AN ASSESSMENT OF SHALLOW WATER TABLES AND THE DEVELOPMENT OF APPROPRIATE DRAINAGE DESIGN CRITERIA FOR SUGARCANE IN PONGOLA, SOUTH AFRICA

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Submitted in fulfilment of the requirements
for a research Masters degree in Engineering

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September, 2012

EXAMINER’S COPY

ABSTRACT

South Africa, in common with all countries with arid or semi-arid climatic conditions, is facing the consequences of irrigation development without effective subsurface drainage. The quality of irrigation water is also decreasing and hence more water is required for leaching. This is resulting in low irrigation water productivity, as a consequence of shallow water tables, thus limiting crop growth. This study investigated the nature and causes of shallow water table problems in the sugarcane fields of Pongola, South Africa. The DRAINMOD model was also assessed for its reliability to be used as drainage design tool in the area.

A water table map of a 32 ha sugarcane field was generated using groundwater table data monitored in 36 piezometers from September 2011 to February 2012. Nearly12 % of the 32 ha sugarcane field was found to be affected by shallow water tables of less than the 1.0 m Design Water Table Depth (WTD). The inability of the adopted Drainage Design Criteria (DDC) to cope with drainage needs was found to be the cause of the poor drainage problem. On the other hand, analysis of WTDs in a field with a poorly-maintained subsurface drainage system confirmed that the drainage problem is exacerbated by poor drainage maintenance. It was recommended that the subsurface DDC in the area be revisited and that timely maintenance also be provided

The DRAINMOD model was calibrated and verified using actual WTD and Drainage Discharge (DD) data. The model evaluation results revealed that the DRAINMOD model can reliably predict WTDs, with a Goodness of fit (R^2), Mean Absolute Error (MAE) and Coefficient of Residual Mass (CRM) of 0.826, 5.341 cm and -0.015, respectively. Similarly, the model evaluation results in predicting DDs were also good, with R^2, MAE and CRM of 0.801, 0.181 mm.day^{-1} and 0.0004, respectively. A further application of the validated model depicted that drain pipes installed at depths ranging from 1.4 m to 1.8 m and a spacing ranging from 55 to 70 m, with a design discharge of 2.5 to 4.2 mm.day^{-1}, were adequate in ensuring safe WTDs between 1.0 and 1.5 m in clay-loam soil. On the other hand, drain depths ranging from 1.4 to 1.8 m and spacing between 25 and 40 m, were found to be appropriate in maintaining WTDs between 1.0 and 1.5 m in clay soil, with drainage design discharge ranging from 2.5 to 5.1 mm.day^{-1}. These findings suggest that the current drain spacing needs to be reduced, in order to maintain the 1 m design water table depth.

Finally, for the adoptability of the DRAINMOD model in the area, the Rosetta program, a component of the HYDRUS-2D, was tested for its reliability in estimating saturated hydraulic conductivities required by the DRAINMOD model. Results of the investigation revealed that the program can reliably be used to estimate saturated hydraulic conductivities from easily-accessed soil data (% sand, silt, clay and soil bulk density), with R^2, MAE and CRM of 0.95, 0.035 $m.day^{-1}$ and -0.031, respectively. Nonetheless, calibration of the DRAINMOD model based on saturated hydraulic conductivity estimated by the Rosetta program was recommended.

The findings of this research will form the basis for implementing an agricultural drainage policy that will ensure sustainable rain-fed and irrigation crop production systems in South Africa.

PREFACE

DECLARATION

I, **MPHATSO MALOTA,** declare that:

1. The research reported in this thesis, except where otherwise indicated, is my original work. My supervisor, Dr Aidan Senzanje provided guidance in ensuring that the research work is up to standard.
2. This thesis has not been submitted for any degree or examination at any other University.
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ACKNOWLEDGEMENTS

This MSc research formed part of a Water Research Commission (WRC) Project titled "Development of Technical and Financial Norms and Standards for Drainage of Irrigated Agriculture". I therefore thank the WRC for funding this research and all the individuals who formed the project team, for their guidance and assistance they gave me.

Sincere appreciation should go to the following:

- The Most High Jah, for everything, without whom I am nothing. May His holy name be glorified.
- My supervisor, Dr A Senzanje for his valuable guidance, support and encouragement. Thank you for your understanding.
- Mr Johan van der Merwe and Mr Sfundo Nkomo of the Pongola agricultural office for all the assistance they gave me during field work.
- Prof. Kourosh Mohammadi of Tarbiat Modares University – Iran, for his assistance in converting weather data files to the appropriate DRAINMOD format.
- Colleagues, staff and students of the School of Engineering for all their support, trust and encouragement.
- Empress Monica and Princess Wathu, for their endurance, unconditional love and encouragement during the whole study period, especially when there appeared to be little progress.
- My mum, brother Joey, and all my sisters for their unending support and love, which they have always given me.
- Peter McIntosh, for always reminding me to pick myself up every time things seemed not to make any progress. Thank you for your positive words of great upliftment.

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LIST OF ABBREVIATIONS

AI - Aridity Index

ASAE - American Society of Agricultural and Biological Engineers)

CF - Cumulative Frequency

CI - Confidence Interval

CRM - Coefficient of Residual Mass

CV - Coefficient of Variation

DD - Drainage discharge

DDC - Drainage Design Criteria

DWAF - Department of Water Affairs and Forestry

EC_e - Electrical conductivity of soil extract

EC_{iw} - Electrical conductivity of irrigation water

FAO - Food and Agriculture Organisation of the United Nations

K_{sat} - Vertical saturated hydraulic conductivity

$K_{L\text{-}sat}$ - Lateral saturated hydraulic conductivity

MAE - Mean Absolute Error

PVC - Polyvinyl Conduit

R^2 - Goodness of fit or Coefficient of Determination

SEPAC - South-eastern Purdue Agricultural Centre

SWCC - Soil Water Characteristic Curve

UNESCO - United Nations Educational, Scientific and Cultural Organization

USDA - United States Department of Agriculture

WRC - Water Research Commission

WTD - Water table depth

1. INTRODUCTION

Waterlogging and soil salinization, which have been eroding the crop production potential of many irrigated lands worldwide, also occurs in South Africa. In addition, food demand in South Africa is also increasing. This is putting more pressure on the government to emphasize the importance of crop production through irrigation. The total area of land in South Africa with irrigation potential is estimated at 1.5 million ha (Backeberg, 2000). According to DWAF (2004), irrigation consumes nearly 62 % of South Africa's surface water resources per year. This is because, approximately 80 % of the land in South Africa lies within a semi-arid climatic region (Freisem and Scheumann, 2001; DWAF, 2004). Thus, irrigated agriculture can not be overlooked in most areas.

Generally-speaking, all irrigation water contains a certain amount of salts (Kahlown and Azam, 2002; FAO, 2006; Singh *et al.,* 2010). Hence, the propensity of salt accumulation within the crop root zone is inevitable. The irrigation engineering community normally prevents this build up of salts in the soil by adding a leaching requirement over and above the irrigation water requirement (FAO, 2007). This means repeatedly recharging the groundwater table every time a farmer irrigates their crop. Therefore, over time, the salt accumulation within the active top soil layers starts to limit crop production, as leaching is no longer achievable due to shallow water tables (Cetin and Kirda, 2003). As a result, these problems of waterlogging and soil salinization begin to unfold simultaneously.

Scientific history indicates that between 2000 and 4000 BC, the Sumerians deserted their agricultural lands in the valleys of Euphrates and Tigris in the Mesopotamia (Luthin, 1964; Pitman and Lauchli, 2002). According to Jacobsen and Adams (1958), Luthin (1964), Boyden (1987) and Ghassem *et al.* (1995), this was attributed to poor drainage, which led to the desertification of the land. In the same light, Santayana (2005) cautions that "those who ignore lessons from history are doomed to repeat them". Unfortunately, looking at the prevailing waterlogging and soil salinization statistics, history appears to be repeating itself. Currently, nearly 500,000 ha of the total world agricultural lands are being deserted annually as a result of waterlogging and soil salinization (Freisem and Scheumann, 2001). It is estimated that nearly 20 % of the world's irrigated land is affected by waterlogging and salinization (Freisem and Scheumann, 2001; Hirekhan *et al*., 2007), with some estimations up to 50 % (Pitman and Lauchli, 2002).

A good example in the South African context are the Boitumelo vineyards, a 2007 government funded project in the Western Cape Province, which were salinized within nine months after commencement of irrigation farming (Armour and Viljoen, 2008). This situation led to a cutback of the cultivated area by nearly 80 % of the initially developed land, leaving only 20 % of the land appropriate for crop production (Armour and Viljoen, 2008).

The need for effective subsurface drainage systems in all irrigated lands cannot be over-emphasized, as it has proven to be the most sustainable and long-term solution to both waterlogging and soil salinity problems (Smedema *et al.,* 2000; Singh *et al.,* 2006; Noria *et al.*, 2007). Like any other agricultural water management system, success is dependent on how well the systems are designed, installed and are maintained. However, from the design perspective, agricultural drainage systems are meant to avert soil salinization and waterlogging from happening, as opposed to reclaiming already waterlogged or salinized soils (Oosterbaan, 2000; Bastiaanssen *et al.,* 2007). Technically, this means that drainage needs must be predicted, based on the excess water being supplied by the irrigation system or rainfall. Therefore, to effectively establish root causes of shallow water tables and soil salinization problems in agricultural areas, their relations with rainfall and irrigation water management practices at a scheme level must be thoroughly understood.

Studies by Manjunatha *et al.* (2004), Srinivasulu *et al.* (2004) and Ritzema *et al.* (2008) clearly show how the lack of a meticulous understanding of the relation among recharge, water table depth and subsurface drainage systems have resulted in the frequent adjustment of subsurface drainage design parameters (drain depth, spacing and design discharge), in the search for more accurate and optimum design parameters. Conversely, drainage installation costs have also increased significantly (Ritzema and Shultz, 2010). It is no longer economical, both in terms of time and money, to physically conduct new drainage experiments by installing drains at varied drain depths and spacing (ASAE Standards, 1999).

Fortunately, the advent of drainage simulation models in the 1970's has enabled drainage engineers to perform thorough analyses of the functionality of various subsurface drainage system design parameter combinations prior to system installation (Bastiaanssen *et al.,* 2007).

For example, the application of the DRAINMOD model (Skaggs, 1978), the WaSim model (Hess *et al.,* 2000) and the SaltMOD model (Oosterbaan, 2000), among others, in Australia (Yang, 2008), India (Hirekhan *et al.,* 2007) and Turkey (Bahceci *et al.,* 2006), clearly show that drainage simulation models provide for a simplistic and cost-effective means of designing subsurface drainage systems, as long as calibration and verification data are available.

Although far-reaching research efforts have concentrated on increasing irrigation water productivity in South Africa (e.g. Masiyandima *et al.* (2002), Speelman *et al.* (2008), Speelman *et al.* (2009) and Yokwe (2009)), similar efforts have not been extended to the agricultural drainage sector. No comprehensive research has been conducted for the past 26 years to improve the design of subsurface drainage systems in South Africa (van der Merwe, 2003). Most importantly, irrigation, rainfall and drainage are all inter-related and therefore need to be managed as a whole. It is also undisputable that climate change is impacting on agricultural water management systems dynamics (Gbetibouo and Hassan, 2005; Abraha and Savage, 2006; Benhin, 2008; Bryan *et al.,* 2009) and farmers have to adjust their farming systems to these changes. The challenge for research is, therefore, to consistently assist these farmers on how best they can adjust their farming systems to adapt to these changes in a more sustainable and cost-effective manner.

With respect to irrigation, rainfall and subsurface drainage in South Africa, the following concerns need to be addressed:

a) What is the extent (area) of shallow water table problems in irrigated fields where subsurface drainage systems were initially installed to address the problem?
b) How severe is the shallow water table problem in relation to the irrigation and rainfall cropping seasons?
c) Can poor irrigation water management, the lack of proper subsurface drainage system maintenance and the inability of natural drainage systems to cope with drainage needs, be contributing to the shallow water table problem?
d) How reliable are the currently adopted drainage design criteria in achieving their design objectives?
e) Are there opportunities for computer simulation models to be applied as drainage design tools?

In line with the aforementioned concerns, the research reported in this document was initiated in the sugarcane fields of Pongola, in the KwaZulu-Natal Province of South Africa. This area was chosen because, subsurface drainage systems are in place, yet problems of shallow water tables are still being reported. This study formed part of a South African Water Research Commission (WRC) Project "The Development of Technical and Financial Standards for the Design and Installation of Drainage Systems in South Africa".

1.1 Study Hypothesis and Objectives

The general hypothesis tested in this study is that the inability of natural drainage and/or the existing subsurface drainage systems to cope with prevailing drainage needs result in shallow water tables in the sugarcane fields of Pongola. The general objective of the study was to determine the nature of shallow water tables in the study area, so that quick and cost-effective means of managing and designing subsurface drainage systems could be adopted. Specifically, the study was conducted to achieve the following objectives:

i. to determine the extent, severity and possible causes of shallow water table problems in the sugarcane fields of Pongola, South Africa,

ii. to simulate water table depths in two different soil types at various combinations of drain depth and spacing, using the DRAINMOD model, after calibration and verification,

iii. to develop appropriate drainage design criteria for sugarcane grown under Pongola soil and climatic conditions, and

iv. to test the reliability of the Rosetta program in estimating saturated soil hydraulic conductivities, based on soil particle size and bulk density data.

In an effort to achieve the above-stated objectives, a field study monitoring of the interaction between irrigation, rainfall and subsurface drainage were carried out at three sugarcane fields in the area from September 2011 to February 2012.

1.2 Thesis Outline

This thesis is structured in a "paper format" and is comprised of four chapters. Chapter 1 contains a general introduction of the study. The extent, severity and possible causes of shallow water table problems at a field scale in Pongola, South Africa are presented in Chapter 2. Chapter 3 focuses on the reliability of the DRAINMOD model in predicting water table depth and drainage discharge and its applicability in developing appropriate drainage design criteria under the Pongola conditions. Finally, Chapter 4 contains a general summary, conclusions and recommendations for future research emanating from the study.

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2. A DIAGNOSIS OF WATER TABLE DYNAMICS IN THE SUGARCANE FIELDS OF PONGOLA, SOUTH AFRICA

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Abstract

Water and land are the two natural resources restraining crop production in South Africa. With the increasing demand for food, emphasis has shifted from the sole reliance on rain fed crop production, to irrigation. The reduction in irrigation water quality from surface water sources is, however, posing a big challenge to the sustainability of irrigated crop production. This is because more water is required for leaching, resulting in shallow water tables in agricultural lands. The installation of well designed subsurface drainage systems alone is not enough; the provision of timely maintenance is also necessary. In this study, the extent and severity of problems as a consequence of shallow waters and their possible causes were investigated at three sugarcane fields in Pongola, South Africa. A water table map of a 32 ha sugarcane field was generated, using observed water table depth (WTD) data from 36 piezometers monitored from September 2011 to February 2012. Out of the total 32 ha under cultivation, 12 % was found to be affected by shallow WTDs of less than the 1.0 m design WTD. The inability of natural drainage to cope with subsurface drainage needs, underground seepage and the poor maintenance of subsurface drainage systems appeared to have contributed to the shallow water tables in the area. Furthermore, the currently adopted drainage design criteria also proved unsatisfactory. The system was designed to maintain mean mid-drain spacing WTD and drain discharge (DD) of 1.0 m and 5.0 mm.day^{-1}, respectively. Contrary to this, on average, observed WTD and DD were found to be 20 % and 50 % less than their respective design levels. The subsurface drainage design criteria adopted at the site needs to be revisited by ensuring that the slope of the land is taken into consideration in the drainage design. Furthermore, timely subsurface drainage maintenance must also be provided.

Key words: Drainage design; drain depth; drain spacing; salinisation; water table depth.

2.1 Introduction

Globally, agricultural land degradation due to soil salinization and waterlogging is advancing at approximately 1.5 million ha per year (Armour and Viljoen, 2008). Soil salinization and waterlogging have not only resulted in the failure of many irrigation schemes to achieve their targeted yield projections (Patil *et al.,* 1982; Gupta and Yadav, 1987; Sinha, *et al.,* 1991; Kool, 1993; Wolde Kirkos and Chawla, 1994; Dandekar and Chougule, 2010), but they have also rendered substantially less land for agricultural use (Jacobsen and Adams, 1958; Freisem and Scheumann, 2001). Despite irrigation and drainage being two inextricable agricultural water management systems (Singh *et al.,* 1999; Hurst *et al.,* 2004; Bahceci *et al.,* 2006; Hirekhan *et al.,* 2007), more often than not, irrigation systems worldwide have been developed without the proper consideration of the need for drainage improvement. According to Vandersypen *et al.* (2007), this is chiefly because more funds are channelled to irrigation development, while the agricultural drainage sector receives little or no financial support.

While there is an increasing worldwide acknowledgment of the links between food security, irrigation and subsurface drainage improvement, generally-speaking, many interventions seem to lack the synchronized effort to meet such wins. For instance, out of the total 270 million ha irrigated worldwide, only 22.2 % is provided with appropriate drainage (Schultz *et al.,* 1999). Africa and Asia account for 90 % of the poorly-drained land (Wood, 2008). Unfortunately, these two continents are also the most affected by hunger and food insecurity (Armour and Viljoen, 2008). In Africa alone, 80 million ha are reported to be waterlogged and salinized (Tana, 2008). This is despite the need to increase the contribution of irrigation to the total world food production, in order to feed the world's growing population.

In a South African context, a total of 1.5 million ha have potential for irrigation, out of which nearly 1.3 million ha have already been developed for irrigation (DWAF, 2004). This indicates that continual expansion of irrigation development in South Africa will soon not be feasible, as the area has almost been fully developed. Efforts must therefore focus on increasing crop yields from the same irrigated land and producing enough food to meet the ever-increasing food demand. However, the current decreasing trend in quality of irrigation water from surface water sources is also threatening the sustainability of irrigated agriculture (DWAF, 2004). High soil salinity levels are affecting crop growth and more water is required for leaching, consequently resulting in waterlogging. For example, in the Boegoeberg and

Kakamas districts in the Western Cape Province, it is predicted that the salinity of irrigation water from surface water sources will increase by 25% in the near future from the current 77-115 dS/m (Volschenk *et al*., 2005). Furthermore, Volschenk *et al*. (2005) highlight that the doubling of soil salinization within a 30 day period in the area, due to high evaporation rates, is also worrisome.

Realizing the need for subsurface drainage systems in irrigated fields, the South African government equipped 54,000 ha of irrigated land with subsurface drainage systems in the 1980's (Freisem and Scheumann, 2001). In addition, Backeberg (2000) report that the South African government provided loans to irrigation farmers to cater for the installation of subsurface drainage systems. Seemingly, it appears that most of these drainage systems have exceeded their technical life span and that they may no longer be effective in achieving their intended objectives. However, according to Katkevitus *et al.* (2000); Stuyt *et al.* (2000) and Rimidis and Dierickx (2003), the performance and efficiency of subsurface drainage systems does not entirely dependent on the age of the system, but also on other factors such as design, installation methods, management practices and climate change. Thus, it is possible that old installed subsurface drainage systems may function satisfactorily due to appropriate design, installation and management practices, while newly-installed systems may fail shortly after their installation (Stuyt *et al.,* 2000).

To evaluate the effectiveness of subsurface drainage systems in achieving their design objectives, certain drainage criteria, which are to achieve optimal drainage system technical performance level, are required (Oosterbaan, 1991; Martinez-Beltran, 2007). Such drainage criteria must stipulate the optimum design parameters so that the crop production systems can also achieve optimum yields (Oosterbaan, 1991; Ritzema, 2007). Design water table depth *(z)*, hydraulic head *(h)* and drain discharge *(q)* (Figure 2.1) are the three drainage design parameters that are generally considered in assessing the extent to which a subsurface drainage system achieves its design objectives (FAO, 2007; Martinez-Beltran, 2007; Ritzema, 2007; Ritzema and Schultz, 2010).

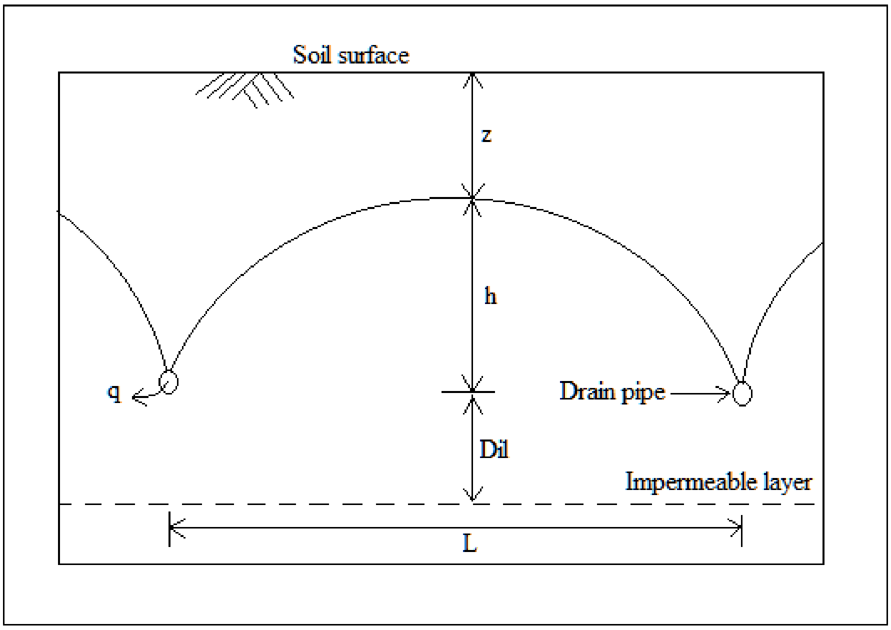


Figure 2.1 Subsurface drainage design parameters (after Smedema and Rycroft, 1983)

It is the duty of research institutions and relevant government departments to ensure that feedback pertaining to the performance of existing subsurface drainage systems is consistently made available to the farmers, so that appropriate measures can be put in place whenever needed.

This study was conducted in the sugarcane fields of Pongola, South Africa, where despite the presence of subsurface drainage systems, shallow water table problems are still being experienced. The research question addressed in this study is as follows: Are the poor choice of drainage design criteria, irrigation water management practices, inappropriate subsurface drainage system maintenance and the lack of artificial subsurface drainage systems be the drivers of shallow water table problems in the sugarcane fields of Pongola, South Africa? The main objective of the study was to determine the extent and severity of shallow water tables and their possible cause(s) in the sugarcane fields of Pongola, South Africa.

2.2 Materials and Methods

This section will describe all the field procedures followed in the data collection and analysis, in line with the study objectives. To start with, a description of the study site and its appropriateness to this study is presented.

