In-field runoff and soil water storage on duplex soils at Paradys Experimental Farm

By

C.B. Bothma

A dissertation submitted in accordance with the requirements for the ***Magister Scientiae Agriculturae degree in Soil Science*** *in the Faculty of Natural and Agricultural Sciences, Department of Soil, Crop and Climate Sciences,University of the Free State, Bloemfontein, South Africa.*

November 2009

Study leader: Prof L.D. Van Rensburg
Co-Study leader Dr. P.A.L. Le Roux

DECLARATION

I herby declare that this dissertation hereby submitted for the Magister Scientiae degree at the University of the Free State, is my own work and has not been submitted to any other University.

I also agree that the University of the Free State has the sole right to the publication of this dissertation

Signed:

ACKNOWLEDGEMENT

I would like to thank the following persons and institutions:

- Prof. L.D. Van Rensburg my study leader for his valuable advice, readiness for consultation, mentorship and his much-needed support through out the project, will always be remembered.
- Dr. P.A.L. Le Roux my co study leader for his valuable advice, his readiness for consultation.
- The Natural Research Foundation for funding the research project.
- Mr. C.H Frankel for his wonderful companionship, and sharing of knowledge and memorable student life during the project.
- The Department of Soil, Crop and Climate Sciences of the University of the Free State, for offering me the research assistantship.
- The staff members in the Department of Soil, Crop and Climate Sciences.
- My beloved parents that gave me the support during this time, I will be forever grateful.
- My brother and sister for their great love and kindness in years when times were really tough.

Finally, I thank the Almighty God who I believe is the ultimate guide of this work and my life in general. I always returned to Him when I got stuck and when times where difficult.

“Don’t confuse a moment in life, with life.”

- Kobus Neethling

ABSTRACT

The in-field rainwater harvesting tillage technique (IRWH), developed by the Agriculture Research Council (ARC), has been scientifically tested on clay soils at Glen Agricultural Institute by comparing with conventional tillage (mould board and disc ploughing). They showed that the IRWH crop production technique is by far more sustainable than conventional tillage. Great progress was made with the transfer of the information to rural communities located in the Thaba Nchu district. More than a thousand households applied IRWH in their homesteads during a period of three seasons of extension. According to socio-economic surveys, IRWH contributed significantly to reduce the risk of food insecurity at household level. Some of families who had access to tractors and implements identified the need to apply the IRWH on their crop fields. A tillage workshop was held at Merino village in November 2003 where several implements were demonstrated, but no-one implement was able to create the well known surface structure of the IRWH to the satisfactory of the community. Hence, the first part of the study was designed to develop and test tractor drawn implements as a primary step for out scaling the IRWH technique.

Several tractor drawn implements were designed and tested in collaboration with Bramley Engineering Company. Only two implements were further tested, viz. the ridge plough designed as a primary tillage tool for creating zero gradient contour rides, and the puddler plough designed as a secondary tillage tool for preparing the micro-basins along the ridge. These implements were demonstrated at Paradys Experimental farm of the University of the Free State to communal farmers, which indicated that the implements are acceptable to them. A land preparation procedure was developed for cultivating crop field sizes up to 150 ha in association with small scale farmers. Standard practices applied in zero tillage for weeding and pest control was adopted for IRWH. Maize was harvested with a combine harvester equipped with precision technology. Unfortunately maize planting commenced late due to the severe drought and was then disrupted by long periods of continuous rain, typical of semi-arid zones. Earlier planting areas gave yields up to 4500 kg ha^{-1}, which provide ample proof that economical yields can be obtained on 50 – 150 ha crop fields. The study concludes that it is possible to commercialize the IRWH crop production technique and hence

demonstrates the bio-physical view point that it is possible for communal and small scale farmers to practice IRWH on their crop fields.

The second part of the study focused on variation in soil properties associated with the soil water storage on crop fields. For this study a 55 ha crop field under IRWH was used. Soils of the field were surveyed and the area was divided into 75 plots of equal size. These plots were used to take soil samples and soil water content. The pipette method was used for determining the clay and silt fractions of the 300 mm soil layers, while the neutron soil water meter was used for measuring the water content in the same layers. A mobile EM38, linked to a global positioning system, was used to estimate soil properties (clay plus silt content and soil water content) from the correlation between EM readings (electrical conductivity; EC, mS m^{-1}) and the measured variables obtained in selected plots. The results showed reasonable good relationships between the EC and clay plus silt content, which allowed the estimation of a textural based management zones for the crop field. The textural relationship was further exploited to estimate the profile available water capacity (PAWC) and hence the delineation of PAWC management zones. A good correlation between EC and soil water content for the profile was obtained, which laid the foundation to estimate soil wetness spatially over the crop field. Thus, this part of the study provided conclusive evidence that it is possible to estimate the variation in soil water storage with electromagnetic induction methods. Hence it opens a new and exciting research field in soil water management that will change the landscape of precision farming in the next decade. It is envisaged that variation in soil water will be managed more intensively over large fields, especially in semi-arid zones, to optimize inputs related fertilization, planting rates, pests and weed control.

The last objective of the study was to improve our understanding of how rainfall characteristics and soil physical properties influence the partitioning of rain into infiltration and runoff in the IRWH system. A mobile rainfall simulator was used to simulate rain storms of three different intensities, *viz*. low (33 mm h^{-1}), medium (59 mm h^{-1}) and high (122 mm h^{-1}). Results obtained from the experiment demonstrated the importance of the influence of rain intensity on the infiltration parameters, such as time to runoff, time to final infiltration rate and final infiltration rate. The correlation matrix and multiple regression statistics make it possible to characterize the interaction between rainfall intensity and soil physical properties to predict the various infiltration

parameters. From the infiltration-runoff relations it was clear that these soils exhibit a high potential to harvest water as required by the IRWH system.

This study left the researchers with the following research challenges, namely (i) the socio-economic factors associated with the application of the mechanized IRWH technique at farm scale and (ii) the application of the EM38 to estimate soil wetness and other chemical properties in a wider range of soils and conditions.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS:

ANOVA	Analysis of variance
AS 1	Aggregate stability > 4 mm
AS 2	Aggregate stability 2 – 4 mm
AS 3	Aggregate stability 1 – 2 mm
AS 4	Aggregate stability < 0.5 mm
Bd	Bloemdal soil form
CEC	Cation exchange capacity
CPN	Cambill Pacific Nuclear
CS	Coarse sand (%)
C silt	Coarse silt (%)
CV	Coefficient of variation
D-index	Index of agreement
DUL	Drained upper limit
EC	Soil electrical conductivity
ECe	Saturation extract
EM	Electromagnetic induction
EM_h	Electromagnetic induction horizontal reading
EM_v	Electromagnetic induction vertical reading
Eo	Potential evaporation
FI	Final infiltration rate
FS	Fine sand (%)
F silt	Fine silt (%)
FSSA	Fertilizer Society of South Africa
GPS	Global positioning system
Ha	Hectares
HCPSZ	High clay plus silt zone
IRWH	In-field rainwater harvesting
I_{bs}	Basin strip
I_{rs}	Runoff strips
LCPSZ	Low clay plus silt zone
LL	Lower limit
MCPSZ	Moderate clay plus silt zone
MS	Medium sand (%)
mS m^{-1}	Milisiemens per meter
Mpa	Mega pascal
OM	Organic matter (%)
PAW	Plant available water
PAWC	Profile available water capacity
PR	Penotrometer resistance
RI	Roughness index
RMSE	Root mean square error
RMSEs	Systematic root mean square error
RMSEu	Unsystematic root mean square error
RWP	Rainwater productivity
Se	Sepane soil form
SS	Soil Slope
TDR	Time domain reflectometry

TFI	Time to reach final infiltration rate
TMU	Terrain morphological units
TR	Time to runoff
TS	Total sand(%)
Tu	Tukulu soil form
UFS	University of the Free State
VFS	Very fine sand (%)

Chapter 1

1. Introduction

1.1 Motivation

World trends: Over the past three decades, global agriculture has made tremendous progress in expanding the world supply of food. Even though the world population has doubled over this period, food production has risen even faster with per capita food supplies increasing from less than 2000 calories per day in 1962 to more than 2500 calories in 1995 (FAO, 2006). The rise in global food production has been credited to better seeds, expanded irrigation, and higher fertilizer and pesticide use. However the prospect of feeding a projected additional 3 billion people over the next 30 years poses more challenges than encountered in the past 30 years. In the short term, global resource experts predict that there will be adequate global food supplies (FAO, 2007), but the distribution of those supplies to malnourished people will be the primary problem.

Food security in Sub-Saharan Africa: Statistics from United Nations (2005) indicated that the poverty rate has declined by six percent since 2000 in Sub Saharan Africa, but the region is far from the goal of reducing poverty and hunger by 50% by 2015.

Although the region receives nearly 3 million tons of food per annum there are still approximately 200 million of its people chronically suffering from food deprivation. Furthermore, transport costs restrict the supply of overproduction in developed counties to these people. It is clear that food production must increase where it is needed most.

Roughly 80% of poor people depend on agriculture for their livelihood (Hatibu, 2003; FAO, 2007). Dryland crop production contributes to 95% of the food production in Sub Sahara Africa. In certain parts of the area droughts are a common phenomenon and lead to crop failure. Somalia, Eritrea and Djibouti are the areas most affected by dry spells and common droughts (Sanders & MacMillan, 2001). Therefore, optimal utilization of the natural resources, water and soil, is critical for a higher sustainability in food production practices.

Water storage in soils can be increased by applying the following techniques, namely: runoff harvesting from roads, footpaths and compounds; runoff from hillsides and rocks; utilization of valley bottoms and water tables; pitting systems and water conservation and runoff farming (Mati & De Lange, 2003).

Food security in South Africa: South Africa is generally perceived as a country that can produce most of its own food and fibre and does not experience food insecurity on a national level. The reality is that this is only true for the commercial agriculture sector and for citizens who earn enough to buy food. The National Department of Agriculture (1998) estimated that 16 million people, *i.e.* 40% of the total population, live in poverty and are affected by food insecurity. The situation is deteriorating as 72% of the poor are dependent on dry land and rain-fed agriculture.

Another limitation is that the larger portion of the affected people is concentrated in the former homelands, characterized by dry semi-arid conditions and marginal soils. Small scale farmers face many challenges among which aridity index, climatic uncertainty, economics of scale (Auerbach, 2003).

Results from socio-economic surveys (Monde, 2003; Fraser *et al*., 2003) showed that most of the households utilize other means as a survival strategy and in many cases abandoned their crop fields to reduce risks (Kundhlande *et al*., 2004). Furthermore, they lack the financial resources to buy enough food of good quality to meet their daily nutritional requirements (Mukhala, 1998). The obvious solution is that people should be capacitated with more sustainable methods to make better use of their natural resources, water and soils. People should return to their lands and should have the opportunity to own a sustainable living, using innovative technology that can overcome the bio-physical constrains. One of the most promising technologies in the field of water harvesting is the in-field rainwater harvesting crop production technique developed by Hensley *et al*. (2000) for marginal soils in semi arid areas as an alternative to the conventional ploughing practice.

Water storage through in-field rainwater harvesting: The theme of this study relates to water harvesting, specifically to the in-field rainwater harvesting technique (IRWH) mentioned in the previous section. The surface layout of the IRWH system differs vastly from conventional tillage systems. It consists of a 2 m runoff strip and a 1 m basin strip integrated as one system (Figure 1.1).

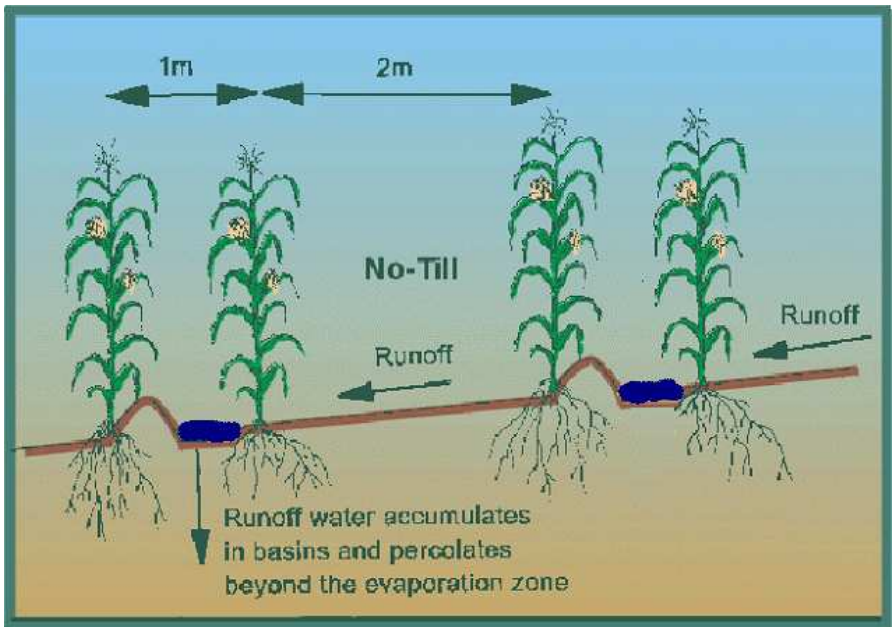


Figure 1.1 A diagrammatic layout of the IRWH-technique, showing the runoff strip (catchment) and basin strip (collection area) modified as micro basins (Botha, 2007).

Several studies were conducted regarding the bio-physical and socio-economical sustainability of the technique on clay and duplex soils. Botha (2007) evaluated the performance of the IRWH on four ecotopes in the central Free State and concluded that the technique is sustainable and superior to mouldboard ploughing conventional tillage. Yields of maize and sunflower were between 30 and 50% higher than that of conventional practices. He explained that the yield advantages could be attributed to the total stoppage of ex-field runoff and reduction of evaporation from the soil, supplying more water for transpiration. The enhancement of in-field runoff towards the basins, induces water availability to the crops, thereby increasing rainwater productivity (RWP) significantly.

1.2 Approach and objectives

The approach of this thesis was to build on the research findings of the Agricultural Research Council (ARC) and the University of the Free State who completed a series of experiments at Glen Agricultural Institute (on-station) and in communities located in the Thaba Nchu district, east of Bloemfontein (Hensley et al. 2000; Botha et al. 2003; Kundhandle et al. 2004; Botha,

2007). The main conclusions drawn from their long term results were that conventional tillage on the clay soils is unsustainable and that IRWH was superior above conventional tillage. Therefore it was argued that it makes no-sense in studying conventional tillage any further and rather concentrates on IRWH.

Several implements on conservation agriculture were demonstrated during a workshop on the mechanization held during October 2003 at Merino village, Thaba Nchu. None of the implements were able to reconstruct the surface structure of IRWH made manually with spade and rakes. Because of this, farmers expressed their need at the workshop for the development of implements to mechanise the IRWH and to developed agronomical guidelines for the implementation of IRWH. These needs were used as bases for formulating the objectives of the first phase of the project (thesis) in Chapter 3, viz:

(i) To develop tractor drawn implements that can mechanise IRWH, and
(ii) To develop a procedure for the application of IRWH tillage operations, which includes the suitability of IRWH on the ecotope, land preparation with IRWH implements and general agronomical practices associated with the application of IRWH.

The second phase of the project focused on obtaining a better understanding of the spatial distribution of soil water storage under IRWH. Soil water storage is ultimately expressed as the difference between the drained upper limit and lower limit of plant available water. The drained upper limit is the highest field-measured water content of a soil profile after it was thoroughly wetted and allowed to drain until drainage became negligible (decrease of 0.1 to 0.2% in water content per day). The lower limit of a profile is defined as the lowest field-measured water content after plants stopped extracting water and plants became dormant or premature as a result of water stress (Ratliff *et al*., 1983). The greater the PAWC, the higher the crop production potential of semi-arid ecotopes would be. Water conservation measures such as fallowing, mulching and rainwater harvesting are used frequently to conserve more water, thereby reducing the climate induced risks of semi-arid zones.

It is often argued that variation in soil water storage is not of importance to small scale farmers. However, in the former homelands land rights on crop field are allocated by the tribal authority and in the case of Thaba Nchu district families do have access to between 0.5 and 5 ha plots in the crop fields (Kundhlande *et al*., 2004). Crop production, however, potential differ significantly

between the plots as illustrated in the soil survey of Hensley *et al*. (2007) and the pilot project of Manona and Baiphethi (2008) on land register. Some of the families were allotted crop fields unsuitable for conventional or IRWH. It is therefore of the utmost importance to develop techniques for quantifying variation in soil water storage. Kundhlande *et al*. (2004) stated clearly that much greater effort is required to promote intensification of these plots.

Reliability, ease of measurement, and ability to detect a variety of soil properties, made spatial EC measurements a common tool used for field and landscape-scale studies related to production properties (Corwin & Lesch, 2005a). Despite the advancement of electromagnetic induction (EM) technology, the application of the science in agriculture is under utilized in Africa particularly South Africa.

The concept of using induced EM fields to measure conductivity of material with EM technology originated in the field of geosciences as far back as half century (Belluigi, 1948; Wait, 1954, 1955). The development of the EM31 and EM38 instruments by Geonics Ltd. (Ontario, Canada) contributed significantly to the application of EM technology in agriculture where it is used for quantifying soil salinity in many developed countries (De Jong *et al.,* 1979; Rhoades and Corwin, 1981; Kingston, 1985; McKenzie *et al*. 1989).

The following objectives were set for phase two:

(i) to seek possible relationships between electrical conductivity measured with the EM38 and textural properties in order to delineate agronomical management zones under IRWH (Chapter 4)
(ii) to predict the spatial variability of profile available water capacity in a crop field under IRWH using the EM38 (Chapter 5)
(iii) to predict spatial variability of soil wetness of a crop field under IRWH using the EM38 (Chapter 5)
(iv) To characterize rainfall-runoff relationships under IRWH as influenced by rain intensity and soil physical properties (Chapter 6).

The research in Chapter 6 focuses on the climate and soil physical properties and its relation to water storage through in-field runoff. Important climatic factors regarding water storage are the amount, duration and intensity of rain events (Tyson, 1986). Rainfall in the drier environments is generally insufficient to meet basic needs for crop production, is poorly distributed over the

growing season, often takes the form of intense bursts and cannot support viable farming economically. Furthermore climatic factors in collaboration with certain soil physical factors may influence the infiltration capacity and runoff from soils. The physical properties related to water storage are initial wetness, matric forces, texture, structure, soil depth, organic material and layering of horizons of soils (Hillel, 2004).

Chapter 2

LITERATURE REVIEW

2.1 Introduction

Rain-fed agriculture is one of the largest sectors in the world. Almost 80% of the agricultural land is in use by rain-fed production systems, providing 60% of the world food production (Stroosnijder, 2003). In a study done by Newton and Williams (2006) they reached the conclusion that some areas within a field exceeded potential yield of the specific area of the field, and the apparent water use exceeded growing season rainfall. According to them the only explanation for this occurrence is that water had either redistributed as runoff or lateral flow, or there was a large carry over of stored water. In other cases the yield was lower than expected from the rainfall, indicating water losses through runoff and therefore poor storage.

Runoff within fields can occur even in relatively flat areas, where unfavourable soil surface conditions impacted negatively on infiltration. The water collect as puddles before flowing into streams. However, most of the water in the puddles evaporates so that very little water contributed to the groundwater (Oweis, *et al*., 1999). Climatic factors also play a significant role regarding the amount of runoff occurring within a field. Climatic factors that should be considered regarding runoff are the amount, duration and intensity of rain events (Tyson, 1986).

From the study by Newton & Williams (2006) it is clear that the water storage ability of soils plays a significant role in the variation of yields occurring within fields. According to Corwin (2006) soil is spatially heterogeneous, as most soil chemical and physical properties can vary significantly within just a few meters. Soil factors that also play a role in water storage are infiltration, permeability of the soil layers, soil texture, structure, soil depth, organic matter and landscape features such as micro-elevation and topography (Corwin, 2006).

Variation in soil physical properties, nutrient levels and water content occur between fields and within fields. These spatial variations result from several factors such as previous farming practices, topography of the land, and nutrient application inaccuracy (Fulton *et al*., 1996). Other

aspects that impacts on the efficient production of crops often concern availability of soil water to crops, which, in turn is affected by climate, soil type, crop water demand, weed competition and incidence of diseases and pests (Newton & Williams, 2006).

The objective of this literature review is to distill information from literature on: (i) water harvesting, especially runoff-inducement on crop fields (ii) the phenomenon of variation in soil properties related to soil water storage and (iii) the ability of the EM38 instrument to measure soil variation.

2.2 Runoff-inducement

2.2.1 Principles and practises

The degradation of natural resources has become a global problem that threatens the livelihoods of millions of poor people. In general it is important to improve the management of natural resources in dry areas.

The most important natural resource in the drier environments is rainfall. Despite its scarcity, rainfall is generally poorly managed, and much of it is lost through runoff and evaporation. Capturing rainwater and utilizing it's efficiency is crucial for the sustainability of communities that rely on dry land agriculture (Oweis *et al.*, 1999).

Rainfall in the drier environments is generally insufficient to meet basic needs for crop production. As it is poorly distributed over the growing season, and often comes in intense bursts, it cannot support viable farming. Furthermore, runoff can occur, even in relatively flat areas, where unfavourable soil surface conditions prevent infiltration, its influence therefore is detrimental. In these conditions water collects as puddles before flowing into streams. Most of this water evaporates; therefore very little water reaches to the groundwater reservoir.

Loss of what little rainfall there is causes severe moisture stress in growing crops (Oweis *et al.*, 1999). It is therefore imperative to focus on opportunities for increasing efficient utilization of limited water in rain-fed smallholder agriculture in semi-arid areas. Rainwater harvesting is one such opportunity that contributes towards the efficient use of rainwater for crop production (Woyessa *et al.*, 2006).

Water harvesting may occur naturally or by intervention. Natural water harvesting can be observed after heavy storms, when water flows to depressions, providing areas for farmers to cultivate. Water harvesting by intervention involves inducing runoff and either collecting or directing it to a target area for use. Rainwater harvesting may be defined as “the process of concentrating precipitation through runoff and storage, for beneficial use” (Oweis *et al.*, 1999).

Water harvesting methods can be divided in micro- and macro-catchments (Figure 2.1). Micro-catchment systems are those in which surface runoff is collected from a small catchment area. Runoff water is usually applied to an adjacent agricultural area, where it is either stored in the root zone and used directly by plants or stored for later use.

On-farm micro-catchment systems are simple in design and can be constructed at low cost. They have higher runoff efficiencies than macro-catchment systems and do not usually need a water conveyance system. Unlike macro-catchment systems the farmer has control within his farm over both catchment and target areas.

Macro-catchment and floodwater-harvesting systems are characterized by capturing runoff water from a relatively large catchment. Often the catchment is a natural rangeland, the steppe, or a mountainous area. Macro-catchment systems are sometimes referred to as “water harvesting from long slopes” or as “harvesting from an external catchment”. Generally runoff capture is much lower than for micro-catchments, ranging from a low percentage to 50% of annual rainfall (Oweis *et al.*, 1999).

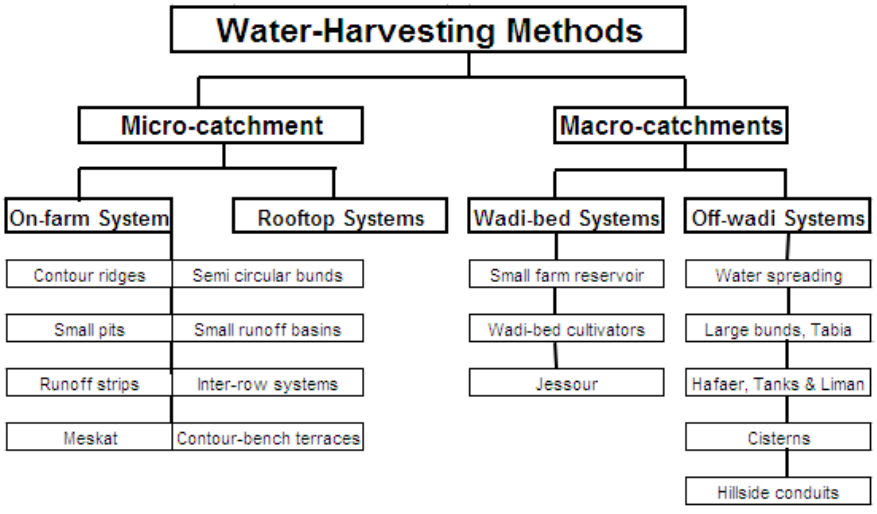


Figure 2.1 General classification of water harvesting systems (Oweis *et al.*, 1999).

The increasing scarcity of good-quality water in most river basins results in intense inter-sector competition for water. The efficient utilization of water can be perceived more comprehensively when the allocation of water in a basin among various users is considered (Woyessa *et al.,* 2006). Water rights, affecting the distribution of water between the catchment and the cultivated areas, and to the various users in the upstream and downstream areas of the watersheds, are among the most important problems associated with these systems (Oweis *et al*., 1999).

The upstream abstraction of water in the catchment upstream may have hydrological impacts on downstream water availability. Increased water withdrawal at the upstream level will have a bearing on the downstream water availability. Increased adoption of rainwater harvesting could have a hydrological impact on the river basin water resources management and have negative implications for water availability to sustain hydro-ecological and ecosystem services. The expected upstream shifts in water-flows may result in complex and unexpected downstream effects, in terms of quantity and quality. In general, though, increasing the residence time of runoff flow in a watershed through rainwater harvesting may have positive environmental, as well as hydrological implications (Woyessa, *et al.,* 2006).

2.2.2 In-field runoff

2.2.2.1 Rainfall characteristics

In the subtropical regions of the earth that are influenced by the semi-permanent high pressure cells of the general circulation of the atmosphere, climates are characterized by a high degree of intra- and inter-annual variability. Rainfall, in particular, is erratic in time and spatial distribution. The climate of southern Africa is influenced strongly by the position of the subcontinent in relation to the major circulation features of the southern hemisphere (Tyson, 1986). The 400 mm isohyet divides South Africa into wetter eastern and drier western parts. In all areas topography exerts a strong control on rainfall and produces clear orographic anomalies, with mountains enhancing and valleys diminishing precipitation (Tyson, 1986).

Much of the rainfall received in the summer rainfall region is of convective origin. In general, over most inland areas rain falls most frequently during the afternoon and early evening (Tyson, 1986). Over most of the eastern summer rainfall region, between 20 and 30 such days are recorded, over the drier western parts fewer than ten may occur (Schulze, 1984).

Annual relative variability of rainfall is less than seasonal variability, which in turn is less than monthly variability (Schulze, 1984). In general variability is least in the season of greatest rainfall and in areas of highest rainfall. In wet years the variability is substantially greater over the drier western parts of South Africa than during dry years (Tyson, 1986).

During the twentieth century a clear spatial pattern of the occurrence of extreme wet and extreme dry years has been established. In extreme wet years, rainfall exceeds 125% of normal rainfall and in extreme dry years it is 75% below the normal rainfall. In South Africa a regular series of alternating wet and dry spells are observed. During a period of wet spells years of above normal rainfall dominates, but dry years are not excluded. During dry spells, years of below-normal rainfall predominate, accelerating desertification, but wet years may occur The process of desertification is well defined as “the impoverishment of arid, semi-arid and some sub-humid ecosystems by the combined impact of man’s activities and drought”. Short-term changes in the general circulation of the atmosphere that produce prolonged periods of drought are almost always the catalyst for producing accelerated desertification (Tyson, 1986).

2.2.2.2. Factors influencing runoff

In the semi-arid areas of Southern Africa water scarcity and low soil fertility are the two main factors limiting food production. Irrigation agriculture is currently the biggest consumer of South Africa’s water resources saving irrigation water by means of efficient farming practices will free precious water supplies for human and industrial consumption (Botha *et. al.,* 2003). In particular, various water conservation techniques, among them rainwater harvesting, are seen as having the potential for increasing available water for successful crop production in semi-arid areas (Botha *et al.,* 2003).

The specific advantages of each of the in-field rainwater harvesting (IRWH) technique are: the basins minimize or stop overall runoff and water erosion; and the untilled, crusted soil on the 2 m width inter-crop row area serves to induce runoff towards the basins. The water stored underneath the runoff strips is of great importance during intense and long dry spells. This water often provides the necessary water supply to prevent crop failure by taking the crop to the next rain event (Botha *et al.,* 2003).

A general reduction in runoff will result from practices that successfully increase the contact time and reduce surface sealing on soils. The runoff and soil loss from natural veld is much lower than from fields under continuous maize production. Owing to the crusting of many soils in

South Africa, runoff from unsuitable soil can increase. Instances occur in South Africa where runoff of water is as much as 32% of the rainfall in a single rain event (Bennie & Hensley, 2001). Most soils in Africa have poor physical and chemical characteristics and are vulnerable to crusting, consequently leading to considerable runoff. Furthermore crusts can form obstacles for seedling emergence (Stroosnijder, 2003).

Crop failure on marginal soils is attributed mainly, among other factors, to the low and erratic rainfall pattern and low potential soils (Hensley *et. al*, 2001). Generally the IRWH techniques, just like conventional tillage, are dependent on rainfall over which the farmer has no control. Nevertheless the former techniques offer an opportunity to a farmer to reduce risk considerably (Botha *et al.*, 2003). In a case study carried out by Bennie and Hensley (2001) it was found that the total biomass of plants produced per unit area is directly related to the amount of water taken up by the plant.

2.3 Variability in soil properties

According to Gordon (2005) effective and efficient management of water is of utmost importance for many agricultural communities. Conserving water has benefits for society, the environment, and agriculture. It is increasingly recognized that, although soil water content changes over time, the spatial pattern of its variability is fairly constant.

Soil water content and water holding capacity are often the main reasons for local yield variation. Soil structure and physical properties affect the availability and movement of soil water and therefore also the nutrient uptake of plants (Farkas *et al.,* 2006). Interpretation of yield maps may improve by a better understanding of water movement and its relationship to rainfall intensity (Newton & Williams, 2006).

In a study by Gordon (2005), he found that coarser textured soils were generally drier, while the water holding capacity of a soil is influenced by other soil processes such as infiltration and redistribution, as well soil properties that relates to permeability, texture, structure, depth and organic matter of the soil; and landscape features such as micro elevation and topography (Corwin, 2006).

2.4 Soil sensors for measuring spatial variation in crop fields

Improved knowledge on the spatial variation in soil properties improves soil management, especially soil water management. The spatial measurement of apparent soil electrical conductivity (EC) is one way of mapping spatial variation. Reliability, ease of measurement, and ability to detect a variety of soil properties, spatial EC measurements has become a common tool for field and landscape-scale studies related to crop production properties (Corwin & Lesch, 2005a). The field-scale application of apparent soil electrical conductivity (EC) to agriculture has its origin in the measurements of soil salinity, which is an arid-zone problem (Corwin & Lesch, 2005a). Among the many advanced sensors recently introduced in precision agriculture, bulk or apparent soil (EC) measuring devices provide the simplest and least expensive measurement of soil variability (Farahani & Buchleiter, 2004). Laboratory measurement of EC is a useful integrator of soil physical, chemical, and biological factors (Smith & Doran, 1996 as cited by Johnson *et al.,* 2001).

