University of Venda

ASSESSING THE USE OF WETTING FRONT DETECTORS IN WATER MANAGEMENT AT DZINDI SMALL SCALE IRRIGATION SCHEME IN LIMPOPO PROVINCE

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Declaration

I, **Maduwa Khathutshelo**, do hereby declare that this dissertation project submitted to the University of Venda for the fulfilment of Masters' Degree in the Department of Hydrology and Water Resources, School of Environmental Sciences, is my own independent work. This work has not been submitted before to any institution by me, or any other person in fulfilment of requirements for any qualification.

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Signature   Date

Acknowledgement

I give thanks to the Almighty God for bringing me this far. I thank you for your endless mercy and giving me strength, courage and wisdom to carry on with this thesis. The journey was not easy but it was worthy.

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Abstract

Irrigation uses the largest amount of water, estimating to 60 % of the total consumption in South Africa. For this reason, the efficient and reasonable use of water by irrigators is of paramount importance. Thus, this study was carried out to assess the suitability of Wetting Front Detectors (WFDs) in improving water management. The study involved an on-farm survey; field installations; testing of WFD technology on selected plots within the scheme; identification of the crops grown; documentation of the current water supply and documentation of the challenges faced by farmers in relation to irrigation. These were carried out to identify the ideal situations in the scheme. Irrigation scheduling helps farmers to know when to irrigate and amount of water required supplying for crop need. The study presented WFD, as a means of improving irrigation efficiency. The WFD is a simple tool that helps farmers to identify what is occurring around the root zone. Four plots with a representative farmer in each of the plot were identified in four Blocks (Block 1 farmer 1, Block 1 farmer 2; Block 2 farmer 1; Block 3 farmer 1 and Block 4 farmer 1). On-farm experiment of the WFD was carried out. However, with Block 4 farmer 1, insufficient data was collected due to absence of LongStop equipment. This also involved field installation, observation and measurements of the LongStops (LSs) and FullStops (FSs) WFDs at placement depth of 30 cm, 45 cm and 60 cm. The efficiency of an irrigation system depends on different performance indicators including Irrigation Efficiency (IE), Conveyance Efficiency (CE), Application Efficiency (AE), Storage Efficiency (SE), Distribution Uniformity (DU) and Coefficient uniformity (CU). In this study, attention was focused only on DU; CU and SE, as represented by water moisture availability. All the DU for all plots in blocks were below the standard DU of furrow, which is 65%. Farmer 2, in Block 1, had a higher DU and CU, which were 60% and 68%, respectively- considered closer to the standard DU value. For the other farmers, their DU and CU prior to irrigation were very low, which indicated that there was uneven distribution of water in these plots. The poor DU in Block 1 farmer 1, indicated by the uneven infiltrated water, resulted in excessive watering. Analysing the WFD showed that farmers were performed well in all the Blocks, except for farmer 1 in Block 1. Average soil moisture content result indicated high water loss through deep percolation. The highest volumes of water recorded before and after irrigation were 131 ml and 159 ml, respectively, for LS90 placed at a depth of 90 cm in Block 2 farmer 1. High volumes of water were collected in Block 1 farmer 2, Block 2 farmer 1 and Block 3 farmer 1 before and after irrigation. The result showed that, the more placement depth down the soil profile, the more accumulation of water in the LSs. Therefore, it was recommended that farmers continue to use the WFD as a tool for irrigation efficiency. However, there is need for improvement and capacity building in using the tool.

Keywords: irrigation scheduling; water use efficiency; wetting front detector; small holder irrigation scheme; on farm water management

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LIST OF ABBREVIATIONS AND ACRONYMS

AD = Lower-quarter Adequacy
AE = Application Efficiency
CE = Conveyance Efficiency
cm = Centimetre
CPA = Communal Property Association
CU = Coefficient Uniformity
DU = Distribution Uniformity
FAO = Food and Agricultural Organization
FS = FullStop™
ha = Hectare
HSRC = Human Sciences Research Council
ICID = International Commission on Irrigation and Drainage
ICUC = Irrigation Consumptive Use Coefficient
IS = Irrigation Sagacity
kPa = kilo Pascal
LS = LongStop™
m = metre
m^3 = cubic meter
ml = millilitre
mm = millimetre
PAE = Potential Application Efficiency
RESIS = Revitalisation of Smallholder Irrigation Schemes
RO = Runoff
RPF = Resource Poor Farmers
SE = Storage Efficiency
SI = Surge Irrigation
SMD = Soil Moisture Deficit
TUT = Tshwane University of Technology
Univen = University of Venda
WFD = Wetting Front Detector
WRC = Water Research Commission
WUA = Water User Association
WUI = Water Use Index
WUE = Water Use Efficiency
WV = Water Volume

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CHAPTER ONE: INTRODUCTION

1.0 Background

Irrigation agriculture is the largest user of water in South Africa. The use is estimated at 60 % of the total water consumption (DWAF, 2002). For this reason, the efficient and prudent use of water by irrigators is of paramount importance. The National Water Act, No. 36 of 1998, (NWA) recognizes the need for the equitable use of water as well as the provision of basic water requirements for the "ecological reserve" (NWA, 1998). The reserve includes basic human consumption and the minimum requirements to ensure the protection of the ecology. In line with the NWA (1998), the water use by irrigators has to be authorised and registered, with a restriction or a limit on the water allocation. Thus to ensure profitability, the irrigators will have to pay particular attention to the performance of their irrigation systems.

Smallholder irrigation schemes in South Africa comprises of irrigation projects that are larger than 5 ha in size and that were either established in the former homelands or initiated in resource-poor areas by previously disadvantaged or black farmers or agencies assisting in scheme development (Gibb, 2004). In 1996, South Africa had about 1.3 million ha under irrigation, of which 0.1 million ha was in the hands of smallholders (Backeberg, 2006). Smallholder irrigators have been categorized into four groups, namely: farmers on irrigation schemes; independent irrigation farmers; community gardeners and home gardeners (De Lange, 1994).

The vagaries of rain-fed agriculture are well known such as water scarcity (dry droughts) and very wet periods (floods) have contributed to crop failure worldwide including in South Africa (Lévite et al., 2003). Thus to ensure a successful crop production, there is a need to practice irrigation by utilising both surface and groundwater irrigation. Tandem with this major water usage, irrigated agriculture is also the largest water wastage main due to inefficient application of irrigation water such as furrow irrigation (Ward and Pulido-Velazquez, 2008). Thus there is a need to use water efficiently by adopting water use technologies such as drip irrigation. This is beneficial since the conserved water may be allocated to other incoming/emerging farmers without the need of construction of new dams (Lévite et al., 2003), improved environmental water flows and sustain irrigation in arid regions (Botha et al., 2003).

1.1 ECOLOGICAL SETTING OF THE AREA

1.1.1 Location of the study area

Dzindi irrigation scheme is a small irrigation scheme located in the village of Itsani, which is situated 10 km west from Thohoyandou Town in the Limpopo Province of South Africa (Figure

1). The other adjacent villages to the scheme include Shayandima, Tshisaulu, Lwamondo and Manamani. The scheme occupies a total command area of 135.6 ha which is subdivided into 106 plots of 1.28 ha each. The geographical location of Dzindi irrigation scheme is S 23^0 01’ 1.3’’ and E 30^0 26’ 10.5’’, in the A91E quaternary catchment of the Levubu/ Letaba Water Management area.

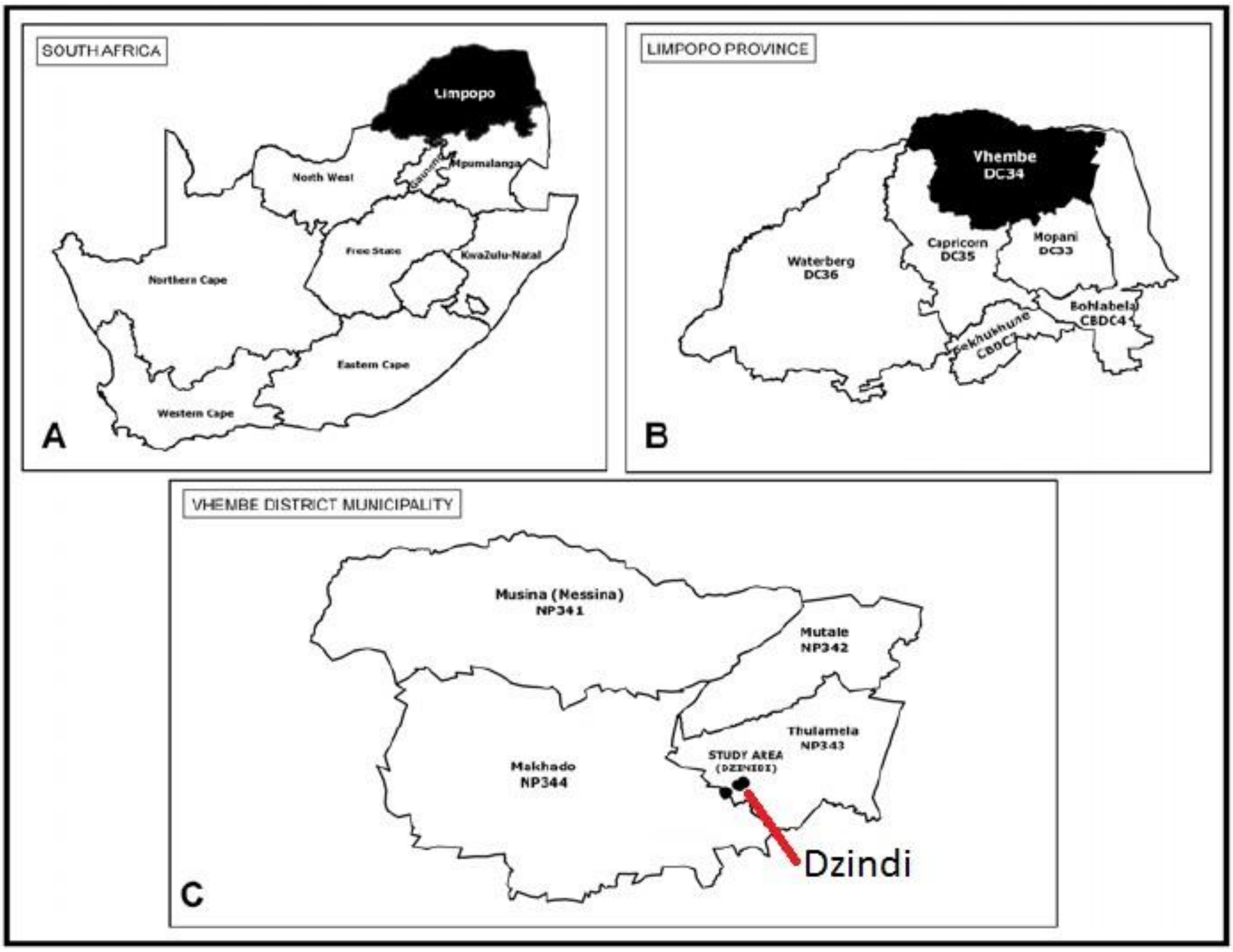


Figure 1: Google Earth Image showing the Dzindi irrigation scheme (Van Averbeke, 2008)

1.1.2 Topography

Dzindi irrigation scheme is bordered to the North by the Soutpansberg, with steep slopes and peaks that rise to 2000 m in some places. Dzindi irrigation scheme itself lies at about 550 m above sea level in a plateau with gently to moderately undulating landscape which is found south of the Soutpansberg Mountains (Acocks, 1998).

1.1.3Vegetation

According to Acocks (1998), Dzindi is located in a vegetation unit called the North-eastern Mountain Sourveld which is found along the southern edge of the Soutpansberg Mountain range.

The dominant species are *Themeda triandra*, *Londetia simplex* and *Rendlia altera* (van Averbeke et al., 2014).

1.1.4The climate in the area

Dzindi irrigation scheme experiences semi-arid and subtropical climate (van Averbeke et al., 2004). It receives an annual rainfall of 697 mm which is similar to that of Thohoyandou. The nearest weather station is Lwamondo. Most of the rains fall during the summer season and stretches from October to March with high evaporation rates (Figure 3) and hence the need for irrigation to compensate for the variation in rainfall and water availability. During summer the area tends to be quite hot and humid becoming mild during the winter season with sunshine of between 6 and 8 hours per day (Figures 4 and 5). Thus the high temperatures contribute to the high evaporation rates.

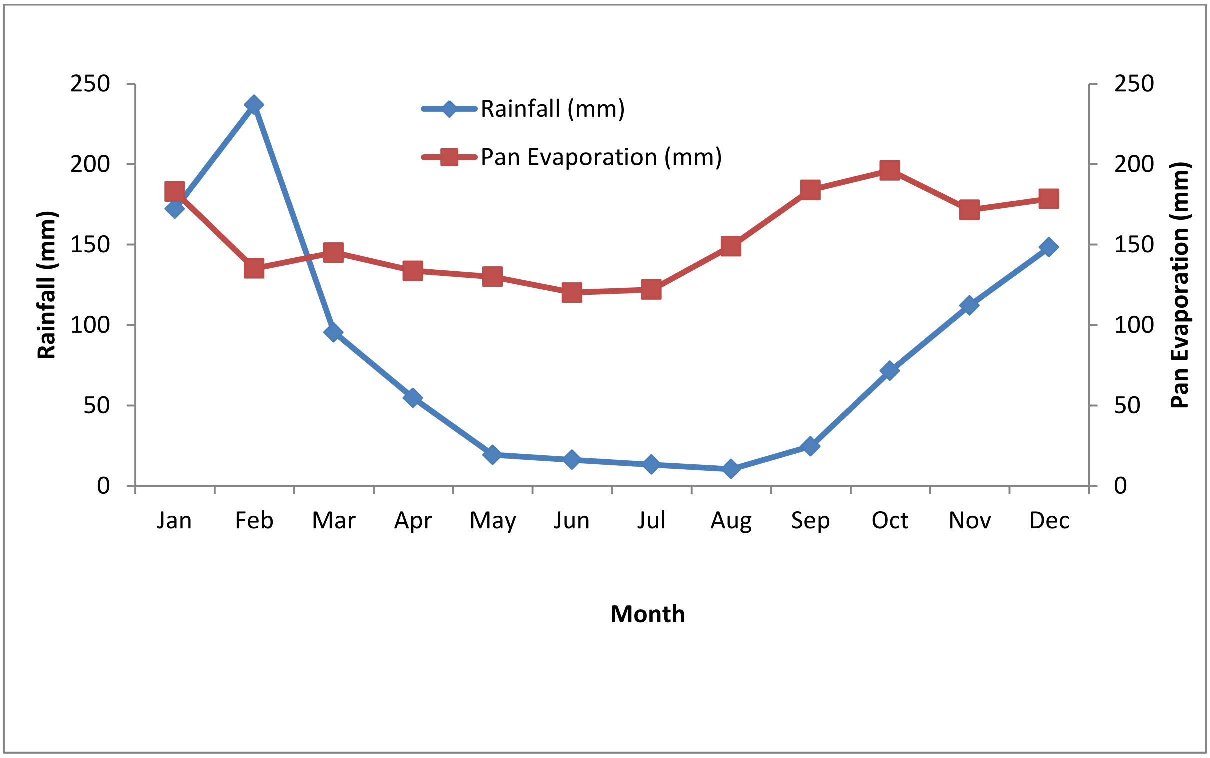


Figure 2: Rainfall and Pan Evaporation in the study area(AGIS, 2004)

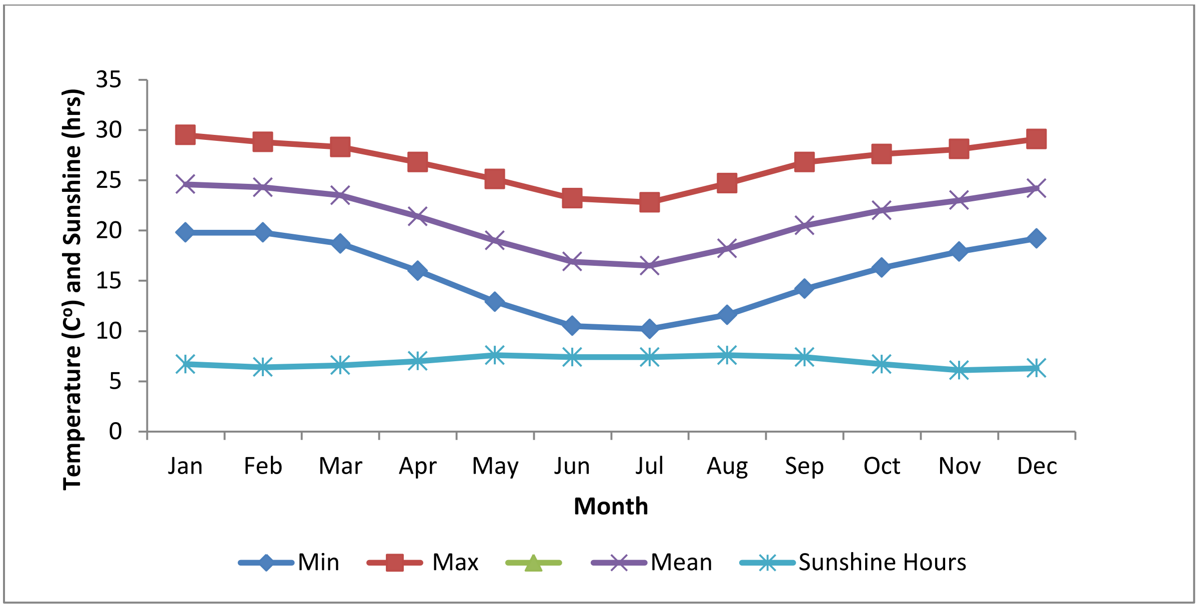


Figure 3**:** Temperature and hours of sunshine in the study area(AGIS, 2004)

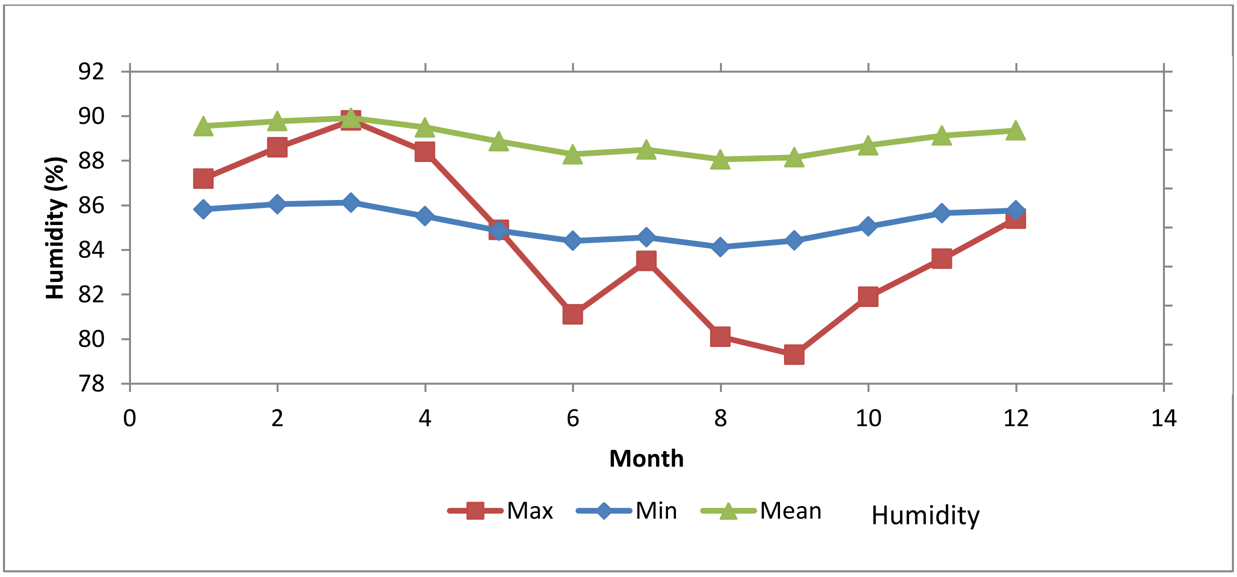


Figure 4**:** Humidity in the study area (AGIS, 2004)

The annual evaporation rate is 1848 mm which exceeds annual rainfall rate of 980 mm (AGIS, 2004). This implies that irrigation requirements in the study are expected to be high and hence there is a need for high water use efficiency. The lowest monthly mean temperatures of about 10.2^{o}C are experienced in July while the monthly maximum temperatures of 29.5^{o}C are experienced in January.

1.1.5 Land use of the study area

The area is mainly used for agriculture (both subsistence and commercial), and also for residential purpose. The surrounding community also practices fishing in Dzindi River which supplies irrigation water to the scheme.

1.1.6 Geology of the area

Lithostratigraphically, Dzindi is situated on the Goudplaats Gneiss belt formation, which is the oldest belt in the area and the base of the Swazian (Brandi, 1987). It is situated near the north-western edge of the unit.

The rock in this belt consists of light and dark grey biotite gneiss and migmatite. Mineralogically, the rocks in this belt consist of Oligoclase, quartz, biotite and hornblende. Before the Dzindi River reaches the scheme, it flows through the rocks of the Sibasa Formation, which form part of the Soutpansberg Group and the rocks occur west of Dzindi River.

The Sibasa Formation is a volcanic succession with sparse intercalations of quartzite, shale and tuff. Its thickness is estimated to be around 2000m. The lavas are blackish or greenish black in colour and consist of altered pyroxene and plagioclase with minor amounts of olivine and opaque minerals. The ground mass is often intensely epidotised and chloritised (Brandi, 1987).

1.1.7 Pedology

A two week soil survey was conducted by Murray (1951) after the establishment of the Dzindi Irrigation. Four main soil types in the area were identified and classified as follows: reddish brown clays, grey sands, grey clays and alluvium. The reddish brown clays in the final analysis were suitable for irrigation. According to Van Averbeke et al., 2004, they classified the soil in Block 2 as soil unit B on the soil map which consisted of soils with impeded drainage.

1.1.8 Water quality and quantity

From a study carried out on the impacts of agricultural practices on Dzindi River by Maduwa (2004), it was shown that the water quality of Dzindi River was moderately impacted due to nutrients from fertilizers applied by farmers who cultivate on the mountainous area of Lwamondo. The microbiological analysis indicated that the Dzindi River water was contaminated (Table 1). During the rainy season, the total coliforms and faecal coliforms counts were high. This was due to the people of the surrounding area who sometimes use the bushes as toilets. The other reason was that animal waste from domestic animals such as donkeys, goats, cattle and dogs are washed into Dzindi River after a rainy event.

Table 1: The microbiological analysis of Dzindi River in May 2003 (Maduwa, 2004)

Sampling points	**Total coliforms**	**Faecal coliforms**	**Faecal streptococci**	**Heterotrophic organisms**				
				0	10^{-1}	10^{-2}	10^{-3}	10^{-4}
VhaVenda Bricks	67	14	1	>300	77	16	8	2
Riverside Zion Christian Church	7	3	1	59	13	2	1	0
Dzindi Fisheries	54	1	2	276	45	2	2	1
Dzindi bridge	72	12	17	144	21	4	1	2

The studies of Van der Stoep and Nthai (2005) and Van Averbeke, (2008) indicated that there is ample water for irrigation in the Dzindi weir. Van der Stoep and Nthai (2005) carried out a study evaluating the water distribution system of the Dzindi irrigation scheme, South Africa. The study showed that: only 18% of the water that was diverted at the weir was required at field level by the actual planted crops based on climatic requirements; approximately 85% of the water diverted at the weir reached the secondary canals leading to the irrigated areas (therefore the losses were 15% of the inflow); of the 15% losses, 5.8% can be directly linked to evaporation and seepage losses, while 9.2% unaccounted for; the losses that occur in the system are mainly at block level and largely due to high return flows (including losses in the secondary canals) and it was estimated that between 50 and 70% of the water that reached the secondary canals is return flow and not used for irrigation. Thus this clearly showed that there was inefficient application of irrigation water and there is a need to improve the water management at farm level.