2.2.1 Study site description

Pongola is located on the north-eastern side of South Africa, close to the South African and Swaziland boarder in the KwaZulu-Natal province as shown Figure 2.2. The area is dominated by clay-loam and clay soils (van der Merwe, 2003) with fairly gentle slopes. The Aridity Index (*AI*) for the area for the past 13 years is 0.12, which, according to UNESCO (1979), is the ratio of mean annual rainfall (*P*) (mm) to mean annual reference potential evapotranspiration (ET_o) (mm). This Aridity Index characterises the area to be an arid region ($0.03<P/ET_o<0.20$). Thus, from April to October (winter season), crop production is mainly through irrigation, while from November to March (summer season), crop production is dependent on both rainfall and irrigation.

Sugarcane fields WMDS (with a well maintained subsurface drainage system) totalling 32 ha and PMDS (with a poorly maintained subsurface drainage system) totalling 20 ha (Figure 2.2) were first artificially drained, using subsurface drainage systems in 1987. However, between 1995 and 2002, it was noticed that shallow groundwater tables were still affecting sugarcane growth in both fields. The subsurface drainage systems were, therefore, abandoned and all the man-holes were filled up. This was followed by a recalculation of the drain depth and spacing, using the steady state drain spacing approach (i.e. using the Hooghoudt (1940) steady state drain spacing equation), and the installation of the current subsurface drainage system in 2003. Details of the existing subsurface drainage systems are given in Table 2.1.

Table 2.1 Drainage system design parameters for the subsurface drainage systems at the two study sites (WMDS and PMDS) (van der Merwe, 2003)

Design Parameter	**Symbol**	**Value**	**Units**
Drain depth	W	1.8	m
Drain spacing	L	54 & 72	m
Design drain discharge	q	5	$mm.day^{-1}$
Design water table depth	z	1	m
Depth to impermeable layer	Dil	≈ 9	m
drain pipe internal radius	r	55	mm

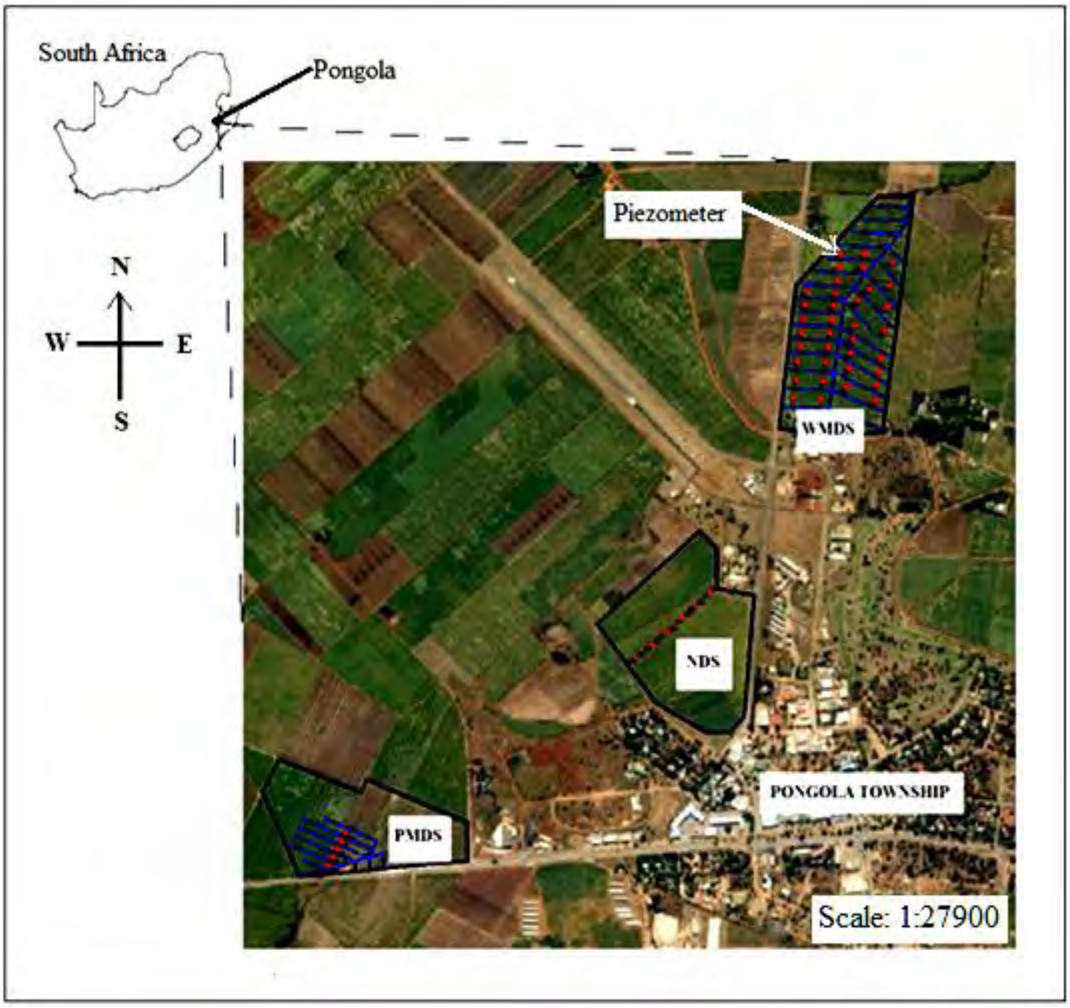


Figure 2.2 Location of the three study sites (WMDS = Well Maintained Subsurface Drainage System, NDS = No Subsurface Drainage System, PMDS = Poorly Maintained Subsurface Drainage System) and distribution of piezometers on each site

Whereas the subsurface drainage system in WMDS has always been maintained following the maintenance frequency recommended by the designer, as given in Table 2.2, the subsurface drainage system in PMDS has never been maintained since its installation. Nonetheless, it is not known whether both subsurface drainage systems in fields WMDS and PMDS are currently performing according to their design objectives, as presented in Table 2.1 or not. For NDS (28 ha), no subsurface drainage system has ever been installed in the field and, similar to WMDS and PMDS, it is currently not known, whether the natural drainage system at the site is effectively controlling shallow water table depth and soil salinisation within the root zone depth or not.

Table 2.2 Details of recommended subsurface drainage maintenance frequency at the site (van der Merwe, 2003)

Age of the drainage system (Yrs)	Maintenance frequency
< 1	Once every 3 months
1 to 2	Once every 6 months
> 2	Once every year

2.2.2 General study approach

The approach followed in this study can be subdivided into two groups:

i. The delineation of shallow water table affected areas in a sugarcane field equipped with a subsurface drainage system (WMDS), which has always been maintained as recommended by the drainage system designer.
ii. The determination of the possible cause(s) of shallow water tables, relevance of subsurface drainage systems and the effect of drainage system maintenance levels on ground water table control. This was achieved through water table monitoring mid-way between two drainage laterals in three sugarcane fields with different drainage conditions: (a) with a well-maintained subsurface drainage system (WMDS), (b) with a poorly-maintained subsurface drainage system (PMDS), and another sugarcane field (c) which relied on a natural drainage system (NDS). Considering that NDS had no artificial drains, the same piezometer spacing as in WMDS and PMDS was therefore adopted.

The selection of the three sugarcane fields (WMDS, PMDS and NDS) was based on the fields having similarities e.g. type of crop, crop stage, depth to impermeable layer, soil type and irrigation method, as shown in Table 2.3.

Table 2.3 Details of similar physical characteristics considered in the selection of the three study sites (WMDS, PMDS and NDS)

Physical characteristic	**Description**
Slope	<3%
Soil type	Clay and clay-loam soil
Depth to impermeable layer	9 m below the soil surface
Crops grown	Sugarcane
Type of irrigation	WMDS = Quick coupling sprinkler irrigation
	PMDS = Quick coupling sprinkler irrigation
	NDS = Centre pivot sprinkler irrigation

It was impossible to find three irrigation fields with the same type of sprinkler irrigation in addition to the other physical characteristics presented in Table 2.3, i.e. field NDS had a centre pivot type of sprinkler irrigation, while the remaining two fields, WMDS and PMDS, are irrigated using quick coupling type of sprinkler irrigation.

Having described the study sites, the following sections will detail the procedure followed in the field to collect the appropriate data and how the data were analysed.

2.2.3 Sampling strategy for groundwater table monitoring points, piezometer installation and water table monitoring procedure

Like any other study, determining the appropriate sampling density that will give a true representation of a property under study is the first step towards obtaining reliable results. For water table mapping in agricultural lands, FAO (1999) recommends a sampling density of four piezometers per 50 ha to be adequate. However, recent studies by FAO (2007) indicate that such a sampling density is still not adequate in mapping water table depths, considering the spatial variation in the soil's physical and chemical properties within a given area. FAO (2007) therefore recommends 5-10 piezometers per 50 ha to be adequate. In this study, a total of 36 piezometers, most of them installed at 54 x 54 m grid nodes on the whole 32 ha field, was found to be reasonable, after a thorough reconnaissance survey of the whole study area.

This translated to 55 piezometers per 50 ha, which exceeds the minimum sampling density suggested by FAO (2007).

The piezometers were manually augured (Figure 2.3a), using a 70 mm outside diameter auger to a depth of 1.7 m from the soil surface. A 50 mm internal diameter, class 4 PVC pipe with perforations, was then lowered in each piezometer to a depth of 1.7 m, while ensuring that a 30 cm length was above the ground level to prevent runoff water from flowing in. End caps were fitted to both ends of the pipe to prevent the intrusion of materials into the piezometer (Figure 2.3b). To prevent clogging of the perforations, coarse sand was back filled through out the whole perforated section of pipe.

WTDs at each piezometer were measured by gradually lowering an electronic dip meter in the piezometer until a sound was heard. Under laboratory conditions, the measurement error of the electronic dip meter was determined to be ±0.5 cm, which, according to van Beers (1983), is within the acceptable range. Figures 2.3(c) and (d) show how WTDs were measured, while Figure 2.4 is a detailed cross-section of one of the piezometers.

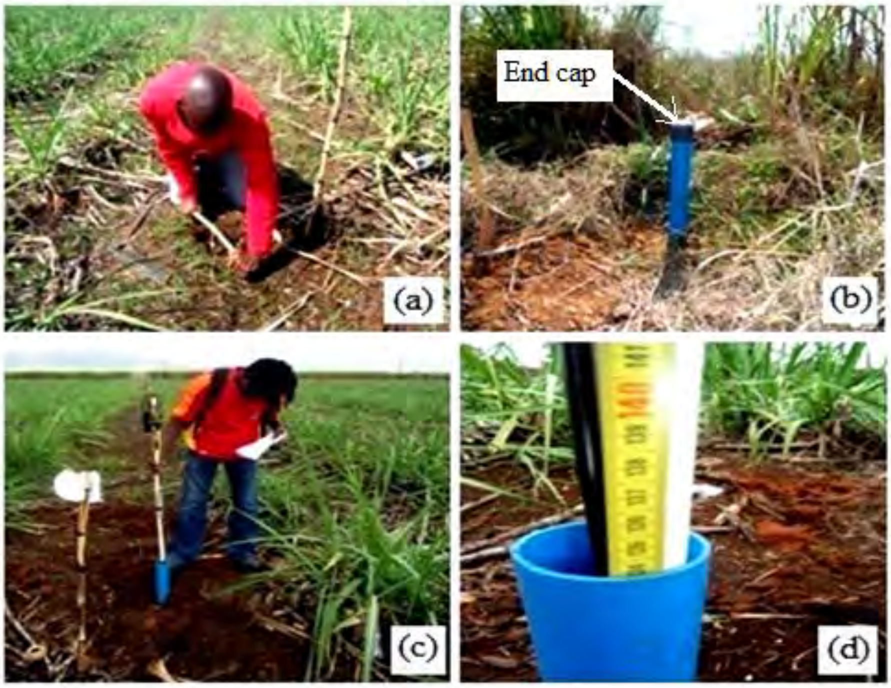


Figure 2.3 Installation of the piezometers and the measurement of groundwater table depth, using an electronic dip mete

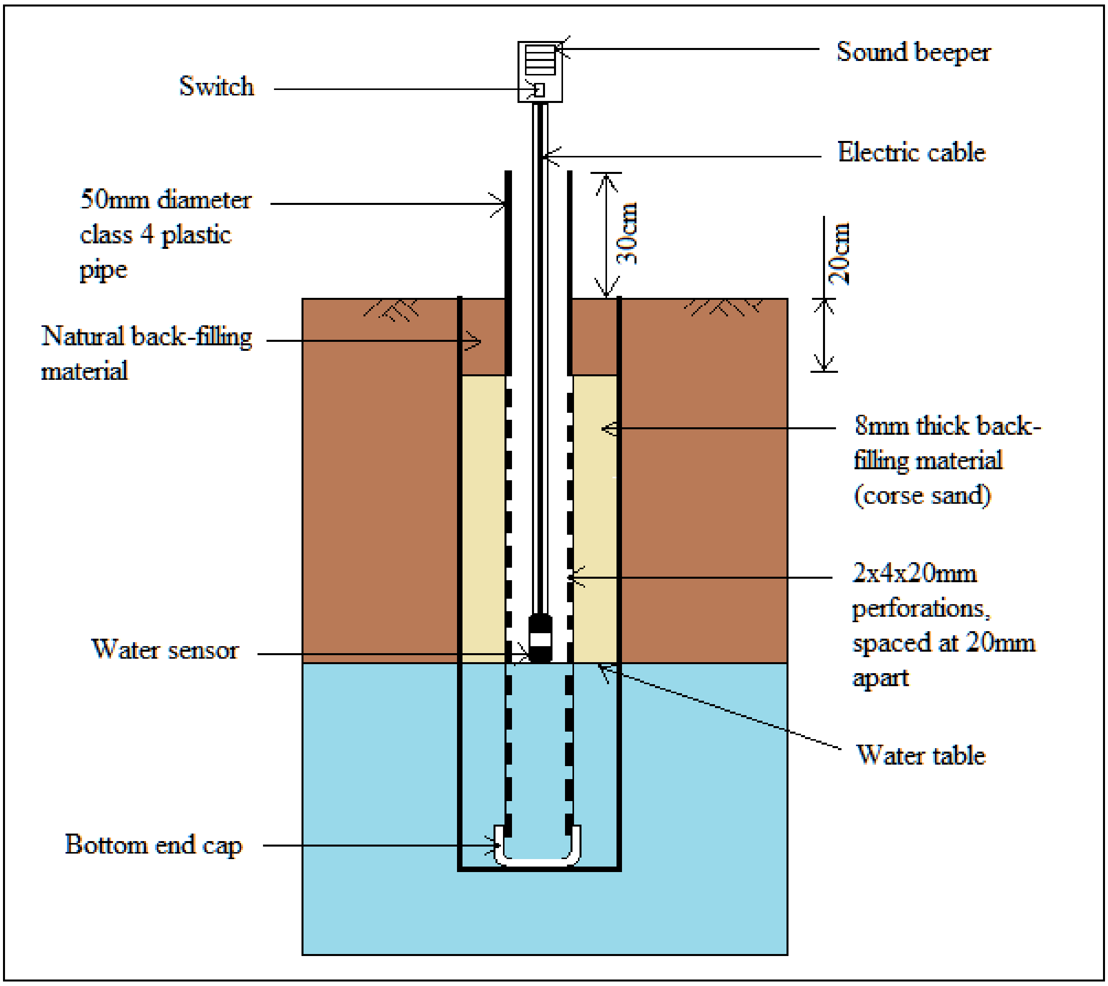


Figure 2.4 A detailed cross-section of one of the piezometers with an electronic dip meter lowered in the piezometer to locate the WTD from the soil surface

For the first three weeks of the study (September 09 to 30, 2011), WTDs were monitored everyday, after which (October 01 to November 30, 2011) a monitoring frequency of once in two days was found to be appropriate. However, during the summer months of December 2011 to February 2012, the water table monitoring frequency was increased again to once per day due to frequent rainfall events.

The latitudes and longitudes of all the locations of the piezometers were taken using a GPS. Average WTDs at each piezometer for both the summer and winter seasons were calculated and recorded. This was followed by the preparation of an XYZ file using the Microsoft Excel, where X, Y and Z are latitude (m), longitude (m) and average WTD (m), respectively. The XYZ file was processed, using Surfer8 software (Bresnahan and Dickenson, 2002) to generate a water table map for the site. The classification of shallow water table affected areas was based on the 1.0 m WTD that the subsurface drainage system at the site was designed to maintain. Using this design water table depth, areas with WTD shallower than 1.0 m were considered to be affected, while those with WTD≥ 1.0 m from the soil surface were considered not to be affected.

To determine the effect of drainage conditions on WTD (i.e. subsurface drainage system maintenance level and presence or absence of artificial subsurface drainage systems), out of the 36 piezometers installed in WMDS, six were installed mid-way between drainage laterals. Similarly, in field PMDS, six piezometers were also installed mid-way between drainage laterals, while the same was done with six piezometers installed in NDS, since there was no subsurface drainage system on it. Figure 2.5 is a schematic view of the locations of the piezometers mid-way between drainage laterals.

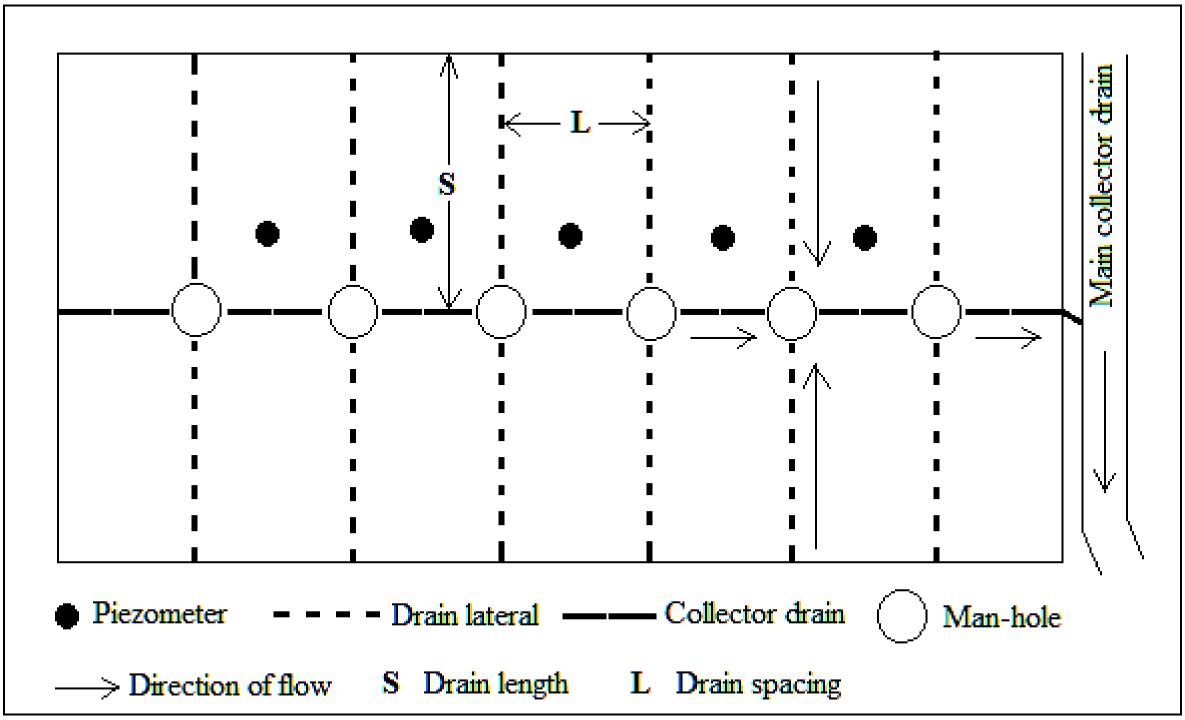


Figure 2.5 A schematic of the layout of piezometers at mid-drain spacing

Water table depths at each of the six piezometers in each field were averaged, as suggested by Manjunatha *et al.* (2004) and statistically compared for any significant differences, using the Analysis of Variance (ANOVA). In addition, cumulative frequencies (CF) of WTDs above the 1.0 m design water table depth were calculated.

2.2.4 Measurement of drainage discharges

Drainage discharges (q) in mm.day^{-1} were manually measured at three drainage outlet points (man-holes) in WMDS, using a bucket and clock. It was quite difficult to find more drain outlet points where drain pipes were well-suspended, while at the same time providing enough clearance below them, where a bucket could be accommodated to effectively measure the discharge. Figure 2.6 shows lateral drain pipes discharging at one of the man-holes where drainage discharges were measured.

Figure 2.6 Drain lateral pipes at a sugarcane field with a properly maintained drainage system (WMDS) discharging at a man-hole, while a collector drain pipe carries the discharged water to an open collector drain

Firstly, DDs were measured in l.sec^{-1} and were later converted to mm.day^{-1} using:

$$q = \frac{86400\ l}{A} = \frac{86400\ l}{SL} \tag{2.1}$$

where *q* is the drainage discharge (mm.day^{-1}); *l* is the measured discharge (l.sec^{-1}); *A* is the drained area (m^2); *L* is the drain spacing (m), and *S* is the drain length (m).

Time series DDs at each measurement point were averaged and were analysed for statistical differences, using ANOVA in Microsoft Excel. Furthermore, the cumulative frequencies of DDs of less than the 5 mm.day^{-1} design discharge were also computed.

It is worth mentioning that besides the existence of a subsurface drainage system at PMDS, it was not possible to measure drainage discharges at drain outlet points, because drainage discharge pipes at all the man-holes were fully submerged by water, as can be seen in Figure 2.7.

Figure 2.7 One of the uncovered and blocked man-holes at a sugarcane field with a poorly-maintained subsurface drainage system (PMDS)

2.2.5 Soil salinity measurement across the soil horizon

Soil samples were collected across the soil profile from three selected points along the main field slope of each of the three fields i.e. the upper, middle and lower sections of each field. The soil samples were collected at 15, 30, 45 and 60 cm depths from the soil surface, which constitutes a soil depth occupying nearly 60% of sugarcane roots (Hurst *et al.,* 2004). The soil samples were collected towards the end of the winter season (25 September, 2011), when crops were produced solely through irrigation. This was because FAO (1999) recommended that soil salinity determination be conducted during the irrigation season, in order to account for salts brought by the irrigation water. The soil samples were analyzed for salinity (EC_e) at the University of KwaZulu-Natal Soil Science Laboratory.

The procedure followed in the analysis mirrors the one outlined by Warrick (2002). The soil samples were air-dried, ground and weighed into 20 g Samples. Distilled water was then added to each 20 g soil sample, in the ratio of 1:5, soil to water, by mass. The soil-water mixture was shaken vigorously for five minutes and was left to stand for 24 hrs in tightly-closed containers. The electrical conductivity of the extract (EC_e) was measured, using the Electrical Conductivity meter (EC meter) by dipping the electrodes in the extract (Douaik *et al.,* 2005) after calibrating it with the HI 7031L conductivity calibration solution. The measured EC_e was then compared to the threshold soil salinity level for sugarcane.

2.2.6 Measurement of rainfall and actual irrigation depth

Daily rainfall depths from September 2011 to February 2012 were measured in all three sugarcane fields, using rain gauges, one installed in each field. Similarly, irrigation depths per irrigation day were also measured. Information regarding the recommended irrigation scheduling, as stipulated by the irrigation design, was obtained from the irrigation personnel at each of the three irrigation fields. Actual irrigation depths per irrigation day were compared to design irrigation depth, while also taking into consideration the recharge from rainfall.