Three types of EC measurement sensors are available: (i) invasive four-electrode ER sensors, (ii) noninvasive EM sensors, and (iii) time domain reflectometry (TDR) sensors. Invasive ER and noninvasive EM sensors are the most popular because the commercial development of a TDR sensor for use on a mobile apparatus has not occurred yet. Invasive four-electrode sensors can take the form of either insertion probes or surface arrays with the latter being the configuration used for mobilized EC measurement systems. Commercial examples of EM sensors include the Geonics EM31 and EM38 soil conductivity meters (Geonics Ltd., Mississauga, Ont., Canada), both of which can be mobilized easily, but the EM38 has been the primary instrument of choice for soil quality and site-specific crop management applications because its depth of penetration most closely corresponds to the root zone (i.e., 0 to 1–1.5 m) (Corwin & Lesch, 2005a).

2.4.1 Application of the EM38

Electrical conductivity of soil provides information about porosity, water saturation, salinity, clay content and organic matter that cannot be duplicated by other geophysical methods of investigation. Electromagnetic induction is considered one of the ways in which the electrical conductivity of the soil can be determined (Pellerin & Wannamaker, 2005).

The two most commonly used EM conductivity meters in soil science and in vadose zone hydrology are the Geonics EM31 and EM38. The EM38 (Figure. 2.2a and b) however, has considerably greater application for agricultural.

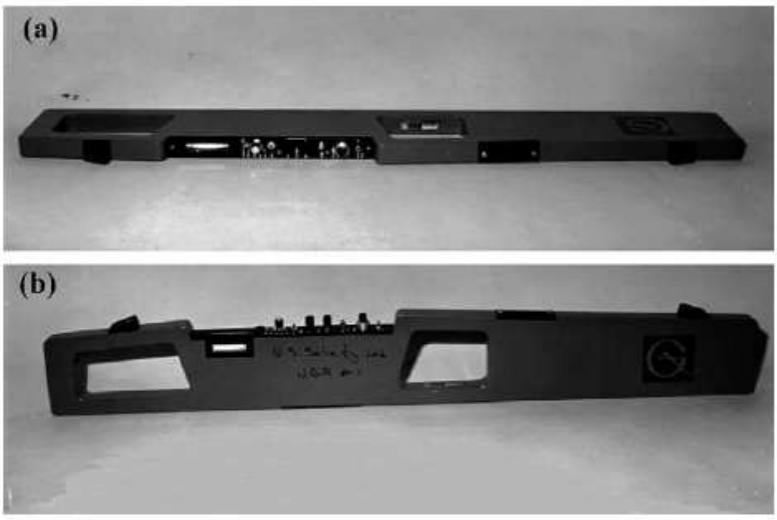


Figure 2.2 (a) The Geonics EM38 electromagnetic soil conductivity meter in the horizontal orientation (b) in vertical orientation (Corwin & Lesch, 2003).

2.4.2 Factors affecting measurements

The EC measurements are particularly well suited for establishing within-field spatial variability of soil properties that contribute to the electrical conductance of the bulk soil because of the quick, easy, and reliable measurements that integrates the influence of soil properties (Corwin & Lesch, 2005 b).

Three pathways of current flow contribute to the EC of a soil: (i) a liquid phase pathway via dissolved solids contained in the soil water occupying the large pores, (ii) a solid-liquid phase pathway primarily via exchangeable cations associated with clay minerals, and (iii) a solid pathway via soil particles that are in direct and continuous contact with one another. These three pathways of current flow are illustrated in Figure 2.3 (Rhoades *et al.,* 1989).

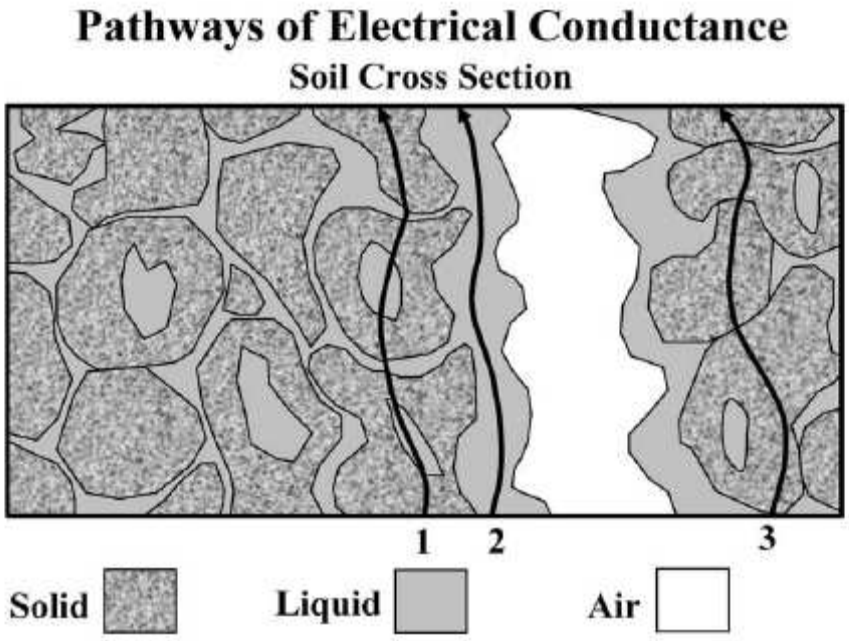


Figure 2.3: Three conductance pathways namely solid, liquid and air phase, for the EC measurements (Rhoades *et al*., 1989).

On account of the three pathways of conductance, the EC measurements are influenced by several soil physical and chemical properties: (i) soil salinity, (ii) saturation percentage, (iii) water content and (iv) bulk density (Corwin & Lesch, 2005c). Furthermore, the exchange surfaces on clays and organic matter provide a solid-liquid phase pathway primarily via exchangeable cations; consequently, clay content and type, cation exchange capacity (CEC), and organic matter are recognized as additional factors influencing EC measurements.

Another factor influencing EC is temperature. Electrical conductivity increases at a rate of approximately 1.9% per degree Celsuis increase in soil temperature. Non-spherical particle shapes and a broad particle-size distribution tend to decrease EC and when non-spherical particles have some preferential alignment in space, the soil becomes anisotropic and its EC depends on the direction in which it is measured (Friedman, 2005).

The soil solution is the only conducting phase, for this reason the volumetric fraction and conductivity of the soil solution are the two dominant factors in determining EC. Nevertheless, the geometry and topology of the aqueous phase are determined by the solid-phase attributes. Furthermore, the contribution of the adsorbed cations to the overall soil EC, significant for

medium- and fine-textured soils, is also determined mostly by the soil's cation exchange capacity, which is a solid-phase attribute (Friedman, 2005).

In-field variation of EC measurements could be contributed to the drifting effect of the EM38. The drift is likely due to temperature effects on the EM38 sensor. However, a simple reflective shade over the sensor could reduce drift effects considerably.

Another source of potential EC variation arises from soil compaction caused by repetitive traffic patterns of heavy agricultural equipment. In many fields, heavy equipment is consistently driven down the same set of furrows when performing tillage and cultivation operations during the growing season. This leads to a systematic pattern of compaction in a subset of furrows throughout the field (Corwin & Lesch, 2005a). Measurements of EC must be interpreted with these influencing factors in mind (Corwin & Lesch, 2005c).

2.4.3 Potential for characterising soil physical properties

Electrical conductivity is a reliable measurement that is taken easily. These geospatial measurements of EC have become one of the most frequently used measurements for characterizing field variability for agricultural applications in First World states. By making use of EC measurements it is possible to gain better information for a better understanding of variation in yields (Johson, Eskbridge & Corwin, 2005).

In the studies by Triantafilis and Lesch (2005) and Lesch *et al*., (2005) they found a very high correlation between the predicted clay percentages and the measured clay percentages. The average predicted clay percentage of 47.7% is close to the measured value of 47.4% and the observed versus prediction correlation estimate (r = 0.88) is very close to the square root of the regression model (R^2 = 90). In a study carried out by Sudduth *et al*. (2005) confirms the finding that the relationship of EC to clay content of soils was surprinsingly high, bearing in mind that the data was collected on different fields at different times of the year.

Soil water content, like salinity, is a dynamic soil property that varies with depth and across the landscape, generally with moderate to high local-scale variability. In areas under uniform irrigation management practices, the degree of spatial water content variability is typically minimal provided significant soil texture variation is not present. However, some fields demonstrate gradual trends in water content across the extent of the field, which may be due to gradual changes in shallow water table levels close to the depth of penetration of measurement

or to abrupt textural discontinuities, or due to non-uniformity of water application (Corwin & Lesch, 2005 a).

In general dry soils are poor conductors, and the EC value is a refection of the volumetric soil water content, the concentration of the dissolved electrolytes in the soil water, and the type and amount of clay present in the soil (McNeil, 1980). In a study by Kachanoski *et al*. (1988), they also found a strong correlation (R^2 = 0.77) between measured volumetric water content and EC measurements at different depth intervals. According to the study they found that spatial variation in water content is not always related to spatial variation in texture of soils.

Chapter 3

Mechanization of the in-field rainwater harvesting technique

3.1 Introduction

Dry land crop production in the semi-arid climate zone on clay soils is by nature complex and risky owing to bio-physical and socio-economical constrains in the agricultural sector. Water and soil conservation are the key factor to overcome the bio-physical constrains, because rainfall is normally of a low, erratic and high intensity nature. The role of soil is to change the instantaneous rainfall events into a continuous supply of water to plants.

High clay and duplex soils complicate the process further as it exhibit low hydraulic conductivity properties, which increases the of unproductive runoff, erosion and evaporation losses. Limiting these losses, and soil degradation, should be the major challenge in any tillage system used on these soils.

Focusing on these goals, Hensley *et al*. (2000) developed the in-field rainwater harvesting crop production technique (Figure 3.1). Water is conserved through the runoff generated on the 2 m wide no-till strips and stored in the 1 m wide basin strips. Once collected, the water penetrates deeper into the soil, thereby increasing the availability of water for the crop. The plant canopy contributes to water conservation as it provides shading that reduces evaporation during the growing season.

Results of IRWH on small plots at various ecotopes in Bloemfontein and Thaba Nchu districts revealed that the yield of summer crops (maize, sunflower and beans) increased between 30 and 50% in comparison with conventional tillage (van Staden, 2000; Botha *et al*., 2003; Botha, 2007). Botha (2007) reports that about a thousand rural households in Thaba Nchu applied the IRWH system in their homestead yards. The IRWH system was, without exception, constructed manually with spades and rakes as indicated in Figure 3.2. Most of the farmers used their produce for own consumption, thereby reducing the risk of household food in security.

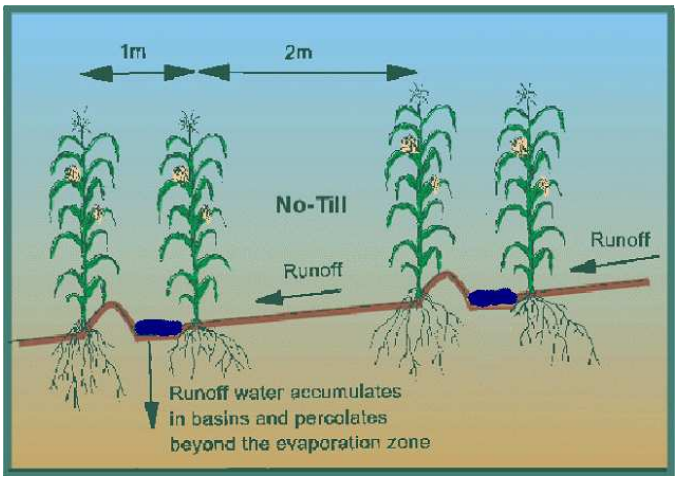


Figure 3.1 A diagrammatic layout of the IRWH-technique, showing the 2 m width runoff strips (catchment) and 1 m width basin strip (collection area) modified as micro basins (Botha, 2007).

Despite of the high acceptability amongst the community members, the area under crop production is not an economical unit from a community perspective (Khundhlande *et al*., 2004). In order to break the chains of poverty as reported by Khundhlande *et al*. (2004), it is imperative to increase current production to a larger economical scale.

In October 2003 the need for mechanization was tested during a workshop, facilitated by the Water Research Commission, at Merino in the Thaba Nchu district. Representatives from most of the 42 villages involved with IRWH, interested parties who had previous experience of commercial crop production, as well as those who owned tractors or were working on commercial farms, participated in the workshop. During the coarse of the workshop several conservation tillage equipment was demonstrated like the basin plough (not water harvesting technique) (van der Merwe, 2006).

In the group discussion that followed, the farmers voiced dissatisfaction with the physical results, because the mechanized surfaces did not mimic the IRWH structures made by hand as indicated in Figure 3.2. However, they acknowledged the need for mechanization and indicated acceptance of the new system, provided that the resultant structures should resemble closely manually constructed IRWH structures. Hence a project was initiated to address the needs of the farmers, aiming to develop, test and mechanized the IRWH system. The aims of the chapter are:

(i) To develop tractor drawn implements that can mechanise IRWH, and

(ii) To develop a procedure for the application of IRWH tillage operations, which includes the suitability of IRWH on the ecotope, land preparation with IRWH implements and general agronomical practices associated with the application of IRWH.

Figure 3.2 Workers busy preparing the IRWH system on communal scale.

3.2 Development, description and testing of implements

Several conceptual implements were designed, built and tested to replicate the specific soil conditions associated with the IRWH, *viz.* the runoff and basin strips (Figure 3.1). All designs and tests were executed in co-operation with Mr. B. Bramley from Bramley Engineering Company in Bloemfontein.

It was clear from the tests that two tillage operations are required, *viz*. a primary tillage activity to make ridges and a secondary activity to create micro-basins. Therefore two implements were selected for a pilot study at Paradys Experimental Farm, namely a ridge plough and the puddler plough.

Ridge plough: The implement was designed to make ridges perpendicular to the slope of the land. It is seen as a primary cultivation operation aiming at laying the foundation for the basin strips by making a 200 – 300 mm ridge along the contour. The implement produces a similar action to that of a reversible plough. The ridge plough consists of a main frame fitted with a right and left mouldboard and shears, with a swivel mounted on the frame to ensure that the centre of

the plough is always consistent during oscillation of the plough (Figure 3.3). Furthermore a short blade grader, 300 mm wide, was required to smooth the open end of the basin so that water can enter the basin with minimum resistance.

Depending on the rainwater harvesting potential, the ridge can be made by ploughing to depths between 150 and 300 mm. The ridge plough has a low traction requirement (45 kW) and therefore, low energy demand, which makes it suitable for small-scale farmers who cultivate between 50 and 150 ha. Experience of hand-made ridges indicates that the ridges can last for 3 and 5 years on clayey soils but it is recommended that ridges should be reconstructed annually on sandy top soils.

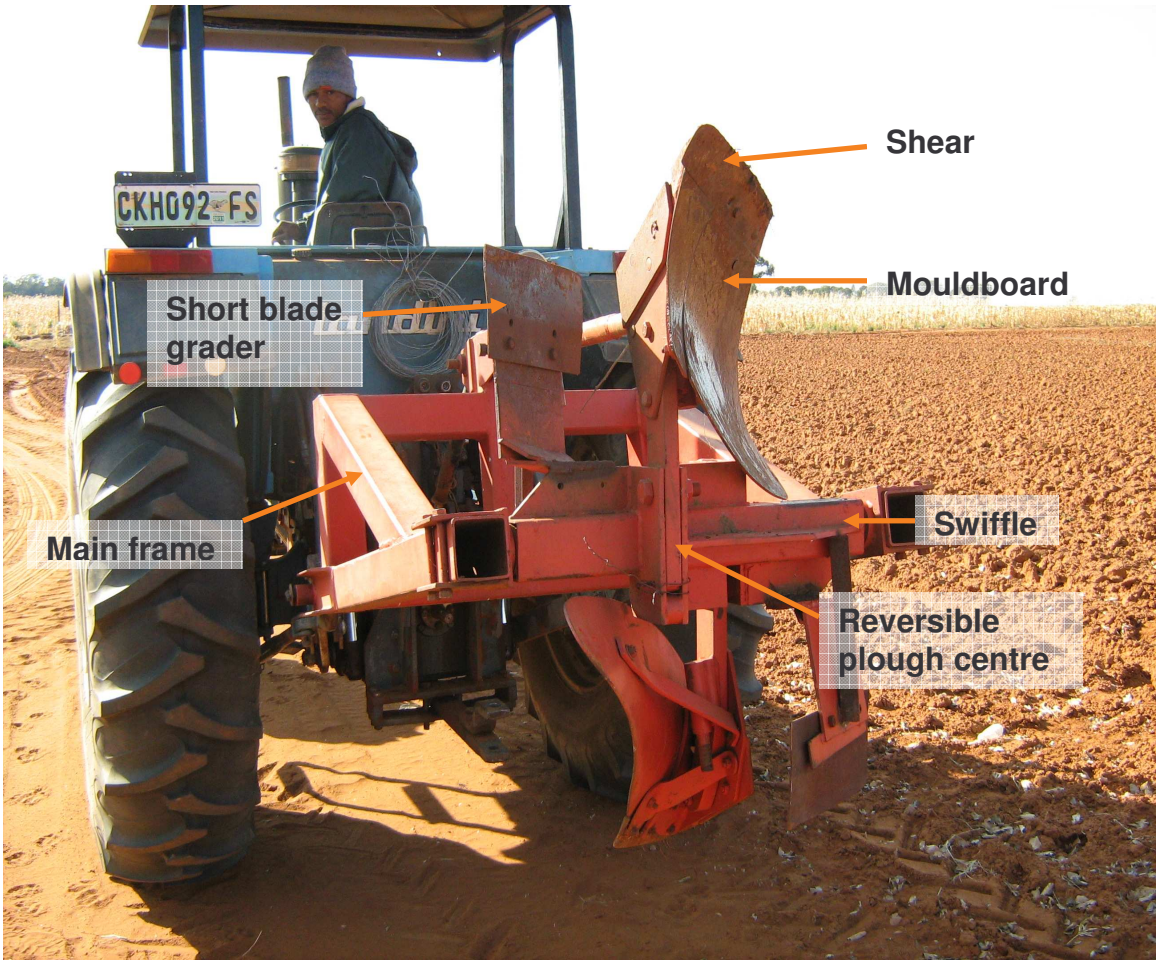


Figure 3.3 One way ridge plough, as developed by Bramley Engineering.

Puddler plough: The implement was designed as a secondary tillage operation method to ensure uniform surface storage of runoff water in the basin strips. The tillage operation entails the making of micro-basins on the up-slope position of the ridge to form the basin strip as indicated in Figure 3.1.

The implement consists of a main frame fitted with ripper shanks and a puddler blade mounted on a heavy cam wheel (Figure 3.4). Micro-basins are created with the off-centre cam wheel, which controls the shape, depth and intervals of the basin, when drawn by the tractor. The ripper shanks help to loosen the soil, making it easier for the blades to shape the basins, while the tension coil supports the blade's penetration on hard soils. The centre of the implement consists of an alignment pivot, enabling the puddler plough to follow the contour lines created by the ridge plough. Effective tillage with this implement requires a minimum traction of 40 kW; therefore it is suitable for small tractors and small scale-farmers.

It is recommended that the implement is used before planting and if necessary also after harvesting to maintain the surface storage capacity.

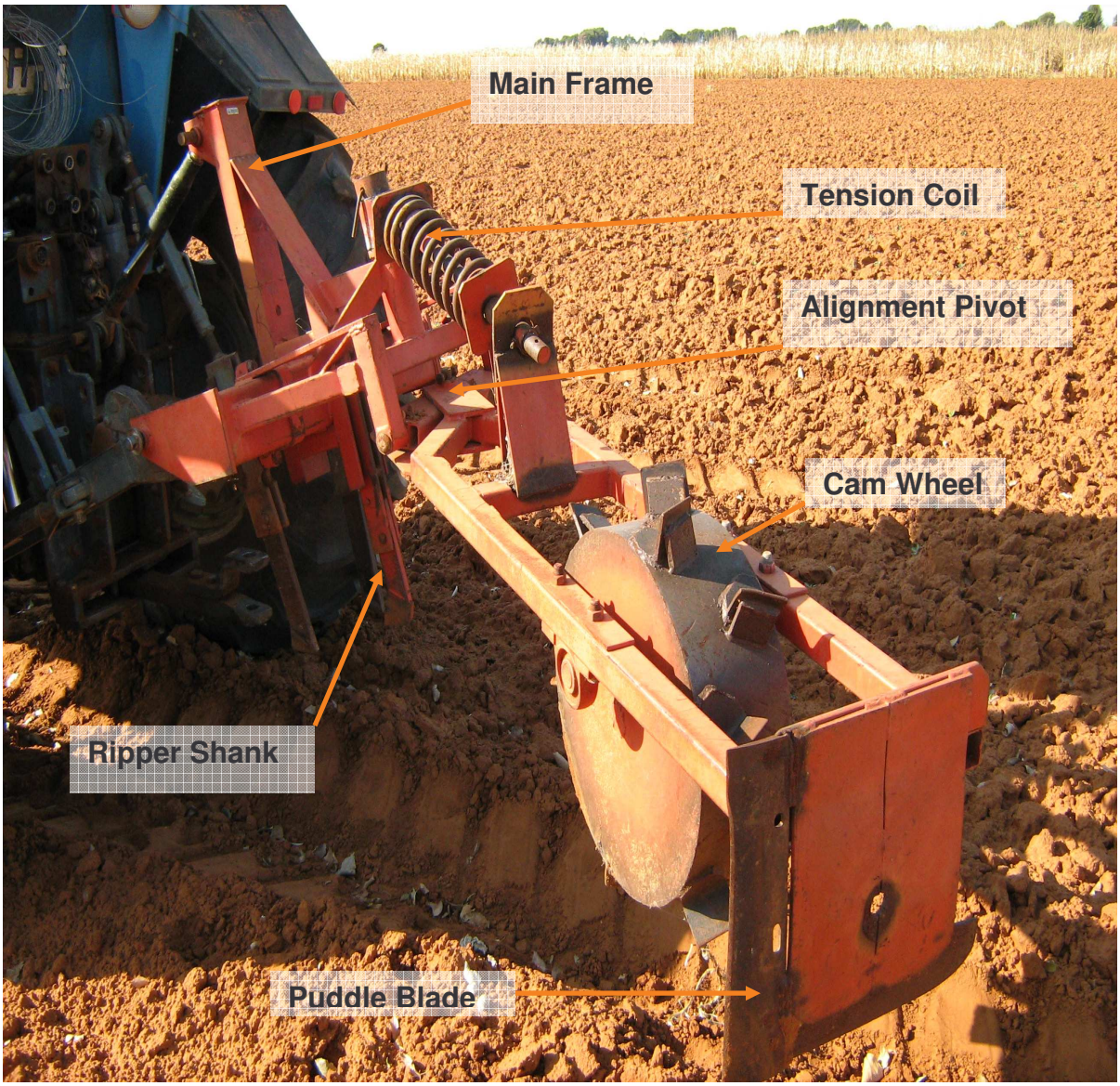


Figure 3.4 The puddler plough as developed by Bramley Engineering.

Both implements were demonstrated during a farmer's day at Paradys Experimental Farm of the University. Two representatives from each of the 42 villages in the Thaba Nchu district attended the demonstrations. In the discussion that followed they expressed their satisfaction with both implements and IRWH structure, hence, setting the foundation for full mechanization.

3.3 Mechanization of IRWH

3.3.1 Land suitability

The study was conducted on a commercial crop field at Paradys Experimental Farm of the University of the Free State, located between the N1 road to Colesberg and the N6 road to Reddersburg, about 10 km from the centre of Bloemfontein. The specific area (54 ha) used for the application of the mechanised IRWH is delineated in Figure 3.5.

The fields are located on the lower 3 and upper 4 terrain morphological units (TMU) of the south facing hill slope of the Paradys soilscape (Hensley *et al.,* 2007) of Land Type Ca22 (Land Type Survey Staff, 2002) (Figure 3.6). The Ca land types have plinthic and upland duplex soils. This land type is dominated by soil series of the semi-duplex soil forms with pedocutanic B horizons: Valsrivier (50%) and Swartland (1%).

The term duplex refers to soils with decreased permeability down the soil profile due to an abrupt transition (Van der Watt & Van Rooyen, 1995). Permeability is not defined. The transition is usually from the A to the B horizon but may also occur lower down in the profile (Chittleborough, 1992, Chittleborough & Oades, 1979). The term duplex is used for several soil forms of South Africa, including all forms with pedocutanic B horizons (Land Type Survey Staff, 2002). In another study of these soils the drainage characteristics of these soils proofed to be limited by the C horizon (Fraenkel, 2009). In actual fact the duplex character is so prominent in the soil profiles that these soils are often mistaken as soils of the Sterkspruit form as indicated by old undated soil maps.

Series of plinthic and other soil forms also occur: Westleigh (14%), Avalon (6%), Sterkspruit (5%), Bainsvlei (3%) and Hutton (6%). Soil properties, such as the high clay content of the top- and subsoil, the structure of the subsoil and depth of the semi-duplex (Valsrivier, Swartland, Sepane) and duplex (Sterkspruit) soils make it unsuitable for crop production with conventional tillage under the prevailing climate. However, the use of IRWH on these soils reduces the risk of crop failure significantly (Botha, 2007).

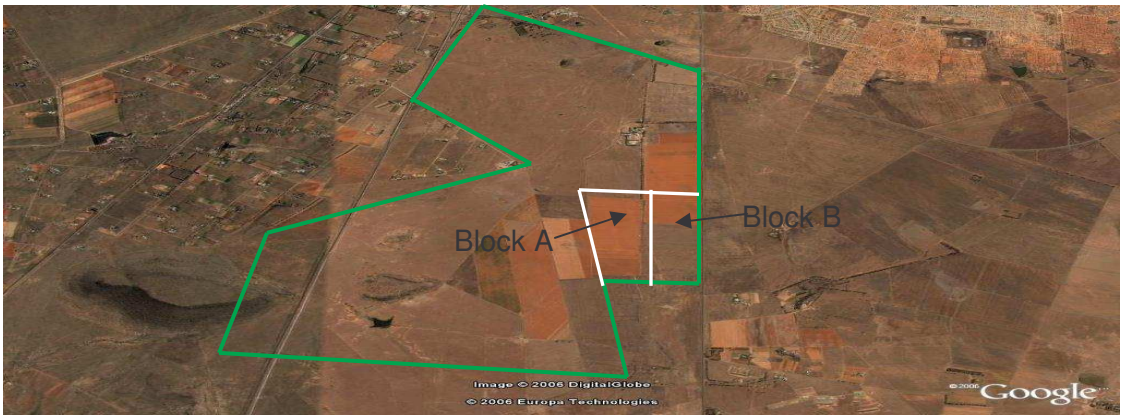


Figure 3.5 A map showing the boarders of Paradys Experimental Farm (demarcated with a green solid line) and the specific 15 ha crop field use in the study (delineated with a white solid line) (-32˚35'21''S,-77˚43'6''E).

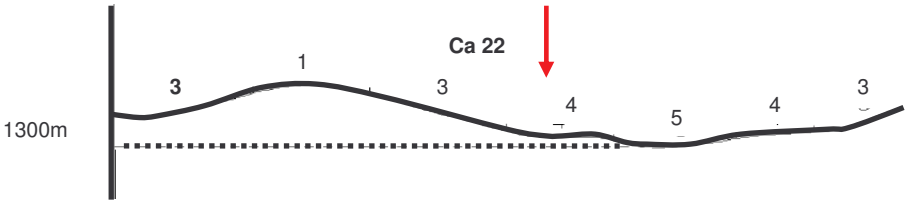


Figure 3.6 Terrain form of Land Type data Ca22 (Land Type Survey Staff, 2002).

The Paradys soilscape is typical of the land type. The west, east and north facing hillslopes of the soilscape (Hensley *et al.*, 2007) are mainly of the Glenrosa and Mispah forms, very shallow, and hence unsuitable for IRWH. Soils from the south facing hill slope are suitable and exhibit mean depths of 700 mm, the minimum depth acceptable for practicing the IRWH system (Joseph, 2007). The selected south facing hillslope of the soilscape is extremly long for the land type (2 500 m) and has a straight-straight slope shape with a very low slope gradient (<1%).

Several profile pits were made along two transects to find suitable ecotopes for applying commercial IRWH on this hillslope. The soils were classified (Soil Classification Working Group, 1991), analysed and described.

The survey revealed that the Tukulu form dominates the hillslope occupying 79% of the total area and is associated with the higher lying areas. The Sepane soil form occurs in the lower lying areas and cover 18% of the area (Figure 3.7).

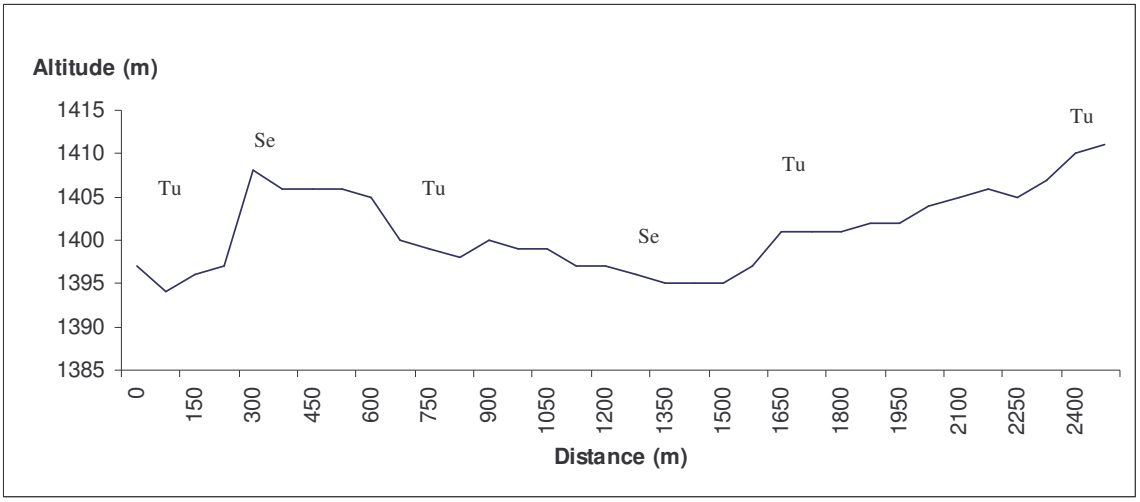


Figure 3.7 South facing hillslope of the Paradys soilscape, Land Type Ca22.

3.3.2 Water availability in ecotope

Water availability: Water for crop production depends directly on climatic factors and indirectly on soil tillage approaches to conserve water. When applying IRWH it is important to obtain information on the runoff potential as it integrates both the climate and the tillage technique.

Owing to insufficient climate data near Paradys Experimental Farm, thirty years of climate data from Glen Agricultural Institute was used to describe the runoff potential for the Paradys-Tukulu/Sepane ecotope. Walker and Tsubo (2003) found that the pattern of rainfall in the central region does not vary much temporally and spatially. The runoff potential is calculated by using a regression equation (Figure 3.8) developed specifically for the ecotope by taking rainfall-runoff data collected from an unpublished rainfall simulator study completed by M Zerizhy at the Department of Soil, Crop and Climate Sciences of the University of the Free State.

