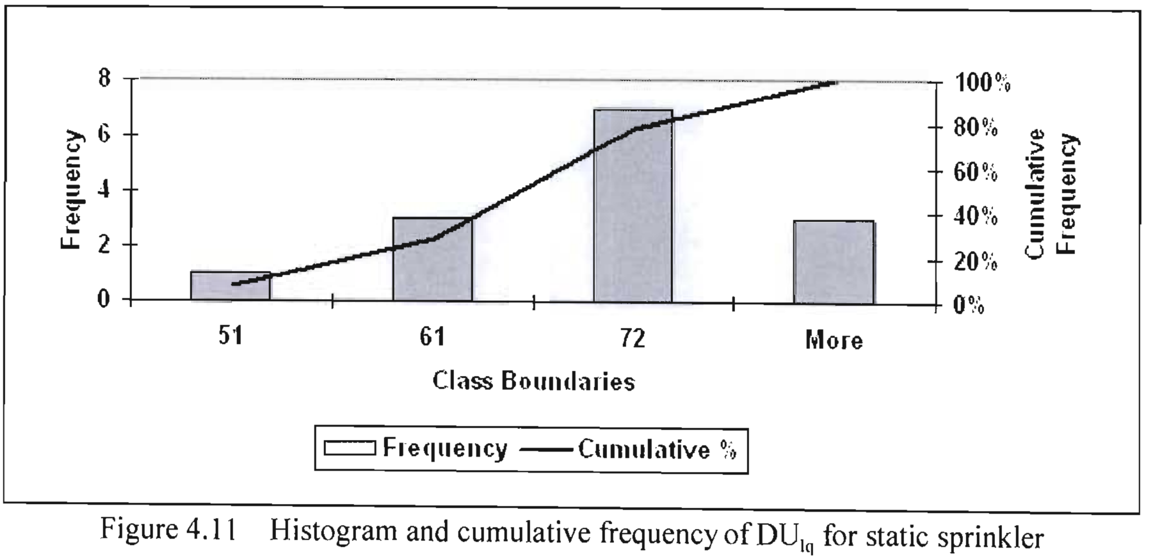

Figure 4.11 Histogram and cumulative frequency of DU_{lq} for static sprinkler

The percentage of centre pivot irrigation systems within the potential field DU_{lq} range of 78% to 90% or higher was 58%. The potential field DU_{lq} range is 70% to 86% for the hand-move irrigation system, with 74% within the above range or higher. The solid-set sprinkler irrigation systems has only 14% that lie within the potential field DU_{lq} range of 73% to 86% or above. From these results it appears that maintenance and design need to be highlighted by the management, especially with the static sprinkler irrigation system, as low uniformity is usually a result of hardware and irrigation system design issues (Raine *et al.*,2005). The AD data was charted for the centre pivot, hand-move and static sprinkler irrigation systems and are contained in Figure 4.12 to 4.14 respectively.

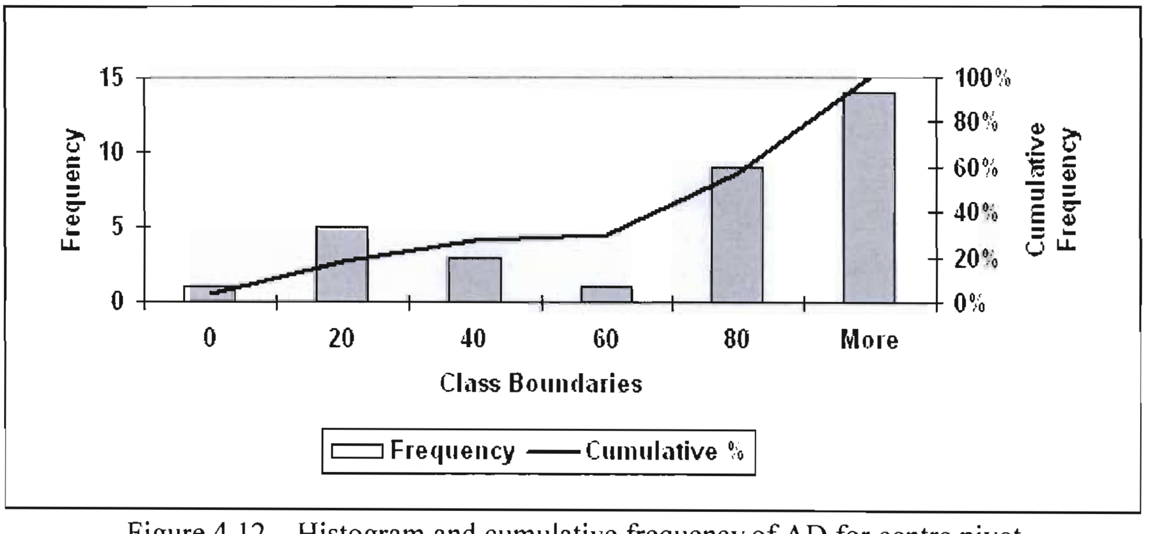

Figure 4.12 Histogram and cumulative frequency of AD for centre pivot

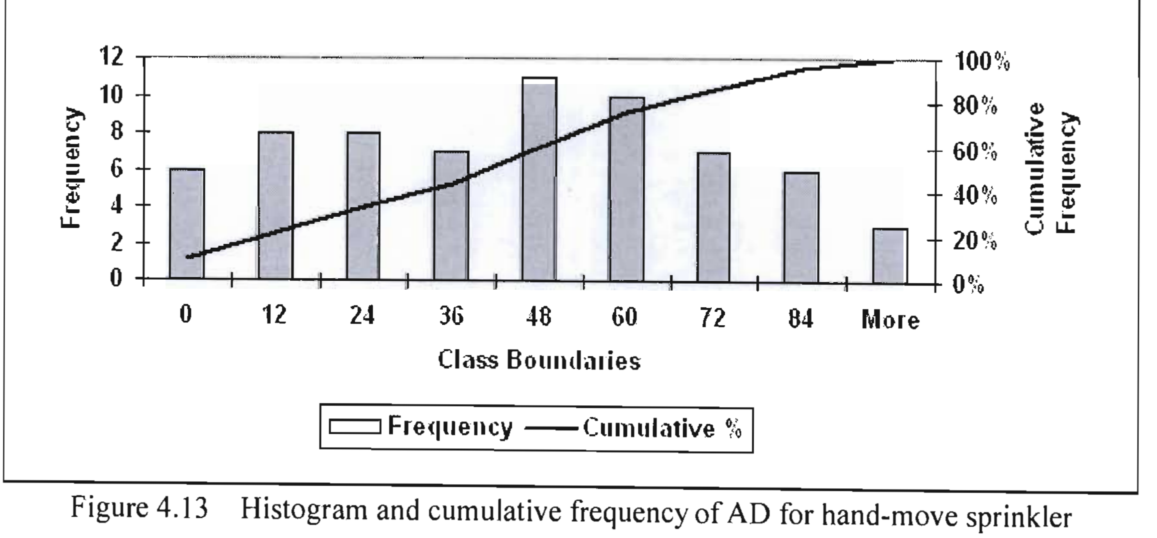

Figure 4.13 Histogram and cumulative frequency of AD for hand-move sprinkler

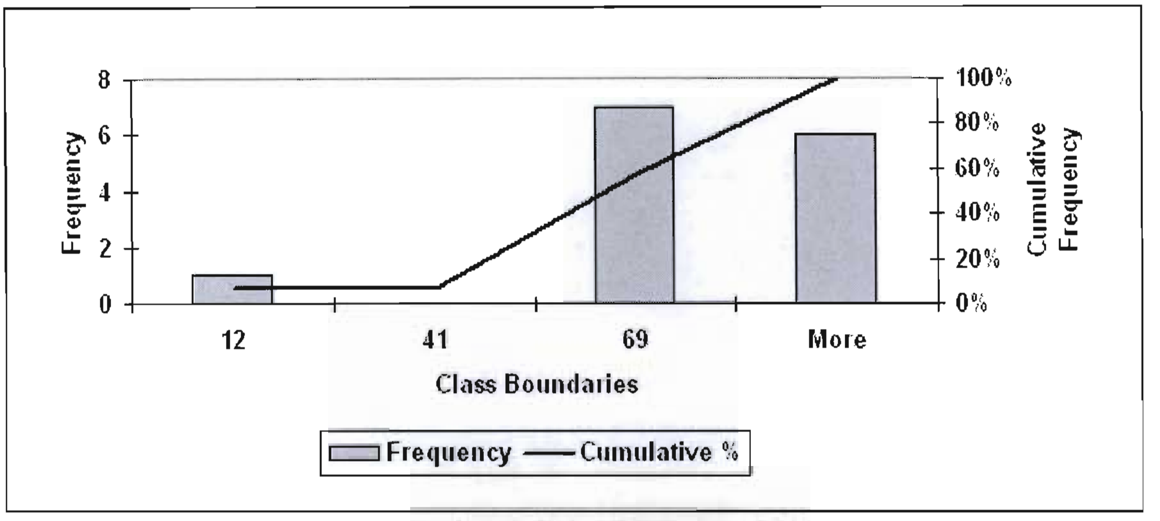

Figure 4.14 Histogram and cumulative frequency of AD for static sprinkler

In regard the AD data, 40% of the centre pivot systems, 13% of the hand-move systems and 20% of the solid-set systems are either equal to or above the target AD value of 80%. These low values are of concern to the author, but can be increased by making certain that sprinkler packages are correctly sized and control panels are correctly calibrated for centre pivots, that the stand-times correctly match the target water application, i.e. correct scheduling, for the hand-move and static sprinkler irrigation systems. Figure 4.15 through to Figure 4.17 contain the DT results for the centre pivot, hand-move and static sprinkler irrigation systems. The DT for centre pivots was calculated from the difference between the target application setting input into the electronic console by the operator and the water collected in the rain-gauges. For hand-move and static irrigation systems the DT was calculated from the differences in the actual flow rates measured from the sprinklers and the water collected in the rain-gauges.

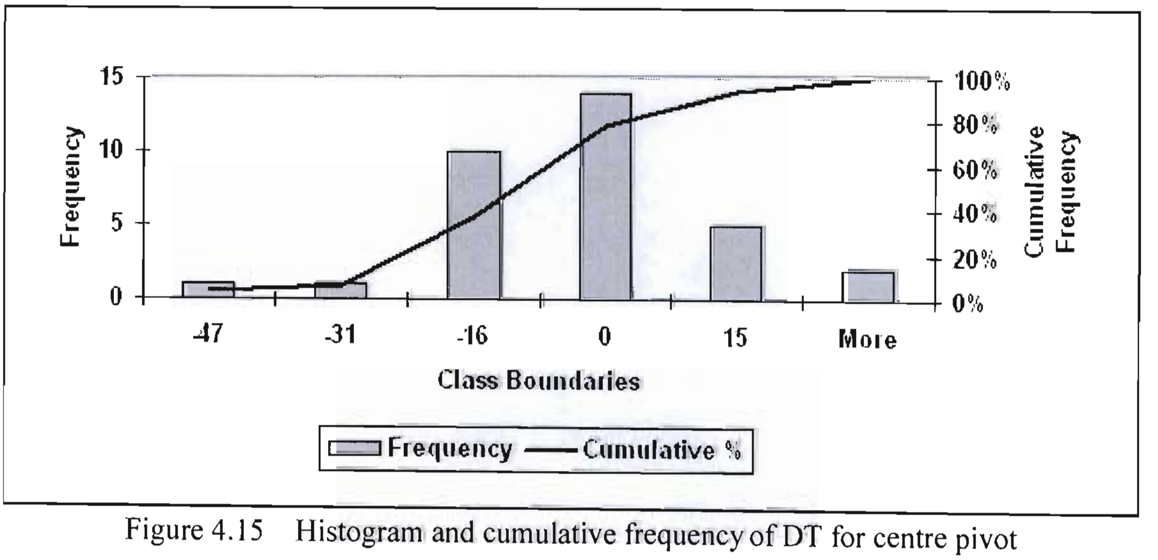

Figure 4.15 Histogram and cumulative frequency of DT for centre pivot

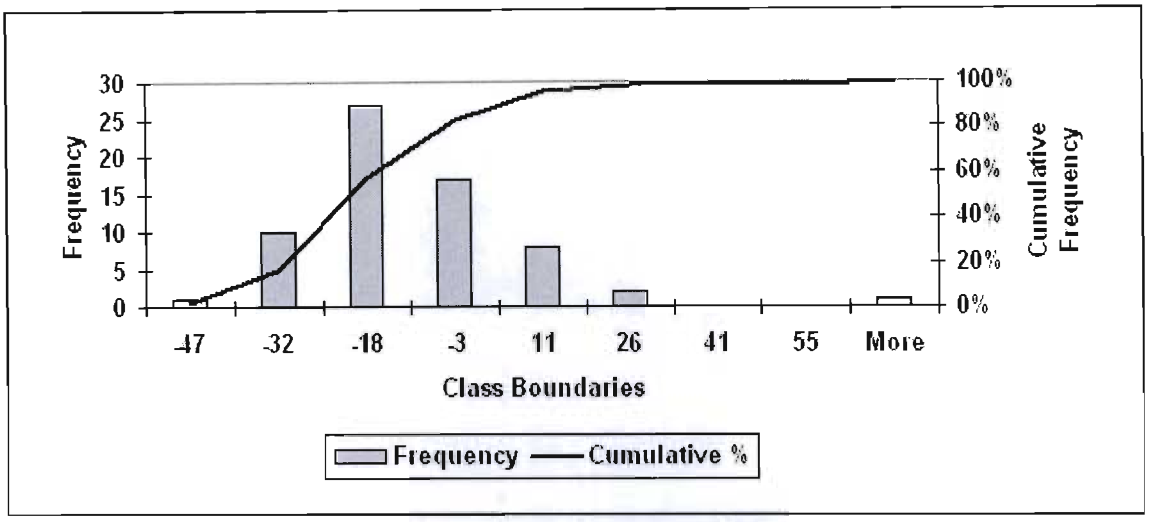

Figure 4.16 Histogram and cumulative frequency of DT for hand-move sprinkler

The average DT for centre pivot was -10%, for hand-move -19% and for the static sprinkler data averaged at -12%. Mostly environmental factors play a role in this discrepancy from the target application and apart from the hand-move sprinkler the DT values of the other two types of sprinkler systems are well within the norm.

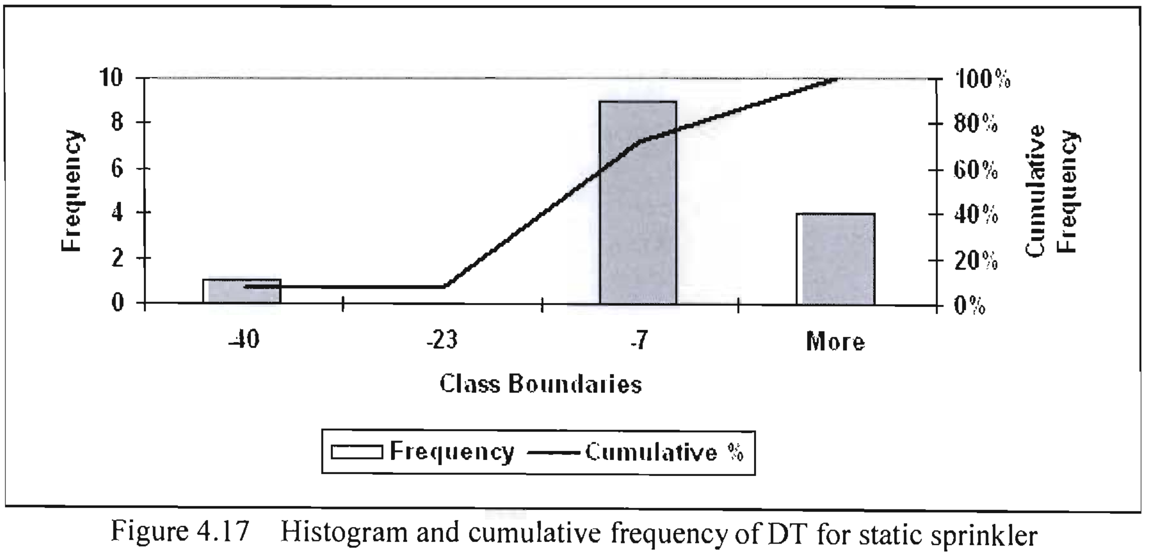

Figure 4.17 Histogram and cumulative frequency of DT for static sprinkler

4.2.2 Factors which affect uniformity

From the measurements taken during the evaluations, possible trends and factors were investigated, which may have had a direct or indirect impact on the uniformity of the sprinkler irrigation systems. Further trends are investigated in the following section, which will include separating the manufacturers of the centre pivots and investigating the effect which management has on the perfomance of irrigation systems.

4.2.2.1 Irrigation system design, maintenance and operation

As far as the MIPU could ascertain, the majority of the centre pivot systems installed in the Lowveld did not have a matching of the infiltration rate of the soil to the application rate of the centre pivot at the specific location included in the designs. The only known instance of this "matching" occurring was with a HVE centre pivot in 1999, when the WMP was involved in suggesting remedial measures which included the installation of booms, in order to match the application rate of a sprinkler package already bought, to the infiltration rate of the soil. The infiltrometer developed by the ARC-ILI (ARC-ILI, 1984) could have been used to improve the designs. Some of the centre pivots evaluated at MSE had excessive runoff at the outer ends of the tower and this was one of the main reasons that the pivots were set to 16 mm per application, as opposed to the ZSAES recommended minimum of 25 mm. Having such a small application can lead to excessive water loss via evaporation from both the soil surface and whilst in the air, as described by Lecler (2004). Another recommendation is to have the wheel-tracks gravelled, to try and prevent wheel slip to less than the value of 3%, as suggested in the literature (USDA, 1997; Kincaid, 2002). This "gravelling" was not witnessed with the majority of centre pivots that were evaluated. Some systems had wheel-tracks that had depths of over 0.3 m deep, an example of which is shown in Figure 4.18.

Figure 4.18 The result of not having the centre pivot wheel-track gravelled

A very important aspect of the centre pivot system are the characteristics of the sprinkler packages, as these determine the spray pattern, droplet size and application rate, all factors which have a role in determining the performance of a system. The sprinkler packages associated with the different manufacturers of centre pivot were: Senniger I-Wob sprinkler packages for the Valley and Nelson sprinkler packages for the Agrico pivots. The operation of the sprinklers influence the required maintenance. For example, the Nelson sprinklers, which operated on a finer spinning mechanism, were easily affected by the clogging from green algae compared to the I-Wob sprinklers, which have a coarser spinning mechanism. The green algae were only found on two pivots at HVE, which are supposed to undergo regular cleaning of the sprinkler packages during the summer.

There are two main manufacturers of centre pivot systems used in the Lowveld, i.e. the Agrico and Valley systems. The results from the evaluations carried out have been separated into these two systems, to try ascertain whether there are any differences as a result of the manufacturer. These two systems are further separated into pivots which operated with the end valve slightly open (this method of operation was only found in practice at MSE), and pivots which operated with the end valve closed. These results are shown in Table 4.3.

Table 4.3 Measured average distribution uniformity (DU_{lq}), adequacy (AD) and deviation from target (DT) performance parameters of the Agrico and Valley centre pivot irrigation systems found in the Lowveld

System Type	Pressure Range (kPa)	DU_{lq} Range (%)	DU_{lq} Average (%)	AD Range (%)	AD Average (%)	DT Average (%)	Number of Evaluations
Agrico: Valve Closed[1]	175 - 335	64 - 89	79	64 - 100	84	-7	10
Agrico: Valve Open[2]		64 - 80	72	67 - 98	84	-2	4
Valley: Valve Closed	140 - 340	71 - 89	81	22 - 91	69	-13	14
Valley: Valve Open		68 - 83	77	13 - 82	28	-21	5

[1] The end valve of the centre pivot remains shut during operation

[2] The end valve of the centre pivot was left open slightly as the Mwenezana Sugar Estate (MSE) management thought it would apply adequate water to the outlying rows of sugarcane

Nine of the ten of the Agrico closed valve configuration were within the DU_{lq} design norm range of 78-90% or above. Two out of the four systems, or 50% of the evaluations of the Agrico open valve configuration, were within the DU_{lq} design norm range. The Valley systems had six out of 14, or 43%, within the DU_{lq} design norm range for the closed valve evaluations. Four out of the five, or 80%, of the open valve evaluations were within the DU_{lq} design norm range. The Valley pivots, on average, were applying 12% less water than the Agrico pivots relative to the target applications. The performance parameters were also separated according to each estate. The average DU_{lq} and AD and DT values for each estate are tabulated in Table 4.4, in order to assess whether the operational management, practised by each respective estate, had a role in affecting a system's performance.

The value of 75% for DU_{lq} for the open end-valve is only just outside the design norm, but is less than the system average (83%). However, the associated AD value (51%) is very low compared to the average for the rest of the estates (76%). This would likely have an effect on crop production, due to some areas of sugarcane receiving inadequate application of water, thereby affecting the yield potential of the crop. It is recommended that the end-valves always be closed.

Table 4.4 Measured pressure ranges and average distribution uniformity (DU_{lq}), adequacy (AD) and deviation from target (DT) performance parameters for centre pivot irrigation systems grouped according to estate

System Type	Pressure Range (kPa)	DU_{lq} Range (%)	DU_{lq} Average (%)	AD Range (%)	AD Average (%)	DT Average (%)	Number of Evaluations
HVE[1]	150 - 340	76 - 86	81	44 -91	78	-8	4
MSE[2]: Valve Closed[4]	175 - 320	64 - 87	79	22 - 100	70	-8	15
MSE: Valve Open[5]	175 - 320	64 - 83	75	13 - 98	51	-9	9
MSE: Combined	175 - 320	64 - 87	77	13 - 100	62	-8	24
TGSE[3]	140 - 335	74 - 89	89	61 - 93	74	-14	5

[1] Hippo Valley Estate

[2] Mwenezana Sugar Estate

[3] Triangle Group Sugar Estate

[4] The end valve of the centre pivot remains shut during operation

[5] The end valve of the centre pivot was left open slightly as the Mwenezana Sugar Estate (MSE) management thought it would apply adequate water to the outlying rows of sugarcane

The highest DU_{lq} value of 89% was measured at TGSE, which is expected as this estate had a regular preventative and corrective maintenance schedule in place, albeit a very basic programme consisting of regular greasing of the pivot, cleaning of sprinkler nozzles and replacement if the sprinklers were not working according to their design. The maintenance programmes at both HVE and MSE were only corrective.

All evaluations for the hand-move sprinkler irrigation systems were carried out at TGSE. This type of irrigation system has been in operation on the estate since the 1970s. This particular system has the most comprehensive preventative and corrective maintenance programme in place of all the Lowveld estates. The programme is so aggressive that the sprinkler nozzles were being scheduled to be replaced every year, thus ensuring that nozzle wear would not be a major factor in affecting the performance of the system. Very few leaking joins or pipes were noticed during the evaluation period, which is attributed to TGSE having a "fields workshop", which specialised in the repair of the aluminium stand pipes and the portable aluminium piping.

It is postulated that this maintenance programme resulted in 74% of the hand-move sprinkler systems evaluated operating within the DU_{lq} design range. However, the low AD values obtained for this system type could be improved substantially with a slight increase in the stand-times. It was also noticed by the MIPU that, on occasion, the hand-move system was being operated under high wind conditions (above 4.5 m/s).

The static sprinkler system used in the Lowveld, known as the "Floppy" sprinkler system, is a relatively new invention, and as such was still undergoing development during the course of the evaluations. The MIPU evaluated an old floppy system and also evaluated a new design at ZSAES, in the same field, two years later. The results of these evaluations are contained in Table 4.5. The new design incorporated improved stability of the three metre high floppy risers made of galvanised steel (the older design used lighter aluminium risers which could be affected by a strong wind), new coupling joints, larger sized disc filters and a rigorous hydraulic design of the piping. Apart from the floppy system operated at ZSAES, none of the other static irrigation systems evaluated had a preventative maintenance schedule, although corrective maintenance was carried out on all the other systems.

Table 4.5 Comparison of the measured pressure range and the average distribution uniformity (DU_{lq}), adequacy (AD) and deviation from target (DT) performance parameters and the average wind speed for the new and old floppy irrigation systems

System Type	Pressure Range (kPa)	DU_{lq} Range (%)	DU_{lq} Average (%)	AD Range (%)	AD Average (%)	Average Wind Speed (m/s)	DT Average (%)	Number of Evaluations
ZSAES[1]: Old	215 - 285	51 - 68	61	50 - 76	67	1.1	-7	5
ZSAES: New	238 - 263	70 - 82	74	79 - 98	87	1.3	-11	4

[1] Zimbabwe Sugar Association Experiment Station

As the results show, a marked increase was attained in the performance of the system, due to the new design, in both the DU_{lq} and the AD, with increases of 20% and 29% respectively. As recorded, the measured average wind speeds were not very different, so wind would not have had a substantial impact on the difference in the performance parameters. The "old" design floppy sprinklers evaluated were one year old, while the age of the "new" design was less than one year old. Hence, it was assumed that system deterioration was not a factor in affecting the differences in performance.

The most significant changes to the design was the increased size of the submain and lateral pipe sizes, and the increase of the disc filter size from 140 to 500 micron, thus resulting in more uniform pressure being made available during the operation of the irrigation system. It was found that with the 140 micron disc filter, owing to its small size, clogged very quickly thus decreasing the available operating pressure during the actual irrigation event and limiting the volume of water applied, which adversely affected performance. During the course of the evaluations carried out on the sprinkler irrigation systems, it was noticed that pressure had a significant impact on the performance parameters to warrant a stand-alone section although pressure is considered an irrigation system design parameter.