Notably, using the EC meter described in the previous sections, the electrical conductivity of the irrigation water (EC_{iw}) on each irrigation day was also measured in order to determine if the water used for irrigation was within the acceptable salinity range. Because of the close proximity of the three sugarcane fields and that irrigation water to all the three fields is diverted from the same source, the EC_{iw} was measured at the water distribution point only. The initial plan was to measure the EC_{iw} even during the summer months of November 2011 to February 2012. However, this could not be fulfilled because the rainfall received during the November 2011 to February 2012 period was enough to meet the entire crop water requirements, hence there was no irrigation from November 2011 to February 2012.

2.3 Results

This section will present all the results obtained after conducting the field work described in the previous sections.

2.3.1 Delineation of shallow water table affected areas

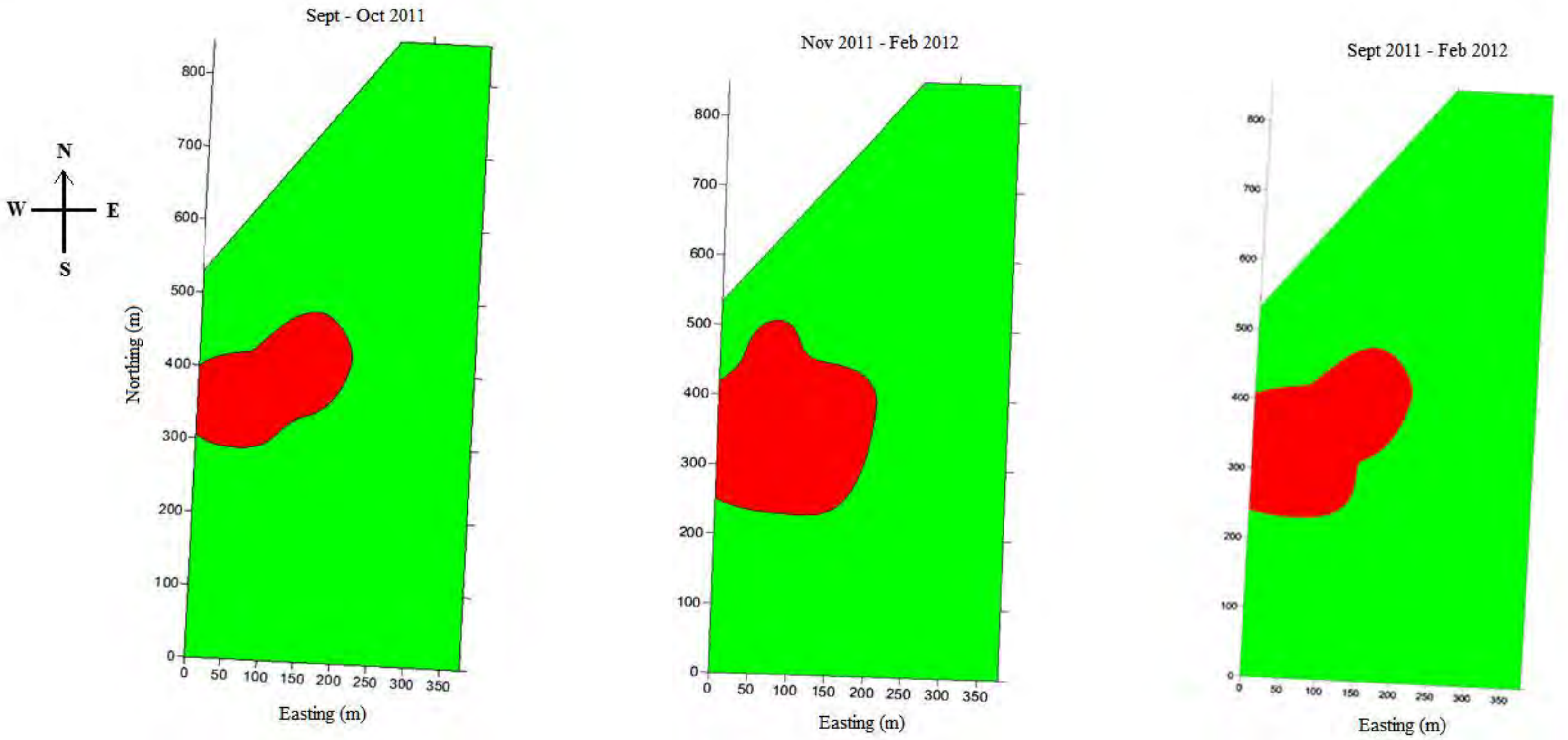
Table 2.4 is a summary of descriptive statistics for mean WTDs used in generating the water table maps for WMDS shown in Figure 2.8. It can be seen that mean WTDs from the 36 piezometers ranged from 0.66 to 1.49 m below the soil surface, with a standard deviation of 0.25. The mean shallowest and deepest WTDs during the monitoring period were 0.66 and 1.49 m, respectively. According to Wilding (1985), a Coefficient of Variation (CV) of less than 35% depicts less variability of a property. It can therefore be seen in Table 3.3 that there was less variability of WTDs at the site with a CV of 21.3%.

Table 2.4 Summary of descriptive statistics of mean water table depths (m) monitored in 36 piezometers used in mapping of WTD for the September 2011 to February 2012 period

Statistic	**Mean WTD (m)**
Mean	1.17
Maximum	1.49
Minimum	0.66
Standard deviation	0.25
Variance	0.061
Coefficient of Variation (CV) (%)	21.3

Water table maps showing the spatial distribution of WTD on the 32 ha sugarcane field for the September to October 2011, November 2011 to February 2012 and September 2011 to February 2012 periods, are shown in Figure 2.8. Whereas the subsurface drainage system was designed to maintain a mean WTD of 1.0 m from the soil surface, the water table maps in Figure 2.8 show that 3.1 ha and 4.16 ha out of the total 32 ha were affected by WTDs of less than 1.0 m from the soil surface for the September to October 2011 and November to

February 2012 seasons, respectively. On the other hand, the water table map for the whole September 2011 to February 2012 season in Figure 2.8 shows that 3.5 ha, which constitutes nearly 12 % of the total 32 ha, was affected by water tables of less than the design WTD . As can be seen in Figure 2.8, shallow water table affected areas are found in the central western side of the field. These shallow water table affected areas are also characterized by low elevations, while those not affected, are characterized by higher elevations.



Key	Area (ha)		
WTD (cm)	Sept - Oct 2011	Nov 2011 - Feb 2012	Sept 2011 - Feb 2012
🟥 0.0 - 1.0 m	3.1	4.16	3.5
🟩 1.0 - 1.5 m	28.9	27.84	28.5

Figure 2.8 Water table maps of a 32 ha sugarcane field (WMDS) generated, using water table data monitored in 36 piezometers from September 2011 to February 2012

2.3.2 Observed water table depths (WTDs) under different drainage treatment

Results of the mean WTDs observed in the six piezometers in each of the three sugarcane fields are shown in Table 2.5. It can be seen that, in field WMDS, the mean WTDs at all the piezometers are not significantly different ($p \leq 0.05$) from each other in both the winter and summer seasons. Similarly, mean WTDs at all the piezometers in PMDS are not significantly different ($p \leq 0.05$) from each other in both the winter and summer seasons. In contrast, it can be seen in Table 2.5 that mean WTDs in NDS in the winter season are significantly different to mean WTDs in the summer season ($p > 0.05$). Furthermore, mean WTDs in the summer season in NDS were are not significantly different to the mean WTDs in summer in PMDS ($p \leq 0.05$).

Considering that subsurface drainage systems for PMDS and WMDS were designed to maintain a mean seasonal WTD of 1.0 m from the soil surface. It can therefore be seen in Table 2.5 that mean WTDs at WMDS and PMDS were well below the 1.0 m depth. The respective mean observed WTDs at WMDS and PMDS are 20 and 57 % less than the 1.0 m design WTD depth.

Table 2.5 Comparison of mean observed water table depths (cm) during the winter and summer seasons in three fields with different drainage treatments (WMDS, PMDS, and NDS)

Drainage Treatment	**Piezometer No.**	**Mean WTD (cm)**	
		Winter Season	**Summer Season**
WMDS	AP1	82^a	79^a
	AP2	81^a	84^a
	AP3	78^a	79^a
	AP4	80^a	81^a
	AP5	83^a	79^a
	AP6	81^a	78^a
NDS	BP1	105^b	40^c
	BP2	102^b	44^c
	BP3	106^b	43^c
	BP4	101^b	44^c
	BP5	101^b	46^c
	BP6	102^b	44^c
PMDS	CP1	42^c	43^c
	CP2	40^c	44^c
	CP3	45^c	43^c
	CP4	46^c	44^c
	CP5	43^c	44^c
	CP6	45^c	46^c

Values with the same superscript depict no significance differences ($p \leq 0.05$) at 95% Confidence Interval

For all the six mid-drain spacing piezometers in WMDS and PMDS, all the days with WTDs above the 1.0 m depth were summed up and expressed as a percentage of the total number of WTD observation days (i.e. cumulative frequency (CF) of days with WTD <1.0 m depth from the soil surface). The same was also done with WTDs observed in piezometers installed in NDS.

Results of the mean CF of WTDs < 1.0 m in all the three fields are shown in Table 2.6. It can be seen that in NDS, the WTD was higher than the design 1.0 m depth throughout the whole study period, with a mean CF of 100 %. On the other hand, WMDS recorded a mean CF of 87 and 89% during the winter and summer seasons, respectively. Surprisingly, despite the absence of an artificial subsurface drainage system in NDS, only 4 % of the water table observation days in winter had WTDs of less than 1.0 m. However, the frequency of shallow WTDs in NDS rose from 4 % in the winter season to 95 % in the summer season. Describing the results in Table 2.6 based on the Sum of Water table Exceedance (SWE), which, according to Setter and Waters (2003), is the total number of days with WTD not satisfying the design WTD requirements, it can be seen that with the exception of winter season at NDS, the water table design requirements were not satisfied in all three fields.

Table 2.6 Average cumulative frequencies (CF) (%) of water table depths shallower than 1.0 m depth under different drainage treatments

Drainage treatment	**Cumulative frequency of exceedance (%)**	
	Winter Season	**Summer Season**
WMDS	87	89
NDS	4	95
PMDS	100	100

2.3.3 Observed drainage discharges

Results of mean drainage discharges measured at the three drain outlet points (man-holes) in WMDS, are shown in Table 2.7. In addition, Table 2.7 also contains the cumulative frequencies of all the days with drain discharges of less than the drainage design discharge of 5 mm.day^{-1}. It should be mentioned that it was very difficult to accurately measure the discharge from the drainage pipes, due to the smaller size if the man-holes. For that reason about three measurements were taken at a man-hole point and average values were calculated. As can be seen in Table 2.7 mean DDs measured at all the three discharge points were not significantly different from each other ($p \leq 0.05$). In all circumstances, it can also be seen in Table 2.7 that the mean DDs were more than 50 % less than the design drainage discharge of 5 mm.day^{-1}. Cumulative frequencies of 100 % at all the three drain outlet points in both the summer and winter seasons show that no drain discharge of equal to or greater than the 5 mm.day^{-1} design discharge was observed through out the whole monitoring period. It is worth noting that during the month of December, 2011 side discharge in the form of axial flow was observed at the other four drain outlet points at the site, as can be seen in Figure 2.9.

Table 2.7 Summary of mean observed drainage discharges (mm.day^{-1}) and cumulative frequencies (%) of drainage discharges of less than the design drainage discharge of 5 mm.day^{-1} calculated for the whole drain discharge observation period

Man-hole	**Mean drainage discharge (mm.day^{-1})**		**Cumulative frequency of exceedance (%)**	
	Winter	**Summer**	**Winter**	**Summer**
MH1	2.36^{d}	2.43^{d}	100	100
MH2	2.41^{d}	2.35^{d}	100	100
MH3	2.34^{d}	2.40^{d}	100	100

Values with the same superscripts depicts no significant differences ($p \leq 0.05$) *at CI=0.95*

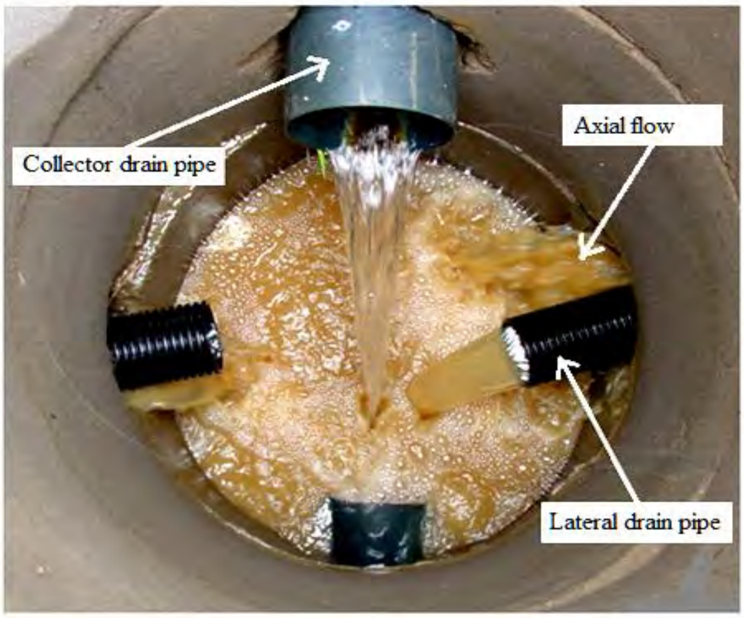


Figure 2.9 Axial flow observed at four drain outlet points in field WMDS during the summer months of November 2011 to February 2012

2.3.4 Irrigation water and soil salinities

The EC_{iw} was measured to characterise the fitness of water used for irrigation in relation to irrigation water quality guidelines. Figure 2.10 shows the fluctuation of EC_{iw} at the three study sites (PMDS, WMDS and NDS). It can be seen that the measured EC_{iw} in all the seven weeks fluctuated between 2.1 and 2.4 dS/m with the minimum and maximum EC_{iw} recorded in the second week of September (2.1 dS/m) and third and fourth weeks of October 2011 (2.4 dS/m), respectively. Maas and Hoffman (1977) reported that the threshold EC_{iw} for sugarcane is 1.7 dS/m. A study of the results in Figure 2.10 in relation to this threshold EC_{iw}, shows that, on average, the measured EC_{iw} was 32 % higher than the EC_{iw} threshold tolerance level of sugarcane.

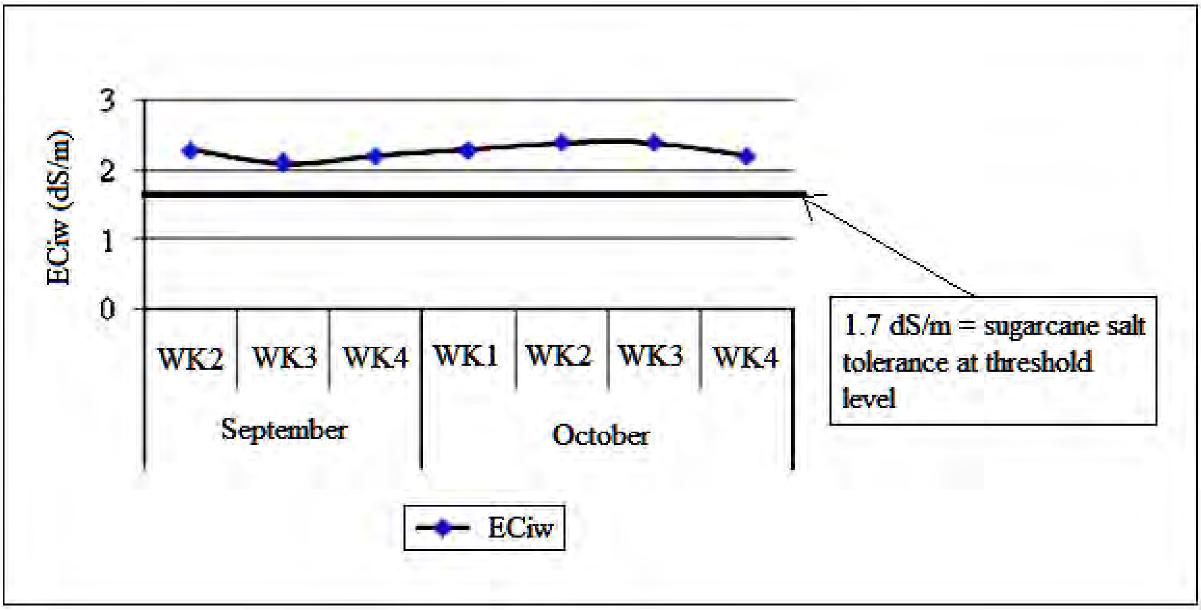


Figure 2.10 Electrical conductivity of irrigation water (EC_{iw}) during the irrigation months of September 2011 and October 2011

The results summarising the mean soil salinity levels (EC_e) at different soil depths within the 0.60 m depth of soil occupied by nearly 60% of sugarcane roots (Paz-Vergara *et al.,* 1980; Hurst *at al.,* 2004; Morris and Tai, 2004) in sugarcane fields PMDS, WMDS and NDS, are presented in Figure 2.11. It can be seen that generally the EC_e trend in WMDS increased with an increase in soil profile depth from 2.1 dS/m to 5.3 dS/m at 5 and 60 cm soil depth, respectively. In PMDS and NDS, the EC_e decreased from 3 dS/m and 4 dS/m to 2.5 dS/m and

3 dS/m, respectively between the 5 and 10 cm soil profile depth. However, from the 30 to 60 cm soil profile depth, the EC_e in PMDS and NDS showed an increasing trend from 2.5 and 3 dS/m to 5.8 and 5.6 dS/m, respectively. According to Syed and El-Swaify (1972), the threshold EC_e for sugarcane is 1.7 dS/m. It is therefore apparent from the results in Figure 2.11 that the root zone EC_e at the three sites is well above the 1.7 dS/m. On the other hand Bernstein (1974) reported that root zone EC_e of 3 dS/m results in a sugarcane yield loss of 10 % of the normal harvest, while root zone EC_e of 5 dS/m results in sugarcane yield reduction of 25 % of the normal harvest. Even though sugarcane yields were not measured in this study, it is evident from Figure 2.11 that root zone EC_e at all the three sites is beyond the 3 and 5 dS/m, which therefore indicates that all the three fields were expected to incur yield reductions of greater than 25 % in this cropping season.

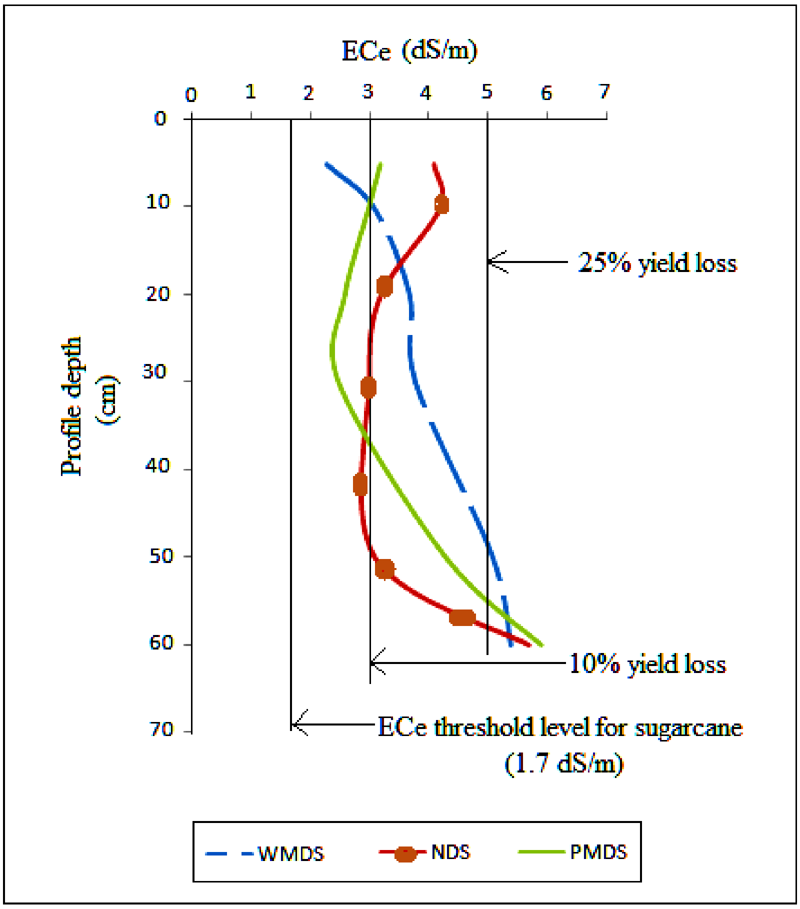


Figure 2.11 Soil salinity variations across the soil profile in three different drainage treatments (PMDS=Poorly maintained drainage system; WMDS=Well maintained drainage system; NDS=No drainage system)

2.3.5 Irrigation water management at the three sites

Results of actual irrigation application depth and rainfall recorded during the irrigation months of September and October 2011 are shown in Figure 2.12. While the irrigation schedules in all the three sugarcane fields were designed to provide 20 mm depth of irrigation water at irrigation intervals of seven days, it can be seen that in all the three fields the irrigation depths per irrigation day were slightly less than the design irrigation depths. Notably, the area received weekly rainfall recharge of 1, 3 and 2 mm during the third week of September and the first and second weeks of October, respectively. A study of the results in Figure 2.12 further shows that fields WMDS and PMDS followed the recommended seven-day irrigation interval by irrigating mean irrigation depths of 17.5 and 16.4 mm per irrigation day, respectively. On the contrary, field NDS doubled the seven-day design irrigation interval by irrigating an average of 19 mm per irrigation day. Thus, field NDS did not adhere to the recommended irrigation interval, while PMDS and WMDS adhered to the recommended seven-days irrigation interval, although applying less than the design depth.

