RAINWATER HARVESTING SYSTEMS AND THEIR INFLUENCES ON FIELD SCALE SOIL HYDRAULIC PROPERTIES, WATER FLUXES AND CROP PRODUCTION

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Submitted in fulfilment of the academic
requirements for the degree of
Doctor of Philosophy

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Pietermaritzburg

March 2009

As the candidate's supervisors we have approved this thesis for submission.

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Prof. S.A. Lorentz

ABSTRACT

South Africa, in common with many parts of Sub-Saharan Africa, is facing increasing water shortages. Limited available water arising from a low and poorly distributed rainfall, must supply domestic, agricultural, industrial and ecosystem needs. Agricultural activities of smallholder farmers, who largely occupy arid to semi-arid areas, are rainfall-driven as they do not have the capacity to develop conventional water sources, such as boreholes and large dams. This situation has led to persistent food shortages, low income and a lack of investments, resulting in high dependency levels of which examples include over reliance on social grants, household crop production that largely relies on external inputs and availability of cheap unskilled labour. A growing global perception that water for agriculture has low value relative to other value uses could further jeopardize the already over exploited agricultural water. Developing economies such as South Africa are likely to favour, in terms of water allocation, e.g. electricity generation through steam turbines relative to irrigation needs because industry plays a more significant role in the economy.

While substantial scientific research has resulted in enhanced yields through in-situ water harvesting and soil and water conservation, as well as crop and soil fertility management and plant breeding, less work has been done to assess the impact of intermittent dry spells on crop yield, particularly with regard to smallholders. Indeed, the interventions that have been promoted to smallholders may provide little buffer against such events. In addition, the increase in yield from many such efforts has been marginal and inconsistent, leading some to conclude that semi-arid environments are hydrologically marginal, have no significant agricultural potential and any attempts to intensify agricultural activities would lead to severe environmental degradation.

This study investigated the rainwater harvesting and storage potential among rainfed farmers in a summer-rainfall region of South Africa. The influences of this practice on soil hydraulic properties, water fluxes and crop production is detailed in subsequent chapters.

Using historical meteorological data, this study commenced with an investigation of the factors that influence the length of maize (*Zea Mays L.*) growing seasons notably the prevalence of early season dry spells and late season low temperature which could be responsible for persistent low maize yields amongst smallholder rainfed farmers (Chapter 2). An increasing trend of dry spells was observed which was found to influence sowing dates and the length of the growing season.

The influence of no-tillage (N_T) as an intervention to secure more root-zone soil moisture was investigated in comparison to conventional tillage (C_T) practices. Field experiments, with the aim of quantifying the extent to which water productivity and yields can be improved among smallholder rainfed farmers in the Potshini catchment, Thukela basin; South Africa (Chapter 8), were conducted during both the dry and growing seasons from 2005/06 – 2007/08 seasons at four sites with similar soil textural properties and slopes. Each site was developed as a runoff plot and was fitted with moisture and runoff measuring devices. Meteorological parameters were measured from a weather station installed nearby. A snapshot electrical resistivity survey was used to compliment soil moisture profiling. The analyses of the different measurements provided information on various water flow paths and potential downstream hydrological effects (Chapter 3). The average cumulative runoff was 7% and 9% of seasonal rainfall in N_T and C_T treatments over the three seasons.

Changes over time in soil hydraulic properties due to tillage were examined at two depths through infiltration tests and determination of their bulk densities. These included changes in steady state infiltration rate and hydraulic conductivity (Chapter 4), interaction between soil infiltration and soil characteristics (Chapter 5) and water conducting porosity and water retention (Chapter 6). In 50% of the sites, N_T treatments showed significantly higher hydraulic conductivity compared to C_T treatments.

In response to an unexploited opportunity identified to produce vegetables in winter, an assessment of the potential for runoff water harvesting systems using polyethylene lining as an alternative cost-effective construction method for underground rainwater storage systems, particularly in areas where groundwater levels fluctuate rapidly was undertaken (Chapter 7). The process from conceptualization through design, construction and utilization of the stored water is described and recommendations for the design and construction of such systems made.

Finally, various case studies which highlight the potential impact of improved soil profile moisture storage, the additional benefits of water stored in tanks and recommendations for tailored policies to support household food and income generation are made (Chapter 8).

DECLARATION 1 - PLAGIARISM

I, ………………………………………. declare that

1. The research reported in this thesis, except where otherwise indicated, is my original research.

2. This thesis has not been submitted for any degree or examination at any other university.

3. This thesis does not contain other persons’ data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons.

4. This thesis does not contain other persons' writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:
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5. This thesis does not contain text, graphics or tables copied and pasted from the Internet, unless specifically acknowledged, and the source being detailed in the thesis and in the References sections.

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DECLARATION 2 - PUBLICATIONS

DETAILS OF CONTRIBUTION TO PUBLICATIONS that form part and/or include research presented in this thesis (include publications in preparation, submitted, in press and published and give details of the contributions of each author to the experimental work and writing of each publication)

Publication 1[a] – Chapter 2 of this thesis

Kosgei, J.R., Jewitt, G.P.W. 2008. Rainfall trends and variability and their influence on sowing dates among smallholder rainfed farmers in the Thukela Basin, South Africa. *Paper in preparation.*

Data collection and analysis for this publication was conducted by Kosgei J.R. with technical advice from Jewitt G.P.W. The publication was written in its entirety by Kosgei J.R. and all figures, data tables and graphs were produced by the same, unless otherwise referenced in the text of the paper. Editing and advice regarding data interpretation was provided by Jewitt G.P.W.

Publication 2[b] – Chapter 3 of this thesis

Kosgei, J.R., Jewitt, G.P.W., Lorentz, S.A. 2008. Field scale exploration of hydrological responses to tillage using hydrometric monitoring and electrical resistivity imaging survey. Paper in preparation.

Field and laboratory experimentation, data collection and analysis for this publication was conducted by Kosgei J.R. with technical advice from Jewitt G.P.W. and Lorentz S.A. The publication was written in its entirety by Kosgei J.R. and all figures, data tables, graphs and photos were produced by the same, unless otherwise referenced in the text of the paper. Lorentz S.A. assisted in the interpretation of GMS calibration functions. Editing and advice regarding data interpretation was provided by Jewitt G.P.W. and Lorentz S.A.