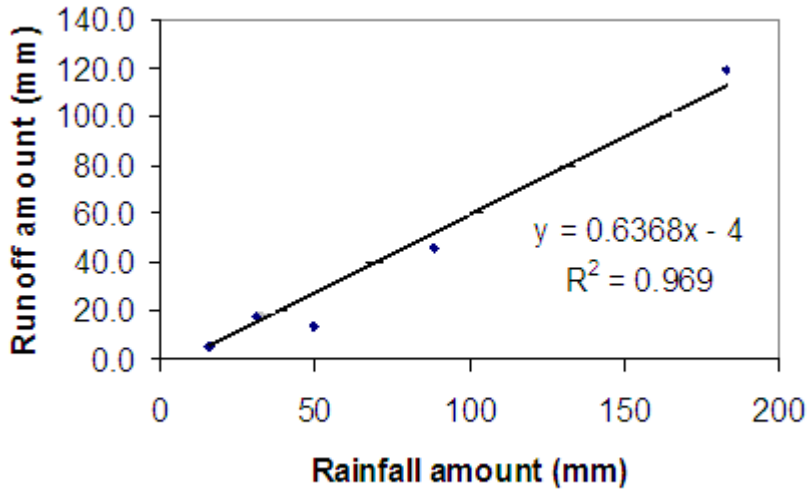


Figure 3.8 Rainfall amount versus runoff generated for the Paradys-Tukulu/Sepane ecotope.

The historical weather data contains daily entries for rainfall, potential evaporation (Eo) and runoff. The cumulative amounts of those parameters were calculated to obtain the annual values. These values were used to derive the probability of each parameter provided on the CPF graph (Figure 3.9).

The semi arid areas of South Africa are known for their low rainwater productivity, leading to low food security in these parts of the country. The climate of these areas plays the biggest role in the lower rainwater productivity of the area. The aridity index of semi arid areas varies between 0.2 and 0.5. The closer the graph of the CPF (Figure 3.9) is to the right-hand bottom corner of the figure, the higher the rainfall and in-field runoff and the lower the Eo.

Another way of analysing the 30 year CPF graph is to state that there is a 80%, 50% and 20% probability to obtain rainfall of 425 mm, 500 mm and 625 mm and an expectation that Eo will amount to 1850 mm, 2375 mm and 2475 mm, respectively, for similar probabilities. For these conditions, the aridity index will be 0.23, 0.21 and 0.25, respectively, illustrating the semi-arid state of the ecotope on the long term. However, during certain months of the summer (March and April) the aridity index rises as high as 0.45, making it possible to cultivate crops in these areas (Botha, 2007).

Increasing the rainfall storage efficiency of soils would lead to a decrease in crop failures owing to low and erratic rainfall events. Runoff losses from fields are one of the main contributors to lower rainfall storage efficiency of soils. Loss of water, owing to runoff from fields ranges, from 6% to 30% on conventionally cultivated fields (Haylett, 1960, Du Plessis & Mostert 1965, Bennie, Strydom & Vrey, 1998). Decreasing the runoff by tillage practises would lead to an increase in rainfall storage efficiency.

The CPF makes it possible to predict the amount of water that would be collected as runoff within the IRWH system by making use of the runoff potential. The runoff potential is calculated by using a regression equation. From Figure 3.9 the probability of non-exceedance at 20%, 50% and 80%, the amount of water stored within the IRWH system could be determined. The collection of runoff water leads to a gain in storage efficiency of soils. From the CPF it is clear that at probabilities of non-exceedance of 20%, 50% and 80%, an amount of 120 mm, 150 mm and 225 mm of runoff could be harvested, respectively, on the Paradys-Tukulu/Sepane ecotope.

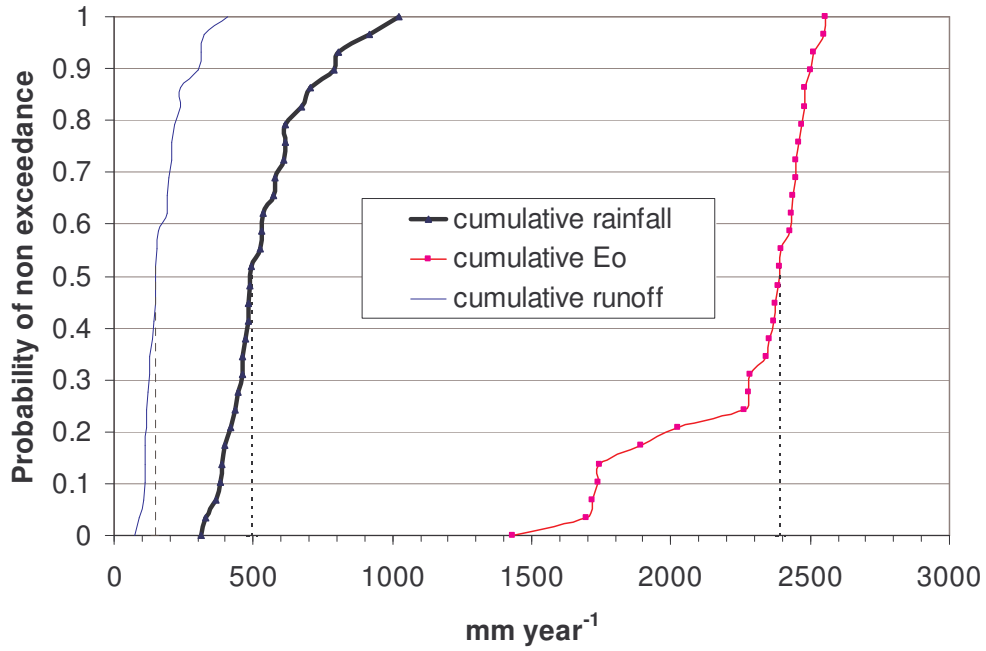


Figure 3.9 Cumulative probability function based on 30 years (1977 -2006) weather data for in-field runoff, rainfall and potential evaporation on the Paradys-Tukulu/Sepane ecotope.

3.3.3 Land preparation for IRWH

Land preparation in IRWH differs conceptually from conventional tillage where mouldboard ploughs are used as the primary tillage activity to invert soils at depths up to 300 mm. In the IRWH crop production system, the ridge plough lays the foundation for the stoppage of runoff from the field as the ridges are constructed on a zero slope gradient.

Under varying topographical conditions, the crop field needs to be divided into terraces and hence a detail or micro topographical map (1:2000) is required to show the variation in the direction, gradient and shape of the slope. An example of such a map, measured with a dumpy level and geo-referenced, is given in Figure 3.10 for the crop fields at Paradys Experimental Farm.

Block A was divided into six terraces (demarcated in Green) that varied between 40 m and 150 m and Block B had five terraces (demarcated in Green) that varied between 100 m and 150 m. Once the terraces were identified, a guide ridge was drawn in the middle of the terrace. A dumpy level was used to mark the zero gradient ridges on the ground at Paradys.

The next important step was to plan and integrate wheel-width of all secondary tillage operations including harvesting, thus applying traffic control measures. For example, in Block A the ridges were spaced at 3 m intervals, parallel to the guide ridge following the basic lay out of a 2 m wide runoff strip and 1 m wide basin strip. All wheel movement takes place at 1.8 m width over the basin strip.

The maize was harvested with a combine precision harvester. Maize production on Block B was planned for silage and the inter-ridge space was calculated to be 3.3 m, thus giving a 2.3 m wide runoff strip and a 1m wide basin strip. In this case the strips were widened to accommodate the wheel movement of the tractor drawn silage cutter and transport wagons.

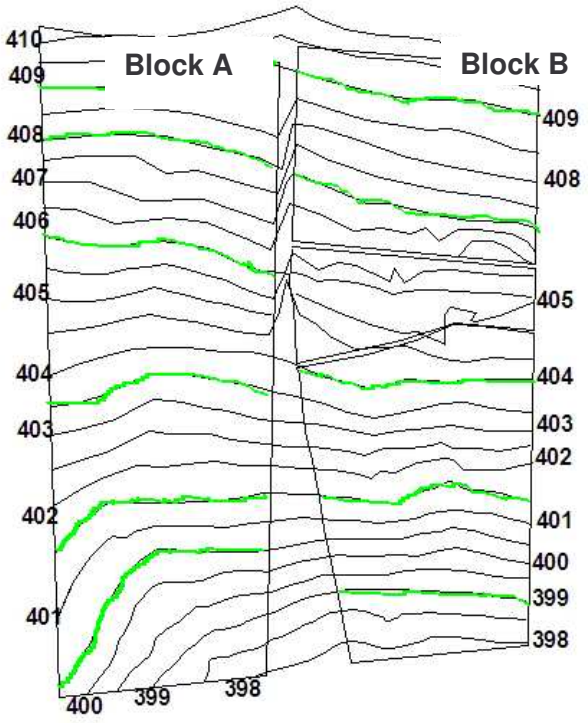


Figure 3.10 Topographical map of the crop fields on the Paradys-Tukulu/Sepane ecotope (scale 1:2000).

Where the gradients were insufficient to induce in-field runoff on some areas an artificial slope was created with a grader drawn by a tractor (Figure 3.11a and b).

(a)

(b)

Figure 3.11 (a) The slope gradient of the runoff strips can be modified with a tractor drawn grader (b) to create a steeper slope towards the basin strip.

Micro-basins were created drawing the puddler plough, described in Section 3.2, as close as possible to the ridge. Despite the rough surface on the runoff strips and the tractor's wheel tract, the system was able to capture the induced runoff from the first rains of the season (Figure 3.12a). As the soil has a high dispersion and surface crusting potential (Fraenkel, 2009), the runoff strips soon became smooth and hard due to the physical and chemical impact of the raindrops that had dispersed the clods. The conditions for collecting water in the basin increased during the season but the storage capacity accommodated these changes. Van Staden (2000) tested the long term sustainability of the micro-basins constructed manually on the Bonheim and Swartland soils at Glen and concluded that it will control individual rainstorms up to 75 mm. His measurements and estimations revealed that it would take about 30 years for the basins to be filled by sediment. However, regular maintenance on an annual basis is recommended, using the basin plough.

It was not always possible to establish a zero slope ridge in the field. Water from erosion gullies drained lateral as can be seen in Figure 3.12b. It is recommended that these gullies should be levelled with a grader before ridging takes place. In some cases a series of ridges (3 – 4) had broken, but the momentum of the flow was interrupted by the down slope ridges (Figure 3.12b and Figure 3.13a). This is remarkable if taken into account that the field received 248 mm rain within two months. The rains were wide-spread in the Bloemfontein district and caused serious water erosion as can be seen on the high potential soil in the Bainsvlei area where conventional tillage is practiced (Figure 3.13).

(a) (b)

Figure 3.12 Illustration of the water harvesting potential of the mechanised IRWH system at the Paradys-Tukulu/Sepane ecotope.

(a) (b)

Figure 3.13 Illustrating (a) how the IRWH –basins had captured the high intensity rainstorms at Paradys and (b) the erosion caused on conventional tillage field on high potential soils in Bainsvlei near Bloemfontein during similar rain seasons.

3.3.4 Other agronomical aspects relevant to mechanization

3.3.4.1 Planting

The cultivar Pannar 6146 (medium to short growth length) was planted on the 3 January 2006 in Block B. Planting in Block A was delayed and hampered by continuous rains and stretched over a week from 14 and the 21 of January. A calibrated twin row maize planter (John Deere model 1750) with the planting units fixed at 1.1 m apart was used to plant the target density of 16 000 plants ha^{-1} in tramlines as indicated in Figure 3.1, and Figure 3.14b. Special measures were taken to avoid planting in the centre of the basins to prevent water logging on seedling emerge and growth.

Fertilizer (4:2:1 (32)) was band-placed (200 mm deep, 50 mm away and below the seed) with modified spring induce shanks at a rate of 200 kg ha^{-1} (N = 36.57 kg ha^{-1}; P =18.28 kg ha^{-1}; K = 9.14 kg ha^{-1}). The target yield was 3 000 kg ha^{-1}. The soil fertility status analyzed as follows (pH (KCL) 4.7; Ca = 1272 (ppm); K = 348.6 (ppm); P = 2.4 (ppm).

(a)

(b)

Figure 3.14 (a) Planter used for planting maize in the IRWH system and (b) maize plants in tram lines in the basin strips.

3.3.4.2 Weeding

Weeds were controlled chemically by spraying Glyphosate: N-phosphonomethyl glycine twice during the fallow period and once during the growing season directly after planting at a rate of 2l/ha. A mixture of Metolachlor (2-chloro-N-(2-ethyl-6-methylphenyl)-N-(2-methoxy-1-methylenthyl)), Atrazine (6-chloro-N-(1-methylethyl)-1, 3, 5-triazine-2,4diamine) and 2.4 D (phenoxyacetics) was sprayed after emergence to control grasses and broad leave weeds at a rate respectively 1 l /ha, 1.3 l /ha and 0.200 l /ha.

3.3.4.3 Harvesting

Due to the late planting in Block A and low heat units during the particular season it was decided to use the maize for silage. Despite the late planting, the plants in Block B1 reached maturity without any frost damage (Figure 3.15). Plants in Block B2 were planted a week later and experienced severe frost damaged. The maize was harvested last week of July with a combine harvester equipped with a yield monitor, which was calibrated and checked before and during harvesting. A yield map was obtained through inverse distance weighing using the SMS Advanced software package (Ag Leader, 2009) (Figure 3.16).

The yield map reflects the effect of frost damage, as explained regarding yields in Block B2, which was generally lower compared with B1. However, the yield map of B1 clearly shows variation caused by other factors, which is difficult to explain owing to the limited information obtained over one season (Fulton *et al*., 1996 and Sadler *et al.,* 1998).

Figure 3.15 Maize crop planted under IRWH, showing the general growth and the runoff strip.

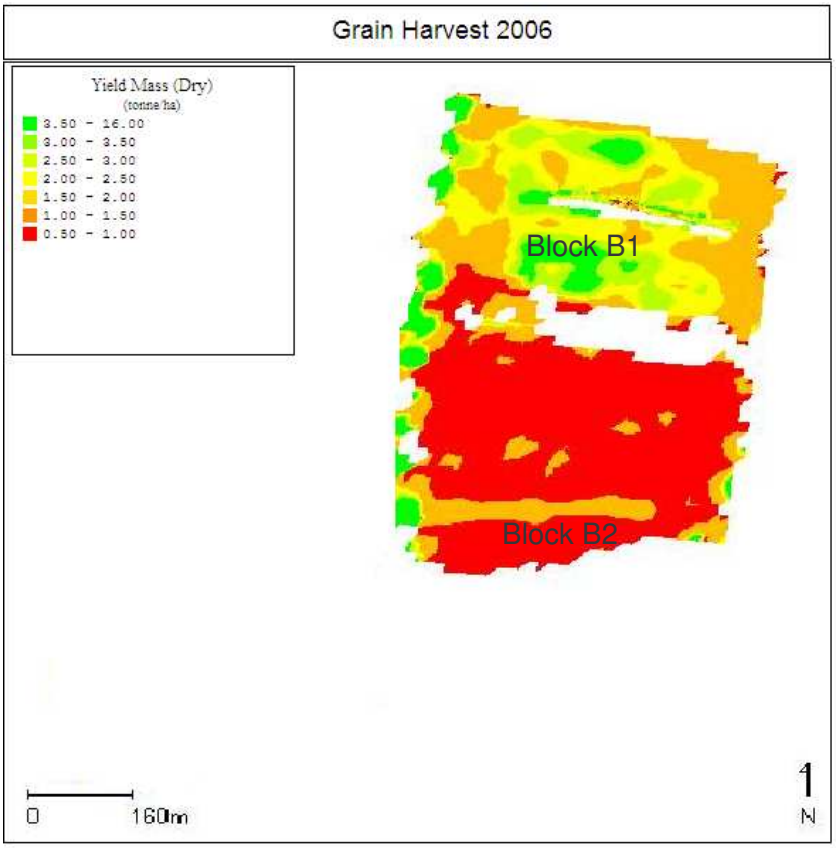


Figure 3.16 Yield map showing the variation in yield at the Paradys-Tukulu/Sepane ecotope under IRWH.

3.4 Conclusions

The research proved that it is possible to mechanise the IRWH crop production system developed by Hensley *et al*. (2000). Two tractor drawn implements were developed, *viz.* a ridge plough and a puddler plough. The ridge plough was designed as a primary tillage tool for making the wall of the basin, while the puddler plough is a secondary tillage tool, making micro-basins along the upslope side of the ridge. These implements were tested in a mechanization programme at the University of the Free State's Experimental Farm. Both implements were found to be efficient in creating the desired surface structure of the IRWH system.

From a water and soil conservation viewpoint, it can be concluded that the in-field structures completely prevented runoff from the land completely and by doing so it stopped water erosion. The runoff strips were generally functioned efficiently regarding inducing in-field runoff towards the basins, while the dead level contoured basin strips were equal to the task of storing the water uniformly over the entire field.

However, there is a potential danger for erosion in the old gullies where it is impossible to obtain a zero gradient ridge contour. Under high intensity rain storms lateral runoff will quickly fill the micro basins. Once filled, they served as a furrow guide that feeds the lower laying basin area, causing overspill and disintegration of the ridge wall. Fortunately in this study, no more than four successive basin strips disintegrated under water pressure over the field. These observations also stress the importance of maintaining the system and it is recommended that the capacity of the basins should be maintained with the puddler plough on a regular basis, at least after harvesting and before planting.

Because the ecotope on which the research was conducted represents about 0.75 million ha in the Free State province and millions of hectares in Sub-Saharan Africa, the conceptual and agronomical lessons learned are of immense value to the local and international communities.

Conceptually, it is clear that the IRWH differs markedly from conventional tillage and requires a complete mind shift toward conservation. The agronomical lessons include the value of assessing the ecotope's suitability for IRWH, how to plan and construct terraces, the layout of guide ridges to establish dead level contour basin strips and the planning of traffic control of all secondary tillage operations.

Chapter 4

Characterising spatial variation in clay plus silt content of a commercial crop field using a mobile EM38

4.1 Introduction

Precision agriculture, also known as site specific agronomical management, is the process of managing crops at a level of spatial resolution smaller than that of the individual field (Carr *et al*., 1991). Managing crop fields at this level of resolution depends heavily on reliable information obtained from measuring soil based factors within-field spatial variability that will affect crop yield (Plant *et al*., 1999).

Several co-operations and consulting groups in South Africa render such services to irrigation and dry land farmers. These services are generally structured to obtain a detailed soil map, which is supported by soil chemical information derived from soil samples taken on a grid over the field. Most service providers use a detail survey (100 X 100 m grid sampling) for irrigation and from a detail to a semi-detail scale (200 x 200 m grids) depending on the aim of the survey and cost-benefit ratio (D Harhoff, personal communication 2009).

Chemical analysis usually includes macro plant nutrients (Ca, Mg, K, P and S) and in some instances also micro nutrients (Fe, Mn, Cu and Zn), pH, electrical conductivity and sodium adsorption ratio. Variability within these parameters is then related to spatial yield data obtained from harvesters equipped with precision agriculture technology, *viz.* a global positioning system, geographical information system and a yield monitor (Joubert, 2004). Utilizing this information, management zones are defined and soil amelioration are applied through variable rate equipment and technology to optimise inputs for obtaining maximum economical and environmental benefits (Sandler *et al.,* 1998; Plant *et al*., 1999; Zhang *et al*., 2000).

Delineation of management zones is as accurate as the data from which it is derived, therefore the challenge is to improve data in terms of efficiency and cost effectiveness.

Among the many advanced sensors, recently introduced in precision agriculture, bulk or apparent soil electrical conductivity (EC) measuring devices, provides the simplest and least expensive soil variability measurements (Triantafilis *et al*., 2000, Farahani & Buchleiter, 2004).

The electrical conductivity of the soil is influenced by a variety of soil physical and chemical properties, such as salinity, texture, bulk density, organic matter, nitrates and temperature (Greenhouse and Slaine, 1983, 1986; Nyquist and Blair, 1991; Jaynes, 1996; Bowling *et al.,* 1997; Brune *et al*., 1999). Commercial examples of electromagnetic (EM) conductivity instruments are the Geonics EM31 and the EM38, both of which can be mobilized.

The EM38 is the primary instrument of choice in site specific crop management applications, because its depth of penetration corresponds closest to the root zone. The instrument is regarded, moreover, as reliable and constant (Corwin & Lesch, 2003; Farahani & Buchleiter, 2004). Results from a study done by Farahani and Buchleiter (2004) suggest, furthermore, that deep EC measurements are better suited for long term soil management zone delineation. Shallow EC measurements, however, reflect higher temporal variability properties, while patterns can be related to prevailing climate, agricultural implements, chemical applications and microbial activity.

One of the most important attributes of the soil, required by landholders for effective soil use and management, is that of clay plus silt content.

Textural properties are inherent in soils and once characterised spatially, they can be used to improve decision making processes related to the management of tillage operations, planting, fertilisation, as well as chemical applications to control weeds and pests (Lui *et al*., 2001; Corwin and Lesch, 2005a).

In order to manage the soil resource effectively, basic information on spatial distribution of clay plus silt fractions are necessary. Furthermore, more intense observations could greatly benefit the Precision Agriculture sector.

Triantafilis and Lesch (2005) are of opinion that the electromagnetic induction methods could be used to determine the clay plus silt content of soils. The aims of this study were, to seek possible relationships between electrical conductivity measured with the EM38 and textural properties in order to delineate agronomical management zones under IRWH

4.2 Materials and methods

4.2.1 Experimental site and treatments

The experiment was conducted on a crop field, demarcated as Block A on the map, of the experimental farm of the University of the Free State (Paradys). The farm is located between the N1 road to Colesberg and the N6 road to Reddersburg, about 10 km from the centre of Bloemfontein. The borders of the farm are presented in Figure 4.1. The 55 ha crop field was divided into conventional tillage strips and mechanised IRWH strips along the contour as described by Fraenkel (2009). For this experiment the total area was devided into 75 plots, each with a dimension of 72 m x 72 m as indicated in Figure 4.2. The conventional tillage plots used by Fraenkel (rows 3,8 and 14) were excluded in this experiment.

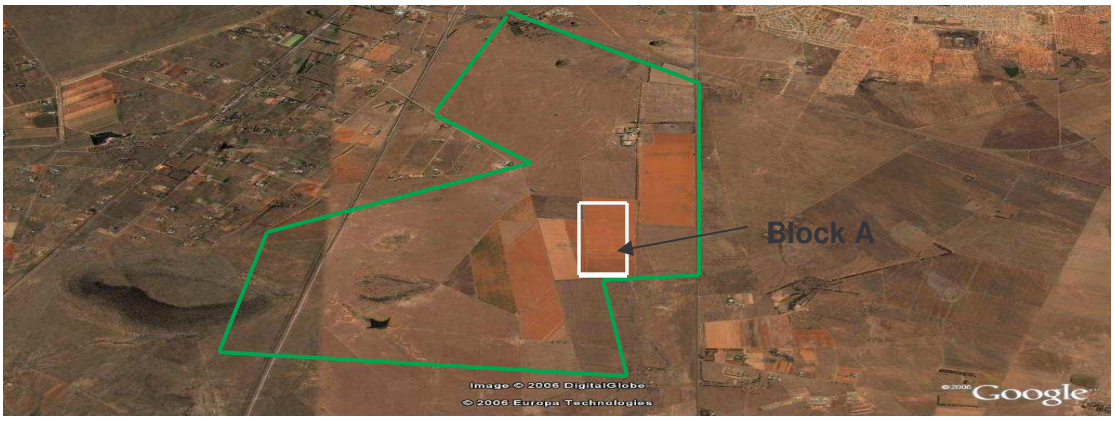


Figure 4.1 A map showing the boarders of Paradys Experimental Farm (demarcated with a solid green line) and the specific 55 ha crop field use in the study, delineated with a solid white line (29.23175˚S, 26.20324˚E).

Land preparation:

The field were divided into conventional tillage and IRWH strips, strips 3, 8 and 14 (Figure 4.2) were prepared conventionally. The areas were ploughed to a depth of 220 mm, and after wards kept clean with a disc plough until the planting action were carried out in January 2006. The rest of the field were prepared on the IRWH technique as described in Section 3.3.3.

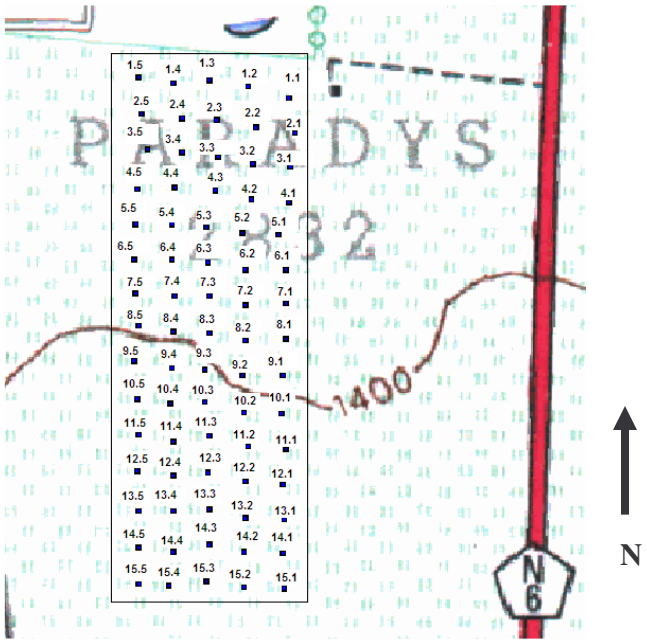


Figure 4.2 Schematic layout of the conventional and IRWH treatments on the 55 ha field at Paradys Experimental Farm.

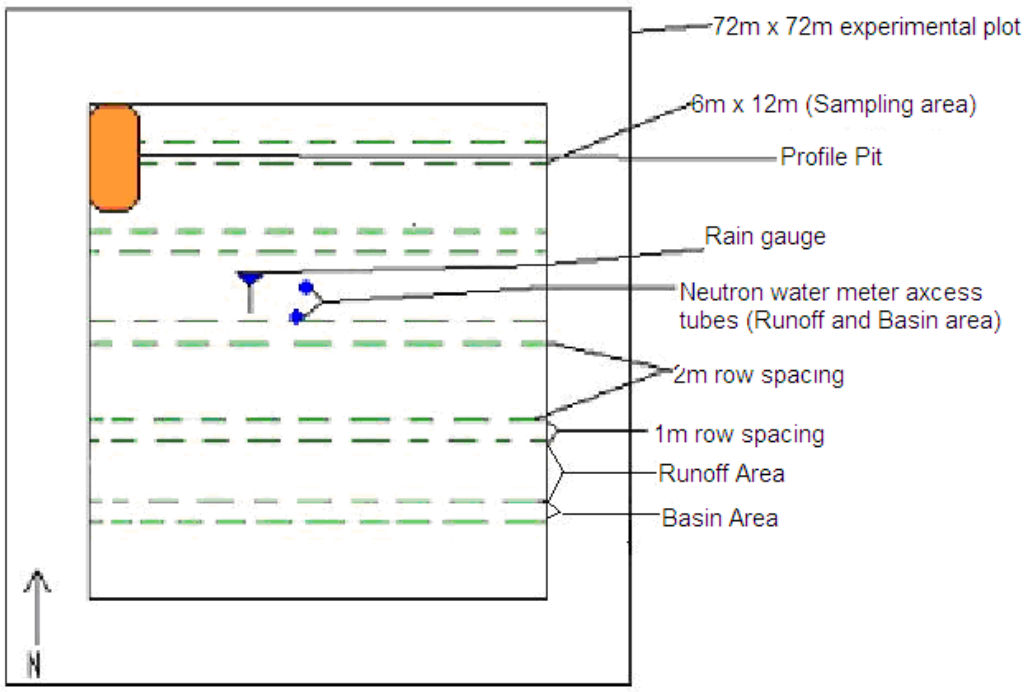


Figure 4.3 Schematic layouts of the IRWH structure and instrumentation used in each of the 75 experimental plots.

4.2.2 Soil Survey

An intensive soil survey was conducted on the 55 ha crop field. Soil cores were sampled over the total depth of the soil with a mobile hydraulic auger on a 50 m x 50 m grid. The 7 cm diameter soil cores were split in half over the length of cores and classified (Soil Classification Working Group 1991). As a quality control the soil characteristics, as presented by the soil cores, were compared with that of 13 profiles. The 13 profiles were described by Fraenkel (2009).

4.2.3 Particle size distribution analyzes

In each of the 75 plots, soils were sampled with a hand auger at 30 cm depth intervals over the total profile, *viz.* 0 – 300 mm (topsoil), 300 – 600 mm (subsoil) and 600 – 900 mm (deep subsoil) The fixed depth intervals was used to synchronized soil water measurements explained in Chapter 5. Seven particle fractions were determined in the soil samples using the pipette method. (The Non – Affiliated Soil Analysis Work Committee 1990). The textural fractions were coarse sand (2 – 0.5 mm), medium sand (0.5 - 0.25mm), fine sand (0.25 – 0.106 mm), very fine sand (0.106 – 0.05 mm), coarse silt (0.05 – 0.02 mm), fine silt (0.02 – 0.002 mm) and clay (≤ 0.002 mm).

4.2.4 EM38 measurements

Electrical conductivity (EC) measurements were done with an EM38 (Geonics) instrument (Figure 4.4a), drawn in a sled behind a quad bike at a speed of approximately 5 km h^{-1} (Figure 4.4b). The measurements were confined to the runoff strips of the IRWH system, *i.e.* every 3 m perpendicular to the slope of the field. Measurements were made twice to obtain the horizontal (EM_h) and vertical (EM_v) readings. It took two days to cover the 55 ha field.

The instrument measures apparent soil electrical conductivity in millisiemens per meter (mS m^{-1}) every 20 cm as it moves over the field. The instrument was calibrated, as described in the manual, three times a day. Moreover, all measurements were geo-referenced and the data processed with Surfer software package (Surfer, 2009).

(a) (b)

Figure 4.4 The EM38 instrument (a) embedded in the sled and (b) towed in a sled behind a quid bike at a speed of approximately 5 km h^{-1} at Paradys Experimental Farm.

4.2.5 Statistical and spatial analysis

From the 75 plots, 15 plots (1.3, 2.3, 3.3, 4.3, 5.3, 6.3 7.3, 8.3, 9.3, 10.3, 11.3, 12.3, 13.3, 14.3, 15.3) were selected randomly to correlate clay plus silt content (%) of the topsoil, subsoil and deep subsoil, with the electrical conductivity readings (mS m^{-1}) of the EM38. Clay plus silt was calculated from the mean of the different layers and also correlated with the EM 38 readings. Linear and logarithmic regression techniques were used for correlating the horizontal (EMh) and vertical coil orientation (EMv) with clay plus silt of all horizons.

Contour maps of the various physical and chemical parameters were drawn with the SMS Advance software package (Ag Leader, 2009), a programme used with great effect in the precision agricultural sector. Furthermore, inverse distance weighing was used to interpolate data while statistical analysis of the data was carried out as described by Willmott (1982).

The statistical analysis use for the models predicting clay plus silt content for the different layers from EM vertical and EM horizontal measurements is based on the Wilmott (1982) procedure. Accordingly the root mean square error, unsystematic root mean square error was systematic root mean square error and d-index of the model prediction were calculated. The statistical analysis comprised of the determination of the root mean square error (RMSE) unsystematic root mean square error (RMSEu), systematic root mean square error (RMSEs) and the index of agreement (D-index) of the model tested. For a good fit the RMSEs should approach zero, the D-index should approach one and the RMSEu should be as close as possible to the RMSE, while R^2 values would give an indication only of the accuracy of the line fit, and not the accuracy of the prediction (Willmott, 1982).