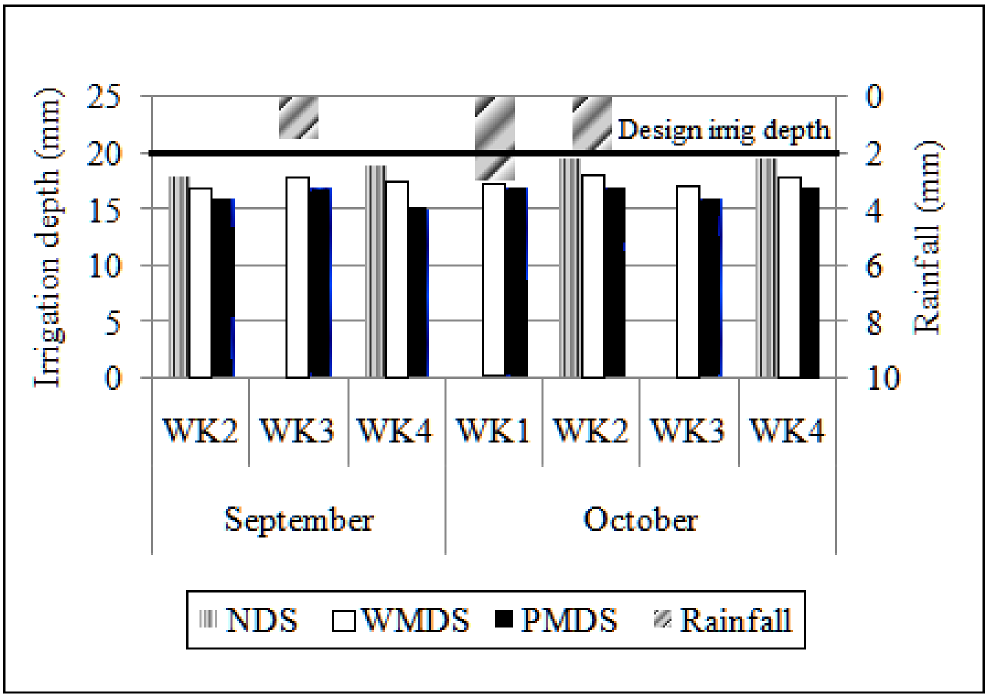


Figure 2.12 Actual depths of irrigation per seven day irrigation interval and the rainfall distribution at the three sugarcane fields during the winter months of September 2011and October 2011

Results of actual and effective daily rainfall distribution during the non-irrigation months of November 2011 to February 2012 are shown in Figure 2.13. It can be seen that the rainfall distribution was somehow sporadic, which according to FAO (2007) is not an unusual phenomenon in arid and semi-arid climatic regions. Furthermore, it can also be seen in Figure 2.13 that even though most of the rainfall events were in the form of drizzles of low intensities of less than 10 mm.day^{-1}, but their frequent occurrences could have justified the absence of irrigation during these months.

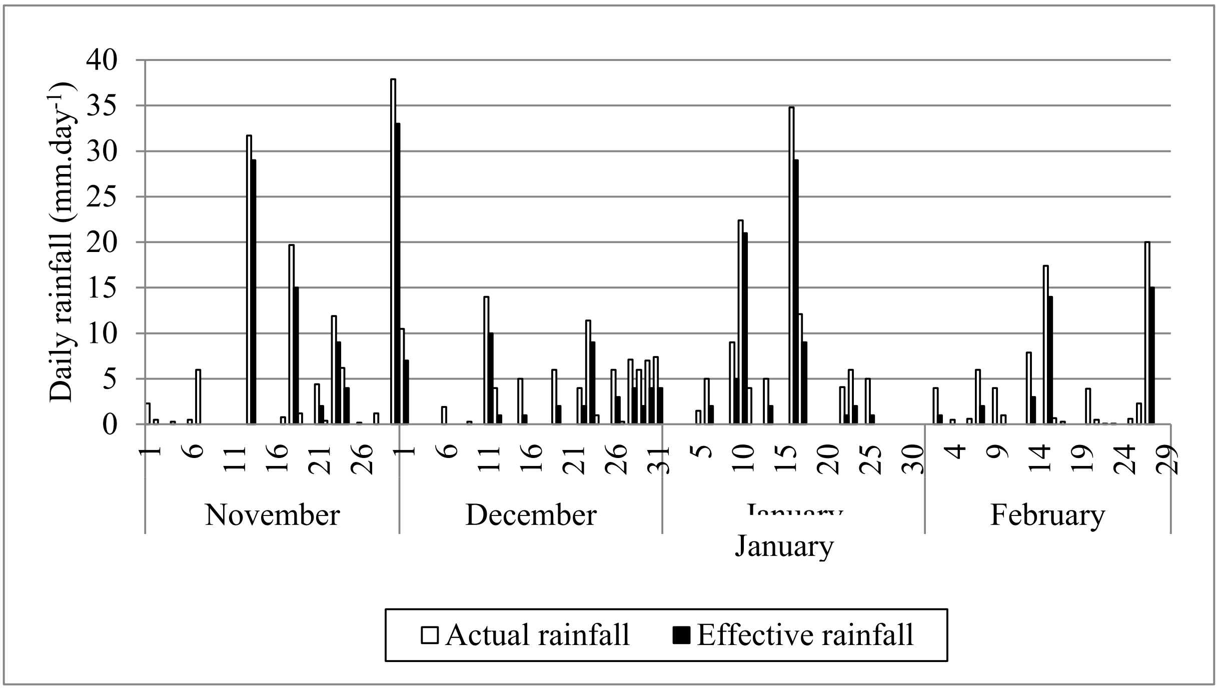


Figure 2.13 Rainfall distribution during the months of November 2011 to February 2012

2.4 Discussion

This section will discuss the results in detail, by providing possible explanations pertaining to their nature. Wherever possible, comparisons or contrasts of the results obtained in this study, with those reported by other authors will also be provided.

2.4.1 Extent of shallow water tables and spatial distribution of shallow water table affected areas

The definitive control of shallow water tables in agricultural fields involves the application of hydraulic principles governing the flow of groundwater both in the saturated and unsaturated soil (Singh *et al.,* 1999). Results of the spatial distribution of WTD in a sugarcane field with a well-maintained subsurface drainage system showed that shallow water tables were more prevalent in low-lying areas than areas of high elevation. This could be attributed to seepage flow from high elevation areas to the low lying areas.

Out of the total 32 ha under sugarcane cultivation in WMDS, 12 % was affected by shallow water tables, while 88 % was not affected. These results are comparable with the general extent of shallow water tables in irrigated areas in South Africa, as reported by Freisem and Scheumann (2001). However, these results are somewhat contradictory to the general extent of shallow water tables in South Africa reported by Backeberg (2000). According to Backeberg (2000) nearly 25 % of all irrigated lands in South Africa are affected by shallow water tables. The possible explanation for such inconsistencies could be due to the fact that different crops have different water table tolerance levels, as a result of differences in root morphology. It is therefore possible that what is considered to be a shallow WTD in one crop might not necessarily be a shallow water table depth in another crop.

Notably, the drain spacing at the site was determined, using the basic steady state Hooghoudt equation (Hooghoudt, 1940), which according to Oosterbaan (1975), does not take into consideration the effect of land slope and entrance resistance on drain spacing. Fipps and Skaggs (1989) and Zeigler (1972) noted that by installing drains in slopping lands at a drain spacing calculated using the basic Hooghoudt equation, it implies that the critical WTD lies mid-way between two drain laterals. However, according to Fipps and Skaggs (1989) and Zeigler (1972) this is not true, particularly when subsurface drains are installed in sloping lands. According to Zeigler (1972) and Fipps and Skaggs (1989), the critical WTD in slopping land lies slightly close to the lateral drain pipe on the high elevation side, and not centrally, as is the case with flat lands. Based on this water table behaviour in slopping lands, it is therefore recommended that the drain spacing at the site be calculated using the modified Hooghoudt equation reported by Oosterbaan (1975).

2.4.2 Irrigation water salinity

With respect to irrigation water salinity at the three fields (WMDS, NDS and PMDS), based on the Tanji and Kielen (2002) general irrigation water quality guidelines, the average EC_{iw} of 2.64 dS/m depicted that the salinity of irrigation water at the site was within the acceptable 0.0-5.0 dS/m range. However, from the sugarcane perspective, the average EC_{iw} at the site was 32% more than 1.7 dS/m, which according to Bernstein *et al.* (1966) and Syed and El-Swaify (1972) is the EC_{iw} salt tolerance level for sugarcane. It is therefore apparent that the EC_{iw} at the site would have a reduction effect in yield crop.

Surprisingly though, the average EC_{iw} of 2.64 dS/m at the site was much lower, compared to 77-105 dS/m of Boegoeberg and Kakamas districts in the Western Cape Province reported by Volschenk *et al.* (2005). Such a great difference could not precisely be explained, because EC_{iw} is dependent on a number of factors ranging from climatic, source of water, agricultural water management and geological factors. For instance, the evaporation rate from the surface water source and irrigation water return flows from irrigation schemes, are some of the factors which, according to Tanji and Kielen (2002), affect EC_{iw}.

2.4.3 Irrigation water management and soil salinity

The inextricability of the irrigation and subsurface drainage systems need not be over-emphasized as it has already been upheld by other authors (e.g. Singh *et al.,* 1999; Hurst *et al.,* 2004; Bahceci *et al.,* 2006; Hirekhan *et al.,* 2007). Maintaining the root zone free of waterlogged conditions alone is not enough in as far as the sustainability of irrigation development is concerned. Considering that the water used for irrigation at the site is not entirely salt free, it is therefore apparent that without appropriate soil salinity management strategies the propensity of salt accumulation in the soil is also inevitable.

While results in Figure 2.12 revealed that the adopted 14 day irrigation interval at NDS was a satisfactory water table management strategy for the winter season, its shortfall was manifested in high salt accumulation in the upper soil layers (Figure 2.11). Possibly, the protracted 14 day irrigation interval led to the soil within the root zone becoming even drier, to the extent that at the end of the 14 day irrigation interval, the 20 mm irrigation depth was not enough to warrant adequate leaching of salts. This, therefore, might have led to accumulation of salts within the upper soil layers at the site. In addition, the mean WTDs observed in the summer season at the site, indicated that the natural drainage was not adequate to cope with the rainfall-induced water table fluctuation in the summer season (CF=95 %). Possibly, this might have also resulted in upward flux of the groundwater during the summer seasons of previous years. Hence, the salt accumulation in the upper soil layers.

On the other hand, EC_e values within the 60 cm soil depth in WMDS showed an increasing trend with soil depth, indicating that, leaching of salts was taking place. Despite this, considering that the root zone EC_e levels were above threshold salt tolerance level for sugarcane, this gave an indication that the leaching of salts to deeper soil layers was not adequate enough. The failure of the subsurface drainage system to maintain the 1.0 m design water table depths (CF=87 and 89 %) might have contributed to the inadequate leaching.

In comparison, the EC_e trends in NDS and PMDS corroborated those found by Chen *et al.* (2010) in the irrigated areas of Xinjiang in northwest China. In their study, Chen *et al.* (2010) reported EC_e values, which first showed a decreasing trend with soil depth in the first 0-40 cm. This was later followed by an increasing EC_e trend within the 45-87 cm soil depth. Chen *et al.* (2010) attributed such an EC_e trend to the use of saline water for irrigation, which was exacerbated by inadequate subsurface drainage. On the other hand, the EC_e trend in WMDS was consistent with the EC_e trend reported by Benyamini *et al.* (2005) in lower the Galilee in the northern part of Israel. Benyamini *et al.* (2005) recommended for increased leaching requirement, in order to prevent further accumulation of salts within the root zone depth.

Although ensuring that actual irrigation depths are on a par with design irrigation depths is of critical importance in ensuring the sustainability of irrigation schemes (Skogerboe and Merkley, 1996), and that this is achievable. However, more often than not, the observed irrigation depths, particularly in sprinkler irrigation systems are 5-20% less than design irrigation depths (Savva and Frenken, 2001). Savva and Frenken (200) reported that water distribution in sprinkler irrigation systems is substantially affected by wind speed. Mistaking the small differences (<20%) observed between design irrigation depth and actual irrigation depths to poor irrigation water management at WMDS and PMDS was therefore irrelevant. Thus, in as far as adhering to the recommended irrigation scheduling, it was clear that, with the exception of NDS, irrigation water management practices at WMDS and PMDS were satisfactory. On the contrary, an irrigation interval of 14 days was adopted at NDS as opposed to the recommended seven-day irrigation interval, which clearly indicated that irrigation water management was unsatisfactory at the site.

Primarily, it appeared that the protracted 14 day irrigation interval was adopted to reduce total recharge to the soil system, consequently overcoming the ill-effects of shallow WTDs at the site. This strategy was indeed a success in the winter season (CF=4% and mean WTD>1.0 m). Unfortunately, the natural drainage failed to cope with shallow WTD during the summer season (CF=95%). This undoubtedly indicates the need for artificial subsurface drainage at the site.

2.4.4 Subsurface system design, operation and maintenance

Mean WTDs in both the summer and winter seasons in a field with a poorly-maintained drainage system (PMDS), were not significantly different ($p>0.05$) to mean summer season water table depths in NDS (Table 2.5). Whereas shallow WTDs in the summer season in NDS were chiefly attributed to the failure of the natural drainage system to maintain optimal WTDs, as a result of uncontrolled recharge through frequent rainfall events (Figure 2.13), the possible explanation to the shallow WTDs in PMDS could be due to the blockage of drain pipes, as a result of lack of timely maintenance. Possibly, high pressure in the buried pipe system might have resulted in the drainage system functioning as a subsurface drip irrigation system, hence creating a high pressure area in the drain pipe and a low pressure in the soil system around the drain pipe, as demonstrated in Figure 2.14.

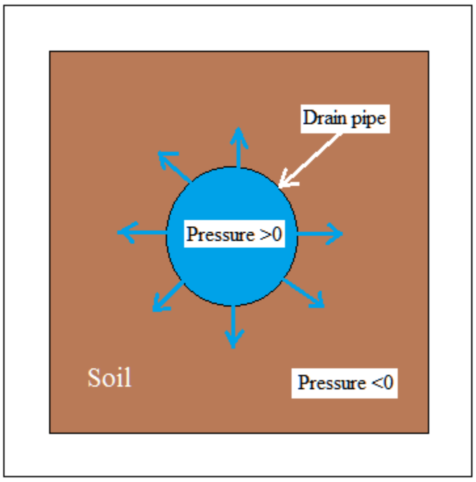


Figure 2.14 High pressure in a drain pipe resulting in the movement of water from the drain pipe to the surrounding soil

These results are somewhat consistent with those of Abdel-Dayem and Ritzema (1990). In their study, Abdel-Dayem and Ritzema (1990) found out that the obstruction of water flow in the collector drains by crop roots in the Nile delta resulted in a pressure build-up in the whole subsurface drainage system, which consequently led to the system not performing as per its design objectives. Similarly, the blockage of drain pipes and man-holes at PMDS, due to lack of appropriate maintenance, could have resulted in over-pressure in the buried drain pipes and hence the observed shallow water tables at the site.

On the other hand, mean observed WTDs mid-way between drain laterals at WMDS were on average, 20 % less than the 1.0 m design WTD. According Stuyt *et al.* (2005), differences between the observed and design WTD of more than 15 % are considered relevant, and cannot be attributed to the heterogeneity of soil hydraulic properties in an area. Considering that the existing subsurface drainage system at WMDS has always been maintained, as recommended by the designer, and that actual irrigation depths were also somewhat in line with design irrigation depths (Figure 2.12), the observed shallow WTDs at WMDS in both the winter and summer seasons were primarily attributed to the failure of the drainage system in achieving its design WTD and DD. Specifically, the failure of the system in achieving its design objectives could be due to the unusually wide drain spacing of 54 and 72 m adopted at the site. FAO (2007) and Smedema and Rycroft (1983) reported that drain pipes in soils of low hydraulic conductivities of <1.5 m.day^{-1} in arid and semi-arid climatic regions are normally installed at a depth of 1.5-2.0 m and with a spacing of 25-35 m.

These findings are in line with those previously found by various authors in other irrigated areas. For instance, Qureshi *et al.* (1997) reported that in Pakistan, drain depths had to be reduced to 1.50-2.10 m from 2.25-2.40 m which were adopted in the 1980's, in order to cope with current drainage needs, which, according to the authors, were a reflection of changes in irrigation water management practices in the area. Similarly, Abdel-Dayem and Ritzema (1990) indicated that to maintain WTD at 1.8 m in the Nile Delta, the prevailed 1.5 m drain depth had to be reduced to 1.2-1.4 m with a corresponding design discharge of 0.4 mm.day^{-1}. Like wise, in this study, the possibility of recalculating the drainage design parameters, particularly the drain spacing, from the currently 54 m in clay soil and 74 m in clay-loam soil, needs to be thoroughly investigated.

Caution must however be taken into consideration by making sure that the subsurface drainage system parameters are not adjusted aggressively. Other factors that affect the performance of subsurface drainage systems must also be taken into consideration. For instance, Samani and Willardson (1981) introduced the concept of hydraulic failure head *(i)*, which they defined as the hydraulic gradient at which the supported sub-soil cannot overcome the drag force of the subsurface water flow. They claimed that under such circumstances, the susceptibility of the supported sub-soil to losing its structural stability is unavoidable. With groundwater flow in the saturated zone, the disintegrated soil particles get carried towards the drain pipe, some of which get trapped within the envelope material (filter material). This phenomenon, according to Stuyt *et al.* (2005), increases the approach flow and entrance head looses in subsurface drainage systems. And considering that drain envelops form part of subsurface drainage systems (Stuyt *et al.,* 2005), it implies that their failure to achieve their intended objectives, consequently result in the failure of the whole subsurface drainage system. The axial flow observed at the four drain discharge points (Figure 2.9) could be an indication of high approach flow and entrance head losses towards the drain pipe. Unfortunately, this observation could not be explored further because it was beyond the scope of this study.

2.5 Concluding Remarks and Recommendations for Future Research

In this study, the importance of effective subsurface drainage systems in agricultural lands has been clearly illustrated. Despite the presence of a well-maintained subsurface drainage system in WMDS, a water table map of the field revealed that 12 % of the 32 ha under cultivation was affected by water tables of less than the 1.0 m design WTD. It was recommended that an interceptor drain be installed across the seepage line of flow to prevent seepage flow affecting the low-lying areas. In addition, the calculation of the drain spacing, using the adjusted Hooghoudt equation (Oosterbaan, 1975), that takes into account the effect of land slope on drain spacing and entrance resistance, needs to be thoroughly investigated.

The analysis of observed WTDs in the area revealed that, as long as the design irrigation schedule is adhered to, the severity of the shallow water table problem between the summer and winter seasons is not significantly different ($p \leq 0.05$). As far as shallow WTDs are concerned, irrigation water management practices at the three sugarcane fields were satisfactory. However, from the root zone soil salinity perspective, deficit irrigation in the area proved to be a flawed strategy in that it resulted in the salinization of upper soil layers. In addition, the salinity of irrigation water in the area needs to be closely monitored to ensure no further accumulation of salts within the root zone depth.

Further analysis of WTDs at mid-drain spacing in a field with a properly-maintained subsurface drainage system (WMDS) revealed that observed WTDs and DDs were not comparable to the system's design expectations. The results showed that there is still room to recalculate drain depth, spacing and drainage design discharge to ensure that the root zone depth is kept free of waterlogged conditions. On the other hand, results of WTDs observed in a field with a poorly maintained subsurface drainage system (PMDS) revealed that the installation of subsurface drainage systems is not enough to control shallow WTDs, but also ensuring that timely maintenance is undertaken.

Future research at the site should focus on investigating the appropriate drain depth, spacing and drainage discharge combination that can adequately result in suitable WTDs in both the summer and winter seasons. Further to that, the effectiveness of the envelope material, with respect to approach flow and entrance head losses, needs to be thoroughly investigated.

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3. MODELING MID-SPAN WATER TABLE DEPTH AND DRAINAGE DISCHARGE DYNAMICS IN A SUGARCANE FIELD IN PONGOLA, SOUTH AFRICA, USING DRAINMOD 6.1

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Abstract

Determining optimal subsurface drainage design parameters through monitoring of water table depth and drainage discharge at various combinations of drain depth and spacing is expensive, both in terms of time and money. Thus, drainage design simulation models provide for a simplistic and cost-effective method of determining most appropriate subsurface drainage design parameters. In this study, the performance of the DRAINMOD model (Version 6.1) in predicting water table depths (WTDs) and drainage discharges (DDs) was investigated at a sugarcane field in Pongola, South Africa. Water table depths were monitored in piezometers installed mid-way between two drains by using an electronic dip meter with a beeper, while DDs were manually measured at drain lateral outlet points, using a bucket and stop watch. Both WTDs and DDs were monitored from September 2011 to February 2012. Results of the DRAINMOD model evaluation in predicting WTD showed that there was a very strong agreement between simulated and observed WTDs with a Goodness of fit (R^2) of 0.826 and a Mean Absolute Error (MAE) of 5.3 cm. Similarly, simulated and observed DDs during the model evaluation period also showed a very strong agreement, with an R^2 value of 0.801 and an MAE of 0.2 mm.day^{-1}. The DRAINMOD model was also applied to simulate WTDs and DDs at various combinations of drain depth and spacing in clay and clay-loam soils to determine optimum drainage design criteria. An analysis of the results showed that drain pipes installed at a spacing ranging from 25 to 40 m and drain depth between 1.4 and 1.8 m were adequate to maintain a mean seasonal WTD of 1.0 to 1.5 m in clay soil at a design discharge of 2.5 to 5.1 mm.day^{-1}. For clay-loam soil, drain depths ranging from 1.4 to 1.8 m installed at a drain spacing of between 55 to 70 m were found to be appropriate in maintaining a mean seasonal WTDs between 1.0 and 1.5 m at a design discharge of 2.5 to 4.2 mm.day^{-1}. Based on these results, it was concluded that the DRAINMOD 6.1 can reliably be used as a subsurface drainage design tool in the Pongola region. This will simplify the design of subsurface drainage systems and the formulation of subsurface drainage design criteria for different crops and soil types found in the area. In order to apply the DRAINMOD model in the area, the Rosetta program was also tested for its reliability in estimating saturated soil hydraulic conductivities as required by the DRAINMOD model. Rosetta estimates of saturated hydraulic conductivity values (based on soil particle size data and bulk density) were compared to in situ determined saturated hydraulic conductivity values. The results of the analysis showed that there was a very strong agreement between the Rosetta estimated and the in-situ determined saturated hydraulic conductivities with an R^2 value of 0.95 and an MAE of 0.035 $m.day^{-1}$. Nonetheless, it is recommended that a thorough calibration and validation of the Rosetta program can be conducted. It was also recommended that the DRAINMOD model can be calibrated, based on the Rosetta program estimated saturated hydraulic conductivities.

Key words: Drain depth; drain spacing; Drainage discharge; DRAINMOD model; water table depth; Rosetta program; saturated soil hydraulic conductivity.

3.1 Introduction

The soil system is one of the most complex natural systems, primarily due to great variations of non-linear processes occurring within it (Wang *et al.,* 2006). The hydrologic and agricultural drainage engineering communities have, however, recognized the vital role played by the soil system in both the hydrological cycle and agricultural crop production systems. According to Romano and Palladino (2002), this is largely because the soil plays a very significant role in the partitioning of irrigation and rainfall into infiltration and runoff. Infiltration is further partitioned into percolation, storage and groundwater recharge, all of which occur at different rates (Romano and Palladino, 2002; Bastiaanssen *et al.,* 2007). It is therefore evident that these continuous changes in the soil water regime result in saturated and unsaturated soil conditions at different times of the year.