1.2 Motivation for the study

Farmers at Dzindi irrigation scheme do not have a way of determining when to irrigate and how much is required. Rather, they only irrigate when time is in line with the irrigation roster. Such a system does not pay attention as to how much water is available after a rain event.

If there was a way of irrigation scheduling in place, it would allow farmers to give each other a chance to irrigate based on water needs than the roster. Under the current practices, there is likely to be over-irrigation or under-irrigation, leading to reduced yields or high input rate as a result of leached nutrients. The field of irrigation scheduling is complex in terms of expertise required and equipment. Therefore, important as it is, it may not be feasible to acquire equipment for irrigation at Dzindi for the subdivision of 106 plots due to economy of scale of farming.

Stirzaker et al. (2004) developed a technology for use by small-scale farmers in irrigation scheduling called the Wetting Front Detector (WFD). The device consists of a funnel that is buried at the rooting depth of crops. When the moisture content is high, after irrigation, a protrusion pops up when pushed by water accumulating in the funnel, and when it is dry, it disappears (Figure 14). Such a device is not expensive to acquire and requires no literacy to operate. Therefore, the device could be suitable for use at Dzindi.

1.3 Justification of the problem

Water use efficiency in irrigation is important since it increases productive use of water by growing more crops per drop thus improving food security. If the technology at hand is tested and it proves suitable, farmers will be encouraged to adopt it. The benefit of such adoption is saving on water use and avoiding over-irrigation and its negative implications to crop productivity. Should the technology not be best suited to the local conditions, then the study will make recommendations as to the additional research work required to have a tool for irrigation scheduling at Dzindi and other small scale irrigation schemes of a similar setting. Thus at farm level, the study provides insights into the strategies adopted by irrigation farmers in managing water for efficient and sustainable uses.

1.4 Study objectives

The objective of this study was to test the suitability of the irrigation technology, Wetting Front Detectors ‘on the farm’ as a means to improve irrigation scheduling at Dzindi irrigation scheme. The specific objectives were: 1) to identify the crops that are grown in Dzindi irrigation scheme; 2) to document the challenges that are faced by the irrigation farmers; 3) to provide a detailed description of Dzindi irrigation farm layout scheme; 4) to document the current water supply system in Dzindi irrigation scheme and 5) to detail the current water scheduling at Dzindi irrigation scheme.

1.5 Hypothesis

The use of Wetting Front Detector improves the efficiency of irrigation among farmers with low technical know-how of water supply to field crops.

CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

Irrigation efficiency is a banner term describing a number of irrigation performance criteria. In order to understand the factors that influence irrigation efficiency, the definitions of the various efficiency terms are needed and the relationship between these and other performance criteria need to be understood. Bos and Nugteren (1990) and Wolters (1992) evaluated irrigation systems from around the world and found that the average application efficiency was less than 70%. An average application efficiency of 53% was observed for furrow irrigation. These averages are well below the design norms used in practice and since the application efficiency is important for the design of irrigation systems, the relationship between uniformity and efficiency needs to be understood to ensure that farmers receive an adequate allocation of water.

In order to estimate the gross amount of irrigation water required, the performance of an irrigation system has to be quantified. This is obtained by using performance criteria to describe the irrigation system. To ensure standardization of these criteria, the definitions need to be clearly stated and the factors that affect these terms need to be understood. In the past there has been confusion over the definitions of irrigation performance criteria. The terms, such as irrigation efficiency, application efficiency and distribution uniformity, have been given different definitions by various evaluators and thus a comparison between different irrigation systems has not always been possible (Wolters, 1992; Burt et al., 1997; Rogers et al., 1997). Therefore, a standard definition of performance criteria was required to enable comparison of irrigation systems. In an attempt to accomplish this, a Task Committee of the American Society of Civil Engineers (ASCE) set about redefining irrigation performance criteria so that they could be used as industry standards and this addresses any confusion in the definitions previously used (ASAE, 1978). This collaborative effort is contained in Burt et al. (1997) and has become the new industry standard on the correct definitions of irrigation performance criteria.

An irrigation efficiency, defined as the ratio of water beneficially used to water applied less change in storage, of 80% does not imply that 20% of the water used is available for conservation. Therefore, the fate of water from an irrigation event needs to be ascertained in order to determine the amount of water that could be conserved (Burt et al., 1997). Since not all losses from irrigation events are recoverable or avoidable, the use of irrigation sagacity as a performance measure gives a better representation of the amount of water available for conservation. Irrigation sagacity includes reasonable uses and is defined as the ratio of water beneficially or reasonably used to water applied less change in storage (Solomon and Burt, 1999). Once the performance and variability of an irrigation system have been quantified, they need to be included into the calculation of the gross irrigation water requirement.

Added to technical efficiency is the complication of beneficial use of water. The National Water Act (NWA, 1998) calls for “efficient and beneficial use of water in the public interest”. Therefore, the implications of technical efficiency will have to be evaluated in economic and social contexts to ensure that the water use is beneficial.

In this document the definitions of performance criteria will be investigated. Of these criteria, particular attention will be paid to the distribution uniformity of an irrigation system, as it is one of the important factors that affect irrigation efficiency. The chapters on definitions are followed by a chapter on the findings of initial workshops held to gain consensus on efficiency terms. Finally, the benefits that can be accrued from improved efficiency, and published efficiency results are presented.

The partitioning of irrigation water into various categories is required to calculate the performance criteria for an irrigation system.

2.2 Partitioning of Irrigation Water

The water balance of the irrigation event needs to be clearly understood and the fates of fractions of the water balance need to be determined in order to evaluate an irrigation system. The amount of water distributed to the crop, the amount of recoverable water, the degree of deep percolation, and the amount of surface runoff need to be quantified or estimated for the calculation of irrigation performance criteria. Fractions of the irrigation water balance can be lumped together into categories, such as beneficial, recoverable, reasonable, required, and useful to estimate performance (Burt et al., 1997). The partitioning of irrigation water, which allows one to calculate irrigation performance criteria, is discussed in the following sections.

2.2.1 Water Balance in an Irrigation Region

The various components of the water balance in an irrigation region, with defined boundaries and for a specific time interval, are described in Figure 5. The specification of boundaries plays an important role in the determination of irrigation performance criteria. The region under consideration for the irrigation water balance is in fact a volume and not just surface area. For example, the plant canopy can form the top boundary and the bottom of the root zone can form the lower boundary. The performance of an irrigation systems is measured by evaluation the components entering and leaving the boundary system (Burt et al., 1997).

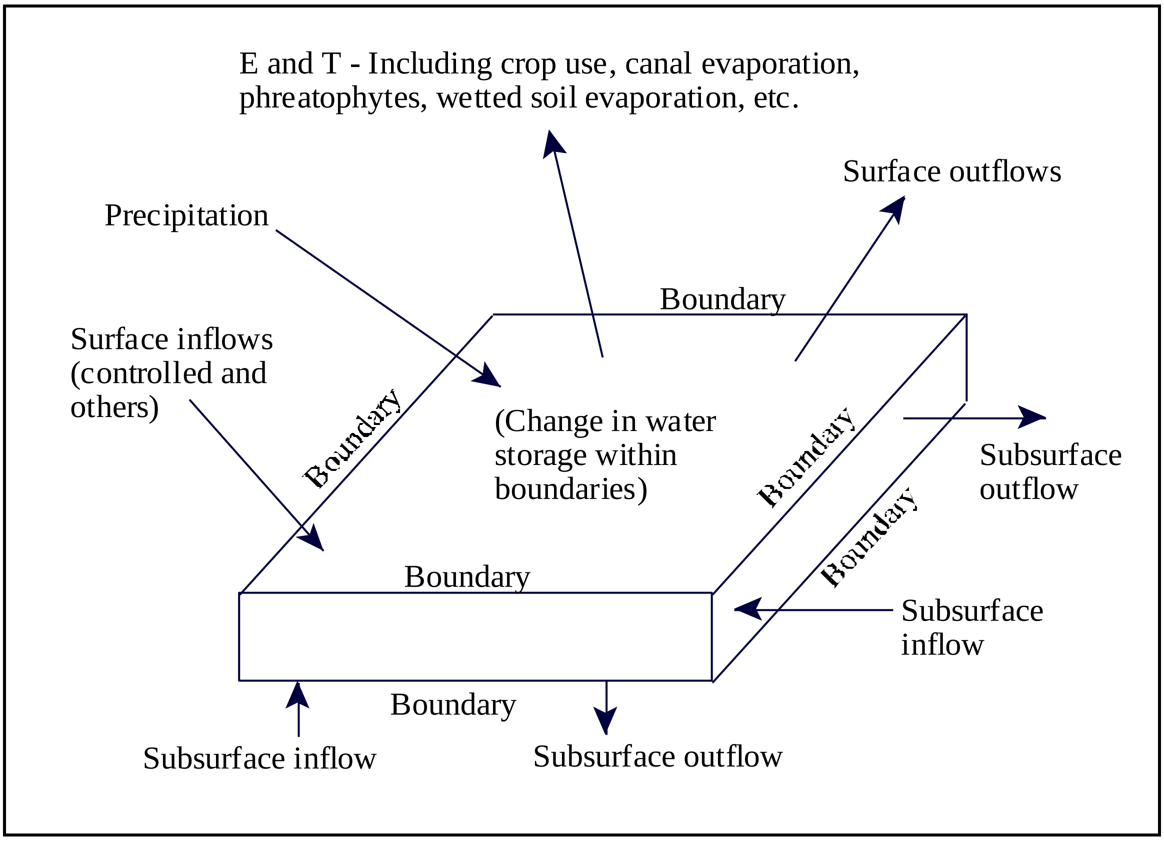


Figure 5**:** Components of a simplified water balance within defined boundaries for specified time interval (Burt et al., 1997)

The definitions of the components of the water balance, as indicated on Figure 5, for use in irrigation system evaluations are evaporation, transpiration, evapotranspiration, crop evapotranspiration, infiltration, deep percolation and runoff.

Evaporation is the transformation of liquid water to gaseous phase (vapour) with input of heating source such as the sun. The rate of evaporation is a function of climatic variables, heat, surface area and soil properties (Burt et al., 1997).Transpiration is the evaporation of water from the surface of plants into the atmosphere. Transpiration is influenced by plant physiology and micro-climate (Burt et al., 1997). Evapotranspiration (ET) is a process that involves water evaporation from the soil and transpiration is water evaporating from surface of plants. Evapotranspiration is influenced by soil texture, type of crop and canopy, irrigation and climatic conditions (Burt et al., 1997). Crop evapotranspiration (ETc) is the evaporation and transpiration of crops in a defined crop field. Crop evapotranspiration is a function of irrigation methods and their scheduling to maintain wet or dry conditions in the crop field (Burt et al., 1997). Infiltration is the water entering the soil and enters the plant root zone. Some of water is temporary stored in the root zone and becomes available to the plant (Burt et al., 1997). Deep percolation is water entering the soil matrix and going beyond the plant root zone and thus is unavailable to the plant (Burt et al., 1997). Runoff (RO) is water moving away from the boundary either on the surface and or sub-surface (groundwater movement) and the water is unavailable to the crop (Burt et al., 1997).

2.2.2 Partitioning of applied irrigation water by availability for recovery

The amount of applied irrigation water that is available for recovery depends on whether the water was consumed or not. Consumptive and non-consumptive uses of irrigation water can be defined as follows:

- Consumptive uses: Irrigation water that ends up in the atmosphere, through evaporation and transpiration, or in the harvested plant tissue, is considered irrecoverable (Burt et al., 1997).
- Non-consumptive uses: These include any other amounts of water that leave the selected region that can be reapplied elsewhere. Runoff, deep percolation and canal spills are considered non-consumptive uses. However, the movement of this water within the boundaries may degrade the quality of the water (Burt et al., 1997).

The partitioning of applied irrigation water can also be conducted on a judgmental basis.

2.2.3 Judgmental partitioning of applied irrigation water

The judgmental partitioning of irrigation water divides the water into categories that include beneficial uses, non-beneficial uses, reasonable uses and unreasonable uses. This method of classification is very subjective and it will therefore vary between evaluators. The beneficial use involves the water uptake by the crop thus leading and contributing to the growth of the crop. Other beneficial uses that add value to crop growth and plant health are: crop evapotranspiration, improving or maintaining soil productivity, such as “salts” leaching, water for climate control, such as frost protection or plant cooling, or seedbed preparation and seed germination, and evapotranspiration from plants beneficial to crop production.

Although the benefits of some of the above can be small, they can make up a considerable portion of the beneficial irrigation water use (Burt et al., 1997). Previously, the only recognized beneficial use of water by a crop was the crop transpiration. Merriam (1999) believes that this should be kept as the only beneficial use of irrigation water and that the other uses should be reclassified. However, Burt et al. (1997) hold the view that the other uses should be included as they do have a beneficial effect on crop production.

Non-beneficial uses involve any water use that is not beneficial. Water uses that fall into this category include (Burt et al., 1997): unnecessary evaporation from a wet soil, excess deep percolation due to non-uniformity of irrigation water application and from excess salt leaching, tail water from irrigations that is not recovered and redistributed, evaporation due to excessively high irrigation frequency, and weed or phreatophyte (ET).

Reasonable water uses are beneficial to the crop as these results in plant growth. However, some water when applied to the crop field may runoff into a wetland. Thus this water is non-beneficial in crop irrigation but is beneficial to the wetland environment and may be considered as non-beneficial but reasonable water (Burt et al., 1997).

Unreasonable uses involve water that is non-beneficial such as the deep water percolation, when water is applied and becomes unavailable to the crop root zone but the water is available to remove excess salts (Burt et al., 1997).Once the partitioning of irrigation water has been determined, the next step is to calculate irrigation performance criteria. The definitions of these criteria are discussed below.

2.3 Definitions of Irrigation Performance Criteria

Performance criteria for evaluating an irrigation system are influenced by the design and management of the irrigation system. Physical properties of a field as well as managerial elements such as scheduling, allowable moisture deficits, and soil moisture deficits at the time of an irrigation event, will have a direct bearing on the calculated performance term for the irrigation system under consideration (Pereira, 1999). For this reason, both design and managerial practices should be taken into consideration when evaluating an irrigation system. This section will address the definition of several irrigation performance indicators including irrigation efficiency, irrigation consumptive use coefficient, irrigation sagacity, distribution uniformity, application efficiency, potential application efficiency, low-quarter adequacy and the coefficient of uniformity. In this chapter, the definitions used by the ASCE Task Committee on

Irrigation and Drainage, in South Africa, and from around the world were presented (ASCE, 1978).

2.3.1 Irrigation efficiency

Irrigation efficiency (IE) can be defined by the following relationship:

$$\mathrm{IE} = \frac{\text{volume of irrigation water beneficiary used}}{\text{volume of irrigation water applied} - \Delta\text{storage of irrigation water}} \mathrm{x}100\% \qquad \text{Equation 1}$$

The denominator in Equation 1 represents the total volume of water that leaves the boundaries but excludes water stored in root zone (Burt et al., 1997). These volumes leave within a specified time, i.e. the interval from just before an irrigation event until just before the next irrigation event. The volume of irrigation water is a sum of crop evapotranspiration, percolation and evaporation. The Δ storage of water becomes zero when water in the boundaries is the same at the start and end of the irrigation period. The irrigation water strictly applies to water that is brought to the crop and excludes rainfall and or contributions from water table (Burt et al., 1997).

The beneficial use term in irrigation efficiency is often improperly defined. Common mistakes are the use of theoretical beneficial uses instead of actual beneficial uses, and the double counting of beneficial uses. An example of double counting is water that is applied for frost protection, which is later available to the crop for evapotranspiration (Burt et al., 1997). Thus care should be exercised when calculating irrigation efficiency. It was noted by Solomon and Burt (1999) that IE is often misinterpreted from the point of view that (100 - IE) % of applied irrigation water can be conserved or reallocated.

2.3.2 Irrigation Consumptive Use Coefficient

Burt et al. (1997) introduced the concept of the irrigation consumptive use coefficient (ICUC).

$$\mathrm{ICUC} = \frac{\text{volume of irrigation water consumptively used}}{\text{volume of irrigation water applied} - \Delta\text{storage of irrigation water}} \mathrm{x}100\% \qquad \text{Equation 2}$$

ICUC can be applied at a field, project, district or farm scale. Water used for salt removal or drainage water may have quality problems that make them unusable. However, this does not mean that they have been consumed, as they can be reused after treatment (Burt et al., 1997).

2.3.3 Irrigation Sagacity

For this purpose, irrigation sagacity (IS) is defined as (Burt et al., 1997):

$$\mathrm{IS} = \frac{\text{volume of irrigation water beneficially and or reasonably used}}{\text{volume of irrigation water applied} - \Delta\text{storage of irrigation water}} \mathrm{x}100\% \qquad \text{Equation 3}$$

Irrigation sagacity (IS) includes a component of IE (beneficial uses) and non-beneficial uses but reasonable uses of water to make the water available to the crop (Burt et al., 1997). The benefits of irrigation water and issues of reasonable water uses are included in the definition of IE in Equation 1. Solomon and Burt (1999) gave the following examples of reasonable losses:

- Losses that cannot be avoided because it would not be economical to prevent them.
- Losses that are the result of technical requirements, such as the evaporation for a reservoir, backwashing of filters for micro irrigation, or spray and evaporation losses from sprinkler systems.
- Losses due to uncertainties, such as soil water capacity, or crop ET since the previous application.
- Losses that contribute to environmental goals and/or requirements.

2.3.4 Distribution Uniformity

In irrigation, the uniformity with which water is applied is as important as how efficiently the applied water was used. When irrigation water is applied haphazard to a field can lead to three scenarios: normal irrigation (uniform), over-irrigation and under-irrigation (non-uniform). It is the last two, over-irrigation and under-irrigation, which may lead water logging (wastage of water, leaching of nutrients, salinization, harming the crop, and growth of weeds). Under-irrigation may lead to less water being available to the crop leading to crop failure. Thus distribution uniformity (DU) is a measure of water that is applied all over the crop field. The average low quarter depth (d_{lq}) in the quarter field that receives lowest amount of water is given as (Burt et al., 1997):

$$d_{lq} = \frac{\text{volume accumulated in 25\% of total area with smallest depths}}{\text{25\% of the total area of elements}} \qquad \text{Equation 4}$$

From this, the low-quarter distribution uniformity, (DU_{lq}), can be defined as:

$$DU_{lq} = \frac{\mathrm{dlq}}{\mathrm{davg}} \qquad \text{Equation 5}$$

$$\mathrm{DUlq} = \frac{\text{average low-quarter depth}}{\text{average depth of water accumulated in all elements}} \qquad \text{Equation 6}$$

where d_{avg} = total volume accumulated in all elements [m^3], divided by the total area of all the elements[m^2], (Burt et al., 1997).

For example, in an orchard a DU = 1.0 may imply that the individual fruit trees may receive the same amount of water even though the elemental area varies (Figure 6). Whereas, in a wheat field with a plant at every point would imply that the whole field receives the same application for a DU = 1.0 (Burt et al., 1997).

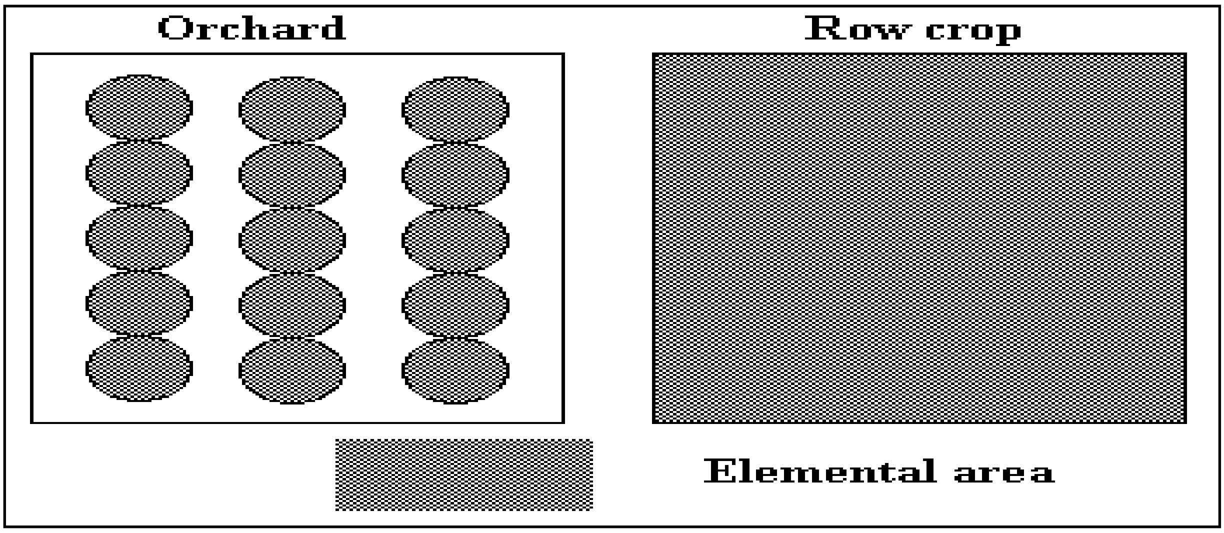


Figure 6: Illustration of elemental area for orchards and row crops (Burt et al., 1997).

Distribution uniformity is not an efficiency term and to emphasize this it should be quoted as a ratio and not a percentage. With irrigation if the DU is high means that the application efficiency (AE) is low (Burt et al., 1997). The above concept of distribution uniformity assumes that a uniform target is desired within the irrigated field. In this study the distribution uniformity (DU) also forms the basis for assessment of water uniformity within the furrow irrigation.

2.3.5 Application Efficiency

The efficiency terms IE, IS and ICUC are difficult to evaluate rapidly and require a detailed quantification of the water balance components. Application efficiency (AE) is based on the concept of meeting a target application depth for an irrigation event. This allows judgmental decisions, such as beneficial or reasonable uses, to be separated from how well the irrigation system is able to meet a target depth of application. The AE term applies only to a single irrigation event. The target depth chosen can be the soil moisture deficit (SMD), or a smaller amount to supplement potential rainfall, or it could contain a desired depth of reclamation water, or it may be a requirement for leaching of salts (Burt et al., 1997). The definition of AE for a single event is thus:

$$\text{AE} = \frac{\text{average depth of irrigation water contributing to target}}{\text{average depth of irrigation water applied}} \text{x}100\% \qquad \text{Equation 7}$$

Implicit in the definition of AE is the assumption that the target depth is uniform across the field and that no time period needs to be specified, as it accounts for a single event only. Since there are some unavoidable evaporation losses in an irrigation event, AE will generally be lower than IE. If the target is equal to the sum of beneficial uses, AE can be used as an estimate of IE (Burt et al., 1997).