Publication 3[c] – Chapter 4 of this thesis

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[a] In proceedings of the 9th WaterNet/WARFSA/GWP-SA conference; 29th-31st October, 2008. Johannesburg, South Africa.

[b] In proceedings of the 7th WaterNet/WARFSA/GWP-SA conference; 30th Oct-1st Nov, 2006. Lilongwe, Malawi.

[c] In proceedings of the 8th WaterNet/WARFSA/GWP-SA conference; 28th-30th October, 2007. Lusaka, Zambia

Kosgei, J.R., Lorentz, S.A., Jewitt, G.P.W. 2008. Describing the dominant surface and near surface changes in soil hydraulic properties due to tillage. I: Estimation of steady-state infiltration rate and hydraulic conductivity. *Paper in preparation*.

Field and laboratory experimentation, data collection and analysis for this publication was conducted by Kosgei J.R. with technical advice from Lorentz S.A. The publication was written in its entirety by Kosgei J.R. and all figures, data tables and graphs were produced by the same, unless otherwise referenced in the text of the paper. Lorentz S.A. created the original spreadsheet that was used to generate soil hydraulic parameters and also assisted the author in setting up HYDRUS-2D. Editing and advice regarding data interpretation was provided by Lorentz S.A and Jewitt G.P.W.

Publication 4 – Chapter 5 of this thesis

Kosgei, J.R., Lorentz, S.A., Jewitt, G.P.W. 2008. Describing the dominant surface and near surface changes in soil hydraulic properties due to tillage. II: Evaluation of the interactions between soil infiltration and soil characteristics. *Paper in preparation*.

Data analysis for this publication was conducted by Kosgei J.R. with technical advice from Jewitt G.P.W. and Lorentz S.A. The publication was written in its entirety by Kosgei J.R. and all figures, data tables and graphs were produced by the same, unless otherwise referenced in the text of the paper. Editing and advice regarding data interpretation was provided by Lorentz S.A and Jewitt G.P.W.

Publication 5[d] – Chapter 6 of this thesis

Kosgei, J.R., Lorentz, S.A., Jewitt, G.P.W. 2008. Describing the dominant surface and near surface changes in soil hydraulic properties due to tillage. III: Water conducting porosity and water retention. *Paper in preparation*.

Field and laboratory experimentation, data collection and analysis for this publication was conducted by Kosgei J.R. with technical advice from Lorentz S.A. The publication was written in its entirety by Kosgei J.R. and all figures, data tables and graphs were produced by the same, unless otherwise referenced in the text of the paper. Editing and advice regarding data interpretation was provided by Lorentz S.A and Jewitt G.P.W.

Publication 6[e] – Chapter 7 of this thesis

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[d] In proceedings of the 8th WaterNet/WARFSA/GWP-SA conference; 28th-30th October, 2007. Lusaka, Zambia

Kosgei, J.R., Lorentz, S.A., Jewitt, G.P.W. 2008. Structural and agrohydrological appraisal of rainwater harvesting storage tanks in rural areas. *Paper under review – Water SA*.

Laboratory analysis, data collection and analysis, design and construction process outlined in this publication was conducted by Kosgei J.R. with technical advice from Lorentz S.A. and Jewitt G.P.W. The publication was written in its entirety by Kosgei J.R. and all figures, data tables, graphs and photos were produced by the same, unless otherwise referenced in the text of the paper. Editing and advice regarding data interpretation was provided by Lorentz S.A and Jewitt G.P.W.

Publication 7[f] – Chapter 8 of this thesis

Kosgei, J.R., Jewitt, G.P.W. 2008. Food production and household income among smallholder rainfed farmers: do biophysical and policy interventions have a common role in arid and semi-arid lands? *Paper in preparation*.

Field data collection and analysis for this publication was conducted by Kosgei J.R. with technical advice from Jewitt G.P.W. The publication was written in its entirety by Kosgei J.R. and all figures, data tables, graphs and photos were produced by the same, unless otherwise referenced in the text of the paper. Editing and advice regarding data interpretation was provided by Jewitt G.P.W.

Publication 8

Kosgei, J.R., Jewitt, G.P.W., Kongo, V.M., Lorentz, S.A. 2007. The influence of tillage on field scale water fluxes and maize yields in semi-arid environments: A case study of Potshini catchment, South Africa. Physics and Chemistry of the Earth 32, 1117-1126.

Field experimentation was undertaken by the author with the assistance of Kongo V.M. Data collection, laboratory experimentation and data analysis for this publication was conducted by Kosgei J.R. with technical advice from Jewitt G.P.W. and Lorentz S.A. The publication was written in its entirety by Kosgei J.R. and all figures, data tables and graphs were produced by the same, unless otherwise referenced in the text of the paper. Editing and advice regarding data interpretation was provided by Jewitt G.P.W., Kongo V.M. and Lorentz S.A.

Signed:

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[e] In proceedings of the 11th SearNet conference; 11th-13th December, 2007. Lilongwe, Malawi.

[f] In proceedings of the 10th SearNet conference; 6th-10th December, 2006. Mombasa, Kenya.

PREFACE

The experimental work described in this thesis was carried out in the School of Bioresources Engineering & Environmental Hydrology, University of KwaZulu-Natal, Pietermaritzburg, from July 2005 to December 2008, under the supervision of Professor Graham P.W. Jewitt.

These studies represent original work by the author and have not otherwise been submitted in any form for any degree or diploma to any tertiary institution. Where use has been made of the work of others it is duly acknowledged in the text.

ACKNOWLEDGEMENTS

First, glory be to God for His grace was sufficient throughout this study. I would like to sincerely thank the following, in no particular order of contribution, for the different roles they played during the 42 months that this study was undertaken:

Prof. G.W.P. Jewitt and Prof. S.A. Lorentz for supervising and guiding this work to its logical conclusion. Much appreciated is the encouragement you gave me through your constructive criticism and ideas that only people of your caliber posses.

Prof. Jeff Smithers, Head of School for ensuring that all conditions are favourable for such a tough task to be accomplished.

Prof. R.E. Schulze for your fatherly motivation and the interest you had on my wellbeing.

My wife Rose and son Ian for your perseverance in loneliness for years for the sake of this study. Thank you for your steadfast support and sweet words of encouragement in times life was tough. My parents, brothers, sisters and in-laws for your prayers, support and bearing all my responsibilities.