4.2.2.2 Pressure

The average system operating pressures that were measured are shown in Figure 4.19, 4.20 and 4.21 for centre pivot, hand-move and the static sprinkler systems respectively. Figure 4.20 includes both "long range" and "spreader" pressure readings. This is due to the fact that the impact sprinklers operated on TGSE have two nozzles per sprinkler.

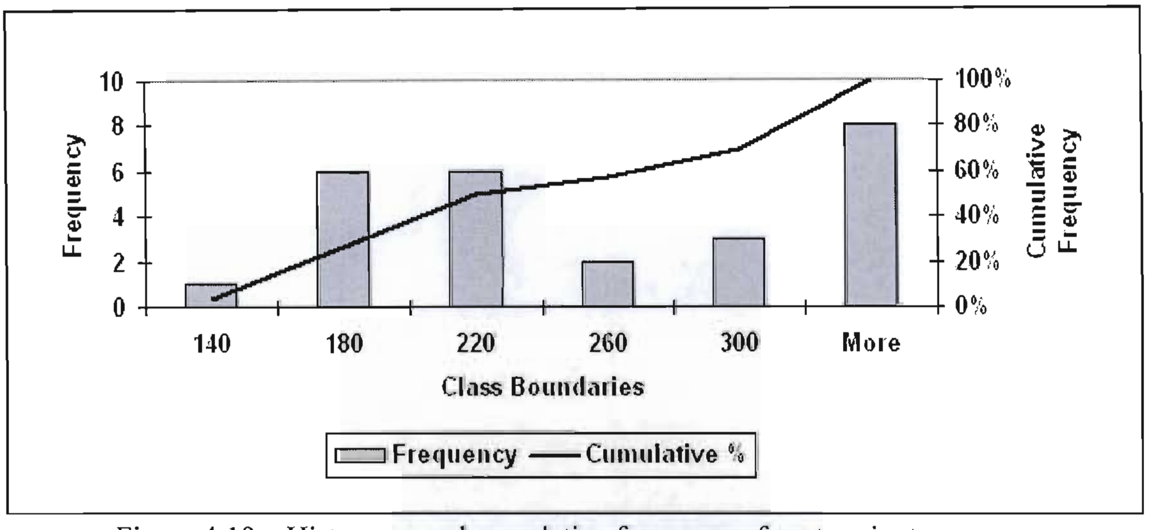

Figure 4.19 Histogram and cumulative frequency of centre pivot pressures

The minimum operating pressure for centre pivot irrigation systems was given by the estates as 200 kPa. Using this pressure as the guideline, 69% of the evaluations of centre pivots had measured pressures equal to or above the estate specified operating pressure. For hand-move sprinkler systems the recommended pressure, according to Reinders (1987), is approximately 60 to 70 times the nozzle size used in the sprinkler. On average, the nozzle size was 5.5 mm, which gives a minimum operating pressure of 330 kPa. TGSE, however, used 400 kPa as the standard pressure (McKersie, 2000). High pressure at the sprinkler nozzle can result in smaller water droplets which may in turn be more prone to being affected by evaporation and wind (Lecler, 2006). Only 15% of the evaluations for hand-move sprinkler met or exceeded the 400 kPa standard pressure. Using the minimum 330 kPa as a target pressure, then 65% of the systems evaluated met or exceeded the target pressure.

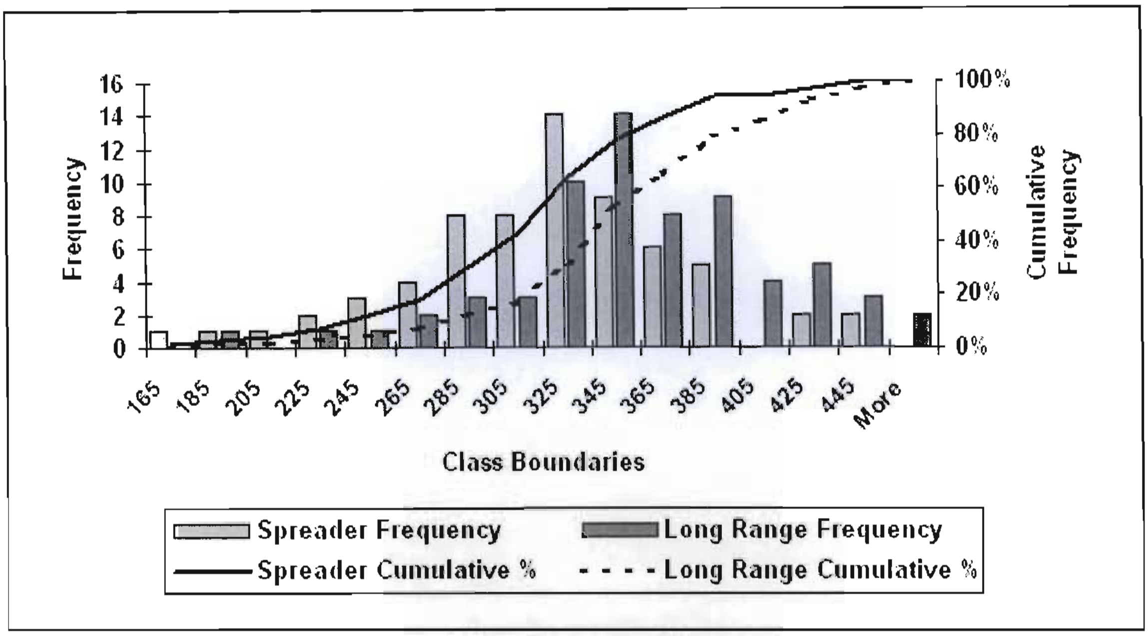

Figure 4.20 Histogram and cumulative frequency of hand-move sprinkler lateral pressures

At TGSE, pressures could be adjusted at the in-field hydrants which supply water to the laterals by adjusting a turn-valve on an elbow joint, fitted over the hydrant. The supervisor is able to check the lateral pressures at a pressure check point installed on the elbow, using a pressure gauge and fitting. At no time did the MIPU observe this practice. The MIPU had assumed that the pressures were controlled from the pump-house. The evaluation results were still used, because, as stipulated, the MIPU evaluates the in-field irrigation systems as operated on the day of the evaluation.

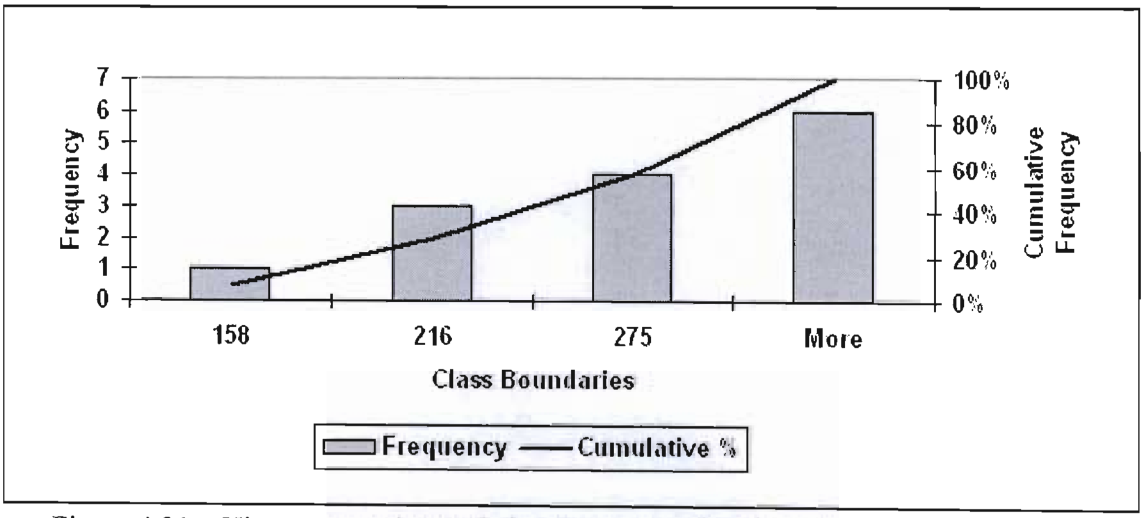

Figure 4.21 Histogram and cumulative frequency of static sprinkler lateral pressures

Hiemstra (1998) states that the minimum operating pressure for the floppy irrigation system, the only type of static sprinkler irrigation system operating in the Lowveld, should be 200 kPa. Using this value as a standard, 77% of the evaluations conducted on the floppy systems were equal to or above the minimum operating pressure. When the pressure data were plotted against the DU_{lq} data collected for the centre pivot and hand move sprinkler systems, as shown in Figure 4.22 and Figure 4.23 respectively, the scatter plot indicated no trend. The reasoning for this could be that with the centre pivots, each sprinkler pressure is controlled by a 100 kPa pressure regulator, and all the console pressures were above that minimum. With the hand-move sprinklers the fact that the majority of these systems operated at or above the design pressure implies that an adverse affect on the DU_{lq} would be minimal.

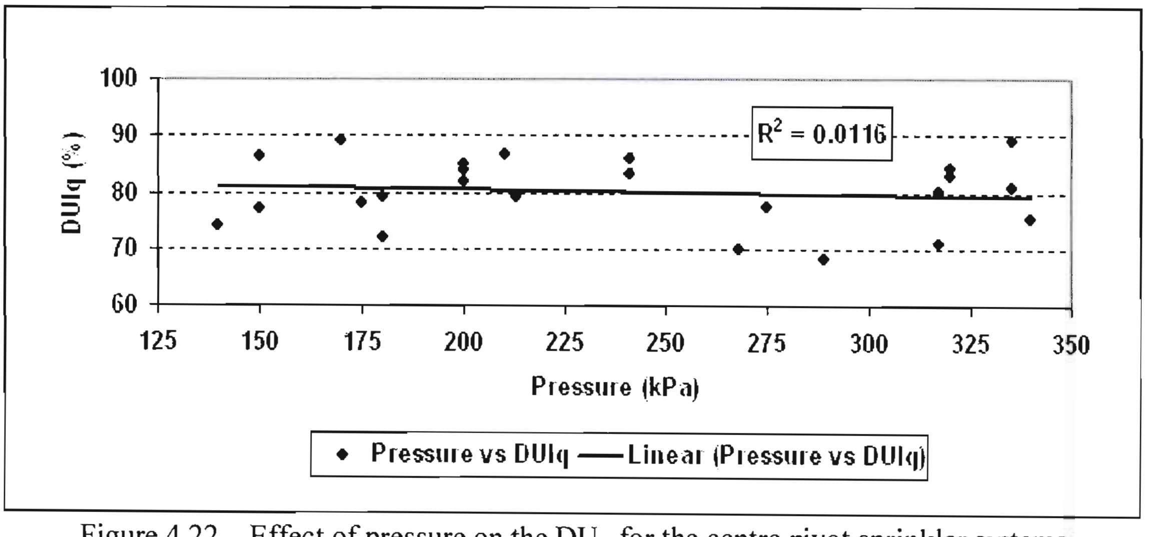

Figure 4.22 Effect of pressure on the DU_{lq} for the centre pivot sprinkler systems

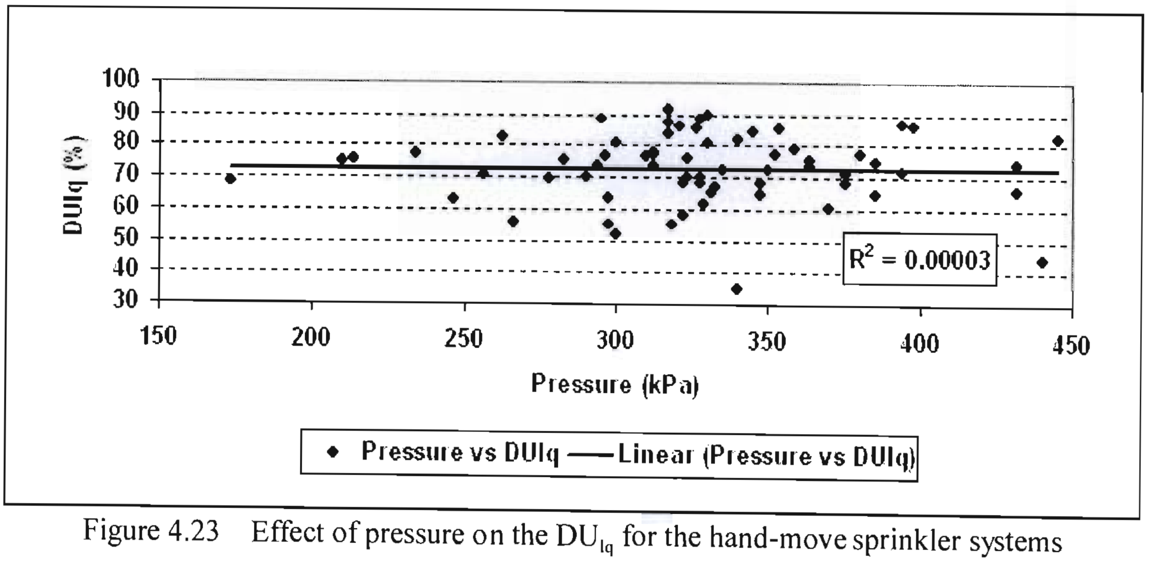

Figure 4.23 Effect of pressure on the DU_{lq} for the hand-move sprinkler systems

The scatter plot in Figure 4.24 indicates a slight trend, however, there is additional unexplained variation. The trend shows that the measured DU_{lq} increased up to a certain pressure then seemed to decrease. It was decided to investigate the relationships for pressure ranging from 200-250 kPa and for pressures greater than 250 kPa, as shown in Figure 4.24. As is evident from the data plotted there is apparently a definite optimum operating pressure range for this particular type of irrigation system. From these results the MIPU advised the floppy sprinkler manufacturers to recommend an operating pressure range of 230-250 kPa for systems operating in the Lowveld. The previous recommendation was a minimum operating pressure of 200 kPa.

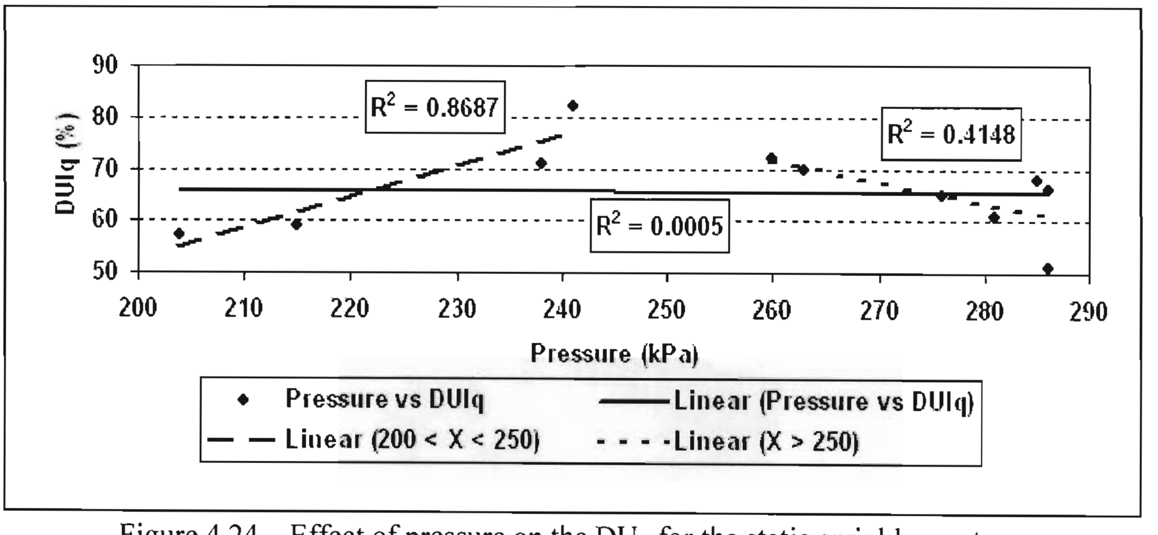

Figure 4.24 Effect of pressure on the DU_{lq} for the static sprinkler systems

4.2.2.3 Water quality

The issue of water quality is almost always associated with sub-surface drip irrigation systems. However, through the course of the evaluations of the various irrigation systems in the Lowveld it was found that the centre pivot and floppy irrigation systems were also affected by water quality. The factors which affected these irrigation systems were:

- Growth of a thick green algae which blocked up the pressure control valves that are situated above the sprinklers and, on occasions, clogging of the sprinkler nozzle and spray plate of the centre pivot irrigation system,
- Growth of a thick algae which blocked up the 120 micron disc filters of the floppy irrigation system, thus leading to interrupted water supply and decreased operating

pressures, and

- Small stones were being sucked into the centre pivot irrigation system, lodging in the plastic nozzle, thereby resulting in a distortion of the size of the nozzle orifice thereby eventually breaking the nozzle completely thus changing the flowrate from the sprinkler.

4.2.2.4 Wind

Wind affects the uniformity of an irrigation system such as overhead sprinkler (Burt *et al.*, 1997). Differences of 10% to 15% in water application have been measured due to wind drift (USDA 1997; Lecler 2004). The wind speeds measured during overhead sprinkler system evaluations are shown in Figures 4.25 to 4.27. Unfortunately, the portable wind speed meter was only purchased when half of the evaluations were already completed for the static sprinkler irrigation systems and the sample size is thus relatively small.

The average wind speed when evaluations were being conducted for centre pivot systems by the MIPU in the Lowveld was 1.70 m/s with the average wind speed for hand-move sprinkler systems being calculated as 2.54 m/s and the average wind speed for static sprinkler systems being 1.15 m/s. From the data it would be a reasonable assumption that the system which would be the most affected by the wind, with regard to the effect on performance of the irrigation system, would be the hand-move irrigation system.

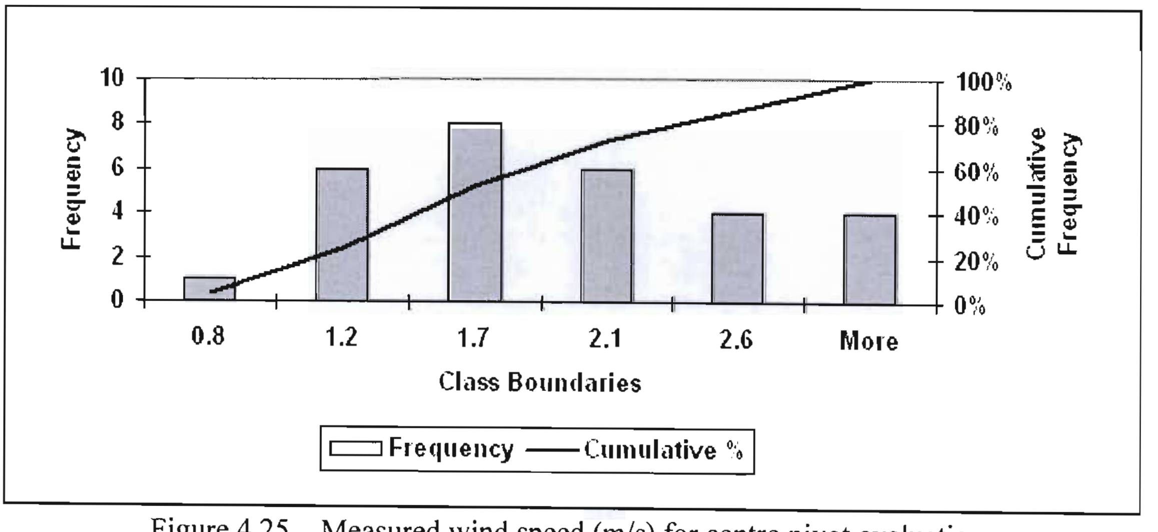

Figure 4.25 Measured wind speed (m/s) for centre pivot evaluations

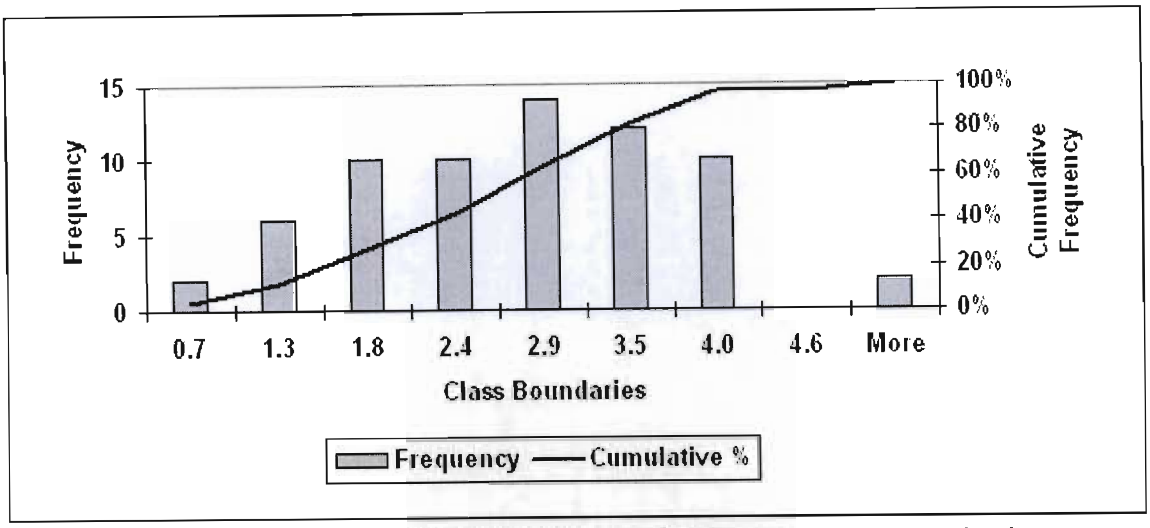

Figure 4.26 Measured wind speed (m/s) for hand-move sprinkler evaluations

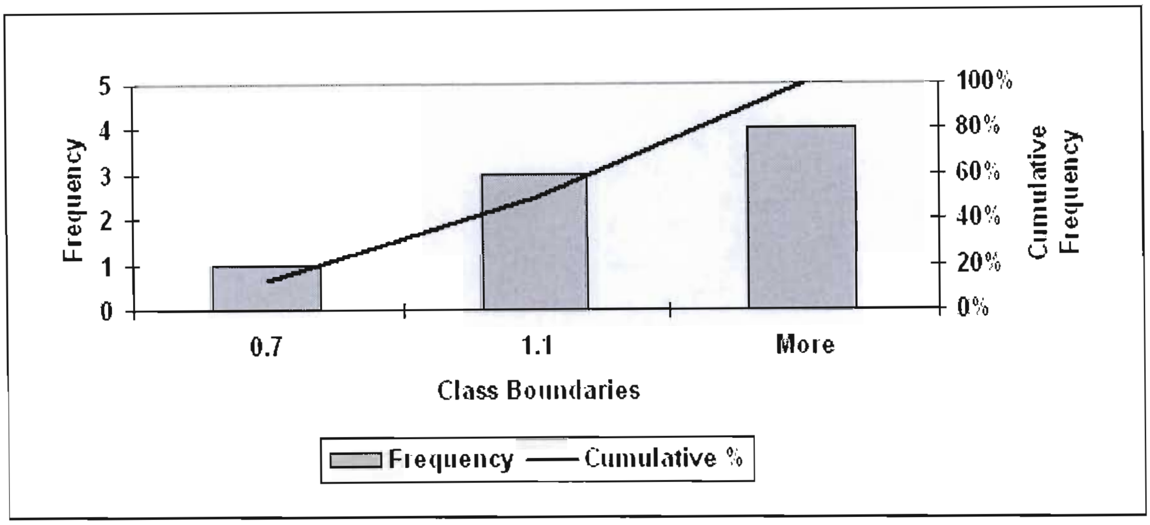

Figure 4.27 Measured wind speed (m/s) for static sprinkler evaluations

The effect that wind speed has on DU_{lq} values is shown in Figure 4.28 for the centre pivot irrigation systems evaluated by the MIPU. Although international literature suggests that wind speed can affect overhead sprinkler systems, the data collected in the Lowveld does not show this to be the case for the centre pivots evaluated by the MIPU. Possible reasoning for this is the fact that a centre pivot is a movable system, so the effect can be "masked" by the movement of the entire irrigation system, together with the fact that the wind speeds were all below 3 m/s, which is considered a medium wind speed. King and Kincaid (1997) noted that centre pivots were only significantly affected by wind speed of over 3.6 m/s.

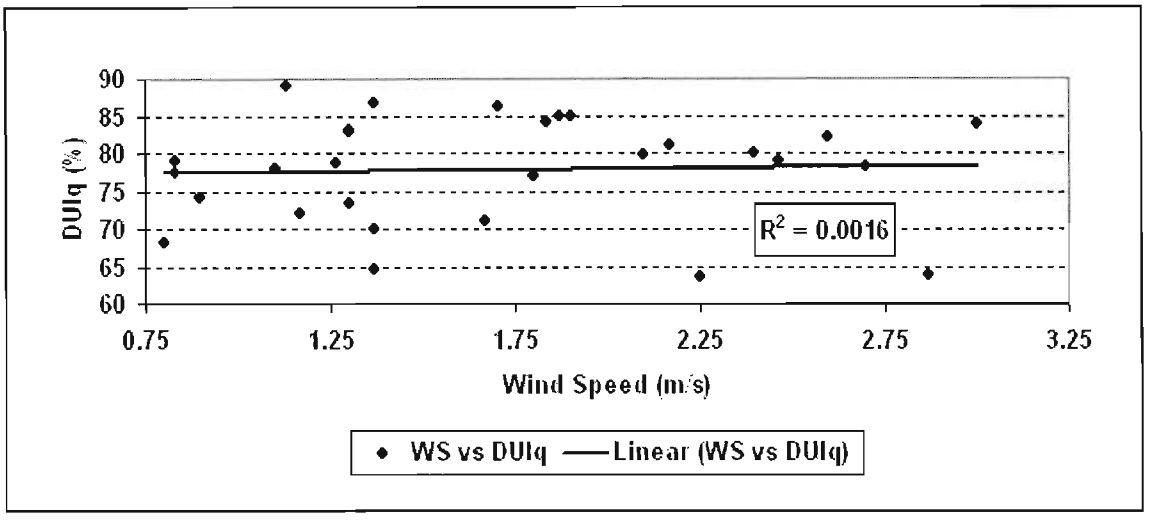

Figure 4.28 Effect of wind speed on the DU_{lq} for centre pivot

The effect of wind on hand-moved systems is shown in Figure 4.29 and demonstrates no obvious trend. Although King and Kincaid (1997) state that the effect that wind has on non-movable sprinklers, from wind speeds of 2.2-4.5 m/s, is twice as great as the effect from wind speeds of 0-2.1 m/s, the MIPU results did not show this pattern. The average DU_{lq} value for 0-2.1 m/s is 77%, with the average DU_{lq} value for 2.2-4.5 m/s being 75%.