2.3.6 Potential Application Efficiency

The potential application efficiency (PAE) is based on stopping the irrigation schedule once target depth (deep percolation) is met and or is visible (Burt et al., 1997). PAE_{lq} is estimated from the minimum values (lower quarter) in the distribution over a specified crop field (Burt et al., 1997):

$$\text{PAElq} = \frac{\text{average depth of irrigation water contributing to target}}{\text{average depth of irrigation water applied such that dlq=target}} \text{x}100\% \qquad \text{Equation 8}$$

The difference in estimation of DU_{lq} and PAE_{lq} is influenced by surface losses, spray drift, runoff and evaporation (Burt et al., 1997):

$$\text{PAE}_{\text{lq}} \approx \text{DU}_{\text{lq}} \text{x} (100 - \%\ \text{surface losses}) \qquad \text{Equation 9}$$

Using equation 9, the estimate for gross irrigation water is possible (Burt et al., 1997):

$$\text{Gross average depth to apply} = \text{Target depth x} \frac{100}{\text{PAE}_{\text{lq}}} \qquad \text{Equation 10}$$

2.3.7 Low-quarter Adequacy

The adequacy is the target depth (minimum) for irrigation definition of AE based on the requirement for all beneficial uses, the low-quarter adequacy (AD_{lq}) is given by (Burt et al., 1997):

$$AD_{lq} = \frac{d_{lq}}{d_{req}} \qquad \text{Equation 11}$$

Where d_{req}= the required depth for all beneficial uses [mm].

With this definition, an $AD_{lq} < 1$ indicates under-irrigation and $AD_{lq} > 1$ indicates over-irrigation. When $AD_{lq} = 1$, then AE = PAE_{lq} and the surface losses match potential values. This definition of adequacy differs from other definitions that are based on the percentage of area adequately irrigated (Burt et al., 1997).

2.3.8 Coefficient of Uniformity

The Christiansen coefficient of uniformity (CU) is widely and acceptable used term used to define uniformity (Christiansen, 1942; Zoldoske et al., 1994) and is expressed as (ASAE, 1993):

$$CU = 100\left(1 - \left(\sum_{s=1}^{n}\left|D_s - \overline{D}\right| \Big/ \sum_{s=1}^{n} D_s\right)\right) \qquad \text{Equation 12}$$

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

Christiansen's CU was modified by Heermann and Hein (1968) for use under centre pivot irrigation systems. Equation 12 is modified to include a term representing the distance from the centre to the catch can, S_s [m]. The modified Heermann-Hein CU_{HH} equation is given by (ASAE, 1993):

$$CU_{HH} = 100\left(1 - \left(\sum_{s=1}^{n} S_s \left|D_s - \frac{\sum_{s=1}^{n} D_s S_s}{\sum_{s=1}^{n} S_s}\right| \Big/ \sum_{s=1}^{n} D_s S_s\right)\right) \qquad \text{Equation 13}$$

The CU and CU_{HH} have three unique features which affect the interpretation of uniformity data (Zoldoske et al., 1994). The first feature deals with understanding of the absolute difference (deviation) between the measured and mean depth of water application. This may imply that the over- and under-irrigation is treated equally. The second feature is that each deviation linearly proportional to the magnitude of each deviation. The last feature is treating CU as average measure which looks at average absolute data *vis* average application. Thus CU indicates on average how uniform the application depths are and does not give an indication of how bad a particular area may be, or how large the area may be (Zoldoske et al., 1994). In this study Christiansen coefficient of uniformity (CU) also forms the basis for assessment of water uniformity within the furrow irrigation.

2.4 Factors Influencing Distribution Uniformity (DU)

The DU of a system is a function of both design and managerial variables that characterize an irrigation event (Pereira, 1999), with the former being more easily characterized. Factors that influence the uniformity of water application during an irrigation event for hand-move, furrow, micro, moving sprinkler, under-tree sprinkler and high-volume gun sprinkler irrigation are summarized in Tables 2 to 4. The components that affect uniformity will differ between various irrigation types and the factors causing non-uniformity will depend on the characteristics of the irrigation system. The components that affect the uniformity of an irrigation event need to be known for the application of statistical methods to determine a global uniformity of an irrigation system.

A uniform application of water to irrigation is due to better design and management and soil texture. Perrens (1984) and Li (1998) showed lateral water flow in an irrigation system resulted in redistribution of soil moisture thus resulting in uniformity in water application.

Table 2: Examples of components that affect uniformity for hand-move and under-tree sprinkler irrigation systems (Burt et al., 1997).

Uniformity component	Factors causing non-uniformity
Hand-move sprinkler irrigation systems	
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.
Under-tree irrigation systems	
Same as hand-move sprinkler systems, except that the sprinkler overlap non-uniformity around each sprinkler is usually not considered if there is one sprinkler for every two trees.	Tree interference can cause large, non-irrigated areas or segments in some cases.

Table 3**:** Examples of components that affect uniformity for furrow irrigation systems (Burt et al., 1997).

Uniformity component	Factors causing non-uniformity
Furrow irrigation systems	
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 degree of compaction due to tractor tyres and tillage.
Different infiltration characteristics across the field.	• Different soil types. • Soil chemical differences. • Texture differences of soil.
Other opportunity time differences throughout a field.	Non-uniform land preparation.
Differences 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 4: Examples of components that affect uniformity for centre pivot irrigation systems (Burt et al., 1997).

Uniformity component	Factors causing non-uniformity
Centre pivot and lateral move irrigation systems	
Sprinkler (spray head) flow rates not proportional to area served.	• Poorly controlled sprinkler pressures. • Elevation changes. • Pressure regulator differences. • Nozzle plugging and wear.
Sprinkler overlaps non-uniformity between adjacent sprinklers.	• Wind. • System travel speed variations. • Elevation of sprinkler (spray head). • Crop interference. • 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.

2.5 Definitions Currently Used in South Africa

The current definitions used by irrigation designers in South Africa are contained in the Irrigation Design Manual published by Agricultural Research Council - Institute for Agricultural Engineering (van der Merwe, 1996). A graphical representation of the relationship amongst the various efficiency terms is shown in Figure 7. The definitions that are currently used are as follows:

- Transportation efficiency (η_t): [% or fraction]

The ratio of the amount of water that leaves the source to the amount of water that reaches the irrigation dam or draw-off point on the farm boundary.

- Distribution efficiency (η_d): [% or fraction]

The ratio of the amount of water that leaves the irrigation dam or draw-off point on the farm boundary that travels through the irrigation system to the amount of water that leaves the emitters. Losses from the irrigation dam are included here.

- Conveyance efficiency (η_c): [% or fraction]

The ratio of the amount of water that leaves the source to the amount of water that leaves the emitters.

$$\eta_c = \eta_t\eta_d$$

- Application efficiency (η_a): [% or fraction]

The ratio of the amount of water that leaves the emitters of the irrigation system to the amount of water that falls onto the soil surface.

- System efficiency (η_s): [% or fraction]

The efficiency with which water from the irrigation dam or draw-off point on the farm boundary is delivered through the irrigation system to the point where it falls onto the soil surface.

$$\eta_s = \eta_d\eta_a$$

- Storage efficiency (η_o): [% or fraction]

The ratio of the amount of water that falls onto the soil surface and infiltrates into the soil to the amount of water that is stored in the root zone of the plant.

- Field application efficiency (η_f): [% or fraction]

The ratio of the amount of water that leaves the emitters to the amount of water that infiltrates into the soil and becomes available in the root zone of the plants.

$$\eta_f = \eta_a\eta_o$$

- Irrigation efficiency (η_i): [% or fraction]

The ratio of the amount of water that leaves the water source to the amount of water that is available in the root zone of the plant.

$$\eta_i = (\eta_t\eta_d)(\eta_a\eta_o)$$

$$= \eta_c\eta_f$$

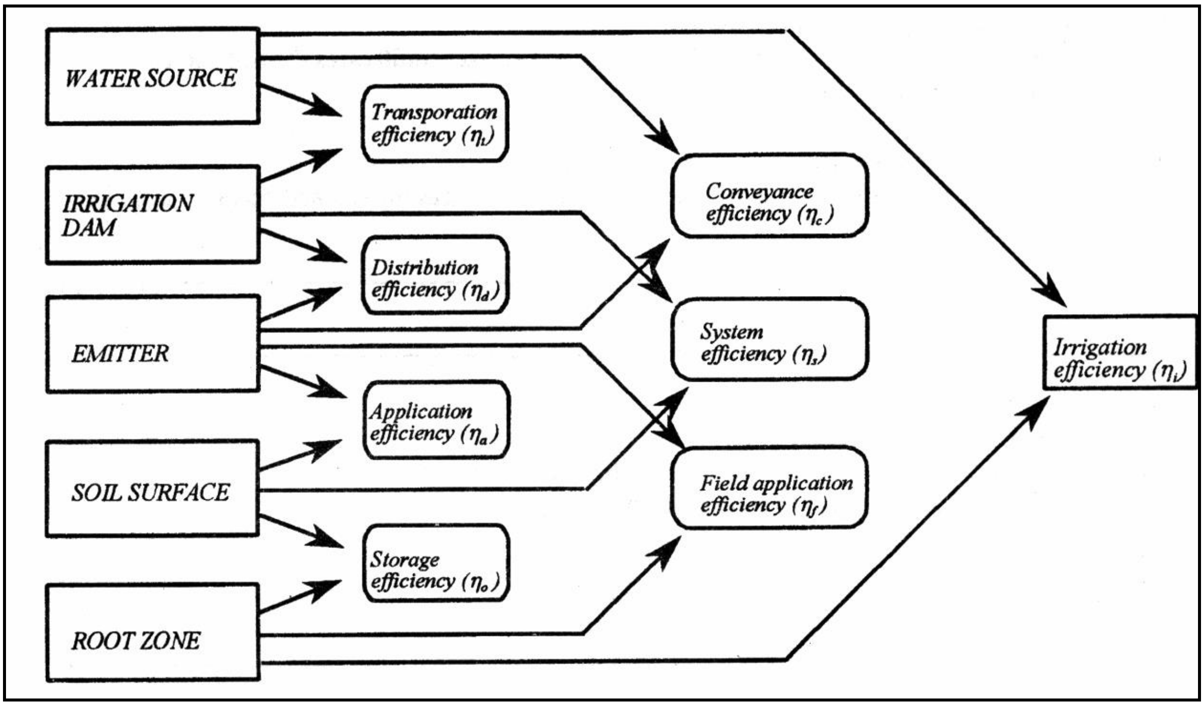


Figure 7**:** The relationship amongst various efficiency concepts (van der Merwe, 1996).

The definitions for efficiency used in soil science in South Africa are as follows (van der Watt and van Rooyen, 1995):

- Irrigation efficiency:

The ratio of water actually consumed by evapotranspiration on a specified area to the amount of water diverted from the source onto the area.

- Application efficiency:

The percentage of water delivered to the field that becomes stored in the root zone and is thus available for crop use.

- Transmission efficiency:

The percentage of the water leaving the source of supply that is delivered to the field.

- Distribution efficiency:

The distribution efficiency is the spreading of irrigation water to the root zone over the irrigated field.

- Replenishment efficiency:

The ratio of the amount of water that enters the root zone to the amount of water required to enter the root zone.

From the above it can be seen that South African soil Scientist and irrigation designers use similar ratios which have different names.

2.6 Definitions Used in Other Countries

Land and Water Australia have completed a two stage, four year project to gain acceptance on efficiency, uniformity and water use efficiency terms. The definitions adopted by the Australian irrigation sector are summarised in Figure 8 (Purcell and Currey, 2003). For example, application efficiency is defined as the water retained in the soil (directly available to crop) divided by the water applied to the crop (Figure 9). In a similar fashion, conveyance efficiency is defined as the water delivered to the farm gate divided by water released from the reservoir. Figure 8 shows how the various efficiencies in a scheme are related to each other. Thus, the overall project efficiency can be calculated as the product of the application, conveyance and field canal/ conduit efficiencies (Purcell and Currey, 2003). A more comprehensive discussion of how the Australian irrigation sector will use this framework is presented in Fairweather et al. (2003). Presented in this document are worked examples from case studies conducted in Australia. The presentation of these case studies is beyond the scope of this review. Further examples of efficiency definitions used around the world are shown in Table 5. All the definitions for a specific efficiency usually incorporate the same portions of the water balance with subtle differences in how the water balance is partitioned.

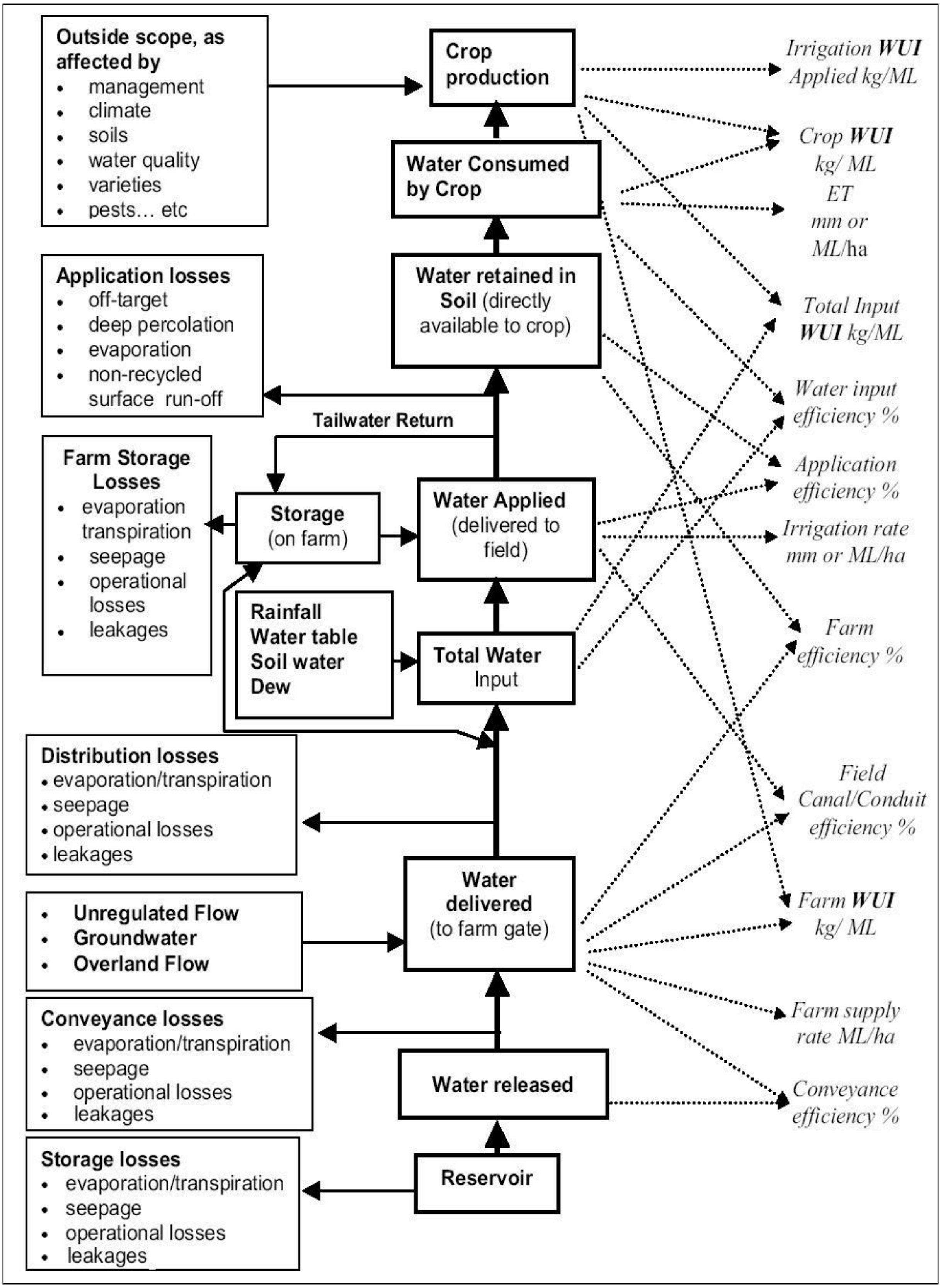


Figure 8: Framework for Water Use Efficiency (Purcell and Currey, 2003).

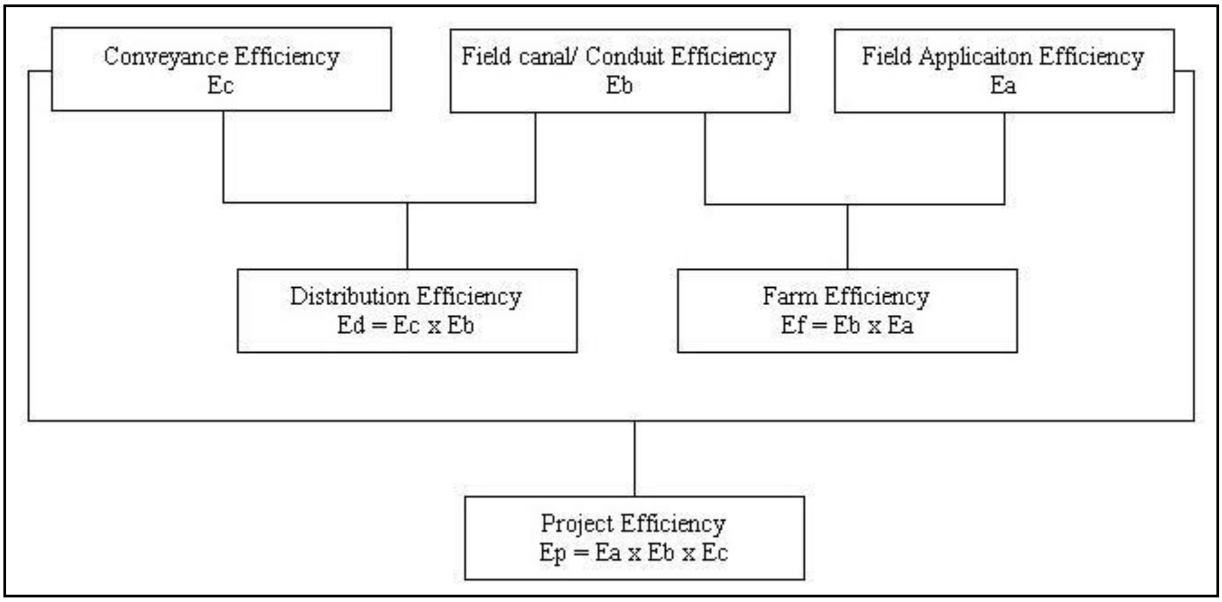


Figure 9**:** Irrigation system efficiency (Purcell and Currey, 2003).

Table 5**:** Examples of recent definitions for various efficiency terms.

Term	Rogers et al., 1997	IAA, 1998	Smith, 2000
Overall Project Efficiency	Water used beneficially/ Water delivered to field	Crop water use/ Total inflow into supply system	Root zone storage/ Main system supply
Conveyance Efficiency	Water delivered to field/ Water diverted from source	Total overflow from supply system Total inflow into supply system	Farm supply/ Main system supply
Distribution Efficiency	-	Water delivered to irrigation field/ Total inflow into supply system	Field application/ Farm supply
Field Application efficiency	Water available for use by the crop/ Water delivered to field	Crop water use/ Water delivered to irrigation field	Root zone storage/ Field application

2.7 Definitions of Water Use Efficiency

The water use efficiency (WUE) of a crop can be expressed in a biological context, as the transpiration ratio, or as an index of a production performance, such as a mass per volume water used. As with irrigation efficiency, there are many interpretations of this term. A few of these definitions will be presented.

Howell (2002) gives the following definitions for various water use efficiencies:

$$WUE_t = \frac{\text{Dry matter yield}}{\text{Transpiration}} \frac{[\text{kg}]}{[\text{mm}]}$$ Equation 14

$$WUE_d = \frac{\text{Dry matter yield}}{\text{Evapotranspiration}} \frac{[\text{kg}]}{[\text{mm}]}$$ Equation 15

$$WUE_y = \frac{\text{Economic yield (eg. grain, lint, etc.)}}{\text{Transpiration}} \frac{[\text{kg}]}{[\text{mm}]}$$ Equation 16

$$WUE = \frac{\text{Economic yield}}{\text{Evapotranspiration}} \frac{[\text{kg}]}{[\text{mm}]}$$ Equation 17

$$\text{Irrigation WUE} = \frac{(\text{Yield with irrigation amount } I_i - \text{Yield without irrigation})}{\text{Irrigation amount } I_i - \text{Irrigation amount } I_o} \frac{[\text{kg}]}{[\text{mm}]}, \text{usually } I_o = 0$$

Equation 18

Purcell and Currey (2003) and Fairweather et al. (2003) use the term water use efficiency to describe the "tool box" of indices of crop water production performance. They prefer using the term Water Use Index to distinguish between efficiencies and measures of crop performance. The various water use indices were shown in the framework diagram in Figure 4.

Smith (2000) defines water use efficiency as "the fraction of water effectively stored in the root zone that is used for crop transpiration". This can be represented as follows:

$$\text{Crop water use efficiency} = cwe = \frac{\text{Transpiration}}{\text{Evapotranspiration}} * \frac{\text{Evapotranspiration}}{\text{Root zone storage}}$$ Equation 19

This is the physiological water use efficiency of the crop. The crop performance to water use is referred to by Smith (2000) as crop water productivity and the definition is given as:

$$\text{Crop water productivity} = cwp = \frac{\text{Yield}}{\text{Transpiration}} \frac{[\text{kg}]}{[\text{m}^3]}$$ Equation 20

Smith (2000) defines the water use efficiency of the crop as:

$$\text{Water use efficiency} = \frac{\text{Transpiration}}{\text{Total water supplied}},$$ Equation 21

The water productivity as:

$$\text{Water use efficiency} = \frac{\text{Yield}}{\text{Total water supplied}} \frac{[\text{kg}]}{[\text{m}^3]}, \qquad \text{Equation 22}$$

and the economic benefits of water productivity investments as:

$$\text{Rate of return}_{\text{Water productivity investments}} = \frac{\text{Yield} * \text{Market price}}{\text{Water investments} + \text{Agricultural investments}}$$

Equation 23

From the many definitions for the efficiency terms presented in this chapter, it is very apparent that consensus needs to be reached so that all practitioners are talking the same language. Before one can start comparing the performance of systems and schemes, a common basis of comparison is needed. Therefore, a set of definitions that are acceptable to the majority of practitioners will have to be developed or adopted.

Considerable thought will have to be placed into developing a set of water use efficiency indices. The major difficulties with defining WUE terms are to determine what data is available for calculating the terms and how they are going to be used for comparison. If the water use of a high yielding, low quality crop is compared to a lower yielding, but higher quality crop, the water use efficiency of the latter crop will be lower. However, the profitability could be greatly increased due to the higher price it may fetch for the improved quality. Comparing crop production in monetary terms is also complicated due to the effects of the market. Prices can fluctuate depending on the supply and demand for a crop. Also, profitability between two producers of the same crop could be significantly different due to differences in management or marketing. Thus, defining indices to effectively compare water use will depend on many complicated variables.

The next section (2.8) presents the findings of workshops held to try and determine a common set of definitions for efficiency and WUE terms for South Africa.

2.8 Preliminary South African Definitions for Efficiency and Water Use Efficiency

The definitions used for irrigation efficiency in South Africa have been varied and not universally applied. In an effort to standardize the definitions for the South African irrigation industry, a workshop was held at Agricultural Research Council - Institute for Agricultural Engineering, Pretoria, on the 23rd of October 2002 (ARC, 2002).

In conceptualizing the definitions for efficiency, the irrigation system, from source to root zone, was divided into two segments (Figure 10). The separation was determined by identifying the party that was responsible for the management of water resources. The segment from the water source to the farm boundary is the responsibility of the Catchment Management Agency (CMA). The Irrigation Boards and Department of Water Affairs and Forestry (DWAF) presently control this section. The second segment is the responsibility of the farmer and extends from the farm edge to the bottom of the root zone. Six efficiency terms were defined during the workshop proceedings. These are presented in the sections that follow (ARC, 2002).