Leboko family group for the support you gave me and my family through prayers, company and companionship.

Mrs Tinisha Chetty for among other things making sure that I settled comfortably when I newly arrived.

Dr. Victor Kongo for laying a solid foundation upon which this work was easily established and for being there until through out.

Michael Four Malinga for your social and technical support that went beyond your terms of reference. Dr. Mudhara for ensuring that tasks in this scientific research are interpreted to the understanding of community members. Nicholas Madondo for being the interface between this research and the Potshini community.

De Winnaar and Jody Sturdy for the complementary work they did in the Potshini catchment.

Technical and support staff of School of Bioresources Engineering & Environmental Hydrology. You all contributed in a special way to this thesis. Just to mention a few, Dr. Senzanje, Cele, Cobus, Sean Thornton-Dibb, Sean Best, Michelle, Horan, Lutchminarain, Swasty and Sabine, thanks so much. Most outstanding are Mrs Kunz and Mrs Moneyvalu.

The IRD visiting scientists (Gaghik, Chaplot, Podwejewski, Janeau and Grellier) for their contribution during fieldwork and data processing.

This work was made possible by the support from field assistants Tenele, Osborne Gwamada and Charmain Mchunu as well as laboratory assistants John Ngeleka and Manqoba Dlamini.

Much gratitude goes to the Potshini community for receiving this research and nurturing it until its time came to an end. Special thanks go to Mduba, Madondo, Hadebe and Mabaso for allowing me to use their fields for experimentation.

GG Mabaso, Mama Cebhekhulu, Dladla, Phakamani, Ncamsile and Ntombi, you made it happen.

Miss Lindiwe Nchingila, staff and learners of the Potshini High School for making learning and research have a commonplace.

The Department of Agriculture, DWAF, WRC and Okhahlamba municipality for the extension support provided.

All postgraduate students at Rabbie Saunders building Subira, Frezghi, Knoesen, Technocrat, Molipa, Tesfaye, Mare, Irene, Mwamburi, Baloyi, Eyob and Celestine for being team players come rain or sunshine.

Many returns to my friends Mrs Makelo, Halima, Annemary, Peris, Nolwandle, Ncho, Nomathamisangqa, Azi, Irene, Khothatso, Peace, Nancy Kipsang and Miriam Sabola for the prayers and continuous words of encouragement that kept me afloat.

Pastor Alvin Antony, his family and the congregation of Hosanna Ministries. Thank you so much for the wonderful fellowship that always gave me hope in this research work. Special thanks to Phumsile and mother Prudence.

The Kenya Community in Pietermaritzburg for the encouragement and for being a family-away-from home. To the families of Njuho, Choge, Mwambi, Mwangi, Venny, Ochuodho, Shisanya and Odhiambo for their invaluable support.

My tennis companions Nelson, Beauty, Sonja and Mercy for making sure that I am weekly refreshed.

The SSI family for their contribution during the annual meetings which continuously improved this study greatly. Special thanks go to Dr. Siza Tumbo for his support and training on the PT model. Jenny Barron made specific contributions on analysis of dry spells.

SIDA, IWMI, IHE-UNESCO, DGIS and WOTRO for funding the ongoing SSI research programme.

UK meteorological services and Prof. Ian Dale (University of Reading) for facilitating *e*-training on INSTAT+ for Windows and giving me free software.

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LIST OF ABBREVIATIONS

ADE - Environmental Data Analysis
ADI - Aggregate Drought Index
AMC - Available Moisture Content
AWC - Available Water Content
B_D - Bulk density
BMDI - Bhalme and Mooly Drought Index
CV - Coefficient of variation
DGIS - The Netherlands Directorate-General of Development Cooperation
DI - Double ring infiltrometers
DWAF - Department of Water and Forest Affairs
ERT - Electrical Resistivity Tomography
GMS - Granula Matrix Sensors
IMA - Index of Moisture Adequacy
IWMI - The International Water Management Institute
K_c - Overall crop coefficient
K_{cb} - Basal crop coefficient
K_e - Soil evaporation coefficient
MAP - Mean Annual Precipitation
MK - Mann-Kendall
PCA - Principal Component Analysis
PM - Penman-Monteith
PSDI - Palmer Drought Severity Index
PT - Parched-Thirst
PVC - Polyvinyl conduit
RAI - Rainfall Anomaly Index
SAWS - South Africa Weather Services
SBEEH - School of Bioresources Engineering & Environmental Hydrology
SCS - Soil Conservation Services
SIDA - Swedish International Development Agency
S_{RC} - Spearman’s rank correlation
SSI - Smallholder System Innovation in Integrated Watershed Management
SWP - Soil Water Potential
SWSI - Surface Water Supply Index

TDR	-	Time Domain Reflectometry
TI	-	Tension disc infiltrometer
VGM	-	Van Genuchten-Mualem
WOTRO	-	The Netherlands Foundation for Advanced Tropical Research
WRC	-	Water Research Commission
WRCC	-	Water retention characteristic curves

1.0 INTRODUCTION

"A sower went out to sow, some seeds fell by the wayside, and fowls came and devoured them up. Some fell upon stony places, where they had not much earth: and forthwith they sprung up, because they had no deepness of earth. And when the sun was up, they were scorched; and because they had no root, they withered away. And some fell among thorns; and the thorns sprung up, and choked them. But other fell into good ground, and brought forth fruit, some a hundredfold, some sixty fold, some thirty fold" (KJV, Matt. 13:1-8). This scripture highlights several crop production challenges in biblical times that are still common and perhaps even more relevant today because food production sufficient to meet current and future human needs is one of the main challenges to mankind today. Trends for the near future are likely to be negative for developing countries, especially in sub-Saharan Africa (SSA), where rainfed agriculture constitutes more than 95% of the agricultural land use, hosts the largest proportion of water-scarcity prone areas and is occupied by a large proportion of the world's food-insecure people and malnourished children (Innocencio et al., 2003; IAC, 2004).