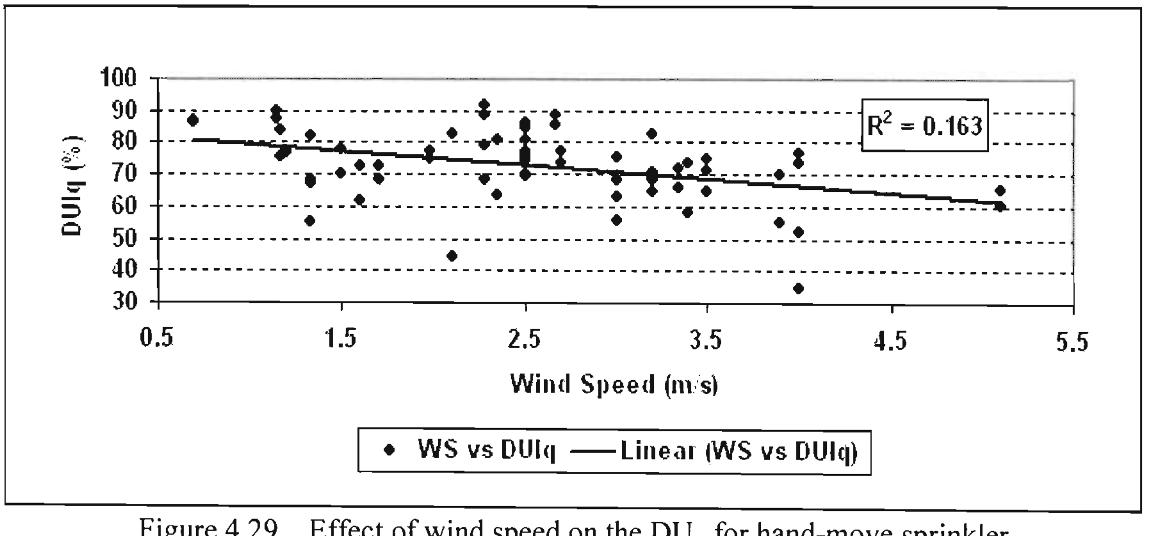

Figure 4.29 Effect of wind speed on the DU_{lq} for hand-move sprinkler

The author noted that during the majority of the MIPU evaluations for the hand-move sprinkler, the wind direction was not constant. This could negate the effect which wind speed may have had on the uniformity. The wind direction was not recorded during the course of this study

Although the sample is not very large for the static sprinkler system, the data obtained are shown in Figure 4.30, which shows the effect the wind speed has on DU_{lq}. At first glance, it would appear that the scatter plot data are showing that there is a slight increase in the uniformity for the static sprinkler. However, it was known that the lowest wind speed data point (0.74 m/s) also coincided with the lowest operating pressure and severe clogging of the disc filters for this particular evaluation. If this particular data point is removed from the data set and another scatter plot drawn, there is no longer a slight trend, which would be expected for wind speeds being under 1.6m/s. This shows that there is no effect of wind speed on the uniformity at such low wind speed values.

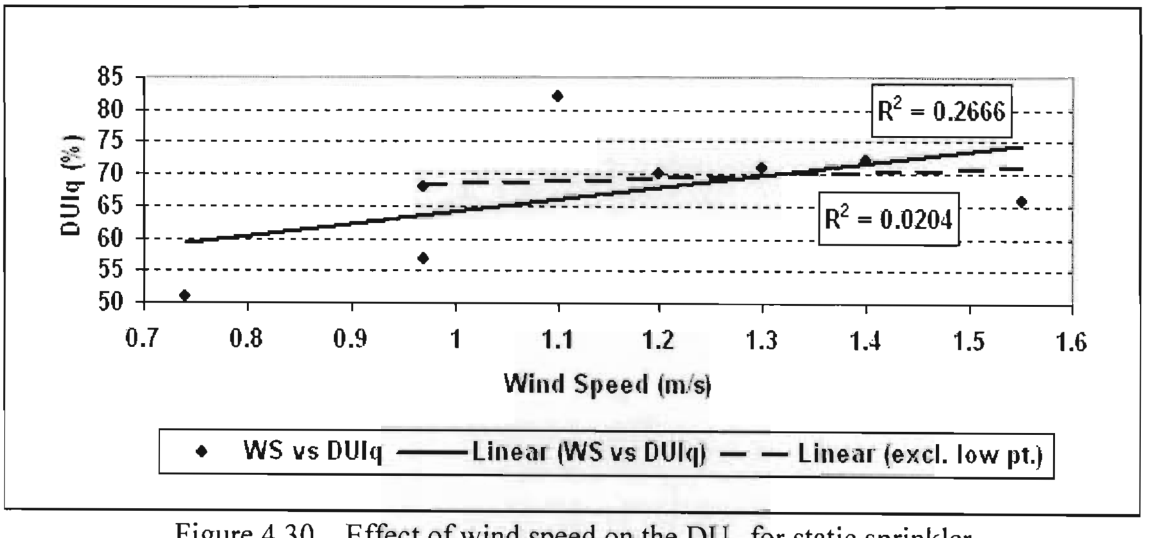

Figure 4.30 Effect of wind speed on the DU_{lq} for static sprinkler

4.3 Sub-Surface Drip

A total of 63 evaluations were conducted on sub-surface drip (SSD) irrigation systems by the ZSAES MIPU during the course of this research.

4.3.1 In-field performance parameters

The DU_{lq}, AD and DT performance parameters which were calculated from the data measured for this system type are shown in Figure 4.31 through to Figure 4.33.

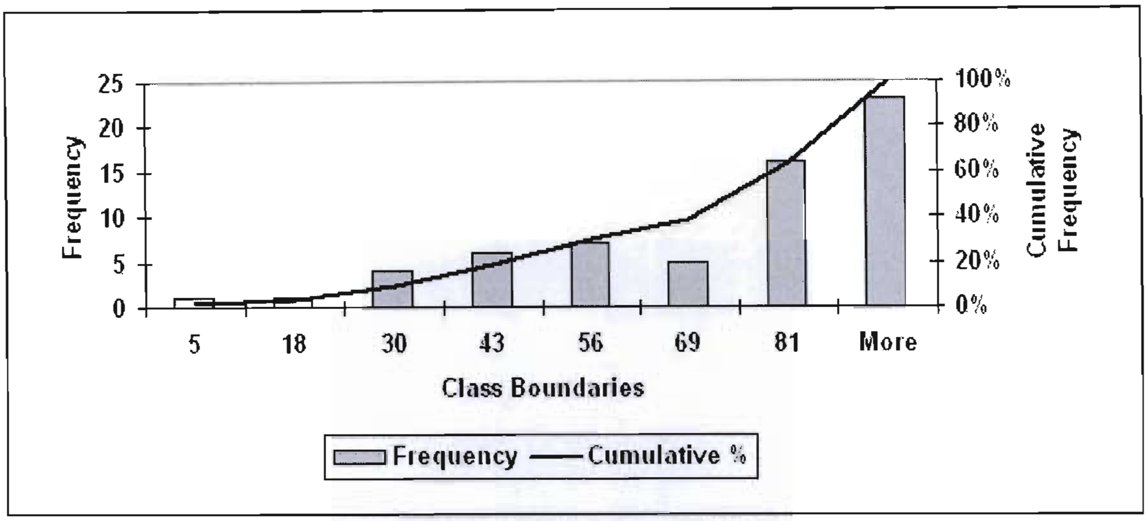

Figure 4.31 Histogram and cumulative frequency of DU_{lq} for sub-surface drip

A percentage of 24% for the sub-surface drip irrigation system evaluations were within the potential field DU_{lq} range of 86% to 90% or higher. This is an extremely low value and points towards the fact that this particular irrigation system is not performing anywhere near the irrigation system's potential. The author maintains that particular emphasis must be placed on adequate and relevant training of the operators for SSD. Inadequate maintenance practices have also contributed towards this low value.

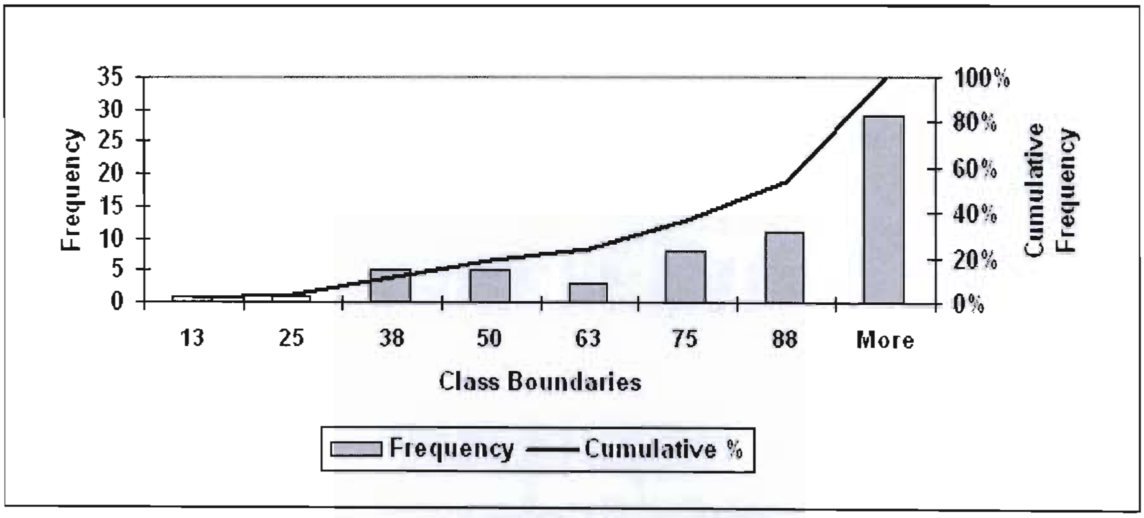

Figure 4.32 Histogram and cumulative frequency of AD for sub-surface drip

The percentage of evaluations either equal or higher than the benchmark AD value of 80% for a high value crop was 63%, with an average AD value of 77%. This parameter would have been affected by incorrect pressures which would affect the water application and incorrect scheduling, issues which are mainly attributed to management. The DT for sub-surface drip was calculated by the difference between the designed application of the emitter at a relevant pressure and the amount collected in the evaluation cup. On the whole, the sub-surface drip systems are applying 9% less water than expected, which could be attributed to emitter blockages and/or incorrect operating pressures.

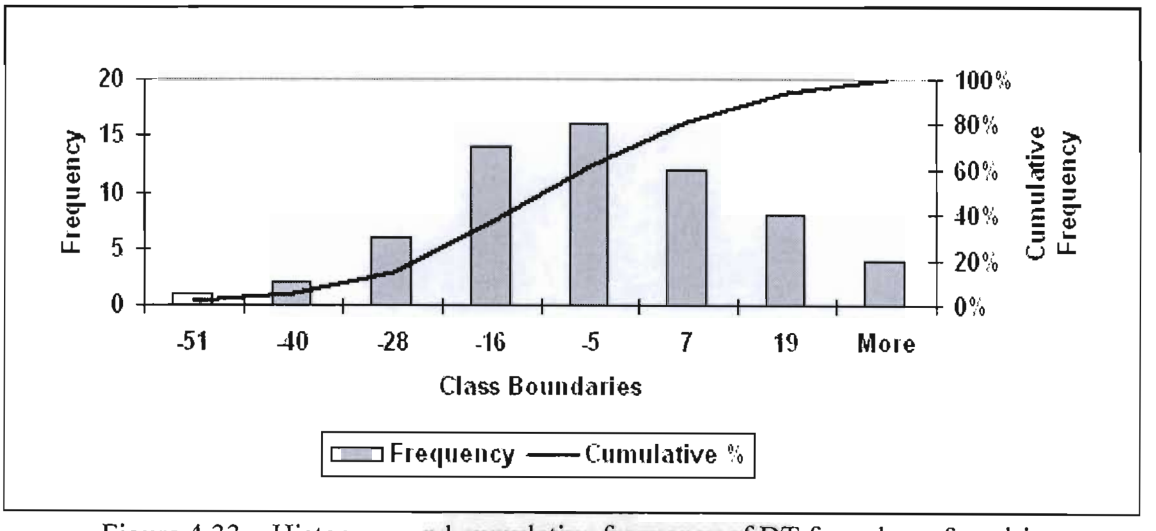

Figure 4.33 Histogram and cumulative frequency of DT for sub-surface drip

It must be noted that certain factors related to the environment, management and system hardware would have played a role in affecting the values given above. However, in order to increase the irrigation system performance, which will in turn increase the benefit to the farmer, a more in-depth assessment of the factors which can affect this performance needs to be undertaken. This follows in the next section.

4.3.2 Factors which affect uniformity

From the measurements taken during the evaluations, possible trends and factors may emerge, which have a direct or indirect impact on the uniformity of the sub-surface drip irrigation system. Further trends are investigated in the following section, which will include separating the designs chosen by the estates, as well as separation of the estates, thus investigating the effect management has on the performance of this type of irrigation system.

4.3.2.1 Irrigation system hardware, maintenance and operation

There were four different designs prominent amongst the systems which were evaluated. System A has the submain feeding the laterals from one side with the flushing manifold separate, and is commonly called the "standard design". System B has the submains also serving as the flushing manifolds, with the laterals being fed from both ends, and is commonly called the "ring design". Further separation of design was in the form of regular and tramline crop spacing. Tramline configurations are also known as "pineapple spacing". The regular design has the laterals 1.5 m apart, with the lateral buried 0.15 m below the sugarcane stool. The tramline design has the laterals 1.8 m apart, also buried 0.15 m, but the sugarcane stools are planted approximately 0.2 m either side of the lateral. The spacing determines the layout of the drip laterals and has a bearing on the size of submains and associated operating pressures. The configurations of the two different spacings are shown in Figure 4.34. The results of the evaluations, differentiated according to the type of design, are shown in Table 4.6.

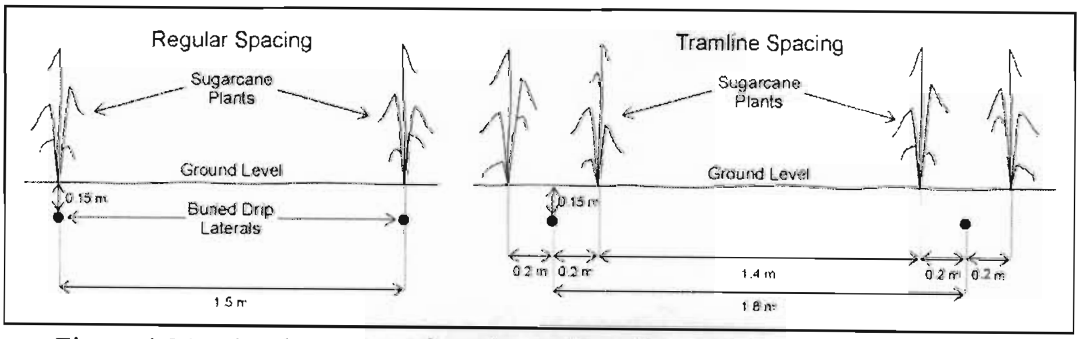

Figure 4.34 Configuration of regular and tramline spacing for sub-surface drip

For system A, the regular layout had 11 out of the 44, or 25%, of the evaluations within the design DU_{lq} range of 86-90% or above, while the tramline layout had 67% within the range. For system B, the regular layout had zero evaluations within the design range, whilst the tramline layout had 33% within the design DU_{lq} range. For the AD values, the 80% minimum value was used as the target value. For system A, the regular layout had 57% of the evaluations either equal to or above the minimum value, whilst the tramline had 100%. For system B, the regular and tramline resulted in 86% and 33% above the design value, respectively.

Table 4.6 Measured submain pressure range and the average distribution uniformity (DU_{lq}), adequacy (AD) and deviation from target (DT) performance parameters and the flushing velocity according to sub-surface drip system design

System Type	Submain Pressure Range (kPa)	DU_{lq} Range (%)	DU_{lq} Average (%)	AD Range (%)	AD Average (%)	DT Average (%)	Flushing Velocity Average (m/s)	Number of Evaluations
System A: Regular	143 - 160	5 - 94	62	13 - 100	72	-14	0.34[1]	44
System A: Tramline	73 - 162	73 - 94	87	93 - 100	96	9	0.4	9
System B: Regular	94 - 176	33 - 82	70	70 - 97	88	-7	0.38	7
System B: Tramline	57 - 119	75 - 92	81	37 - 97	57	-10	0.18	3

[1] The flushing manifolds of 26 of the evaluated fields had their flushing manifolds re-designed just before this evaluation. Prior to re-design the average flushing velocity for each field was between 0.14 - 0.29 m/s which is below the design range of 0.3 - 0.5 m/s.

The average under-application of 14% relative to the design application was due mainly to the number of blockages in the TGSE system. The MIPU found that the design of system B required highly skilled workers to operate because pressures had to be changed for the flushing operation and thereafter had to be reset. As a result the pressures were seldom set correctly, which affected the application amount in a negative manner. The 9% over-application of water by the tramline system A was due mainly to farmers being under the impression that more water needed to be applied, because two rows of cane were being irrigated. Thus, in general, it was a management mis-perception which contributed to the over-application.

The flushing of laterals is important in order to clear them of debris and precipitates which could clog emitters and the design norm should be between 0.3-0.5 m/s in order to achieve this objective (Burt and Styles, 1999). The low 0.18 m/s value for the system B tramline was due to the fact that the workers did not understand the need to adjust the pressure control valves at the field edge to a higher setting, in order to achieve the correct velocities. For the under-trained worker, this was an "involved" process, so they just left the settings alone. As a result, the correct flushing velocities were not achieved, thereby giving debris and precipitates the opportunity to clog the emitters. During the course of the MIPU evaluations, it was noticed that SSD required intensive and specialised management. There was a definite difference in the management of SSD, when comparing the large estates and private farmers. Therefore the performance parameters were grouped according to these two categories, as shown in Table 4.7.

As shown by the tabulated results, there is a significant difference in the performance parameters of DU_{lq} and AD between the estates and private farmers. To try explain this vast difference the MIPU also investigated the percentages of blocked emitters in the field. The estate evaluations had an average of 10% whilst the private farmers had on average 4%, which contributed to the difference in 25% in AD and the 16% difference in the DT values obtained. It was also found that the estate evaluations were run on systems which had design flaws, such as incorrectly sized flushing manifolds (subsequently replaced), which would have contributed to blocking of emitters.

Table 4.7 Measured submain pressure range and the average distribution uniformity (DU_{lq}), adequacy (AD) and deviation from target (DT) performance parameters and the flushing velocity according to the estates and Private Farmers (PF) style of management for the sub-surface drip irrigation system

System Type	Submain Pressure Range (kPa)	DU_{lq} Range (%)	DU_{lq} Average (%)	AD Range (%)	AD Average (%)	DT Average (%)	Flushing Velocity Average (m/s)	Number of Evaluations
Estates	43 - 138	5 - 93	52	13 - 100	63	-18	0.37[1]	29
PF	57 - 176	33 - 94	81	37 - 100	88	-2	0.29	34

[1] The flushing manifolds of 26 of the evaluated fields had their flushing manifolds re-designed just before this evaluation. Prior to re-design the average flushing velocity for each field was between 0.14 - 0.29 m/s, which is below the design range of 0.3 - 0.5 m/s.

The MIPU also found that one of the estate SSD system intakes from a storage dam was incorrectly designed and had allowed fine silt into the drip system. The designers had not made allowance for the natural siltation of a storage dam and had placed the intake at just 0.2 m above the ground level in the dam. Consequently, silt was being sucked into the SSD system. This would have been a major contributing factor to emitter blockages for this system and thus would have affected the system performance. After the MIPU investigated the source of the fine silt and found the inadequate design, the intake was redesigned so that water would be drawn 1.5 m from the bottom of the dam, thus decreasing the likelihood of more silt being introduced into the SSD irrigation system.

One major maintenance issue which was noted by the MIPU was that the field-edge valve stations were not being checked regularly, which was difficult for most workers as they were not given appropriate pressure checking instrumentation. These valve stations also had small filters and diaphragms which should have been cleaned at least once a year. It appeared as if the estates had tried to apply the same management criteria which they had used for either furrow irrigation or hand-move sprinkler to the sub-surface drip irrigation system by not having the operators of the SSD irrigation systems trained accordingly. There was also no associated preventative maintenance programme in place on the estates.

The private farmers did not have very robust maintenance programmes either, but at least there was something being done to try maintain the system in working order such as the acid treatment of the drip laterals to try rectify and/or decrease emitter blockage. Owing to the fact that this system is mostly underground, the need for corrective maintenance can be very difficult to ascertain and factors such as emitter blockage can be cumulative over time. Prevention of the factors which contribute to this system's low performance is the best practice. Regular system evaluations and training of skilled operators will also help in this regard.

4.3.2.2 Pressure

As Burt *et al.* (1997) have previously stated, pressures can be a factor in affecting an irrigation systems performance, particularly in the overhead sprinkler and drip irrigation systems. The SSD irrigation systems which are found in the Lowveld require in-field pressure to operate correctly. The measured average submain operating pressures for SSD irrigation systems are shown in Figure 4.35. The systems evaluated had different design operating pressure, thus the deviation, in per cent, from the design operating pressure is shown in Figure 4.36.

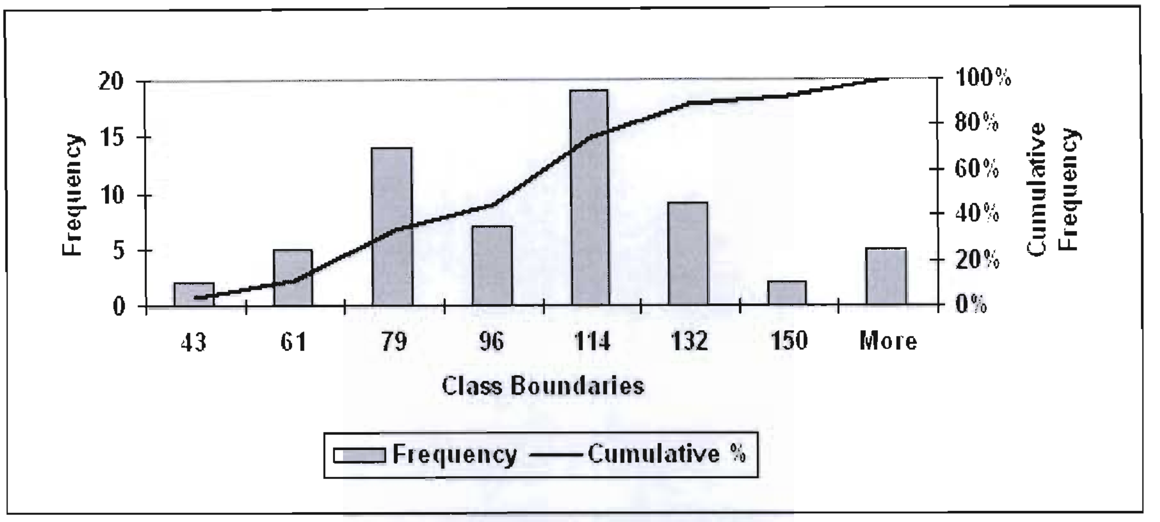

Figure 4.35 Measured submain pressures for sub-surface drip

As seen from Figure 4.35 the majority of sub-surface drip irrigation system pressures are between 79 kPa to 132 kPa. For an irrigation system which is heavily reliant on accurate pressures to determine the correct application rate of water to the crop, this spread is cause for concem. It is suggested that close attention be paid to the operating pressures at the field-edge hydrants.