4.3 Results and discussion

4.3.1 Description of soil forms and their spatial distribution

Three soil forms are present in the 55 ha field, *viz* the Tukulu Dikeni (1220), Sepane Katdoorn (1210) and the Bloemdal Roodeplaat (3200) (Soil Classification Working Group, 1991) (Table 4.1 and Figure 4.5). All the A-horizons have an apedal massive structure, while the structure of the B-horizons vary from a weak developed sub- angular blocky structure with medium size structural units (10 - 25 mm) in the Tukulu to a medium developed blocky structure with medium ped sizes (10 -15 mm) in the Sepane soil form. All the C-horizons exhibited a prismatic structure of which the grade varies from medium to strong in the Tukulu to well developed in both the Sepane and Bloemdal. Ped sizes of the Tukulu soil falls into the 5 – 15 mm range and that of the Bloemdal and Sepane in the 10 – 25 mm range.

Transitions between horizons differed markedly in soil forms. In the Bloemdal they are smooth and flat for the A, B and C horizons, respectively, while in the Tukulu they are clear between the A- and B- horizons and abrupt between the B- and C- horizons. The Sepane, however, has an abrupt transition between the A- and B- horizons and a clear transition from the B- to the C- horizons. Mottles of red, yellow, grey and black colours are in abundance in the C- horizons of all soil forms. None of the horizons tested positively for free lime.

Based on the detailed observations made from the soil cores, a soil map was produced that delineates the three described soils found in the 55 ha field (Figure 4.5). The Tukulu soil form covers 75% of the field, therefore dominating the area, but with no particular association with topography. The Bloemdal covers 10% of the area and occurs mainly in the middle of the field. The Sepane's covers 15% of the field and are is associated mainly with the middle and lower positions on the topographical sequence.

Mapping of soil basic units is the first step towards organising variability in a scientific manner. However, the variability of inherent properties such as textural fractions and dynamic properties might vary more within soil units than between soil units.

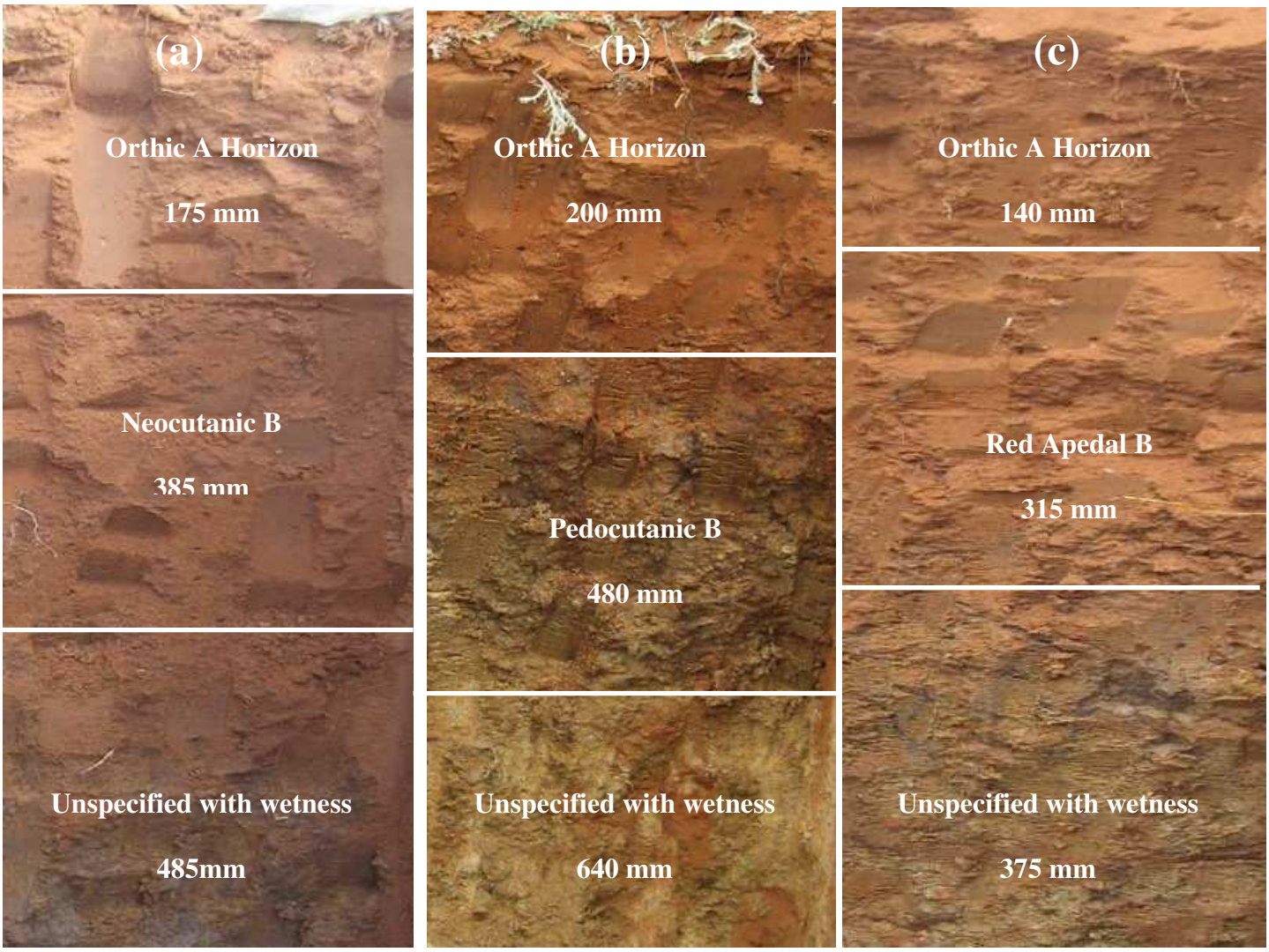


Figure 4.5 Model soil forms identified at the experimental field, namely (a) Tukulu, (b) Sepane and (c) the Bloemdal soil form.

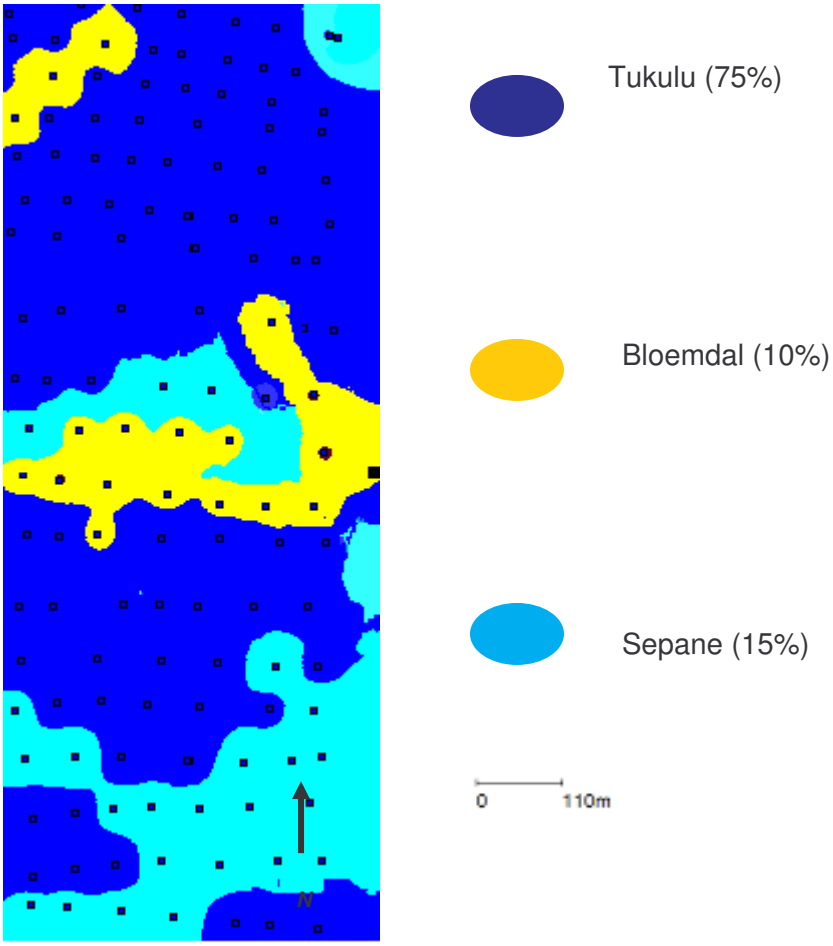


Figure 4.6 Soil map showing the spatial distribution of the three main soils found at the crop field surveyed at Paradys Experimental Farm.

4.3.2 Spatial variation in clay and silt fractions

Spatial variation in clay and silt fractions of the different soil forms was characterised by a range of statistical parameters, viz. minimum, maximum, means and the coefficient of variation of the different soil layers (Table 4.1). Comparing the CV results of the different textural fractions within the soil, depth layers reveal that the variation in clay content is considerably smaller than in coarse silt and fine silt fractions. The results show that the CV's and the means of the fractions in the different soil types per layer are of similar magnitude. From this it was deduced that there is no strong relationship between textural properties and soil forms, hence it makes sense to combine the data and treat it as a crop field. The mean clay content of the field

increased from 24.2% in the top 300 mm layer to 39.2% in the 300-600 mm layer and to 45.9% in the bottom layer. The corresponding CV's are 14.8, 12.8 and 8.1%.

Table 4.1 Range of statistical parameters (%) that characterise variability of selected textural fractions in the different soil layers of the Bloemdal (Bd), Tukulu (Tu) and Sepane (Se) as well as the field

	Soil layers		0 - 300 mm				300 - 600 mm				600 - 900 mm			
	Parameter	n	Min	Max	Mean	CV	Min	Max	Mean	CV	Min	Max	Mean	CV
Coarse Silt	Bd	14	1.0	3.0	1.6	48.1	1.0	3.0	1.6	41.1	1.0	2.0	1.3	36.5
	Tu	42	1.0	3.0	1.3	43.0	1.0	3.0	1.5	41.6	1.0	4.0	1.5	44.8
	Se	19	1.0	2.0	1.6	30.4	1.0	2.0	1.5	34.8	1.0	2.0	1.3	36.3
	Field	75	1.0	3.0	1.4	41.5	1.0	3.0	1.5	39.5	1.0	4.0	1.4	42.1
Fine Silt	Bd	14	1.0	8.0	3.4	55.6	0.0	4.0	2.4	47.7	0.0	5.0	1.3	52.2
	Tu	42	1.0	6.0	3.0	42.3	1.0	8.0	3.8	53.2	1.0	9.0	3.3	55.7
	Se	19	1.0	8.0	4.5	45.0	1.0	8.0	4.3	47.6	1.0	7.0	3.5	47.6
	Field	75	1.0	8.0	3.5	49.5	0.0	8.0	3.7	54.0	0.0	9.0	3.2	53.7
Clay	Bd	14	17.0	29.0	22.9	14.7	33.0	51.0	39.5	13.8	39.0	50.0	44.8	8.2
	Tu	42	16.0	32.0	24.3	13.8	27.0	48.0	39.2	12.6	39.0	51.0	46.2	6.9
	Se	19	18.0	33.0	24.7	14.8	28.0	46.0	38.8	13.4	39.0	55.0	46.0	10.4
	Field	75	16.0	33.0	24.2	14.8	27.0	51.0	39.2	12.8	39.0	55.0	45.9	8.1
Clay + Silt	Bd	14	23.0	34.0	27.8	12.6	36.0	53.0	43.5	12.5	43.0	55.0	48.6	8.8
	Tu	42	19.0	36.0	28.6	13.6	31.0	53.0	44.5	13.3	42.0	59.0	51.0	7.4
	Se	19	21.0	41.0	30.8	18.5	36.0	53.0	44.6	12.1	42.0	59.0	50.8	9.5
	Field	75	19.0	41.0	29.0	15.3	31.0	53.0	44.4	12.7	42.0	59.0	50.3	8.3

4.3.3 Spatial distribution in clay plus silt content in the crop field

The EM38 was used to measure EC spatially in both the vertical (EM_v) and horizontal (EM_h) orientation in the 55 ha field. As a first step, correlations were made between EM readings in the vertical and horizontal orientation and clay plus silt content. Only the best fit for each layer of soil (top soil, subsoil and deep subsoil, as well as for the profile) are depicted in Figure 4.7.

The EM readings in the vertical coil orientation seemed to produce the best fit in all the layers, except in the subsoil (300 – 600 mm) layer where the horizontal reading produced the best fit. This was expected for the deeper layers and not for the top layer, as theoretically horizontal inductions are most sensitive at the surface while its sensitivity decreases towards the 750 mm depth. Vertical inductions on the other hand are most sensitive down to 400 mm depth while

their sensitivity decreases progressively towards the bottom of the potential root zone of 1500 mm (Noguea's *et al*., 2006).

The correlation statistics revealed further that all the layers, except the 300 – 600 mm, exhibit a positive slope, indicating that the EM readings increase with an increase in clay plus silt content.

The strongest correlation (R^2 = 0.85) was found in the top layer with both the slope and the intercept of the model highly significant ($p < 0.05$) revealing standard errors of 5.6 and 0.1, respectively. The RMSE for the model amounted to 2.42. The statistical parameters of the 300 – 600 mm layer and the 600 – 900 mm layer, however, are not as strong as in the top layer, *viz.* R^2 of 0.24 and 0.21, RMSE of 4.86 and 3.42 with standard errors for the intercept of 3.8 and 6.4 revealing standard errors for the slope of 0.4 and 0.2, respectively.

The intercept of the 300 - 600 mm model is highly significant ($p < 0.05$) but the slope insignificant ($p = 0.06$). Both the intercept and slope of the 600 -900 mm model are significant. In the 0 – 900 mm layer, the R^2 is 0.59; RMSE is 2.991; the slope is highly significant, while the standard error amounts to 6.9 and 0.2 for the intercept and slope, respectively.

Only the regression models that resulted in a positive relationship between EM readings and clay plus silt content were statistically tested using an independent data set from the remaining of the 75 plots. The results are presented in Figure 4.8. The best prediction was obtained with the topsoil model (d-index of 0.69), followed by the profile (d-index of 0.54) and then the deep subsoil (0.459). Only a few predictions were below the -20% deviation line as indicated in Figure 4.8, which shows that the EM38 could be used to predict clay plus silt content once the model has been verified. Rhoades *et al*., (1989); Corwin and Lesch (2003) and Corwin *et al*., (2006) too found good relationships between EM readings and several soil properties.

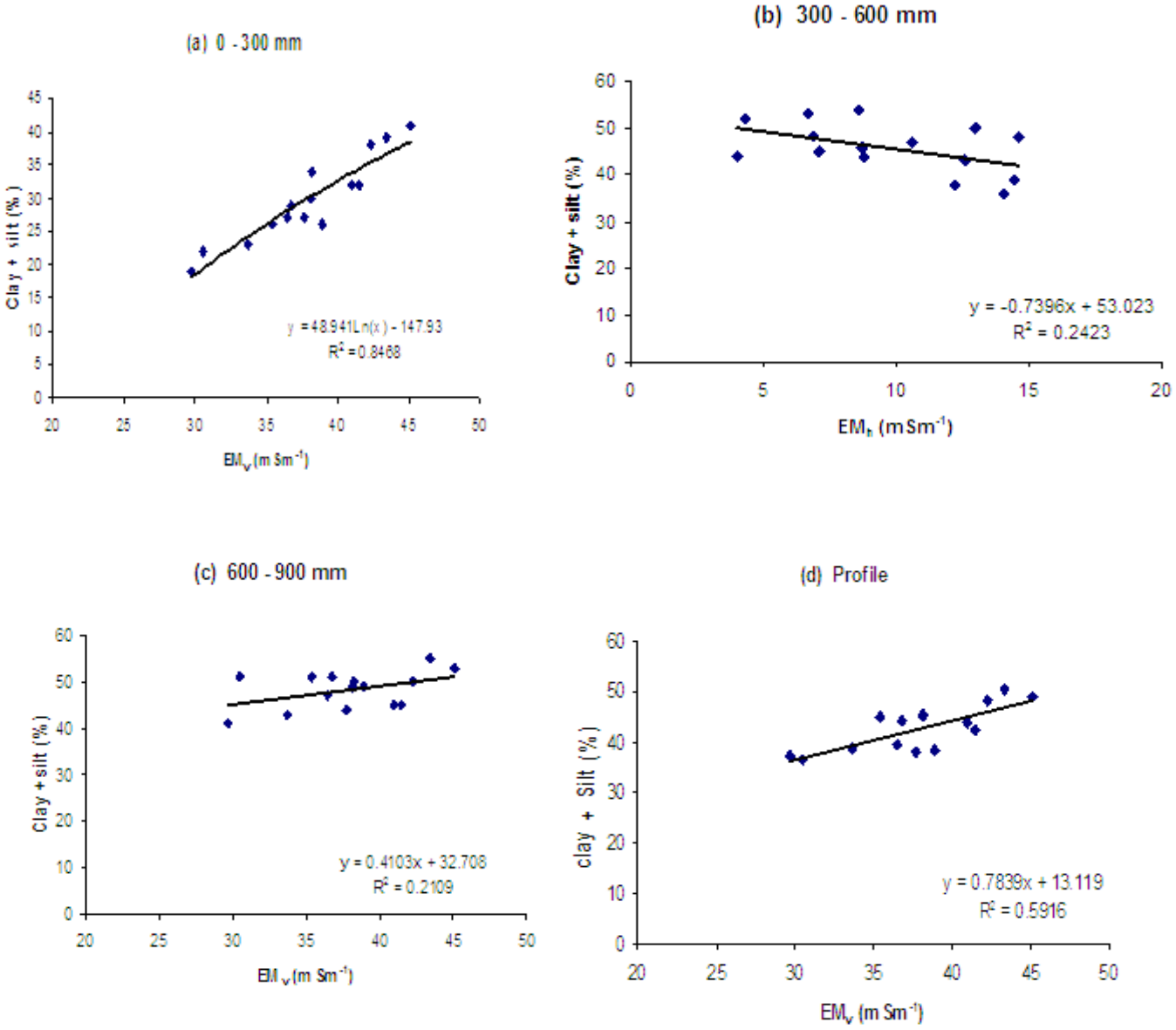
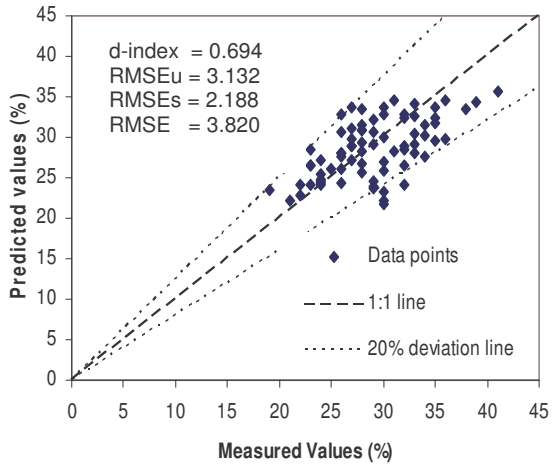
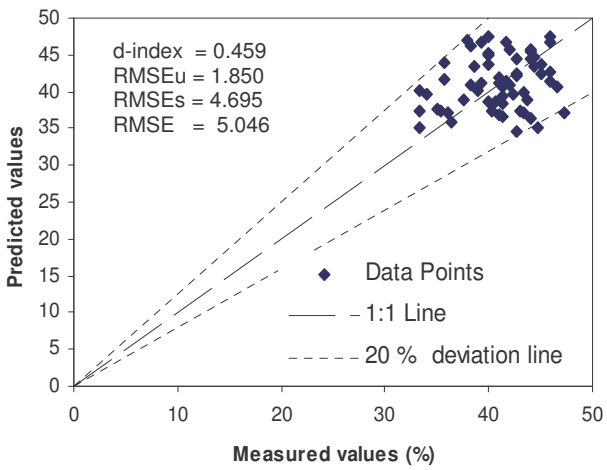


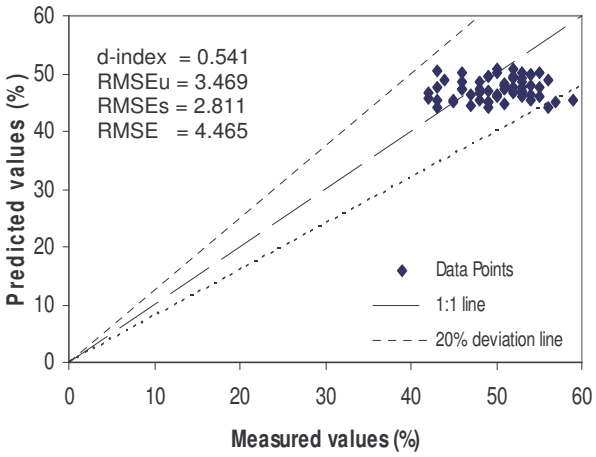
Figure 4.7 Relationships between clay plus silt percentage and EM measurements taken in the vertical coil orientation for (a) the 0-300 mm soil depth, (b) the 300 – 600 mm, (c) the 600 – 900 mm and (d) the profile (0 - 900 mm).



(a)



(b)



(c)

Figure 4.8 Statistical results of model performance to predict the clay plus silt contents (%) from EM38 readings using an independent data set: (a) reflects on the model used for the 0-300 mm soil depth,(b) on the 600-900 mm and (c) on the profile (0 - 900 mm depth).

Finally, these models were used to predict the spatial distribution of clay plus silt content based on EM38 measurements taken on each of the runoff strips of the 55 ha field.

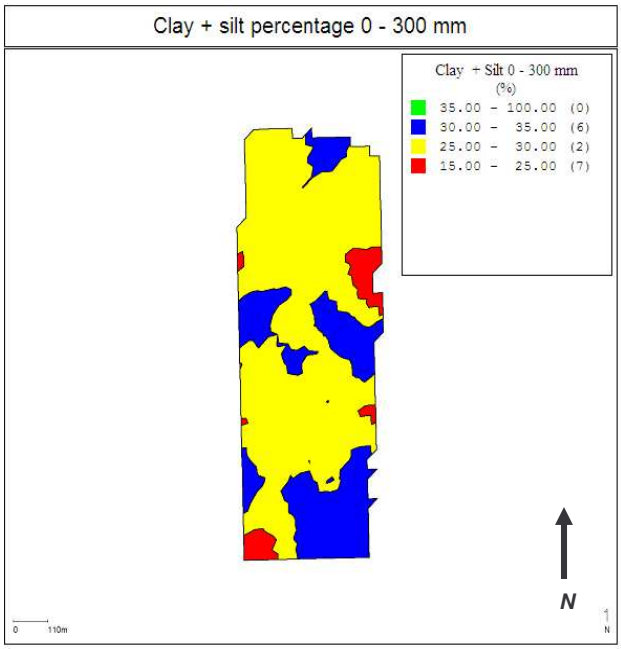
From this data set maps were drawn delineating possible management zones for the topsoil (0 - 300 mm), deep subsoil (600 – 900 mm) and profile (0 – 900 mm) layers as displayed in Figures 4.9a – c, respectively.

Based on the spatial distribution of the clay plus silt content, the topsoil or plough layer map shows three management zones, viz. a relative low clay plus silt content (15 - 25%), followed by a moderate clay plus silt content (25 - 30%) and a high clay plus silt content (30 – 35%). The three zones occupy 5%, 70% and 25% of the total area of the field.

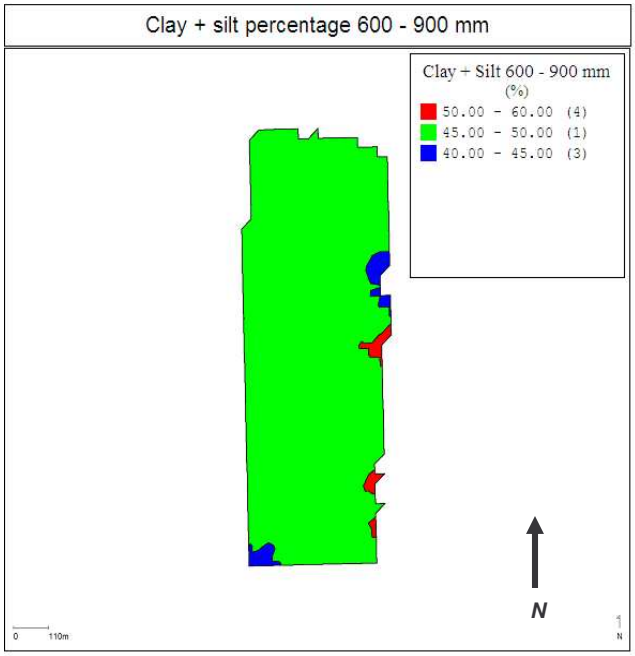
The deep subsoil clay plus silt layer reflects mainly on the C-horizon which contains a non-diagnostic prismatic layer, irrespective of the soil type. The clay plus silt range of 45 – 50 % makes up 97% of the entire field.

The textural map of the profile indicated three zones, viz. 35 – 40%, 40 – 45 % and 45 – 50%, which occupying 26%, 70% and 4%, of the field respectively.

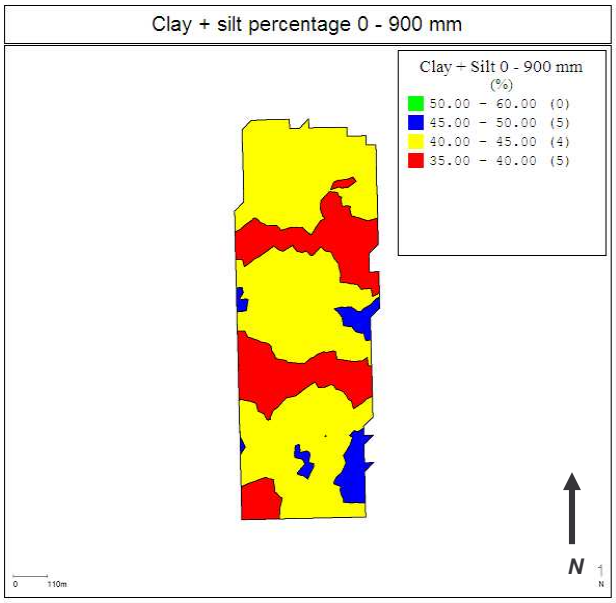
From the procedure followed and the statistical results it can be concluded that the EM38 could be used to predict the clay plus silt content of the top soil, deep subsoil and total profile of commercial fields located in the Ca22 land types. This is attributed to the ability of the instrument to measure EC every 20 cm while it is towed behind a quad bike at a speed of approximately 5 km h^{-1}. The spatial position of each measurement was obtained by a GPS system mounted on the bike. This makes the prediction of clay plus silt economical viable while information obtained from the maps can be applied for improving management skills in dry land crop farming. The results concur with the findings of Rhoades *et al.* (1989), Corwin and Lesch (2003) and Corwin *et al.,* (2006) which stated that it is possible to predict soil properties from EM readings.



(a)



(b)



(c)

Figure 4.9 Clay plus silt management zones for the (a) 0-300 mm soil horizon, (b) 300 – 600 mm horizon, (c) 600 -900 mm soil horizon and (d) average clay plus silt content for profile.

4.3.4 Significance of the textural based management zones with respect to dry land agriculture

The textural based management zones, described in Figure 4.9a for the top soil, revealed three zones, *viz.* the 15 - 25% or relative low clay plus silt zone (LCPSZ), 25 - 30% or moderate clay plus silt zone (MCPSZ) and a 30 – 35% or high clay plus silt zone (HCPSZ), and provided insight into tillage approaches.

Generally, the soils of the LCPZ compact easily when wet and under pressure, induced by heavy machinery, giving rise to layers with high mechanical impedance. These layers restrict root growth with harmful effects to plant development and yield (Bennie and Burger, 1981; Bennie and Krynauw, 1985; Bennie and van Antwerpen, 1988).

Ample evidence of plough layers were observed during the soil survey in the LCPZ zone at depths that varied between 150 mm to 350 mm. However, the risk of compaction reduced considerably from the LCPSZ *via* the MCPSZ to the HCPSZ due to the increase in the clay content and the presence of a large amount of Montmorillonite and illite in the clay fraction.

These soils swell and shrink during wet and dry periods, which naturally alleviate compaction. However, surface crusting will probably increase from LCPSZ via MCPSZ to the HCPSZ owing to an increase in clay content in these zones (Van der Watt and Valentin, 1991) and the generally low organic matter content of the layer, irrespective of the soil type (Du Toit *et al*., 1994).

Surface crusting is associated with runoff and erosion which make both the MCPSZ and HCPSZ high-risk areas to be treated with care under conventional (ploughing) tillage practices. However, under IRWH the rainwater productivity will probably increase from LCPSZ to HCPSZ due to expected higher in-field runoff associated with the increase in clay plus silt content across the zones (Hensley *et al*., 2000; Botha *et al*., 2003; Botha, 2007).

Preparation for a seedbed requires different strategies. It is expected that the increase in clay plus silt content will cause larger and stronger clods and hence an increase in the number of secondary tillage operations from LCPSZ to HCPSZ in order to create a smooth and crumble soil structure for planting.

An increase in clay plus silt content is also associated with an increase in surface roughness, which can retard runoff under IRWH system, especially in the first year of establishing the technique.

The management zones of the deep subsoil (Figure 4.9 b) suggest that the prismatic nature of the layer will not restrict the rooting depth of the field only (Callot *et al*., 1982; Logsdon *et al*., 1987), but will also control the internal drainage and percolation.

Furthermore, Fraenkel (2009) determined the hydraulic conductivity – soil water content relation of the layer and from his curves it was calculated that K varied between 0.002 mm day^{-1} (Tukulu soil type) and 0.34 mm day^{-1} (Bloemdal soil type) at relatively high soil water content of 0.28 mm mm^{-1}.

The management zones of the profile presented in Figure 4.9 c clearly indicated that the mean clay plus silt content of the field are very high. Based on the relationship between the percentage yield advantage per mm depth cultivated (y) and percentage clay content (x) ($Y = -0.112x + 0.1827$, $R^2 = 0.74$) of van Rensburg (2009), it is clear that there is no advantage in tilling the soil deeper than 200 mm under conventional tillage. This can be ascribed to the swelling and shrinking properties that lead to vertical cracks in the soil during successive wet and dry cycles as indicated by the moderate to strong structure present in the B and C horizons. The tillage guidelines of FSSA (2007) suggest, moreover, that these soils will perform better under conservation practices such as no-till or IRWH.

4.4 Conclusion

From the study it can be concluded that reliable in situ correlations between EC, measured with the mobile EM 38, and clay plus silt content were found for the topsoil, deep subsoil and over the profile. These equations were used to estimate clay plus silt from about 80 000 EC readings made with the mobile EM38 system over the entire land. The large amount of readings was obtained by towing the EM38 in a sled behind a quad bike at a speed of 5 km h^{-1}. Measurements were taken over two days at 3 m intervals perpendicular to the slope of the land. The measurements were geo-referenced by using a Trimble GPS system, making it possible to delineate clay plus silt classes that can serve as managing zones. The significance or impact of these management zones on dry land agriculture had been discussed and it was concluded that

farmers and managers can use the textural based maps to re-evaluate current tillage practices on marginal clay soils in semi-arid zones.

The use of EM 38 measurements to delineate textural based management zones should be of great advantage to the Precision Agricultural sector for optimising inputs regarding soil potential and hence maximizing profits. Future studies should therefore utilize the mobile EM38 system improving soil maps, constructing advance soil potential maps and investigating the possibility to obtain soil water maps for crop lands. These aspects will be addressed in Chapter 5.