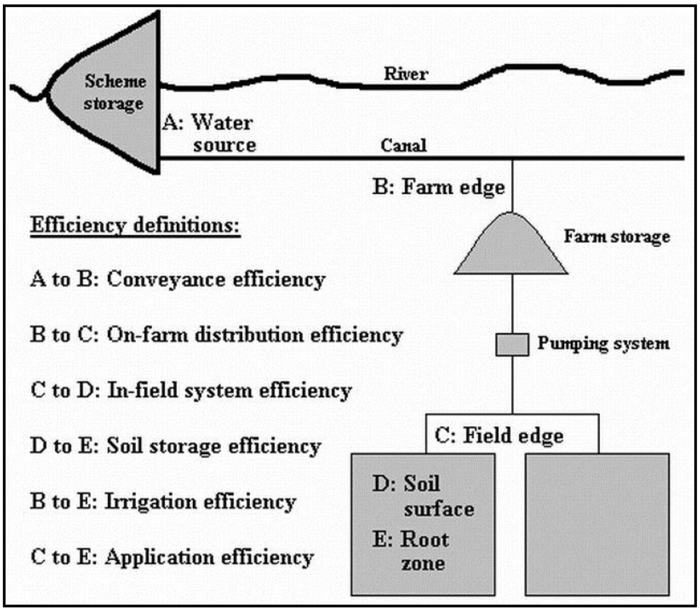


Figure 10**:** Definitions of irrigation efficiency within the irrigation system.

2.8.1 Conveyance efficiency

The conveyance efficiency of the system in Figure 8 can be defined as the ratio of the water that leaves point A to the water that arrives at point B. Losses that can occur between points A and B include (ARC, 2002):

- Canal seepage,
- Canal evaporation, or
- Water extraction by alien or natural vegetation.

Minimizing losses in this portion of the system will be the domain of the CMA.

2.8.2 On-farm distribution efficiency

The on-farm distribution efficiency can be defined as the ratio of the amount of water arriving at the field edge (Point C) to the amount of water arriving at the farm edge (Point B). The losses that could occur in this segment are (ARC, 2002):

- Pipe or canal distribution losses, or
- Seepage and evaporation from on-farm storage dams.

In some schemes, night storage dams are a necessity due to the delivery pattern of water. In such cases, unavoidable losses should be seen as a reasonable use of water.

2.8.3 In-field system efficiency

The in-field distribution efficiency can be defined as the ratio of the amount of water that reaches the soil surface (Point D) to the amount of water delivered to the field edge (Point C). The losses that could occur between Points C and D include (ARC, 2002):

- Spray and evaporation losses from sprinkler and micro spray irrigation systems.
- Surface runoff and evaporation from surface ponding in flood irrigation systems.
- Crop interception losses.

2.8.4 Soil storage efficiency

The soil storage efficiency can be defined as the ratio of the amount of water that is stored in the root zone (Point E) to the amount of water delivered to the soil surface (Point D) (ARC, 2002). Here the main loss will be deep percolation that can be managed by following correct scheduling practices.

2.8.5 Irrigation efficiency

The irrigation efficiency of the whole irrigation system can be defined as the ratio of the amount of water that is stored in the root zone (Point E) to the amount of water delivered to the farm edge (Point B) (ARC, 2002). It can also be represented as the product of the on-farm distribution, in-field storage and soil storage efficiencies.

2.8.6 Application efficiency

The application efficiency can be defined as the ratio of the amount of water stored in the root zone (Point E) to the amount of water delivered to the field edge (Point C) (ARC, 2002). The application efficiency can also be seen as the product of the in-field system and soil storage efficiencies.

2.9 Discussion of Efficiency Terms

The CMA will be responsible for the efficiency of the scheme delivery system. Therefore, the onus is on them to manage and maintain the delivery infrastructure of the scheme to ensure that the required amount of water arrives at the farm edge. Before drastic changes to an irrigation delivery system are implemented, a study of the potential effects of the improvements must be conducted. The losses from the canal system may be a source of water for wetlands or groundwater recharge. Correcting the faults in the system may cause the ecology of the region to be upset, or it may cause groundwater reserves to diminish (ARC, 2002).

From there, the farmer is responsible for the efficiency of the irrigation system. The farmer will have to minimize losses by maintaining and correctly managing his irrigation system (ARC, 2002). Losses that are unreasonable uses of water should be eliminated. However, the economic viability and sustainability of these measures will have to be investigated before they are implemented. The farmer should not be penalized for losses that are unavoidable due to the nature of the irrigation or water delivery system. However, these losses should be kept to an acceptable minimum by following correct design and management procedures. Regular inspection and maintenance of the irrigation system will help identify and minimize losses.

Instead of speaking of root zone storage or surface application, the concept of a target depth should be incorporated into the definitions. This is to account for reasonable water uses that are not considered losses, such as the leaching requirement of the crop. Including this reasonable use with root zone storage will improve the efficiency of the system, without increasing the overall water use. Other reasonable uses such as water used for frost protection, crop cooling, or windbreaks and cover crops, should also be incorporated into the target depth. Including these terms will improve the reported efficiency of the system and indicate more efficient use of water resources.

2.10 Summary of Efficiency Terms

Incorporating the above concepts into the efficiency definitions yields the following definitions:

Conveyance Efficiency (CE): $CE = \frac{\text{water delivered to farm edge}}{\text{water diverted from source}}$

On-farm Distribution Efficiency (ODE):

$$ODE = \frac{\text{amount of water arriving at the field edge} + \text{reasonable storage system losses}}{\text{amount of water delivered to the farm edge}}$$

In-field System Efficiency (ISE):

$$ISE = \frac{\text{amount of water contributing to the target at the soil surface}}{\text{amount of water arriving at the field edge} + \text{reasonable storage system losses}}$$

Soil Storage Efficiency (SSE):

$$\text{SSE} = \frac{\text{amount of water contributing to the target}}{\text{amount of water contributing to the target at the soil surface}}$$

Irrigation Efficiency (IE):

$$\text{IE} = \frac{\text{amount of water contributing to the target}}{\text{amount of water delivered to the farm edge}} = \text{ODE} \cdot \text{ISE} \cdot \text{SSE}$$

Application Efficiency (AE):

$$\text{AE} = \frac{\text{amount of water contributing to the target}}{\text{amount of water delivered to the field edge} + \text{reasonable storage system losses}}$$

AE = ISE · SSE

2.11 Definitions of Water Use Efficiency

In the group discussions at the workshop, the following points were raised (ARC, 2002):

- Transpiration is difficult to determine, therefore evapotranspiration should be used instead.
- The use of economic value of crops as an input into the definition of water use efficiency will yield highly varied results. This is due to the sensitivity that producers may have to disclosing accurate income information, the marketing structures in place and the variability in crop price for the same yield.
- The quality and quantity of the crop should be taken into account in the calculation of WUE. For example, the WUE of export quality crops may be vastly different to lower grades of crops. Hence, the economic return from the export quality produce may be higher than higher yielding, lower quality produce.
- Table grapes and fruit crops cannot be expressed in terms of dry matter yield.
- Only marketable yield should be considered.
- When deciding on definitions and use of WUE terms, it must be decided what is being compared. The definitions will have to account for comparisons between crops, comparisons between farms, comparison between areas, and comparison between agriculture and other water users.
- Some felt that the WUE terms should be area weighted by including per hectare in the units.

There were two schools of thought as to how WUE terms should be determined. The first group derived three definitions for water use efficiency. These were:

$$\text{Physical yield: }\ \text{WUE} = \frac{\text{Yield}}{\text{Evapotranspiration}} = \frac{\text{kg}}{\text{mm}}$$

$$\text{Economic yield: }\ \text{WUE} = \frac{\text{Economic value}}{\text{Evapotranspiration}} = \frac{\text{R}}{\text{mm}}$$

$$\text{Economic yield modified for quality: }\ \text{WUE} = \frac{\text{Economic value and export income}}{\text{Evapotranspiration}} = \frac{\text{kg}}{\text{mm}}$$

In the above equations, the evapotranspiration could be replaced with the total water supplied to include the inefficiencies of supplying the irrigation water (ARC, 2002). For comparing the same crop on the same area, the irrigation WUE should be expressed as yield divided by the total irrigation water use. For comparing different crops in different areas, the WUE should be expressed as the yield (kg or R value) divided by the evapotranspiration after the total water balance and the effective rainfall have been taken into account.

The second group felt that only one definition was useful and reliable. They defined WUE as:

$$\text{WUE} = \frac{\text{Evapotranspiration}}{\text{Total water supplied}}$$

The group suggested that SAPWAT be used to determine crop water requirements for specific areas. Then the management practices could be compared in terms of another water use efficiency term (yield divided by total water supplied as compared to crop water requirements).

The overall efficiency of the irrigation system should take into account all reasonable water uses. These reasonable uses will have to be defined for the South African irrigation industry and will be crop and irrigation system type specific.

From the workshop, it was suggested that the In-field System Efficiency should be used for design purposes when sizing the irrigation system (ARC, 2002). The Application Efficiency should be used for scheduling irrigation applications and the Irrigation Efficiency should be used for water allocation purposes.

By including all reasonable losses into the target amount of irrigation water required, the efficiency of the irrigation system will be improved. This will show that water resources are being effectively and efficiently used. This will also indicate to what extent there may be potential water savings within a system.

Minimum performance levels for the efficiency terms of the different types of irrigation systems will have to be developed. Similarly, norms for design purposes will have to be developed and accepted.

There is still much debate on the definitions of comparable water use efficiency terms, which will require a more in-depth investigation to finalize (ARC, 2002). The main point raised was that care needs to be taken when determining and comparing ratios. There are economic, social, political and strategic considerations that have to be taken into account when assessing the productivity of water use. For this reason, the water use efficiency terms will have to be used in conjunction with other sources of information when assessing the use of water.

Once the definitions of efficiency and water use efficiency have been chosen, the benefits from improved efficiency need to be explored. The following section details some of the benefits of improved efficiency as well as presenting methods of improving efficiency.

2.12 Benefits from improved irrigation efficiency

In order to develop best management practices for improving irrigation efficiency, a better understanding of the performance of current and alternate irrigation practices and their potential effect on water quality is needed (Rice et al., 2001). The lack of suitable information on the performance of irrigation systems in an area can make it difficult to identify improved practices and effectively target irrigation extension programs (Wigginton and Raine, 2000). A major constraint in understanding water use is the difficulty with its measurement and quantification (Burton et al., 1999).

It is relatively easy to make mistakes when evaluating the efficiency of an irrigation system, as not all losses are actually wasted water as they may be reused in the same or downstream systems (Palacios-Vélez, 1994; Perry, 1999). Therefore, improved irrigation efficiency may not be a source of extra water within catchments as inefficient upstream users are often the supply for downstream users (Burt, 1996). Reuse of irrigation water does occur in some regions and the potential for reuse exists in other regions (Solomon and Davidoff, 1999). Legislation that focuses on improving on-farm efficiency may ignore the potential effects of improved irrigation efficiency on the hydrologic system. This is especially important where return flows form a major component of the hydrologic system within a region (Huffaker and Whittlesey, 2000).

There may be internal and external benefits from improvements in irrigation efficiency. Internal benefits may accrue to the individuals that modify their systems to improve efficiency. External benefits will not result in returns for individuals who make an investment in improving efficiency. Therefore, this could be a potential source of failure for improving irrigation efficiency (Heaney et al., 2001).

To improve the efficiency of irrigation systems, the use of irrigation scheduling needs to be promoted and at the same time the design and management of irrigation systems need to be improved (Augier et al., 1996).

2.13 Motivation to Improve Irrigation Efficiency

The main driving forces behind improving irrigation efficiency will be both environmental and economical in nature. The potential environmental benefits and problems will be the driving forces behind improving irrigation efficiency. Some of these benefits are:

a) Reduction in soil and water pollution by minimizing percolation (Zhi, 1996).
b) In a study conducted in Australia by Heaney et al. (2001), they modelled that a 5% improvement in irrigation efficiency could result in 20% reduction in soil salinity levels.
c) Improved soil aeration and a reduction in poisonous compounds by lowering the groundwater table (Zhi, 1996).
d) Improved microclimate conditions in the fields (Zhi, 1996).
e) Reduced rice diseases and insect pests (Zhi, 1996).
f) Improved regional water balance and advancement in the development of the regional economy (Zhi, 1996).
g) Benefits that can be accrued from reduced drainage and improved efficiency are increased yields, reduced water and production costs, and reduced costs of drainage disposal (Hanson and Fulton, 1994).

Some of the environmental problems faced are:

- Declining water tables due to the scarcity of water (Sharma, 1999).
- Rising water tables caused by the mismanagement of water (Sharma, 1999).
- Salt accumulation due to the landlocked nature of some regions (Sharma, 1999).

- Increasing demand for fresh water supplies for municipal and industrial sectors (Sharma, 1999).
- Pollution of groundwater due to the excessive application of nutrients, pesticides and insecticides (Sharma, 1999).
- Inappropriate tillage practices and excessive or indiscriminate use of irrigation water could lead to the degradation of arable land (Lal, 1994).

The economic factors that will drive an improvement in irrigation efficiency will be cost reduction and increased profitability. The cost of water will be a motivating factor. While the cost of water is relatively inexpensive, there will be little incentive to reduce the amount of water used by using deficit irrigation that will reduce production (Wichelns, 2002; Mottram and de Jager, 1994; Warkentin, 1994). Mottram and de Jager (1994) hold that only irrigators who are prepared to improve their management practices will attain the benefits of irrigation. Thus, irrigation boards and other professional organizations must encourage the improvement of practices.

The water resources management that will be required in catchments will have to follow an integrated approach with participation from all stakeholders. However, some challenges will be faced when implementing this strategy. From a survey of participants within irrigation schemes in South Africa, Mottram and de Jager (1994) drew the following conclusions about the irrigation schemes:

- Management decisions made by irrigation boards are not always acceptable to all the irrigators.
- Disputes can arise between two irrigation boards that share a water resource.
- There is neither accurate nor consistent monitoring of river flow in the schemes.
- Delivery systems are not calibrated on a regular basis and irrigators are not aware of the actual delivery they receive.
- The irrigation systems that are used are not always suited to the soil type, land slope, soil depth, or crop type.
- The irrigators tend to over-irrigate.
- There is a tendency to stop irrigation before the crops have reached physiological maturity, which results in reduced yields.
- There are shortages in storage dams, which could result in a shortfall in the water supply. This can also create dissension when limited resources have to be shared.

- Many basic agronomic practices are not being carried out. Poor seedbeds and poor germination are a result of hasty planting in double cropping fields. Weed control is often insufficient.

Before a plan can be implemented to improve irrigation efficiency, there are many factors that need to be considered and the next section (2.14) deal with such.

2.14 Factors to Consider for Irrigation System Selection and Management

In the selection and design of irrigation systems there are many factors to consider (Figure 11). The appropriate design will make the optimal use of the resources available. The available resources will dictate the type of system that can be successfully used. The type of system chosen will also determine the type and degree of management that is required. When deciding on what type of system to invest in, careful consideration of the pros and cons of the different types of systems must be taken into account. Deferring capital costs may cost more in the long run. For example, surface irrigation systems should not been seen as a simple irrigation system as a high degree of management is needed to control the irrigation due to the heterogeneities in an irrigation field. For this reason, it is not surprising that surface irrigation systems are inefficient (Kay, 1990).

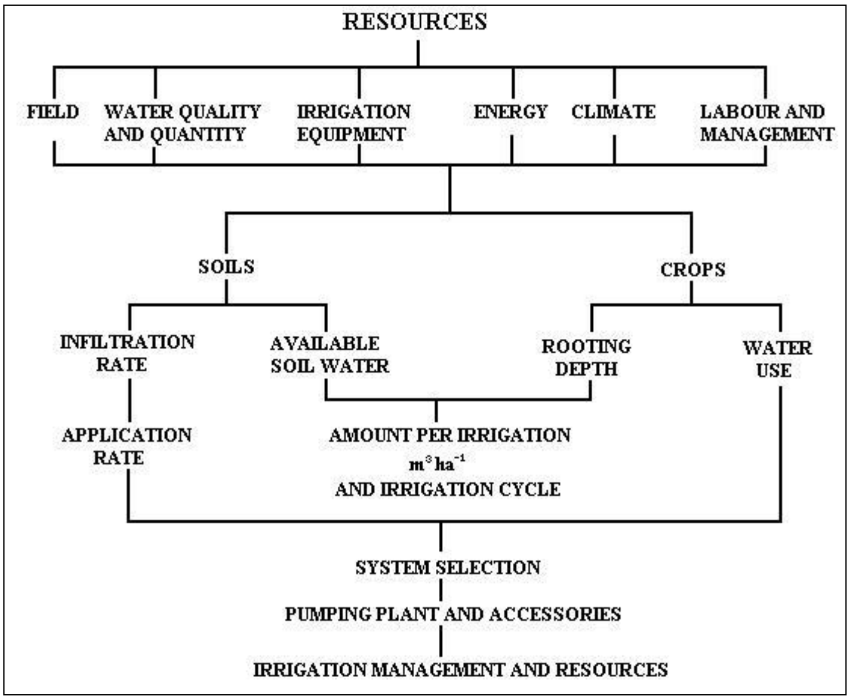


Figure 11**:** Flow chart of factors to be considered for irrigation system selection and management (Mottram and de Jager, 1994).

When deciding on a course of actions to improve irrigation efficiency, it must be ascertained as to whether there would be any harmful or detrimental effects to the system. For example, a canal system that has been lined to reduce seepage can cause reduced groundwater recharge (Palacios-Vélez, 1994). Therefore, action plans to improve water use efficiency must be carefully analysed to determine the economic, ecological and social implications of these plans (Palacios-Vélez, 1994). There will be differences between political and economic (technical) objectives when it comes to improving irrigation efficiency and the allocation of water resources (Allan, 1999). Carter et al. (1999) propose the following steps when analysing water losses in an irrigation scheme that will aid in developing a plan to improve irrigation efficiency:

- Identify and quantify all flows, highlight and categorize all losses.
- Quantify a realistic expectation for each loss.
- Decide whether each loss is of concern or not and identify priorities for losses.
- Identify the cause of losses that have been prioritized.
- Identify necessary and achievable actions to reduce or control losses that have been prioritized.
- Decide on a remedial programme of actions.

After the source and causes of poor efficiency have been identified then methods to improve irrigation efficiency can be implemented.

2.15 Ways to Improve Irrigation Efficiency

There are many ways to improve irrigation efficiency that are based on a few themes. These are equipment or method based or management based. To improve overall project efficiency the following aspects can be considered (Mottram and de Jager, 1994):

- The most advantage must be made of rainfall to reduce net irrigation water requirements by leaving soil moisture storage available for rainfall.
- Accurate irrigation scheduling.

Taking advantages of rainfall can be achieved in various ways as follows:

- By capturing and conserving as much of the rainfall in the soil as can be utilized by the crop. This involves:
  - Reducing runoff to safe levels by contour-farming and tillage practice;
  - Promoting infiltration of water into the soil.
- By ensuring that the crop grows as efficiently as possible with the water which is available – sound agronomic practices result in optimal utilization of water. This can be achieved by:
  - Ensuring an optimal plant population (a good stand);
  - Ensuring adequate control of pests and diseases;

  - Ensuring adequate weed control;
  - Ensuring that the target yield and consequently the fertilization programme are tailored to the quantity of water available.
- Excess runoff must be conserved in adequate storage dams for later use.
- There are certain constraints to irrigation scheduling. These are:
- Constraints due to water supply. The availability and quantity of irrigation water supply will influence the kind of scheduling that can be applied (Augier et al., 1996). The way in which irrigation water is supplied may prevent farmers from implementing optimal water management strategies. Problems that may arise are: rotational supply of irrigation water, unreliable water supplies, or too little flexibility in the timing of water deliveries (Wichelns, 2002).
- Constraints due to on-farm irrigation techniques and equipment. The performance of the irrigation system will depend on the management skill of the irrigator, the irrigation technique and on the quality of the equipment and the design of the system (Augier et al., 1996).

After years of working with farmers to improve efficiency in California, the Irrigation Training and Research Centre (Burt, 1998) notes that there are only a few “tricks” that can be applied to improve the efficiency of various irrigation systems. Some of these are:

- Surface systems:
  - Land grading,
  - Reasonably short furrow lengths, and
  - Tail water return systems.
- Sprinkler systems:
  - The number one factor is the quality of the sprinkler overlap,
  - Adequate pressure, and
  - Maintenance to avoid leaks.
- Drip and micro spray for trees:
  - Use of pressure compensated drippers,
  - Use of subsurface drip,
  - Treating plugging problems caused by iron, calcium and manganese with phosphates or polyphosphates.

The delivery of water in irrigation schemes is often a source of poor performance. Wichelns (2002) gives the following examples of policy recommendations for eliminating inefficiencies on farms and in regional delivery systems:

- Improvements in the definition and enforcement of water rights in areas where these rights are uncertain or not secure,
- Water pricing or allocation strategies that take the scarcity of water into account,
- Using water charging or restrictions to motivate irrigators to reduce off-farm and negative impacts of irrigation and drainage,
- Removal of direct and indirect taxation that reduces the revenue retained by the farmers from crop production,
- Low-interest loans and cost-sharing to finance farm-level developments in infrastructure and equipment for water conservation,
- Programs that enable farmer access to complementary production inputs, such as credit, fertilizers, and pesticides,
- Training, and
- Improved farmer organisation in case of scheme.

Martínez-Austria (1994) suggests the following improved irrigation techniques:

- The selection of an irrigation system that is appropriate for the area in which the irrigation is to take place.
- Using surge irrigation (SI). This is a variant of furrow irrigation where the water supply is pulsed on and off in a planned time periods (e.g. on for 1 hour off for 1 hour 30 minutes).
- Using deficit irrigation (DI). This is the watering strategy that can be applied by different types of irrigation application methods. The correct application of DI requires thorough understanding of the yield response to water (crop sensitivity to drought stress) and of th economic impact of reductions in harvest.
- Reusing water. This is also known as water reclamation and regarded as one of the principles of water management.
- Using Low energy precision application (LEPA) irrigation systems (Fipps and New, 1994). The systems are designed to apply water more efficiently for center pivot irrigation systems. This reduces water use and water pump energy consumption by 15- 30%.

Better results can often be achieved by upgrading an irrigation system. In a trial conducted by Mateos et al. (1991) on cotton using drip and furrow irrigation they found that the drip irrigation had an application efficiency that was 30% higher than furrow irrigation. However, they concluded that cotton production is more dependent on the water regime than on the irrigation system used.

2.15.1 Options for surface irrigation systems

Possible ways to improve surface irrigation techniques are land levelling, mechanization of surface irrigation systems, automation of water supply systems, flow management, control of performance using simulation models, and optimization of water flows and infiltration rates (Augier et al., 1996). The uniformity and efficiency of surface irrigation systems could be improved by using low pressure supply pipelines instead of open canal systems (Smout, 1999).

Bali et al. (2001) used reduced-runoff strategies to improve the efficiency of surface irrigation for alfalfa. They realized a reduction of 28% in water use and the applied water yield efficiency increased from 8.9 to 15.2 kg/ha-mm. Tail-water runoff was reduced to 2% with the alfalfa stands showing little signs of stress or yield reduction. By following this strategy, the occurrence of root saturation can be minimized (Bali et al., 2001).