In agricultural crop production systems, the emphasis is on maintaining water table depths below the crop root zone depth (Horton and Kirkham, 1999; Ritzema *et al.,* 2006), i.e. sustaining a good balance of soil air, water and temperature within the root zone (Shultz *et al.,* 2007). According to Smedema and Ochs (1998) and Vandersypen *et al.* (2007), such soil conditions are sustainably achieved by installing subsurface drainage systems in agricultural lands. The challenge, however, is how to accurately determine an optimum combination of drain depth, spacing and drainage discharge (Figure 2.1 in Chapter 2) that can best suit a given cropping system (Bos and Boers, 2006; Shultz *et al.,* 2007).

Historically, determination of optimal drain depth, spacing and drainage design discharge has been achieved through the physical monitoring of groundwater table depth at varied drain depth and spacing combinations (ASAE Standards, 1999). However, this method is expensive in terms of setting up the experimental plots. In addition, the time requirements for this method make it unsuitable for agricultural water management systems in that they require timely decisions (FAO, 2007). It is therefore not surprising that the use of computer based drainage design simulation models such as the DRAINMOD (Skaggs 1978), SaltMOD (Oosterbaan, 2000) and WaSim (Hess *et al.,* 2000) are increasingly becoming more reliable in subsurface drainage design. However, Skaggs and Chescheir (2003) and Wang *et al.* (2006) state that the unavailability of accurately-measured saturated soil hydraulic conductivity data seems to be limiting the adoption of these simulation models in many areas .

In the South African context, nearly a quarter of the total 1.3 million ha under irrigation is affected by soil salinisation and waterlogging (Backeberg, 2000). Unfortunately, the problem appears to be escalating (DWAF, 2004). Furthermore, there are no generally well-established and accepted subsurface drainage design criteria in South Africa. The current drainage design approaches were developed in an adhoc manner more than 25 years ago (van der Merwe, 2003). There is evidently an urgent need to address the problem in a more cost-effective manner.

This study is focused on improving the design of subsurface drainage systems in South Africa using the DRAINMOD model. The study was conducted in Pongola, which is one of the areas in South Africa, where, despite the presence of subsurface drainage systems, shallow water table depths are still affecting crop growth. The research question addressed by the study was: Can the DRAINMOD model reliably be applied as a subsurface drainage design tool in the Pongola region? For the adoptability of the DRAINMOD model in the area, the Rosetta program (Schaap *et al.,* 2001), a sub-model in HYDRUS-2D (Simunek *et al.,* 1996) was tested for its reliability in estimating the saturated hydraulic conductivities required by the DRAINMOD model as a soil hydraulic input parameter.

The specific objectives of the study are: (i) to simulate the depth of water table in response to recharge in two soil types under various drain depths and spacing combinations, using the DRAINMOD model, (ii) using the DRAINMOD model, to develop appropriate drainage design criteria for sugarcane production in the Pongola area, and (iii) to test the reliability of the Rosetta program in estimating saturated hydraulic conductivities from particle size distribution data and bulk density. A brief description of the DRAINMOD model is provided in the subsequent section. The reader is referred to Skaggs (1978) for a detailed description of the DRAINMOD model.

3.2 Description of the DRAINMOD Model

The DRAINMOD model is one of the most widely-applied models in subsurface drainage system design (Skaggs, 1976, 1978; Wang *et al.,* 2006; FAO, 2007). According to Skaggs (1978) the DRAINMOD model uses functional algorithms to approximate the hydrological components in soils with shallow water tables. Inputs of the model are weather data, soil data and crop information, while its outputs are daily water table depth, drainage discharge, infiltration and runoff. These outputs are primarily estimated from the water balance of a unit soil section located mid-way between two drains using:

$$\Delta V_a = D + ET + DS - F \tag{3.1}$$

where ΔV_a is the change in water pore space (cm) at any time increment Δt (hr); F is the amount of water flowing into the unit soil as infiltration (cm); D is the amount of water flowing out of the soil inform of drainage (cm), ET is evapotranspiration (cm) and DS is deep seepage (cm).

The derivation of the water balance equation is detailed by Skaggs and Chescheir (1999). Precipitation (P) recharges the soil system, which is assumed to undergo no significant change in volume. Thus, the difference between the water leaving and entering the system must be zero. Drainage (D) is computed from the water table drawdown, which constitutes the increase in free water pore space (ΔV_a). On the other hand, computation of deep seepage (DS) is based on the Darcy's empirical law (Craig, 2004) given as:

$$q = AK_{sat}i \tag{3.2a}$$

Or

$$v = \frac{q}{A} = K_{sat}i \tag{3.2b}$$

Where q is the volume of water draining per unit time ($cm^3.sec^{-1}$); A is the cross-sectional area of soil corresponding to the flow q (cm^2); i is the hydraulic gradient; K_{sat} is the saturated hydraulic conductivity ($cm.sec^{-1}$) and v is the discharge velocity ($cm.sec^{-1}$).

It therefore follows that as long as A, K_{sat} and i (in Equation 3.2a) are known, then deep seepage (taken as q in Equation 3.2) can be computed easily. Evapotranspiration, being a function of weather conditions and the type of crop (FAO, 1999) is estimated from crop coefficients and evaporation using data recorded by weather stations. The DRAINMOD model estimates infiltration from the Green Ampt model (Dayyani *et al.,* 2009), a sub-model incorporated in the DRAINMOD model.

Daily water table depths at different drain spacing are computed from the modified steady state Hooghoudt equation (Hooghoudt, 1940):

$$q = \frac{8K_{sat2}d_e h + 4K_{sat1}h^2}{L^2} \tag{3.3}$$

Where L is the drain spacing (m); K_{sat1} and K_{sat2} are the saturated soil hydraulic conductivities ($m.day^{-1}$) for soil layers above and below the drainage base, respectively; d_e is the equivalent depth (m); and h is the hydraulic head mid-way between two drains (m) (Oosterbaan, 1975; Fipps and Skaggs, 1989). According to Oosterbaan (1975), d_e is a function of the depth to impermeable layer (Dil), drain depth, drain spacing and drain pipe radius, as depicted in Figure 2.1 in Chapter 2.

Notably, derivation of the Hooghoudt equation is based on the assumption that equilibrium drainage discharge and recharge rate of the system do exist (Skaggs, 1978, 1980, 1990). Flow of water to the drains is due to the available hydraulic head (h) at mid-drain spacing. Thus, vertical and horizontal water movement below and above the water table is a function of saturated hydraulic conductivity (K_{sat}) and the available hydraulic head (h). It is therefore apparent that, considering the same drain depth and spacing, the flow rate to the drains in soils with different K_{sat} values will be different.

The DRAINMOD model was chosen in this study because it has been tested under a wide range of climatic, crop and soil conditions. For instance, results of the DRAINMOD model performance in Israel (Sanai and Jain, 2006), Iowa (Singh *et al.,* 2006), South-eastern Purdue Agricultural Center, USA (SEPAC), USA (Wang *et al.,* 2006), Virginia, USA (Mc Mahon *et al.,* (1988), Canada (Madramootoo *et al.,* 2009 and Schukla *et al.,* 1994), Italy (Bixio and Bortolini, 1997), and North Carolina, USA (Skaggs 1982), clearly indicate that the DRAINMOD model can reliably mimic subsurface drainage systems under a wide range of soil types and climatic conditions.

3.3 Materials and Methods

This section will present all the field based measurement followed to collect the appropriate DRAINMOD model input data, particularly for the calibration and validation of the model and all the simulation runs performed. A description of the study site will be presented first, after which, a general study approach will be presented.

3.3.1 Study site description

This study was conducted on a 32 ha sugarcane field in Pongola, KwaZulu-Natal province in South Africa as shown in Figure 3.1. The reader is referred to Section 2.2.1 of Chapter 2, where a detailed description of the study site (field WMDS) has already been presented.

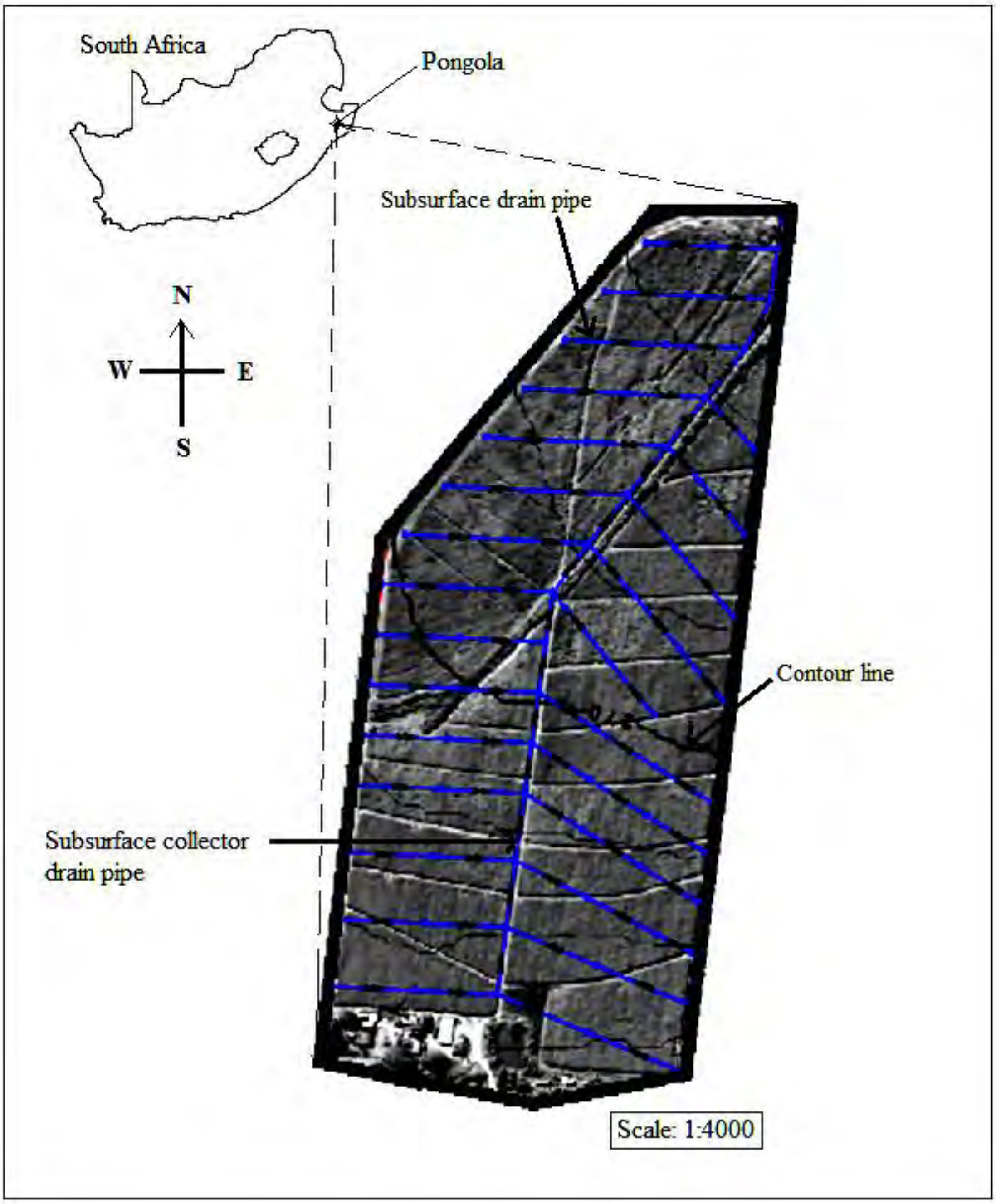

Figure 3.1 Location of study site and the layout of the subsurface drainage system on the 32 ha sugarcane field (van der Merwe, 2003)

3.3.2 General study approach

The general approach adopted in this study is shown in Figure 3.2. A basic description of the Rosetta program will be provided in Section 3.3.5, while its detailed description can be found in Shaap *et al.* (2001).

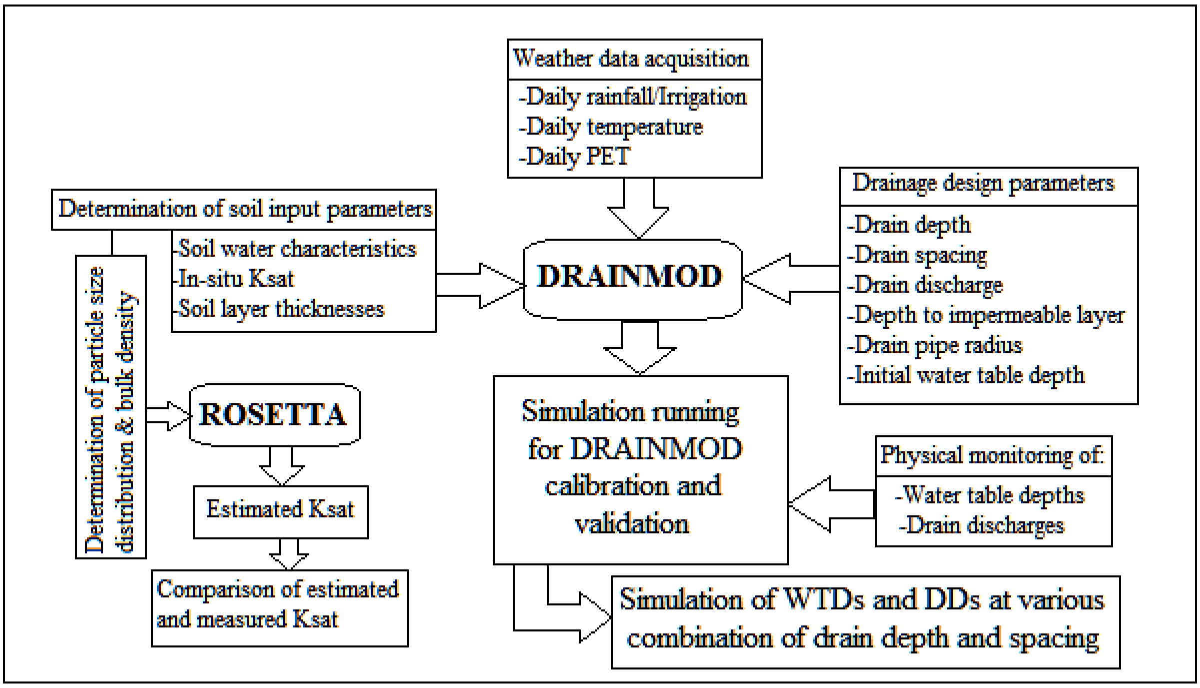

Figure 3.2 General approach to this study

3.3.3 Field measurement of water table depths and drain discharges

Much of the material for this section has been already described in Sections 2.2.3 and 2.2.4 of Chapter 2. Therefore, the reader is advised to refer to these sections for the methodology followed in the installation of piezometers mid-way between two drain laterals and the measurement of drainage discharges at drain outlet points (Figure 2.6 in Chapter 2). It should be mentioned that even though water table depths were monitored in six piezometers at the site, drainage discharges were monitored at three drain outlet points only. Hence, only the water table depth data from the three piezometers corresponding to the three drain outlet points were considered for modeling purposes.

3.3.4 Measurement of saturated hydraulic conductivity (K_{sat})

Soil hydraulic conductivity (K_{sat}) values were measured using an in-situ method i.e. the auger-hole method (van Beers, 1983), which according to Oosterbaan and Nijland (1994), is the most accurate and yet the simplest method, as opposed to laboratory methods. Prior to carrying out K_{sat} tests, five trenches were dug in the field (north, south, east, west and center) to a depth of 2.3 m from the soil surface. This was done to characterize any heterogeneities in soil layer boundaries and to determine the number and thicknesses of the soil profile layers from the soil surface. The field was then divided into three sections (upper, middle and lower sections). Three 70 mm diameter auger-holes were drilled in each of the upper and middle sections, while four auger-holes were drilled in the lower section. This made a total of 10 auger-holes drilled in the whole field used to determine a representative mean K_{sat} value for the whole field during model calibration, as recommended by Sobieraj *et al.* (2001).

The measurement procedure followed during the K_{sat} measurement is given by van Beers (1983). It was observed that the auger smeared the surface of the auger-hole during the drilling process. The water level in the auger-hole was therefore left to stabilize for one day, in order to allow for a true water table to be established. On the following day, the water table depth in the auger-hole was determined and was followed by the bailing out of about one quarter of the water depth in the auger-hole. After which, water level readings in the hole were then taken every10 seconds, using a Laser meter (HANNA Instruments) that was mounted on top of the access tube, as demonstrated in Figure 3.3.

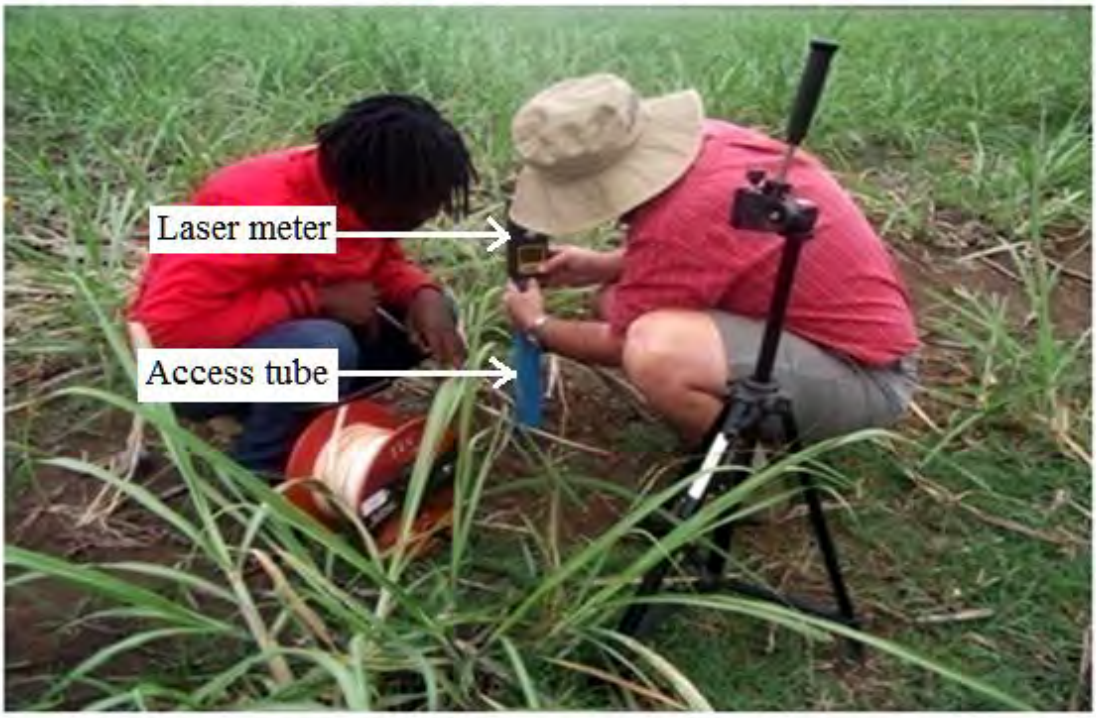

Figure 3.3 Measurement of K_{sat} using the auger-hole method

About five readings were taken successively at each auger-hole and average changes in water table depths (cm) per unit time (sec) were then calculated and recorded. Saturated hydraulic conductivity values in m.day^{-1} were computed as (Ernest, 1950):

$$K_{sat} = \frac{400a}{(20 + h/a)(2 - y/h)y} \frac{\Delta y}{\Delta t} \tag{3.4}$$

where Δy is the rise in water level during the test (cm); Δt is the time taken for rise in water level measurement (sec); a is the radius of the auger-hole (cm); h is the depth of the water table to the bottom of the auger-hole (cm); y is the depth of water table to the beginning of the test reading (cm). Figure 3.4 shows a section of one of the auger-holes, during the K_{sat} measurement, using the auger-hole method.

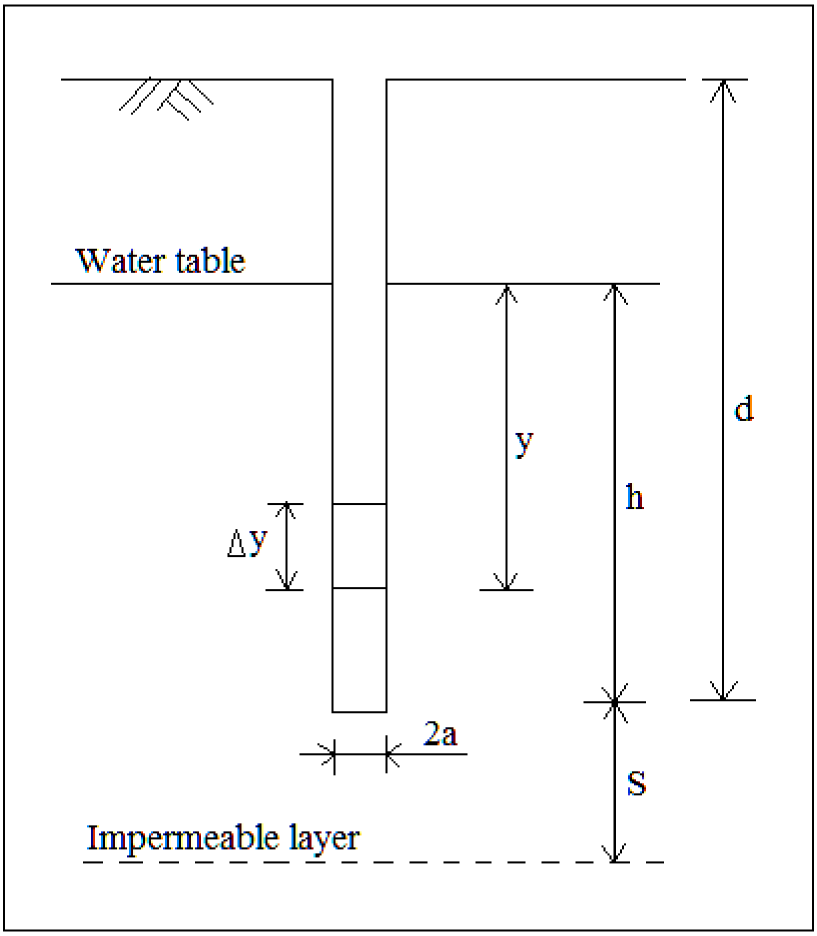

Figure 3.4 A section of one of the auger-holes where K_{sat} was measured, using the auger-hole method (after van Beers, 1983)

3.3.5 Soil particle size distribution and estimation of K_{sat} values using the Rosetta program

Saturated hydraulic conductivity values were also estimated using the Rosetta program, based on soil particle size distribution (% sand, silt and clay) and soil bulk density (g.cm^{-3}). This program was selected because Schaap *et al.* (2001) and Salazar *et al.* (2008) found that it can effectively estimate K_{sat} values from the soil particle size distribution data. In addition to estimating K_{sat} values, the Rosetta program is also capable of predicting the van Genuchten (1980) soil water retention $[\theta(h)]$ and unsaturated hydraulic conductivities (K) (Schaap *et al.,* 2001). According to Schaap and Leij (1998) and Schaap *et al.* (2001), the van Genuchten water retention model is given by:

$$\theta(h) = \frac{\theta_s + \theta_r}{\left[1 + (\alpha h)^n\right]^{1-(1/n)}} \qquad h<0 \qquad (3.5a)$$

$$\theta(h) = \theta_s \qquad h>0 \qquad (3.5b)$$

where θ_s and θ_r are saturated and residual moisture content ($cm^3.cm^{-3}$), respectively; h is the soil water pressure head (cm) at a given soil moisture content; n (>1) is the measure of pore-size distribution and α (>0) is related to the inverse of air entry pressure (cm^{-1}) (van Genuchten, 1980).