Chapter 5

Estimating spatial distribution of profile available water capacity and soil wetness in a commercial crop land using a mechanised electromagnetic induction method (EM38)

5.1 Introduction

Despite the advancement of electromagnetic induction (EMI) technology, the application of the science in agriculture is under utilized in Africa, particularly in South Africa. The concept of using induced EMI fields to measure conductivity of material with EMI technology originated in the field of geosciences as far back as a half century ago (Belluigi, 1948; Wait, 1954, 1955). The development of the EM31 and EM38 instruments by Geonics Ltd. (Ontario, Canada) contributed significantly to the application of EM technology in other disciplines, especially agriculture, where it is used for quantifying soil salinity in many developed countries (De Jong *et al.,* 1979; Rhoades and Corwin, 1981; Kingston, 1985; McKenzie *et al*. 1989).

Johnston *et al*. (1994) was the first researcher who used the EM38 to characterize soil salinity in irrigation fields of South Africa. Johnston *et al*. (1994) continued the work by comparing the EM38 with conventional methods of measuring soil salinity*, viz.* the sampling of soil with an auger on a grid basis, followed by analysis of the water extract in the laboratory.

They concluded that the conventional method was slow, laborious and expensive in comparison to the EM38. The authors stated that the cost of the survey was a mere 10% of the conventional procedure. More recently, Noguees *et al.,* (2006) confirmed that the use of the EM38 considerably reduced operational costs in delineating salinity phases on a regional scale (1:25000) in European and developing countries, especially if a single calibration of EM data is present.

Johnston *et al*., (1994) developed calibration equations that converted EM readings into single–valued electrical conductivity of the saturation extract (ECe) for South African soil conditions. Eight calibration curves were derived from data obtained from 110 sites, which covered seven of the major irrigation schemes in South Africa.

They observed that both texture and soil water content influenced the EM readings and grouped the calibration equations into five textural classes (course, medium, fine, smectic clays and other than smectic clays) and divided it further into two water levels based on percentage of available water content (30 to 85% and >85%).

The dependence of bulk soil electrical conductivity on both texture and soil water content is well established (Rhoades *et al.,* 1976; McNeil, 1980; Rhoades and Corwin, 1981). Kachanoski *et al.*, (1988) and Sheets and Hendrickx (1995) exploited the potential of the Geonics EM31 and EM38 terrain meters to measure soil water content. In the horizontal coil orientation, both instruments give an average EC to a soil depth equal to the length of the instruments, viz. 4.0 m and 1.0 m for the EM31 and EM38, respectively. Vertical coil orientation of the instruments yielded average EC values from the surface to approximately 6 m and 1.5 m, respectively (Kachanoski *et al.,* 1988). Thus, the use of the instruments depends on the situation or aim. For quantifying the water balance of the root zone of field crops, the EM38 will probably suits the situation better, because rooting depths vary between 1 and 2 m (van Antwerpen, 1988; Bennie *et al.*, 1988). If the interest is to monitor water table heights near the root zone, then the EM31 will be a better instrument because it could measures soil water content beyond the root zone.

Furthermore, in soils with clay contents that vary from 2.5% and 44.4% and water contents that vary between 0.064 and 0.362 m^3 m^{-3}, Kachanoski *et al.*, (1988) found that the coefficient of determination varied between 0.88 and 0.94 for the linear correlation of EM readings and volumetric soil water content at various soil depths from the surface up to 6 m. They found, moreover, that the use of quadratic equations improved the correlation further (R^2= 0.96), confirming the general curvilinear response found by Rhoades *et al.* (1976). Accordingly, the response in the relationship is linear up to a threshold water content of 0.25 m^3 m^{-3}, after which it approaches a still value at higher soil water contents. Given the fact that EM measurements are non-invasive and cover depths up to 6 m from the surface, the standard errors reported by both Kachanoski *et al.*, (1988) and Sheets and Hendrickx (1995) are very low, in the order of 0.02 m^3 m^{-3}.

Sheets and Hendrickx (1995) proved, furthermore, that the EM31 is not only capable of measuring soil water content spatially along a transect of 1950 m in the of New Mexico State University College Ranch, but also temporally. They developed a single regression model that can estimate volumetric water content reasonably accurate (R^2= 0.64). According to the textural analysis, the soils appear to be very uniform with a mean clay content of 13.8% (±3.9%). Apart

from the fact that the instruments are expensive and require specialised software packages to retrieve and process data, the only other disadvantage of the EM instruments appears to be the empiric nature of the regression equations that correlate EC measurements with soil water content (Kachanoski *et al.,* 1988).

The EM application in agriculture advanced rapidly in many developed countries, especially as a result of the mechanisation of the instruments (Carter *et al*., 1993), the development of electronic equipment and software for storage and retrieval of measured data (Steinberger *et al*., 2009), the geo-referencing of measuring points with GPS systems (Auernhammer *et al*., 2001) and software for interpolating data with ease. All these technologies contributed in unique ways towards obtaining primarily salinity maps. However they also provide the potential for characterising texture and soil water spatially on large commercial crop fields, with a high level of accuracy and efficiency (Corwin & Lesch 2003). This could provide invaluable feedback on various agricultural management practices, especially in semi-arid environments were water is considered to be the main production risk in crop production systems.

The general objective of this chapter is to demonstrate the potential of the EM38 to derive spatial maps of profile available water capacity and soil wetness of a commercial crop field under in-field rainwater harvesting (IRWH) located in a semi-arid zone in the central part of South Africa.

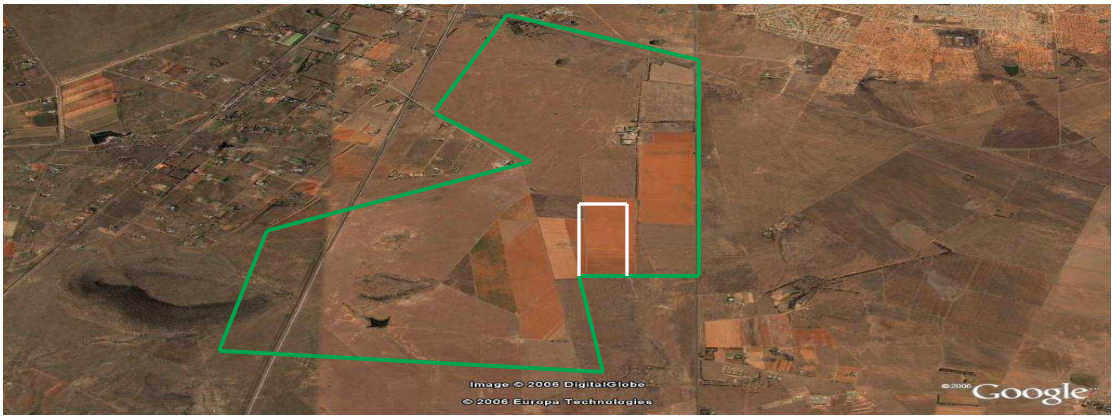
5.2 Materials and methods

5.2.1 Experimental site and treatments

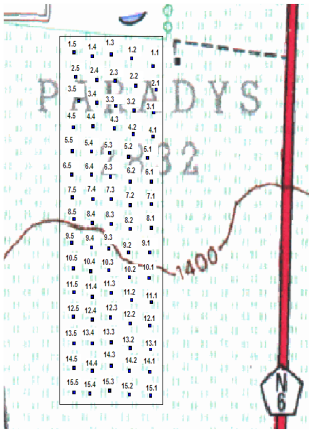
The experiment was conducted on Paradys Experimental farm of the University of the Free State, located between the N1 road to Colesberg and the N6 road to Reddersburg, about 10 km from the centre of Bloemfontein. The borders of the farm and the site are presented in Figure 5.1a by a green and a black line, respectively.

The 55 ha crop field was subdivided into 75 experimental plots (Figure 5.1b). Rows 3, 8 and 14 were treated as conventional plots by being plougher to a depth of 250 mm. The rest of the rows were treated as IRWH plots. Each plot was 72 m x 72 m with rows consisting of a two meter runoff area and a one meter basin area (Figure 5.1c).

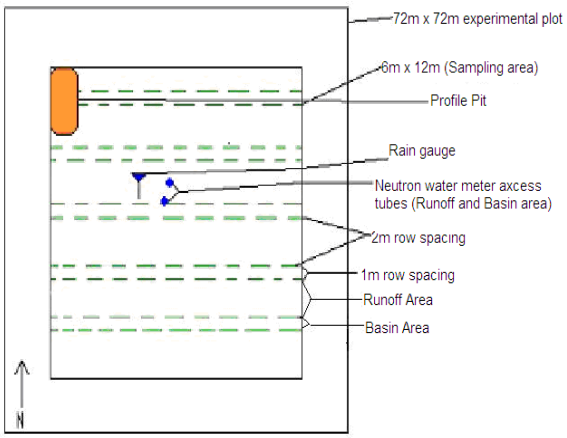
(a)



(b)



(c)



N

Figure 5.1 (a) A map showing the boarders of Paradys Experimental Farm (demarcated with a green solid line) and the specific 55 ha crop field use in the study, delineated with a white solid line (-32˚35'21''S,-77˚43'6''E), (b) Schematic layout of the experiment with the 75 plots and (c) the position of the neutron excess tubes, basins and runoff areas within a plot.

5.2.2 Electrical conductivity measurements with EM38

Electrical conductivity (EC) measurements were taken with an EM38 (Geonics) instrument, drawn in a sled behind a quad bike at a speed of approximately 5 km h^{-1} (Figure 5.2 a, b) on 2 July 2007. The measurements were confined to the runoff strips of the IRWH system, *i.e.* every 3 m perpendicular to the slope of the field.

Measurements were taken twice to obtain coil configurations orientated in the horizontal (EM_h) and vertical (EM_v) level. It took 2 days to cover the 55 ha field. The instrument measures apparent soil electrical conductivity in millisiemens per meter (mS m^{-1}) every 2 - 5 cm as it is drawn over the field. The instrument was calibrated, as described in the manual, three times a day. Furthermore, all measurements were geo-referenced and the data processed with Surfer software package.

(a)

(b)

Figure 5.2 The EM38 instrument (a) embed in the sled and (b) towed behind a quad bike at a speed of approximately 5 km h^{-1}.

5.2.3 Soil sampling and measurements

A detail soil survey was conducted on the 55 ha crop field using a mobile hydraulic auger. Observations were done on a 50 m x 50 m grid and the 15 cm diameter soil cores were stored in a pvc pipe (Figure 5.3), whereafter a detail soil description was carried out. The core samples were divided into 300 mm intervals and a textural analysis was carried out using the standard pipette method (The Non – Affiliated Soil Analysis Work Committee 1990). A map was drawn of the soil depth using SMS Advance (Ag Leader, 2009) soft ware package of the 55 ha field.

Soil depth was measured by lowering a calibrated measuring stick into the auger hole, taking the depth from the soil surface to the parent material.

Figure 5.3 Sampled soil cores taken with the hydraulic auger.

5.2.4 Profile available water capacity (PAWC) and its spatial determination

In order to construct a spatial distribution map of PAWC for the 55 ha field, both mean clay plus silt content (%) and soil depth (mm) are required spatially before the estimation procedure could be applied.

Profile available water capacity (PAWC) was originally defined by Boedt and Laker (1985) as, the difference between the drained upper limit (DUL) and the lower limit (LL) of plant available water (PAW) (Equation 5.1).

Bennie *et al*. (1988) and Bennie *et al*. (1998), furthermore, showed that both the limits depend on soil, plant and climatic conditions, which can be estimated fairly accurately with the SWAMP model (Bennie et al., 1998), provided that the correct soil, plant and atmospheric inputs are available. However, from a planning point of view, it is not necessary to make such accurate or precise predictions, as simple empirical models or pedo-transfer functions, too, can provide realistic estimates of the PAWC. Van Rensburg (1988) developed such pedo-transfer functions to estimate the volumetric soil water content at DUL and LL (Equations 5.2 and 5.3) from clay plus silt content (%). PAWC (mm) can then be calculated by subtracting DUL from LL for a specific soil depth as indicated in Equation 5.1.

$$PAWC = (DUL \times soil\ depth) - (LL \times soil\ depth) \quad (5.1)$$

$$\Theta_{DUL} = 0.0037\ (Clay + Silt\ \%) + 0.139 \quad (5.2)$$

$$\Theta_{LL} = 0.00385\ (Clay + Silt\ \%) + 0.0125 \quad (5.3)$$

Θ_{DUL} = Volumetric soil water content at DUL (mm mm^{-1})

Θ_{LL} = Volumetric soil water content at LL (mm mm^{-1})

The procedure followed to estimate PAWC for the profile as follows:

(i)The mean clay plus silt content of the profile was estimated with the Equation 5.4 which relates the EC of the EM38 to the mean clay plus silt content of the profile:

$$Y = 0.7839x + 13.119 \quad (5.4)$$

Where y = clay plus silt content (%)

X = electrical conductivity (mS m^{-1})

(ii) The spatial distribution of the mean clay plus silt content of the field was derived from the correlation results obtained by EC measurements taken with the mobile EM38 and the mean clay plus silt content of the profile. Finally maps were drawn with SMS Advance (Ag Leader, 2007) soft ware package.

5.2.5 Volumetric soil water content measurements and its spatial determination

The Campbell Pacific Nuclear (CPN) 503DR hydroprobe was used for measuring soil water content (mm. mm^{-1}). Therefore, neutron water excess tubes were installed in the basin and the runoff area in each of the 75 plots. Soil water measurements were taken at 300 mm depth intervals from 0 to 900 mm on 1 July 2007 and expressed in percentage. For the water content of the profile the mean values of the soil layers were used. The count ratio of the probe was calibrated with soil water content obtained from standard gravimetric soil samples taken near

the probes and then converted to volumetric water content using bulk densities obtained with the core sampling method.

Calibration equation: From the 75 plots, 15 plots were randomly selected and linear regression functions were applied for developing calibration equations between EC measured with the EM38 and volumetric soil water content measured with the neutron soil water meter. For the purpose of the study EC measurements were taken in the horizontal (EM_h) and vertical coil orientation (EM_v) while statistical analysis of the data was carried out on the basis as described by Willmott (1982).

The statistical analysis use for the models predicting clay plus silt content for the different layers from EM vertical and EM horizontal measurements is based on the Wilmott (1982) procedure. Accordingly the root mean square error, unsystematic root mean square error was systematic root mean square error and d-index of the model prediction was calculated. The statistical analysis comprised of the determination of the root mean square error (RMSE) unsystematic root mean square error (RMSEu), systematic root mean square error (RMSEs) and the index of agreement (D-index) of the model tested. For a good fit the RMSEs should approach zero, the D-index should approach one and the RMSEu should be as close as possible to the RMSE, while R^2 values would give an indication only of the accuracy of the line fit, and not the accuracy of the prediction (Willmott, 1982).

5.3 Results and discussion

5.3.1 Spatial distribution of the electrical conductivity

The statistical results on the EM readings, measured in the vertical coil orientation, revealed that they ranged from a minimum of 27.5 mS m^{-1} to a maximum of 45.1 mS m^{-1} with a mean EC of 36.2 mS m^{-1}. For the horizontal coil orientation, the minimum was 2.3 mS m^{-1} and the maximum 31.1 mS m^{-1} with a mean EC of 12.5 mS m^{-1}. The spatial distribution of EC in the vertical and horizontal orientation over the 55 ha field was interpolated and mapped in Figure 5.4a and b, respectively. Theoretically, the vertical readings represent values that should reflect on the rooting zone up to 1500 mm soil depth, while the horizontal readings represent the surface or near surface conditions (0 – 750 mm). It is evident that the EC of the vertical readings

are considerably higher than that of the horizontal readings, probably due to the increase in clay content with soil depth.

Three EC classes were delineated as indicated in Figure 5.4 a and b. However, there is no apparent visual relationship between soil types (Figure 4.6, Chapter 4) and the EC classes for either the vertical or horizontal coil orientation.

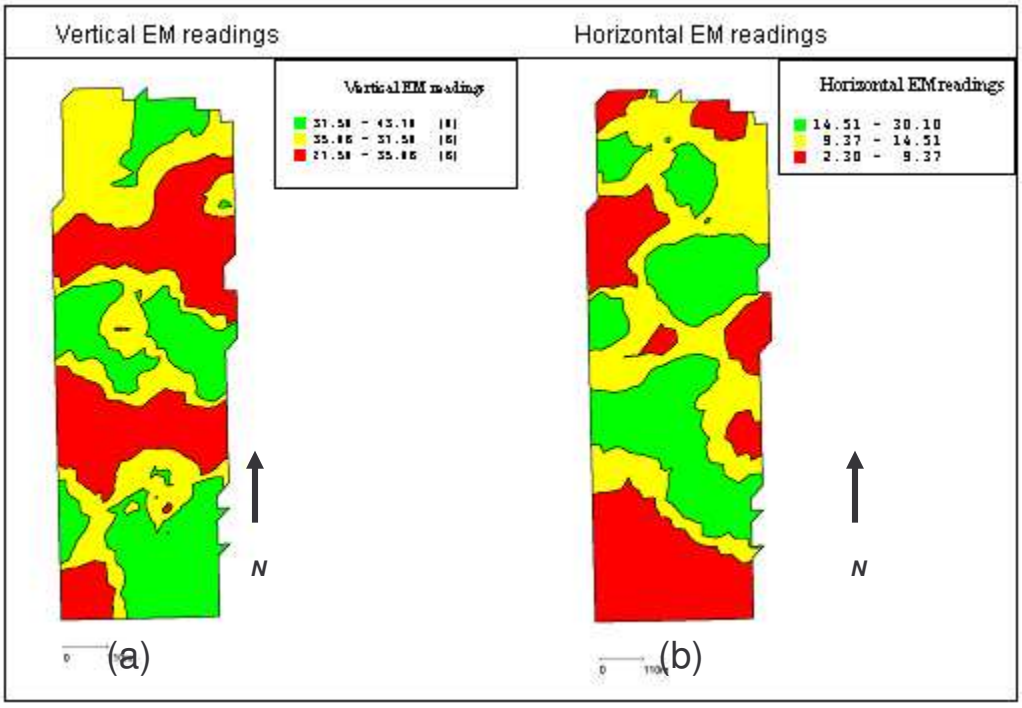


Figure 5.4 The spatial distribution of the EC (mS m^{-1}) in the 55 ha, measured with the EM 38 in the (a) vertical coil orientation (b) and the horizontal coil orientation modes.

5.3.2 Spatial distribution of profile available water capacity

The results of the spatial distribution of soil depth are presented in Figure 5.5. Three depths zones were arbitraries delineated, *viz*. 600 – 900 mm, 450 – 600 mm and 300 – 450 mm. The respective area for the zones were 16.5 ha, 35.75 ha and 2.75 ha.

Joseph (2007) proposed, for example, a soil depth of > 700 mm as a guide for the selection of soils suitable for IRWH. This is probably true, but it needs to be quantified with crop models using long-term climate data. The best information available is that of Hensley *et al.,* (2003) and Botha (2007) who made such long-term predictions for the Glen/Bonheim, Glen/Swartland,

Khumo/Swartland and Vlakspruit/Arcadia using the CYP-SA model and long-term climate to obtain cumulative distribution graphs for maize yields.

They found at a 50% change of achievement that IRWH will give maize yields of 2 200, 2 300, 2 500 and 2 500 kg ha^{-1} for the respective ecotopes (Hensley et al 2003). Unfortunately, the soil depths were all 1 200 mm and no clear conclusion could be reached on soil depth.

With respect to the clay + silt content, three distinct zones were identified *viz.* moderately high clay plus silt content (35 - 40%), high clay plus silt content (40 - 45%) and very high clay plus silt content (45 - 50%) (Figure 5.5a). The area statistics revealed that they occupy 26%, 70% and 4% of the total area of the field.

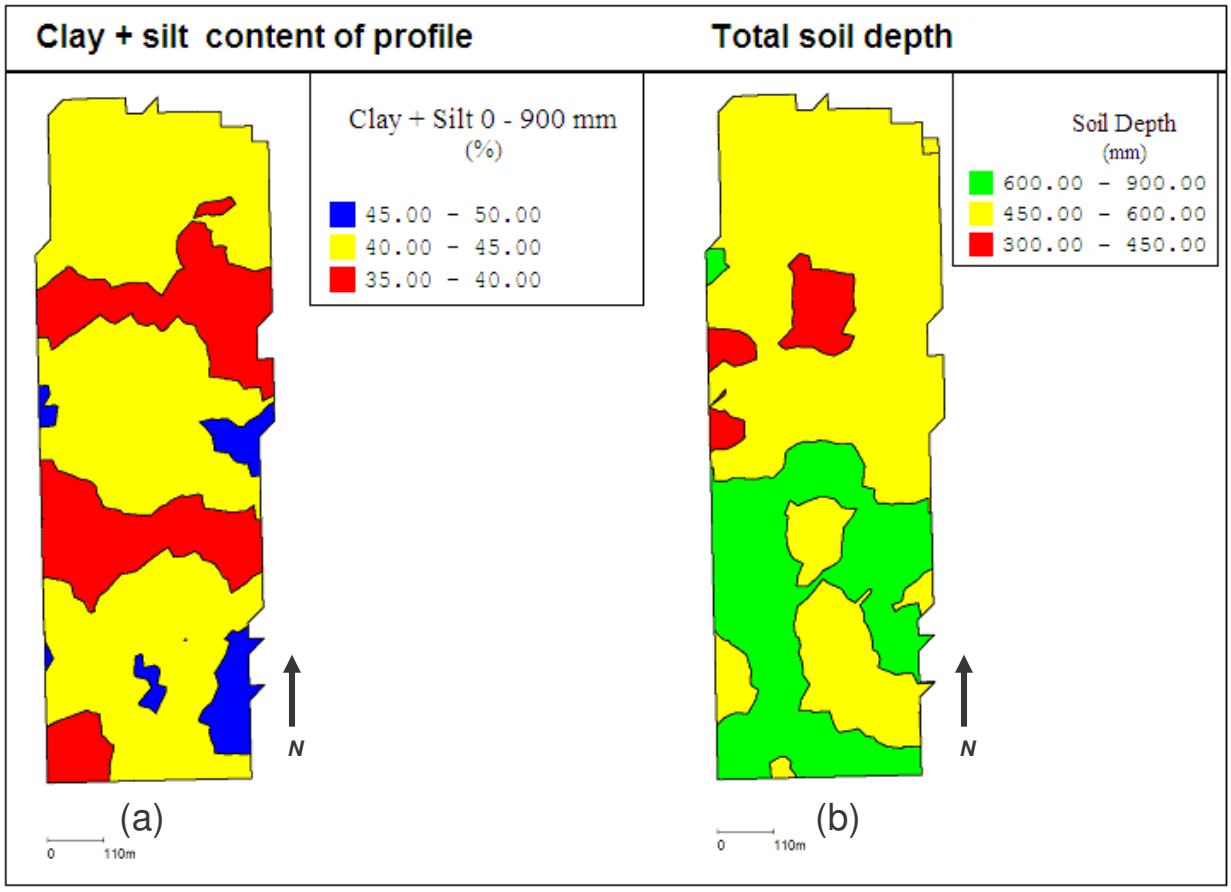


Figure 5.5 Spatial distribution of the (a) clay plus silt distribution of the profile and (b) soil depth classes in the 55 ha crop field.

Bennie et al. (1994) stated that the PAWC concept is a superior method for selecting soils for dry land production, because it integrates important soil physical properties relevant for soil water storage and supply, root and canopy characteristics and prevailing climatic conditions that determine crop yields. Such information is not always readily available, especially for IRWH. Therefore, the procedure explained in Section 5.2.4 was followed to obtain PAWC with units of mm. mm^{-1} .The results on the spatial integration of PAWC for the crop field are displayed in Figure 5.6.

Three management zones were identified, *viz*. zone one with a PAWC > 80 mm^{-1} comprising of 3.577 ha, zone two with a PAWC between 50 – 80 mm^{-1} and an area of 51.68 ha and zone three with a PAWC < 50 mm^{-1}, covering 0.685 ha.

The first management zone represents the area of least biological risk, probably comparable to the production risks of the ecotopes studied by Hensley *et al.,* (2003) and Botha (2006). Yields of up to 4 000 kg ha^{-1} were obtained on similar IRWH plots adjacent to the field during the 2005/2006 maize season (Van Rensburg *et al.,* 2007). It can be expected that production risks regarding drought will increase in zone two and three where the PAWC decreases relatively to zone one.

Another production threat associated with low PAWC soils is water logging, especially in the case of IRWH, which is designed to increase the water content in the basin and below the basin area. Van Staden (2000) showed that the IRWH-basins could capture with ease high intensity rain events up to 75 mm on the Swartland and Bonheim soil types at Glen Agricultural Institute without any breakage of the basins or overspill of water. The lower the PAWC, the lower the soil water storage potential and the greater the potential risk for water logging.

However, not much information exists on critical levels of PAWC associated with maize production in these soils. Hensley *et al.* (1997) observed, for example, that in a hydromorphic soil (Ermelo/Longlands maize ecotope) where the water table remained at a depth of about 500 mm from the surface for most of the growing season, the yields were poor and recommended water table depths of more than 600 mm to prevent water logging. The permeability of the subsoil and parent material also plays an important role, but in the case of the Paradys ecotope it seems to be low as most of the field is underlayed by a high clay layer with a non diagnostic prismatic structure. According to Fraenkel (2009) the saturated hydraulic conductivity (Ks) of this layer varies between 0.01 and 0.16 mm day^{-1}.

Future research should focus on IRWH guidelines for soils, especially PAWC because it can play a significant role in lowering production risks and also in identifying management zones for precision farming in semi-arid zones (Newton & Williams, 2006). These management zones could be treated separately by using variable rate applicators for applying fertilizers and seeding according to the potential of a certain area within a field (Sadler *et al.,* 1998).

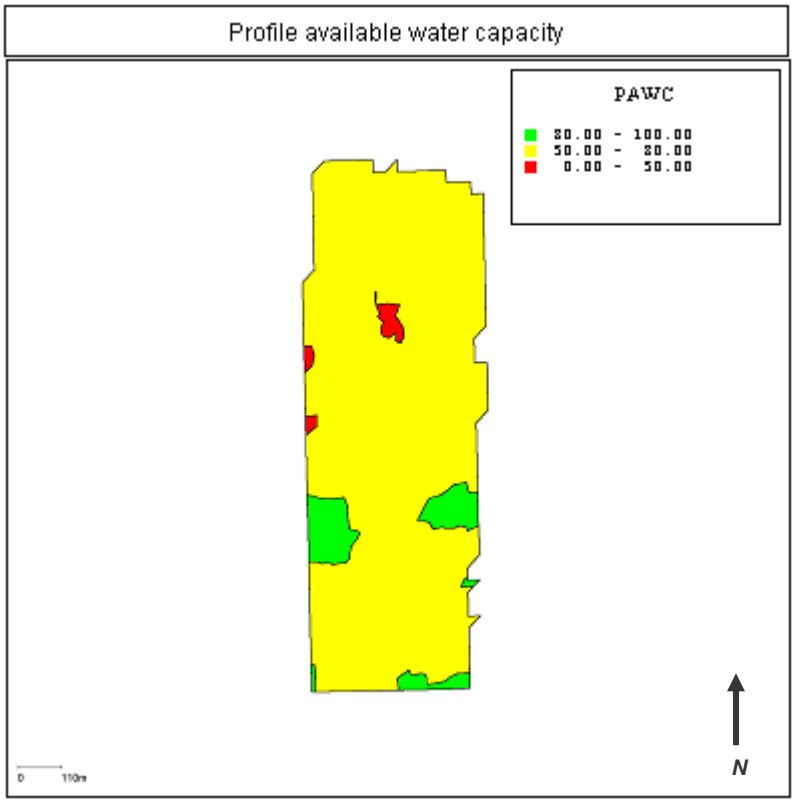


Figure 5.6 Variation in the PAWC of the 55 ha experimental field.

5.3.3 Evaluation of the EM38 to measure soil water content

This section focuses on the ability of the EM38 to measure volumetric soil water content of a crop field. Therefore, calibration equations were developed to convert EM38 readings into volumetric soil water content followed by the verification of the calibration equations with an independent data set.

Calibration equations: As explained, 15 plots were selected for developing the calibration equation that gives the relationship between EC measurements and volumetric soil water

content. The results for the best correlation fit for each soil layer, viz. 0 – 300 mm (top soil), 300 – 600 mm (subsoil), 600 – 900 mm (deep sub soil) and for 0 - 900 mm (profile) are presented in Figure 5.7. As in the case of clay + silt content, the best fit was obtained with the vertical coil orientation in all the layers, except the sub soil where the horizontal readings yielded the best correlation with a negative slope. In all other cases the slopes were positive, indicating an increase in soil water content with an increase in EC.

The strongest correlations were observed in the profile (R^2= 0.71) and in the top layer (R^2= 0.69), followed by the deep sub soil (R^2= 0.36) and the sub soil (R^2= 0.26). Regression statistics, furthermore, revealed that all intercepts are highly significant ($p < 0.01$). Both the slopes of the profile and top layer are highly significant, followed by the deep sub soil which is significant ($p < 0.05$) and the sub soil which is insignificant ($P = 0.6$).

Standard error for the intercepts amounted to 5.2, 2.6, 5.6 and 2.5% in the top soil, sub soil, deep sub soil and profile, respectively while the standard error for the slopes is 0.1, 0.2, 0.1 and 0.1, respectively. The RMSE for the model amounted to 1.95, 3.93, 3.1 and 1.28, respectively.

Verification of calibration equations: The performance of all the calibration functions was statistically tested with soil water content measurements using the neutron soil water meter in the remaining 60 plots - the results are summarised in Figure 5.8.

The relative high d-index results make it clear that the EM38 is able to measure soil water content in the various layers of soil and in the profile with some degree of accuracy. Though the accuracy is not as high as that obtained with specialised soil water sensors such as TDR (2% standard error), ECH_20 10, 20 and TEC capacitance sensors (2% standard error) and neutron soil water meters (2% standard error) (Ferré & Topp, 2002; Dorais *et al.,* 2005; Fares and Polyakov, 2006; Van der Westhuisen and van Rensburg, 2009). However, the EM38 has the advantage as it is a non-invasive procedure which samples from a large soil volume. For example, under the conservative assumption that the instrument measures a lateral distance of about 0.1 m, it can be calculated that it integrates soil water content over a sampling volume of 0.1 and 0.15 m^3 in the horizontal and vertical coil orientation, respectively. This is significantly larger than the soil volume measured with the well-established neutron soil water meter with a maximum sphere of influence of approximately 0.03 m^3, or than the more advance ECH_20 sensors from Degagon, which samples from between 0.003 to 0.006 m^3 depending on the length of the probes.