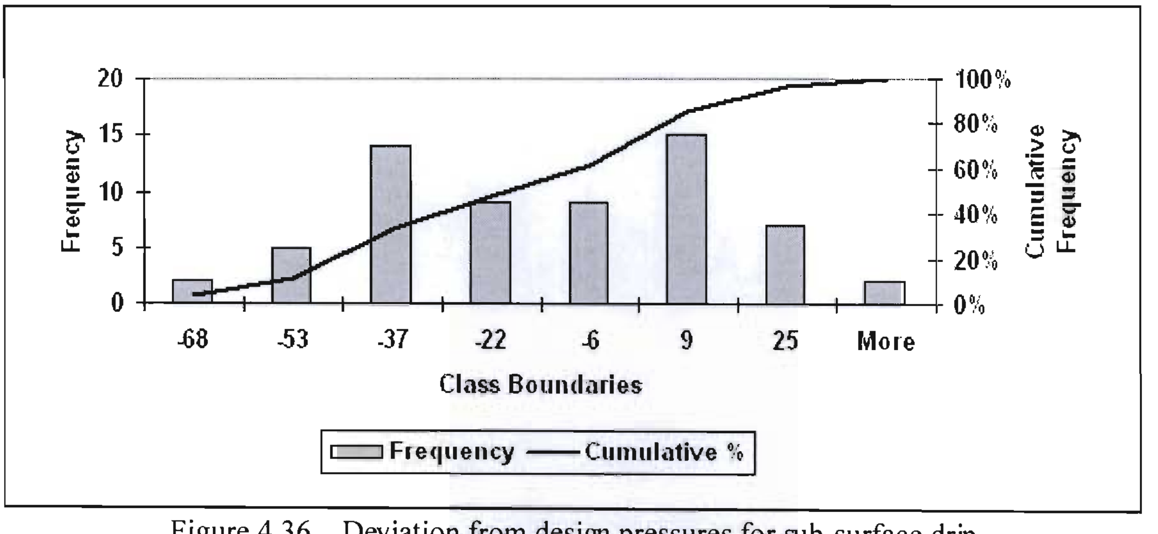

Figure 4.36 Deviation from design pressures for sub-surface drip

From the data in Figure 4.36 it may be deduced that over 70% of the sub-surface drip irrigation systems are operating below the designed operating pressure, with the rest operating above the design norm. The author found that this was regularly due to the fact that there were no pressure gauges with a needle fitting issued to the sub-surface drip operators. This would have allowed the operating pressures at the field-edge hydrants to be regularly checked and kept to the design operating pressure. None of the SSD irrigation systems which were evaluated had pressure compensating emitters installed. For this reason changes in pressure will have an effect on the performance of the systems. As evident from the scatter plots in Figure 4.37 and Figure 4.38, there are slight trends showing correlation between pressure deviation and uniformity, however, there is additional unexplained variation.

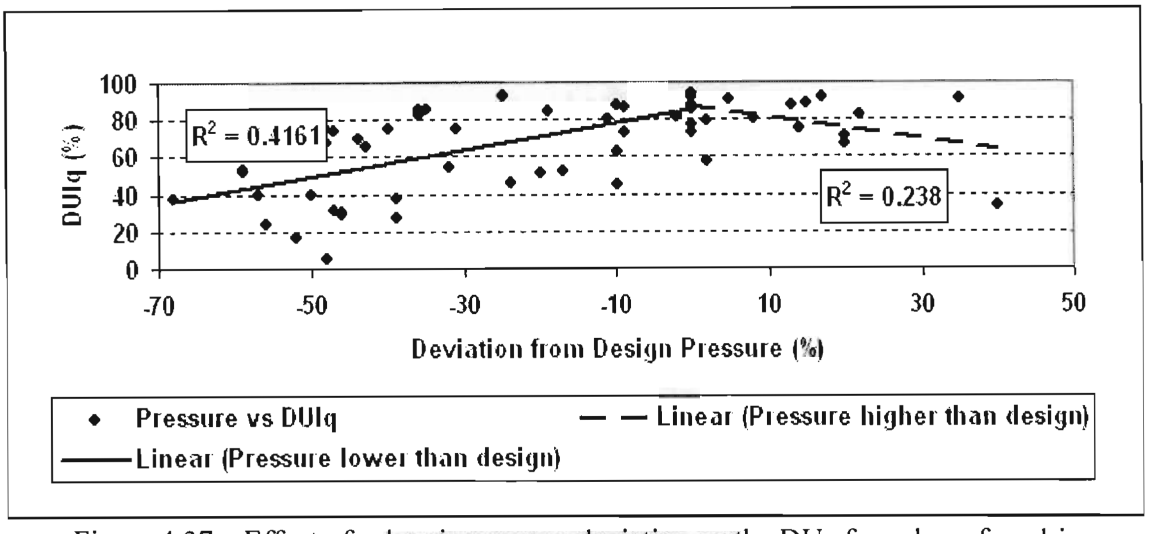

Figure 4.37 Effect of submain pressure deviation on the DU_{lq} for sub-surface drip

The South African Irrigation Institute (SABI) stipulates that the system should be designed in such a way as to ensure a deviation of less than 20% (SABI, 2000). For the data shown in Figure 4.37, only 47% of the submains are operating within the design norm. The variation along the length of the submain will also affect the DU_{lq}, and this is seen in Figure 4.38, where only 41% of the measured submains are operating within the design specifications.

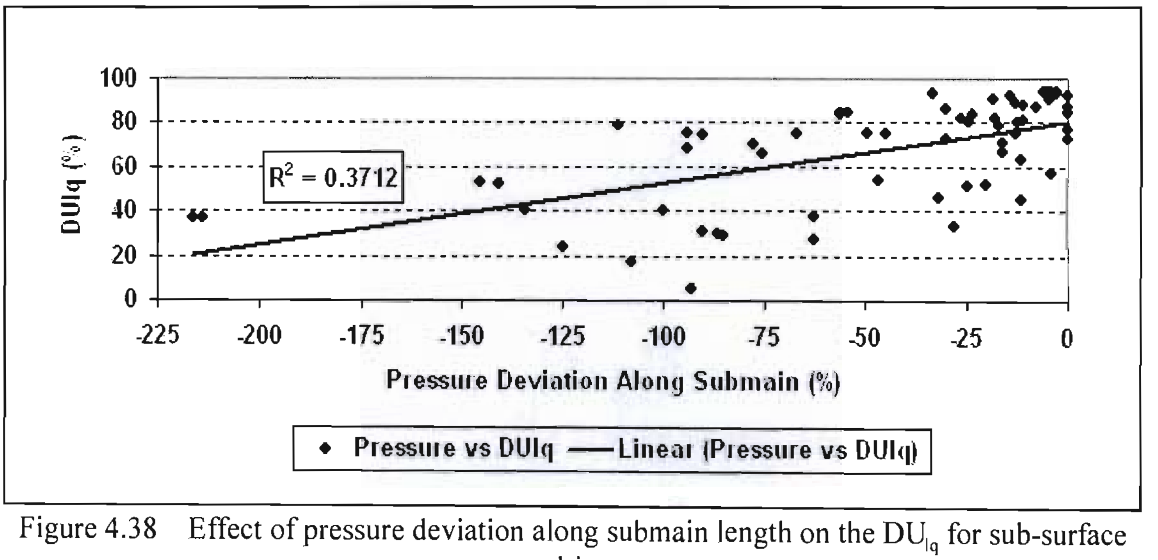

Figure 4.38 Effect of pressure deviation along submain length on the DU_{lq} for sub-surface drip

4.3.2.3 Water quality

No results of any pre-design or any other water analysis were provided by any farmers, although such analysis should be standard practice (Hassan, 1998; Anon., 1999; Burt and Styles, 1999). Owing to the fact that water quality analysis was expensive, and originally the samples were required to be transported over 500 kilometres for testing, not many farmers were willing to have water samples taken and an analysis carried out.

However, during the course of the WMP programme, the chemistry laboratory at ZSAES developed the capability to carry out a basic water quality test which included analysis of the major factors described in Table 2.5. The results from 19 water quality analysis tests are shown in Table 4.8a and Table 4.8b. Because there was a cost associated with each individual factor being analysed, some farmers only requested that certain elements be analysed.

Table 4.8a Results of water quality analysis

ANALYSIS	A	B	C	D	E	F	G	H	I	J
pH	7.09	6.26	6.82	7.11	7.49	7.82	7.69	7.88	7.44	8.37
Conductivity	123	120	173	172	173	158	200	835	982	758
Iron	0.14	0.04	0.51	1.2	0.9	1.2	1.3	<0.1	<0.1	0.59
Manganese	<0.01	0.01	<0.01	<0.1	<0.1	0.1	<0.1	<0.01	<0.01	0.05
Magnesium	3.7	3.5	5.8	10.5	10.1	2.7	17.5	11.79	13.37	11.04
Bicarbonate	4.1	3.1	-	-	-	57	-	350.9	387.46	442.4
Sodium	11.3	11.1	14	20.9	21.4	11	16.5	181.2	185.3	226.4
Potassium	4.4	4.4	<.01	1	1.2	2	0.9	4.3	4.69	3.13
Chloride	-	-	17	17.5	17.1	12.4	12.6	3.82	3.8	4.82
Hydrogen Sulphide	6.7	3.9	1.22	0.08	0.05	-	<0.1	-	-	-
Suspended Solids	-	-	-	15	16	-	-	50	20	10
Dissolved Solids	-	-	-	-	-	-	-	300	330	580

Table 4.8b Results of water quality analysis (continued)

ANALYSIS	K	L	M	N	O	P	Q	R	S
pH	6.55	8.26	8.46	7.34	7.49	7.43	7.29	7.34	7.37
Conductivity	108	447	470	96	97	97	96	96	99
Iron	1.01	0.01	0.03	1.3	1.3	1.3	1.8	1.9	1.8
Manganese	0.01	0	0.12	0.05	0.04	0.05	0.11	0.15	0.13
Magnesium	1.94	7.32	7.2	0.48	0.36	0.36	0.6	0.6	0.48
Bicarbonate	82.37	295.85	292.8	54.9	57.95	57.9	64.05	57.95	61
Sodium	27.76	122.13	119.37	8.05	9.43	8.05	8.74	8.74	8.97
Potassium	5.08	4.29	3.9	25.35	24.57	23.4	24.18	25.74	24.57
Chloride	<0.15	<0.15	<0.15	6.1	7.3	8.5	4.9	6.1	7.3
Hydrogen Sulphide	-	-	-	5.7	10.2	-	-	-	-
Suspended Solids	15	40	40	0	0	40	50	50	50
Dissolved Solids	200	300	300	50	50	60	100	50	100

Burt *et al.* (1998) state that water quality is closely linked to the clogging of emitters which, in turn, affects the magnitude and evenness of the distribution of water in the field. The scatter plot in Figure 4.39 indicates there may be a slight trend, however, there is additional unexplained variation. The trend highlighted a negative correlation between emitter blockage and the DU_{lq}.

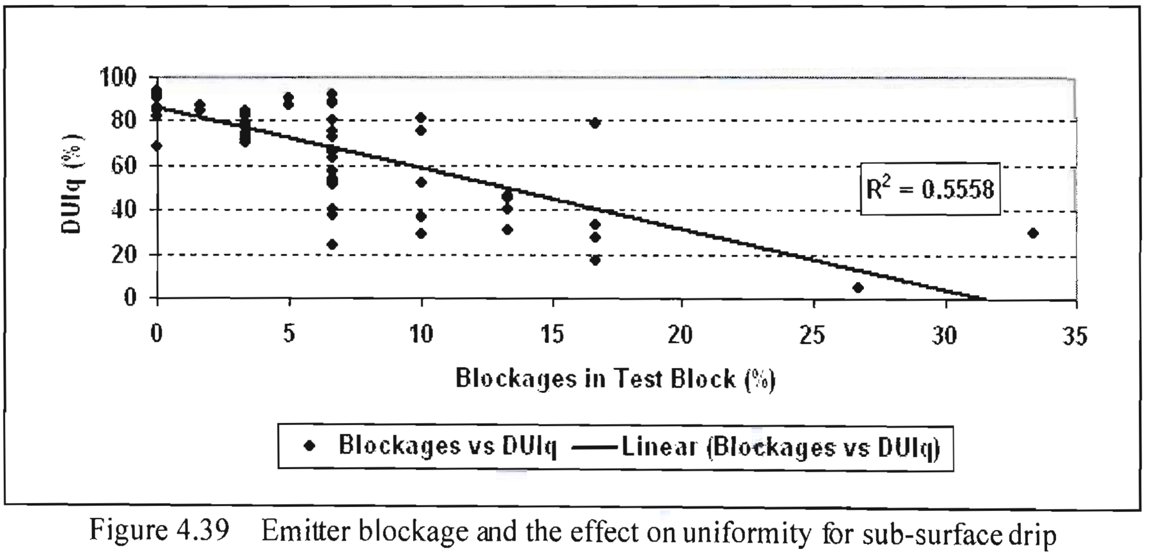

Figure 4.39 Emitter blockage and the effect on uniformity for sub-surface drip

In order to try and narrow down the main factors responsible for emitter clogging and to determine appropriate corrective or preventative measures, the MIPU requested that invasive evaluations of blocked emitters be carried out. This entailed the blocked emitters and a section of the accompanying lateral being removed from the field, and taken to the ZSAES laboratory for analysis. However, owing to the fact that spare connectors were not readily available, and the perceived damage to the drip system being evaluated, only three growers allowed this procedure to be done. Each sample comprised of a minimum of three emitters. As shown in Table 4.9, iron, manganese, calcium, magnesium, silica (sand) and alumino-silicates (clay) were the major elements in the precipitates which were taken out of the emitters during the course of the MIPU evaluations. The correlating emitter and water samples are shown in Table 4.10.

Table 4.9 Major elements found in blocked emitters

Emitter Sample	Element as a percentage of the precipitate taken from the blocked emitters						
	Iron	Manganese	Calcium	Magnesium	Sand	Clay	Other
A	18.3	4.5	6.7	0.5	29.0	40.0	1.0
B	41.0	6.0	10.7	0.7	25.0	14.0	2.6
C	36.0	6.0	29.1	3.6	19.0	4.0	2.3

Table 4.10 Associated emitter and water samples

Emitter Sample	Water Sample
A	K
B	E
C	J

There were high levels of iron in all the water analysis results. The high pH in water sample J (cf Table 4.8a) is likely to be associated with calcium carbonate and/or magnesium carbonate precipitating, which is shown in the associated emitter sample C (cf Table 4.9).

4.4 Comparison of the Different Irrigation Systems

The in-field performances of irrigation systems were examined in this study according to stated MIPU objectives (cf Chapter 1) The comparison of the various irrigation systems was therefore undertaken in this context. The economics of the entire cropping system should also be taken into consideration, but that was beyond the scope of this study. Two additional differences exist when trying to compare irrigation systems. The first is the difference in the volume of water which an irrigation system needs to apply in order to achieve a certain yield (English, 2000). For example, assuming that the irrigation systems are well designed and managed, a comparison within the first four months of the sugarcane crops growth cycle of a furrow system with a sprinkler system, will show differences in the beneficial use of water between the two systems as a consequence of 100% of the in-field surface area being wetted for sprinkler irrigation, compared to an average of 50-60% for the furrow irrigation.

The second difference is the labour component. Farmers often make the error of only considering the number of workers that they need for a certain size of irrigated area, instead of also including the degree of skill and training that a worker must have for a particular system to operate effectively and efficiently. It became apparent during the course of the MIPU evaluations that farmers took workers from one system, e.g. a furrow irrigation system, and expected them to manage a sophisticated system such as sub-surface drip, without adequate training in management and maintenance skills. This inevitably led to a drop in the performance of the irrigation systems and associated crop yields. The performance parameters of AD, DT and DU_{lq} are listed in Table 4.11 for the various irrigation systems which were evaluated.

For the furrow system, the in-row furrow irrigation systems had a higher DU and AD than the inter-row, but on average they were over-applying up to 24% relative to the water required to reach the target application. The estates with shorter furrows and slightly steeper slopes with larger applications had the higher AD and DU_{lq} values in the in-row category (cf Table 4.1). The results from the evaluation of inter-row layouts indicated an under-application of water, with an average of 14%, and they were also under-performing with respect to AD and DU_{lq} compared to their respective in-row furrows on each estate. One of the reasons for this could be the fact that the same management and design criteria were being applied to the inter-row furrow system, which should not be the case, as it is a separate and different type of irrigation system. As an example, water will flow down an inter-row furrow much faster than an in-row furrow, given the same soil type, furrow slope and furrow shape. If the farmer wants to attain the same target application as the in-row then there should be a smaller inflow rate and longer contact time.

Table 4.11 Measured average distribution uniformity (DU_{lq}), adequacy (AD) and deviation from target (DT) performance parameters for MIPU evaluated irrigation systems in the Lowveld of Zimbabwe

System	Estate	DU Range (%)	DU Average (%)	AD Range (%)	AD Average (%)	DT Average (%)	Number of Evaluations
FURROW							
In-row	HVE[1]	16 - 93	66	0 - 100	58	24	62
	ME[2]	2 - 93	61	0 - 100	50	15	112
	TGSE[3]	7 - 96	73	0 - 100	56	21	265
	ALL	2 - 96	69	0 - 100	55	24	439
Inter-row	HVE	46 - 80	64	0 - 100	43	7	14
	ME	8 - 93	56	0 - 92	29	(23)[7]	29
	ALL	8 - 93	58	0 - 100	33	(14)	43
All Furrow	ALL	2 - 96	68	0 - 100	53	16	482
SPRINKLER							
Centre Pivot A	MSE[4]	64 - 85	76	64 - 100	83	(3)	12
(Agrico)	TGSE	81 - 89	85	75 - 93	84	(17)	2
	ALL	64 - 89	77	64 - 100	83	(5)	14
Centre Pivot B	HVE	76 - 86	81	44 - 91	78	(8)	4
(Valley)	MSE	68 - 87	79	2 - 86	49	(16)	12
	TGSE	74 - 89	80	61 - 75	67	(18)	3
	ALL	68 - 89	80	2 - 91	59	(15)	19
All Centre Pivot	ALL	64 - 89	78	2 - 100	65	(9)	33
Hand-move	TGSE	35 - 91	73	0 - 96	42	(19)	66
All Hand-move	ALL	35 - 91	73	0 - 96	42	(19)	66
Static	PF[5] old[6]	51 - 69	62	48 - 76	63	(8)	8
	PF new	70 - 82	74	79 - 98	87	(11)	4
	TGSE	61 - 78	70	12 - 57	35	(28)	2
All Static	ALL	51 - 82	67	12 - 98	65	(12)	14
DRIP							
Sub-surface A	HVE	91 - 93	92	100-100	100	19	2
	PF	68 - 94	85	70 - 100	93	1	24
	TGSE	5 - 94	49	13 - 97	60	(21)	27
	ALL	5 - 94	66	13 - 100	75	(10)	53
Sub-surface B	PF	33 - 92	73	37 - 93	79	(8)	10
	ALL	33 - 92	73	37 - 93	79	(8)	10
All Sub-surface	ALL	5 - 94	68	13 - 100	77	(9)	63

[1] Hippo Valley Estate

[2] Mkwasine Estate

[3] Triangle Group Sugar Estate

[4] Mwenezana Sugar Estate

[5] Private Farmers

[6] Old design of the floppy (static) sprinkler irrigation system

[7] Brackets (X) enclose a negative number

However, as seen from the MIPU data, this was not the case, with the majority of inflows matching those of the in-row furrows, but the contact times were much shorter, thus leading to deficit irrigation. The question can also be asked if the target applications for the two different furrow irrigation systems should be kept the same, i.e. if flow rates were kept constant, in-row furrow could have the cut-off times shortened to apply smaller target application amounts, but have the water applied more frequently. This type of irrigation practice is known to suite shallow soils (Lecler, 2006).

In the author's opinion, more research should be conducted in the area of the effect of the design of in-row and inter-row furrows on the system performance. This should include the furrow length, slope and shape, together with the development of guidelines for "best management practice", for each respective furrow design. Overall the uniformity of furrow is within the DU_{lq} design range of 65-87%, but the adequacy is 27% below the optimum AD value of 80%. On average, the furrow systems are exceeding the target application by 16%.

With regard to centre pivot irrigation systems, the B type centre pivot marginally outperformed the A type by less than 3% when considering the uniformity. However, this trend is reversed when the adequacy figures are compared. The 24% difference in the adequacy could be largely explained due to the three centre pivots at MSE having consoles which were not correctly set, and were thus applying less water than what was seen on the console. If the results from the three pivots are ignored, the adequacy of the type A pivots would increase to 82%, then being only 1% less than type B.

Overall the uniformity of the centre pivot system is within the DU_{lq} design range of 78-90%, with the adequacy being 15% below the target adequacy of 80%. However, if the three MSE pivots are ignored, this value increases to 81%, which is 1% above the target adequacy value. On average 9% less water was being applied than scheduled, which can be explained by losses such as wind drift and spray evaporation, which can be as high as 10-15% (Lecler, 2004).

Of the farms that were evaluated by the MIPU, only TGSE used hand-move sprinkler systems. The 73% uniformity was within the design range of 70-86%, but the adequacy was 38% below the target value of 80%. This could be explained by the stand-times not being long enough, although losses from wind drift and evaporation also have an impact. The 19% under-application of water supports the fact that the stand-times were not sufficient. Owing to the fact that the uniformity values were high, a small change in the stand-times would lead to a large increase in the adequacy value. The MIPU also noted that, although most of the evaluations were conducted below the threshold wind speed value of 4.5 m/s, TGSE were observed to operate under such conditions, which would adversely affect the uniformity and adequacy of water application. This could be due to the fact that with such a large estate, if high wind conditions prevailed for a long period, the managers felt that they could not postpone irrigation indefinitely.

The static system design in the Lowveld, called the floppy system, was still undergoing new design implementation. The majority of the systems were of the old design, with the average DU_{lq} being only 67%, which is 6% below the design range of 73-86%, and with an adequacy of 65% which is 15% below the 80% adequacy target value. The low 35% AD value and 28% DT value for TGSE would mainly have been due to the fact that the filters at the field edge were under-designed. They thus clogged up very quickly, which required frequent cleaning and thus affected the operating pressure and amount of water allowed through into the system. However, the four MIPU evaluations of the new design gave an average DU_{lq} of 74%, which is within the design range, with the AD at 87%. This system type is under-irrigating by 12%, which is within the expected loss for a sprinkler irrigation systems.

Out of the sub-surface drip systems, the system design B had higher in-field performance values than system A. However, it was known that the TGSE evaluations were from a poorly designed, managed and poorly maintained irrigation system. If the TGSE evaluations are disregarded, system A has a DU_{lq} of 83% and an AD value of 94%, which are 10% and 15% higher than the respective values obtained from system B. This changes the overall DU_{lq} value for the rest of the sub-surface drip systems from 68% to 82%, which is just below the design range of 86-90%, while the AD value increases from 77% to 89%, which is above the 80% target value. TGSE were, at the time of writing, considering replacement of the 75 ha sub-surface drip scheme with a centre pivot.

The actual performance and potentially best performing irrigation systems evaluated by the MIPU are ranked in Table 4.12, taking all three performance parameters of AD, DT and DU_{lq} into consideration. The actual performance includes all the systems combined and the potential is obtained by taking the best performing irrigation system in each category. Results reported in the literature, as presented in Chapter 2, are also included in Table 4.12.

Table 4.12 Ranking of the actual and potential best performing irrigation systems evaluated by the MIPU, and potential performance obtained from the literature

RANK	ACTUAL LOWVELD MIPU	POTENTIAL LOWVELD MIPU	POTENTIAL REPORTED IN LITERATURE MIPU
1	Centre Pivot Sprinkler	Sub-surface Drip	Sub-surface Drip
2	Hand-move Sprinkler	Centre Pivot	Centre Pivot
3	Sub-surface Drip	Static Sprinkler	Static Sprinkler
4	Furrow	Furrow	Hand-move Sprinkler
5	Static Sprinkler	Hand-move Sprinkler	Furrow

The only difference in rank between the two potential groupings, listed above, were the furrow and hand-move sprinkler. For the Lowveld MIPU results, although the hand-move sprinkler had an overall higher DU_{lq} of 73% compared to 68% for furrow, the author felt that the combination of the higher AD and positive DT value for the furrow would eventually out-perform the hand-move sprinkler, and was ranked at a higher value.

The DU_{lq} results obtained from the international literature and the average DU_{lq} values recorded by the Lowveld MIPUs for the various irrigation systems, are listed in Table 4.13. The main differences that exist between the two evaluation sets are for the furrow and sub-surface drip systems.

Table 4.13 Comparison of the Lowveld and international MIPU evaluation values for DU_{lq}

IRRIGATION SYSTEM	LOWVELD MIPU (%)	INTERNATIONAL MIPU(%)
Furrow	68	79
Centre Pivot	78	73
Hand-move sprinkler	73	72
Static sprinkler	67	66
Sub-surface Drip	68	74

For the furrow irrigation system values, the difference could be explained by the fact that the results from international studies are taken from developed countries which have higher technical and management expertise and have access to more sophisticated irrigation system hardware for this particular system, e.g. automated control of the inflow and cut-off times and laser levelling of fields. For the sub-surface drip, if TGSE data were ignored, the uniformity value would be 82%, thus indicating how poor design and management can affect the performance of this type of irrigation system.

The main focus of the research reported in Chapter 4 of this dissertation was described by the objectives (i) through to (iv) in Chapter 1. In addition to these objectives, the author decided that addition data and tools which were developed during the course of the project, and which could be used to enhance irrigation system performance, should be included in the dissertation. The importance of the data and tools require that they be presented as a stand-alone chapter.

5. ADDITIONAL DATA AND TOOLS FROM THIS RESEARCH WHICH CAN ENHANCE IRRIGATION SYSTEM PERFORMANCE

During the course of the MIPU evaluations, the author realised that there were additional data and tools developed which could be used to enhance and improve the performance of an irrigation system. These included evaluation spreadsheets; installations evaluations; maintenance schedules; measurement tools; scheduling charts and data compatible with simulation software. The additional data and tools could be used to enlighten and empower the farmer to ensure that the entire crop production system becomes and/or remains efficient.

5.1 Evaluation Spreadsheets

Spreadsheets had to be developed to calculate the various performance parameters for all the evaluations conducted by the MIPU on the different irrigation systems, examples of which are shown in Appendix C. Van Niekerk (2000) provided the original spreadsheets which were then adapted by the author for the MIPU data. These spreadsheets are arranged simply so that data, which are captured using the evaluation sheets in Appendix A, can be input easily and can be used effectively by persons with appropriate knowledge of computers and spreadsheet programmes.