Using Equations 3.5a and 3.5b, in juxtaposition with the Mualem (1976) pore-size distribution model yields, the van Genuchten-Mualem model (Equation 3.6), which according to van Genuchten (1980) and Schaap *et al.* (2001), is then used to estimate the K_{sat} values and is given by:

$$K(S_e) = K_0 S_e^L \left\{1 - \left[1 - S_e^{n/(n-1)}\right]^{1-(1/n)}\right\}^2 \qquad (3.6)$$

where S_e is the effective saturation ($cm^3.cm^{-3}$) and is given as:

$$S_e = \frac{\theta(h) - \theta_r}{\theta_s - \theta_r} = \left[1 + (\alpha h)^n\right]^{1/(n-1)} \qquad (3.7)$$

where K_0 is the matching point at saturation ($m.day^{-1}$) and is comparable, but not entirely equal to K_{sat}; L (<0) is an empirical connectivity parameter, in most cases assumed to be 0.5 (Mualem, 1976).

Undisturbed soil samples were collected from the same chosen 10 locations, where auger-hole tests were conducted (Section 3.3.4). The samples were collected within the same soil layer in which the water table was resting during auger-hole testing (between 0.50 – 1.60 m from the soil surface). Soil bulk densities were first determined, followed by the soil particle size analysis, using the standard sieve-pipette method (Gee and Bauder, 1986).

The soil samples were air-dried, crushed and sodium pyrophosphate was then added as a dispersing agent. This was followed by passing the soil sample through a 2 mm sieve to determine the sand fraction (>0.053 mm). The pipette method was used, to determine the silt (0.002-0.053 mm) and clay (<0.002 mm) fractions, based on the Stokes Law (Lamb, 1964). The soil particle size analysis was done at the University of KwaZulu-Natal Soil Science laboratory.

The soil particle size distribution data and bulk densities (g.cm^{-3}) were then input to the Rosetta program to estimate K_{sat} values for each of the land units where the samples were collected. The in-situ measured K_{sat} values were compared to the Rosetta estimated K_{sat} values. Three statistical parameters were used to characterize the K_{sat} estimation performance of the program, namely, the Mean Absolute Error (MAE) (Equation 3.8) (El-Sadek, 2007), the Pearson's product-moment correlation (R^2) (Equation 3.9) (Wang *et al.,* 2006), also known as the Goodness-of-fit (Shahin *et al.,* 1993; Legates and McCabe, 1999; Vazquez *et al.,* 2002) and the Coefficient of Residual Mass (CRM) (Equation 3.10) (El-Sadek, 2007). These three statistical parameters were chosen because, according to Anderson and Woessner (1992) and Vazquez *et al.* (2002), they provide both quantitative and objective justifications in assessing the performance of a model in estimating a particular soil property.

$$MAE = \frac{\sum_{i=1}^{N} \left| (O_i - P_i) \right|}{N} \tag{3.8}$$

$$R^2 = \left[\frac{\sum_{i=1}^{N} (O_i - \bar{O})(P_i - \bar{P})}{\sqrt{\sum_{i=1}^{N} (O_i - \bar{O})^2} \sqrt{\sum_{i=1}^{N} (P_i - \bar{P})^2}} \right]^2 \tag{3.9}$$

$$CRM = \frac{\sum_{i=1}^{N} O_i - \sum_{i=1}^{N} P_i}{\sum_{i=1}^{N} O_i} \tag{3.10}$$

where P_i is the simulated value, O_i is the observed value, and N is the number of data entries.

MAE describes the accuracy of a model in making right predictions by measuring the average magnitude of errors between the simulated and the observed values (Shahin *et al.,* 1993; Legates and Mc Cabe, 1999; Vazquez *et al.,* 2002). According to Moraisi *et al.* (2007) and El-Sadek (2007), the MAE has a minimum value of 0.0, with values closer to 0.0 indicating a better agreement between measured and estimated values. The Goodness-of -measures how the estimated and measured data sets correlate and has minimum and maximum values of 0.0 and 1.0, respectively, with values closer to 1.0 indicating a better correlation between the two data sets (Shahin *et al.,* 1993; Legates and Mc Cabe 1999; Vazquez *et al.,* 2002). On the other hand, CRM characterizes the model's tendency to over-estimate (CRM<0) or under-estimate a property (CRM>0) (El-Sadek, 2007).

3.3.6 Measurement of soil water characteristics $\theta(h)$

The DRAINMOD model requires the following relationships in order for it to establish a soil water balance: (i) water table depth and volume of water drained (ii) water table depth and upward flux and (iii) Green Ampt infiltration parameters and recharge (Singh *et al.,* 2006). According to Skaggs (1978), the model calculates these parameters from the soil water characteristic data of the top soil layer i.e. residual moisture content (θ) versus soil water pressure heads (h).

Soil water pressure heads (m) and their respective soil moisture contents ($cm^3.cm^{-3}$) were measured using a pressure plate at the University of KwaZulu-Natal School of Engineering laboratory. Richards (1948) and Klute (1986) found out that the pressure plate laboratory method can reliably measure soil water characteristics, when undisturbed soil samples are used.

Undisturbed soil samples were collected from the upper soil layer (0–40 cm) using 50 mm internal diameter and 50 mm long stainless steel rings. Refer to Figure 3.5 for a schematic description of the laboratory set up.

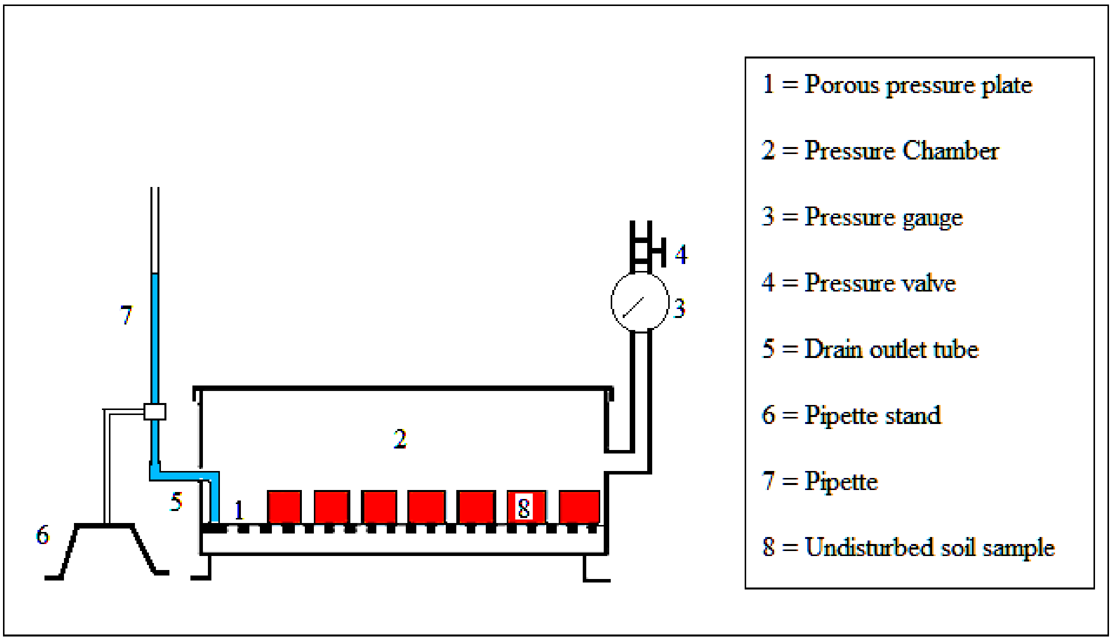

Figure 3.5 A schematic of the pressure plate used to measure soil water characteristics (after Warrick, 2000)

Firstly, the soil cores and the porous pressure plate were fully saturated in a vacuum chamber for three days, after which, the soil cores were carefully weighed without subjecting them to any pressure. The soil cores were then placed on the porous plate in the pressure chamber and tightly closed. A 10 m pressure was imposed on the soil sample so that water could drain out of the soil sample, as a result of the applied pressure. The rise in water level draining from the soil samples through the pipette was left to stabilize, after which, the soil cores were then removed from the pressure chamber, weighed and placed back in the pressure chamber. The applied pressure was then increased and the same procedure was followed for increased pressures of 20, 40, 110 and 150 m. The 0 to 150 m pressure range was chosen because Skaggs (1978) highlights that the DRAINMOD model requires the very last soil moisture content ($cm^3.cm^{-3}$) to be calculated, after subjecting a soil sample to a pressure of $\geq$10 m, while the rest of the soil water contents can be calculated after subjecting the soil samples to lower pressures.

The soil cores were then oven-dried at 105 ^{o}C for 24 hours and the soil water contents at each respective pressure setting were calculated as:

$$\theta_v = W_i \frac{\rho_{soil}}{\rho_{water}} \tag{3.11}$$

where θ_v is the volumetric soil water content (cm^3.cm^{-3}); W_i is the soil water content by mass (g.g^{-1}) (wet basis); ρ_{soil} is the bulk density of the soil sample (g.cm^{-3}); ρ_{water} is the density of water (1g.cm^{-3}) (Warrick, 2000).

The van Genuchten soil water retention model was fitted to the measured $\theta(h)$ data, using the RETC program (van Genuchten *et al.,* 1992) – a HYDRUS-2D soil water retention optimization program. In addition, mean moisture contents (cm^3.cm^{-3}) and their respective pressure heads (0-150 m) were calculated and input into DRAINMOD 6.1.

3.3.7 Weather data

A fourteen year weather data (daily rainfall, potential evapotranspiration (PET) and minimum and maximum temperature) from 1998 to 2012 was obtained from the Pongola SASRI weather database, located about three kilometers from the study site. Weather data records for the years prior to 1998 were incomplete for some days, hence they could not be used because the DRAINMOD model requires completed daily weather data records. The DRAINMOD weather file also requires the inclusion of the irrigation component (mm.day^{-1}) in the rainfall input file to account for any recharge to the soil system through irrigation. Hence, depths of irrigation water per irrigation day (mm.day^{-1}) were measured using a rain gauge installed at the study site. This was followed by the modification of the rainfall file to include irrigation depths for each irrigation day throughout the whole study period. The PET, rainfall and temperature data files prepared in the Microsoft Excel spreadsheet were then converted to the DRAINMOD model data input format, using the DRAINMOD model weather data utility program.

3.3.8 DRAINMOD model calibration, evaluation and statistical analysis

Calibration is the process where-by default model input parameters are systematically adjusted to attain the best possible agreement between simulated and observed data sets, whereas validation is the process of testing the model's reliability in making appropriate predictions based on the calibrated parameters (Singh *et al.,* 2006). It is recommended that two independent data sets be used during the calibration and validation periods, in order to avoid ambiguities when making recommendations concerning the model's dependability (Schaap *et al.,* 2001; Dayyani *et al.,* 2009; Dayyani *et al.,* 2010;). Therefore, the October 1998 to September 1999 water table depth (WTD) and drainage discharge (DD) data were chosen to be used for calibration, while the data set from September 2011 to February 2012 was used for validation purposes. The calibration procedure adopted in this study was similar to that of Dayyani *et al.* (2009) and Dayyani *et al.* (2010). It was assumed that the K_{sat} values did not have significant changes during the 1998-2012 period. This was because the cropping system and cultivation practices at the site had not changed.

Literature shows that the DRAINMOD model can be calibrated on a trial-and-error basis (Dayyani *et al.,* 2010), by adjusting any or a set of input parameters presented in Table 3.1, until an optimal agreement between observed and simulated data sets is attained.

Table 3.1 DRAINMOD model calibration parameters based on literature

Calibration parameter(s)	**Source(s)**
Lateral hydraulic conductivity, maximum soil surface storage depth, crop root depth	Zhao *et al.* (2000)
Monthly ET factors	Jin and Sands (2003)
Drainage coefficient, saturation soil water content, residual soil water content, lateral saturated hydraulic conductivity of soil layers	Haan and Skaggs (2003) Singh *et al.* (2006)
Vertical hydraulic conductivity of the bottom soil layers	Wang *et al.* (2006)

The lateral saturated hydraulic conductivity ($K_{L\text{-}sat}$) for the bottom soil layer was set at twice the vertical saturated hydraulic conductivity (K_{sat}), while $K_{L\text{-}sat}$ for the top soil layer was set equal to the K_{sat}, as suggested by Skaggs (1978). In addition, considering that crop residues were observed on the soil surface at the study site and that crop residues increase soil surface water storage (Gilley, 1994), the soil surface water storage depth was set at 2 cm, contrary to the default 0.5 cm depth.

Time series of WTDs and DDs were simulated using the DRAINMOD model after every alteration of an input parameter or set of parameters. Simulated WTDs and DDs were then compared to observed WTDs and DDs. Initially, the agreement between the two data sets were assessed by visual judgments from WTD and DD hydrographs (Moraisi *et al.,* 2007; Dayyani *et al.,* 2009), and later on, quantitative statistical model performance parameters (Equations 3.8, 3.9 and 3.10) were employed, as suggested by Legates and McCabe (1999) and Vazquez *et al.* (2002). Statistical parameters in both the calibration and validation periods for both WTD and DD data sets were calculated and tabulated.

3.3.9 DRAINMOD simulation runs at various drain depths and spacing combinations

Scenarios were simulated to represent two soil types i.e. clay-loam and clay soil. These two soil types were chosen because they were the two soil textural classes found at the site. Input parameters such as the K_{sat} values, details of the soil profile layers and the soil water characteristics, were dependent on the type of soil, while input parameters such as type of crop, crop root elongation (m) with respect to time (days) and weather data, were kept constant in both the clay and clay-loam soils. For clay soil, simulation scenarios were run with drain depths ranging from 1.4 to 1.8 m and drain spacing from 25 to 40 m at 3 m intervals. On the other hand, for clay-loam soil, simulation scenarios were run at drain depths ranging from 1.4 to 1.8 m, with drain spacing from 55 to 70 m. The selection of this drain depth and spacing simulation range for both soil types was based on a drain depth and spacing guide for KwaZulu-Natal developed by Russell and van der Merwe (1997). For every simulation scenario, the mean WTD and DD were computed and were presented graphically.

3.4 Results

This section present all the results obtained from the field measurements explained in the previous sections.

3.4.1 Soil profile physical properties at the site

Results summarizing the bulk densities of the soil profile at the site are shown in Table 3.2. From the five trenches that were dug at the site, it was observed that the soil profile had two layers, top layer (0.40 m thick) and the bottom layer (>1.90 m thick). It was also noted that the bottom layer extends beyond the 1.8 m drain depth level. When studying results of mean soil bulk densities of the two soil layers in Table 3.2, it can be seen that bulk densities of the top soil layer are generally higher than those of the bottom layer. According to Wilding (1985) a CV ≤ 35 % indicates less variability of a property, while a CV > 35 % indicates a high variability of a property. Using that classification, it can be seen that there is less variability of bulk densities in both the top and bottom layers, with CVs of 5.5 and 3.7 %, respectively.

Table 3.2 Summary of soil bulk densities ($g.cm^{-3}$) for the two soil profile layers above the drainage base

Statistic	**Top layer (0.40 m thick)**	**Bottom layer (>1.90 m thick)**
Maximum	2.81	1.99
Minimum	2.48	1.76
Mean	2.64	1.88
Standard dev	1.45	0.07
Variance	0.02	0.01
CV (%)	5.50	3.77

After determining the bulk densities of the soil samples collected in both the top and bottom soil layers, soil samples from the bottom soil layer were further analyzed for particle size distribution and soil textural class determination, using the USDA classification system (Warrick, 2000). Results of the analysis are shown in Table 3.3. This table shows that the bottom soil layer at locations A2 and A3 is characterized by clay-loam soil, with a mean bulk density of 1.8 $g.cm^{-3}$. On the other hand, the rest of the locations are characterized by clay soil with a mean bulk density of 1.90 $g.cm^{-3}$.

Results of soil classification at the site by van der Merwe (2003) revealed that the top soil layer is dominated by sandy-clay soil. Comparing those results with the results shown in Table 3.3 clearly show that the soil textural class of the bottom layer varies spatially, which is contrary to that of the top soil layer.

Table 3.3 Particle size distribution, soil textural classification and bulk densities for bottom layer soil samples obtained from different locations on the 32 ha sugarcane field

Location	**Bulk density ($g.cm^{-3}$)**	**Sand (%)**	**Clay (%)**	**Silt (%)**	**Soil textural class**
A2	1.76	31.3	18.2	50.5	Clay-loam
A3	1.84	48.4	31.8	19.8	Clay-loam
A5	1.99	20.0	49.9	30.1	Clay
A6	1.95	22.1	48.3	29.6	Clay
A7	1.97	21.8	44.0	34.2	Clay
A8	1.89	23.0	48.7	28.3	Clay
A12	1.86	22.7	45.3	32.0	Clay
A13	1.82	20.2	49.7	30.1	Clay
A16	1.87	22.7	46.1	31.2	Clay
A34	1.87	22.3	46.7	31.0	Clay

3.4.2 Saturated hydraulic conductivities (K_{sat})

A summary of measured K_{sat} values for the bottom soil layer, regardless of a particular type of soil, are shown in Table 3.4. The minimum and maximum K_{sat} values are 0.17 and 0.70 $m.day^{-1}$, respectively. The mean K_{sat} value at the site is 0.32 $m.day^{-1}$, with a standard deviation of 0.16 $m.day^{-1}$. An analysis of the measured K_{sat} values for the bottom soil layer in Table 3.4, shows that there is a high variability of K_{sat} values at the site with a CV of 50 %.

Table 3.4 Descriptive statistics of all the measured K_{sat} values using the auger-hole method

Statistic	**K_{sat} ($m.day^{-1}$)**
Minimum	0.17
Maximum	0.70
Mean	0.32
Median	0.25
Variance	0.03
Standard deviation	0.16
C V (%)	50

Results of measured K_{sat} values for the bottom soil layer in relation to the two soil textural classes found at the site are shown in Figure 3.6. Comparing mean K_{sat} values for the two soil textural classes in Figure 3.6, shows that clay soil has a lower K_{sat} values, with a mean K_{sat} of 0.24 m.day^{-1}, while clay-loam soil has higher K_{sat} values, with a mean K_{sat} of 0.6 m.day^{-1}. According to Smedema and Rycroft (1983), K_{sat} values for clay and clay-loam soils range from 0.2 to 2 m.day^{-1}.

Comparing the bottom layer K_{sat} values shown in Figure 3.6 with top layer K_{sat} values, which according to van der Merwe (2003) are in the range of 0.9 to 1.05 m.day^{-1}, clearly shows that K_{sat} values for the top layer are higher than those of the bottom layer (0.17 to 0.70 m.day^{-1}).

It is worth noting that the section of the field in which the soil textural class is characterized as clay soil in Figure 3.5, corresponded to that section of the field where drain pipes were installed at a depth of 1.8 m and a spacing of 54 m, while the rest of the field characterized by clay-loam soil corresponded to the field section where drain pipes were installed at a depth of 1.8 m and a spacing of 72 m.

Results showing the correlation between the Rosetta program estimated K_{sat} values and the in-situ determined K_{sat} values, are shown in Figure 3.6. with Table 3.5 summarizing the statistical performance of the Rosetta program in estimating K_{sat} values, based on soil physical properties. A good correlation between measured and estimated K_{sat} values can be seen in Figure 3.6. From Table 3.5, it can be seen that despite the Rosetta program has a tendency of slightly under-estimating K_{sat} values with a CRM of 0.031, generally, the estimated and measured K_{sat} values correlated very well, with a very strong R^2 value of 0.95 and a very small MAE value of 0.035 m.day^{-1}.

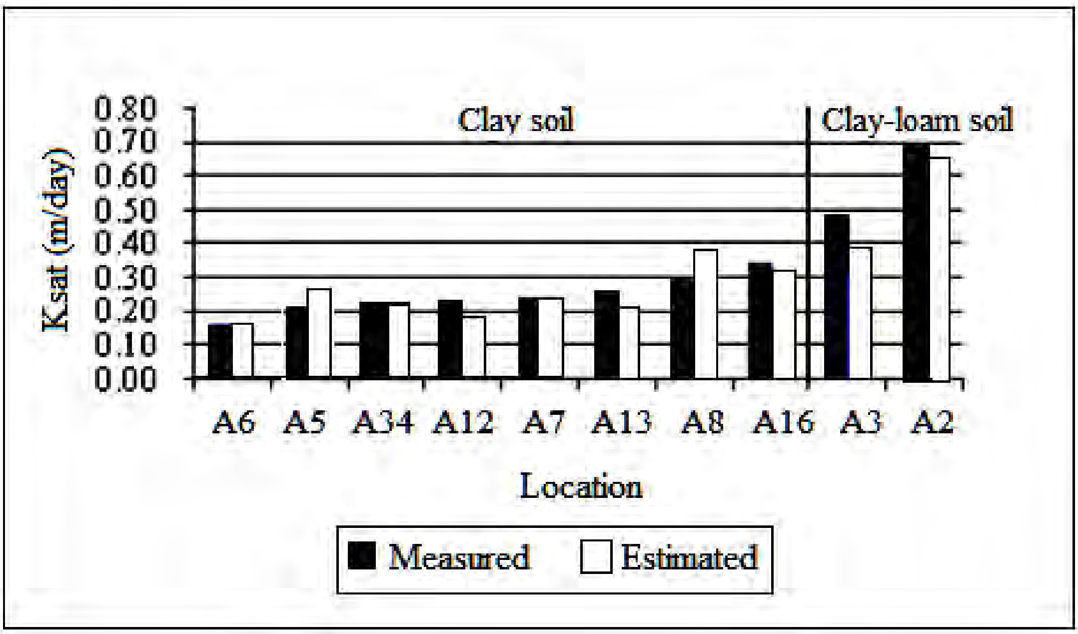

Figure 3.6 A comparison of the Rosetta estimated and the measured K_{sat} values for different land units and soil types

Table 3.5 Statistical performance of the Rosetta program in estimating K_{sat} values, using soil particle size distribution data (% sand, silt, clay and bulk density)

Statistical parameter	**Statistic**
MAE	0.035 m.day^{-1}
R^2	0.950
CRM	0.031

3.4.3 Soil water characteristic curves (SWCCs)

A summary of the results of the mean moisture content at different pressure heads are presented in Table 3.6. It can be seen in the table that there is less variability of moisture contents at all the pressure heads (CV < 35 %). Furthermore, it is evident that the variability of moisture content increases with increased pressure heads, ranging from CV of 6.38 % at a pressure head of 0.00 m to a CV of 8.58 % at a pressure head of 15000 cm.