In addition to an exponential growth in population, inadequate water (Lal, 1991; Postel, 1999; Seyam et al., 2002; Rockström, 2003) and poor soils (Foth and Ellis, 1997; Klaij and Vachaud, 1999; Fox and Rockström, 2000; Rockström and Falkenmark, 2000; Lafond et al., 2006) have been cited as causes of inadequate food in developing countries. Rockström (2000) argued that a high risk of annual droughts and dry spells[7] during critical growth phases of the crop combined with poor agronomic practices at field scale are the major factors that impose a gap between the actual amount of food produced and its potential in SSA. The pattern and amount of rainfall are key factors that affect agricultural systems in this region, in particular because maize, which has relatively high water requirements and is very sensitive to water stress, is the most important crop (Makadho, 1998; Philips et al., 1998; Martin et al., 2000; Cavero et al., 2000; Jones and Thornton, 2003; Walker, 2005) grown under rainfed conditions (Raes, 2004; Hassan, 2006; Kosgei et al., 2007) as a staple food by many smallholder resource-poor farmers (Walker, 2005; Kosgei et al., 2007). However, Gowing (2003) observed that low crop production was still common in many parts of SSA even where the seasonal rainfall total is reasonable. This was attributed by Rockström (1999) to high unproductive water flows dominated by rapid runoff

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[7] Any consecutive number of days with rainfall less than 1 mm

which flows as a “flood wave” to sinks, from where it is often not economical to recover for beneficial use (Hatibu et al., 2000).

While substantial scientific research has resulted in enhanced yields through in-situ water harvesting and soil and water conservation, as well as crop and soil fertility management and plant breeding, less work has been done to assess the impact of intermittent inter- and intra-seasonal dry spells on crop yield, particularly with regard to smallholders. Indeed, the interventions that have been promoted to smallholders may provide little buffer against such events. In addition, the increase in yield from many such efforts has been marginal and inconsistent, leading some to conclude that semi-arid environments are hydrologically marginal, have no significant agricultural potential and any attempts to intensify agricultural activities would lead to severe environmental degradation.

Polak (2005) suggested four simultaneous revolutions if hunger and poverty in semi-arid tropics are to be alleviated. These revolutions should be in water, agriculture, markets and one in design based on the pursuit of affordability to support the former three. This supports earlier suggestions by Postel (1999) to spread technologies that enable farmers get more crops per drop of water used. However, findings from other regions cannot be universally applicable (Lal, 1989; Moreno et al., 1997) because the effect of a specific management system on factors of production and productivity depends on the biophysical, meteorological and socio-economic conditions at the focal site, emphasizing the need to develop interventions tailored to a particular environment. Nevertheless, once tested and verified these mitigation measures may be related to similar environments so long as the key environmental variables tally.

Driven by a lack of research linking crop water requirements, the effects of water stress on crop growth (biomass production), and strategies to manage crop water deficits and periods of stress in smallholder rainfed agriculture (Rockström and Falkenmark, 2000), a recent research initiative, the Smallholder System Innovations (SSI) in Integrated Watershed Management programme (Rockström et al., 2004) has undertaken research for the past four years aimed at identifying ways to address these challenges in a holistic manner through field trials in South

Africa and Tanzania. The focus is on water system innovations (WSIs)[8] while securing water to sustain critical ecological functions in vulnerable semi-arid tropical and sub-tropical river basins. The SSI programme, specifically through Project 2 (Fig. 1.1), envisaged identifying specific constraints responsible for the low levels of food production among smallholder rainfed farmers and provides recommendations to reverse the existing situation.

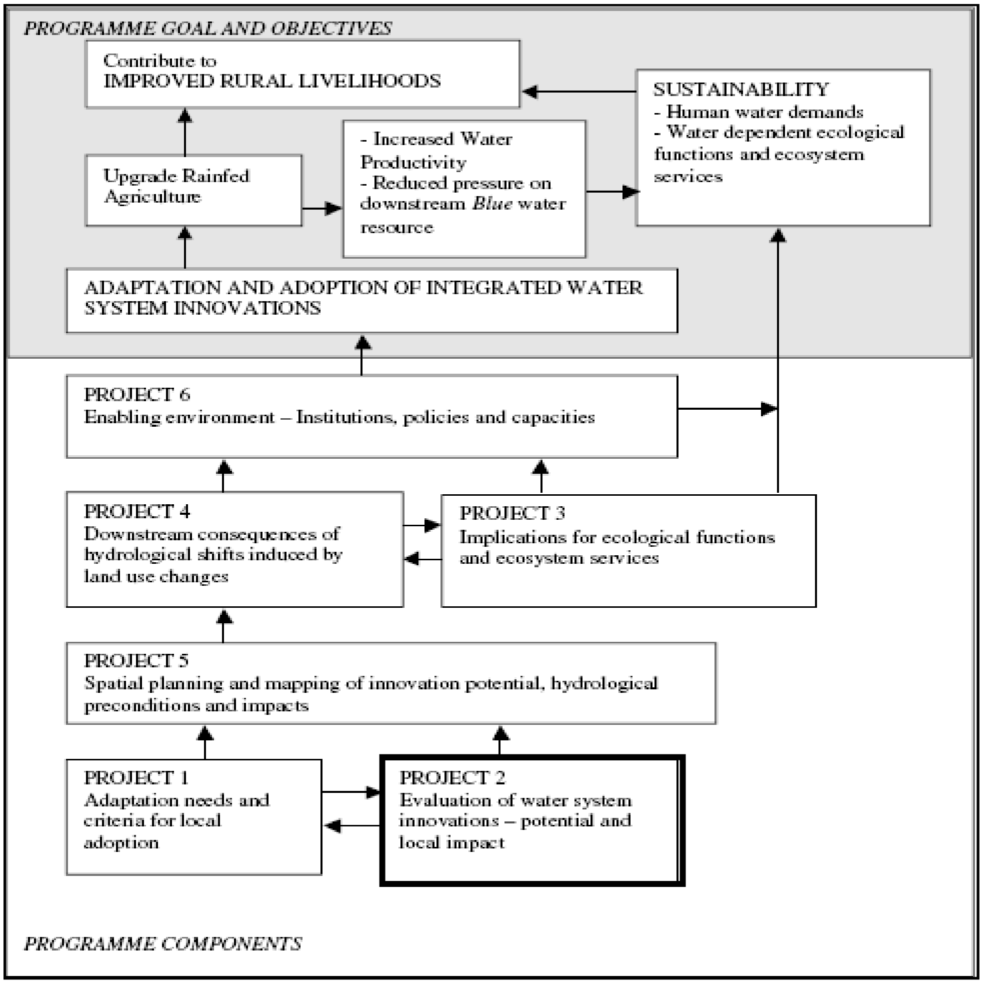

Figure 1.1: SSI programme goal, objectives, components and inter-linkages (Rockström et al., 2004; SSI, 2004)

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[8] Practices that aim at improving water productivity (increasing water use efficiencies) while conserving resources e.g. water harvesting, drip irrigation, precision agriculture and conservation farming technologies (Rockström et al., 2004).