5.2 Installation Evaluation

Farmers who had irrigation systems installed before the start of the MIPU project had no way of ensuring that what the irrigation system designer and installer had sold them, was actually working according to design. In the USA it is suggested that farmers and designers enter into an agreement whereby the irrigation system is evaluated by a MIPU once installed and before final payment is made, to ensure that the performance of the new irrigation system is within design thresholds (Burt, 1995). If the irrigation system does not perform according to the design norms, remedial action should be implemented by the designer. Koegelenberg and Breedt (2003) have also suggested a similar process for South Africa.

5.3 Maintenance Schedules

All irrigation systems, irrespective of when they were installed, should have a current, up-to-date maintenance manual. This manual should cover both preventative and corrective maintenance for the irrigation system. During the course of the MIPU evaluations, when these manuals were requested so as to check whether the maintenance schedules had been adhered to, nearly 90% of the farmers/managers did not have any such literature. The reasons for this ranged from "I was never given anything that I could call a Maintenance Manual", to "the Maintenance Manual was lost.".

No matter what the explanation, the fact remains that all irrigation systems, from furrow to sub-surface drip, should have a comprehensive preventative and corrective maintenance schedule in operation. This should ensure that the irrigation system works according to design and that the hardware lasts the appropriate length of time. Having such a manual may also assist the farmer in understanding and appreciating how the irrigation system works. Many farmers that had systems evaluated by the MIPU, were of the opinion that as long as they saw water being applied to the field, the irrigation system was working appropriately.

An example of a case where the MIPU realised that a preventative and corrective maintenance programme had not been managed properly, and its effects, are presented below. When one of the centre pivots was evaluated on one of the estates it was immediately noticed that five sprinklers along the length of the pivot were missing and had been replaced by punctured shampoo bottles, as shown in Figure 5.1. Information was also attained that this particular pivot had not had any major maintenance checks since it had been installed, over five years previously. Owing to the fact that the operator was not trained in the workings and maintenance of a centre pivot, there was no understanding of the concept that the replacement "sprinklers" would affect the application rate at respective distances along the pivot, and thus affect the overall performance of the system. After the evaluation, a new sprinkler package was ordered. Figure 5.2 shows the application rate along the length of the pivot before and after the new sprinkler package was fitted. The DU_{lq} improved from a value of 44% for the old sprinkler set to 70% for the new sprinkler set.

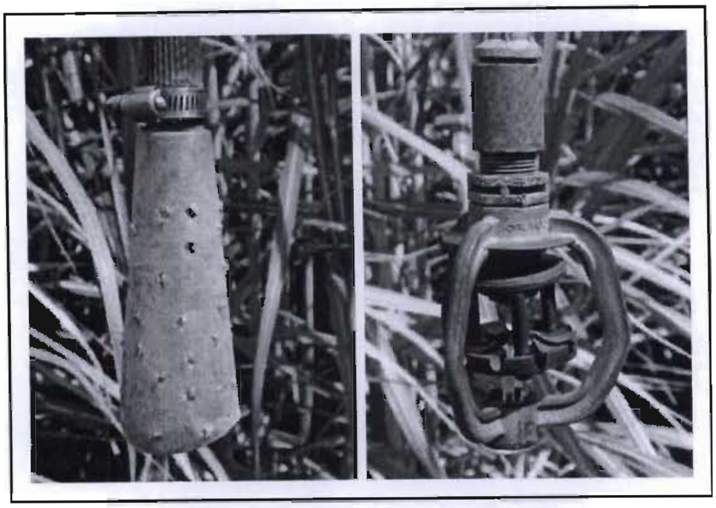

Figure 5.1 Photo of a punctured shampoo bottle in place of an I-Wob sprinkler on a centre pivot system at an estate

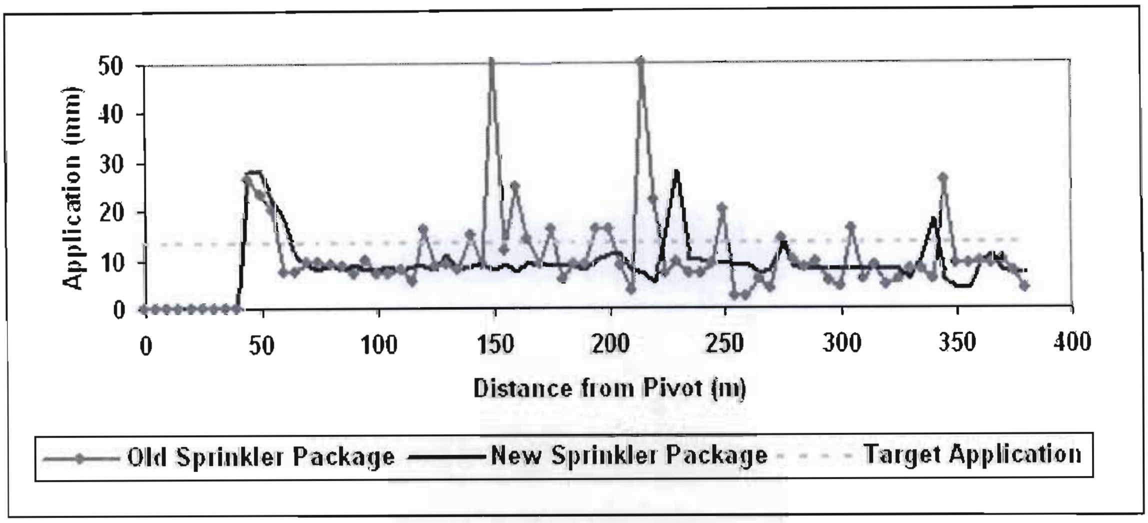

Figure 5.2 Graph showing the water application along a centre pivot before and after replacement of the sprinkler package at an estate

Comprehensive maintenance schedules can be attained from appropriate and reputable designers for all irrigation systems. However, sometimes localised conditions, such as water quality as in the case of sub-surface drip irrigation systems, requires additional localised maintenance procedures. These procedures can be formulated with the input of the farmer, MIPU and irrigation system designer. It must be noted that, in this study, it was not the objective of the MIPU to formulate maintenance schedules, but to ascertain whether preventative or corrective maintenance procedures, or the lack thereof, had an effect on a system's performance.

5.4 Measurement Tools

The "Greller" and the "conical pressure nozzle" (cf Figure 3.2 and Figure 3.8) were the two measurement tools designed by the MIPU in order to effect easy and reliable data gathering in the furrow and sub-surface drip irrigation evaluations respectively. The Greller is not only used for evaluations, it is now also used to estimate the inflow into furrows using certain sizes and amounts of syphons by farmers. The conical pressure nozzle is a very simple and easy instrument which is in everyday use to ensure sub-surface drip irrigation systems are operating at design pressures.

5.5 Scheduling of Irrigation Using Charts and Simulation Software

Various data from MIPU evaluations can be incorporated in graphs/spreadsheets and simulation software which, in turn, can help a farmer with the important issue concerning the management of water application, i.e. irrigation scheduling.

5.5.1 Adequacy chart

Data from evaluations can be input to a chart format which can be used by farmers to visually understand what is happening to the water distribution in-field. This chart is known as an adequacy chart and shows the in-field variation in water application. An example of one of these charts is shown in Figure 5.3. The chart is for a single field and is from a sub-surface drip evaluation. The lower line represents the measured application rate (MAR) as opposed to the specified design application rate (DAR). The more level the MAR line is, the more uniform the water distribution is within the field. If the per cent field area value where the MAR line crosses the DAR line is subtracted from 100% the result will be the per cent of the field which receives the required rate of water application. It can be seen from the example that 79% of the field is below the DAR [100-79=21], and only 21% of the field is operating at the designed application rate or above.

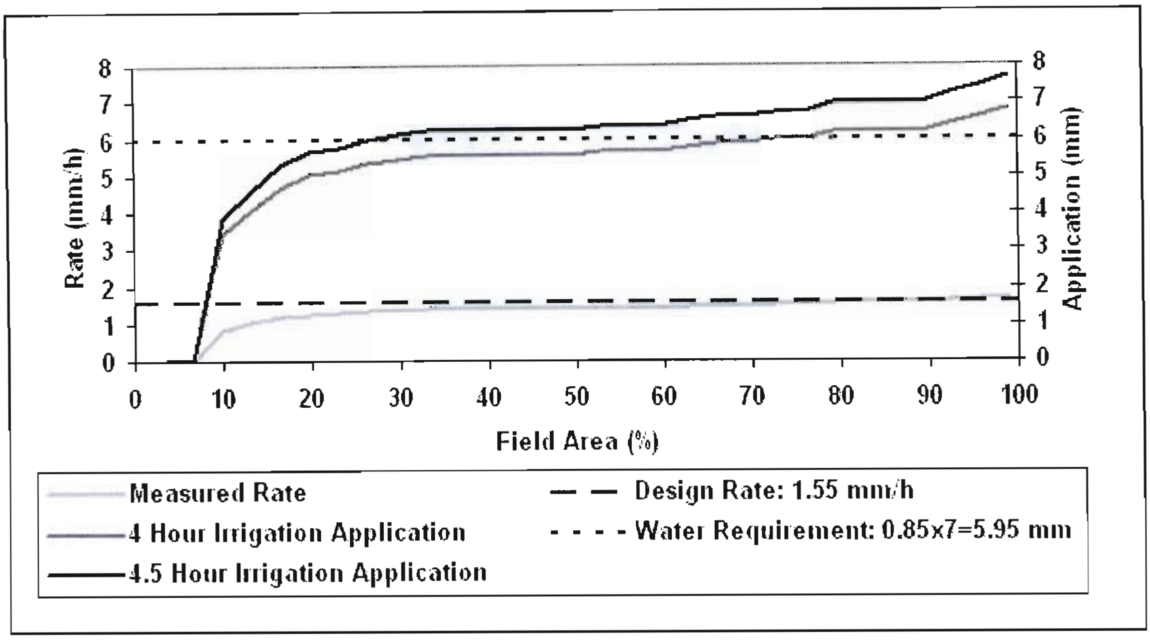

Figure 5.3 Example of an adequacy chart

However, the upper portion of Figure 5.3 is the area that the farmer will be most interested in. This shows how well a 4.5 hour daily irrigation time replenishes average peak daily crop water requirements for this specific field. The average peak daily crop water requirement is based on evidence from research trials that support the use of a crop canopy factor of 0.85 and, based on more than 25 years of climate data, results in an average daily summer A-Pan value of 7 mm (Lecler, 2000). In this example the daily crop water requirement is calculated to be 5.95 mm [0.85x7=5.95]. A good benchmark irrigation time for the system shown, for the months of October-January, for a full canopy crop is therefore 4.5 hours/day which gives an adequacy value of 74%. This value is obtained by following the "4.5 hour irrigation" line until it intersects the horizontal "water requirement" line and taking a vertical line from that exact point down to the Field Area axis. Where the vertical line intersects the X axis, this value is subtracted from 100, to give the AD value, which in this example is 74% [100-26=74]. An additional 4 hour/day line was included to illustrate the difference in AD, which would decrease by 46% if a 4 hour/day option was chosen by the farmer instead of the 4.5 hour/day option.

The problem with increasing the AD is that additional water would then be used non-beneficially, so the farmer must decide on a balance between over-application and under-application within the field. Crop canopy factors will change depending on the age of the crop, as will the A-pan value. The ZSAES sugarcane production manual (Clowes and Breakwell, 1998) contains these expected monthly values throughout the year. Alternatively, the daily A-pan values can be requested from the ZSAES Irrigation Department. This concept can be applied on a weekly or a monthly basis for each field that is evaluated. The farmer can then visually note, from the charted area, how the irrigation system within a specific field has performed after input of the appropriate data.

It must be noted that with the centre pivot irrigation adequacy chart, each sprinkler on a centre pivot does not represent the same area, but actually covers different areas along the length. To illustrate this the data taken from one of the MIPU evaluations of a centre pivot is charted, with the correct and incorrect adequacy lines and is shown in Figure 5.4. For example, if the incorrect adequacy line was used, which assumes that each sprinkler represents the same area, a value of AD = 36% [100-64=36] would be attained and, if the correct adequacy line is used which applied the correct area weighting to each sprinkler, a value of AD = 58% [100-42=58] is attained, which represents a 22% difference.

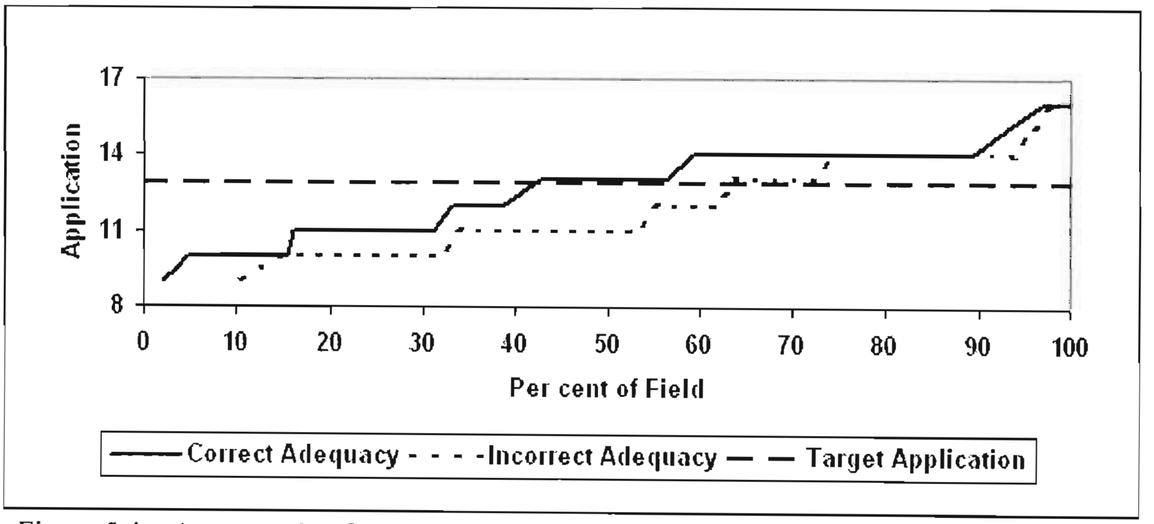

Figure 5.4 An example of correct and incorrect adequacy lines for a centre pivot irrigation system

5.5.2 Surface irrigation simulation model

Walker (2006) states that SIRMOD is a comprehensive software package for simulating the hydraulics of surface irrigation systems at the field level and which can be used to select a combination of sizes and operational parameters which maximise performance, and is also a convenient way to merge field data with the simulation and design components. In Australia the SIRMOD programme is most commonly used to refine the management of furrow irrigation systems. To demonstrate how this programme could be used with MIPU data, Raine (2006) was requested by the MIPU to corroborate SIRMOD runs which modelled in-field furrow data from the HVE. The approach used was that in-field information was entered into the programme and the Manning's roughness coefficient (n) was manipulated until the simulated advance and recession curves approximately fit the measured data. Thus the simulation was "calibrated" to fit the measured data. Figure 5.5 shows the matching of the SIRMOD simulated data and actual MIPU data measured in a furrow evaluation from the HVE. Once the calibration was complete, the performance parameters of DU_{lq} and AD generated by SIRMOD can be obtained.

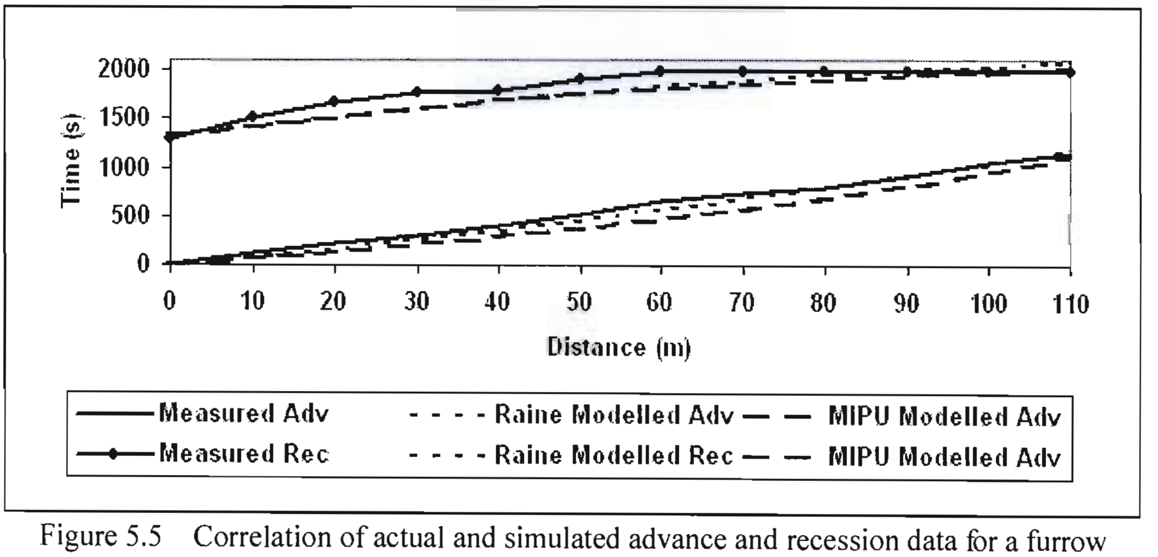

Figure 5.5 Correlation of actual and simulated advance and recession data for a furrow irrigation evaluation

Using the calibrated SIRMOD configuration, the effects of changes to the contact time or in-flow rate on system performance can be evaluated and can aid in management decisions. Design components, such as furrow shape, length and slope can also be modified to evaluate what effect they may have on a furrow irrigation system's performance, but these are more allied to the design of a new system than to the management of a current furrow irrigation system. Examples of the input and simulation screens for this particular example of the SIRMOD model are shown in Appendix D. In the output from SIRMOD the Requirement Efficiency (RE) is equivalent to the AD.

The data from SIRMOD for the HVE data resulted in a DU_{lq} = 99% and with an AD = 100%, but with an outflow of 2.7 m^3 of water from the furrow end. By simply changing the inflow rate into the furrow from 6.6 l/s to 4 l/s the DU_{lq} value decreased to 94% while AD value remained at 100%, but the outflow from the furrow was now only 0.1 m^3, which was considered an acceptable loss by the manager. Such simple adjustments can help immensely, in controlling and adapting a furrow irrigation system in order to either attain or maintain design norm performance levels.

5.5.3 *ZIMsched 2.0*

Lecler (2004) states that *ZIMsched 2.0* is a deterministic crop and irrigation systems computer simulations model which was developed in order to estimate how water management, different irrigation system characteristics, and the in-field measurements of irrigation systems operating characteristics derived by a MIPU, impacted on crop yields and the water balance. Lecler (2004) also states that the *ZIMshed 2.0* model is considered unique in terms of not only the synthesis and integration of the water budgeting and crop yield algorithms, but also because this translates into the unique capability of distinguishing between different types of irrigation system and accounting for different levels of irrigation system performance. An example is the MIPU derived measurements of DU_{lq} values. The model also predicts yields for sugarcane. The application of *ZIMshed 2.0* to analyse MIPU and other water management information and data is explained in detail by Lecler (2004).

6. DISCUSSION AND CONCLUSIONS

From a review of relevant international literature it is evident that the in-field evaluation of an irrigation system involves an understanding and appreciation of the water balance. It is also evident that there are a wide range of views on the interpretation of the various irrigation performance parameters which are calculated within the water balance. Provided that the numerators and denominators of the performance equations are clearly defined within a specified time and space, irrigation system evaluations should be able to be interpreted and compared by different researchers and irrigation system evaluators worldwide. The review also pointed towards the fact that the irrigation system's performance parameters, viz. Adequacy (AD), Application Efficiency (AE) and Distribution Uniformity (DU_{lq}) are all interrelated. However, published results from the international evaluations only include uniformity and efficiency parameters. In the author's opinion AD should also be included in evaluation results as it gives a clear indication of what is happening within a field, with regards the water application.

In order to calculate the above-mentioned irrigation performance parameters, data have to be collected. In this study this was undertaken by following a standardised in-field evaluation procedure for the relevant irrigation system. There are a number of procedures available in the literature, as different countries and institutions may have slightly different standards, but the aim and result are the same, i.e. to collate reliable data for use in calculating irrigation system's performance. Factors such as poor design, poor management, poor maintenance and poor water quality testing procedures can all individually, or through various combinations, influence the performance of an irrigation system. Studies reported in the literature showed that the in-field evaluation of irrigation systems can help determine which of these factors influence the performance of an irrigation system and the evaluations can thus be beneficial to a farmer.

The five groupings of farmers whose irrigation systems were evaluated were Hippo Valley Estate (HVE), Mkwasine Estate (ME), Mwenezana Sugar Estate (MSE), Private Farmers (PF) and Triangle Group Sugar Estate (TGSE). The selected and developed methods of in-field irrigation system evaluation were robust, quick and inexpensive and deemed accurate enough for the purposes of the Water Management Project (WMP) within which the MIPU operated. For example, the "Greller" was developed for use in the furrow irrigation system evaluation procedure and was found to be simple, robust and accurate enough to be used in measuring the inflow into furrows on the estates. The evaluation procedures developed/adopted were "single event" evaluations. As a consequence, if a system was evaluated on a subsequent day, it is accepted that the performance parameters calculated may be slightly different. It was also accepted that the number of furrows evaluated is small compared to the actual number of furrows in the industry, but nevertheless the study results still give a general overview of the state of irrigation systems within the sugarcane industry in the study area.

As a result of the increased need for specialised equipment to help collect data which could determine the efficiency of an irrigation system, the author decided to report on the AD and DU_{lq}, but included the Deviation from Target (DT) as another performance term which was deemed to provide important information on the irrigation system's water usage.

An initial area of concern in the furrow evaluation results was the range in the calibrated syphon "discharge coefficient" values, which ranged from 0.60 to 0.69 with a mean of 0.65, in contrast to a value of 0.62 reported in the literature. Subsequently it was decided by the author that a value of 0.65 was reasonable. However, because an accurate measurement of inflow is required, more research should be conducted into the affect that the syphon discharge coefficient and the height difference between the supply canal and the furrow have on the inflow of water into a furrow, especially under the Lowveld conditions. The author believes that farmers assume that the specified application is what is actually applied on the field, which is seldom correct. It is proposed that the Greller can also help in this regard, as it is a tool which can be used by farmers to check the inflow to furrows, relatively simply.

The centre pivot evaluation method chosen was fast and simple. Only one line of rain-gauges was chosen, which was deemed adequate to collect the required data. This is a viewpoint also shared by Koegelenberg and Breedt (2003). The installation of pressure check points, both at the central tower and at the wheel towers, would make it much safer and easier for the evaluator to collect information with regard to pressures. For this study an assumption was made that if the central tower pressure was at least 200 kPa, then a 50 ha pivot would still have adequate pressure at the last sprinkler to operate correctly. The author suggests that any MIPU team should also have a light-weight "funnel", for use in collecting sprinkler outflow at any chosen sprinkler along the centre pivot length and an automatic rain-gauge, which could be used to determine the application rate of the last centre pivot tower, and thus help determine if the application rate of the pivot is matched with the infiltration rate of the soil.

The author takes the view that the more data collected in-field, the better. For the hand-move sprinkler evaluation procedure, the procurement of additional rain-gauges would enable an increase in the number of data points from 25 to 36, thereby allowing the use of a 3 m X 3 m spacing. It would also be easier and quicker to set-up the evaluation grid on this spacing. For the hand-move and static sprinkler evaluations, the one issue experienced by the MIPU was how to quantify the "leaning" effect of the risers. Although no tool was developed to quantify this, it is felt that there should be a tool, as it is known that this phenomenon can affect the in-field performance. It is also suggested that a portable in-line flowmeter be procured for the hand-move sprinkler evaluation. The flowmeter can be used to measure the application rate and in-field water losses during the evaluation.

The non-availability, and invasive nature, of using plastic screws to close holes which were needed to check pressures along sub-surface drip laterals led to the development of a conical nozzle. This was the main development of tools needed for the in-field evaluation of the sub-surface drip irrigation system. An additional use that arose from the development of this tool is that the pressures along a submain could also be determined. This could be done by disconnecting the lateral and inserting the nozzle in the blanco pipe, which is the pipe that connects the submain to the lateral, thereby enabling a check to be performed to determine whether the operation of the system met the design specifications.

Overall the furrow irrigation system was operating within the design norm, with a DU_{lq} of 68%. However, the overall performance of this system is affected by the low AD values and over-application of water is evident from the 16% DT value. As a consequence of the fact that the DT was calculated with a data range from -100% to 150% times that of the target application, the mean DT value is skewed to a more positive value, but still gives a general indication of the state of furrow irrigation in the Lowveld. The data presented in Table 4.1 led to the conclusion that some parts of the furrow are getting far more water than others, which could result in leaching of nutrients and water logging of the crop in some areas, both of which will affect crop yields. Low AD values and high DT values can be brought about by a multitude of factors, such as the slope of the furrow not being consistent or furrow ends being blocked, leading to large amounts of water "ponding" at the bottom of the furrow and being the cause of over-application in that particular area. This may happen if a large amount of water is applied with an unmatched cut-off time. In general the in-row furrow performed better than the inter-row furrow irrigation configuration. One of the reasons for this could be that although the systems are different, they are being managed in the same way. Inflow rates and cut-off times must correspond to the type of furrow system in use. This generic treatment of furrow irrigation systems is an area of concern and must be addressed.

The data collected on wetted perimeter, furrow slope, furrow length and the number of the irrigation, were charted for all the estates against the DU_{lq}. This was done to try ascertain if any of the afore-mentioned factors affected the uniformity of the furrow irrigation system. The results showed that no trends were present. Additional data which were of interest were the follow-through evaluations performed at ME on the in-row furrow systems, which showed a general decrease in the DU_{lq} with an increase in application rate through the growing season. Unlike the other irrigation systems, the dynamics of the water flow down an in-row furrow system changes with age. This is attributed mainly to the growth of the sugarcane crop in the furrow. The more area in the furrow that is taken up by the crop, the more impediment to water flow, and thus operators have to wait longer before the water reaches the end of the furrow. However, it is the view of the author that these trends can be attributed to poor management, which in turn controls the maintenance and scheduling aspects of an irrigation system. If the manager knows how the furrow system is operating, decisions can be made to ensure that the negative effects of factors such as wetted perimeter, furrow slope, furrow length, number of irrigation and crop age on the performance of a furrow irrigation system, are kept to a minimum.