Feedback control systems can be used to dynamically control the irrigation event to improve irrigation efficiency (Clemmens, 1992). Surge irrigation with a cutback in flow volume can be used to improve the efficiency of surface irrigation systems (Kay, 1990). Unger and Musick (1990) highlight the advantages of using ridge tillage to improve the uniformity and performance of surface irrigation systems.

Hanson and Fulton (1994) give the following methods to improve surface irrigation systems:

- Reduce the length of the irrigation field and reduce the irrigation set time.
- Increase the furrow or border flow rate. The increased flow rate increases the wetted area and thus increases the infiltration rate.
- Convert to surge irrigation.
- Compact the furrows with a cylindrical “torpedo” to smooth and compact the furrow to improve the water advance across the field.
- Convert to alternate furrow irrigation.
- Alternately, the surface irrigation system could be converted to a pressurized system.
- Slope

2.15.2 Options for micro irrigation systems

Augier et al. (1996) suggest the following improvements for micro irrigation:

- High quality of irrigation equipment, as micro irrigation systems needs to be more reliable and have higher uniformity than other irrigation systems because of the increased risk.

- System monitoring, and preventative and curative maintenance are required.
- Use of upgraded design techniques.
- Control and prevention of soil salinization.

Batchelor et al. (1996) evaluated the use of low head drip irrigation systems for low-cost vegetable production. They found that the low head drip systems were more efficient than traditional flood irrigation. They also investigated the use of subsurface pipe irrigation, pitcher irrigation and improved flood irrigation using mulches. The performance of the subsurface pipe was seen as an intermediate between flood and micro-irrigation (Batchelor et al., 1996).

Surface drip irrigation systems constantly keep the area under the drip emitter saturated because of the high frequency of irrigation. In semi-arid areas this can result in a significant amount of evaporation from the soil surface. Meshkat et al. (1998) investigated the use of sand tubes under the drip emitters to minimize the evaporation. The sand tube is a core of sandy soil that replaces the original soil. It has a higher infiltration rate and thus decreases the evaporation by preventing surface ponding of water. Meshkat et al. (1998) found that the evaporation from the soil surface decreased from 30 to 3.7% under experimental conditions.

2.15.3 Options for overhead systems

For sprinkler irrigation systems, Augier et al. (1996) give the following suggestions to improve performance:

- Selection of equipment according to its performance.
- Information and training for irrigators to improve control and management skills.
- Popularization of methods for evaluating the actual performance of irrigation systems at a field level.
- Improving irrigation design methods to include the effects on performance of local parameters that affect the performance of the irrigation system.
- System automation to ensure high performance.

Sprinkler irrigation systems should be operated at the required pressure and at the correct spacing. The sprinkler system should be inspected regularly as part of a maintenance schedule to ensure good uniformity (Ascough and Kiker, 2002).

2.15.4 Scheduling and management options

The effective management of an irrigation system is crucial for high performance. The Primary Industries and Resources Department in South Australia (PIRSA) list the following best management practices for irrigation systems (PIRSA, 1999):

- Rate irrigation highly within the management system. If irrigation is seen as a low management priority then irrigation performance is likely to be poor. Successful growers tend to practice intensive management in all aspects of crop production.
- Proper soils information. Detailed soil information is needed for accurate scheduling of irrigation water applications.
- Irrigation systems must be correctly designed and maintained. Emitter delivery cannot vary by more than ±5%. The distribution uniformity of full cover irrigation systems must be greater than 75%.
- All aspects of each irrigation event should be monitored. The soil moisture status before an irrigation event should be monitored to correctly time the application. The system performance and uniformity of application should be monitored throughout the season to allow for minor adjustments to the system to ensure performance. The soil moisture after an irrigation event should be monitored to determine the fate of the applied water.
- Objective monitoring tools should be used to schedule irrigation. Good quantitative information provides consistent information for management decisions.
- More than one tool should be used for scheduling irrigation. It is dangerous to rely on one tool for scheduling and to ignore other evidence that may suggest problems with the irrigation strategy.
- Retain control of irrigation scheduling. Entirely automatic irrigation scheduling tools should be avoided. All this versus group dynamic?
- Remain open to new information. New and better tools are continuously being developed.

Proper irrigation management will reduce the amount of over-irrigation and thereby reduce deep percolation losses and nutrient losses (Rice et al., 2001). Therefore, systems should be evaluated regularly to ensure that the performance of the system is adequate (Ascough and Kiker, 2002). In Colorado in the USA, irrigators are improving the water use efficiency of their irrigation systems by trapping free water using crop residues and monitoring soil moisture (Farrell, 2002).

In green house situations where a growth media is used instead of soil, using cyclic irrigation scheduling can increase the irrigation efficiency. The water is applied in smaller amounts and thus reduces the amount of deep percolation (Tyler et al., 1996a). The efficiency of an irrigation system in a greenhouse can be improved by minimizing the leaching fraction. The nutrient efficiency can also be improved by the leaching of fewer nutrients (Tyler et al., 1996).

By applying less water than the reference evapotranspiration (ET), the water use efficiency of crops can be increased. Al-Kaisi et al. (1997) conducted studies on winter wheat where they varied the rate of water replacement. The rates at which water was replaced were: 0ET, 0.33ET, 0.66ET, 1.0ET, and 1.33ET. The 0.33ET replacement rate had the highest water use efficiency. However, the grain and dry matter yield steadily increased as the rate increased up to 1.0ET. Thus, in areas where there is a water scarcity, the irrigation schedule can be adapted to a deficit irrigation strategy in order to increase water use efficiency.

In a study on sugar cane under different irrigation schedules and nitrogen levels Singh and Mohan (1994) found that, in general, the water use efficiency of the crop decreased with increased irrigation frequency. They also found that yield was the same when irrigation water was applied at 100% and 120% of cumulative pan evaporation.

Site-specific soil information plays an important role in the management of irrigation systems. Oosthuizen et al. (1996) found that this sort of information accounted for 97 to 99% of returns generated from using future weather information. The law of diminishing returns applies to the benefits that can be accrued from additional irrigation information. Irrigators may not be willing to pay to obtain perfect plant-growth information if they have adequate soil moisture and future rainfall information (Oosthuizen et al., 1996). Xiuqing et al. (2001) studied how the infiltration rate of soil changed during freeze-thaw stages. They concluded that understanding how the infiltration rate of soil changes will enable irrigators to adjust their irrigation practices to improve irrigation efficiency. In areas where subsurface drainage is used to lower ground water tables, the drainage system must be correctly designed and managed. Christen et al. (2001) found that in many cases the subsurface drainage is removing more water than it was designed to.

Irrigation management should make allowances for rainfall and this means that an irrigation system that has good control over the depth that can be applied will have to be used, i.e. sprinklers and micro-irrigation (Christen et al., 2001). Where there is a limited water supply, rainfall must be conjunctively used. Optimal irrigation strategies can be developed depending on the available water supplies and the level of yield required (Varlev et al., 1996).

Water use efficiency can be improved by reducing the amount of water lost to drainage, canopy interception, and soil evaporation. The water use efficiency can also be improved by employing better crop production techniques and by utilizing higher yielding crop varieties (Batchelor et al., 1996).

Lal (1994) investigated the effect of tillage practices on water management. Tillage techniques can provide an optimum soil moisture regime in the root zone by:

- enhancing the efficiency of irrigation water,
- draining excess water from the root zone,
- regulating water quality and decreasing sediment and contaminants in water,
- conserving soil and water,
- facilitating water harvesting, and
- modifying the structure of soil to provide favourable, plant specific conditions in the root zone.

Furthermore, the water use efficiency of irrigation can be improved by (Lal, 1994):

- alleviating soil compaction by sub-soiling,
- using ridge tillage to conserve moisture and regulate the flow of water through the furrow,
- using a mulch-based conservation tillage system.

De Jager and Kennedy (1996) conducted a study at Douglas, Free State, of different levels of technology used for the scheduling of wheat. They evaluated the effect of using high, intermediate and minimum technology to determine the amount and timing of irrigation water. The high technology level consisted of using an automatic weather station and a crop simulation model. In the intermediate technology level the cumulative reference crop evaporation was replenished before the onset of crop stress. The Penman-Monteith equation was used for this purpose. The minimum technology level employed the application of fixed amounts at fixed intervals. This method was the conventional method applied at the time. De Jager and Kennedy (1996) found that the application efficiency of the irrigation system for the season could be improved by 36% by following the high technology method on centre pivot irrigation.

From studies conducted by Oosthuizen et al. (1996) they found that for the same yields, the amount of water used could be greatly reduced by following more sophisticated irrigation management strategies. In one situation they found that the amount of water used was less the amount available under limited water supply conditions. The strategies that they investigated included different levels of soil-water, plant and weather information, ranging from none to highly advanced (Oosthuizen et al., 1996).

In irrigation schemes there are often discrepancies between the water distributed to the farmers and the irrigation schedules determined (Horst, 1996). Some possible solutions suggested by Horst (1996) to address these problems are:

- Improvements to the present approaches to irrigation scheduling and delivery. The use of new irrigation scheduling techniques, such as water stress indicators, water-yield functions or simulation models, could be investigated. However, the operational success of these methods would have to be demonstrated due to the large data, monitoring and processing requirements.
- Automation of control systems in the irrigation delivery network. However, this will require highly skilled staff to operate and maintain such a system.
- Simplification of irrigation scheduling and water division technology.

2.15.5 Modelling approaches to improve performance

Computers and software programs provide useful tools for managing irrigation system performance. The most common programs used are optimization packages and simulation models.

Linear programming techniques can be used for planning strategies for optimizing the area to plant and the amount of water to apply during the various crop stages (Mottram and de Jager, 1994). Wardlaw (1999) used a linear programming approach to optimize water allocations. This method has potential real-time applications for water allocations in systems. Zerihun et al. (2001) have developed an optimality algorithm for the design and management of furrow irrigation systems as a function of furrow length or flow rate.

Simulation models have been extensively used to gauge the performance of surface irrigation systems. They have been used to:

- Evaluate the differences in performance between strategies (Izadi et al., 1991),
- Predict the performance of systems that have varying inflow rates (Gharbi et al., 1993), or precision land levelling (Fangmeier et al., 1999), or heterogeneous soil intake properties (Mailhol et al., 1999), and
- Optimize irrigation water application strategies (Hibbs et al., 1992; Tyagi et al., 1993).
- Look at the effects of ‘what if’ scenarios for integrated water resources management (Franks and Falconer, 1999).
- Select the optimum cropping plan, to test and improve a provisional irrigation using an irrigation simulator, and as scheduling tools (Deumier et al., 1996).

Modelling approaches have also been used to:

- Optimize regional water resources (Shangguan et al., 2002),
- Find the optimum centre pivot irrigation design package taking tillage practices into account (Mohamoud et al., 1992), or

- Create operation diagrams for irrigation management that relate flow rate and advance time to application efficiency and degree of adequacy of irrigation (Losada et al., 1990).

2.16 Existing performance of irrigation systems

The performance of irrigation systems needs to be determined in order to measure their effect on water resources. Some measures of performance are more easily determined than others. The application efficiency of an irrigation system can more readily be measured than the overall irrigation efficiency. For this reason, the application efficiency and uniformity of irrigation is usually evaluated.

The International Institute for Land Reclamation and Improvement (ILRI) conducted a large-scale study on irrigation systems around the world (Bos and Nugteren, 1990; Wolters, 1992). They found that the average application efficiency of systems was below 70%. The application efficiency was 53% for furrow irrigation systems.

In a four year study of conventional and alternate row furrow irrigation on cotton Rice et al. (2001) estimated the irrigation efficiency over a four-year period for these two treatments. The average irrigation efficiency for conventional furrow irrigation ranged from 56 to 62% and for alternate row from 60 to 66%. They state that these efficiencies were low and that they could have been improved by using improved scheduling techniques. This would decrease the amount of over-irrigation, which would reduce deep percolation and nitrate loss (Rice et al., 2001). Rice et al. (2001) used the definition for irrigation efficiency given by Burt et al. (1997), which is the amount of water beneficially used over the amount of water applied less the change in storage.

Yonts et al. (1991) determined the performance of furrow irrigation systems for three different types of tillage practices (plough, rotary tillage and minimum tillage). They used the following definition of application efficiency: the ratio of the volume of water stored in the root zone to the total volume of irrigation water applied. They reported application efficiencies ranging from 41 to 66% in the first year of evaluation and from 33 to 76% in the second year of evaluation on fields with 0.2% slope. On a field with a 1.2% they reported application efficiencies of 47 to 91%. There were considerable differences for the application efficiency between the types of tillage treatments used. The minimum tillage showed better application efficiency in general due to the increase in the infiltration rate of the soil. The rate of applied water and the crop grown also influenced the application efficiency of the irrigation (Yonts et al., 1991).

Mankarious et al. (1991) determined the application and irrigation efficiencies for furrow irrigation in Egypt for small-level basins. They reported application efficiencies ranging from 37 to 93% and irrigation efficiencies of 25 to 80%. They found that the average application efficiency on sandy soils was 45% and that the average on alluvial soils was 70%. They attribute the low efficiencies in sandy soils to the high infiltration rate and low water retention properties of the soil. On other sites the low efficiency was caused in part by high conveyance losses from the supply furrows. They also reported that there was no clear link between the application efficiency and the application rate used (Mankarious et al., 1991).

Al-Jamal et al. (2001) compared the irrigation efficiencies of sprinkler, trickle and furrow irrigation on onions. They defined the irrigation efficiency (IE) as the evapotranspiration (E_t) divided by the total amount of irrigation water applied during the season (including rainfall). The irrigation water use efficiency (IWUE) was estimated as the yield divided by the amount of irrigation and the water use efficiency was estimated as the dry yield divided by the E_t. They irrigated onions at 40, 60, 80, 100 and 120% of non-stress E_t. The onions grown with subsurface drip irrigation had IE values that ranged from 45% for non-stressed conditions to 77% for stressed conditions. For sprinkler irrigation the IE values ranged from 80 to 100%. However, they found that the maximum yield occurred at an IE of 93%. The IE values for furrow irrigation were high (>70%) because of the limited amount of water that the farmers had available with which to irrigate. They found that subsurface drip and furrow irrigation had low IWUE and that sprinkler irrigation gave the best IWUE. They pointed out that trying to improve the WUE of onions by employing water stress techniques would not be successful (Al-Jamal et al., 2001).

Playán et al. (2000) presented results on a study of 15 surface irrigation systems. They used the definitions of Burt et al. (1997) for the low quarter distribution uniformity (DU_{lq}) and application efficiency (AE). The DU_{lq} values ranged from 58.5 to 99.8% and the AE values ranged from 29.2 to 90.0%. The average DU_{lq} and AE reported were 88.6% and 61.6%, respectively (Playán et al., 2000).

Omezzine and Zaibet (1998) give examples of the irrigation efficiency for 11 fields of spring tomatoes in Oman. They define the irrigation efficiency as the estimated crop water demand divided by the irrigation water supplied. The irrigation efficiency of the 11 systems ranged from 33 to 100% with an average of 58%. The majority of systems had very low irrigation efficiencies.

Mateos et al. (1991) conducted a study in cotton comparing drip and furrow irrigation. They define irrigation efficiency as the amount of water infiltrated divided by the amount of water supplied. Since all the water for the drip irrigation system infiltrated, the efficiency was 100%. For the furrow irrigation system, the runoff amount to 30% of the water applied. Therefore, the efficiency of the furrow system was 70% (Mateos et al., 1991).

Schneider (2000) presents a summary of efficiency and uniformity studies conducted on LEPA sprinklers and spray sprinkler systems. The definition of Burt et al. (1997) was used for application efficiency. Christiansen (1942) coefficient of uniformity and the Heermann and Hein (1968) modified uniformity coefficient for centre pivots, were used to define irrigation uniformity. For LEPA sprinkler systems the application efficiency was in the range of 95 to 98%, and the uniformity was in the 94 to 97% range. For spray sprinkler systems, the application efficiency exceeds 90% when there is negligible runoff and deep percolation. The uniformity for spray sprinkler systems was in the 75 to 85% range.

De Jager and Kennedy (1996) investigated the performance of centre pivot and flood irrigation in the Orange Free State, South Africa. They evaluated the application efficiency for three levels of technology for the management of the irrigation system. These were high, intermediate and low technology. They defined application efficiency as the evapotranspiration divided by the sum of irrigation applied and rainfall. The average application efficiencies were 84, 54 and 27% for the three levels of technology (De Jager and Kennedy, 1996).

The application efficiency of two management techniques for furrow irrigation in cotton in Australia was evaluated by Dalton (2001). The definition for application efficiency was the volume of water used divided by the volume of water delivered. In one field conventional irrigation practices were used, and in another a furrow-advance monitoring device and modified strategies were used. For the first field the efficiency ranged from 73 to 96%, with an average of 83%. In the second field the efficiency ranged from 67 to 96%, with an average of 84%. The distribution uniformity as calculated using the SIRMOD simulation model. The reported uniformities for the first field ranged from 87 to 98%, and for the second field from 92 to 98%.

Ascough and Kiker (2002) report application efficiencies and distribution uniformities for centre pivot, dragline, floppy, semi-permanent sprinkler and surface and subsurface drip irrigation systems used in the South African sugar industry. These results are summarized in Figure 12 and

Tables 6 below. The definitions used for application efficiency (AE) and low quarter distribution uniformity (DU_{lq}) follows those of Burt et al. (1997).

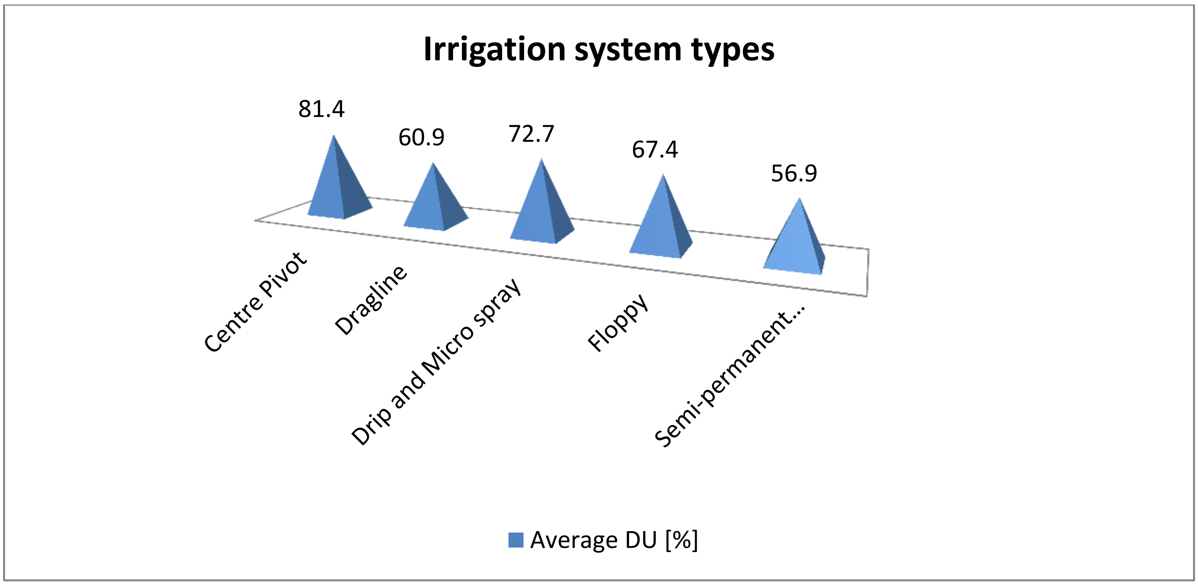


Figure 12: Summary of uniformity parameters by irrigation type (Ascough and Kiker, 2002).

Table 6: Summary of application efficiency by type of irrigation system (Ascough and Kiker, 2002).

	Type of irrigation system				
	All systems	Centre pivot	Dragline	Floppy	Semi-permanent sprinkler
Average AE [%]	77.0	83.6	73.5	76.7	78.9
Minimum AE [%]	58.9	76.3	58.9	63.5	64.6
Maximum AE [%]	93.8	93.8	89.3	85.4	91.1

Palacios-Vélez (1994) gave an example of the calculation of the application efficiency of a furrow irrigation system. The definition of application efficiency used was the volume of water stored in the root zone divided by the volume of water received by the plot. The application efficiency for this system was 61%.

Tyler et al. (1996a) investigated the application efficiency of drip irrigation in container-grown plants. They defined the application efficiency as the amount of water applied minus the amount of water lost divided by amount of water applied. They investigated the difference between applying a given amount of water in 1, 2, 3 and 6 irrigations. The application efficiency for these strategies was 38, 52, 55 and 49%, respectively (Tyler et al., 1996a). However, in nurseries it is possible to capture and reuse the runoff out of the greenhouses that will greatly improve the overall efficiency.

Mottram and de Jager (1994) give two examples of application efficiency and overall project efficiency for two farms in the Little Tugela/ Sterkspruit system in South Africa. They defined the application efficiency as the net irrigation requirement divided by the water applied by irrigation system to the cropped surface, and the overall project efficiency as the net irrigation requirement divided by the total water supplied to the irrigation project. The two examples for application efficiency were 52 and 92%, with a corresponding project efficiency of 33 and 73% respectively.

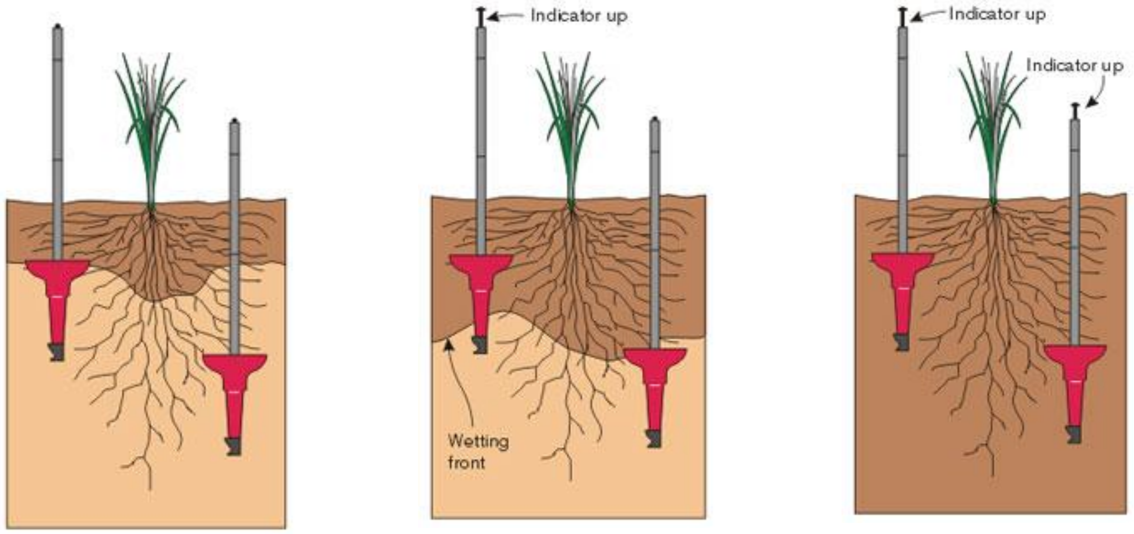
Wichelns (2002) reports that the average farm level efficiency in Egypt were in the range of 40 to 50%. However, at basin level the efficiency increases to around 80% because of reuse within the basin. The remaining 20% is beneficially used by other sectors. Therefore at basin level, there is not much real water saving that can be made through improved irrigation efficiency.

Mailhol et al. (1999) evaluated the application efficiency of closed end and free drain furrows. The average application efficiency and coefficient of variation of application efficiency for closed end furrows were 78% and 8%, respectively. For free drain furrows the average application efficiency dropped to 70% and the coefficient of variation of application efficiency increased to 11%.