This study (Project 2) forms one of the six projects in the SSI programme. The linkages of the projects towards contributing to the common programme goal are illustrated in the layout in Fig. 1.1. The programme was designed in an interactive and integrative manner where different projects share data, results and lessons and outputs from some form input data to the others.

An underlying theme in this study is that available soil moisture is a major limiting factor to improved yields and that this is influenced by how much depletion and replenishment occurs in a given time scale. Thus to improve yields, an understanding of the interaction of rainfall amounts and distribution, soil properties and seasonal crop water requirements is necessary. In many previous studies, these factors have been analyzed in isolation, resulting in unreliable inferences. In most instances, the availability of plant extractable soil moisture in the root zone may be more critical than the frequency of occurrence of the dry spells. However, the combination of the rainfall amounts, the duration and distribution of the dry spells as well as soil properties affect the level of moisture availability in the root zone. Therefore, there is a need to consider rainfall characteristics and seasonal crop water requirements in relation to local soil hydraulic properties to fully understand this relationship.

South Africa is unique from other parts of SSA in that 90% of its food is currently produced by commercial farmers who comprise a small portion of the population. Coupled with a strong social grant programme this suggests that majority of the population can access food by purchasing. Evidence from this study showed that this is typical of smallholder farmers, where various climatic and social factors limit food production, and the limited financial resources used to supplement food requirements. This makes them very vulnerable to hunger because food prices are dictated by regional trade whilst the financial resources of the farmers are limited. Hence the need to identify alternative measures. This study focused on the potential of rainwater harvesting and storage and further investigated the induced changes in the soil hydraulic properties, water fluxes and crop production.

With respect to crop production among smallholder rainfed farmers in South Africa, the following needed to be identified:

a) What is the difference between the potential and the typical yields? Could dry spells and/or droughts be responsible for this?

b) What is the perception of farmers to dry spells and what realistic hydrological transformations can be undertaken to improve on-farm yields while safeguarding ecosystem productivity? To what extent are they likely to improve yields of smallholder rainfed farmers?

c) What key soil properties influence moisture transitions in the study area?

d) Which combination of rainwater harvesting[9] technologies, water delivery systems and water application method(s) leads to optimum water productivity?

e) Are there opportunities for synergistic productivity improvements by integrating soil and water management?

f) What processes and conditions are necessary prior to the implementation and adoption/adaptation of crop improvement technologies in the study area?

The research reported herein aimed to address these concerns through a focused study in the Potshini catchment, Thukela Basin in South Africa, guided by the hypothesis and objectives described below.

1.1 Hypothesis and objectives.

The overall hypothesis of this study was that an evaluation process can be developed that allows for the determination of the suitability of rainwater harvesting technologies and the assessment of biophysical and socio-economic changes in the Thukela River basin. The general objective of the study was to identify and implement suitable WSIs and analyze their influences on soil hydraulic properties, water fluxes and crop production. The specific objectives were to:

- determine the frequency, severity and effects of droughts and dry spells on crop production;
- identify water flow paths resulting from two tillage practices and assess their impacts on crop production;
- investigate the effects of tillage on soil hydraulic properties; and
- identify and evaluate rainwater harvesting technologies, water delivery systems and viable application methods.

To achieve these objectives, desktop studies, field instrumentation and monitoring of assorted parameters and laboratory analyses of various samples were performed as summarized below.

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[9] Rainwater harvesting comprise all conventional approaches to soil and water conservation, spanning from methods designed to enhance infiltration of rainwater into the soil (*in-situ*) to systems which runoff is generated, concentrated and directed to cropped areas (micro-catchment) as well as those with components that collect, transfer and store runoff for use at later periods (macro-catchment systems with storage) (Hatibu and Mahoo, 2000)

1.2 Outline and structure of the thesis

This thesis, structured in a “paper format”, is composed of seven integrated papers. In addition, a brief introduction and background information constitutes Chapter 1 while a summary of conclusions and recommendations are presented in Chapter 9. Chapters 2 through 7 address the aforementioned objectives in a sequential manner. Key linkages between Chapters are emphasized which when combined with the introductory and the final Chapter, form a coherent document. The papers comprising Chapters 2 to 7 have been prepared in accordance with the guidelines provided by the Faculty of Science & Agriculture, University of KwaZulu-Natal and the requirements of scientific peer reviewed journals. A list of references is provided at the end of each Chapter. A brief description of each of the Chapters is given in the following section.

Chapter 2 commences with analyses of daily rainfall time series data (1901-1999) from eight weather stations in the Thukela catchment in an attempt to deduce abrupt changes and/or trends in climatic patterns. The Mann-Kendall (MK) test (Mann, 1945), Kendall test (Kendall, 1975) and the Spearman’s rank correlation (SRC) coefficients were used to detect trends while the Pettitt’s test (Pettitt, 1979) was performed to identify abrupt changes in the annual time series. Several other statistical analyses were done which enabled the derivation of indices that contributed to the evaluation of suitable sowing dates and the risks of maize production (Zea Mays L.) in the Thukela basin. INSTAT+ for Windows (Stern, 2003) was used to identify the suitable sowing dates. The length of the growing season was constrained by dry spells at the beginning of the season and soil moisture and heat units at the end.

In an endeavor to address the identified challenges from dry spells, field-scale experimentation and monitoring was undertaken to quantify water flow fluxes that occur under no-till (N_T) and conventional tillage (C_T) in four sites under maize (*Zea Mays L.*) production in the Potshini catchment, South Africa during the 2005/06 - 2007/08 seasons. The findings are reported in Chapter 3.

Through infiltration tests using tension disc and double ring infiltrometers, the effects of the tillage systems viz. N_T and C_T on soil steady state infiltration and hydraulic conductivity are evaluated in Chapter 4. In Chapter 5, descriptive statistics, Principal Component Analysis (PCA) and coinertia analysis are used to derive and extract relationships between hydraulic conductivity and selected soil physical properties. Chapter 6 provides an investigation of the influence of tillage systems on pore indices and water retention characteristics.