With regard to the overhead irrigation systems, out of the centre pivot, hand-move and static sprinkler systems which were operating in the Lowveld, only the static sprinkler was found to generally operate outside of the design DU_{lq} range. This was due to the fact that most of the evaluations conducted were on already established "old design" floppy sprinkler systems which gave consistently lower values compared to the "new design". Of concern though, are the low AD values for all the overhead systems. To recall, the AD is determined by calculating the percentage of the field which receives the target amount of water, with the target figure for the particular field being decided by the scheduler/farmer. These values could easily be increased by lengthening the irrigation stand times by a small margin. The average DT values for the centre pivot and static irrigation systems are within accepted standards for losses, but the average hand-move irrigation system value of a negative 19% DT value is high. The negative 19% DT value could be due to the combination of high wind speeds and high operating pressures, which not only adversely affect the uniformity of the water application, but the volume as well.

In addition to the system hardware, maintenance and operation of the overhead irrigation systems, the additional factors of pressure, water quality and wind were also examined to determine if they had any effect on the performance of the irrigation systems. For the centre pivot systems it was noted that there was no matching of the infiltration characteristics of the soil to the application rate of the sprinkler package during the design of the system. There were not many centre pivot systems which had gravelling of the wheel tracks, which is recommended so as to limit wheel slip to less than 3%, as wheel slip is known to affect DU_{lq}. The MSE practice of operating centre pivots with the end-valve open results in lower AD values and the centre pivots were not designed to be operated with the end-valve open. It is recommended that this practice be discontinued, as it is detrimental to the overall crop production system. The higher DU_{lq} values found at TGSE are attributed to the basic maintenance programme in place. This provides evidence that both preventative and corrective maintenance programs are essential to the good performance of a centre pivot irrigation system. The author, through the MIPU, has instituted training for centre pivot operators on the issue of basic maintenance and operation.

In regard to the effect of operating pressure on the centre pivots, no trend was found. The reasoning for this could be related to the pressure regulators above each sprinkler nozzle. The regulators are set at a value of 100 kPa and all the centre pivots which had pressure gauges and were evaluated in the Lowveld, were above this base value. On the issue of water quality, HVE had two pivots which experienced problems with algal growth. This was attributed to the fact that regenerated water containing fertilisers was being used and thus facilitated the growth of the algae. It is recommended that HVE should institute a preventative maintenance regime which will treat the water before it passes through the pivot. This could entail the installation of a chlorination injection point in the supply canal to deter subsequent algal growth and strainers to stop the masses of algal growth already formed, from passing into the holding dam before the water is pumped through the pivot onto the sugarcane. HVE also experienced a problem with small stones breaking the sprinkler nozzles. This could be reduced by either including a sand-trap filter in the mainline just before the central tower, or redesigning the pump intake. The wind speeds experienced during the MIPU evaluations of the centre pivots did not affect the performance of this system to any major degree.

The hand-move irrigation systems were only used by TGSE. This estate had an appropriate preventative and corrective maintenance programme which resulted in the fact that 74% of the hand-move sprinkler systems evaluated were within the DU_{lq} design norm. However, the AD values obtained were low, but could be improved through a small increase in the stand-times. Despite the over-compensation by TGSE with regard to operational pressure, the results obtained indicate that pressure, as a stand-alone factor, had no negative impact on the systems' performance. However, if one looks at the entire system from an economic perspective, questions could be raised about the excessive energy usage and the associated pumping costs relative to the high pressures, but this study was concentrating on the in-field performance. In isolation, wind speed did not have an effect on this system. It is recommended that in future, wind direction also be recorded when evaluating overhead sprinkler irrigation systems.

The static sprinkler system found in the Lowveld known as the "Floppy", as already stated earlier, was undergoing design development during the course of the MIPU evaluations and had the least number of evaluations, as there were only a few installed in the Lowveld. Improvements in design which were thought to positively influence the performance of the system were the galvanised steel risers, which were sturdier than the previous aluminium ones and were less affected by being blown skew by the wind, the 500 micron disc filters which, although small enough to stop small debris and stones, did not affect the operating pressure as did the previous 120 micron filters and the improved hydraulic design.

The results obtained showed that pressure did affect the performance of the floppy sprinkler, even though the sprinklers did have a pressure control valve mechanism incorporated in the sprinkler head. The results from the MIPU evaluations show that a minimum pressure exists for this particular type of irrigation system for optimal performance and is 230 kPa, slightly higher than the 200 kPa suggested by the designer. If algal growth was present in the water, the clogging of the small 120 micron disc filters occurred rapidly, causing a decrease in the water application and operating pressures. Irrigation therefore had to be interrupted while the filters were cleaned. The author suggests that the small 120 micron disc filters be replaced by the 500 micron discs and that the water source be treated with chlorine and sieves be placed by the suction side of the pump unit.

The results obtained clearly indicate that the performance of sub-surface drip systems are affected by the level of management and the operating pressures. Although the different designs gave different levels of performance, it is evident that it is the management of these designs which has a substantial impact on the performance parameters. This could be seen from the results which show that all the design types have the ability to attain high AD, DU_{lq}, and low DT values. The difference in management and the effects on this particular system were very noticeable when the MIPU results from the private farmers and the estates were compared. The private farmers had more intensive and involved management and employed workers with higher skills in the area of maintenance and operation. When operating SSD irrigation systems, attention needs to be paid to the pressures at the field-edge pressure control valves (hydrants). The high cost of pressure compensating laterals resulted in none having been installed in any of the systems evaluated and fluctuating, or incorrect, pressures had a significant negative effect on the performance of this system. The trends contained in the MIPU data confirms this. The MIPU also found that some submains were not adequately designed and the pressure loss along some of the lengths of the submains were excessive. It is suggested that when such cases are uncovered, the designer institute remedial measures, at their cost.

None of the sub-surface drip systems evaluated by the MIPU had pre-installation water quality checks to assess the suitability of the water for use in SSD. Although the cost of testing the quality of the water was considered high, the MIPU tried to educate farmers in the knowledge that the life span of a sub-surface drip irrigation system could be severely curtailed by water which had high concentrations of certain chemicals and which could lead to precipitates being formed, which clog up emitters. Water of low quality being used for irrigation by SSD could also lead to precipitates being formed due to the chemigation process that the farmer practices. The installation of the in-field component of SSD below ground level makes it very difficult to visually see what is happening, and frequently problems are only evident once the harvested yield is below expectation. Iron was found to be a problem in the water used for irrigation of the sub-surface drip systems in the Lowveld. The MIPU therefore collated relevant literature, as shown in Table 2.5, and assisted the farmers in formulating a preventative and corrective maintenance programme. Typically this programme involved treating the water with chemicals such as acids and/or chlorine, constant checking of submain pressures and ensuring a correct flushing programme. The MIPU results showed that the relatively poor performance of the TGSE drip system was largely attributable to initial design flaws and inappropriate management of the irrigation system, particularly regarding the flushing and pressures.

Through good design and management the Lowveld sugarcane farmers could realise the true potential performance of the various irrigation systems, which should result in an economic benefit to the farmer. It is interesting that the ranking of the types of irrigation systems using the potential performance of the Lowveld MIPU evaluations and potential performance of international MIPU evaluations are closely matched, thus showing that the Lowveld irrigation systems have the potential to operate to international standards. When the DU_{lq} values are compared from this and other studies, the main differences in performance are between the furrow (11%) and sub-surface drip (6%) systems, which the author attributes to the availability of specialised management and equipment.

Additional data and tools were developed during the course of this project that could be used by farmers to help ensure a better understanding of the workings of a particular type of irrigation system, and to assist in the management of the system. These tools include evaluation spreadsheets which could be mastered using a couple of days training and basic computer literacy. The MIPU offers an installation evaluation which ensures that newly installed irrigation systems are operating according to design and performance standards. This service also ensures the integrity and competency of irrigation system designers and installers within the Lowveld sugarcane industry.

Maintenance, both preventative and corrective, is extremely important in ensuring that an irrigation system is performing within design norms. The evaluations conducted by the MIPU serve as a check system in order to make certain a farmer is taking appropriate care of the irrigation system. In addition, the hardware of an irrigation system which is well maintained will last longer than one which is not. The development of the Greller and conical pressure nozzle by the MIPU can be utilised by farmers to determine inflow rates into a furrow and hence to decide on the number of syphons per furrow and to calculate appropriate cut-off times. The specially designed pressure nozzle can be used in everyday use by the sub-surface drip operator to check that the in-field pressures are correct.

The adequacy chart is simple, but has the ability to be the most effective tool to be developed during the course of this study. It contains the information on AD, DT and DU_{lq}, thus all the relevant information that a farmer requires when determining how to best irrigate a field. Adequacy charts are "field specific", i.e. if a farmer wants an adequacy chart for a particular field, the field needs to be evaluated in order for the chart to be created. Farmers need to be careful not to confuse an "application" chart with an adequacy chart for a centre pivot irrigation system. The misconception arises due to the fact that with pivots each sprinkler represents a different area. Thus, if a farmer uses the wrong chart, the decisions are based on incorrect assumptions.

The surface simulation software model SIRMOD can be used to calculate the performance parameters for surface irrigation to an accurate degree using the in-field data collected by the MIPU. It can also be used as a training/management tool to show farmers how design and management decisions can affect a furrow irrigation systems performance. *ZIMshed 2.0*, a deterministic crop and irrigation systems computer simulation model, has the capability of showing the impact that the performance of irrigation systems hardware has on a seasonal water balance by accounting for different scheduling approaches and giving predictions of associated crop yield impacts. All MIPU data collected during this study are compatible with both these models.

Evaluation methodologies were adapted and applied for all the irrigation systems currently in use in the sugarcane industry within the Lowveld of Zimbabwe. The performance parameters of AD, DT and DU_{lq} were determined for the different irrigation systems, in relation to international standards. Factors which can affect a system's performance were investigated and collated and a comparison of the performance parameters of the different irrigation systems was shown. In addition, tools were developed which could be of great potential benefit to the farmer. A valuable database has been collated which helps local farmers to benchmark and to measure their systems against in the future. It is also possible that the repetitive nature of certain management and design variables which may be detrimental to system performance under local conditions, can eventually be rendered obsolete. These evaluation data can also be used to help facilitate objective decisions regarding the selection of irrigation systems to suit particular environments.

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APPENDIX A: EVALUATION SHEETS

A.1 EVALUATION SHEET: Furrow Irrigation System

Farm and System Information

Farm name: ....Designer of system:..........................Installation date:....................

Field number:...................................Field TAM:..........................Field area:.................................

Target application [mm]:.............Predominant soil type:...............Cut/Plant Date.......................

Scheduling programme (tick): Yes.......Details..No........

Maintenance programme (tick): Yes.....Details...No........

Re-ridged (tick): Yes...........No..........Date re-ridged...........................Implement used................

Furrow type (tick): In-row...........Inter-row............Number of furrows in evaluation..................

Length of furrow:......................Spacing of furrows........................Furrow shape.......................

Furrow end (tick): Blocked...........Open ended:...........Times crop irrigated before today............

Size of syphon:..Number of syphons per furrow:..................................

Date of evaluation:..........................Time at start:..........................Time at end:..........................

Met Data (taken at the beginning, middle and end of an evaluation with hand-held WeatherMeter)

Wind speed: Start.......................................Middle..........................End.......................................

Temperature: Start.....................................Middle..........................End.......................................

Humidity: Start..Middle..........................End......................................

Furrow Dimension Readings (use the flexible 100m tape measure and 3m metal tape measure)

Position	Beginning	Middle	End
Top width of furrow			
Bottom width of furrow			
Depth of furrow			
Wetted perimeter			
Depth of water in furrow			

Inflow/Recession, Advance/Outflow and Slope Readings (Tools: Greller, WSC flume, Pegs, Hammer, 100m measuring tape, Dumpy level and staff and 2 x stopwatches)

Note: Stopwatches must be synchronised at the start of the evaluation. This evaluation takes two (2) people. Person A collects the data for inflow and recession while Person B collects the data for Advance and Outflow. Person A must write "cut-off with exact time, when syphons are lifted out by irrigator. Additional recording sheets for Inflow and Outflow are given. Slope readings with dumpy level equipment can be done before or after evaluation.

Person A				Both	Person B			
Inflow		Recession		Slope	Advance		Outflow	
Time [s]	Greller [cm]	Position [m]	Time [s]	Staff reading [m]	Position [m]	Time [s]	Gauge [cm]	Time taken every 30 sec [s]
0		Start			Start			
30		10			10			
60		20			20			
90		30			30			
120		40			40			
150		50			50			
180		60			60			
210		70			70			
240		80			80			
270		90			90			
300		100			100			
330		110			110			
360		120			120			
390		130			130			
420		140			140			
450		150			150			
480		160			160			
510		170			170			
540		180			180			
570		190			190			
600		200			200			

General Comments/Sketches (Include anything which evaluator may feel is important)

Person A: Additional recording sheet for Inflow readings					
Time [s]	Greller [cm]	Time [s]	Greller [cm]	Time [s]	Greller [cm]
630		1560		2460	
690		1590		2490	
720		1620		2520	
750		1650		2550	
780		1680		2580	
810		1710		2610	
840		1740		2640	
870		1770		2670	
900		1800		2700	
930		1830		2730	
960		1860		2760	
990		1890		2790	
1020		1920		2820	
1050		1950		2850	
1080		1980		2880	
1110		2010		2910	
1140		2040		2940	
1170		2070		2970	
1200		2100		3000	
1230		2130		3030	
1260		2160		3060	
1290		2190		3090	
1320		2220		3120	
1350		2250		3150	
1380		2280		3180	
1410		2310		3210	
1440		2340		3240	
1470		2370		3270	
1500		2400		3300	
1530		2430		3330	

Person B: Additional recording sheet for Outflow readings					
Time [s]	Gauge [cm]	Time [s]	Gauge [cm]	Time [s]	Gauge [cm]

A.2 EVALUATION SHEET: Centre Pivot Sprinkler Irrigation System

Farm and System Information

Farm name: ....Designer of system:..........................Installation date:....................

System type (tick appropriate): Valley............Agrico...............ZimMatic.............Other..............

Target application [mm]:.............Predominant soil type:...............Cut/Plant Date.......................

Field number:.................................Field TAM:.........................Field area:.................................

Scheduling programme (tick): Yes.......Details..No........

Maintenance programme (tick): Yes.....Details..No........

Filters used in system (tick): Yes..........Details...No........

Date of evaluation:...........................Time at start:........................Time at end:............................

Met Data (taken at the beginning, middle and end of an evaluation with WeatherMeter)

Wind speed: Start.................................Middle..........................End...

Wind direction: Start..............................Middle..........................End...

Temperature: Start.................................Middle..........................End...

Humidity: Start......................................Middle..........................End...

Pressure Readings (use needle and pitot fittings connected to 500 kPa pressure gauge)

Mainline Pressure:............................Central Tower:...........................Pivot End:......................

Number of spans:..............Number of sprinklers:..............Overhang (tick): Yes..........No.............

Length of pivot:......................End gun (tick): Yes...........No.............End gun radius:................

Console Readings (list all relevant data)

Speed setting [%]:..........Application amount [mm]:...........Pressure at pivot centre [kPa]:............

Travel direction of pivot(tick appropriate): Clockwise...................Anti-clockwise.......................

Distribution Readings (Use rain-gauges, hammer, aluminium tube, pegs and 100m tape measure)

Note: First gauge placed underneath last sprinkler of last span/overhang, then gauges are placed 8m apart till pivot centre is reached. Mark with a tick, gauges that are moved due to interference with tower wheels.

Note: Evaluation is conducted at an application rate of between 16mm and 25mm.

Position	Distance from Pivot Centre [m]	Gauge Reading [mm]	Position	Distance from Pivot Centre [m]	Gauge Reading [mm]
1			36		

2			37		
3			38		
4			39		
5			40		
6			41		
7			42		
8			43		
9			44		
10			45		
11			46		
12			47		
13			48		
14			49		
15			50		
16			51		
17			52		
18			53		
19			54		
20			55		
21			56		
22			57		
23			58		
24			59		
25			60		
26			61		
27			62		
28			63		
29			64		
30			65		
31			66		
32			67		
33			68		

34			69		
35			70		

Travel Speed Readings (mark positions of the last wheel of the last tower, from when it begins to move till when it stops for the third time. Use pegs, hammer and 100m tape measure)

Wheel Position [m]	Time [s]	Distance covered [m]
Begins to move		
Wheel stops (movement 1)		
Begins to move		
Wheel stops (movement 2)		
Begins to move		
Wheel stops (movement 3)		

Intensity Readings (Matching Infiltration rate of soil to Application rate of pivot. Use automatic rain-gauge and record value every two minutes. Place gauge in the radial path underneath the last sprinkler on the last span/overhang)

Time [min]	Automatic Gauge Reading [mm]
2	
4	
6	
8	
10	
12	
14	
16	
18	
20	

General Comments/Sketches (Include anything which evaluator may feel is important)

A.3 EVALUATION SHEET: Static (Floppy) and Hand-move Sprinkler Irrigation System

Farm and System Information

Farm name: ....Designer of system:..........................Installation date:....................

System type (tick appropriate): Floppy.....................Hand-move..

Target application [mm]:.............Predominant soil type:...............Cut/Plant Date.......................

Field number:.................................Field TAM:.........................Field area:..................................

Scheduling programme (tick): Yes.......Details...No........

Maintenance programme (tick): Yes.....Details...No........

Filters used in system (tick): Yes..........Details...No........

Date of evaluation:...........................Time at start:.........................Time at end:..........................

Met Data (taken at the beginning, middle and end of an evaluation with WeatherMeter)

Wind speed: Start....................................Middle............................End.......................................

Wind direction: Start..............................Middle.............................End.......................................

Temperature: Start...................................Middle............................End.......................................

Humidity: Start..Middle............................End.......................................

Pressure Readings (use needle and pitot fittings connected to 500kPa pressure gauge)

Pressure at hydrant: Mainline...Submain..

Distance between laterals:........................Distance between sprinklers on lateral:........................

Length of lateral A:..................................Number of sprinklers per lateral:..................................

Length of lateral B:...................................Number of sprinklers per lateral:..................................

Note: Mark with a tick, the sprinkler positions which are on the outside of the grid arrangement.

Sprinkler Position and Riser Height (m)	Nozzle Pressures down Lateral A (kPa)		Nozzle Pressures down Lateral B (kPa)	
	Large Nozzle	Small Nozzle	Large Nozzle	Small Nozzle
1				
2				
3				
4				
5				
6				
7				
8				

9				

Flow Readings (Use hosepipe, 25L marked bucket)

Note: Mark with a tick, the sprinkler positions which are on the outside of the grid arrangement.

Sprinkler Position	Nozzle Flows down Lateral A				Nozzle Flows down Lateral B			
	Large Nozzle		Small Nozzle		Large Nozzle		Small Nozzle	
	time	flow	time	flow	time	flow	time	flow
1								
2								
3								
4								
5								
6								
7								
8								
9								
10								

Distribution Readings (Use rain-gauges, hammer, aluminium tube, pegs and 100m measuring tape)

Grid System (tick appropriate): 7x6 @ 2mX2m......6x6 @ 3mX3m.......5x5 @ 3.6mX3.6m.........

Position	a	b	c	d	e	f
1						
2						
3						
4						
5						
6						
7						

General Comments/Sketches (Include anything which evaluator may feel is important)

A.4 EVALUATION SHEET: Sub-surface Drip Irrigation System

Farm and System Information

Farm name: ....Designer of system:..........................Installation date:.....................

System type (tick appropriate): A(Normal)................B(Ring)..................C(Other).........................

Target application [mm]:.............Predominant soil type:...............Cut/Plant Date.......................

Field number:...............................Field TAM:..........................Field area:.................................

Scheduling programme (tick): Yes.......Details...No........

Maintenance programme (tick): Yes.....Details...No........

Filters used in system (tick): Yes.........Details...No........

Emitter type:....................................Pressure compensating (tick): Yes.............No...................

Lateral type:....................Lateral internal diameter[mm]:..........Number laterals in block:...............

Emitter spacing[m]:.........................Lateral spacing[m]:...................Lateral length [m].............

Emitter design flow [l/h]............................Design operating pressure [kPa]:..............................

Date of evaluation:...........................Time at start:........................Time at end:............................

Met Data (taken at the beginning, middle and end of an evaluation with WeatherMeter)

Wind speed: Start....................................Middle............................End.....................................

Temperature: Start...................................Middle............................End.....................................

Humidity: Start...Middle............................End.....................................

Pressure Readings (use needle and conical fittings connected to 250kPa pressure gauge)

Note: Pressure points taken down length of submain at the six chosen lateral positions. Disconnect lateral from blanco and fit conical pressure fitting into blanco end, then into lateral end.

Pressure at hydrant: Mainline...Submain...

Position	a	b	c	d	e	f
Submain line						
Lateral						
Lateral						
Flushing manifold						

Distribution Readings (Use cups, piece of string, 25mm measuring cylinder and stopwatch)

Note: Readings taken over three (3) minutes. Five (5) evaluation points chosen down six (6) chosen laterals. Holes must be dug that are big enough to accommodate easy insertion and withdrawal of plastic cups. Remember to place string around lateral on either side of the emitter, so as to prevent water not being collected in cup. First and last emitters are chosen a metre into the field, from the blanco connection.

Position	a	b	c	d	e	f
Start						
L/4						
L/2						
3L/4						
End						

<u>Flowmeter Readings</u> (Use Arad digital flowmeter)

Note: Fit the Arad flowmeter between the lateral and the blanco which leads into the flushing manifold. Let the flowmeter be in operation till the reading has stabilised, usually less than two (2) minutes.