2.17 FullStop Wetting Front Detectors in South Africa

2.17.1 Description of the Wetting Front Detector (WFD)

The FullStop Wetting Front Detector (WFD) is a radically different concept, designed to help improve the accuracy of irrigation (Figure 13). A FullStop WFD needs no wires, batteries, computers or loggers. But just because the instrument is simple, it does not mean it won't change the way you irrigate. The FullStop shows you how deep the water has penetrated into soil after irrigation. It also stores a sample of water from the soil so that fertilizer and salt levels can be monitored (Stirzaker et. al., 2004).



Shallow Indicator: DOWN
Deep Indicator: DOWN
If neither indicator is triggered, then watering is generally too shallow.

Shallow Indicator: UP
Deep Indicator: DOWN
Water has moved past the shallow detector to the lower part of the root zone.

Shallow Indicator: UP
Deep Indicator: UP
The deep indicator should be triggered only when it is necessary to fill the whole root zone.

Figure 123: An example of a Wetting Front Detectors at certain soil depth (Stirzaker et. al., 2004)

For furrow irrigation, the Wetting Front Detectors are positioned half under the furrow (shallow response) and half under the bed with the extension tube rising through the shoulder of the bed (deep response) (Figure 14).

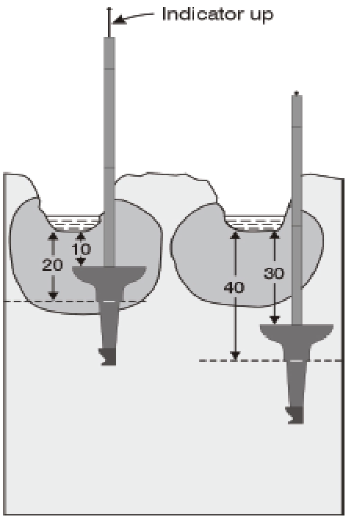


Figure 134: The location of the wetting front detectors in furrow irrigation system (Steven and Stirzaker, 2010). Depth is in centimetres.

M'Marete et.al. (2007) defines the WFDs as an inexpensive and robust devices that are used for scheduling irrigation by giving a yes/no response as to whether a wetting front has reached a particular depth in the soil. It was further indicated that there are two types of WFDs namely, the FullStop (FS) and LongStop (LS) WFDs.

2.17.2 Success of WFDs elsewhere in South Africa

The WFD technology has been installed in a number of small and large scale irrigation systems to assess the new technology and contribute to the water management in these irrigation systems. The installation of the pilot WFDs in the small scale irrigation schemes of Mafefe, Grootfontein, Malegale, Elandskraal, Tswelopele and Bon O'Dire, all in Limpopo province had mixed success in improving irrigation management (Steven and Stirzaker, 2010). However at Mafefe and Grootfontein there were no installation of WFDs due to unavailability of irrigation water but the irrigation farmers were trained in the use of the WFDs. In Malegale and Elandskraal irrigation schemes, the irrigation water was available and the WFDs were installed in the fields for pilot studies. Some of the farmers reported a response of the WFD that were installed in the shallow and deeper section of the irrigation furrow. In Tswelopele irrigation scheme, the installation of WFD contributed to better irrigation scheduling in order to have an improved distribution of water to their fields. In Bon O'Dire, the WFDs were installed, the short and long furrow irrigation. Here the irrigation farmers were able to notice how effective their irrigation schedules were since there was a greater response of WFDs at the head of the furrow than at the tail.

2.18 Conclusion

The literature review showed that there are many ways to improve irrigation efficiency. One key way of achieving water use efficiency is accurate irrigation scheduling. There are certain constraints to irrigation scheduling. These are:

- Constraints due to water supply. The availability and quantity of irrigation water supply will influence the kind of scheduling that can be applied (Augier et al., 1996). The way in which irrigation water is supplied may prevent farmers from implementing optimal water management strategies. Problems that may arise are: rotational supply of irrigation water, unreliable water supplies, or too little flexibility in the timing of water deliveries (Wichelns, 2002).
- Constraints due to on-farm irrigation techniques and equipment. The performance of the irrigation system will depend on the management skill of the irrigator, the irrigation technique and on the quality of the equipment and the design of the system (Augier et al., 1996).

The problem at Dzindi irrigation scheme is that of a lack of equipment and expertise to do irrigation scheduling, although water supply is also limited as an irrigation roster is used. Irrigation scheduling can improve productivity brought about by taking advantage of rainfall and avoiding over-irrigation. Apart from that, the on-farm saving of water during irrigation can assist with regard to water availability for use elsewhere.

CHAPTER THREE: MATERIALS AND METHODS

3.1 Introduction

The study involves an on-farm survey of the Dzindi irrigation scheme and field installation and testing of the WFD technology on selected plots on the Dzindi irrigation scheme and also looks at the challenges faced by farmers in relation to irrigation.

3.2 The Location of the study area

Dzindi Irrigation Scheme is a small irrigation scheme located in the village of Itsani, which is situated 10 km west from Thohoyandou Town in the Limpopo Province of South Africa (Figure 15). The other adjacent villages to the scheme include Shayandima, Tshisaulu, Lwamondo and Manamani. The geographical location of Dzindi Irrigation Scheme is S 23^0 01' 1.3'' and E 30^0 26' 10.5'', in the A91E quaternary catchment of the Levubu/ Letaba Water Management area.

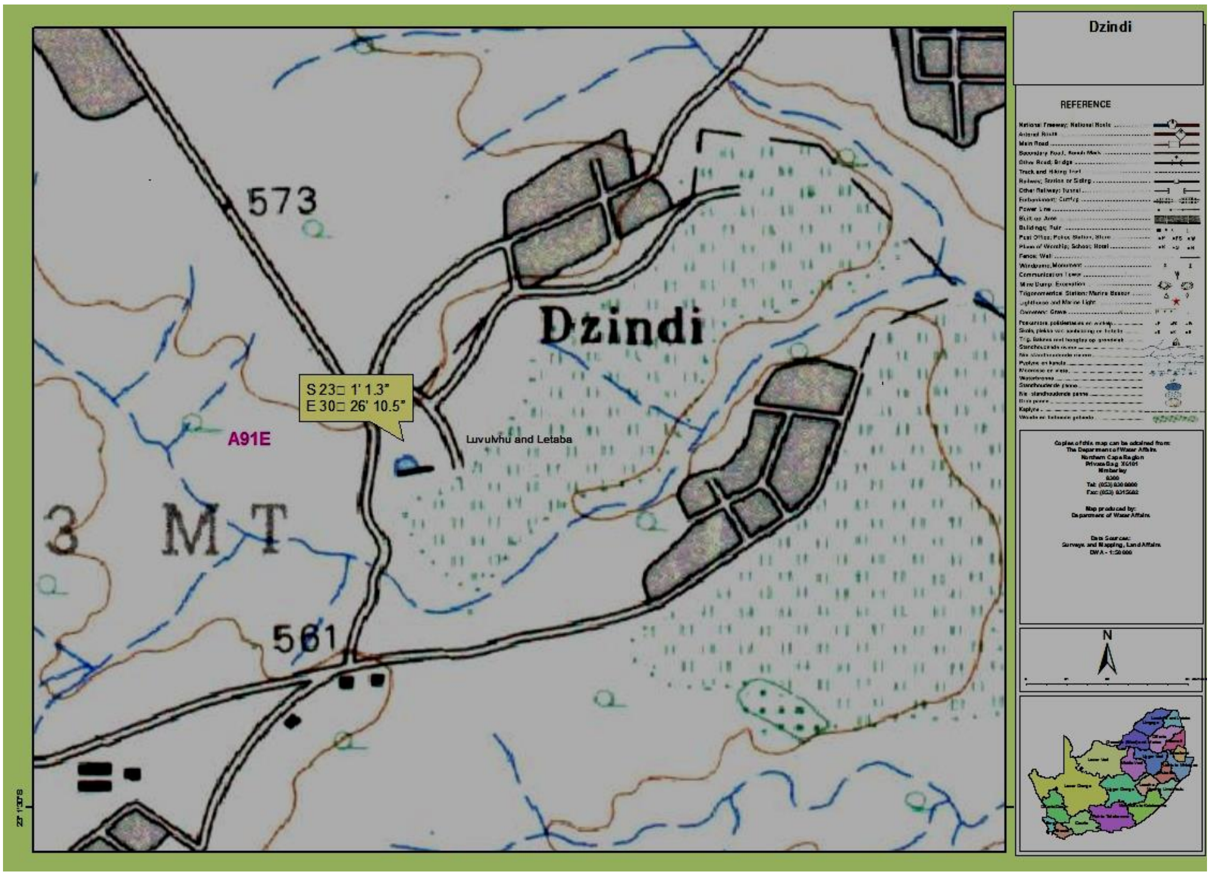


Figure 145: Location of Dzindi Irrigation scheme

3.3The on-farm survey at Dzindi irrigation scheme

3.3.1 Crops grown in Dzindi irrigation scheme

From the focus group discussions which were held during the first week of March 2004 with farmers while introducing them about the project and gathering of the information regarding the scheme, the data on the types of crops that are grown at the Dzindi irrigation scheme was obtained. The detail of crops and vegetables is fully documented on the following chapter. However, the farmers indicated that vegetables like Cabbages, Chinese cabbage, Nightshade, Tomatoes, Onions, Muxe and Swiss chard are normally grown in winter season while crops such as maize, pumpkins, green peppers and groundnuts are the principle summer crops. They also indicated that during summer season, they do crop mixing of maize and groundnuts as to enrich the soil fertility.

3.3.2 The Challenges faced by the irrigation farmers

In order to document the challenges experienced by farmers at Dzindi irrigation scheme, a focus group discussion was conducted. A group of 12 farmers from the scheme participated in the focus group discussions. The farmers were represented in terms of the four blocks, whereby three farmers from each block volunteered and with the help of the Extension Officer who normally interact with these farmers and has got knowledge regarding the scheme, indicated that the volunteered farmers are always hands on and available on site . There was no specific sampling method for selecting the participating farmers. Rather farmers were sampling conveniently by inviting three farmers from the four blocks who are interested in participating on the study.

A checklist consisting of issues for discussion was prepared for collecting the information during the two meetings (one session in the morning and the other in the afternoon) held at the scheme during the last week of March 2004 as shown below:

- Water User Association (WUA) or Communal Property Association (CPA)
- Land ownership
- Plot holder marginalisation
- Land invasion
- Infrastructure damage
- Irrigation scheduling
- Market
- Soils suitability

In analysing the data, a method of text analysis was used. The issues appearing on the checklist were used as themes. The common accounts by the participants were coded to reveal where the farmers had a common grounds. The information was reported in a form of a narrative.

3.4 On-farm experimentation of the Wetting Front Detectors

3.4.1 The Selection of Plots

The plots were selected with the help of the Extension Officer at Dzindi irrigation scheme; farmers were invited on two occasions to attend meetings in which the project was introduced to the farmers by the researchers. In both meetings, a total of about 30 farmers attended. After introducing the project to the farmers, a proposal was put forward for them to state whether they were interested in taking part in the study. A total of 12 farmers volunteered to take part in the study and only five plots were selected as representative of the whole scheme. From the five plots, two were in block 1 and each on block 2, 3 and 4 respectively.

3.4.2 Field Installation, Observation and Measurements

This involves installation of the LongStops (LSs) and FullStops (FSs) Wetting Front Detectors (WFDs). Stirzaker et al. (2004) describe these as tools for use by small scale farmers in irrigation scheduling. By FSs we simply mean that when the soil is full, the farmer must stop irrigating. The WFDs operates in a manner that catches some of the infiltrating water in the funnel. The water then seeps through a filter at the base of the funnel and gets collected in a small reservoir. This causes Styrofoam rods to float, thus activating a magnetically latched indicator above the soil surface. The tools are not expensive to acquire and requires no literacy to operate.

The WFDs were designed to be a soil water monitoring tool that worked in a way farmers could visualise. The funnel was buried in the root zone. If sufficient irrigation water percolated past, the funnel collected some water which activated a float, visible at the soil surface. Water sample can be collected from these devices and used for measuring salt and fertilizers levels in the soil.

Field installation also includes watermarks and neutron probe access tubes to the selected plots (Table 7). The placements of these instruments were both across and centre of the furrow bed irrespective of the spacing. The 60 and 90 cm LSs were deployed at Dzindi irrigation scheme at placement depths of 30, 60 and 90 cm. The FSs were placed both at the shoulders of the furrows and at the centre of the beds. The placement depths for the FSs were 30, 45 and 60 cm. An Auger, spade and a measuring tape was used for the preparation of holes for the instruments.

The visual observation of the instruments to check response and measurements of water volumes were done before irrigation and after irrigation. The FSs were checked and their response recorded and reset before irrigation, where necessary. After the farmers had applied water to the furrows under investigation, water was allowed to percolate. Measurements were taken after about 2 hours following irrigation.

Table 7: Installation of instruments in the farmers' field

Placement/ measuring depth (cm)	LongStops				Watermark sensors		Watermark	Neutron probe measurements
	Replicate A (Upper strip)		Replicate B (lower strip)		Replicate A (S = Furrow Shoulder)	Replicate B (C = Furrow Centre)		
	LS90	LS60	LS90	LS60				
15								X
30	113	123	213	223	F13S	F23C	X	X
45					F12S	F22C	Temperature sensor	X
60	112	122	212	222	F11S	F21C	X	X
75								X
90	111	121	211	221				X
105								X
120								X

All the farmers planted maize, except the farmer selected in Block 4. In Block 4 the farmers did not plant in summer and therefore, observations only started after he planted vegetables. On the other hand, there were no LSs for him. However, watermarks, FS, and neutron probe access tubes were installed in his plot.

3.4.3Experimental layout

A representative bed was selected in a farmers' plot. The number of strips in the bed were determined and divided by 3. The instruments were installed in the middle strip, upper and lower third of the plot. A representative furrow in each strip (usually the middle one) was selected for installation of the instruments. Figure 16 below shows a general layout of the experiment. The Watermark sensors were also installed in the upper and lower one third of the plot. Farmers were urged to carry out their duties as they normally do. This enabled the researcher to understand clearly what, when, how, and why farmers do what they do. After observing the farmers, then the researcher engaged the farmers by questioning and probing using the checklist developed during the group focus meeting. The detectors, especially the FS become a focal point from where the dialogue with farmers would be centered.

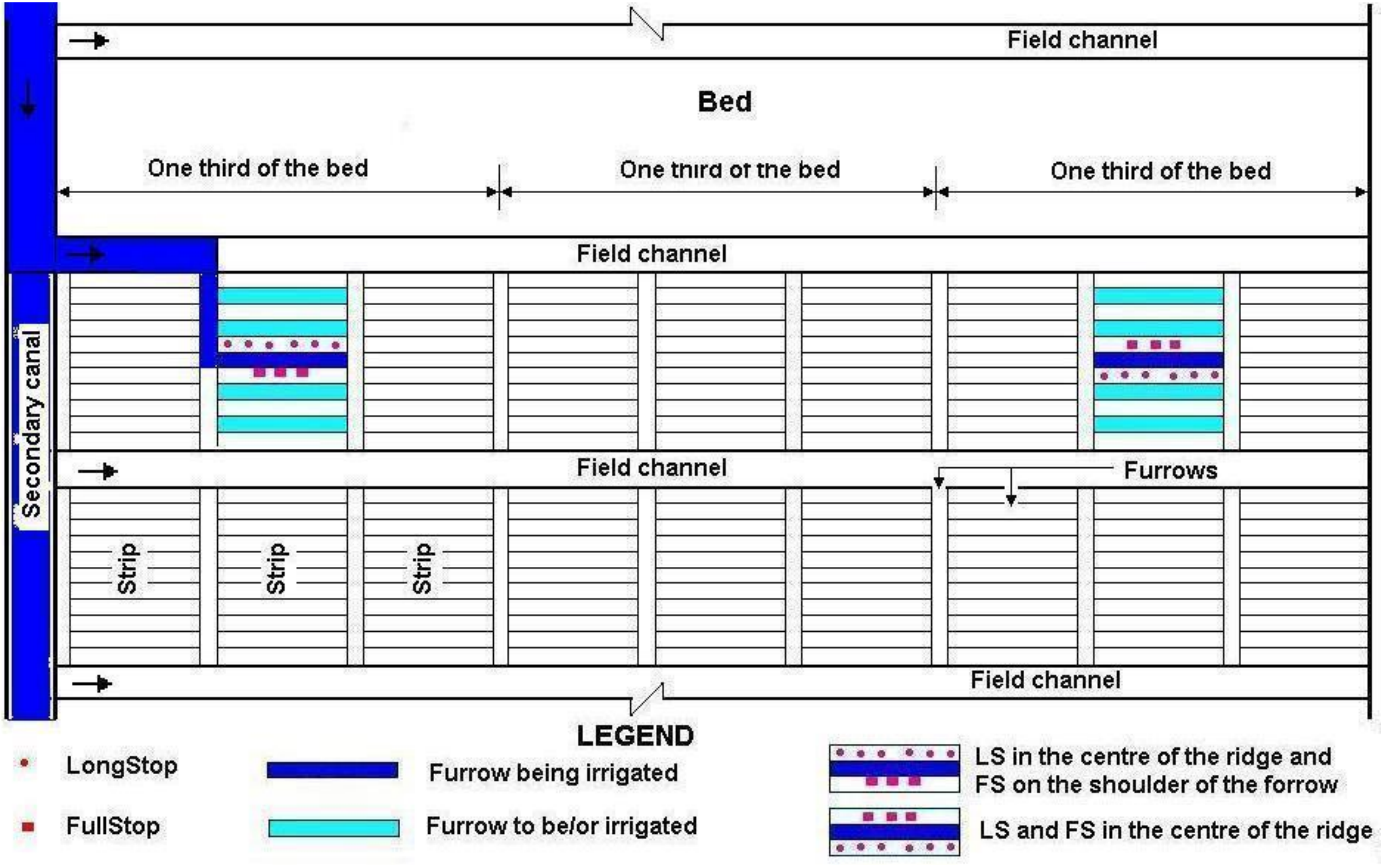


Figure 156: The layout of the farmers' fields and location of the wetting front detectors

Although the objective of the research was to get at least two farmers per irrigation block, this was not possible owing to logistical problems. Due to the difficulty of monitoring the experiment in more than one plot per day, it was decided to select farmers based on the irrigation timetable in order to avoid clashes. There was also another limiting factor – the number of farmers that could take part due to insufficiency of instruments to be installed. There were only 5 Watermark loggers and 48 LongStops (LSs) available. A final decision was made to install 12 LSs in each farmers field, meaning that only 1 farmer per irrigation block could participate in the study. To make sure that farmers did not irrigate on the same day, from the list of those who had shown interest, one farmer was selected from each block.

3.5Ethics Consideration

In the conduct of the study, the Human Sciences Research Council (HSRC) code of ethics of research was applied (HSRC, 1997). During the meeting focus group discussion, informed consent was sought from all participants. The objectives of the study were explained and it was indicated that the outcome of the research project would be presented as feedback for their consideration in future. They were informed that their participation was voluntary, that their responses would remain confidential, and that they had the right to end their participation at any time without the need to provide a reason. Assigning fictitious names or numbers in the transcription of the interviews maintained anonymity of respondents and participants.

3.6 Data Analysis

The data for the experiments were analysed using descriptive statistics using MS Excel and the data was presented in form of tables and graphs.

Thus distribution uniformity (DU) is calculated from equations 4 and 5 (Burt et al., 1997):

$$d_{lq}=\frac{\text{volume accumulated in 25\% of total area with smallest depths}}{\text{25\% of the total area of elements}} \qquad \text{Equation 224}$$

From this the low-quarter distribution uniformity, (DU_{lq}), can be defined as:

$$DU_{lq} = \frac{dlq}{davg}$$ Equation 225

The Christiansen coefficient of uniformity (CU) is calculated from equation 12 (Christiansen, 1942):

$$CU = 100\left(1\text{-}\left(\sum_{s=1}^{n}\left|D_s - \overline{D}\right| \Big/ \sum_{s=1}^{n} D_s\right)\right)$$ Equation 266

All the LongStop data were converted into tensions, using the estimate of 23 ml per unit kPa (i.e. for a 60 cm LS, 23 ml = 5 kPa, 46 ml = 4 kPa). Generally all depths move in synchrony with irrigation events, and the depth of wetting is quite evident although sometimes a response at 90 and not at 60 cm was observed.

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 Crops grown in Dzindi irrigation scheme

The Farmers at Dzindi irrigation scheme practice both commercial and subsistence farming. Several crops are grown in the study area depending on which types of crops are suitable and in which season of the year. Some crops are grown in summer, while others are grown in winter. During winter, the farmers grow vegetables including cabbage (*Brassica oleracea*), Swiss chard (*Spinacia oleracea*), Chinese cabbage (*Brassica rapa L ssp. chininensis*), Muxe (*Solanum retroflexum*), and Onions (*Allium ceppa*). In summer, the farmers grow tomatoes (*Lycopersicon Iycopersicum*), green peppers (*Capsicum annum*), maize (*Zea mays*), pumpkins (*Cucurbita maxima*), groundnuts (*Arachis hypogaea*) and Bambara groundnuts (*Vigna subterranea*). Most of the crops and vegetables produced in Dzindi irrigation scheme are for subsistence farming (food security) although farmers take some of their produce and sell them to the surrounding areas since there is no local market or Agriparks in place. The most common vegetables which are for commercial are Swiss chard, Chinese cabbage, Muxe and Tomatoes.

4.2 The Challenges faced by the irrigation farmers

Whilst preparing for the study, the farmers forming part of Dzindi irrigation scheme were asked of challenges that they are facing in order to find out which specific problems related to irrigation. Farmers had common ground regarding the challenges. The information acquired was reported in a form of narrative and a yes or no response was acquired. The summary of challenges is listed as follows:

- Formation of a Water User Association (WUA) and a Communal Property Association (CPA) poses threats as they are supposed to pay for water they are using.
- The problem of land ownership: Transferring the title from state to plot holder.
- Poor plot holder families at Dzindi irrigation scheme are marginalized further and possibly even criminalized as a result of their difficulty or inability to pay.
- Another problem is the continued threat of land invasion. Being located at the edge of local urban expansion, the threat is real and imminent because the demand for residential land is high.
- Deterioration of the water conveyance system at Dzindi irrigation scheme. The occurrence of disaster such as the flood of 2000 destroyed the main canal, fences and the pipe that conveys water to the Dam in Block 1.

- Tractors also damage the concrete furrows that bring water to the plots due to careless driving.
- Irrigation scheduling is done once per week, so water is limited.
- No market for the produce.
- Only reddish brown clayey soils are suitable for irrigation hence limited land for expansion due to the fact that the majority of the surrounding area rely on agriculture to overcome poverty.

Farmers in the study area do recognize water supply and irrigation scheduling as factors challenging their farming and indicated that if the above mentioned areas of concern are addressed, the scheme can perform well.

4.3 Description of Dzindi irrigation layout scheme

The total irrigated area at Dzindi irrigation scheme amounts to 136 ha. The irrigation scheme consists of 4 irrigation blocks as shown in Figure 17 and the combination of these blocks totals to 106 plots (Table 8). Each farmer has approximately 1.28 ha of irrigable land.