To mitigate longer dry spells adequately and diversify crop production, an assessment of the suitability of polythene lining as an alternative cost-effective method of underground rainwater storage, especially in rural areas where groundwater levels fluctuate rapidly, is provided and the benefits of accessing a reliable water supply are highlighted in Chapter 7. Chapter 8 provides a synthesis of the impact of innovative soil management, soil profile moisture storage, the additional benefits of water stored in tanks and the contribution of policies and partnerships towards household food and income generation with examples drawn from a LandCare programme and the SSI programme. Key conclusions and recommendations are provided in Chapter 9.

1.3 Scientific relevance and innovative aspects of the study

The focus of crop production improvement initiatives in the past usually focused on in-situ water harvesting, soil and water conservation and crop and soil fertility management. This study has integrated these strategies within the framework of systems innovations, indigenous and/or novel, with a core focus on water harvesting, drip irrigation and conservation farming systems. Thus, this research provides a new contribution through:

- Systems research on the potential for “upgrading” rainfed agriculture in semi-arid environments by linking climate, water, soil and plant management;
- Identification of biophysical and socio-economic preconditions determining the potential of water system innovations in rainfed agriculture;
- Development of tools and methodologies for assessment of environmental, social and economic impacts of widespread adoption of field scale WSIs; and
- Linking science and community livelihoods where findings of the study contribute to traditional decision making processes especially regarding livestock-crop production dynamics.

The scientific significance is further enhanced by the integration of three essential, but generally omitted characteristics of semi-arid rainfed agriculture in the study area: (1) the frequent occurrence of yield impacting dry spells; (2) the role played by water in terms of risk management at field scale; and (3) the water productivity improvements. Furthermore, although examples of this study are drawn from the Potshini catchment, the lessons learnt are applicable to the majority of smallholder rainfed farmers in many parts of sub-Saharan Africa.

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2.0 RAINFALL TRENDS AND VARIABILITY AND THEIR INFLUENCE ON SOWING DATES AMONG SMALLHOLDER RAINFED FARMERS IN THE THUKELA BASIN, SOUTH AFRICA

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Abstract

Smallholder farmers occupy fragile environments where relatively small perturbations in water input can have a strong effect on the generation of livelihood goods and services. Timeliness in operations e.g. sowing and weed control is crucial. To understand how and when water limits crop production and thus seek ways to optimize its use, knowledge of its temporal and spatial quantities and trends is necessary. This information could also aid decision making in traditional leadership typical of rural smallholder farmers.

Using daily rainfall time series data (1901-1999) from eight weather stations in the Thukela catchment, the Mann-Kendall (MK) test, Kendall test and the Spearman's rank correlation (SRC) coefficients were used to detect trends in the annual and monthly rainfall. Pettitt's test was conducted to identify abrupt changes in the annual time series. Several other statistical analyses were done which enabled the derivation of indices that contributed to the evaluation of suitable sowing dates and the risks of maize production (*Zea Mays L.*) in the Thukela basin. INSTAT+ for Windows was used to identify the suitable sowing dates. The length of the growing season was constrained by dry spells at the beginning of the season and soil moisture and heat units at the end.

Increasing trends in annual rainfall of up to 5.5 mm/year were observed in some stations. This was attributed to increases in rainfall intensities and/or amounts per day rather than an increase in rainy days. Rainfall was more variable in winter compared to summer. On average the return period of droughts was between 2-4 years in all stations. Rainfall variability was found to influence sowing dates. Although dry spell occurrences were higher in 1951-1999 compared to 1901-1950, there was an advance in the potential date of sowing of up to 2.5 weeks in some

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cases. However, during sowing, the range of probability of occurrence of dry spells in stations with mean annual precipitation (MAP) > 800 mm was 15-25% while in those with MAP <800 mm the range was 35-50%. Early season dry spells were found to play a more significant role in crop production than the seasonal amount of rainfall.

Keywords: Dry spells; sowing date; trend; rainfall; risk.

2.1 Introduction

Despite technological advances in plant breeding, fertilizers and irrigation systems, climate is a key factor in agricultural production (Makadho, 1996). Crop production in many tropical semi-arid areas of Africa is frequently frustrated by the erratic nature of rainfall (Adiku et al., 1997; Martin et al., 2000; Tsubo et al., 2005) even when the seasonal rainfall total is reasonable (Gowing, 2003). In these areas, water is often the most limiting factor for biological activities and relatively small perturbations in water input can have a strong effect on the generation of ecosystem goods and services (Lázaro et al., 2001) and may cause significant long-term changes in human livelihoods.

The pattern and amount of rainfall are key factors that affect agricultural systems in this region because maize, which has relatively high water requirements and is very sensitive to water stress, is the most important crop (Makadho, 1996; Philips et al., 1998; Martin et al., 2000; Cavero et al., 2000; Jones and Thornton, 2003; Walker, 2005). In addition, it is grown under rainfed conditions (Raes, 2004; Hassan, 2006; Kosgei et al., 2007) as a staple food by smallholder resource-poor farmers (Walker, 2005; Kosgei et al., 2007). The agricultural community has continually been exposed to risks and uncertainties by the unpredictable weather patterns (Abraha and Savage, 2006; Garcia et al., 2007). Grundstein and Bentley (2001) defined three types of dry spells/droughts: an agricultural, a meteorological and a hydrologic drought, depending on the stages of occurrence or extremes of the water deficit. This kind of categorization is similar to that adopted by other studies (e.g. Twomlow, 1994; Rockström and Falkenmark, 2000; Barron et al., 2003; Keyantash and Dracup, 2004; Raes et al., 2004; Smakhtin and Hughes, 2004; Kipkorir et al., 2007; Smakhtin and Hughes, 2007; Mugalavai et al., 2008). Smakhtin and Hughes (2007) argued that the success of their mitigation measures depends, amongst other factors, on how well the droughts are defined and their characteristics quantified in terms of beginning, end, spatial extent and severity.