Table 3.6 Variability of average moisture contents at different pressure heads

Pressure head (cm)	**Mean moisture content ($cm^3.cm^{-3}$)**	**CV (%)**
0	0.55	6.38
1000	0.54	6.51
2000	0.50	7.92
4000	0.48	8.29
11000	0.46	8.55
15000	0.45	8.58

The results of SWCCs obtained by fitting measured $\theta(h)$ data to the van Genuchten (1980) soil water retention model using the RETC program, are shown in Figure 3.7. In all circumstances, it can be seen that the RETC program fitted all the measured $\theta(h)$ data very well to the van Genuchten soil water retention model, with very strong R^2 values ranging from 0.975 to 0.992. As expected, in all situations, the moisture content of the soil decreased as the pressure head increased. Furthermore, in all the SWCCs, the deflection towards equilibrium pressure head was between 20 and 60 m of pressure.

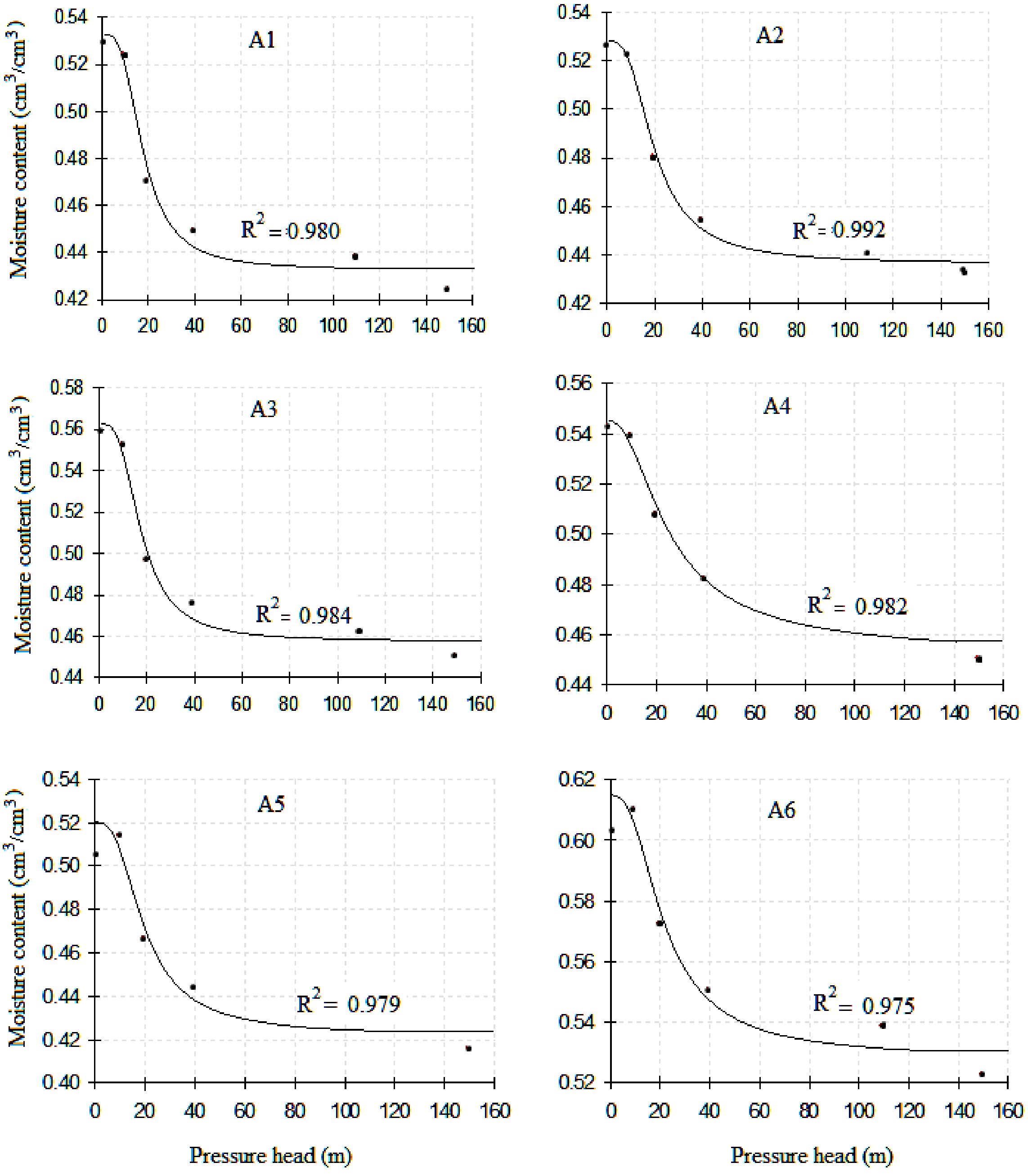

Figure 3.7 Soil water characteristic curves fitted, using the RETC program, based on the van Genuchten (1980) soil water retention model for the six sandy-loam soil samples (A1-A6) collected from the top soil layer (• Laboratory measured, ─ Fitted)

3.4.4 Performance characterization of the DRAINMOD model

The DRAINMOD model simulation for the October 1998 to September 1999 period was used for calibration. During the calibration period, the adopted drain depth and spacing were 1.8 m and 90 m, respectively, while a drain depth and spacing of 1.8 m and 54 m, respectively, were used during the validation period. This was because the drainage system in the 1998-1999 period was installed at a drain depth and spacing of 1.8 and 90 m, respectively, while in the 2003-2012 period, the system was reinstalled at a drain depth and spacing of 1.8 and 54 m, respectively.

Details of the input parameters that were adjusted during the DRAINMOD model calibration are shown in Table 3.7.

Table 3.7 Details of the DRAINMOD model calibration parameters

Input parameter	**Description**	**Calibrated parameter**
Top soil layer lateral hydraulic conductivity ($K_{1L\text{-}sat}$)	Set at equal to measured vertical K_{sat}	0.96 m.day^{-1}
Bottom soil layer lateral hydraulic conductivity ($K_{2L\text{-}sat}$)	Set at twice the measured vertical K_{sat}	0.48 m.day^{-1}
Maximum soil surface storage depth (cm)	Set at four times the default 0.5 cm depth	2 cm

Considering that no significant differences were observed among mean WTD at piezometers AP1, AP2 and AP3 (Table 2.5 in Chapter 2), the WTD data from one piezometer were selected to be used in validating the DRAINMOD model. To avoid bias in selecting data to use in validating the DRAINMOD model, random numbers were assigned to AP1, AP2 and AP3. Water table depth data from AP2 were then randomly selected to be compared to simulated WTD data during validation, while DD data from MH2, which corresponded to AP2, were compared to simulated DD.

3.4.4.1 DRAINMOD model performance during calibration

The results of time series of observed and simulated WTD and DD hydrographs during the calibration period are shown in Figures 3.8 and 3.9, respectively. As expected of arid and semi-arid climatic conditions, both observed and simulated WTDs in Figure 3.9 show a fluctuating trend. Furthermore, it can be seen in Figure 3.8 that fluctuation of WTD continued, even on rain-free and non-irrigation days. According to Skaggs (1980) and Gupta and Yadav (1993), continual WTD or DD fluctuation during the zero recharge days depicts the presence of unsteady state WTD and DD. According to FAO (2007) unsteady state WTD and DD are not a strange phenomenon in arid and semi-arid climates. It can also be seen in Figure 3.8 that peak WTDs coincided with peak rainfall/irrigation days, indicating that the water table was indeed reacting to the recharge through rainfall and irrigation. A reaction factor (α), calculated from the observed water table fluctuation was found to be 0.12 day^{-1}, which according to Smedema and Rycroft (1983), indicates that the water table at the site reacts slowly to the recharge through rainfall or irrigation.

An analysis of the results in Figure 3.8 further indicate that the model predicted shallow WTDs of less than 100 cm better than the deeper WTDs of more than 100 cm. In addition, the results show that generally the model predicted WTDs reasonably well, with a very strong R^2 value of 0.967 and a small MAE of 18.84 cm. A CRM of -0.117 indicates that the model has a general tendency of over-estimating WTDs.

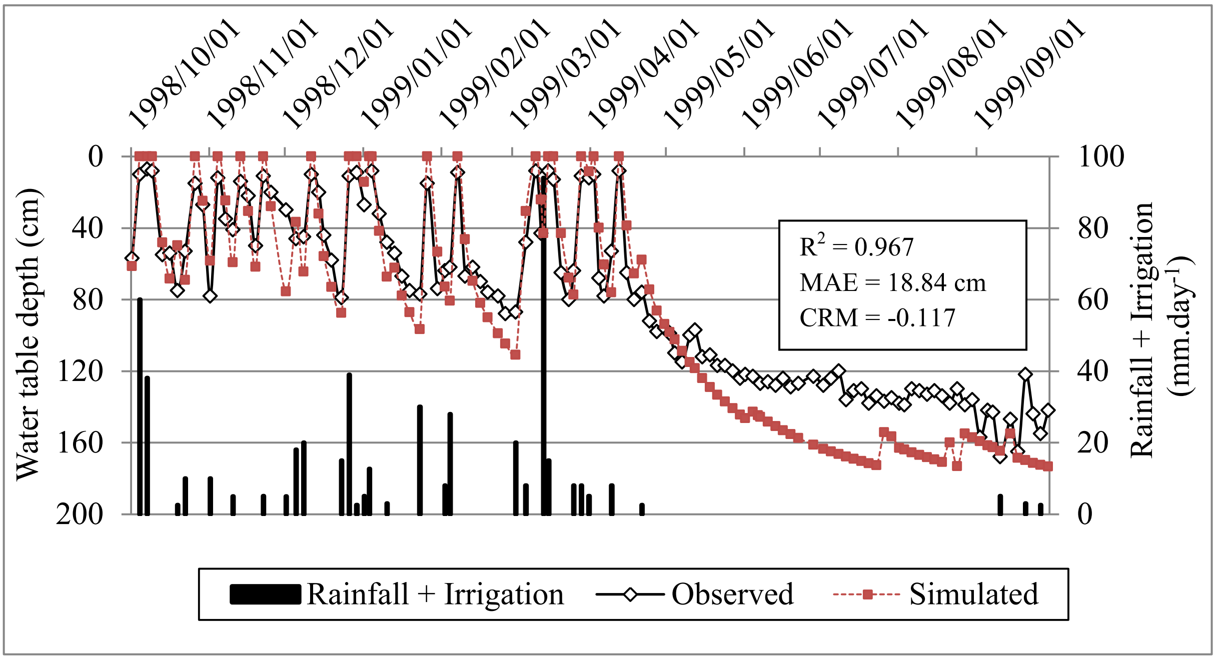

Figure 3.8 Observed and simulated water table fluctuation during the model calibration period (October 1998 to September 1999)

Results of time series observed and simulated DD hydrographs during the calibration period (September 1998 to October 1999) are shown in Figure 3.9. Just like the DRAINMOD model calibration results in simulating WTDs, both the observed and simulated DD hydrographs show a fluctuating trend, depicting the presence of unsteady state DD behavior. A study of the results in Figure 3.9 also shows that the model predicted DDs of greater than 2 mm.day^{-1} better than DDs of less than 2 mm.day^{-1}. Statistically, observed and simulated DD hydrographs show a strong agreement, with a high R^2 and a small MEA of 0.893 and 0.603 mm.day^{-1}, respectively.

A comparison of the R^2 values between pairs of observed and simulated WTD in Figure 3.8 and DD in Figure 3.9, shows that the model performed better in predicting WTD ($R^2 = 0.967$) than DD ($R^2 = 0.893$). Unlike the results of observed and simulated WTD (Figure 3.8) in which the model over-estimated DDs, contrary results were obtained in Figure 3.9 (CRM>0), giving an indication that the model also under-estimated DD during the calibration period.

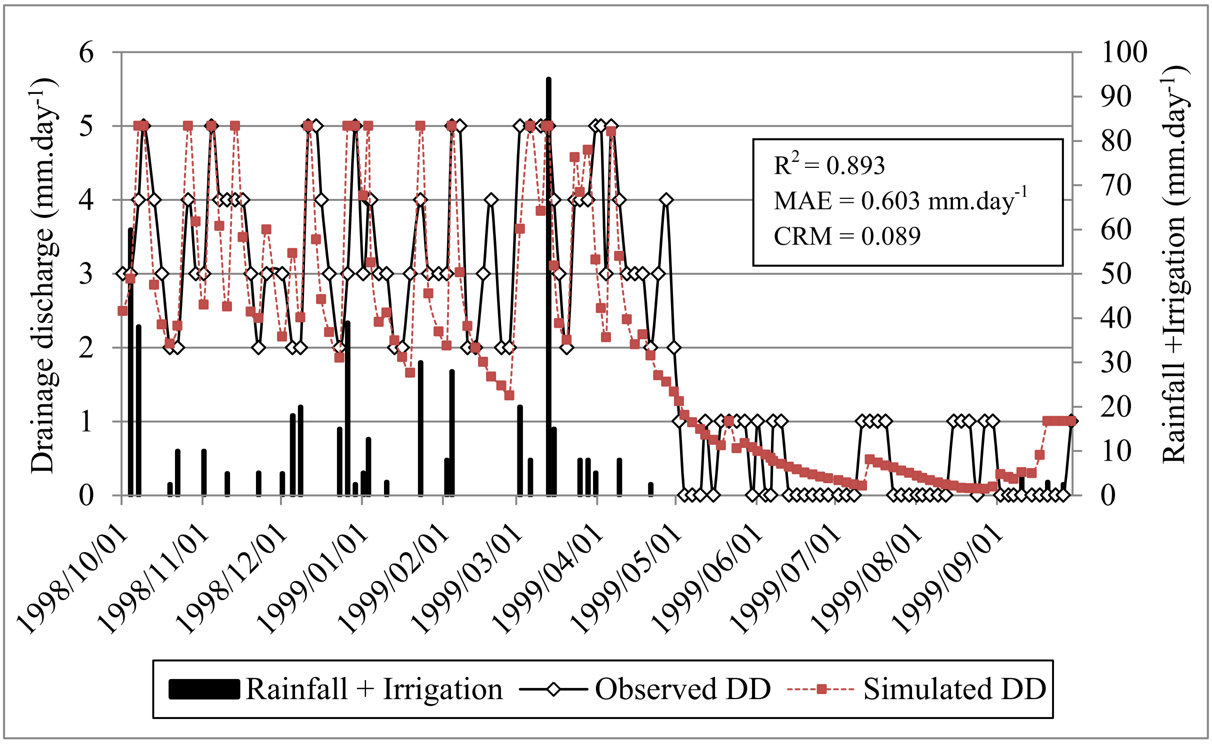

Figure 3.9 Observed and simulated drainage discharge hydrographs during the model calibration period (October 1998 to September 1999)

3.4.4.2 DRAINMOD model performance during validation

Results of the DRAINMOD model performance in simulating WTD during the validation period are shown in Figure 3.10. A visual judgment of these results clearly shows that the observed and simulated WTD fluctuations correlated very well. This is statistically proven by a very strong R^2 value of 0.826 and a small MAE of 5.341 cm. The negative CRM value of -0.015 depicts that the model over-estimated WTD during the validation period. However, comparing the MAE of 18.84 cm obtained during the calibration period (Figure 3.8) and the MAE of 5.341 cm obtained during the validation period, as seen in Figure 3.10, gives an indication that there are small differences between individual pairs of observed and simulated WTD during the validation period than the calibration period.

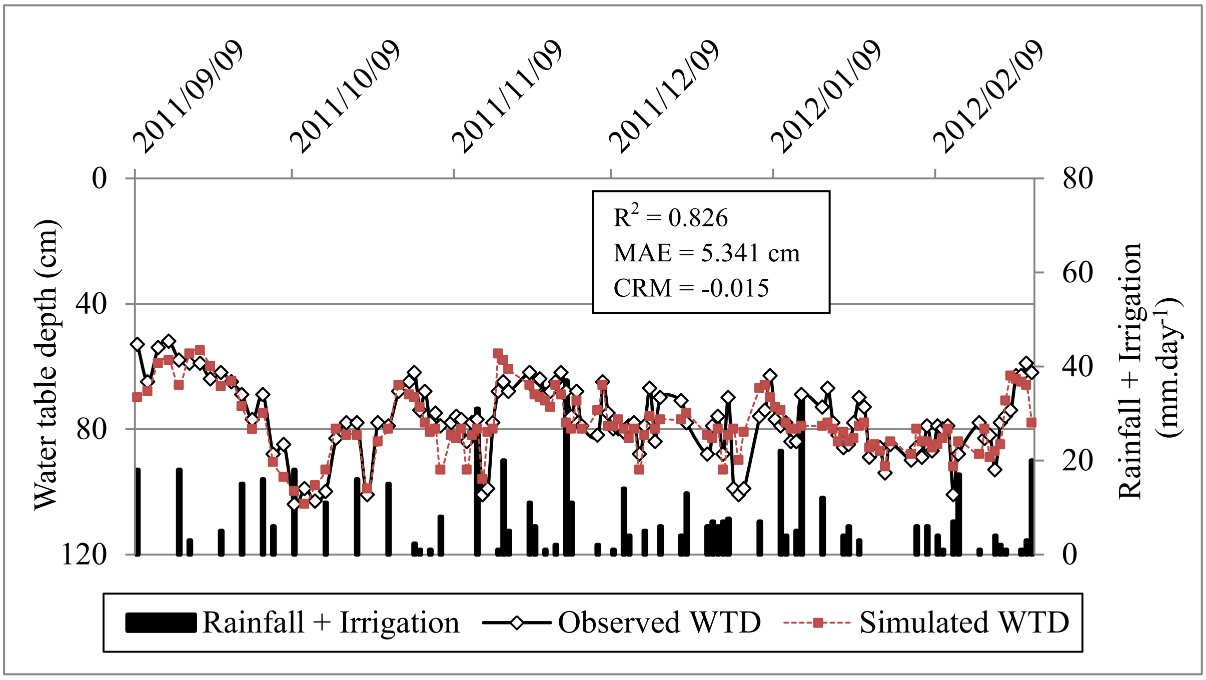

Figure 3.10 Observed and simulated water table fluctuation during the validation period (September 2011 to February 2012)

Results of the DRAINMOD model performance in predicting DDs during the validation period are shown in Figure 3.11. A very good correlation between the observed and simulated drainage discharge hydrographs can visually be deduced in Figure 3.11. Statistically, the correlation between the observed and simulated DDs is strong, with an R^2 value of 0.801 and a small MAE of 0.181mm.day^{-1}. Unlike the calibration results of observed and simulated DD (Figure 3.10), where the model showed a general tendency of over-estimating WTDs, the results in Figure 3.11 show that the DRAINMOD model has a general tendency of neither under-estimating or over-estimating DDs with a CRM of 0.0004, which is very close to zero.

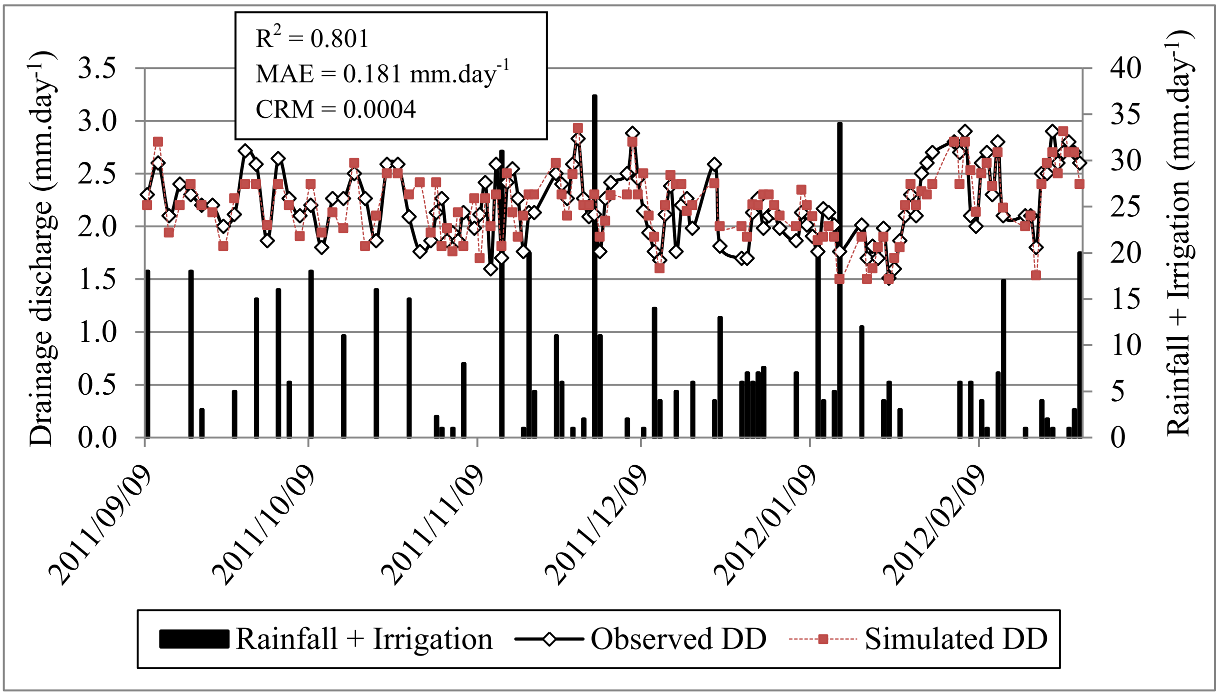

Figure 3.11 Observed and simulated drainage discharge hydrographs during the validation period (September 2011 to February 2012)

3.4.5 Simulation scenarios at various drain depths and spacing combinations for two different soils types

The calibrated DRAINMOD model was used to simulate WTDs and DDs for subsurface drainage systems installed in clay ($K_{sat} = 0.24\ m.day^{-1}$) and clay-loam soils ($K_{sat}=0.6 m.day^{-1}$). The results of mean simulated WTDs and their respective mean DDs at various combinations of drain depth and spacing are shown in Figures 3.12 and 3.13. It is evident from the results in Figure 3.12 that, when considering a constant drain depth, mean WTDs below the soil surface increase with decreasing drain spacing, and vice versa. For instance, in clay soil, it can be seen in Figure 3.12 that for a subsurface drainage system installed at a drain depth of 1.4 m and its corresponding drain spacing of 40 m, the system establishes a mean WTD of 1.0 m. However, at the same 1.4 m drain depth, the system establishes a mean WTD of 1.11 m, when the drain pipes are installed at a closer spacing of 25 m.

Furthermore, the results in Figure 3.12 show that considering drain pipes installed in clay soil at drain depth ranging from 1.4 to 1.8 m, mean WTDs between 1.0 and 1.5 m can be established, when the drain pipes are installed at a spacing ranging from 25 to 40 m. On the other hand, by installing drain pipes at the same 1.4 to 1.8 m drain depth, mean WTDs between 1.0 and 1.5 m can be established in clay-loam soil when drains are installed at a relatively wider spacing, ranging from 55 to 70 m.

Results of mean DDs at various combinations of drain depth and spacing in Figure 3.13, show that when keeping the drain depth constant in both clay and clay-loam soils, mean DDs increases with decreasing drain spacing and vice versa. Furthermore, it can be seen in Figure 3.13 that generally mean DDs increase with increasing drain depth when drain spacing and type of soil are kept constant.