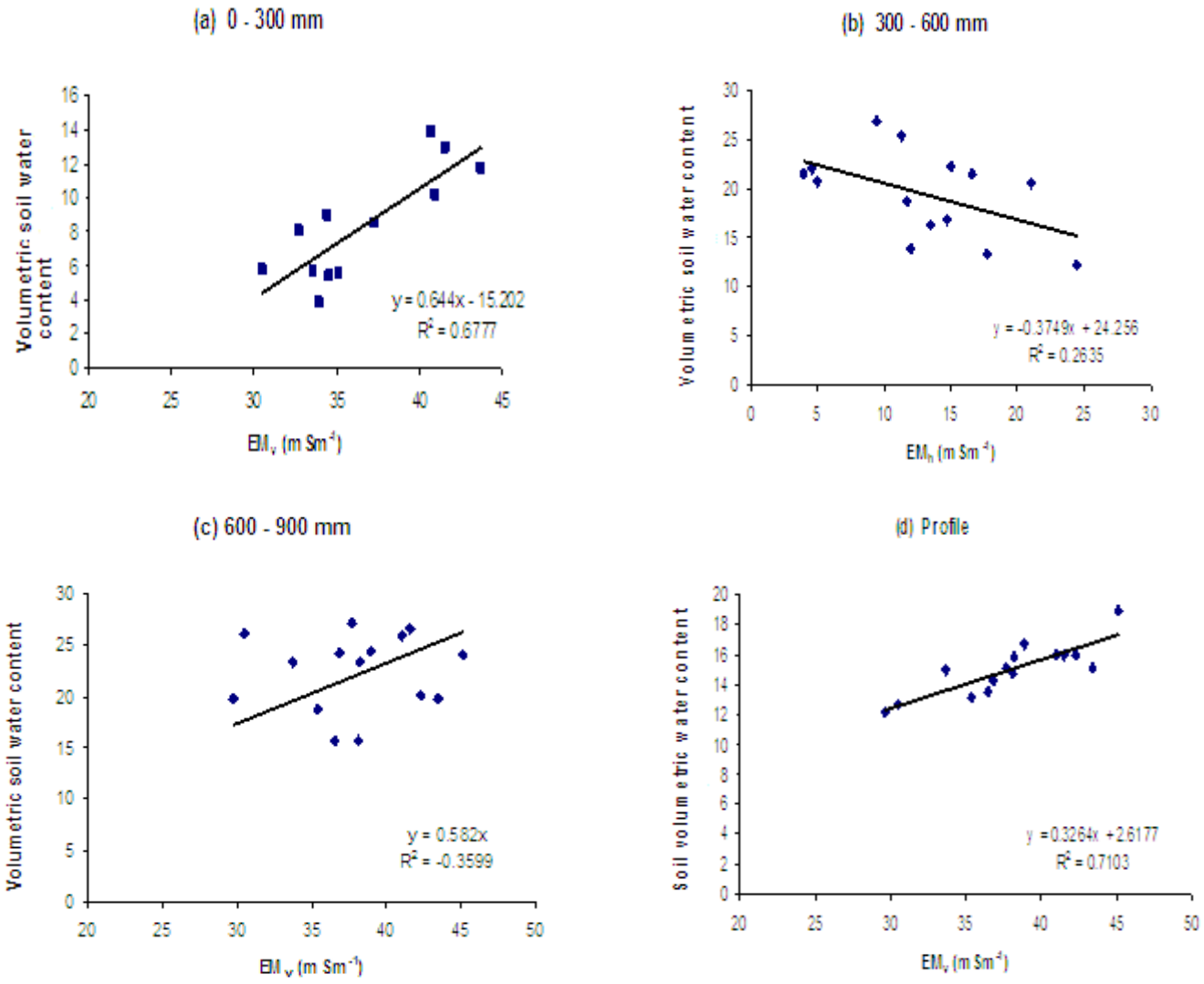
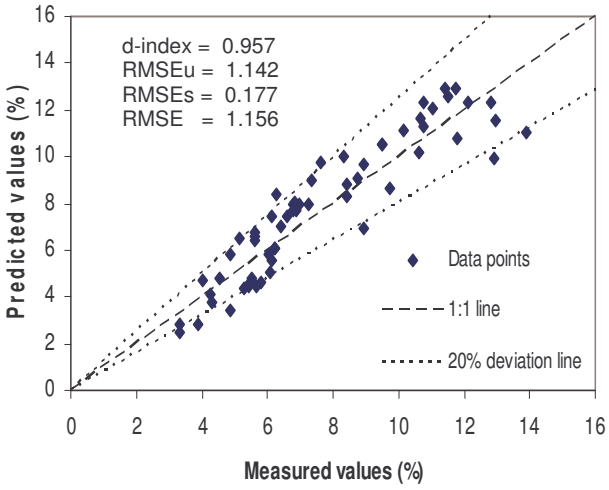
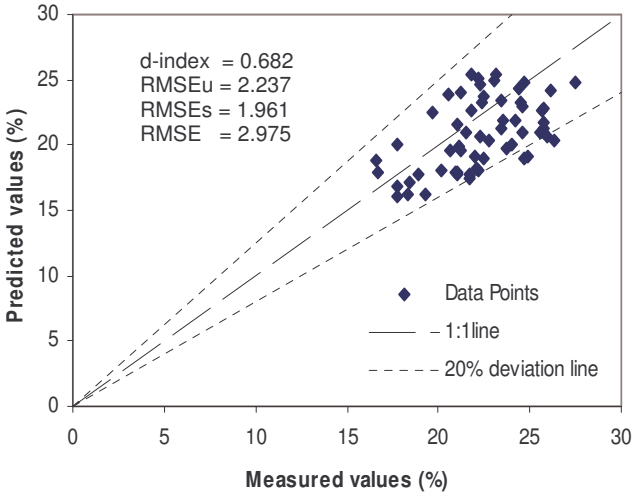


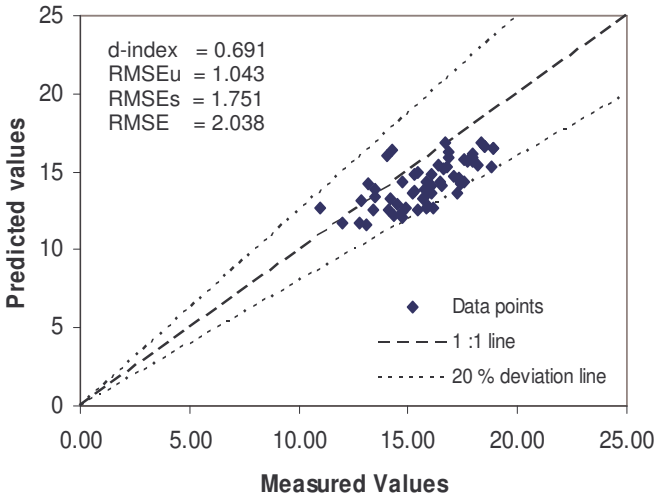
Figure 5.7 Relationships between volumetric soil water content and EM measurements taken in the vertical and horizontal coil orientation for (a) the 0-300 mm soil depth, (b) the 300 – 600 mm, (c) the 600 – 900 mm and (d) the profile (0 - 900 mm).

(a)



(b)





(c)

Figure 5.8 Statistical results on model performance to soil water content from EM38 readings using an independent data set: (a) reflects on the model used for the 0-300 mm soil depth, (b) on the 600-900 mm and (c) on the profile (0 - 900 mm depth).

Another unique advantage of the EM38 is that it can cover large areas when mobilised, 50 – 100 ha day^{-1} depending on the uniformity of the terrain, at a fraction of the cost and time required from specialised soil water sensors. This research confirmed the statement made by Corwin (2006) that electromagnetic induction methods can be used to determine water content of the soil.

5.3.4 Spatial distribution of soil wetness in crop field

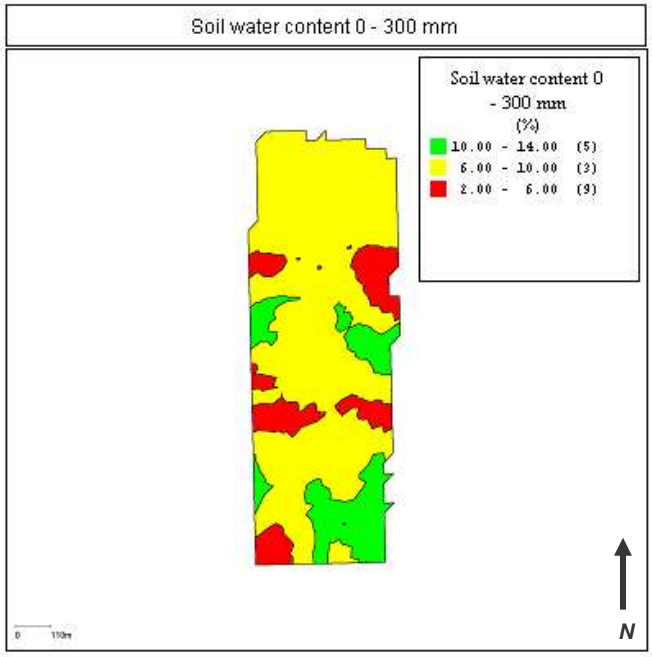
The models in Figure 5.8 were used to delineate maps of the spatial distribution of the volumetric soil water content for the 0 – 300 mm, 300 – 600 mm, 600 – 900 mm layers and the profile obtained with the mobilized EM38.

These maps were divided into soil water content management zones depicted in Figure 5.9. For example Figure 5.9a illustrates three soil water zones in the top layer (0 – 300 mm), showing that the field is generally dry, *viz*. 13% of the top soil is very dry (2 to 6% soil water content), 72% of the field is dry (6 - 10% soil water content) and only 15% is slightly wet (10 - 14% soil water content). This is typical for winter fallow periods when the evaporation is about 0.5 mm day^{-1} for long periods without rain (*Bennie et al.,* 1994).

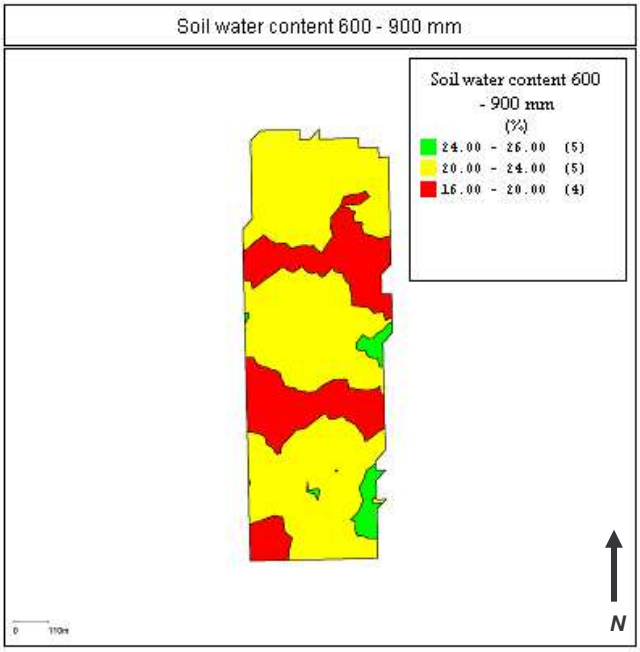
From the water content zones of the 600 – 900 mm soil layer (Figure 5.9b) it can be deducted that the deep soil is generally wet; water contents rages from 24 to 26% (wet) over 3% of the field; 20 – 24% soil water content (moderately wet) over 70% of the field; 16 - 20% soil water content (slightly wet) over 27% of the field.

The EM38 also provides an integrated water content over the total soil depth (Figure 5.9c) and according to the results two soil water zones evolved, showing that there is ample room for soil water storage in the profile and over the field; 74% of the field have soil water levels between 10 and 15% and a small fraction of the field (16%) can be regarded as truly wet (15 – 20%).

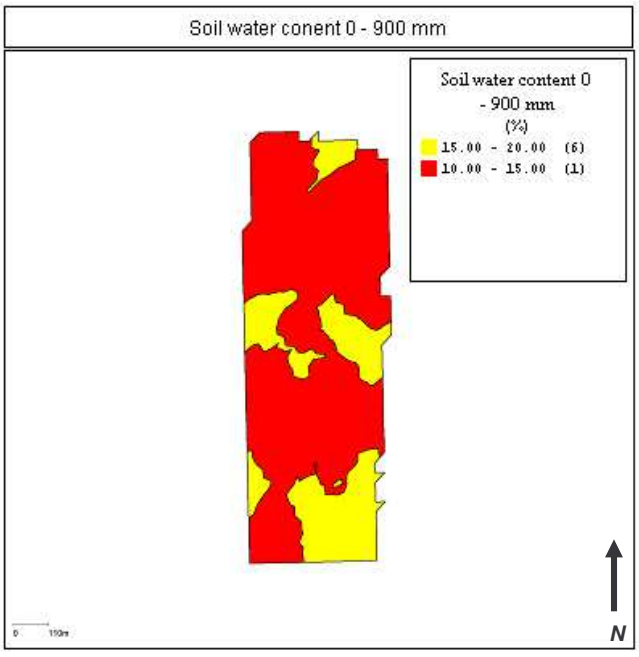
From the procedures followed and the statistical results it is evident that the EM38 could be used to predict the volumetric soil water content of the topsoil, subsoil and total profile of commercial fields located in the CA22 land types. This is ascribed to the ability of the instrument to measure the EC every 2 – 5 cm, while it is towed behind a quad bike at a speed of approximately 5 km h^{-1}. The spatial position of each measurement was obtained by a GPS



(a)



(b)



(c)

Figure 5.9 Soil water content management zones of (a) the 0 – 300 mm horizon, (b) 600 – 900 mm horizon and (c) the average soil water content of 900 mm profile.

system mounted on the bike. This makes the prediction of volumetric soil water content economical viable. Moreover, information obtained from the maps can be applied to improve management skills in dry land crop farming and assist better interpretation of yield maps of crops (Corwin & Lesch 2005a, Friedman 2005).

The research has most significant implications for the commercialization of the IRWH technique and other crop production systems. For example, Botha *et. al* (2003) estimated the effect of five pre-plant soil water levels on the long-term production risks of maize under IRWH, viz full or 100% of PAWC, 75% of PAWC, 50% of PAWC, 25% of PAWC and near zero% of PAWC. Thus, measuring water content under dry land conditions can reduce production risks significantly. The EM38 technology provides also additional information of soil water content over the entire crop field, affording the opportunity to make more informed decisions on: where to plant, when to plant, what seeding rates to apply and at what rate to apply fertilizers.

Furthermore, Newton and Williams (2006) raised the concern that the available water in the profile plays a vital role in identifying management zones, and is a major factor restricting the development of precision agricultural technology in semi-arid environments. They are, moreover, of the opinion that the interpretation of yield maps may be improved by a better understanding of water movement and its relationship to rainfall intensity (Newton & Williams, 2006).

Currently, such innovations are absent on commercial scale in South Africa and the instruments in use are too expensive and too laborious for measuring volumetric water content of large fields.

The EM38 technology provides also additional information of soil water content over the entire crop field, affording the opportunity to make more informed decisions on: where to plant, when to plant, what seeding rates to apply and at what rate fertilizers should be used.

Spatial water content information on crop lands can also contributes towards decreasing risks for financial institution rendering services to crop farmers in semi-arid zones. Some

crop insurance companies already demand spatial soil water maps from farmers before insurance is granted (J van den Berg, personal communication, 2008).

5.4 Conclusion

The experiment was conducted on a commercial crop field (55 ha) located on Paradys Experimental Farm of the University of the Free State located south of Bloemfontein. The aim of this study was to identify the ability of electromagnetic induction readings taken at high density by the mobile EM 38 to be converted into spatial distribution of profile available water capacity and soil wetness. This study has important implications for commercialising the IRWH technique and other crop productions systems.

From the study it can be concluded that reliable *in situ* correlations between measured EC values and spatial distribution of soil wetness were found for the topsoil, subsoil and deep subsoil. Furthermore, clay plus silt management zones were linked to soil depth, giving rise to PAWC maps. The study also indicated that determining soil water content under dry land agriculture can reduce risks significantly and aid with the decision making process.

The mobile EM38 towed behind a quad bike provides also additional information of soil water content over the entire crop field georefrenced with a GPS fitted to the device. This technology affords the opportunity for making more informed decisions on: where to plant, when to plant, what seeding rates to apply and at what rate to apply fertilizers according to the spatial variation in soil wetness and PAWC.

This type of data is of great significance for the Precision Agriculture sector of South Africa owing to the fact that identifying management zones is a major factor restricting the development of precision agriculture technology in semi-arid environments. A Better understanding and interpretation of yield maps could also lead to better delineated management zones.

Chapter 6

Infiltration-runoff relations under in-field rainwater harvesting as affected by rainfall intensity and soil physical properties

6.1 Introduction

Maximising water storage in the root zone is of primary importance in selecting water conservation tillage practices for crop production in semi-arid zones. In the past considerable research effort has been directed towards procedures that improve infiltration.

Based on long term tillage experiments on mainly sandy soils in the Free State Province of South Africa, Bennie *et al*. (1994) recommended ploughing and frequent loosening of the soil (conventional tillage) as the best management practice for improving infiltration during the fallow period. Conventional tillage practices are, however, generally widely criticised owing to the way in which they degrade both the physical and biological properties of soils. For example, Kosgei (2009) showed over a wide range of soils in the Potshini catchment (Limpopo Province, South Africa) that in comparison to no-till the advantage of having a high steady-state infiltration rate and hydraulic conductivity induced by mouldboard ox-drawn ploughing was only temporary. White (1987), furthermore, explained that the shearing forces generated by cultivation implements, rupture both macro and micro aggregates, which weakens the soil structure. Moreover, the finer material produced by slaking and dispersion during the aggregate breakdown may block pores and decrease infiltration rates. Furthermore, low infiltration rates could also contribute to surface sealing as a result of physical disintegration of soil structure and the compaction caused by raindrop impact (Agassi *et al,* 1985). Therefore, on conventionally tilled fields, low infiltration rates will eventually lead to a high percentage of runoff and low soil water storage (Bronick & Lal, 2005).

The IRWH crop production technique proposed by Hensley *et al*. (2000) makes use of the advantages of low infiltration rates and no-till on duplex and clay soils in semi arid areas to optimise water storage in the root zone. Rainwater harvesting systems (Oweis *et al.,* 1999) as well as the IRWH technique characteristically have a catchment (runoff strip) and a collection (run-on) strip. In the case of Hensley *et al*. (2000) the IRWH system indicated as a two-meter wide runoff strip and one meter wide run-on strip in Figure 1, respectively.

Runoff is induced on the runoff strips by creating and maintaining a flat, bare, uncultivated (no-till) surface, thereby promoting maximum crust formation and a low infiltration rate (Figure 6.1). The run-on strip is constructed on the contour with a basin plough and users are encouraged to mulch the basin area as a conservation measure.

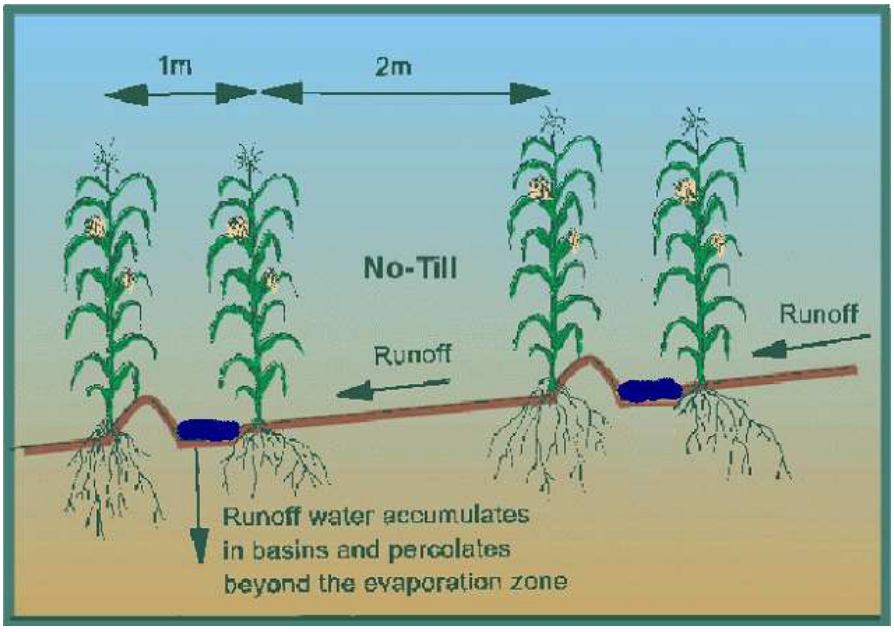


Figure 6.1 A diagrammatic layout of the IRWH-technique, showing the runoff area (catchment) and runoff area (collection area) modified as micro basins (Botha, 2007).

Crop performance under IRWH has been thoroughly tested on-station at the Glen Agricultural Institute regarding yield and rain water productivity (RWP). Both these indicators increased dramatically (30 – 50%) in comparison to conventional tillage

(Botha *et al*., 2004; Van Rensburg *et al.,* 2003; Botha, 2007). The benefit of IRWH has also been demonstrated by the Glen ARC – ISCW research team in some of the communities in the Thaba Nchu district (Botha *et al*., 2004). Within three years approximately a thousand households have modified and adopted IRWH in their gardens and backyards to combat food insecurity at household level (Kundhlande *et al.,* 2004).

Although IRWH is regarded as a simple, but sound tillage method, the hydraulic processes that drive crop performance and rain water productivity are not yet fully understood. Additional studies are needed for commercial application of the technique.

The partitioning of rain into infiltration and runoff on runoff strips, and the subsequent storage thereof in both the runoff and run-on strips is complex. It is influenced, amongst other factors, by climatic and soil physical properties. Climatic factors of importance are the amount, duration and intensity of the storms (Tyson, 1986) while soil physical properties related to infiltrability depend on the initial wetness and matrics forces, texture, structure and layering of horizons of soils (Hillel, 2004).

It is difficult to study these factors under natural conditions in the short term owing to the erratic nature of rainfall in semi-arid zones and the high costs involved in the setting up and maintaining of instruments in small scale farming environments. Mobile rainfall simulators, such as those described by Bennie *et al.* (1994), however, provide the means for studying infiltration-runoff relationships on runoff strips of the IRWH system under highly controlled conditions. Rainstorm characteristics such as the duration, intensity and total rainfall can be controlled under simulator conditions and therefore set as treatments.

The objectives of this study were to characterize rainfall-runoff relationships under IRWH as influenced by rain intensity and soil physical properties.

6.2 Materials and methods

6.2.1 Experimental approach and treatments

Infiltration is a dynamic process that includes water application in the form of rain, its entry, transmission and storage in the soil. Although it is always better to study a natural phenomenon, such as infiltration under *in situ* conditions, it is not always possible. A rainstorm that develops over a commercial field may vary spatially regarding its duration, intensity and amount (Tyson, 1986). In order to simulate these factors a mobile rainfall simulator was used to establish three rain intensities, *viz*. 33, 59 and 122 mm h^{-1}. The duration of the simulated rainstorms was in all cases 90 minutes, resulting in a total application of 49.5, 88.5 and 183 mm, respectively.

These treatments were employed on nine of the 75 plots of an IRWH crop field located on the Experimental Farm of the University of the Free State. Treatments were not replicated. The nine plots were selected to represent the larger area on the basis of the clay + silt contents (%) of their 0 – 300 mm layer, *viz.* 33% (plot 8.1), 23% (plot 8.3), 24% (plot 8.4), 25% (plot 9.2), 30% (plot 10.2), 19% (plot 11.3), 41% (plot 13.3), 30% (plot 13.4), 35% (plot 14.1).

Bennie *et al.* (1994) suggested that clay content is one of the major soil properties that affects infiltration. Furthermore, Fraenkel (2009) found that clay content of the A-horizon was correlated strongly to most of the soil physical properties (organic carbon content; modulus of rupture; bulk density; various water stable aggregate sizes; soil depth) on the particular field. These soil physical properties of the A horizons of the nine selected plots were determined and correlated against various infiltration parameters.

The selection of the nine plots for this study was based on the clay content of the 0 – 300 mm layer. The hypothesis was that this property would correlate strongly with the other soil physical properties, which eventually control the infiltration rate, transmission and storage of rainwater in the soil and runoff.

6.2.2 Description of the HoFrey rain simulator

Rain intensities were simulated with the HoFrey rainfall simulator of the Department of Soil, Crop and Climate Sciences, UFS (Figure 6.2). The design of the simulator was based on the oscillating overhead sprinkler type described by Meyer and Harmon (1979) and Claassens and Van der Watt (1993). According to Bennie *et al.* (1994) this design produces a reasonable distribution pattern of raindrop sizes under field conditions. The system comprises of a mobile and height-adjustable sprinkler chamber, a 1 m X 1 m confined runoff frame, a pressure adjustable pump unit and a tri-osmosis apparatus coupled to a 2500 litre tank mounted on a trailer. The rainfall simulator fits on a trailer which can be towed by a vehicle.

Figure 6.2 The HoFrey rainfall simulator, comprising of the sprinkler chamber, pressure adjustable pump unit, tri-osmoses filter and tank mounted on the trailer. The runoff-frame and gutter were installed under the spraying chamber that was levelled on two wheel tracts.

The rain simulator was towed to the experimental site where the target area was randomly selected on the runoff strips of the selected IRWH-plots. The 1 m^2 runoff plot was prepared by forcing the frame to a depth of 100 mm into the soil and installing the gutter and container to collect runoff. Next the sprinkler chamber was brought into position and the desired rainstorm intensity applied. Runoff was measured every 5 minutes throughout the simulation period and the infiltration rate was calculated from the difference between the application rate and the runoff rate while the application rate was measured with a rain gauge installed at the surface of the runoff plot. The quality of the filtered water was tested before the application and the electrical conductivity was never higher than 20 mS m^{-1}. The rainfall simulations started the 2 September 2007 and terminated on the 9 September 2007.

6.2.3 Infiltration indicators

Four indicators were used to study the infiltration process on the selected plots, *viz*. time to runoff (TR, min), time to reach the final infiltration rate (TFI, min) and final infiltration rate (FI, mm h^{-1}). With the exception of TR, all the other indicators were obtained from the observed infiltration-runoff graphs as illustrated in Figure 6.3. TFI was identified as the point where the infiltration started to be near constant (steady state). FI represents the mean infiltration rates between TFI and the end of the storm while RSI represents the rainstorm intensity and TR was observed as the point in time when the first runoff water reached the collection can.

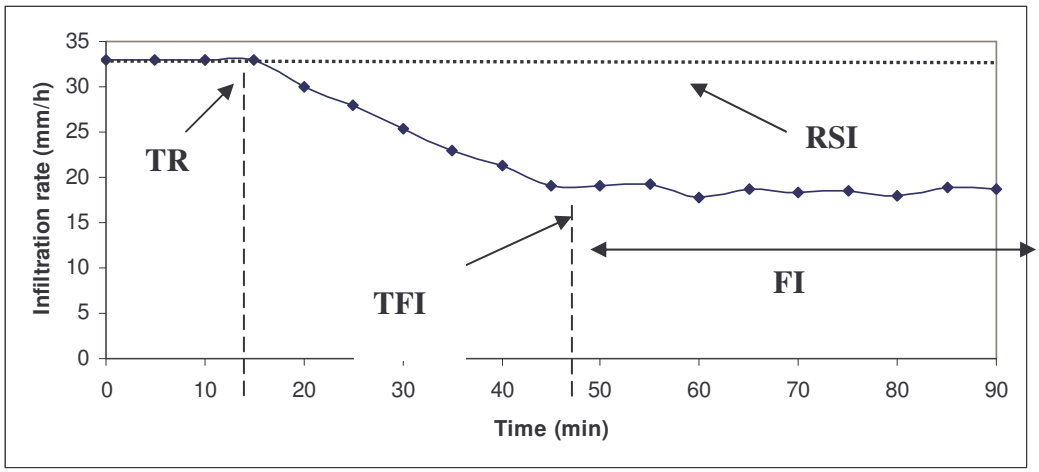


Figure 6.3 An example of an idealised infiltration-runoff graph obtained during the infiltration tests on the runoff strips of the IRWH tillage practice, where TR = time to runoff, TFI = time to final infiltration, RSI = rainstorm intensity and FI= the final infiltration rate.

6.2.4 Soil physical measurements

6.2.4.1 Slope

The slope of the runoff areas was measured in triplicate and the mean taken with a simple handmade elevation device, illustrated in Figure 6.4. The device consists of a 5 m transparent U tube, fixed on two measuring sticks approximately 2 m long with the base of the U tube lying on the ground. The tube was filled with coloured water to make the menisci visible. A two-step procedure was followed during all measurements. First, the two measuring sticks were placed at a randomly chosen point in an up-slope plant row, and the height of the menisci recorded. Next one of the measuring sticks was moved down slope to the next plant row at the lower end of the runoff strip and menisci levels were again recorded. A 2 m long rope was attached to the bottom of the measuring sticks to ensure a constant horizontal distance between them. Before every measurement, the tube was inspected for air bubbles and, if present they were removed. Furthermore, the slope was calculated as a percentage (Y) as follows: Y = ((reading upslope (cm) – reading down slope (cm)) / 200) x 100.

Figure 6.4 Handmade elevation measuring device, used to measure the slope of the runoff strips over a fix distance of two meters.

6.2.4.2 Surface roughness

The surface roughness index was determined in triplicate on the runoff strips with a 100 peg-board method (Zobeck & Onstad, 1987). The method uses pegs (100 mm long x 25 mm diameter), evenly spaced on an 800 mm x 800 mm board, *viz* 10 x 10 holes with 60 mm intervals between rows and pegs (Figure 6.5). The diameter of the holes in the board needs to be slightly greater than the diameter of the pegs so that it can move up and down freely..

Figure 6.5 Handmade surface roughness measuring device, used to measure the roughness index of the 75 plots.

The board was placed randomly on the soil surface. Next the vertical distance (in mm) to the soil surface was calculated as (100 - peg length) above the board while the mean value was taken as the roughness index of the surface. Measurements were taken in triplicate, and showed that the lower the mean value, the smoother the surface roughness.

6.2.4.3 Organic matter content

A composite soil sample was taken from the 0 – 300 mm soil layer of the runoff strips and the LECO method was used to analyse the Organic C (Wang & Anderson, 1998). These values were then expressed as organic matter content (%).

6.2.4.4 Particle size distribution analyzes

Seven particle size fractions were determined with the pipette method as described by the Non – Affiliated Soil Analysis Work Committee (1990). The textural fractions were coarse sand (2 – 0.5 mm), medium sand (0.5 - 0.25 mm), fine sand (0.25 – 0.106 mm), very fine sand (0.106 – 0.05 mm), coarse silt (0.05 – 0.02 mm), fine silt (0.02 – 0.002 mm) and clay (< 0.002 mm).

6.2.4.5 Aggregate stability

Approximately 1 kg topsoil from the runoff strips was sampled with a spade and the soil samples carefully transferred to a drying room (30 – 35°C).

After having dried for a week the samples were prepared for the wet sieving procedure described by Kemper & Rosenau (1986) using a series of four sieves with mesh sizes of 4 mm, 2 mm, 1 mm and 0.5 mm. During the procedure the simulator oscillated at a frequency of 36 cycle's min^{-1} at 10 min per sample.

The water stable aggregates were expressed as a percentage of the total weight of the original dried samples.

6.2.4.6 Mechanical resistance of the soil surface

The mechanical resistance of the soil surface on the runoff strips was determined with a hand-held penetrometer. Five measurements were taken per plot and the mean calculated for statistical analysis.

6.2.5 Statistical analysis

The infiltration data, as affected by the simulated rain intensity treatments, measured on the nine plots was subjected to analysis of variance (ANOVA) using NCSS 2000 (Hintze, 2000) while the LSD Tuckey (LSD_{TK}) test was performed to compare treatment means at P = 0.05.

Owing to experimental constraints it was not possible to determine the effect of the soil physical properties on infiltration as a sole factor, therefore, the combined effect of rainfall intensity and physical parameters were characterised, using multiple regression techniques. Soil physical properties, too, were ranked by means of a correlation matrix (r) analysis using the NCSS 2000 package of Hintze (2000).