Position	a	b	c	d	e	f
End						

<u>General Comments/Sketches</u> (Include anything which evaluator may feel is important)

APPENDIX B: ADDITIONAL DU_{lq} CHARTS FOR THE FURROW IRRIGATION SYSTEMS

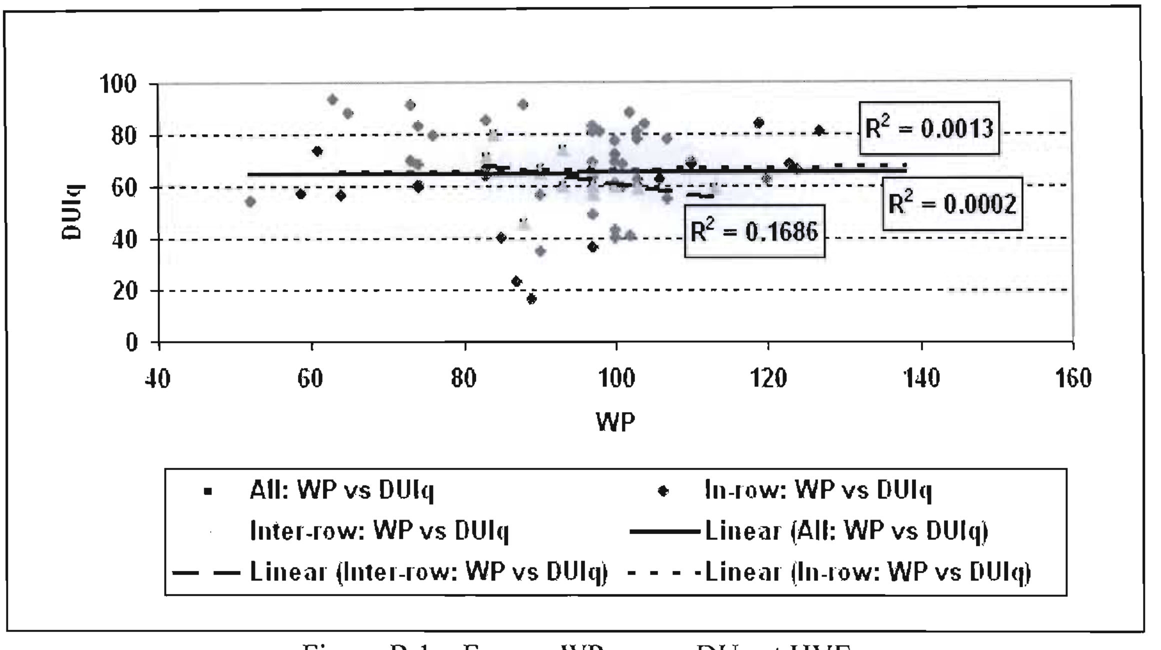


Figure B.1 Furrow WP versus DU_{lq} at HVE

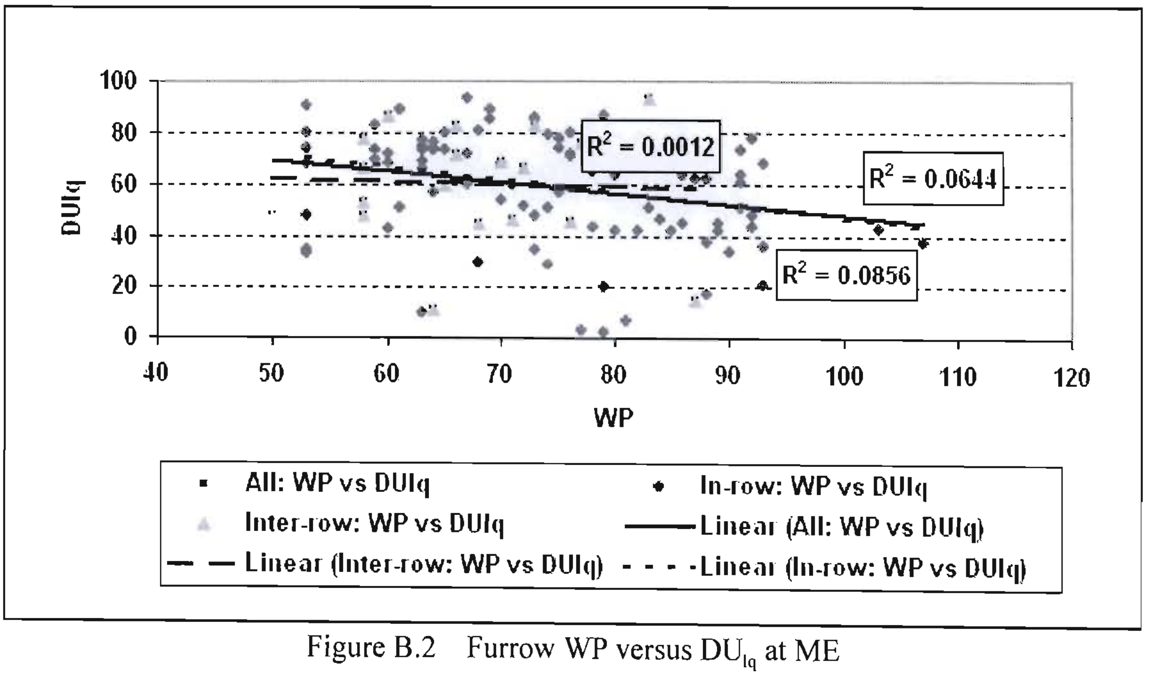


Figure B.2 Furrow WP versus DU_{lq} at ME

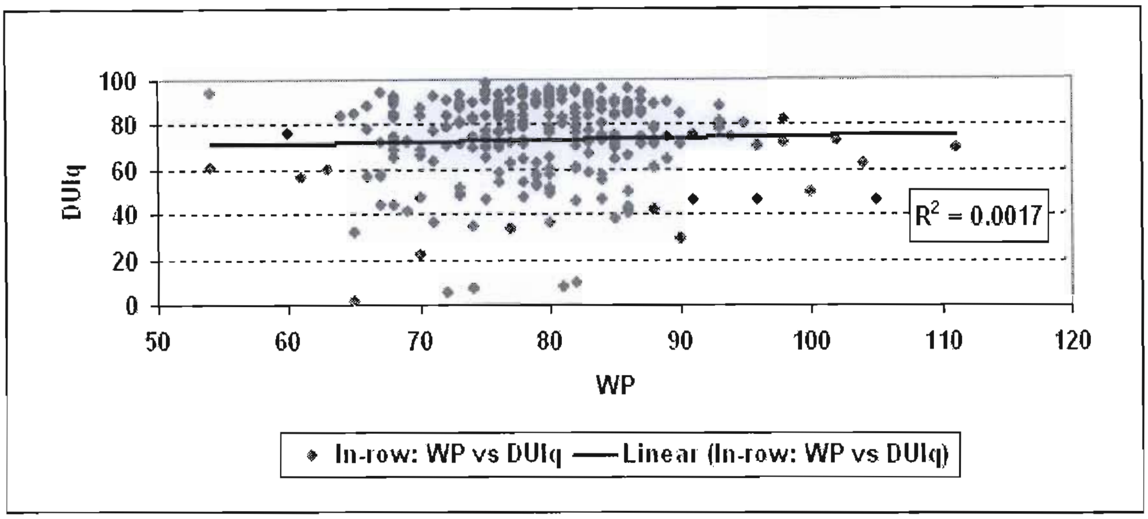


Figure B.3 Furrow WP versus DU_{lq} at TGSE

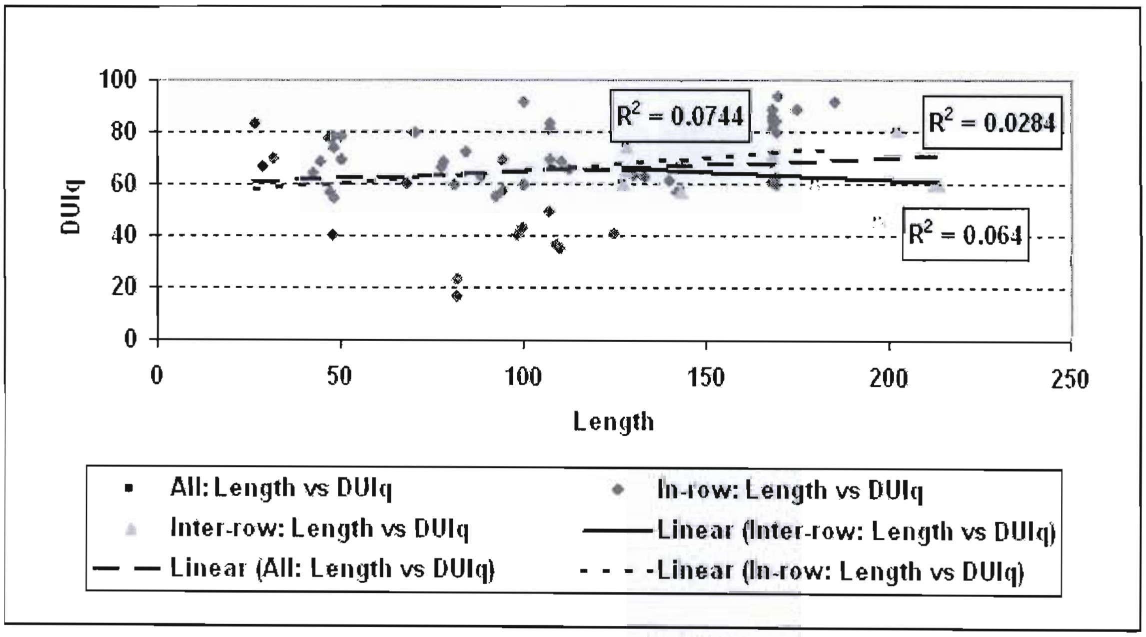


Figure B.4 Furrow length versus DU_{lq} at HVE

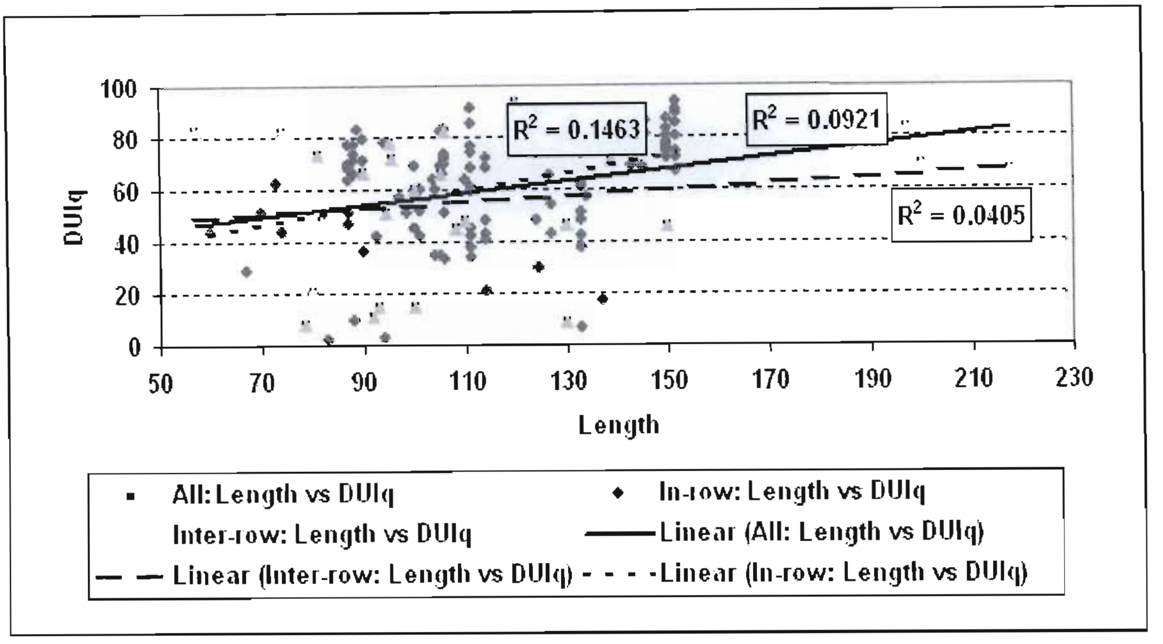


Figure B.5 Furrow length versus DU_{lq} at ME

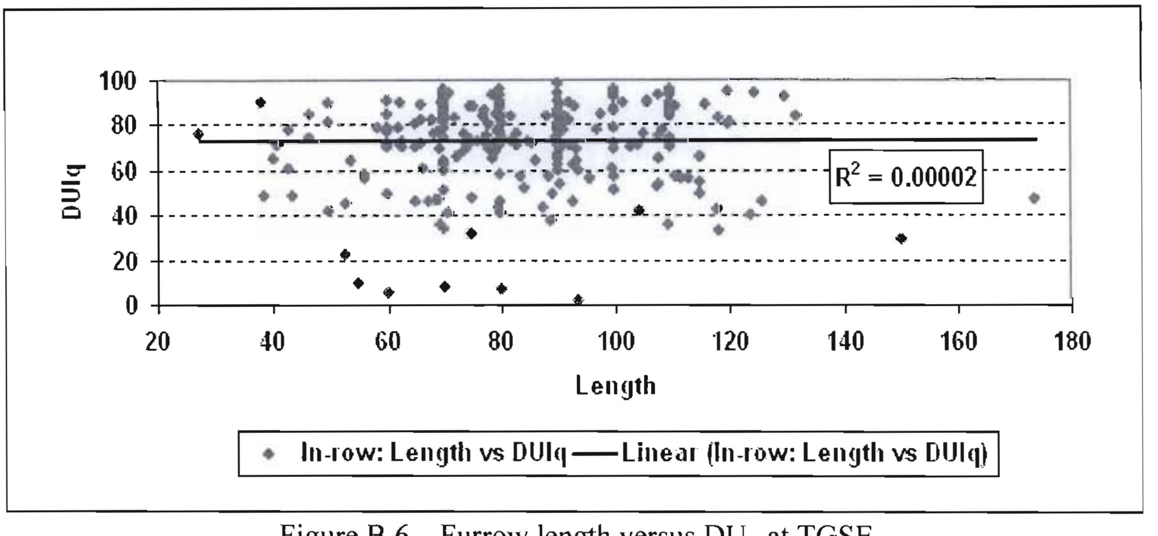


Figure B.6 Furrow length versus DU_{lq} at TGSE

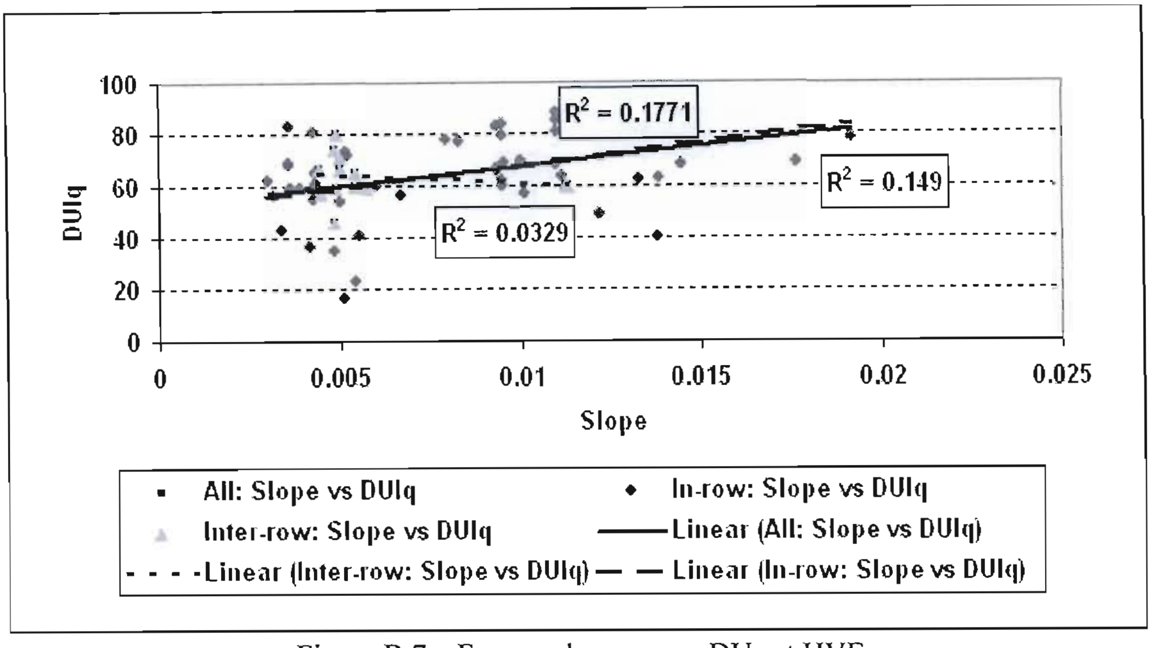


Figure B.7 Furrow slope versus DU_{lq} at HVE

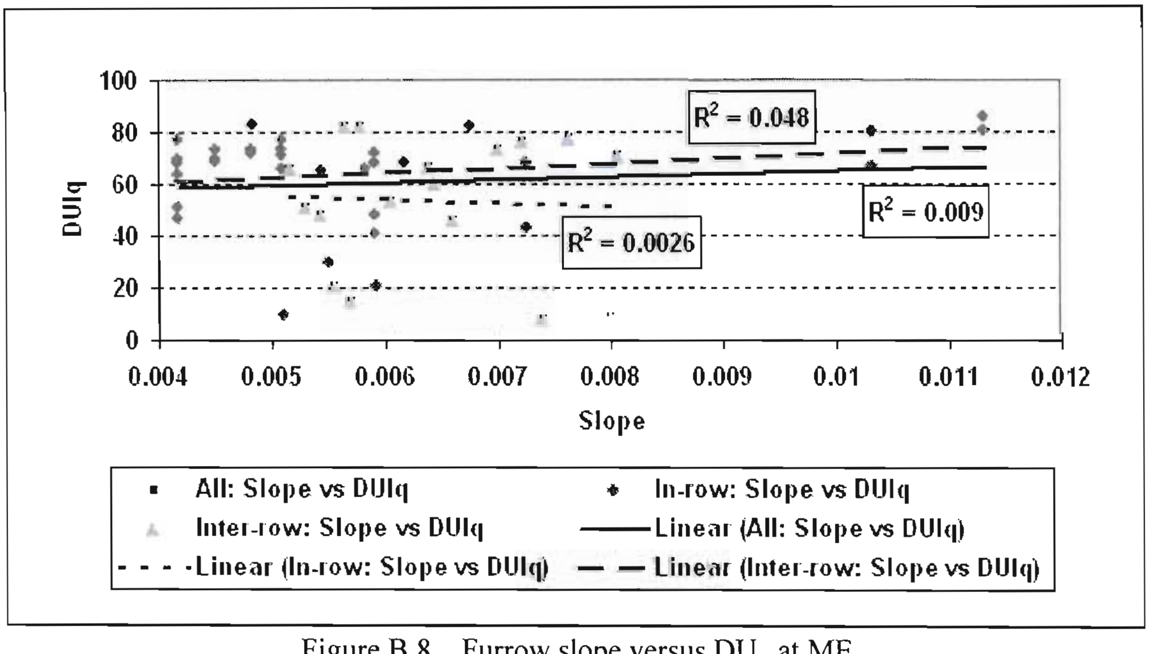


Figure B.8 Furrow slope versus DU_{lq} at ME

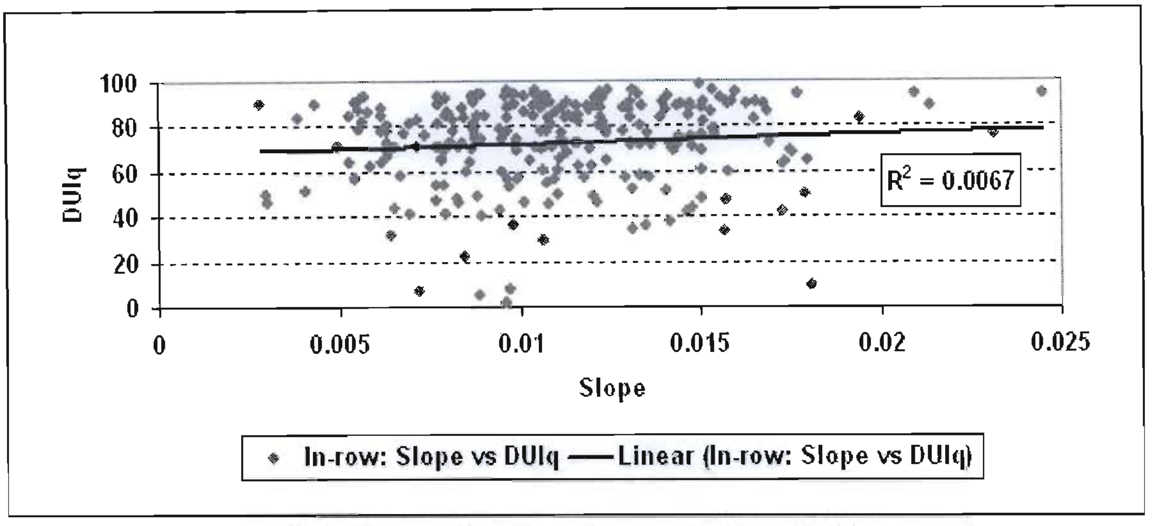


Figure B.9 Furrow slope versus DU_{lq} at TGSE

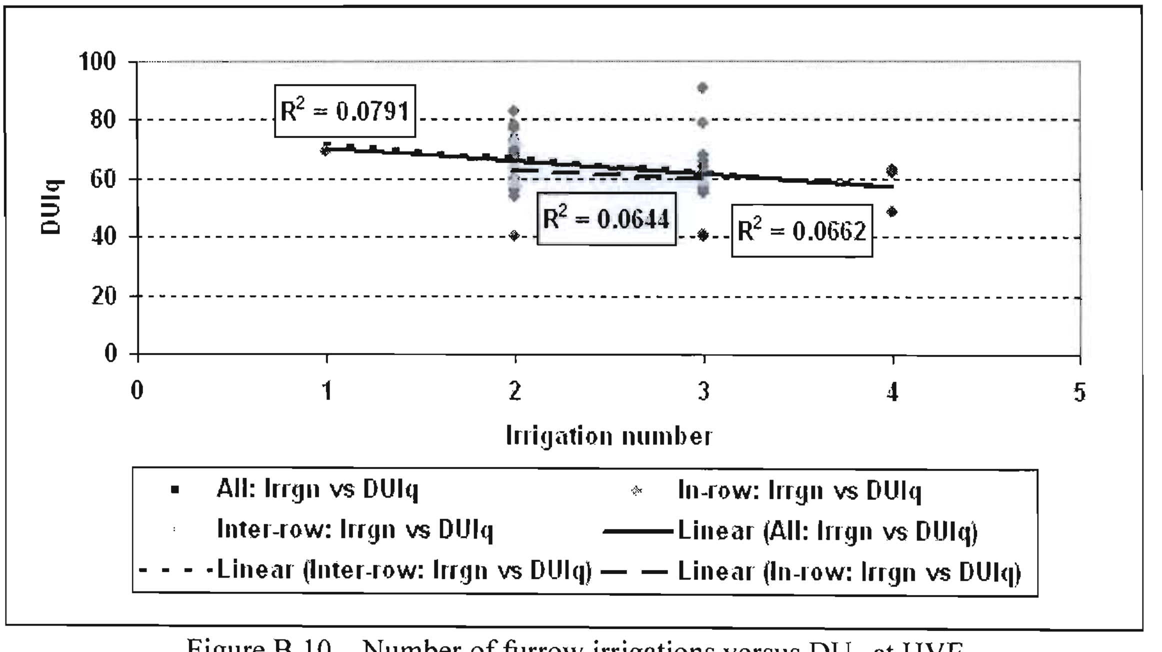


Figure B.10 Number of furrow irrigations versus DU_{lq} at HVE

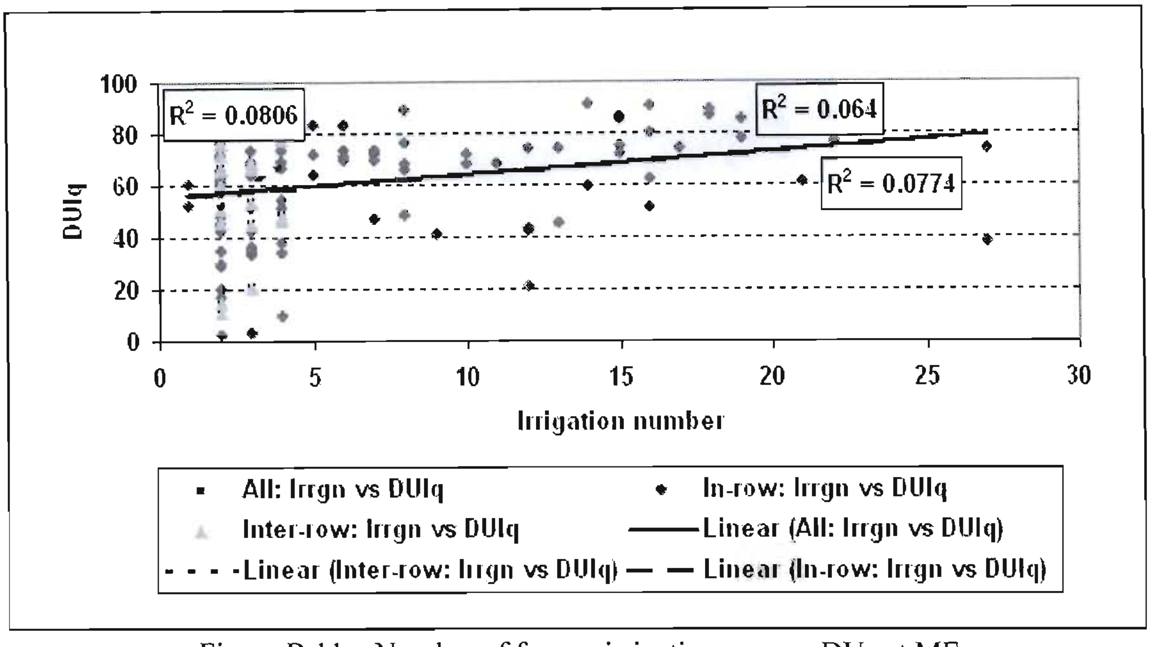


Figure B.11 Number of furrow irrigations versus DU_{lq} at ME

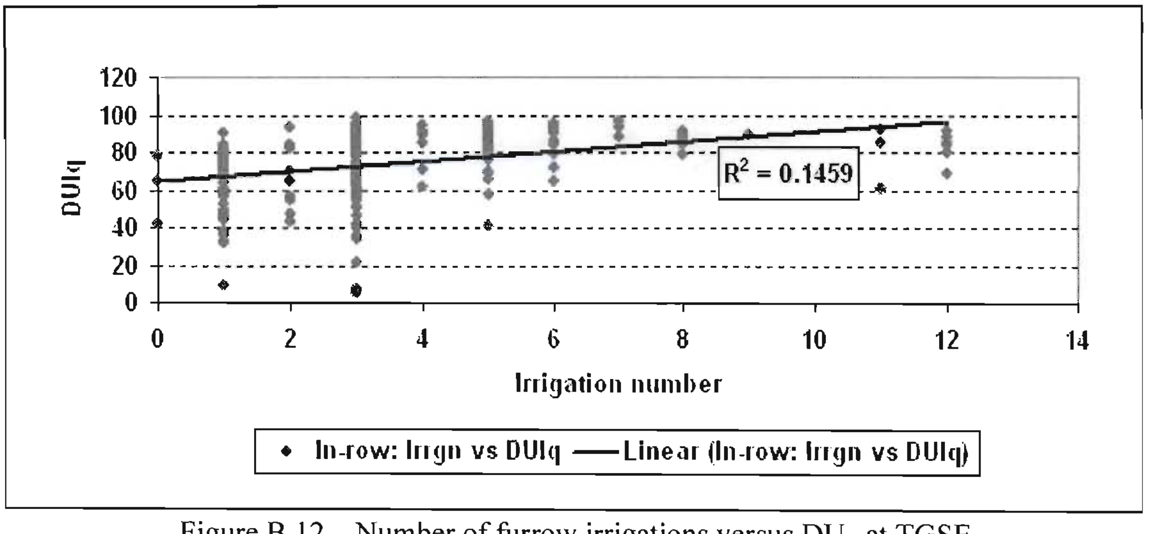


Figure B.12 Number of furrow irrigations versus DU_{lq} at TGSE

APPENDIX C: EVALUATION SPREADSHEETS

There were four evaluation spreadsheets developed using the Corel Quattro Pro computer package. The spreadsheets were developed in such a way so as to capture the relevant information and to then calculate an irrigation systems' in-field performance using the equations from Chapter 2. Figures C.1 through to Figure C.4 are examples of the actual spreadsheets used for the relevant irrigation systems.