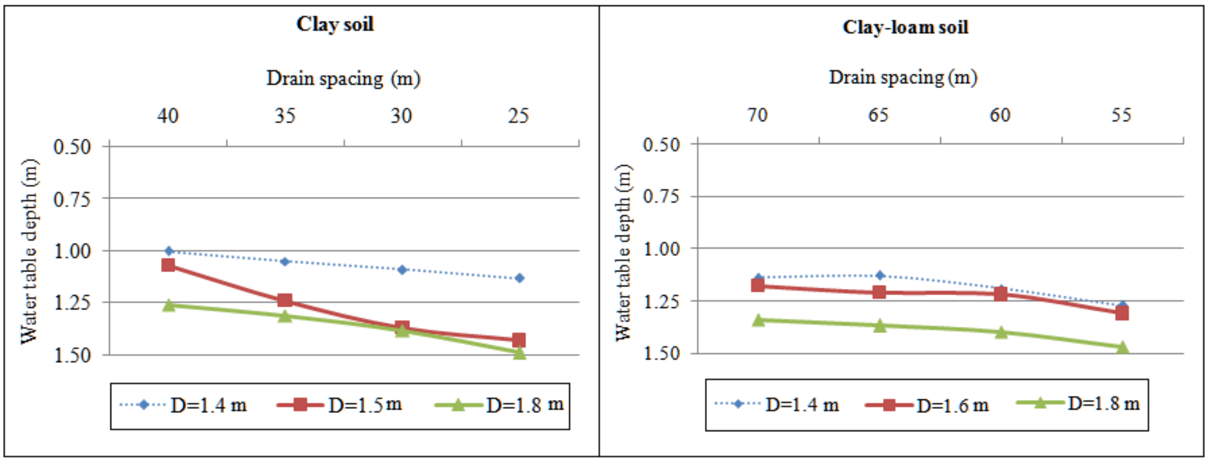

Figure 3.12 Mean water table depths in clay and clay-loam soils simulated at different drain depth (m) and spacing (m) combinations

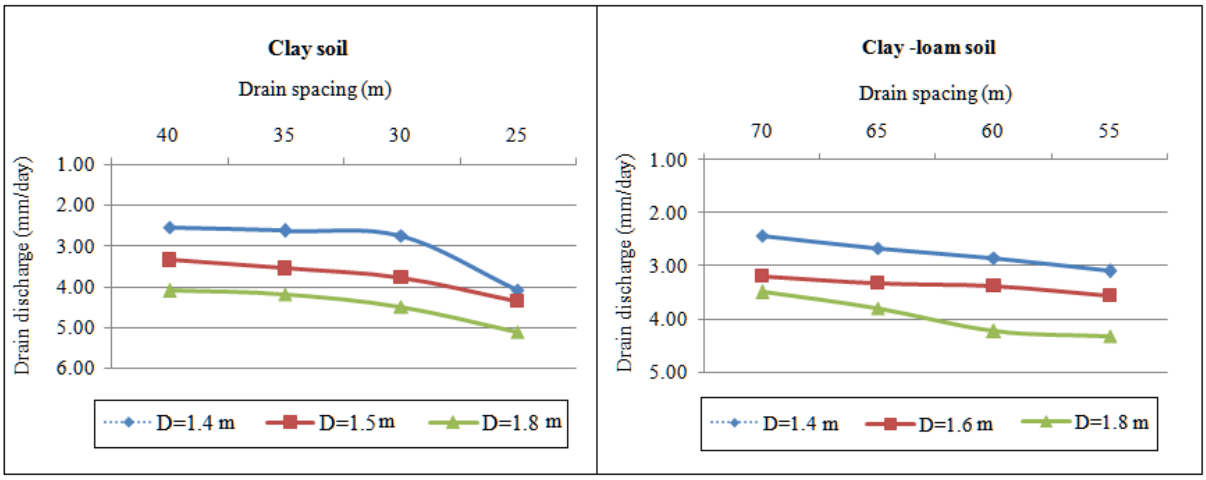

Figure 3.13 Mean drainage discharges in clay and clay-loam soils simulated at different drain depth (m) and spacing (m) combinations

3.5 Discussion

This section presents a discussion of the results obtained in the previous sections, particularly by making comparisons with results reported by other authors. Explanations related to the nature of the results obtained in the results section will also be provided.

3.5.1 Description of soil hydraulic properties at the study site

The design of subsurface drainage systems for water table control in agricultural fields requires a thorough understanding of soil hydraulic properties governing the flow of groundwater both in the saturated and unsaturated zones. According to Cameira *et al*. (2000) and Manyame *et al.* (2007), K_{sat} and soil water characteristics are the two crucial soil hydraulic properties that are required when designing subsurface drainage systems.

3.5.1.1 Saturated hydraulic conductivities (K_{sat})

According to Twarakavi *et al.* (2008), K_{sat} values are significantly affected by soil textural class. Results of K_{sat} of the top soil layer at the site reported by van der Merwe (2003) were in the range of 0.9 to 1.05 $m.day^{-1}$, which were generally higher compared to K_{sat} values of the bottom soil layer, both for clay and clay-loam soils. The difference in K_{sat} values between the top and bottom soil layers were chiefly attributed to the differences in soil textural classes in the two soil layers.

These results were partly comparable to those of Kosgei *et al.* (2009). In their study, in the Thukela basin, South Africa, Kosgei *et al.* (2009) found that K_{sat} values were slightly higher in the top soil layer than those of the bottom soil layer. They attributed this phenomenon to frequent soil tillage operations in the top soil layer, which therefore increased the soil porosity and hence the higher K_{sat} values in the top soil layer. However, in this study, since soil bulk densities of the top soil layer were higher than those of the bottom soil layer, and since ploughing at the site is done after every four or so years, the high K_{sat} values in the top soil layer could not be attributed to tillage operations. If the ploughing operation was to be done annually at the site, the top layer K_{sat} values could possibly become even greater than what was observed. Thus, it made more sense to attribute the K_{sat} difference to the difference in the soil textural classes between the top and bottom soil layers.

The accurate measurement of K_{sat} values, using in-situ methods, is strenuous (van Genuchten and Leij, 1992; Wosten *et al.,* 2001; Manyame *et al.,* 2007). It is therefore not surprising that use of indirect methods to estimate this soil property is increasingly becoming more useful. Results of the comparison between measured and the Rosetta estimated K_{sat} values indicated that the Rosetta program, can accurately estimate K_{sat} values based on soil particle size distribution data and bulk density. The program estimated K_{sat} values better than those reported by Schaap *et al.* (2001), in which laboratory determined K_{sat} values were compared to the Rosetta estimated K_{sat} values. According to Moriasi *et al.* (2007), laboratory methods have a tendency to over-estimate soil properties, including K_{sat} values, largely because of soil disturbances during core sampling. It is therefore evident that by using laboratory determined K_{sat} values in evaluating the Rosetta performance, Schaap *et al*. (2001) assumed that the laboratory determined K_{sat} values were correct. However, for K_{sat} used in drainage simulation modeling, Skaggs (1978; 1980) and Dayyani *et al.* (2009) state that the DRAINMOD model is very sensitive to this hydraulic parameter and that it must be accurately measured.

The use of the Laser meter (±1 mm measurement error) during the in-situ K_{sat} test in this study, might have reduced measurement errors quite significantly. The improved performance of the Rosetta program was therefore attributed to the comparison of the in-situ measured K_{sat} values to estimated K_{sat} values. Possibly, this approached reduced the magnitude of differences between the estimated and the in-situ determined K_{sat} at each location. In addition, the use of the standard sieve-pipette method in determining soil particle size distribution, as opposed to using other non-recommended methods, might have improved the K_{sat} estimation performance of the Rosetta program.

3.5.1.2 Soil water characteristic curves (SWCCs)

According to Millan and Gonzalez-Posada (2005), soil moisture content decreases with increasing soil water pressure heads until an equilibrium soil water pressure head is attained. This equilibrium soil water pressure head forms the permanent wilting point, beyond which plant roots cannot extract any more water from the soil (Smedema and Rycroft, 1983). The decreasing trends of fitted soil water characteristic curves (SWCCs) were in agreement with expectations. Similar trends of SWCCs have been widely reported by other authors (e.g. Vogel *et al.,* 2001; Twarakavi *et al.,* 2008 and Nasta *et al.,* 2009).

The deflection of SWCCs between 20 and 60 m pressure heads towards the attainment of equilibrium soil water pressure heads, mirrored those of sandy-clay and clay-loamy soils reported by Carsel and Parrish (1988) and sandy soils reported by van den Berg *et al.* (1997). It was encouraging to note that the soil textural class of the top soil layer at the site was also clay-loam, as reported by van der Merwe (2003). Therefore, to some extent, the trend of SWCCs in Figure 3.6 corresponded well with their respective soil textural class. This indicates that the pressure plates can be relied on to measure Soil Water Characteristics (SWC) when other equipment, is not available.

3.5.2 Performance evaluation of the DRAINMOD model

According to Skaggs (1978), the DRAINMOD model was initially developed to simulate WTDs and DDs under humid climatic conditions, where shallow water table depths are more prevalent (Sanai and Jain, 2006). This could explain the reason why the model appeared not to simulate deep WTDs, as accurately as was the case with shallow WTDs, particularly during the calibration period. The results of the DRAINMOD model evaluation at a sugarcane field in north-eastern New South Wales, Australia, reported by Yang (2008) also showed that the model failed to simulate WTDs of more than 0.8 m as accurately as was case with WTD less than 0.8 m.

It was nevertheless encouraging that the general performance results of the DRAINMOD model in simulating WTDs and DDs, during the calibration period, were better than the results reported by Dayyani *et al.* (2009). In their DRAINMOD model simulation study in the Quebec region of Canada, Dayyani *et al.* (2009) reported that the model predicted WTDs and DDs with R^2 values of 0.77 and 0.73, respectively, during the calibration period. These R^2 values are lower than R^2 values of 0.967 and 0.893 found in this study in the calibration period. However, besides these encouraging results, Dayyani *et al.* (2009) model validation results improved with R^2 values of 0.93 and 0.90 for WTD and DD, respectively, which were higher than R^2 values of 0.826 and 0.801 found in this study, during the validation period. Dayyani *et al.* (2009) used very precise and automated water level and drainage discharge data loggers to locate the depth of the water table and measure daily drainage discharges, respectively. This could explain why model validation results reported by Dayyani *et al.* (2009) were better than the validation results found in this study.

On another encouraging note, the DRAINMOD model in this study predicted better WTDs than the results reported by Singh *et al.* (2006). Singh *et al.* (2006) found that the model predicted the WTD with R^2 values of 0.89 and 0.88 during the calibration and validation periods, respectively, which were very close to the R^2 values of 0.967 and 0.826 found in this study during the calibration and validation periods. The MAE of 5.41 cm found between observed and simulated WTDs during the validation period was smaller than the 7.0 cm found by Yang (2008).

Yang (2008) reports that the accurate estimation of K_{sat} values to be used in the simulation of WTD and DD using the DRAINMOD model, enhances the adoptability of the model in an area, while the use of measured daily PET data, improves the performance of the model. Notably, during their drainage simulation studies, both Singh *et al.* (2006) and Dayyani *et al.* (2009) used estimated PET data, SWC and laboratory determined K_{sat} values as model inputs. The better performance of the DRAINMOD model in this study was to a large extent attributed to the use of measured PET data, SWC and in-situ determined K_{sat} values as input parameters. In addition, the use of an electronic dip meter in locating the position of the WTD as opposed to other methods e.g. float meters, might have improved the quality of observed WTD data quite significantly. This reduced the differences between observed and simulated WTD values. Nonetheless, the use of WTD data loggers could have improved the quality of the results even more.

The slightly weaker agreement between the observed and the estimated DDs in both the calibration and validation periods could be explained by the use of a low accuracy drainage discharge measurement method when measuring DDs, both during the 1998–1999 and 2011–2012 periods. The bucket and clock method adopted in this study might have led to so many measurement errors. Possibly, such errors resulted in greater differences between observed and simulated DDs. However, this could have been improved by using DD measurement equipment with a data logging mechanism. Unfortunately, this could not be achieved because of inadequate funds available for research equipment.

3.5.3 DRAINMOD simulation runs at varied drain depth and spacing combinations

The design of subsurface drainage systems for crop production systems involves appropriate determination of drain depth, spacing and drainage discharge in relation to a particular type of soil and crop (Hooghoudt, 1940). Results of mean simulated WTDs and DDs confirmed the prevailing designs of installing drain pipes at shallow depths, in order to establish water WTDs near the soil surface and vice versa. The possible explanation to this water table behavior could be due to reduced hydraulic heads at mid-drain spacing which, according to Dagan (1964), has a direct effect on both WTD at mid-drain spacing and drain discharge at drain outlet points.

However, considering a constant drain depth and soil type, in as far as establishing deeper WTD is concerned, installing drain pipes at a closer spacing appeared to be a better option. This was attributed to the elliptical water table shape with a very steep cone of depression, which according to Rimidis and Dierickx (2003), increases the drain flux towards the drain pipe, hence the high water table draw down (Δh) at mid-drain spacing and the increased drainage discharges.

On the other hand, the analysis of mean WTDs at various combinations of drain depth and spacing in clay and clay-loam soils suggested that closer drain spacing in clay soil and a wider drain spacing in clay-loam soils are more likely to establish the same mean seasonal WTD when drain depth is kept constant in both soil types. This was explained by differences in K_{sat} values for the two soil types, corroborating the description behind the Hooghoudt drain spacing equation in Section 3.2.

In a study of a similar nature conducted in the Southern part of Louisiana, USA, Carter and Camp (1994) found out that by considering the same type of soil and a constant drain depth, shallow WTDs are established when drain pipes are installed at a wider spacing, while deeper WTDs are established when drain pipes are installed at a closer spacing. On the other hand, in Southeast Queensland, Australia, Cook and Rassan (2002) found that considering a subsurface drainage system with drain pipes installed at the same drain depth in two soil types with different K_{sat} values, the same WTD can be established in both soil types, but with drain pipes installed at a wider spacing in the soil with a higher K_{sat} value, and vice versa. This indicates that the results found in this study corroborated well with study findings reported by Carter and Camp (1994) and Cook and Rassan (2002).

According to Oosterbaan (2002) and FAO (2007), the use Hooghoudt equation in arid and semi-arid conditions is based on a mean seasonal WTD and drainage discharge. Thus, it is apparent that under these climatic conditions the application of the Hooghoudt equation is not entirely based on a steady state criterion, but a dynamic equilibrium WTD and DD (Oosterbaan, 2002). It therefore follows that based on the simulation results obtained in this study, respective drain depth, spacing and drainage discharge of 1.4 to 1.8 m, 55 to 70 m and 2.5 to 4.2 mm.day^{-1}, would be appropriate to ensure safe WTD between 1.0 and 1.5 m depth for sugarcane grown in clay-loam soil. On the other hand, for sugarcane grown in clay soil, respective drain depth, spacing and drainage discharge of 1.4 to 1.8 m, 25 to 40 m and 2.5 to 5.1 mm.day^{-1} appeared to be appropriate to ensure a WTD between 1.0 m and 1.5 m from the soil surface.

It is recommended that the final selection of drain depth and spacing combination to be adopted at the site should be considered with caution, by making sure that drainage measures are not taken aggressively. Installation costs and available installation equipment in the area must be taken into consideration. In addition, efforts must also aim at selecting a drain depth and spacing combination that would considerably reduce irrigation water requirements by optimizing on the soil moisture contribution to the root zone depth in the form of groundwater contribution.

3.6 Concluding Remarks, Recommendations and Future Research

In this study, the reliability of the DRAINMOD model to predict WTD and DD, and the Rosetta program to predict K_{sat} values, were investigated at a sugarcane field in Pongola. Although the analysis of the DRAINMOD model evaluation results depicted that the model had a tendency of over-estimating WTDs (CRM<0) and under-estimating DDs (CRM>0), the general performance of the model in both the calibration and validation periods showed that it can still reliably be used as a subsurface drainage design tool under the Pongola conditions (R^2>0.80). Similarly, a basic performance characterization of the Rosetta program in estimating K_{sat} values, based on % sand, silt and clay, and soil bulk density, also proved satisfactory, with $R^2 = 0.95$.

The intention of this study was not to comprehensively calibrate and validate the Rosetta program. The Rosetta program performance characterization procedure adopted in this study was meant to merely get a basic understanding of how close the program can estimate K_{sat} values, based on soil particle size distribution data of the soils found at the site. A thorough calibration and validation of the Rosetta program requires a large and accurately measured K_{sat} data set (Schaap *et al.,* 2001), which is extremely difficult to find. It is therefore encouraged that for WTD and DD simulations using the DRAINMOD model, the use of measured data, particularly K_{sat}, SWC and PET, should be used whenever possible. Use of estimated input parameters should only be applied as an alternative when in-situ measured data are not available.

A detailed analysis of simulated WTDs and DDs at various drain depths and spacing combinations supported the generally prevailing design of installing drain pipes at a closer spacing in soils with low K_{sat} values and a wider drain spacing in soils of high K_{sat} values, as reported by other authors (e.g. Manjunatha *et al.* (2004) and Ritzema and Schultz (2010)). It therefore followed that, in order to maintain WTD between 1.0 to 1.5 m below the soil surface, the currently adopted 72 m drain spacing in clay-loam soil can be reduced to a spacing between 55 and 70 m, with drain pipes installed at a drain depth of between 1.4 and 1.8 m and drainage design discharge in the range of 2.5 to 4.2 mm.day^{-1}. For clay soil, simulated WTD and DD results revealed that WTD between 1.0 to 1.5 m can be achieved by installing drain pipes at a spacing between 25 and 40 m, with a drain depth ranging from 1.4 to 1.80 m and corresponding drainage discharge ranging from 2.5 to 5.1 mm.day^{-1}. Nevertheless, future verification of these drainage design criteria is of paramount importance before they can be widely adopted in the area. In addition, like previous DRAINMOD model simulation studies, long simulation periods are required to assess the control of shallow water tables in the area.

Most of the DRAINMOD model simulation runs in this study were made to suit the objectives of the study, which required WTD and DD simulated at various drain depth and spacing combinations only. However, the DRAINMOD model can also simulate the effects of varying drain depth and spacing on crop yields and drain effluent quality (e.g. Singh *et al.*, 2006). It would therefore be interesting to test the reliability of the DRAINMOD model in simulating all the above mentioned outputs. This will enhance the appropriate selection of drain depth and spacing combinations, not only based on WTD, but also on crop yields. Furthermore, this will also support future research of linking the DRAINMOD model outputs (yield, water table depth, drainage discharge and effluent quality at various drain depth and spacing combinations) to a drainage system cost minimization model.

3.7 References

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4. SUMMARY, CONCLUSIONS AND FUTURE RESEARCH NEEDS

With respect to irrigation, rainfall and water tables in agricultural lands, the objectives of the work reported in this thesis was to:

- Determine the extent, severity and possible causes of shallow water tables in sugarcane fields of Pongola.
- Simulate water table depths and drainage discharges in two different soil types at various combinations of drain depth and spacing, using the DRAINMOD model.
- Develop appropriate drainage design criteria for sugarcane grown in those two soil types, using the DRAINMOD model.
- Test the reliability of the Rosetta program in estimating saturated soil hydraulic conductivities, using soil particle size and bulk density data.

4.1 Extent, Severity and Possible Causes of Shallow Water Tables

The delineation of shallow water table affected areas in agricultural fields even where subsurface drainage systems are installed to avert the problem, will continue to be of utmost importance. Despite a subsurface drainage system being in place and maintained according to the designers recommendations, nearly 12 % of the cultivated area was found to be affected by shallow water tables of less than the 1.0 m design water table depth. The observed water table depths and drainage discharges mid-way between two drain laterals and drain discharge points, respectively, confirmed that that the system is not functioning as per its design specifications.

An analysis of time series water table fluctuations in sugarcane fields with well and poorly-maintained subsurface drainage systems revealed that the severity of the shallow water table problem in the area is prevalent in both the summer and winter seasons. However, contrary to expectations, the water table depth in a field which relied on a natural drainage was acceptably deep, during the winter seasons. This was attributed to the deficit irrigation practiced, which substantially reduced recharge to the soil system during the winter season. Despite the absence of shallow water tables in the winter season, the impact of the lack of a subsurface drainage system at the site was, however, reflected in the high soil salinity levels in the upper soil layers, which impairs crop growth. Furthermore, the natural subsurface drainage failed to maintained optimal water table depths during the summer season. It was therefore recommended that a subsurface drainage system be installed at the site, to prevent both shallow water table and soil salinity problems and that subsurface drainage system maintenance must also be provided in time.

4.2 Simulated Water Table Depths for Clay and Clay-loam Soils and the Development of Appropriate Drainage Design Criteria

The performance of the DRAINMOD model in simulating WTD and DD in both the calibration and validation periods proved satisfactory (R^2>0.80). Further application of the calibrated model, revealed that closer drain spacing are more appropriate in clay than in clay-loam soils. This was largely attributed to the two soil types having different saturated hydraulic conductivity values. Based on the DRAINMOD model simulated WTDs and DDs in clay soil, it was found that, a drain depth of 1.4 to 1.8 m and spacing of 55 to 70 m, at a drainage design discharge of 2.5 to 4.2 mm. day^{-1} would be appropriate to maintain water table depths not shallower than 1.0 m below the soil surface. For clay-loam soil, drain depths ranging from 1.4 to 1.8 m and drain spacing between 25 to 40 m, with design discharges in the range of 2.5 and 4.2 mm.day^{-1} were found to be appropriate. Nevertheless, further of these drainage design criteria is of paramount importance, before they can be fully adopted in the area.

This study has shown that the knowledge of saturated hydraulic conductivity plays a very significant role in determining appropriate subsurface drainage design parameters. It is therefore recommended that only those methods that can estimate the parameter as accurately as possible must be applied. Although the Rosetta program estimated saturated hydraulic conductivities reasonably accurate, with R^2 value of 0.95, a comprehensive calibration and validation of the DRAINMOD model, based on the Rosetta estimated saturated hydraulic conductivities, is necessary before the Rosetta program and DRAINMOD model can unswervingly be treated as two models complementing each other.

4.3 Future Research

With regard to the research findings in this study, it is recommended that future research in the study area must focus on:

- Exploring the possibility of installing an interceptor drain between the high and low elevation areas to intercept seepage flow towards low lying areas.
- Investigating the effectiveness of the envelope material with respect to approach flow, entrance and radial head loses.
- Comprehensive calibration and validation of the Rosetta program in estimating saturated hydraulic conductivities, based on easily accessed soil data. In addition, calibration of the DRAINMOD model, based on the Rosetta estimated saturated hydraulic conductivities.
- Testing the reliability of the DAINMOD model in simulating crop yields and drain effluent quality, as a function of drain depth, spacing and drainage discharge.
- Economic analysis of the overall drainage system, as part of the drainage design.
- Continual verification of the developed subsurface drainage design criteria before they can be adopted fully.
- Overall economic analysis of installing drainage systems.