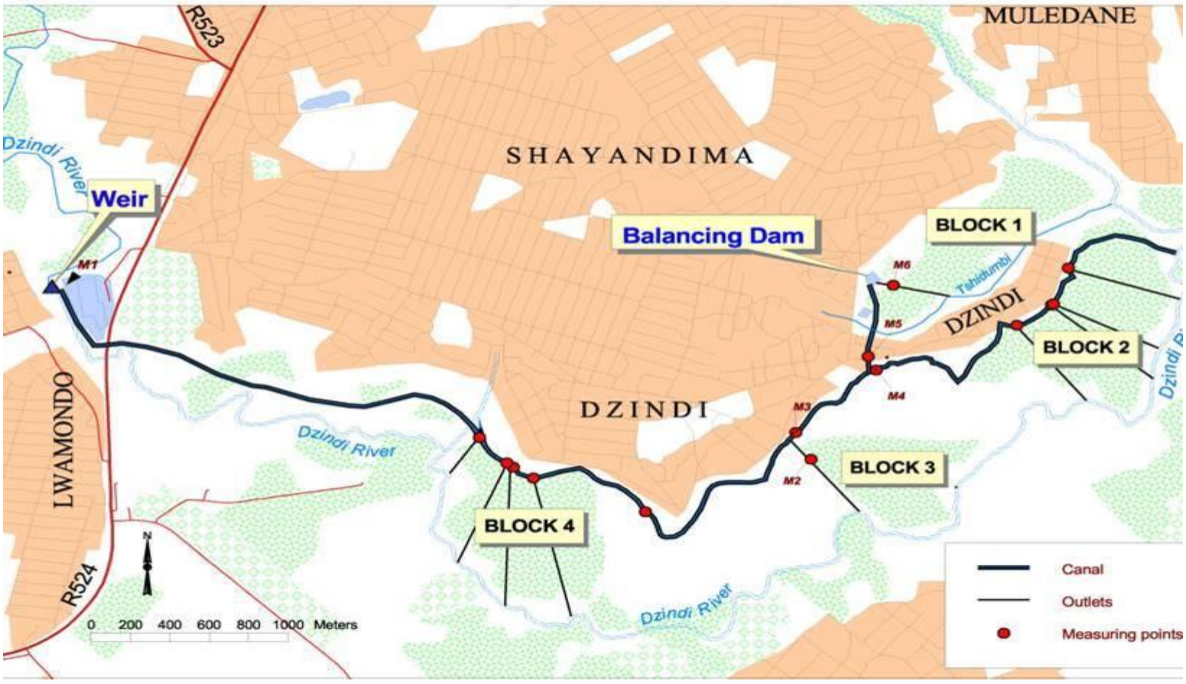


Figure 167: A typical layout of farmers' plots in Dzindi and its distribution canal (van der Stoep & Nthai, 2005).

The plots are divided into a number of beds ranging between 10 and 36. The lengths of the beds varied from 30 to 90 m, while the width varied from 4 to 10 m. Each bed is further subdivided into strips. The length of the strips was found to vary from 5 to 10 m. On average, a typical bed would have 7 to 12 strips. Furrow spacing' were found to vary from 50 to 90 cm, with 70 cm being the most frequent.

The farmers practice short furrow irrigation. De Lange (1994) describes short furrow irrigation as a form of surface irrigation whereby a field is subdivided into small narrow basins separated from each other by earth ridges. Table 8 shows the distribution of plots per Irrigation Block.

Table 8: Distribution of Plots per Irrigation Blocks in the Dzindi Irrigation Scheme

Irrigation Blocks	Block 1	Block 2	Block 3	Block 4	Total
Number of plots	25	35	13	33	106
Selected plots	2	1	1	1	5

Table 8 also shows the plots that have been selected for the current study. In number the plots are 5 across the four blocks.

4.4 Water supply system in Dzindi irrigation scheme

The Dzindi River is the main source of irrigation water. Water for domestic is supplied by the Thohoyandou municipality. The concrete canal from the weir distributes the water to the four irrigation Blocks. While the concrete furrow brings water to the farmers’ plots or field.

The distribution of furrows has been designed to allow water to enter the fields at regular intervals. In three of the four irrigation blocks, the main canal directly supplies the secondary distribution furrow, which brings the irrigation water to plot edge. In Block 1, the canal supplies water to an earthen dam, from where it is transferred to the distribution furrows and the plots.

4.5 The Current Water scheduling at Dzindi

The time to irrigate at Dzindi irrigation scheme is of crucial importance as water allocation is subject to limitations. The amount of water entering the scheme is sufficient only to allow each farmer to irrigate his or her field once per week.

Each day, two farmers per irrigation block or section of block have the right to draw water from the distribution or secondary canal furrow that serves their section. It was indicated that, one farmer draws water during the morning and the other during the afternoon, but farmers in Dzindi irrigation scheme applied water the whole day due to limited amount of water available. The rule applies during daylight hours only. During the night, those who are willing to work or irrigate may use water. The water flows continuously through the main canal. All water that is not used returns to the River (Letsoalo et al., 2003).

4.6 Assessing the Distribution Uniformity and Coefficient of Uniformity

As already indicated on literature review, the uniformity with which water is applied is as important as how efficiently the applied water was used. This also plays an important role on the growth of the plant. For the crops to grow in a uniform pattern, the uniformity of applying water is crucial so that each part of the irrigated area receives the same amount of water. The uniformity of application also plays an essential role in determining water allocations and the gross amount of irrigation water to apply. In order to ensure that better uniformity of the WFD Detector is achieved, the field was prepared using the hand hoe, augers and measuring tape (Figure 18).

Figure 178: Tools used in preparation for the installation of Wetting Front Detectors

All the farmers planted maize, except the farmer selected in Block 4 (Figure 19). In Block 4 the farmers did not plant in summer and therefore, observations only started after he planted vegetables. On the other hand, there were no Longstops (LSs) for him. Water volumes in the LS were always measured before irrigation and after irrigation. The FullStops (FSs) were checked and their response recorded and reset before irrigation, where necessary (Figures 19 and 20).

Figure 189: Wetting front detectors in one of the farmer's field

Figure 20: Photo showing the FullStop and Longstop (90 cm and 60 cm)

The results of Distribution Uniformity (DU) and Coefficient Uniformity (CU) for all four plots in three blocks are as indicated on Tables 10 and 11.

The WFDs were installed in the farmers’ fields to determine the distribution of irrigation water before the fields were irrigated. The results show that all the distribution uniformity (DU) for all plots in blocks was below the standard DU of furrow which is 65% (Table 9; Figure 21). The farmer 2 in block 1 had a higher DU and CU of 60% and 68% respectively which was closer to the standard DU value. For the other farmers their DU and CU before irrigation were very low which indicated that there was uneven distribution of water in these plots. This is due to the fact that farmers irrigate once per week as per the schedule which makes it difficult for the soil to allow water to infiltrate and percolate to the wetting front zone properly. The poor DU, indicated by the uneven infiltrated water, has resulted in excessive watering in these blocks. That is, more or less water was applied than necessary to satisfy the crops.

Table 9**:** Results of DU and CU (%) as per the three Blocks Before Irrigation

	Block 1 Farmer 1	**Block 1 Farmer 2**	**Block 2 Farmer 1**	**Block 3 Farmer 1**
DU in %	5.2	60.2	37.9	43.2
CU in %	13.0	68.2	42.8	52.3
SD	2.9	28.9	42.0	15.5
CV	1.2	0.4	0.6	0.4

Note: Standard Deviation (SD) and Coefficient of Variation (CV)

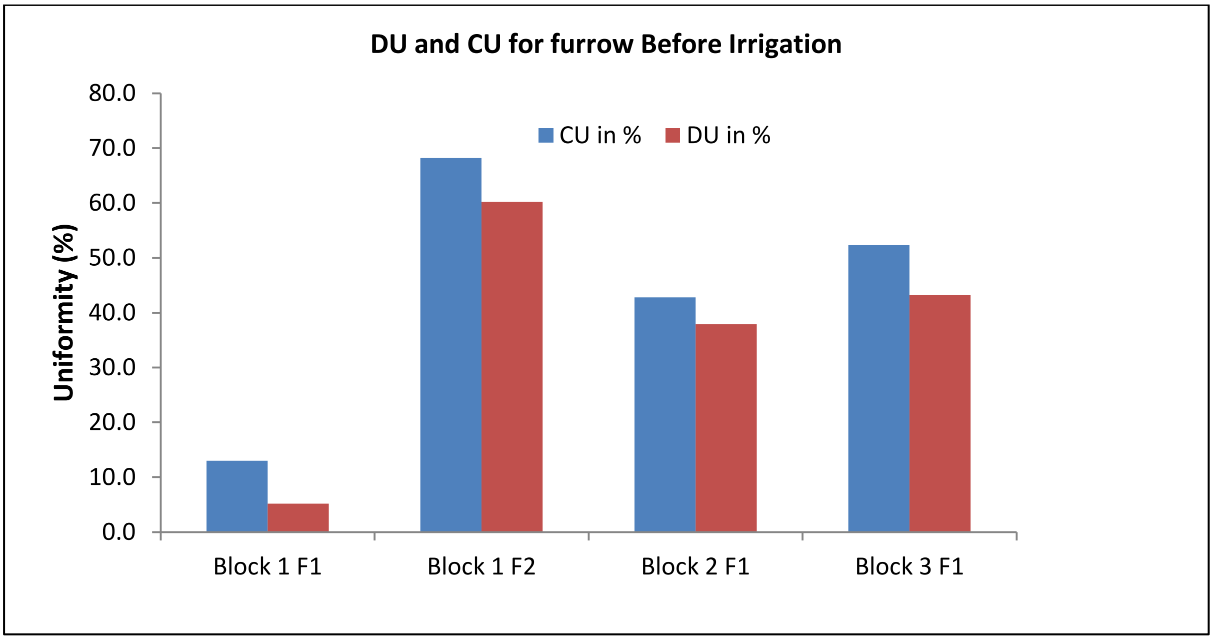


Figure 219**:** DU and CU relationship Before Irrigation

Then a week later, the fields were irrigated and the WFDs showed that there was a slight improvement in the distribution of water (Table 10; Figure 22). The farmer 2 in block 1 had a higher DU and CU of 63% and 68% respectively which was closer to the standard DU value. The farmer 1 in block 3 had a slight higher DU and CU of 60% and 72% respectively which was also closer to the standard DU value. The farmer 1 in block 2 also improve his irrigation strategy with DU and CU which were above 55%. But the farmer 1 in block 1, the DU and CU after irrigation were very low which indicated that there was uneven distribution of water in this plot. The DU results of this study are slightly lower than the DU results of 66% of van der Stoep & Nthai (2005) for the same Dzindi irrigation scheme.

Table 10: Results of DU and CU (%) as per the three Blocks After Irrigation

	Block 1 Farmer 1	Block 1 Farmer 2	Block 2 Farmer 1	Block 3 Farmer 1
DU in %	0.0	63.0	55.2	60.1
CU in %	1.9	67.6	59.6	72.1
SD	7.1	34.7	43.8	21.8
CV	1.2	0.4	0.6	0.4

Note: Standard Deviation (SD) and Coefficient of Variation (CV)

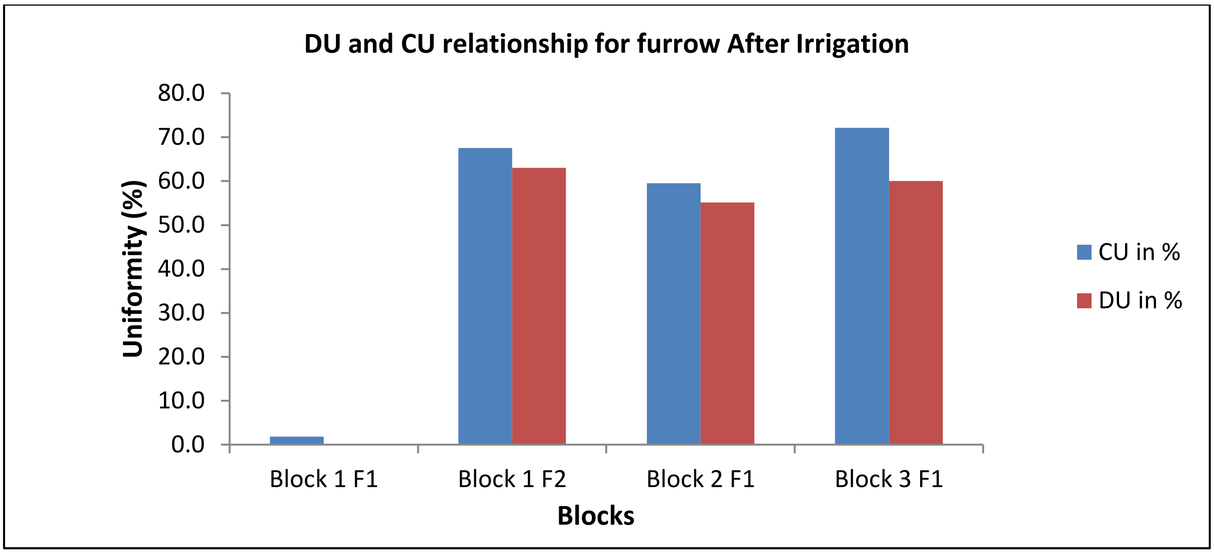


Figure 202**:** DU and CU relationship After Irrigation

Ayana et al. (2006) indicated that a completely uniform application would have a DU of 100%. The more unevenly the system distributes water, the smaller the DU value. High uniformity and water use efficiency can be achieved if the water is rapidly distributed over the entire basin so that the difference in infiltration opportunity time is small throughout the basin (Dedrick et al., 1982). Therefore, the above results simply show that water was distributed well in Block 1 famer 1, Block 1 farmer 2, Block 2 farmer 1 and Block 3 farmer 1. Hence the land was prepared well and the soil was levelled properly as to allow uniform distribution and infiltration to reach the wetting zone. Variation in soil infiltration characteristics can affect the water distribution uniformities attained in the plot. For instance, the DU and CU for farmer 1 in block 1 are poor due to the fact that water movement were restricted as a result of the sandy soil found in that plot which does not hold much water. The amounts of water collected in the LSs were an indication of the response of the detectors. Even though factors such as the amount of water applied in the furrow, soil type and length of furrow had an effect on the detector response, it was also observed that the way the farmer manages the water once it is let in the furrow matters a lot. For instance, it was observed and discussions were held with the farmer 1 in block1 pointing out that he did not give sufficient time for water to infiltrate in the soil. High uniformity occurs only with farmer 2 in block 1, however the DU is still less than the standard distribution uniformity for furrow irrigation. The significant loss of water in this regard is due to deep percolation. In this case, farmer 1 in block 1 has accumulated some volume of water due to the time it takes to settle which is one week before the farmer irrigates again. Hence, it is due to the fact that farmers irrigate once per week as per the schedule which makes it difficult for the soil to allow water to infiltrate and percolate to the wetting front zone properly.

4.7 The wetting pattern in the different farmers' fields

By comparing the responses of the LongStop Wetting Front Detector (LS WFD) and the Fullstop wetting front detector (FS WFD), with an exception of Block1 farmer 1, the LSs performed fairly well but the FSs did better than was expected (Table 11). This was due to the fact that the farmer gave sufficient time to allow water to infiltrate into the soil.

Table 11: Mean Activation frequency of the WFDs

BLOCK	**Activation frequency of LS90 after irrigation (%)**			**Activation frequency of LS60 after irrigation (%)**		
	111	**112**	**113**	**121**	**122**	**123**
Block 1 farmer 1	0.0	0.0	12.5	0.0	37.5	25.0
Block 1 Farmer 2	55.0	95.0	100.0	61.1	55.6	66.7
Block 2 Farmer 1	100.0	54.2	95.8	58.3	50.0	70.8
Block 3 Farmer 1	42.9	46.7	89.0	42.3	53.8	92.3

With the LSs, there was no observable trend between placement depths and the length of the LSs. At times, the shallow ones responded better than the deep ones and vice versa. As indicated before, allowing sufficient time for water to penetrate and infiltrate into the soil plays an important role. The same applies to the length of the LSs. Under the controlled experiment at Univen which was undertaken to test and examine the response of these devices before they were installed at Dzindi irrigation scheme, the LS60 seemed to perform better than the LS90 but in the farmers' fields, no definite trend was observed. It was assumed that farmers might have under-irrigated in this case.

In Blocks 1 and 3, the FSs responded very well (Tables 12 to 15). This was due to the fact that both canals in blocks feeding the furrows were carrying sufficient water that resulted in high infiltration into the soil. The same cannot be said of Block 2 farmer 1 where the global mean response was about 40% of the time (Table 14).

But the farmer 1 in block 1, though the DU and CU after irrigation were very low but FS response was favourable with an average of 82% (Table 12). The reason for low FS is that there was uneven distribution uniformity and much water percolates deep down the root zone, hence low DU and CU.

Table 12**:** FullStop responses in Block1 farmer 1 using the WFDs

Events	**FS-A response before irrigation**			**FS-A response after irrigation**			**FS-B response before irrigation**			**FS-B response after irrigation**			**Mean**
	F11S	**F12S**	**F13S**	**F11S**	**F12S**	**F13S**	**F21C**	**F22C**	**F23C**	**F21C**	**F22C**	**F23C**	
Number of no activations	5	1	2	0	0	0	4	2	2	1	0	0	1.4
Number of activations	7	6	5	3	3	3	3	5	5	2	3	3	4.0
Total number of events	12	7	7	3	3	3	7	7	7	3	3	3	5.4
Percentage frequency of activation (%)	71	86	71	100	100	100	43	71	71	67	100	100	81.7

The farmer 2 in block 1 had a slight higher DU and CU of 63% and 66% respectively and this is confirmed by the FS mean response of 50% (Table 13). In this case, water has been evenly distributed and it was given enough time to infiltrate into the wetting zone. Hence, the DU and CU values were higher. For block 1, the LS90 stayed wet to 90 cm at top of furrow and stayed wet to 60 cm at bottom of furrow and the LS60 stayed wet to 90 cm at top of furrow but drying out to 60 cm at bottom of furrow (Figure 23).

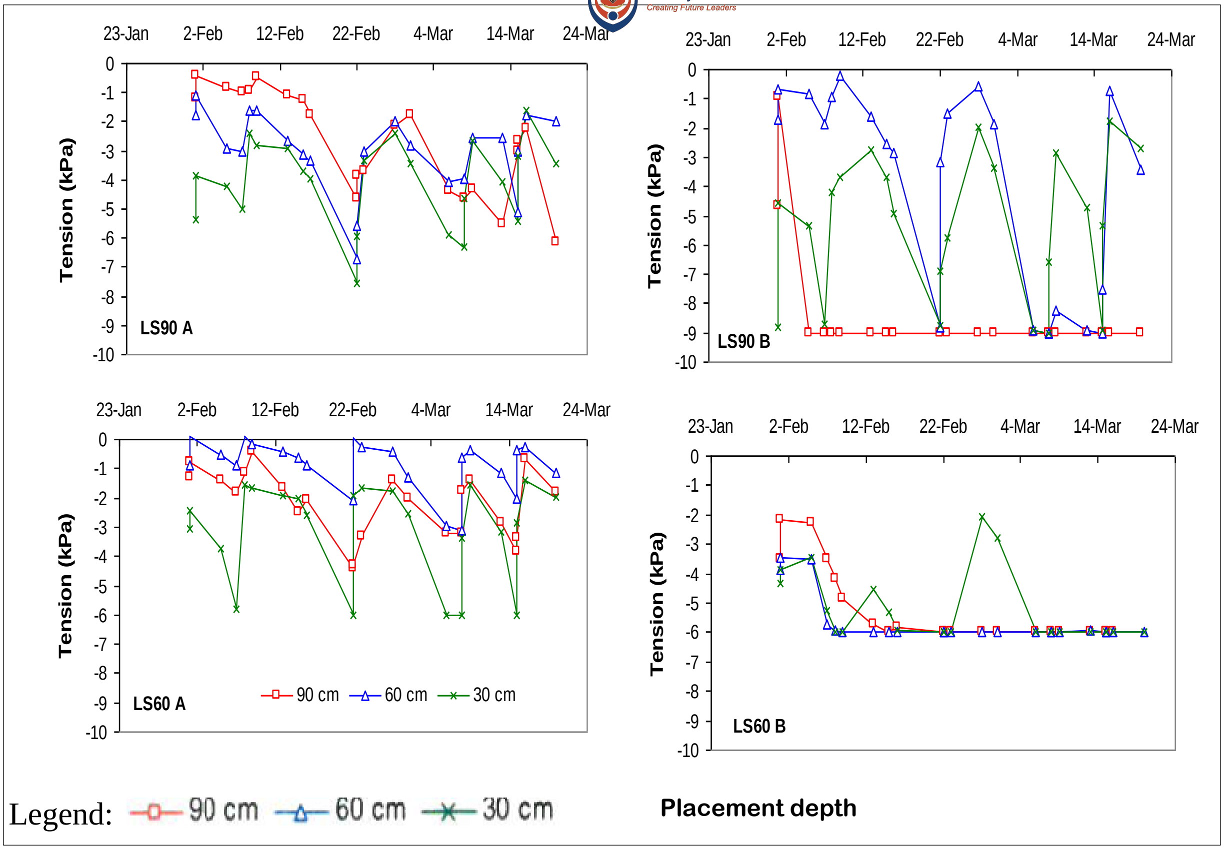


Figure 213: Responses of the LongStop Wetting Front Detector and the Fullstop wetting front detector for block 1

Table 13:FullStop responses in Block1 farmer 2 using the WFDs

Events	FS-A response before irrigation			FS-A response after irrigation			FS-B response before irrigation			FS-B response after irrigation			Mean
	F11S	F12S	F13S	F11S	F12S	F13S	F21C	F22C	F23C	F21C	F22C	F23C	
Number of no activations	6	1	8	7	3	7	0	11	5	**3**	8	5	5.3
Number of activations	7	12	5	3	7	3	12	1	7	6	1	4	5.7
Total number of events	13	13	13	10	10	10	12	12	12	9	9	9	11.0
Percentage frequency of activation (%)	54	92	38	30	70	30	100	8	58	67	11	44	50.3

The farmer 1 in block 2 also improves his irrigation strategy with DU and CU which were above 55% and this corresponded to a low FS mean response of 40% (Table 14). The low FS response might be due to sandy nature of soil which did not retain moisture for long time.

Table 64: FullStop responses in Block 2 farmer 1 using the WFDs

Events	**FS-A response before irrigation**			**FS-A response after irrigation**			**FS-B response before irrigation**			**FS-B response after irrigation**			**Mean**
	F11S	**F12S**	**F13S**	**F11S**	**F12S**	**F13S**	**F21C**	**F22C**	**F23C**	**F21C**	**F22C**	**F23C**	
Number of no activations	2	3	2	3	4	2	10	8	10	11	10	11	6.3
Number of activations	8	7	8	9	8	10	0	2	0	0	1	0	4.4
Total number of events	10	10	10	12	12	12	10	10	10	11	11	11	10.8
Percentage frequency of activation (%)	80	70	80	75	67	83	0	20	0	0	9	0	40.3

For block 2, the LS90 showed 2 fronts to 30 cm at top of furrow, no fronts were observed at bottom of furrow and the LS60 showed zero fronts at top of furrow, showed 3 to 4 fronts to 60 cm at bottom of furrow (Figure 24).