Schulze et al. (2001) pointed out that southern Africa experiences a high inter-annual and intra-annual variability of rainfall which, according to Warbuton (2005), increases the challenges of detecting changes in rainfall patterns, especially in arid to semi arid areas where hydrological amplifications occur and small perturbations in rainfall result in non-linear or exaggerated responses in runoff (Schulze, 1995; Schulze, 2005; Dlamini, 2006). Summarizing work from several studies around the world, Warbuton (2005) noted increasing rainfall trends in the USA, Canada, UK, parts of China, equatorial East Africa and south coastal regions of west Africa. Most of the positive trends were attributed to increasing frequency of wet days and/or more amount of rain on a wet day. Decreasing trends were reported in parts of China and North Africa. Southern Africa had generally no strong trends on annual rainfall but sub-annual and seasonal inconsistent trends were observed. However, increased intensities that have led to floods were deduced. The mountainous parts of South Africa had more rainy days per month and increased monthly totals compared to the coastal regions. Dry spells of longer durations were reported to be on the increase which could further increase chances of crop failure among smallholder rainfed farmers in summer-rainfall parts of South Africa. From a study in central Argentina, Pasquini et al. (2006) showed significant increases in about one half of their precipitation data series during the second half of the twentieth century. Mixed trends of increasing and decreasing rainfall were reported in Iran with only about 10% of the 20 stations studied having trends that were significant at $p \leq 0.05$ (Modarres and Silva, 2007).

Although droughts spanning years have devastating effects, the impacts of recurrent dry spells are greater because in the case of long duration droughts smallholder farmers attempt crop production perhaps only in the first two seasons before they surrender while for recurrent dry spells, farmers invest each season in land preparation, inputs and other agronomic practices but do not realize (adequate) yields to off-set their costs. From a review of various studies, Raes et al. (2004) and Kipkorir et al. (2007) observed that in many parts of sub-humid to semi-arid Africa, the rainy season begins with some light showers followed by dry spells that can cause poor crop emergence or desiccate a young crop. Although favorable crop growth conditions at all stages are desirable, successful germination and good initial establishment is vital to resource-poor farmers. For these farmers, replanting is a non-justified added cost on already incurred expenses during land preparation, purchase of seed and fertilizer and sowing that is often met with a lot of constraint. Therefore, identifying the appropriate time to sow is likely to improve chances of good yields as well as alleviate unnecessary costs of re-sowing (Twomlow, 1994).

In addition, most smallholder communities practice mixed farming. In the Thukela Basin livestock graze in the farmlands immediately after harvest until the traditional leadership (*Induna*), at the beginning of the next season, issues a decree for the animals to be taken back to a secluded area where they are kept throughout summer. The timing of this decision is arbitrary. Which week should the *Induna* require that the cattle be moved from the cropping areas in anticipation of land preparation and sowing? This is a question whose answer can only be given after careful analyses of rainfall patterns and other weather parameters.

The hypothesis of this study was that rainfall characteristics are the primary limiting factors for maize (*Zea Mays L.*) production in the Thukela basin. The specific objectives were to:

a). Investigate changes in long-term rainfall characteristics in eight weather stations;

b). Identify occurrences of droughts and dry spells; and

c). Evaluate the influence of early season dry spells and late season low temperatures on sowing dates, length of growing season and the risk of failure to achieve optimum yields in maize production in the basin.

Long-term historical rainfall data (1901-1999) from eight weather stations in the Thukela basin, South Africa was used. Focus was concentrated on the prevalence of early season dry spells which could be responsible for persistent low maize yields amongst smallholder rainfed farmers in the basin. Both the accumulated depth and the water balance approaches, considering a scenario with and without a qualifying criterion of dry spells in each case, were used. It is common practice for farmers to respond to start of rains differently. In this study, a 'bold strategy' is considered to be that adopted by farmers who sow at the potential start of the season whilst a 'cautious strategy' is regarded to be adopted by farmers who sow later. These analyses of planting dates were used to quantify the risk of failure of crop development over a 30-day period following sowing. Soil moisture content falling below a set threshold and late season temperatures below a certain threshold determined the end of the season.

2.2 Methodology

2.2.1 Location, basin description and land use

This study was carried out in the Thukela River basin (Figure 2.1). According to DWAF (2004) the Thukela basin covers approximately 30,000 km^2, and flows from the Drakensberg Mountains, meanders eastwards through central KwaZulu-Natal and discharges into the Indian Ocean near Durban. The Thukela is a highly diverse basin, with valuable aquatic and terrestrial ecosystems, mixed with subsistence and commercial farming activities. The integrity of terrestrial, aquatic and riparian ecosystems in the Thukela catchment is threatened by both the economically developed and developing water use sectors (Taylor et al., 2001).

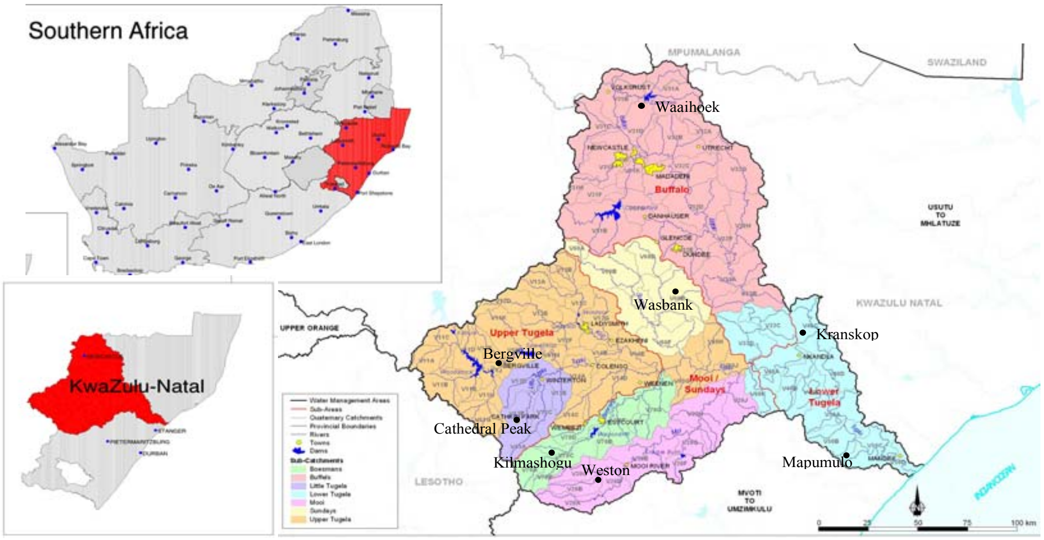

Figure 2.1: Spatial position of the Thukela basin, its 7 water management key areas, 87 quaternary catchments and the distribution of rainfall stations used in this study (After SSI, 2003; DWAF, 2004)