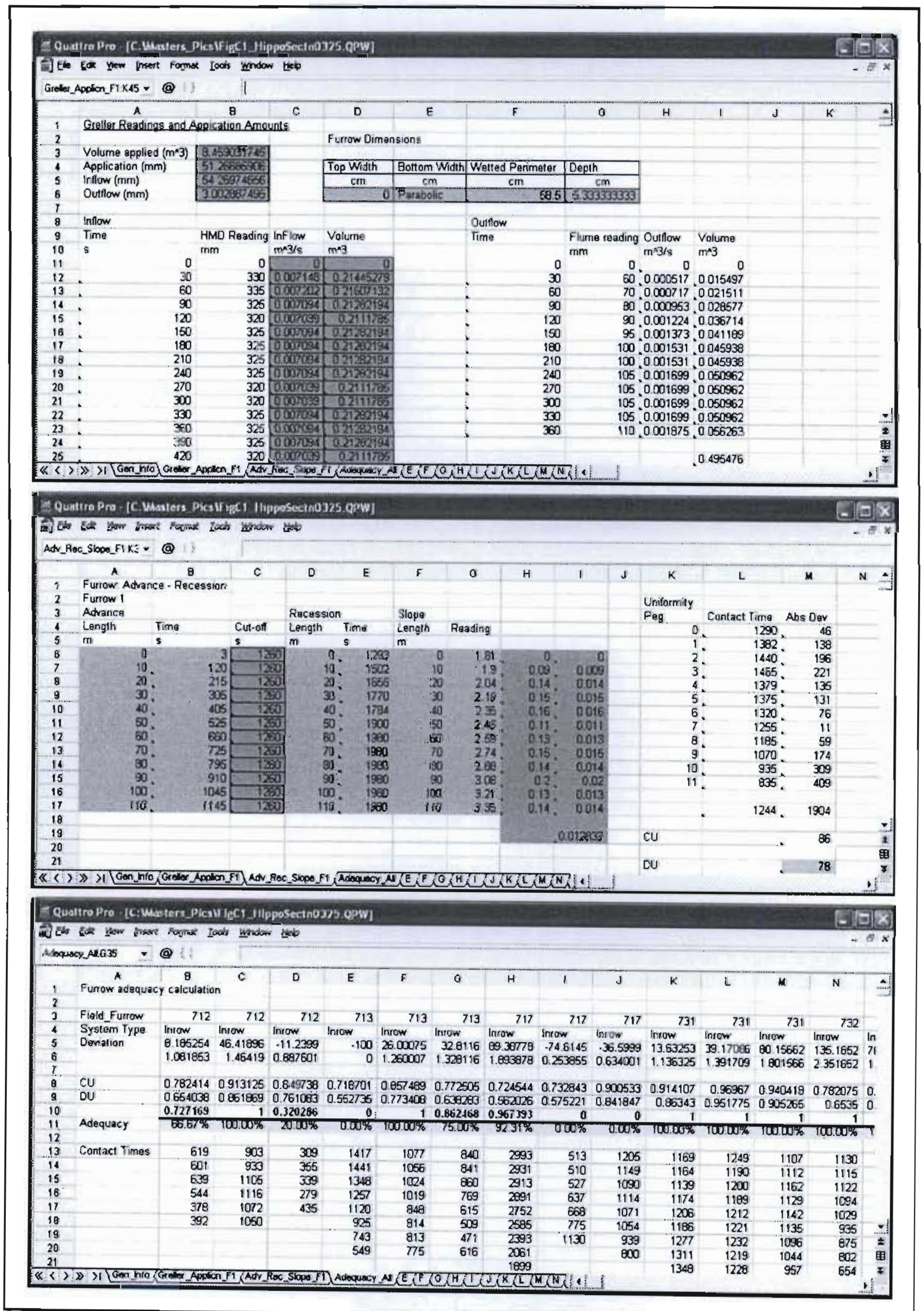
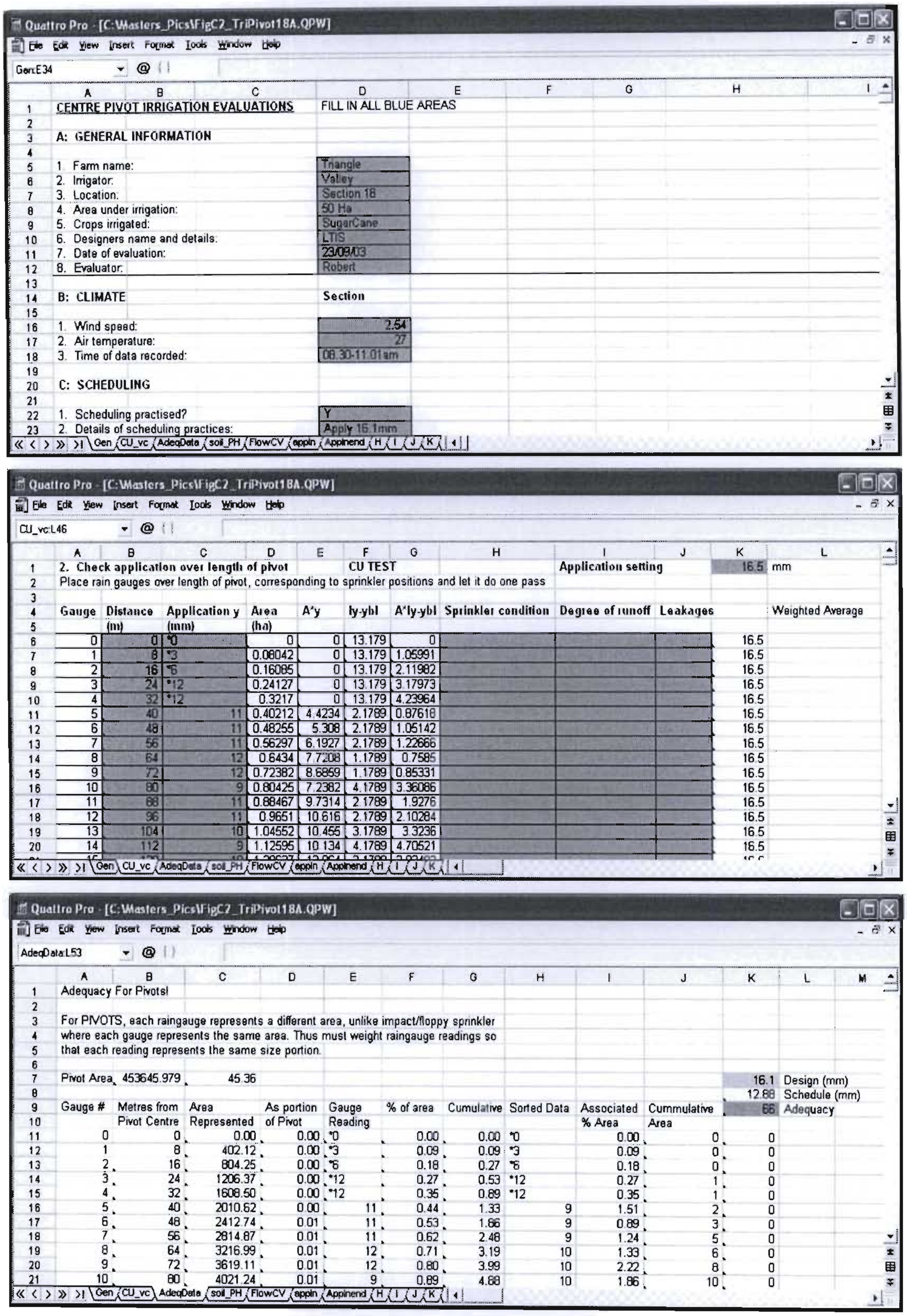


Figure C.1 Example of evaluation spreadsheets for all furrow irrigation systems



Quattro Pro - [C:\Masters_Pics\FigC2_TriPivot18A.QPW]

Gen:E34

CENTRE PIVOT IRRIGATION EVALUATIONS	FILL IN ALL BLUE AREAS
A: GENERAL INFORMATION	
1. Farm name:	Triangle
2. Irrigator:	Valley
3. Location:	Section 18
4. Area under irrigation:	50 Ha
5. Crops irrigated:	SugarCane
6. Designers name and details:	LTIS
7. Date of evaluation:	23/09/03
8. Evaluator:	Robert
B: CLIMATE	**Section**
1. Wind speed:	2.54
2. Air temperature:	27
3. Time of data recorded:	08.30-11.01am
C: SCHEDULING	
1. Scheduling practised?	Y
2. Details of scheduling practices:	Apply 16.1mm

Quattro Pro - [C:\Masters_Pics\FigC2_TriPivot18A.QPW]

CU_vc:L46

2. Check application over length of pivot — **CU TEST** — **Application setting** 16.5 mm

Place rain gauges over length of pivot, corresponding to sprinkler positions and let it do one pass

Gauge	Distance (m)	Application y (mm)	Area (ha)	A*y	ly-ybl	A*ly-ybl	Sprinkler condition	Degree of runoff	Leakages		Weighted Average
0	0	*0	0	0	13.179	0				16.5	
1	8	*3	0.08042	0	13.179	1.05991				16.5	
2	16	*6	0.16085	0	13.179	2.11982				16.5	
3	24	*12	0.24127	0	13.179	3.17973				16.5	
4	32	*12	0.3217	0	13.179	4.23964				16.5	
5	40	11	0.40212	4.4234	2.1789	0.87618				16.5	
6	48	11	0.48255	5.308	2.1789	1.05142				16.5	
7	56	11	0.56297	6.1927	2.1789	1.22666				16.5	
8	64	12	0.6434	7.7208	1.1789	0.7585				16.5	
9	72	12	0.72382	8.6859	1.1789	0.85331				16.5	
10	80	9	0.80425	7.2382	4.1789	3.36086				16.5	
11	88	11	0.88467	9.7314	2.1789	1.9276				16.5	
12	96	11	0.9651	10.616	2.1789	2.10284				16.5	
13	104	10	1.04552	10.455	3.1789	3.3236				16.5	
14	112	9	1.12595	10.134	4.1789	4.70521				16.5	

Quattro Pro - [C:\Masters_Pics\FigC2_TriPivot18A.QPW]

AdeqData:L53

Adequacy For Pivots!

For PIVOTS, each raingauge represents a different area, unlike impact/floppy sprinkler where each gauge represents the same area. Thus must weight raingauge readings so that each reading represents the same size portion.

Pivot Area 453645.979 45.36

16.1 Design (mm)
12.88 Schedule (mm)
66 Adequacy

Gauge #	Metres from Pivot Centre	Area Represented	As portion of Pivot	Gauge Reading	% of area	Cumulative	Sorted Data	Associated % Area	Cummulative Area	
0	0	0.00	0.00	*0	0.00	0.00	*0	0.00	0	0
1	8	402.12	0.00	*3	0.09	0.09	*3	0.09	0	0
2	16	804.25	0.00	*6	0.18	0.27	*6	0.18	0	0
3	24	1206.37	0.00	*12	0.27	0.53	*12	0.27	1	0
4	32	1608.50	0.00	*12	0.35	0.89	*12	0.35	1	0
5	40	2010.62	0.00	11	0.44	1.33	9	1.51	2	0
6	48	2412.74	0.01	11	0.53	1.66	9	0.89	3	0
7	56	2814.87	0.01	11	0.62	2.48	9	1.24	5	0
8	64	3216.99	0.01	12	0.71	3.19	10	1.33	6	0
9	72	3619.11	0.01	12	0.80	3.99	10	2.22	8	0
10	80	4021.24	0.01	9	0.89	4.88	10	1.86	10	0

Figure C.2 Example of evaluation spreadsheets for centre pivot irrigation systems

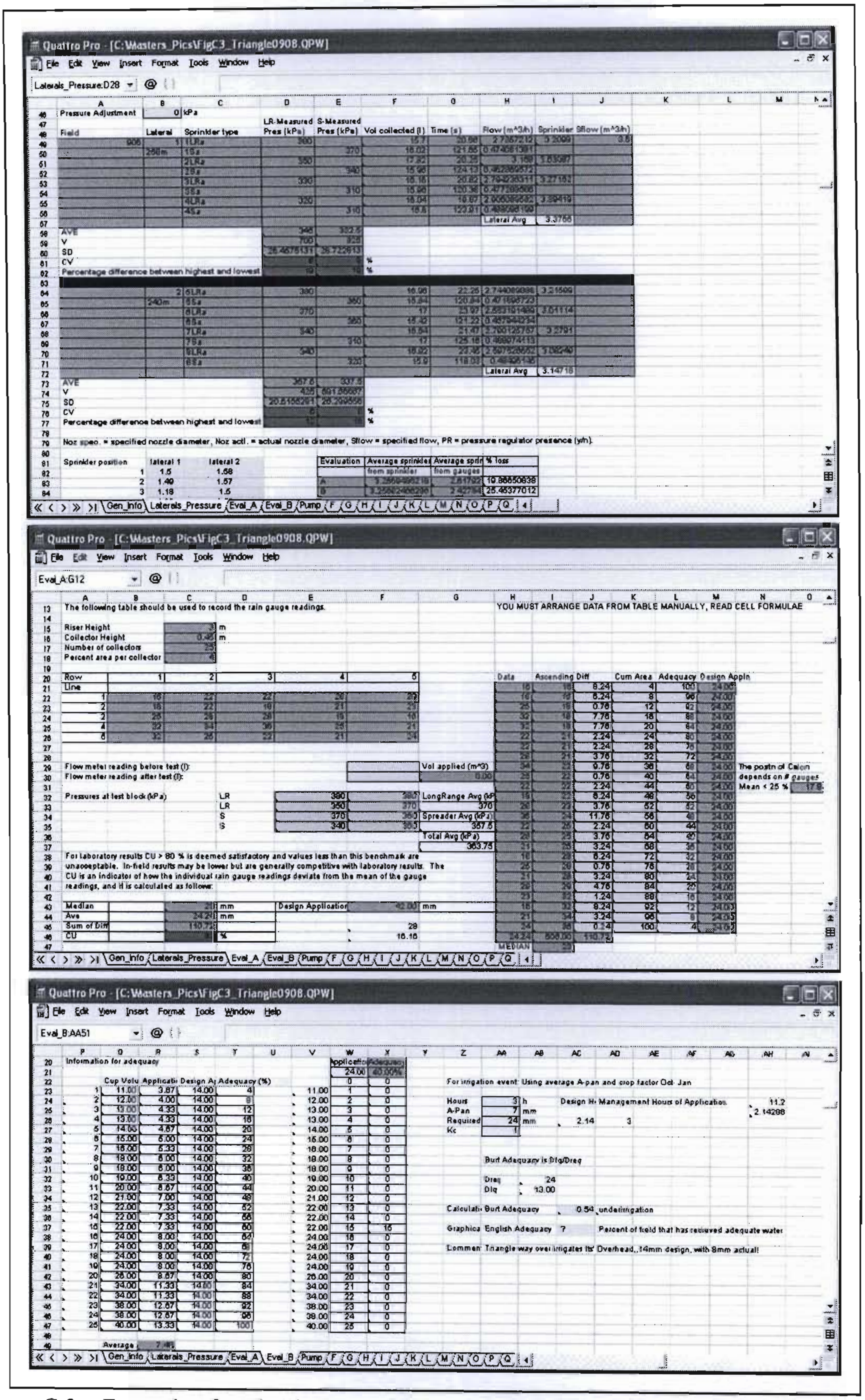


Figure C.3 Example of evaluation spreadsheets for hand-move and static sprinkler irrigation systems

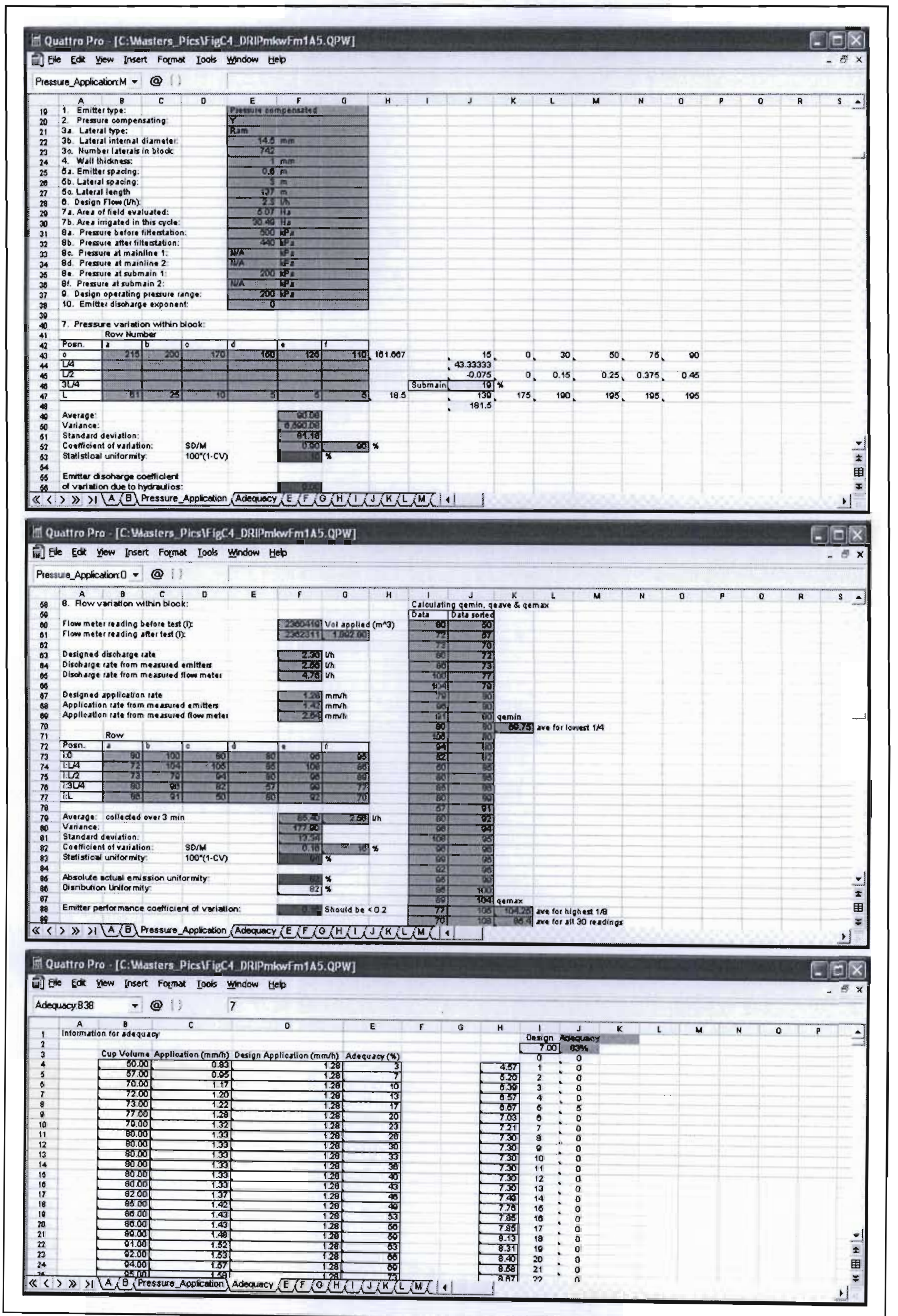


Figure C.4 Example of evaluation spreadsheets for sub-surface drip irrigation systems

APPENDIX D: SIMULATION SOFTWARE

This appendix contains examples of the screen images of the SIRMOD furrow simulation software model. Figure D.1 shows what type of data is required to be input into the model, using the data from the HVE furrow and which is used to calibrate the model and the simulated performance. Figure D.2 shows the adjusted HVE furrow inflow data and the resultant performance parameters and the decrease in the outflow.

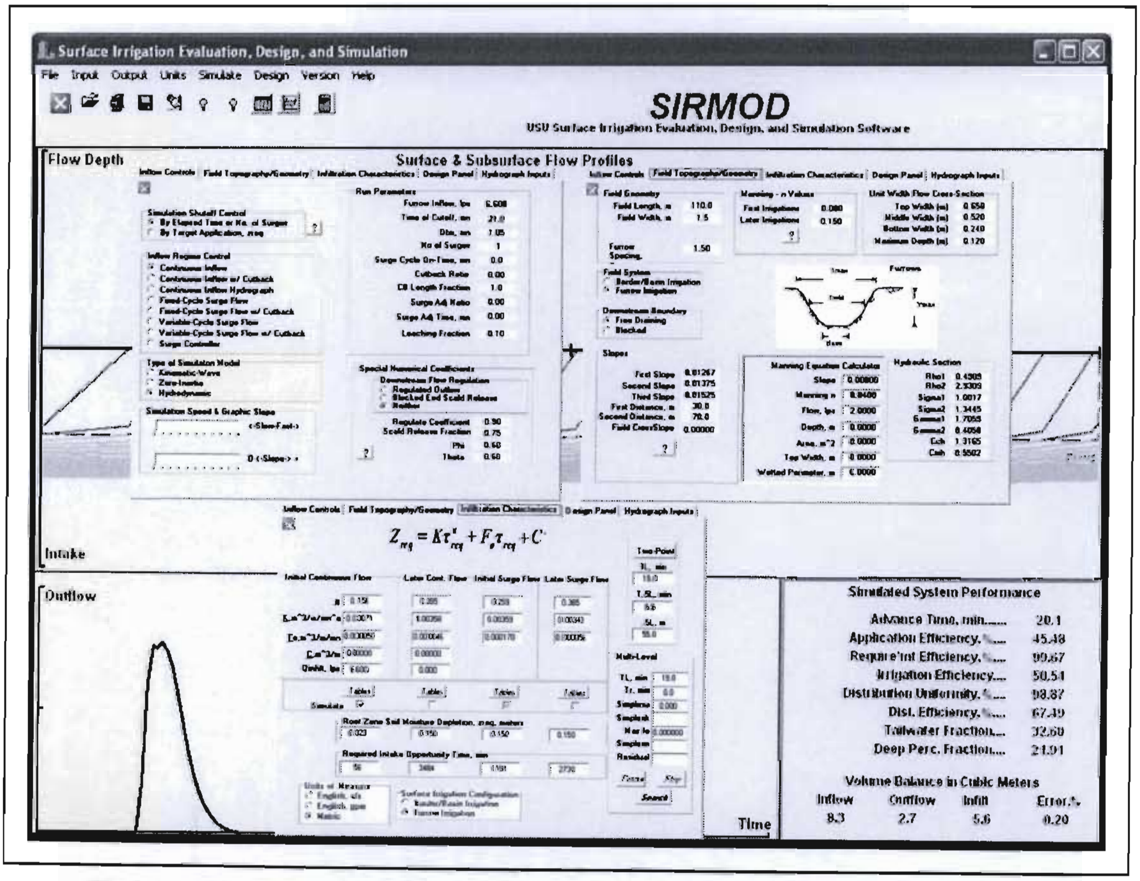


Figure D.1 Examples of the input screens for the SIRMOD simulation model

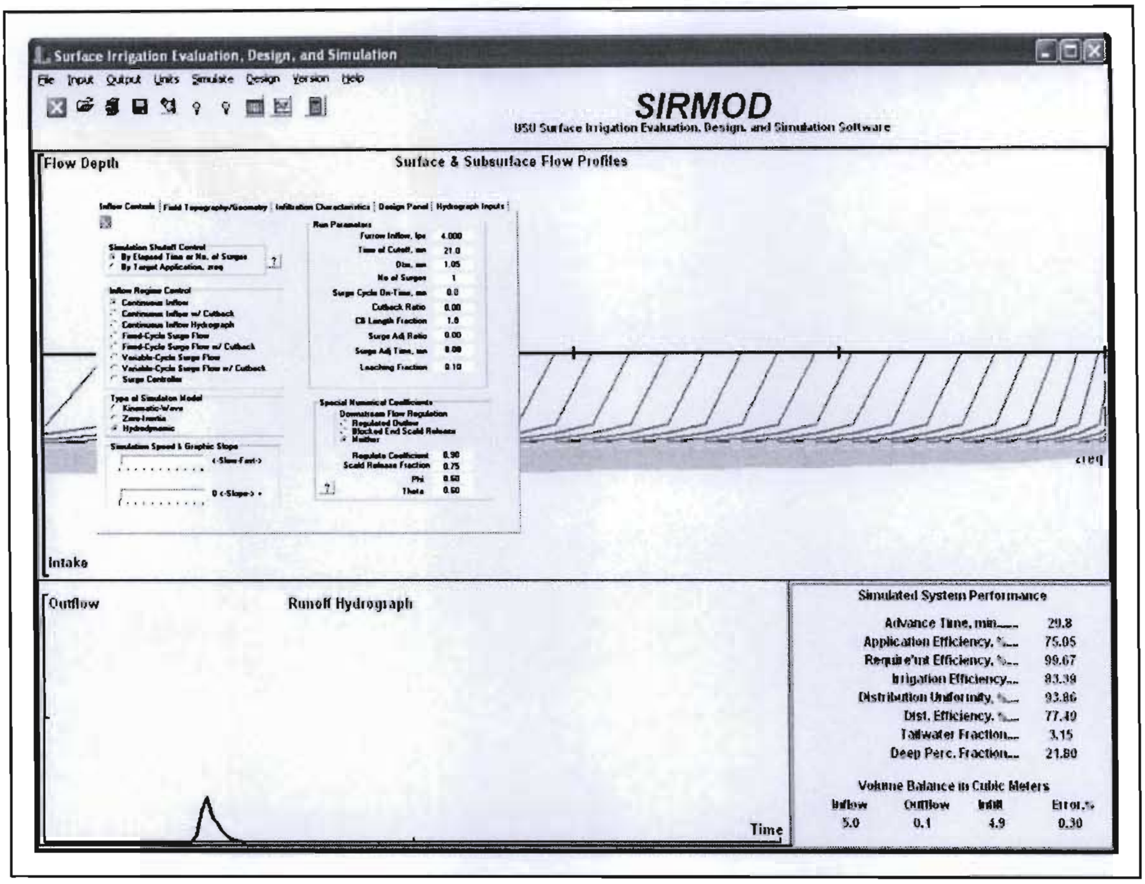


Figure D.2 Example of how the adjusted HVE furrow data changes aspects of the resultant performance values