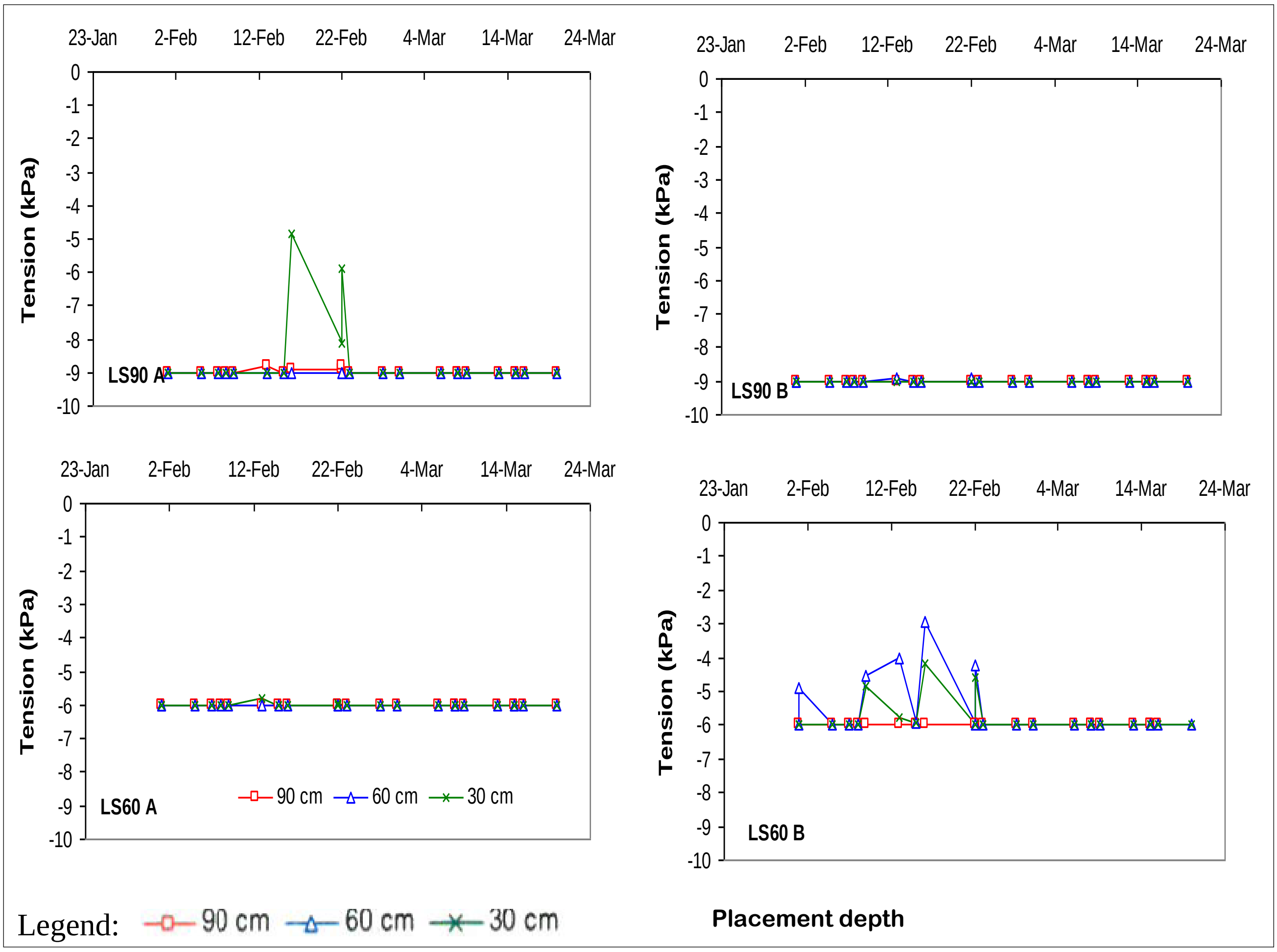


Figure 224: Responses of the LongStop Wetting Front Detector and the Fullstop wetting front detector for block 2

The farmer 1 in block 3 had a slight higher DU and CU of 60% and 72% respectively which was confirmed by higher FS mean response of 83% (Table 15).

Table 75**:** FullStop responses in Block3 farmer 1 using the WFDs

Events	**FS-A response before irrigation**			**FS-A response after irrigation**			**FS-B response before irrigation**			**FS-B response after irrigation**			**Mean**
	F11S	**F12S**	**F13S**	**F11S**	**F12S**	**F13S**	**F21C**	**F22C**	**F23C**	**F21C**	**F22C**	**F23C**	
Number of no activations	1	1	1	1	1	1	4	1	4	3	3	3	2.0
Number of activations	13	13	13	10	10	10	10	13	10	7	7	7	10.3
Total number of events	14	14	14	11	11	11	14	14	14	10	10	10	12.3
Percentage frequency of activation (%)	93	93	93	91	91	91	71	93	71	70	70	70	83.1

For block 3, the LS90, stayed very wet to 90 cm at top of furrow, but dries out at 60 cm, similar at end of furrow and LS60 stayed wet to 90 cm at top of furrow and dries out at 3 and 60, wetter at bottom of furrow (Figure 25).

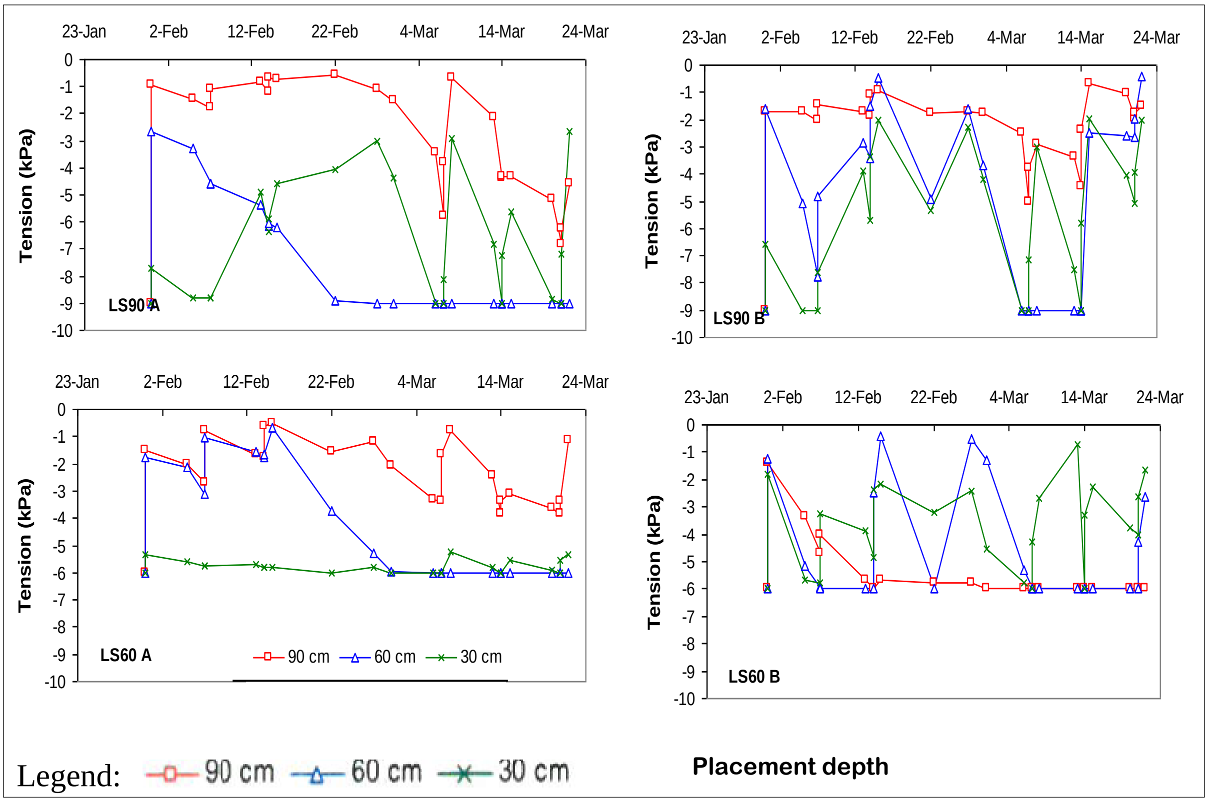


Figure 235: Responses of the LongStop Wetting Front Detector and the FullStop wetting front detector for block 3

For block 4, LS90, the wet fronts were reaching all depths at top of furrow, but mostly just to 30 cm at bottom and LS60, wet fronts were reaching all depths at top of furrow, but mostly just to 30 cm at bottom (Figure 26).

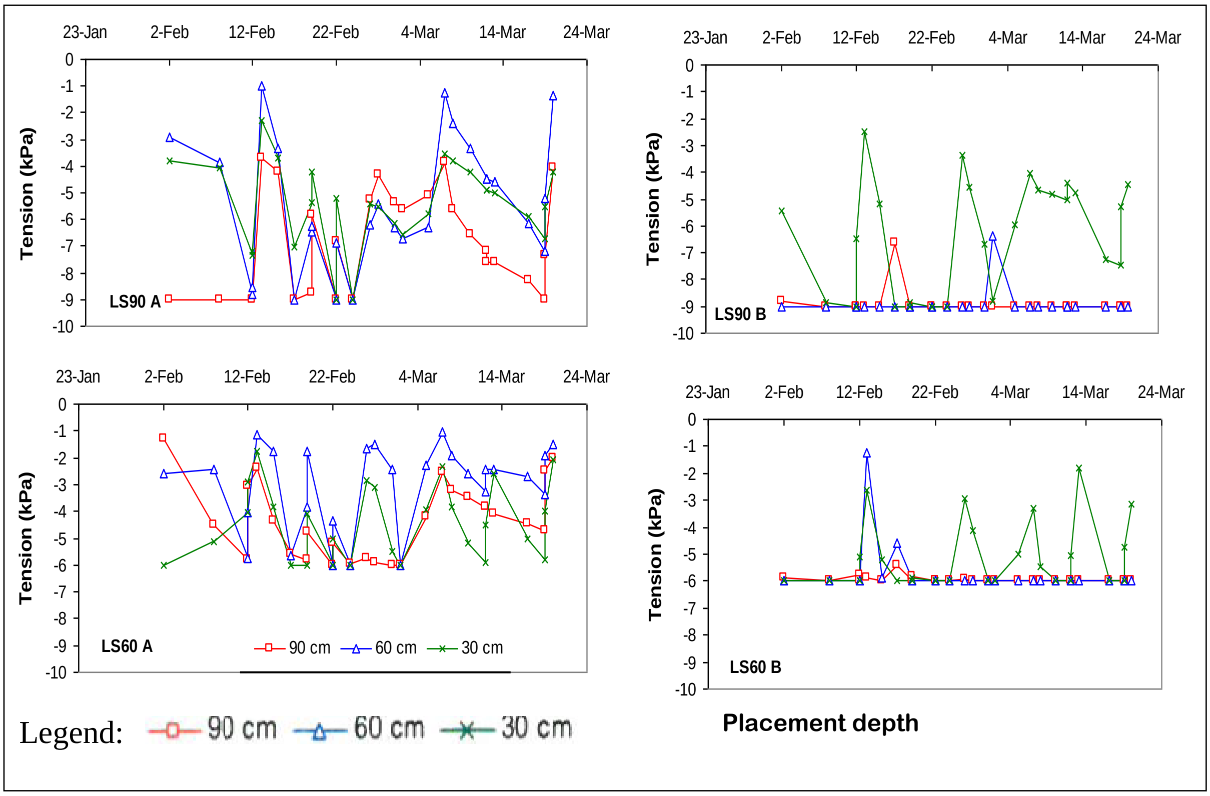


Figure 246: Responses of the LongStop Wetting Front Detector and the Fullstop wetting front detector for block 4.

Generally all depths move in synchrony with irrigation events, and the depth of wetting is quite evident although sometimes a response at 90 and not at 60 cm was observed. Where a response is observed at 90 cm, it simply means that the farmers' in this case were doing deep irrigation, water was moving out of the root zone.

No wetting front has been detected in Block 2 farmers' plot after irrigation. This may be the result of soil which was now sandy and does not hold moisture for a long period of time. It was observed that when water is brought to the plot, it immediately percolates or infiltrate deep down into the soil beyond the root zone. Although the previous study indicated that the soil in all farmers' plots were reddish in colour, the situation in this plot was different to the other plots since the soils were now loamy to sandy as a result of sands from road reserve being eroded to the farm plot. The soil study of Murray (1951) after the establishment of Dzindi irrigation scheme was able to identify four main soil types: reddish brown clays, grey sands, grey clays and alluvium. Later another study by Van Averbeke (2008) was able to identify another fifth soil type at Dzindi irrigation scheme, which was clay. According to van

Averbeke et al. (2014) Annual Report, they classified the soil in Block 2 as soil unit B on the soil map consisted of soils with impeded drainage. They were classified as soils of the Westleigh form (Soil Classification Working Group, 1991). Generally they were deep soils, but the morphology of the B-horizon (distinct high-chroma mottles embedded in a grey coloured matrix) indicated that root development was subject to restrictions as a result of occasional water logging. Root density declines with soil depth, and as a result, plants preferentially extract water from the surface layers, resulting in a triangular water extraction pattern.

The farmer in Block 2 did not record any wetting fronts after irrigation (Figure 27A). The Farmer 1 in Block 1 recorded a number of strong wet fronts at both locations but is wetter at the top of the furrow than the bottom (Figure 27B). The farmer 1 in Block 3 only recorded wetting fronts at the bottom of the furrow whilst the soil dries at the top of the furrow (Figure 27C). The farmer 1 in block 4 recorded numerous fronts at the top of the furrow and only one at the bottom (Figure 27D).

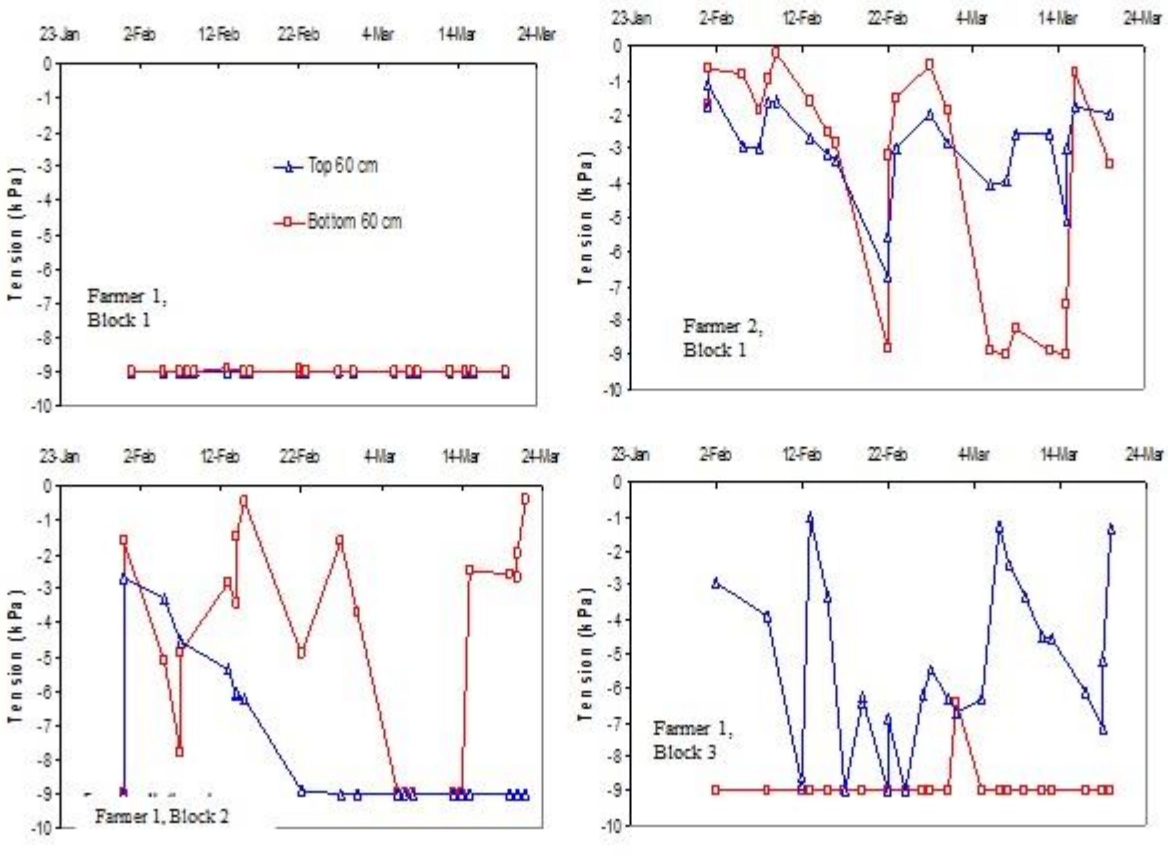


Figure 257: Summary of all four farmers showing only the LongStop 90 at 60 cm depth at top and bottom of field

Generally they were deep soils, but the morphology of the B-horizon (distinct high-chroma mottles embedded in a grey coloured matrix) indicated that root development was subject to restrictions as a result of occasional water logging. Root density declines with soil depth, and as a result, plants preferentially extract water from the surface layers, resulting in a triangular water extraction pattern. Averbeke et al. (2014) Annual Report, they classified the soil in Block 2 as soil unit B on the soil map consisted of soils with impeded drainage. They were classified as soils of the Westleigh form (Soil Classification Working Group, 1991). Soil moisture contents in different farmer's fields were also measured before and after irrigation. The results of the average soil moisture content before and after irrigation are as indicated on Table 16.

Table 86: Average soil moisture volume (ml) before and after irrigation

		LS90			LS60		
Farmers field	**Time of irrigation**	**30 cm**	**60 cm**	**90 cm**	**30 cm**	**60 cm**	**90 cm**
Block 1 farmer 1	Before irrigation	6.6	0.3	0.8	3.3	6.3	0
	After irrigation	11.9	0.0	0.3	8.5	16.3	0
Block 1 farmer 2	Before irrigation	80.8	116	74.9	32.2	57.8	50.5
	After irrigation	120.1	136.7	83	55.1	69.5	53.8
Block 2 farmer 1	Before irrigation	36	49.5	130.5	15.8	20.9	37.9
	After irrigation	93.1	74.6	158.5	42	44.4	57.2
Block 3 farmer 1	Before irrigation	50.5	31.6	17.2	6.9	25.6	14.1
	After irrigation	88.8	48.4	33.6	51.2	48.5	25.7

The above table simply shows the volumes of water that has been measured and recorded in both LS90 and LS60 before and after irrigation. Much water has been collected in Block 1 farmer 2, Block 2 farmer 1 and Block 3 farmer 1 before and after irrigation. The highest volumes of water recorded before and after irrigation were 131ml and 159 ml respectively for LS90 placed at a depth of 90 cm in Block 2 farmer 1.The results simply tell much that the more the placement depth down the soil profile, that there is more accumulation of water. However, for Block 1 farmer 1 much of the water is lost through deep percolation especially for LS60 at a placement depth of 90 cm. Table 17 below indicates the percentage of soil moisture gain or loss after irrigation.

Table 97: Percentage of soil moisture gain or loss after irrigation

soil profile	**% Soil moisture gain or loss after irrigation**							
	LS90				**LS60**			
	block 1 farmer 1	Block 1 farmer 2	Block 2 farmer 1	Block 3 farmer 1	block 1 farmer 1	Block 1 farmer 2	Block 2 farmer 1	Block 3 farmer 1
30 cm	80	49	159	76	61	71	166	642
60 cm	-100	18	51	53	1530	20	112	89
90 cm	-6.25	11	21	95	0	7	51	82

Much of the water was lost in Block 1 farmer 1 for LS90 as a result of deep percolation in both placement depth of 60 cm and 90 cm and conversely there was a gain LS60 at 60 cm. It is evident that after irrigation has taken place, much water accumulates with the LSs.

Yusuf (2004) investigated the soil moisture contents down the profile to the depth of 90 cm and discovered that the soil moisture contents down the profile has an increasing trend and these phenomena lead to the conclusion that water was lost by deep percolation than runoff and evaporation.

During field observation and measurements of the volumes of water from the WFD technology before and after irrigation, farmers in each representative Block were always on site as to observe the performance of the tool. Farmers indicated that the device is straightforward to use and it does not require any technical know-how rather the indicator just pop up which simply mean that no more irrigation is required. They also indicated the tool is user friendly and affordable such that one can be able to set it up for implementation without any supervision.

From the analyses above, it is therefore recommended that farmers do adopt the use of WFD technology as a means of improving irrigation scheduling. The tool is cheap and easily accessible in most agricultural farmer's practice shops which are recommended by the Food and Agricultural Organisation (FAO).

CHAPTER FIVE: CONCLUSION & RECOMMENDATIONS

5.1 CONCLUSIONS

The study was initiated to test the suitability of the irrigation scheduling technology, Wetting Front Detectors "on farm" as a means to improve irrigation scheduling at Dzindi irrigation scheme.

From the challenges documented, it was found that farmers in the study area do recognize water supply and irrigation scheduling as factors challenging their farming.

During field observation of the WFDs, it was discovered that farmers were very fond of the tool. They indicated that the device is straightforward to use and it does not require any technical know-how rather the indicator just pop up which simply tells much that no more irrigation is required. They also indicated the tool is user friendly and affordable such that one can be able to set it up without any supervision.

It could be deduced from the study that the technology at hand can improve water management at farm level through water use efficiency in irrigation and increases the productive use of water by growing more crops per drop thus resulting in food security. This could be achieved if the field is well prepared and the soil is levelled for better distribution uniformity.

Performance of irrigation systems is evaluated by means of different performance indicators including Distribution Uniformity (DU) and Coefficient Uniformity (CU). At Dzindi irrigation scheme, two critical performance indicators were considered namely the DU and CU because of their suitability to furrow irrigation system. The results of these two performance indicators shows that water was evenly distributed on most of the farmer's fields. Poor DU occurred in Block 1 farmer 1 where much of the water was lost through deep percolation to the root zone.

The responses of the LongStop Wetting Front Detector (LS WFD) and the Fullstop wetting front detector (FS WFD), showed that, the LSs performed fairly well but the FSs did better than was expected. This was due to the fact that the farmer gave sufficient time to allow water to infiltrate into the soil. The results of the average soil moisture content indicated that the highest volumes of water were lost through deep percolation.

From the analyses of the Wetting Front Detectors, it has been shown that farmers were explicitly doing well in terms of DU and CU. There is need for improvement to use an efficient irrigation system since furrow irrigation is one of the irrigation system that loses a lot of water during distribution to the field through deep percolation, runoff and evapotranspiration. Therefore, the Wetting Front Detector can be considered as a tool for irrigation scheduling to guide farmers as to when to irrigate and how much the crop require. However, there is a need for improvement and capacity building in using this tool.

5.2 RECOMMENDATIONS

Since this is a transition and for the scheme to adopt the Wetting Front Detectors as tested, the following needs to be taken into account in order to improve irrigation scheduling:

- Water continues to be a scarce resource and needs to be protected, used, managed, conserved, developed and controlled in a sustainable manner. Most of the canals conveying water to the Dzindi irrigation scheme and to the furrows are broken and lack of tractors contributes to the poor irrigation efficiency. Therefore, there is need for improvement of conveyance systems and infrastructure and this can only happen through the Revitalisation of Smallholder Irrigation Schemes (RESIS) and assistance offered through Resource Poor Farmers (RPF) grants.

- Further studies need to be undertaken which will focus on the mapping of the soils in each Block and not mapped as a single unit. This will enable one to determine whether the poor distribution uniformity that occurs at Block 1 farmer 1 was a result of soils or not.

- The study did not test the quality of water samples that were collected from the LSs and FSs Wetting Front Detectors for fertilisers and salt levels at the farmers' field due to some unforeseen conditions. Since the study encourages farmers to continue to use the tool for irrigation scheduling, it is therefore recommended that future research take this into consideration because fertilisers and salt content has a serious implication on the growth of crops.

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