6.3 Results and discussion

6.3.1 Status of soil physical properties and their interaction

The Ap-horizon originates from eolian deposits, mixed with clayey soil derived from underlying parent material such as sandstone, mudstone and dolerite. These parent materials deliver high activity clays, which have a large surface area, high cation exchange capacity, high charge density and expandability that can promote interaction between soil physical properties. The statistical results that provide more information on the variation and interaction amongst the soil physical properties are presented in Tables 6.1 and 6.3. The organic matter content varied between 0.3% and 0.5%, which is regarded as low, but typical, for topsoils in semi-arid climatic zones. It can be assumed that four decades of ploughing, discing and other secondary tillage actions on this field have caused rapid deterioration of the organic matter (Simon *et al.,* 2009).

Unlike organic matter, textural properties (clay content) are permanent soil characteristics. The clay content varied between 16% and 33% with a mean of 23.4%. Clay and organic matter provide the primary mechanism for the aggregation of soil particles, and hence for soil structure development (Soane, 1990; Dinel *et al.,* 1997; Dimoyiannis *et al.,* 1998; Schulten & Leinweber, 2000; Chenu *et al.,* 2000). Aggregates normally relate positively to cementing agents such as clay or clay plus silt, organic matter, Fe and Al oxides and flocculants such as Ca (Oades & Waters, 1991; Dalal & Bridge, 1996). In this study however no strong relationship between aggregators such as clay ($r = -0.05$), clay plus silt ($r = -0.08$) and organic matter ($r = 0.28$) existed.

For this study the surface storage capacity was characterised prior to the infiltration experiment, showing that the roughness index varied between 10.4 mm and 16.8 mm. The mean roughness index of 13.4 mm is considerably lower than that of a freshly cultivated runoff strip (25.5 mm) and proved that rain events had smoothed the surface since the preparation of the field.

All the water stable aggregate fractions showed a low percentage of water stable aggregates (< 4%) confirming the natural ability to of the soils to disperse under the force of the raindrops to form a hard surface crust.

The strength of the crust at the time of the experiment was characterised with a hand held penetrometer. The statistical results indicated that the crust was not strong at the time and varied between 0.2 Mpa and 0.6 Mpa, which correlated poorly with organic matter content ($r = 0.12$), slightly with clay content ($r = 0.21$) and strongly with clay plus silt content ($r = 0.66$). According to Panuska *et al*. (2008) it is known that crusting can influence infiltration-runoff relationships.

Table 6.1 Statistical results describing the variability of measurements over the nine experimental plots used

Soil physical property / parameter	Min	Max	Mean	CV
Clay (%)	16.0	33.0	23.4	22.2
Coarse sand (%)	0.6	1.3	0.8	26.7
Medium sand (%)	2.5	5.2	3.5	29.2
Fine sand (%)	41.3	68.1	52.5	13.9
Very fine sand (%)	6.8	14.5	9.8	25.9
Total sand (%)	59.8	80.8	66.8	9.8
Coarse silt (%)	1.0	3.0	1.7	42.4
Fine silt (%)	2.0	6.0	3.8	39.2
Organic matter content (%)	0.3	0.5	0.4	19.4
Penetrometer resistance (MPa)	0.2	0.6	0.4	29.7
Aggregate stability > 4 mm	0.9	3.5	2.1	44.4
Aggregate stability 2-4 mm	1.3	3.1	2.0	29.6
Aggregate stability 1-2 mm	0.2	2.4	0.8	86.3
Aggregate stability < 0.5 mm	0.3	0.8	0.5	32.5
Roughness index (mm)	10.4	16.8	13.4	15.3
Soil slope (%)	0.1	0.8	0.4	55.7

6.3.2 Relation of infiltration to rain intensity and soil physical properties

The mean infiltration rates of the soil in response to the low (33 mm h^{-1}), medium (59 mm h^{-1}) and high (122 mm h^{-1}) rain intensity are depicted in Figure 6.6. The LSD_{TK}-values plotted suggest that the infiltration process was influenced significantly by rain intensity treatments and the magnitude differ during the development of the storms.

In order to describe the effect in detail, four indicators were used, *viz*. the time to runoff (TR), time to final infiltration rate (TFI) and final infiltration rates (FI). The statistical results of the indicators are summarized in Table 6.1 and the interaction with the soil physical properties are summarised in Table 6.4.

Table 6.2 Mean infiltration measurements for the low, medium and high RSI. Statistical significance (P<0.05) between the results with different RSI is indicated by differences in superscript symbols a, b and c in the rows.

Infiltration indicator	Rainstorm intensity			
	Low	Medium	High	Mean
Time to runoff (min)	11.1[a]	6.1[b]	5.6 [b]	7.5
Time to final infiltration (min)	63.3[a]	51.1[ab]	38.8[b]	51.1
Final infiltration rate (mm h^{-1})	19.1[a]	21.8 [a]	34.5[b]	25.1

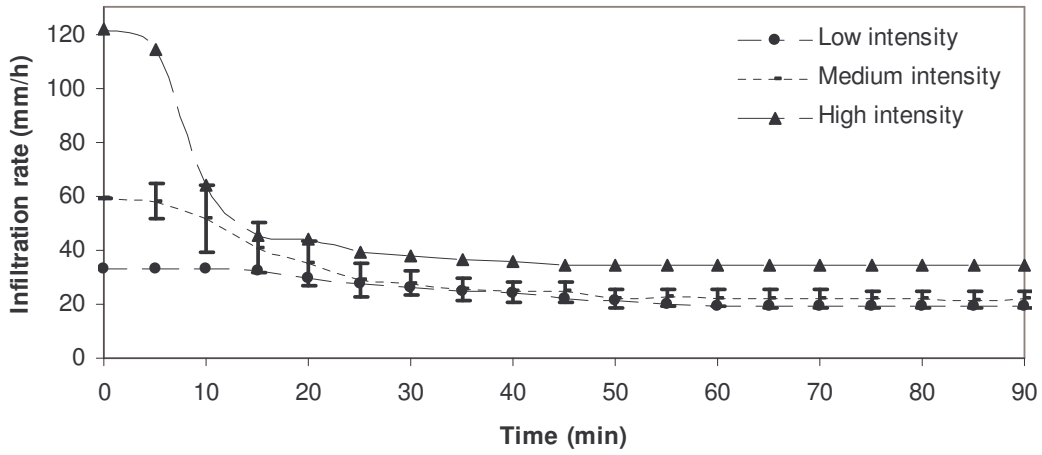


Figure 6.6 Effect of different simulated RSI treatments on infiltration rates of the runoff strips of the IRWH system. Bars indicate $LSD_{(TK)(0.05)}$.

Time to runoff: Theoretically, the time to runoff depends on factors such as the size of the micro depressions created by the presence of clods or aggregates (surface capacity), the permeability of the crust, strength of the surface peds and rain intensity. The relative importance of these factors was indirectly determined by relating roughness index (RNI, mm), organic matter content (OMC, %), clay + silt content (C+S, %) and rain intensity (RI, mm h^{-1}) to TR using multiple regression techniques (Equation 6.1). The

coefficient of determinations indicated that RI is by far the most important determinant of TR. Rain intensities explained 80 % of total variation measured over the nine plots and the soil physical properties collectively improved the prediction by a further 16%.

This was surprisingly, especially in the light of the TR varying between 5 and 20 minutes in the low rain intensity treatment, between 5 and 10 minutes in the medium rain intensity treatment and between 5 and 10 minutes in the high rain intensity treatment. It is clear that the TR was significantly shorter in the medium and high RI treatments in comparison with the low RI. Anderson (2007) also reported that the time to runoff decreases with an increase in rain intensity. The obvious explanation is that the higher rain intensities led to faster filling and over topping of the micro depressions. The presence of a relative strong and positive relationship between the physical properties (OMC, R^2= 0.42; C+S, R^2= 0.36; RNI, R^2= 0.27) and TR confirmed the general principle that the rougher the surface of the soil and the more stable the clods are, the longer it will take before runoff starts, hence the larger TR values.

Correlations between the physical properties and TR in the high intensity treatment are considerably lower than at the lower RI, confirming the secondary role of these properties in maintaining their surface structure under the disruptive force of high rainfall intensities. Dispersion of the aggregates occurred readily as indicated by the low percentage of water stable aggregates in Table 6.1.

$$TR = 7.8352 - 0.0523\ (RI) + 21.03\ (OMC) + 0.0383\ (RNI) - 0.171\ (C+S)\ (R^2 = 0.86) \quad (6.1)$$

Despite the occurrence of earlier runoff on the high RI treatment, significantly more water infiltrated during the TR period in comparison to the low and medium RSI treatments. The mean cumulative infiltration (I) over the TR period amounted to 6.1, 5.9 and 11.4 mm in the low medium and high intensity treatments, respectively. This can be attributed towards faster rate of ponding in the micro depressions, which probably created an additional hydraulic head and higher infiltration rate.

Time to final infiltration rate: From the graphs in Figure 6.6 it is clear that the infiltration process changed drastically after the end of the TR phase. Rain intensities exceed the infiltrability of the soil in all the RI treatments and runoff increased as the soil became increasingly wet until it reached steady state conditions. This is a clear indication that the infiltration process is supply controlled in all treatments. The mean TFI for the low, medium and high intensity treatments amounted to 63, 51 and 39 minutes, with high intensity treatment significantly lower than the low intensity treatment (Table 6.2).

The medium TFI did not differ significantly from the other treatments. Bennie *et al*. (1994) also stated that the TFI increased with a decrease in IR for four soil types in the Free State Province in South Africa.

The large variation in the TFI values over the nine plots, *i.e*. a time span difference of between 50 and 75 minutes before the first and last plot reached the TFI in the low RI treatment, between 35 and 75 minutes in the medium RI and between 20 and 40 minutes in the high RI (Table 6.2), confirmed that the soil physical properties have some influence on the infiltration process of this phase. To quantify the effect, TFI was related to both RI and soil physical properties through multiple regression fittings.

From the properties listed in Table 6.4, roughness index, organic matter content and clay plus silt content explained most of the variation in TFI, although collectively only accounted for 12% of the total variation in Equation 6.2:

$$TFI = 57.75 - 0.259\,(RI) - 32.325\,(OMC) + 2.346\,(RNI) - 0.256\,(C+S)\ (R^2 = 0.92) \quad (6.2)$$

As in the case of TR, RI explains by far the largest portion of the total variation (80%). The lack of strong relationships between the soil physical properties and TFI resulting from various RI treatments (Table 6.4), confirmed the secondary role of the soil physical properties in controlling the infiltration process.

All the treatments showed a negative relationship between TFI and clay plus silt, which increased progressively, while the negative relationship strengthened as rain intensity

increased. This relationship demonstrates that once the cohesive and adhesive forces that hold particles together have been overcome by the destructive force of raindrop energy, dispersion dominates.

Dispersion increases as the clay and silt content increases and this process intensifies with an increase in rain intensity. The stronger the structure of the soil, the better it can resist the destructive force of the raindrops thereby creating a greater potential for maintaining the surface storage capacity.

Shorter TFI-values will result in lower infiltration rates and hence less infiltration and more runoff. During the TFI the mean cumulative infiltration amounted to 11, 15 and 27 mm for the low, medium and high RI treatments, respectively.

Final infiltration rate (FI): Considering the variation observed in FI as indicated by the statistical parameters in Table 6.2, FI varied between 16.2 and 22.9 mm h^{-1} in the low rain intensity treatment, between 18.7 and 25.8 mm h^{-1} in the medium rain intensity treatment and between 30.7 and 41.4 mm h^{-1} in the high rain intensity treatment, it can be deduced that the soil physical properties had affected the FI. However, the multiple regression correlation of FI with both RI and selected soil physical properties (OMC, RNI and penetrometer resistance abbreviated as PR and express in MPa) suggest that rain intensity is by far the most important factor that controls the final infiltration rate (R^2= 0.86). Collectively, the R^2 increased slightly by 4% when the physical properties were included in the correlations. The final equation is:

$$FI = 21.91 + 0.176\ (RI) + 0.266\ (OMC) - 0.504\ (RNI) - 6.56\ (PR)\ (R^2 = 0.88) \qquad (6.3)$$

The correlation statistics in Table 6.4 confirmed the secondary role of the soil physical properties, while the low percentage of water stable aggregates (Table 6.1) confirmed the unstable nature of the surface peds upon wetting, causing it to disperse naturally. However, the energy of the raindrops had kept the particles loose preventing them from forming a dense crust.

For a crust to become an effective hydraulic barrier, it needs to be baked for a considerable length of time under high temperatures (Morin *et al.,* 1981), giving the Fe and Mn oxides enough time to chemically cement the crust. In this experiment the crust was not yet hardened, as indicated by the penetrometer resistance in Table 6.1, therefore raindrops continued to disrupt the formation of a dense crust.

Under these conditions the final infiltration actually increased with an increase in intensity of the storm. The LSD values in Figure 6.6 indicate that the FI of the high RI was significantly higher than the other two RI treatments. Bennie *et al.* (1994), Morin & Benyamini (1977) and Armand *et al.* (2008) showed that the degree of surface sealing decreased with an increase in the application rate.

Table 6.3 Correlation matrix (r) that describe the interaction between the selected soil physical properties

	Clay	CS	MS	FS	VFS	TS	C silt	F silt	OM	PR	AS 1	AS 2	AS 3	AS 4	RI	SS	C+S
Clay	1	-0.27	-0.19	-0.52	0.04	-0.61	0.45	0.83	0.21	0.27	0.27	-0.15	0.84	0.49	-0.05	0.04	0.99
CS	-0.27	1	-0.44	-0.52	0.65	-0.36	0.01	-0.42	0.28	0.47	-0.37	-0.07	-0.36	-0.02	-0.52	0.24	-0.29
MS	-0.19	-0.44	1	0.75	-0.65	0.73	0.20	-0.02	0.29	-0.56	0.33	-0.05	-0.07	-0.25	0.24	0.26	-0.13
FS	-0.52	-0.52	0.75	1	-0.66	0.96	-0.38	-0.29	-0.28	-0.56	0.08	-0.04	-0.31	-0.51	-0.15	0.15	-0.50
VFS	0.04	0.65	-0.65	-0.66	1	-0.43	-0.21	-0.40	0.01	0.39	-0.19	0.02	-0.10	0.19	-0.43	0.19	-0.08
TS	0.61	0.36	0.73	0.96	-0.43	1	-0.48	-0.49	-0.25	-0.47	0.05	-0.04	0.41	-0.54	0.60	0.29	-0.62
C silt	0.45	0.01	0.20	-0.38	-0.21	-0.48	1	0.52	0.59	-0.16	0.11	-0.10	0.34	0.22	-0.26	-0.18	0.56
F silt	0.83	-0.42	-0.02	-0.29	-0.40	-0.49	0.52	1	0.29	0.02	0.22	-0.14	0.65	0.32	0.17	-0.16	0.90
OM	0.21	0.28	0.29	-0.28	0.01	-0.25	0.59	0.29	1	0.12	0.46	0.27	-0.10	0.37	-0.28	-0.05	0.28
PR	0.27	0.47	-0.56	-0.56	0.39	-0.47	-0.16	0.02	0.12	1	-0.40	-0.39	0.03	-0.06	-0.14	0.39	0.66
AS 1	0.27	-0.37	0.33	0.08	-0.19	0.05	0.11	0.22	0.46	-0.40	1	0.77	0.19	0.76	0.12	-0.36	0.26
As 2	-0.15	-0.07	-0.05	-0.04	0.02	-0.04	-0.10	-0.14	0.27	-0.39	0.77	1	-0.25	0.69	0.36	-0.71	-0.15
As 3	0.84	-0.36	-0.07	-0.31	-0.10	0.41	0.34	0.65	-0.10	0.03	0.19	-0.25	1	0.44	0.46	0.19	0.82
As 4	0.49	-0.02	-0.25	-0.51	0.19	-0.54	0.22	0.32	0.37	-0.06	0.76	0.69	0.44	1	-0.19	-0.40	0.47
RI	-0.05	-0.52	0.24	-0.15	-0.43	0.60	-0.26	0.17	-0.28	-0.14	0.36	0.46	-0.19	0.47	1	-0.20	-0.08
SS	0.04	0.24	0.26	0.15	0.19	0.29	-0.18	-0.16	-0.05	0.39	-0.36	-0.71	0.19	-0.40	-0.20	1	-0.02
(C+S)	0.99	-0.29	-0.13	-0.50	-0.08	-0.62	0.56	0.90	0.28	0.66	0.26	-0.15	0.82	0.47	-0.08	-0.02	1

Coarse sand (%) = CS; Medium sand (%) = MS; Fine sand (%) = FS; Very fine sand (%) = VFS; Total sand (%) = TS; Coarse silt (%) = C silt; Fine silt (%) = F silt; Organic matter (%) = OM; Penotrometer resistance (Mpa) = PR; Aggregate stability > 4mm = AS 1; Aggregate stability 2-4 mm = AS 2; Aggregate stability 1-2 mm = AS 3; Aggregate stability < 0.5 mm = AS 4; Roughness index = RI; Soil slope (%) = SS; Clay plus silt (%) = C+S

Table 6.4 Coefficients of determination (R^2) values obtained from linear regression between soil physical measurements and infiltration indicators at various rainfall intensity treatments

Parameter	Time to runoff			Time final infiltration			Final infiltration rate		
Intensity	**Low**	**Meduim**	**High**	**Low**	**Meduim**	**High**	**Low**	**Meduim**	**High**
Organic matter content (%)	0.42	0.18	-0.06	0.25	0.17	0.82	-0.21	0.16	-0.08
Coarse sand (%)	0.19	-0.01	-0.04	-0.01	0.02	0.00	-0.01	0.00	0.03
Medium sand (%)	0.11	0.77	0.02	0.00	0.01	-0.08	0.11	0.19	-0.02
Fine sand (%)	0.00	-0.37	0.08	0.01	-0.03	0.03	0.18	0.04	0.03
Very fine sand (%)	0.01	0.39	0.01	0.00	0.01	0.09	-0.01	-0.18	-0.03
Total sand (%) (%)	0.00	0.32	0.15	0.02	-0.02	0.07	0.24	0.02	0.01
Coarse silt (%)	-0.09	0.27	-0.13	-0.05	0.13	-0.31	-0.06	0.10	-0.30
Fine silt (%)	-0.05	-0.01	-0.04	-0.09	-0.01	-0.29	-0.18	0.06	0.00
Clay (%)	-0.10	-0.10	-0.06	-0.13	-0.05	-0.07	-0.02	0.09	-0.02
Clay + silt (%)	0.36	0.34	-0.14	-0.13	-0.32	-0.51	-0.05	0.10	-0.02
Penetrometer resistance(MPa)	0.02	0.31	0.21	-0.03	0.01	0.00	-0.30	-0.05	-0.24
Aggregate stability >4 mm	0.00	0.13	-0.11	0.14	0.01	0.26	0.01	0.00	0.02
Aggregate stability 2-4 mm	0.00	0.02	0.20	0.24	0.02	0.11	-0.01	-0.11	0.05
Aggregate stability 1-2 mm	-0.10	-0.03	-0.03	-0.01	-0.03	0.00	0.05	0.28	0.00
Aggregate stability<0.5 mm	0.00	-0.01	0.24	0.15	0.03	-0.16	-0.01	0.00	0.03
Roughness index (mm)	0.27	-0.02	0.03	0.29	0.47	-0.04	-0.07	-0.34	-0.20
Soil slope (%)	0.08	0.01	0.20	-0.26	-0.01	0.07	0.13	0.17	0.01

6.3.3 Importance of infiltration-runoff partitioning for IRWH

The results demonstrated the vulnerability of these duplex soils to rain intensity under conventional tillage where the soil is exposed to the impact of rain intensity during the fallow period or where the plants have a leaf area index less than one during the growing season. The main reason for this phenomenon is probably because the soil surface structure that relates to the surface storage capacity is easily destroyed by the impact of raindrop energy. The organic matter in the soil was generally too low to prevent intense dispersion of soil particles and the crust that normally follows after dispersion. Crusting is regarded by conventional tillage practitioners as a negative phenomenon. They manage the impact by breaking the crusts with secondary tillage activities. The downside is that the more often the soil is tilled the easier the crust will reform owing to the loss of organic matter associated with frequent tillage in semi-arid environments (Smith & Elliott, 1990).

The formation of a crust at the surface of the runoff strips in the IRWH system is perceived as a positive phenomenon that should be harnessed and managed accordingly. No-till practices are therefore recommended on the 2 m wide runoff strip so that the crust can induce runoff.

The simulated runoff and infiltration on the runoff strips resulted in 14 mm and 35.5 mm; 46 mm and 42.5 mm; 119 mm and 64 mm; on the low, medium and high rain intensity treatments, respectively (Table 6.5). Thus, for a field under IRWH, it can be estimated that a total of 77.5 mm, 180.5 mm and 421 mm of water will infiltrate in the 1 m wide basin strips (I_{bs}), respectively [$I_{bs} = P + (2xR)$]. From this the infiltration ratio between the basin strips and the runoff strips (I_{bs}:I_{rs}) can be calculated.

The results show that the ratio increases with an increase in storm intensity, which implies that for every 1 mm rain that infiltrates in the runoff strip, 2.2 mm, 4.3 mm and 6.6 mm will infiltrate in the basin strips under the low medium and high rain intensity storms, respectively. Botha *et al.* (2003) reported ratios that varied between 2.7 and 2.8 for the fallow periods of the three year maize-sunflower crop cycle under IRWH. The ratio of the high intensity storm seems exceptionally high, but it represents an extreme case, which probably would occur once in 100 years. However, more water in the basin means better availability to the crop and greater rainwater productivity (Botha, 2007).

Table 6.5 Partitioning of infiltration and runoff during the different simulated rainfall intensity storms

Intensity of the storm (mm h^{-1})	Total rain of storm (mm)	Time of storm (min)	Runoff (mm)	Infiltration in the Runoff area (I_{rs}) (mm)	Infiltration in basin area (I_{bs}) (mm)	I_{bs}:I_{rs}
33	49.5	90	14	35.5	77.5	2.18
59	88.5	90	46	42.5	180.5	4.25
122	183	90	119	64	421	6.58

6.4 Conclusion

Rain intensity treatments created with the mobile rainfall simulator (HoFrey) in a commercial field under in-field rainwater harvesting, located on the experimental farm of the University of the Orange Free State's near Bloemfontein, provided valuable information on the infiltration-runoff process that drives water harvesting on pseudo duplex soils. It was proved that rainfall intensity affected the infiltration parameters, such as time to runoff, time to final infiltration and final infiltration rate significantly. The correlation matrix and multiple regression statistics confirmed the dominance of rain intensity over the soil physical properties in controlling the infiltration process. The main reason is attributed to the dispersive nature of the soils when subjected to the energy of the raindrop induced by the simulated rainstorms.

The surface structure expressed by soil physical properties, such as the roughness index, clay plus silt content, organic matter, various aggregate sizes, was easily destroyed with an increase in rain intensity. This had influenced the time to runoff and time to final infiltration negatively with respect to infiltration, but on the other hand increased the final infiltration rates.

Other researchers found similar trends and they too attributed the higher infiltration rates to the phenomenon that high intensity raindrops disrupt the crust and the final infiltration actually increases with an increase in rain intensity beyond a certain threshold value which was shown here to be greater than 60 mm h^{-1}.

It was possible to characterise the interaction between rainfall intensity and soil physical parameters in relation to the infiltration parameters by multiple regression equations. There is a strong possibility that these equations could be used in future research for infiltration and hence water harvesting from the runoff strips in the in-field rain water harvesting system. The final infiltration rates obtained in this experiment correlated 90% with the intensity of the storm and soil surface characteristics such as the roughness index, organic matter content and penerometer resistance of the crust

From the results that describe the general relationship between infiltration in the basin strips and that of the runoff strips, it can be concluded that the pseudo duplex soils have great potential for in-field rainwater harvesting. Very high infiltration ratios were obtained, which indicated that for every 1 mm of rain than infiltrating in the runoff strip, between 2.2 mm and 4.9 mm would infiltrate in the basin strips. The upper value seems highly unlikely, seeing that Botha *et al.* (2003) reported ratios that varied between 2.7 and 2.8 for the fallow periods of the three year maize-sunflower crop cycle under IRWH on clay soils located on the experimental farm of Glen Agricultural Institute, north of Bloemfontein. However, more water in the basin should improve the rainwater productivity, because water is stored in greater amounts closer to the roots.

Chapter 7

Summary and recommendations

7.1 Summary

The study stems from needs express by communal farmers from the Thaba Nchu district (about 60 km east of Bloemfontein) who wanted to apply the in-field rainwater harvesting (IRWH) on their crop lands. A tillage workshop was held at Merino villages in November 2003 and various implements were demonstrated. Although they appreciated the opportunity to learn more about soil tillage, they were dissatisfied with the inability of the implements to simulate the physical surface structure of their hand-made IRWH-plots. Thus, the intention of the first part of the study was to developed tractor drawn implements to create the desired IRWH surface structure and to mechanized the IRWH technique for large scale production of crops (up to 150 ha fields).

The second part of the study concerns the estimation of variation in soil properties that relates to soil water storage, *viz* texture, soil depth and soil water content. In the final section of the study the focus shifts to the influence of rainfall intensity and soil physical properties, and its relation to water storage through in-field runoff.

To realize the first goal tractor drawn implements were designed, built and tested to replicate the soil surface structure of IRWH.

Tests indicated that two implements were required for reproducing the structure, viz. the ridge and puddle ploughs. The ridge plough was designed as a primary tillage tool, making a ridge along a contour, which serves as a wall for the basin strip. The puddle plough was designed as a secondary tillage tool, making micro-basins on the up-slope side of the ridge for controlling lateral runoff. These implements were used to cultivate more than a 100 ha of maize under IRWH at Paradys Experimental Farm of the University of the Free State, south of Bloemfontein. As part of the mechanization

planning, the soils and climate were analysed regarding its potential for harvesting and storing runoff. Cumulative probability function showed that the Paradys-Tukulu/Sepane ecotope is suitable for IRWH, which direct the research to fully mechanise IRWH.

A procedure was developed for land preparation which entails a detail topographical map to divide the field into terraces and how to plan and construct the guide-ridges and micro-basins. The width of runoff strips depends on traffic control of the secondary tillage operation, which includes planting, weeding, pest control and harvesting. Two runoff strips (width 2.3 m and 2 m) were tested for accommodating the tillage operations associated with silage and maize grain production, respectively.

Both mechanization systems worked well. The capacity and strength of basins were thoroughly tested during the first two months after the basins were constructed. It rained about 250 mm, mainly in the form of high intensity storms. Observations showed that the micro-basins assisted in controlling lateral runoff and directly contributed to uniform storage of rain over the entire field. Results revealed moreover that there is a high potential for breaking the basins if the slope of the ridge-wall deviates from the targeted zero gradient contour line, especially in or near old gullies. However, runoff water never gathered momentum to cause basin-walls to break over a series of runoff strips. It was clear that the technique stopped runoff from the field and hence water erosion.

Late and excessive rain delayed planting and affected yield. Maize yields of up to 4 500 kg ha^{-1} were harvested where the crop had been planted in the first week of January, indicating that small scale farmers can apply IRWH on their crop fields.

Spatial distribution of soil physical properties related to soil water storage, *viz*. clay plus silt content and soil water contents, are of vital importance for managing water availability in semi-arid zones, especially on clay soils.

Electromagnetic induction (EMI) technology, such as the EM38, measures the electrical conductivity of soils and when calibrated it can make a significant contribution towards improving our understanding of the spatial distribution of the properties soil.

Several researchers have shown the cost-benefit advantage of using these instruments as an alternative to conventional grid sampling and spatial analysis of salinity in crop lands. Despite this obvious advantage the instruments are not widely used in South

Africa. This has opened the opportunity to explore the ability of the EM38 to measure soil properties such as clay and soil wetness, in order to characterise these properties spatially in the crop field.

A 55 ha crop field under IRWH at Paradys Experimental Farm was used to conduct the experiment. On 2 Julie 2007 the EM38 was drawn in a sled behind a quad bike at a speed of approximately 5 km h^{-1} on every second runoff strip of the IRWH system (*i.e.* 6 m strips), in the horizontal (EM_h) and vertical (EM_v) coil orientation.

The instrument measures apparent soil electrical conductivity in millisiemens per meter (mS m^{-1}) every 20 cm as it is drawn over the field. All measurements were geo-referenced and the data processed with Surfer software package. A detail soil survey was conducted on the 55 ha crop field using a mobile hydraulic auger. Samples were divided into 300 mm intervals and a soil particle analysis was made using the standard pipette method. Seventy five neutron excess tubes were inserted on a grid basis over the field and volumetric water content was measured in 300 mm intervals up to a depth of 900 mm.

There was no apparent visual relationship between soil forms and EC classes derived from the vertical or horizontal coil orientation EM readings. Significant relationships between EC measurements and clay plus silt content were obtained, which made it possible to estimate the spatial distribution thereof. This relationship was furthermore used to estimate the profile available water capacity and its distribution over the crop field. Unlike in most of the soil layers, a good relationship (R^2 = 0.7) between EM readings and soil water content for the profile was obtained. This made it possible to estimate soil wetness from the recorded EM readings over the entire field. Information like this is highly significant for the small scale farmer in the former homelands, especially in the semi-arid areas where many of the management decisions are based on soil wetness and PAWC. This technology affords the opportunity for improving management decisions on: where to plant, when to plant, what seeding rates to be used, what fertilizer rates?

Realizing the final goal of the dissertation a better understanding of how rainfall characteristics and soil physical properties influence the partitioning of rain into infiltration and runoff in the IRWH system.

It is difficult to study these factors in natural conditions in the short term, owing to the erratic nature of rainfall in semi-arid zones. To solve this problem a mobile rainfall simulator was used to simulate rainstorms of three different intensities, viz. low (33 mm h^{-1}), medium (59 mm h^{-1}) and high (122 mm h^{-1}) on nine of the 75 plots of the experiment. Plots were selected on the basis of their clay plus silt content in the 0 – 300 mm soil layer to represent the full variation in textural classes.

Results obtained from the experiment demonstrated the importance of the influence of rain intensity on the infiltration parameters, such as time to runoff, time to final infiltration rate and final infiltration rate. The influence was shown to be significant statistically. The phenomenon was attributed to the destructive nature of the raindrops and the inherent dispersive nature of the soil upon wetting. The correlation matrix and multiple regression statistics make it possible to characterise the interaction between rainfall intensity and soil physical properties for predicting various infiltration parameters. From the infiltration-runoff relations it was clear that the soils exhibit a high potential for harvesting water as required by the IRWH system.

It can be concluded that the study had realized its main goals and thereby providing a basis for farmers, especially small scale farmers, to apply the technique on their crop fields.

7.2 Recommendations

7.2.1 Extentionist

The development and testing of implements for the commercialization of the IRWH technique has the advantage that practices and processes were stipulated regarding factors and events that should be taken into consideration for the commercialization of the IRWH on commercial scale by communal farmers (Chapter 3). The process and steps needed for implementation of the technique and for identifying soils suitable for the commercialization of the technique is explained step by step.

The mobile EM38 provides scientific information for encouraging farmers to apply the EM38 on commercial scale in order to support soil surveys and to identify textural based management zones for precision agriculture (Chapter 4).

The research also demonstrated that now it is possible to measure the spatial distribution of soil water content indirectly with the EM38 (Chapter 5). This kind of information could help farmers to improve their decisions on when to plant, where to plant, what plant population and fertilizer rates to apply. For the communal farmer who depends solely on his/her 0.5 - 5 ha plot for survival the technologies developed can assist in evaluating his/her fields, because every square cm counts.

The information obtained from studying the infiltration-runoff relations on clay soils indicated that soil physical properties of soils plays an insignificant role regarding factors influencing the infiltration- runoff relationships of soils. The rainstorm intensity however, is the biggest factor influencing the runoff-infiltration relationships on clay soils. The variation in rainstorm intensity is the main contributor towards the variation in infiltration runoff relationships.

The importance of the infiltration-runoff relationships for the IRWH technique is that it assists in gaining better information. In high intensity rainstorm events dispersion of the structure occur on conventional fields leading to crusting that is regarded as detrimental in conventional tillage practices. In the study the organic matter content of the soils was too low to prevent the formation of crust. Under the IRWH system crusting is regarded as beneficial for soils. Furthermore, the data collected can be used for determining infiltration ratios between basin and runoff strips and indicates the infiltration ratio increases with an increase in storm intensity.

7.2.2 Researchers

7.2.2.1 Mechanization of the IRWH technique.

The mechanization of the IRWH technique holds the key to the revitalization of communal crop lands. What is required is that the tractor drawn implements should be tested in different soil and climate conditions (ecotopes) and adapted accordingly. The ARC at Glen Agricultural Institute is currently testing the implements in three provinces.

Furthermore, an in depth study on the socio-economic constrains and challenges on the out scaling of IRWH is urgently required.

7.2.2.2 Mobile EM38

The research on the ability of the EM38 to estimate soil physical, chemical and biological properties is in its initial stage and requires much more attention before it can be applied to different soil and climate conditions. It is envisaged that this type of research will change the landscape of precision agriculture in semi-arid zones. Precision agriculture is driven forwards mainly by input based service providers such as fertilizer, seed and chemical companies. Water, however, is the main driver of crop production in semi-arid conditions hence the spatial distribution of soil water and the related soil factors need special research attention. Accurate estimation of the spatial dimensions of these factors has the advantage of reducing inputs costs based on available water and the potential production.

7.2.2.3 Infiltration runoff relations

The best practice for studying infiltration-runoff relationships on ecotypes is *in situ*, but the equipment is expensive, the maintenance cost is high and research capacity cannot always be maintained over the period normally required to obtain long term data. The rainfall simulator makes it possible to simulate rainstorm events and could reduce most of the above-mentioned factors. Mobile rainfall simulators, such as the HoFrey used in this study, can be used to obtain valuable information for determining the potential water that can be harvested from the runoff strips. This work should be extended to other ecotopes.

References

AGASSI, M., MORIN, J. & SHAINBERG, I., 1985. Effects of raindrop impact energy and water salanity on infiltration rates in sodic soils. *Soil Sci. Soc. Am. J*. 49, 187 – 190.

AG LEADER, 2009. SMS Basic. http://www.agleader.com, 15 January, 2009.

ANDERSON, J.J., 2007. Rainfall-runoff relationships and yield responses of maize and dry beans on the Glen-Bonheim ecotope using conventional tillage and in-field rainwater harvesting. Ph.D. thesis, University of the UFS, Bloemfontein.

ARMAND, R., BOCKSTALLER, C., AUZET, A.V. & VAN DIJK, P., 2008. Runoff generation related to intra field soil surface characteristics variability: Application to conservation tillage context. *Soil & Tillage Res*. Article in press.

AUERBACH, R., 2003. Rainwater harvesting. A literature survey. Rainman Landcare Foundation PO Box 2349. Hillcrest 3650.

AUERNHAMMER, H., DEMMEL, M. & SPANGLER, A., 2000. Automatic process-data acquisition with GPS and LBS. *In*: Abstracts of AgEng, Warwick 2000. Agricultural Engineering into the Third Millennium. Paper number 00-IT-005, pp 1–21.

BAKHSH, A., JAYNES, D.B., COLVIN, T.S., KANWAR, R.S., 2000. Spatio-temporal analysis of yield variability for a corn-soybean field in Iowa. *Trans. ASEAE* 43, 31-38.

BELLUIGI, A., 1948. Coupling of a vertical coil with a homogeneous earth. *Geophysics* 14, 501 – 507.

BENNIE, A.T.P., 1995. Sound water management concepts and their application at farm level. *In* : ATP Bennie (ed.). pp 287-294 Proc. S. Afr. Irrig. Symp. Durban.

BENNIE, A.T.P & BURGER, R. DU T., 1981. Root characteristics of different crops as affected by mechanical resistance in fine sandy soils. Proc of the 10th NationalCongress of the SSSSA Tech. Comm. No. 180, Dept of Agriculture and Fisheries, Pretoria.

BENNIE, A.T.P., COETZEE, M.J., VAN ANTWERPEN, R., VAN RENSBURG, L.D. & BURGER, R. DU T., 1988. ‘n Waterbalansmodel vir besproeiing gebaseer op profielwatervoorsieningstempo en gewaswaterbehoeftes. WRC report no. 144/1/88. Water Research Commission, Pretoria.

BENNIE, A.T.P. & HENSLEY, M., 2001. Maximizing precipitation utilization in dry land agriculture in South Africa – a review. *J. Hydrology*. 241, 124-139.

BENNIE, A.T.P., HOFMANN, J.E., COETZEE, M.J. & VREY, H.S., 1994. Opgaring en benutting van reënwater in grond vir die stabilisering van plantproduksie in halfdroë gebeide. WRC report no. 227/1/94. Water Research Commission, Pretoria.

BENNIE, A.T.P. & KRYNAUW, G.N., 1985. Causes, adverse effects and control of soil compaction. *S. Afr. J. Plant Soil*. 2, 109 – 114.

BENNIE, A.T.P., STRYDOM, M.G. & VREY, H.S., 1998. The use of computer models or agricultural water management on ecotope level [Afr]. Water Research Commission, Report no. TT 102/98, Pretoria.

BENNIE, A.T.P. & VAN ANTWERPEN, R., 1988. An evaluation of emperical root growth models to describe root distribution in compacted soils. *In*: Proc. 11th Congress of I.S.T.R.O., Edinburgh, Scotland.

BOEDT, L.J.J. & LAKER, M.C., 1985. The development of profile available water capacity models. WRC, Report no. 98/1/85. Water Research Commission, Pretoria.

BOTHA, J.J., 2007. Evaluation of maize and sunflower production in semi arid area using in field rainwater harvesting Ph.D. thesis University of the UFS, Bloemfontein.

BOTHA, J.J. & VAN RNSBURG, L.D., 2004. Water harvesting to promote food security and employment. Land Care report to the National Department of the Agriculture, Pretoria.

BOTHA, J.J., VAN RENSBURG, L.D., ANDERSON, J.J., HENSLEY, M., MACHELI, M.S., VAN STADEN, P.P., KUNDHLANDE, G., GROENEWALD, D.G. & BAIPHETHI, M.N., 2003. Water conservation techniques on small plots in semi arid areas to enhance rainfall use efficiency, food security, and sustainable crop production. WRC report no. 1176/1/03. Water Research Commission, Pretoria.

BOWLING, S.D., SCHULTE, D.D. & WOLDT, W.E., 1997. A geophysical and geostatistical methodology for evaluating potential subsurface contamination from feedlot runoff retention ponds. ASAE Paper No. 972087, 1997 ASAE Winter Meetings, December 1997, Chicago, IL ASAE, St. Joseph, MI, USA.

BRONICK, C.J. & LAL, R., 2005. Soil structure and management a review. *Geoderma.* 124, 3-22.

BRUNE, D.E., DRAPCHO, C.M., RADCLIFF, D.E., HARTER, T. & ZHANG, R., 1999. Electromagnetic survey to rapidly assess water quality in agricultural watersheds. ASAE Paper No. 992176, ASAE, St. Joseph, MI, USA.

CALLOT, G., CHAMAYOU, H., MAERTENS, C. & SALSAC, L., 1982. A better understanding of soil – roots interactions. Effects on mineral nutrition. *Soil Sci. Soc. Am. J.* 20, 1235 – 1242.

CARTER, L.M., RHOADES, J.D. & CHESSON, J.H., 1993. Mechanization of soil salinity assessment for mapping. *In:* ASAE Winter Meetings, 12 – 17 December. Chicago, IL. ASAE, St. Joseph, MI, USA (ASAE Paper No. 931557).

CARR, P.M., CARLSON, G.R., JACOBSEN, J.S., NIELSEN, G.A. & SKOGLEY, E.O., 1991. Spatial variability of soil properties. *J. Prod. Agric.* 4, 57-88.

CHENU, C., LE BISSONNAIS, Y. & ARROUYAS, D., 2000. Organic matter influence on clay wetability and soil aggregate stability. *Soil Sci. Soc. Am. J.* 64, 1479 – 1486.

CHITTLEBOROUGH, D.J., 1992. Formation and pedology of duplex soils. Australian *Journal of Experimental Agriculture.* 32(7) 815 – 825.

CHITTLEBOROUGH, D.J. & OADES, J.M., 1979. The development of a red-brown earth. I. A reinterpretation of published data. *Australian Journal of Soil Research* 17(3) 371 – 381.

CLAASSENS, A.S. & VAN DER WATT, H.v.H., 1993. An inexpensive, portable rain simulator: Construction and test data. *S. Afr. J. Plant Soil.* 10, 6-11.

CORWIN, D.L., 2006. Delineating site specific crop management units: Precision agriculture applications in GIS. www.ars.usda.gov/research/publications.htm?SEQ-NO-115=181958.

CORWIN, D.L. & LESCH, S.M., 2003. Application of soil electrical conductivity to precision agriculture: theory, principles, and guidelines. *Agron. J.* 95, 455-471.

CORWIN, D.L. & LESCH, S.M., 2005(a). Characterizing soil spatial variability with apparent soil electrical conductivity Part I Survey Protocols. *Computers and Electronics in Agriculture.* 46, 103-133.

CORWIN, D.L. & LESCH, S.M., 2005(b). Characterizing soil spatial variability with apparent soil electrical conductivity Part II Case Study. *Computers and Electronics in Agriculture.* 46, 135-152.

CORWIN, D.L. & LESCH, S.M., 2005(c). Apparent soil electrical conductivity measurements in agriculture. *Computers and Electronics in Agriculture.* 46, 11-43.

CORWIN, D.L., LESCH, S.M., OSTER, J.D. & KAFFKA, S.R., 2006. Monitoring management-induced spatio-temporal changes in soil quality through soil sampling directed by apparent electrical conductivity. *Geoderma*. 131, 369 – 387.

DALAL, R.C. & BRIDGE, B.J., 1996. Aggregation and organic matter storage in sub-humid and semi arid soils. *In:* Carter, M.R., Stewart, B.A. (Eds.), Structure and Organic matter storage in agricultural soils. pp: 263 – 307CRC Press, Boca Raton, FL.

DE JONG, E., BALLANTYNE, A.K., CAMERON, D.R. & REED, D.W.L., 1979. Measurement of apparent electircal conductivity of soils by an electromagnetic induction probe to aid salinity surveys. *Soil Sci. Am. J*. 43, 810 – 812.

DIMOYIANNIS, D.G., TSADILAS, C.D. & VALMIS, S., 1998. Factors affecting aggregate instability of Greek agricultural soils. Commun. *Soil Sci. Plant Anal*. 29, 1239 – 1251.

DINEL, H., RIGHI, D., HARDY, M. & JAMBU, P., 1997. Neutral lipids and structural stability of physical degraded soils. *Agrochimica.* 41, 97 – 108.

DORIAS, M., CARON, J., BEGIN, G., GOSSELIN, A., GAUDREAU, L. & MENARD, C., 2005. Equipment performance for determining water needs of tomato plants grown in sawdust based medium and rockwool. *Acta Hort*. 691, 293 – 304.

DU PLESSIS, M.C.F. & MOSTERT, J.W.C., 1965. Runoff and soil loss at the Agricultural Research Centre at Glen. [Afr]. *S. Afr. J. Agric. Sci*. 8, 1051-1060.

DU TOIT, M.E., DU PREEZ, C.C., HENSLEY. M. & BENNIE, A.T.P., 1994. Effek van bewerking op die organiese materiaalinhoud van geselekteerde droëlandgronde in Suid-Afrika. *S. Afr. J. Plant. Soil.* 11, 71 – 80.

FAO, 2007. Statistics www.fao.org 15 January 2007.

FARAHANI, H.J. & BUCHLEITER, G.W., 2004. Temporal stability of soil electrical conductivity in irrigated sandy fields in Colorado. *Trans. ASEAE* 47, 79 - 90.

FARES, A. & POLOYAKOV, V., 2006. Advances in crop water management using capacitive water sensors. *Adv. Agron*. 90, 43 – 77.

FARKAS, C.S., RISTOLAINEN, A. & ALAKUKKU, L., 2006. Simulation modeling of soil water regime of a heavy clay soil in Southern Finland. http://ica.ipan.lubln.pl/abstracts/farkas. 15 January 2007.

FERRE, P.A. & TOPP, G.C., 2002. The soil solution phase. *In:* J.H. Dane & G.C. Topp (eds.) Methods of soil analysis, Part 4, Physical Methods. SSSA, Madison, USA.

FRAENKEL, C.H., 2009. Spatial variability of selected soil properties in and between map units. M.Sc thesis, University of the UFS.

FRASER, G.C.G., MONDE, N. & VAN AVERBEKE, W., 2003. Food security on South Africa: A case study of rural livelihoods in the Eastern Cape Province. *In*: Lieb Nieuwoudt and Jan Groenewald (eds), The challenge of change: Agriculture, Land and the South African Economy, Pp 171 – 183Pietermaritzburg University of Natal Press.

FRIEDMAN, S. P., 2005. Soil properties influencing apparent electrical conductivity. *Computers and Electronics in Agriculture.* 46, 45-70.

FULTON, J.P., WELLS, L.G., SHEARER, S.A. & BARNHISEL, R.I., 1996. Spatial variation of soil physical proeprties a precursor to precision tillage. ASAE Paper No. 961002. www.bae.uky.edu/precag/PrecisionAg/Reports/PrecisionTillage.htm 15 January 2007.

GORDON, S., 2005. Assessing temporal stability and spatial variability of soil water patterns with implications for precision water management. *Agricultural Water Management.* 223-243.

GREEN, W.H. & AMPT, G.A., 1911. Studies on soil physics: I. Flow of air and water through soils. *J. Agr. Sci*. 4, 1-24.

GREENHOUSE, J.P. & SLAINE, D.D., 1983. The use of reconnaissance electromagnetic methods to map contaminant migration. *Ground Water Monit. Rev*. 3 (2) 47 – 59.

GREENHOUSE, J.P. & SLAINE D.D., 1986. Geophysical modeling and mapping of contaminated groundwater around three waste disposal sites in southern Ontario. *Can. Geotech.* J. 23, 372 – 384.

HATIBU, N., 2003. The role of modern innovations and technologies in sustainable agriculture for development: Implications for water management approaches and processes. *In* D. Beukes, M de Villiers, S Mkize, H Saaly & L van Rensburg (eds.)

Proceedings of the symposuim and workshop on water conservation technologies for sustainable dry land agriculture in sub-Saharan Africa (WCT), Bloemfontein.

HAYLETT, D.G., 1960. Runoff and soil erosion studies at Pretoria. *S. Afr. J. Agric. Sci*. 3, 379-394.

HENSLEY, M., BOTHA, JJ., ANDERSON, J.J., VAN STADEN, P.P. & DU TOIT, A., 2000. Optimising rainfall use efficiency for developing farmers with limited access to irrigation water. WRC Report 878/1/00, Water Research Commision, Pretoria.

HENSLEY, M., LE ROUX, P.A.L., GUTTER, J. & ZERIZGHY. M.G., 2007. A Procedure for improved soil survey technique for delineating land suitable for Rainwater harvesting. WRC Report no. TT 311/07, Water Research Commission, Pretoria.

HILLEL, D.H.,2004 Enviromental soil physics. Academic Press, New York, USA.

HUDSON, N. W., 1987. Soil and water conservation in semiarid areas. Silsoe Associates Amphill, Bedford, United Kingdom, Food and Agriculture Organization of the United Nations, Rome.

HINTZE, J., 2000. NCSS help system: Multiple regressions. Kaysville, Utah.

IRMAK, A, JONES, J.W., BATCHELOR, W.D. & PAZ, J.O., 2001. Estimating spatially variable soil properties for application of crop models in precision farming. *Trans. ASEAE 44*, 1343-1353.

JAYNES, D.B., 1996. Improved soil mapping using electromagnetic induction surveys. *In:* P.C. Robert, R.H. Rust & W.E. Larson Proceedings of the Third International Conference on precision Agriculture, pp 169 – 179. Minneapolis.

JOHNSON, C.K., DORAN, J.W., DUKE, H.R. & WIENHOLD, B.J., 2001. Field-scale electrical conductivity mapping for delineating soil condition. *Soil Sci. Soc. Am. J*. 65, 1829-1837.

JOHNSON, C.K., ESKRIDGE, K.M. & CORWIN, D.L., 2005. Apparent soil electrical conductivity applications for designing and evaluating field-scale experiments. *Computers and Electronics in Agriculture.* 46, 181-202.

JOHNSTON, M.A., MEYER, J.H., SAVAGE, M.J. & VAN ANTWERPEN, R., 1994. Electromagnetic induction as a technique for diagnosing and mapping soil salinity. *In:* Proceedings of The South Africa Sugar Technologists Association 65-69 .

JOSEPH, L.F., 2007. Maize response to in-field rainwater harvesting on the Fort Hare/Oakleaf ecotope. M.Sc. thesis, University of the Free State, Bloemfontein.

JOUBERT, C 2004. Precision agriculture and variable rate application of fertilizers and lime. Presentation by Geo-Agri Technologies.

KACHANOSKI, R.G., GREGORICH, E. G. & VAN WESENBEECK, I.J., 1988. Estimating spatial variations of soil water content using nonconducting electromagnetic inductive methods. *Can. J. Soil Sci.* 68, 715 – 722.

KEMPER, W.D & ROSENAU, R.C, 1986. Aggregate stability and size distribution. American Society of Agronomy – Soil science Society of America: *In:* Methods of soil analysis, Part 1. Physical and Mineralogical methods. 425-439.

KINGSTON, G., 1985. Electromagnetic inductive instruments for use in surveys of soil salinity, Proc Aust Soc Sug Cane Technol. 1985, 79 – 84.

KOSGEI, J.R., 2009. Rainwater harvesting systems and their influences onfield scale soil hydrology propeties, water fluxes and crop production Ph.D. thesis, University of Natal, Pitermaritzburg.

KUNDHLANDE, G., GROENEWALD, D.G., BAIPHETHI, M.N., VILJOEN, G, BOTHA, J.J., VAN RENSBURG, L.D. & ANDERSON, J.J., 2004. Socio-economic study on water conservation techniques in semi-arid areas. WRC Report no., 1267/1/04, Water Research Commission, Pretoria.

LAND TYPE SURVEY STAFF, 2002. Memoirs on the agricultural natural resources of South Africa, No. 14. Land types of the maps 2828 Kimberley, 2826 Winburg, 2924 Koffiefontein, 2926 Bloemfontein. ARC – ISCW, Pretoria, South Africa.

LIU, J., GOERING, C.E. & TIAN, L., 2001. A Neutral network for setting target corn yields. *Trans. ASEAE* 44, 705-713.

LESCH, S.M., CORWIN, D.L. & ROBINSON, D.A., 2005. Apparent soil electrical conductivity mapping as an agricultural management tool in arid zone soils. *Computers and Electronics in Agriculture.* 46, 351-378.

LOGSDON, S.D., RENEAU, R.B., Jnr & PARKER, J.C., 1987. Corn seedling root growth as influenced by soil physical properties. *J. Agron*. 79, 221 – 224.

MANONA. S. & BAIPHETI, M., 2008. Developing a land register and a set of rules for application of In-field rainwater harvesting in three villages in Thaba Nchu: A pilot project. WRC Report no.,TT367/08, Water research commission, Pretoria

MATI, B.M. & DE LANGE, M., 2003. Emerging practices in water management under rain-fed agriculture in eastern Africa. *In* D. Beukes, M de Villiers, S Mkize, H Saaly & L van Rensburg (eds.) Proceedings of the symposuim and workshop on water conservation technologies for sustainable dry land agriculture in sub-Saharan Africa (WCT), Bloemfontein.

McKENZIE, R.C., CHOMISTEK., W. & CLARK, N.F., 1989. Conversion of electromagnetic inductance readings to saturated paste extract values in soils for different temperature, texture and moisture conditions. *Can. J. Soil Sci*. 69, 25 – 32.

Mc NEIL., 1980 Electromagnetic terrain conductivity measurements at low induction numbers. Tech note TN-6 Geonics Ltd. Mississauga. Ont.

MEYER, L.D. & HARMON, W.C., 1979. Multiple-intensity rainfall simulator for erosion research on row sideslopes. *Trans. ASEAE* 22, 100-103.

MORIN, J. & BENYAMINI, Y., 1977. Rainfall infiltration into bare soils. *Water Resour. Res*. 3, 813-817.

MONDE, N., 2003. Household food security in rural areas of Central Eastern Cape: The case of Guquka in Victoria East and Koloni in Middledrift Districts. Unpublished Ph.D .thesis, University of Fort Hare, Alice.

MORIN, J., BENYAMINI, Y. & MICHAELI, A., 1981. The effect of raindrop impact on the dynamics of soil surface crusting and water movement in the profile. *J of Hydrology.* 52, 321-335.

MUKHALA, E., 1998. Radiation and water utilization efficiency by mono-culture and inter-crop to suit small-scale irrigation farming. Ph.D. thesis University of the Free State, Bloemfontein.

MVSA, FERTILIZER GUIDELINES, 2007. Po Box 75510, Lynwoodrif, 0040 South Africa.

NEWTON, P. & WILLIAMS, B., 2006. Conceptual implications for water use of cereals derived from spatial variability in yield maps. www.nre.vic.gov.au, 15 January 2007.

NOGUEES, J., ROBINSON, D.A. & HERRERO, J., 2006. Incorporating electromagnetic induction methods into regional soil salinity survey of irrigation districts. *Soil Sci. Soc. Am. J.* 70, 2075-2085.

NYQUIST, J.E. & BLAIR, M.S., 1991. Geophysical tracking and data logging system: description and case history. *Geophysics.* 56. (7), 1114 – 1121.

OADES, J.M. & WATERS, A.G., 1991. Aggregate hierarchy in soils. *Aust. J Soil Res.* 29, 815 – 828.

OWEIS, T., HACHUM, A. & KIJNE, J., 1999. Water harvesitng and supplemenatary irigation for imrpoved water use efficiency in dry areas. System-wide initiative on water management (SWIM) paper no.7 International Water Management Institute, Colombo, Sri Lanka.

PANUSKA, J.C., KARTHIKEYAN, K.G. & MILLER, P.S., 2008. Impact of surface roughness and crusting on particle size distribution of edge of field sediments. *Geoderma* 145, 315-324.

PELLERIN, L. & WANNAMAKER, P.E., 2005. Multi-dimensional electromagnetic modeling and inversion with application to near-surface earth investigations. *Computers and Electronics in Agriculture.* 46, 91-102.

PLANT, R.E., MERMER, A., PETTYGROVE, G.S., VAYSSIERES, M.P., YOUNG, J.A., MILLER, R.O., JACKSON, L.F., DENISON, R.F. & PHELPS, K., 1999. Factors underlying grain yield spatial variability in three irrigated wheat fields. *Trans ASAE.* 42, 1187-1202.

RATLIFF, L.F., RITCHIE, J.T. & CASSEL, D.K., 1983. Field-measured limits of soil water availability as related to laboratory-measured properties. *Soil Sci. Soc. Amer. J.* 47, 770 – 775.

RHOADES, J.D. & CORWIN, D.L., 1981. Determining soil electrical conductivity-depth relations using an inductive electromagnetic soil conductivity meter. *Soil Sci. Soc. Am. J.* 49, 822 – 827

RHOADES, J.D., MANTEGHI, N.A., SHOUSE, P.J. & ALVES, W.J., 1989. Soil electrical conductivity and soil salinity: new formulations and calibrations. *Soil Sci. Soc. Am. J.* 53, 433-439.

RHOADES, J.D., RAATS, P.A.C. & PRATHER, R.J., 1976. Effects of liquid-phase electrical conductivity, water content, and surface conductivity on bulk soil electrical conductivity. *Soil Sci. Soc. Am. J.* 40, 651 – 655.

SANDLER, E.J., BUSSCHER, W.J., BAUER, P.J. & KARLEN, D.L., 1998. Spatial scale requirements for precision farming: A case study in the Southeastern *USA. Agron. J.* 90, 191-197.

SANDERS. J.H. & MACMILLAN.D, 2001. Agricultural technology for the semiarid African horn Vol. 1. Regional Synthesis, IGAD/INTOSORMIL/USAID-REDSO. Djibouti.

SCHEPPERS, J.S., 1996. Precision farming: One key to Qulity water. *Fluid Journal, Spring.* 1996 1-3.

SCHULZE, B.R., 1984. Climate of South Africa: *In:* Part 8 General survey, WB 28, South African Weather Bureau ,5th edition, Pretoria

SCHULTEN, H.R. & LEINWEBER, P., 2000. New insights into organic mineral particles: Composition, properties and models of molecular structure. *Biol. Fertil. Soils.* 30, 399 – 432.

SHEETS, K.R. & HENDRICKX, J.M.H., 1995. Noninvasive soil water content measurements using electromagnetic induction. Water Resour. Res. 31, 2401 – 2409.

SIMON, T., JAVUREK, M., MIKANOVA, O. & VACH, M., 2009. The influence of tillage systems on soil organic matter and soil hydrology. *Soil & Tillage Res*. 105, 44 – 48.

SMITH, J.L. & ELLIOTT, L.F., 1990. Tillage and residue management effects on soil organic matter dynamics in semiarid regions. Advances in Soil Sciences, Volume 13.

SOANE, B.D., 1989. The role of organic matter in soil compactibility: A review of some practical aspects. *Soil & Tillage Res*. 16, 179 – 201.

SOIL CLASSIFICATION WORK GROUP., 1991. Soil Classification a taxonomic system for South Africa. Department of Agricultural Development, Pretoria, 1991.

STROOSNIJDER, L., 2003. Technologies for improving rainwater use efficiency in semi-arid Africa, 92-102. *In* D. Beukes, M de Villiers, S Mkize, H Saaly & L van Rensburg (eds.) Proceedings of the symposuim and workshop on water conservation technologies for sustainable dry land agriculture in sub-Saharan Africa (WCT), Bloemfontein.

STEINBERGER, G., ROTHMUND, M. & AUERNHAMMER, H., 2009. Mobile farm equipment as a data source in an agricultural service architecture. *Computers and Electronics in agriculture.* 65, 238-245.

SUDDUTH, K.A., KITCHEN, N.R., WIEBOLD, W.J., BATCHELOR, W.D., BOLLERO, G.A., BULLOCK, D.G., CLAY, D.E., PALM, H.L., PIERCE.F.J., SHULER, R.T. & THELEN, K.D., 2005. Relating apparent electrical conductivity to soil properties across the north-central USA. *Computers and Electronics in Agriculture* 46, 263-283.

SURFER, 2009. www.goldensoftware.com 15 January 2009.

THE NON-AFFILIATED SOIL ANALYSIS WORK COMMITTEE., 1990. Handbook of standard soil testing methods for advisory purposes. SSSSA, Pretoria.

TRIANTAFILIS, J., LESCH, S.M., 2005. Mapping clay content variation using electromagnetic induction techniques. *Computers and Electronics in Agriculture. 46, 203-237.*

TRIANTAFILIS, J., LASLETT, G.M. & Mc BRATNEY, A.B., 2000. Calibrating an Electromagnetic induction instrument to measure salinity in soil under irrigated cotton. *Soil Sci. Soc. Am. J.* 64, 1009 – 1017.

TYSON, P.D., 1986. Climatic change and variability in Southern Africa.

UNITED NATIONS, 2005. The millennium development goals report. United Nations Department of Public Information, New York.

VAN ANTWERPEN, R., 1988. Die evaluasie van verskillende empiriese modelle vir die voorspelling van wortelgroei: M.Sc. Agric. Verhandeling, Universiteit van die Vrystaat, Bloemfontein.

VAN DER MERWE, G.M.E., 2006. The use of water harvesting techniques on vertisols to provide stable crop production on rural farms in the Bafokeng District of the North West Province. Report GW/A/2006/38. Agricultural Research Council – Institute for Soil, Climate and Water, Pretoria

VAN DER WATT, H.v.H & VAN ROOYEN, T.H., 1995. A glossary of soil science. The Soil Science Society of South Africa, Pretoria.

VAN DER WATT, H.v.H. & VALENTIN, I., 1991. Soil crusting: The African view. Proc. Int. Symp. On Soil Crusting, Georgia.

VAN DER WESTHUIZEN, R.J. & VAN RENSBURG, L.D., 2009. Laboratory procedure to calibrate EC – 10 and EC – 20 capacitance sensor in coir. Submitted for publication, 2009.

VAN RENSBURG, L.D., 1988. Die voorspelling van grondgeinduseerde plantwaterstremmning vir geselkteerde grond-plant-atmosfeersisteme. M.Sc. Verhandeling Universiteit van die Vrystaat, Bloemfontein.

VAN RENSBURG, L.D., NHLABATHI, N.N., ANDERSON, J.J., BOTHA, J.J., VAN STADEN, P.P. & KUSCHKE, R., 2003. Modelling evaporation from the soil surface as affected by mulching and soil factors. Final report to OSWU, ARC – ISCW, Pretoria.

VAN RENSBURG, L.D., 2009. Advances in soil physics: Application in irrigation and dry land crop production. Submitted for publication, 2009.

VAN STADEN, P.P., 2000. The effect of runoff-storage relationships on rainwater utiliaztion by maize on clay soils with draught risk. M.Sc thesis, University of the Free State, Bloemfontein.

WAIT, J.R., 1954. Mutual coupling of loops lying on the ground. *Geophysics.* 19, 290 – 296.

WAIT, J.R., 1955. Mutual electromagnetic coupling of loops over a homogeneous ground. *Geophysics.* 20, 630 – 637.

WALKER, S. & TSUBO, M., 2003. Estimation of rainfall intensity for potential crop production on clay soils with in-field water harvesting practices in a semi-arid area., WRC Report no. 1094/1/02 Water Research Commission, Pretoria.

WANG, D. & ANDERSON, W., 1998. Direct measurement of organic carbon content in soils by the LECO CR – 12 carbon analyzer. *Communications in Soil Science and Plant Analysis.* 19, 15 – 21.

WHITE, I. & BROADBRIDGE, P., 1998. Constant rate rainfall infiltration: A versatile nonlinear model. *Water Resour. Res.* 24, 155-162.

WHITE, R.E., 1987. Introduction to the principles and practices of soil Science 12th edition. Blackwell Scientific Oxford, UK.

WILLMOTT, C.J., 1982. Some comments on the evaluation of model performance. *Bulletin Am. Meteorological Soc.* 63, 1309 – 1313.

WOYESSA, Y.E., PRETORUIS, E., VAN HEERDEN, P.S., HENSLEY, M. & VAN RENSBURG, L.D., 2006. Impact of land use on river basin water balance: A case study of the Modder River Basin, South Africa. Colombo, Sri Lanka: Comprehensive Assessment Secretariat 37p. Comprehensive Assessment Research Report 12.

ZHANG, N., MAOHAU, W. & NING, W., 2000. Precision Agriculture – A Worldwide overview. ICETS 2000- Session 6, 112-122.

ZOBECK, T.M. & ONSTAD, C.A., 1987. Tillage and rainfall effects on random roughness : A review. *Soil & Tillage Res*. 9, 1-20.