The rainfall stations used in this study, shown in Table 1.1, were chosen so as to represent the seven primary catchments (water management key areas – Upper Thukela, Little Thukela, Bushmans, Mooi, Sundays, Buffalo and Lower Thukela) in the Thukela basin (DWAF, 2004), elevation and relative longitudinal position in the basin. Three stations, Weston, Cathedral Peak and Kilmashogue, have altitudes above 1400 masl. Apart from Weston (Mooi), Cathedral Peak (Little Thukela) and Kilmashogue (Bushmans) stations are situated around the Drakensberg Mountains which could have an influence on rainfall in these stations. Wasbank (Sundays), Kranskop (Lower Thukela), Bergville (Upper Thukela) and Waaihoek (Buffalo) stations are between 1000–1400 masl while the remaining station, Mapumulo (Lower Thukela) is below 1000 masl. In the basin, humans experience water scarcity related to increased pressure on finite soil and water resources, and due to increased land degradation (DWAF, 2000) and highly seasonal rains that fall between October and March.

Table 2.1: Weather stations, location, elevation, their geographical coordinates, soil types and total available water per 0.25 m depth of soil

Station	Altitude	Latitude	Longitude	MAP	Soil type	TAW[10]
Weston	1464	29^{0}13’	30^{0}02’	661	Clay	36
Bergville	1151	28^{0}44’	29^{0}21’	710	Sandy	30
Mapumulo	544	29^{0}10’	31^{0}04’	982	Clay	36
Waaihoek	1355	27^{0}46’	30^{0}25’	391	Sandy	33
Wasbank	1072	28^{0}19’	30^{0}06’	627	Clay	36
Kilmashogue	1501	29^{0}10’	29^{0}52’	819	Clay	30
Kranskop	1078	28^{0}58’	30^{0}51’	780	Clay	36
Cathedral	1512	28^{0}57	29^{0}12’	1090	Clay	30

The basin is predominantly occupied by large scale commercial farmers involved in maize, wheat and livestock production and smallholder resource-poor subsistence farmers (Walker, 2005) who own small parcels of land (Kosgei et al., 2007) with maize as the only major crop grown. Cattle are also kept in large numbers. They graze on secluded ground in summer and within the cropped land in winter, as it contains plenty of maize residues in good years. The cattle schedule is controlled by the *Induna* and it is coincided with the onset of sowing and end of harvesting. Findings of this study are likely to improve the certainty of this decision making organ.

2.2.2 Rainfall data: source, quality, homogeneity and normality tests

Ninety nine years (1901-1999) of daily rainfall records from eight SAWS[11] meteorological stations were used in this study. The data was obtained from the School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal database consisting of close to 350 million rainfall values derived from 11269 daily rainfall stations (Lynch, 2003).

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[10] Total available water mm/0.25 m soil depth

[11] South Africa Weather Services

Thus, an extraction utility (Kunz, 2004) was used to select the rainfall data from the 8 stations over the desired record length. The average portion of reliable observed data was 55% with a range of 42-68%. The mean (and range) of patched and missing data was 44% (28-57%) and 1% (0.1-4.4%), respectively. Lynch (2003) described the patching process and the methods used. The tests applied to the rainfall data are described below.

2.2.2.1 Homogeneity test

Rainfall data series of a considerable number of years may not reflect uniform conditions because changes in instrumentation, sensor calibration, maintenance procedure, site, measurement technique, observation times, personnel or codes may have occurred within the period under consideration creating fluctuations that are not caused by weather and climate alone (Jones, 1995 in Lázaro et al., 2001; Mebrhatu et al., 2004). The Thom test (Buishand, 1982; Rodrigo et al., 1999; Lázaro et al., 2001; Modarres and da Silva, 2007), a method that tests the variation in a series with regard to the median or by comparing the data of the station of interest with neighboring stations, is able to distinguish between homogeneous and non-homogeneous data sets. In this study, the Thom test was used to test if the annual time series data were homogeneous or not.

Although the Thom test is nonparametric, Sneyers (1992) in Rodrigo et al. (1999) acknowledged that nonparametric statistics are more useful when the distribution of the data is unknown or non-normal. In this test, the median of the time series is computed and is then compared with each value in the time series. A similar code is assigned to all values greater than the median. This also applies to those less than the median. A value is rejected when it is equal to the median. Each uninterrupted series of similar coding constitutes a 'run'. The number of runs, R, of values higher and lower than the median is counted. Under the null hypothesis this statistic has an approximately normal distribution of mean E(R) and Var(R) expressed as:

$$E(R) = \frac{N+2}{N}; \qquad Var(R) = \frac{N(N-2)}{4(N-1)} \tag{2.1}$$

N = Number of years of rainfall record

The Z statistic is defined as:

$$Z_T = \frac{R - E(R)}{\sqrt{Var(R)}} \tag{2.2}$$

If $|Z_T|$<2.58, the time series is homogeneous at 99% confidence level.

2.2.2.2 Normality test

Annual rainfall is not necessarily normally distributed (Stephens, 1974) except in wet regions (Edwards et al., 1983). Jackson (1977) indicated that rainfall distributions are markedly skewed in semi-arid areas. Rodrigo et al. (1999) suggested the use of non-parametric methods instead of making comparisons based only on descriptive statistics which in most cases are useful when the data series is drawn from a normal distribution. In their case, the Spearman coefficient was used. In this study, the Anderson-Darling test (Stephens, 1974) was used to test if the annual time series data were normally distributed whereas analyses of coefficients of kurtosis and skewness were used to test the mean monthly data series.

In the Anderson-Darling test, the required statistic (A^2) was calculated from the Z-values using the expression below:

$$A^2 = -n - \frac{1}{n}\left\{\sum_{i=1}^{n}(2i-1)\left[\ln F(Z_i) + \ln F(1 - Z_{n+1-i}\right]\right\} \tag{2.3}$$

where F is the cumulative distribution function of the normal distribution and Z_i are the ordered observations.

In addition, graphs of residuals (normal probability plot of residuals, histogram of residuals, residuals versus fitted values and residual versus order of the data) were plotted. Together with histogram of residuals, the normal probability plots of residuals can show skewness and outliers. Missing terms and non-constant variance can be detected from a plot of residuals versus fitted values. The plot of residual versus order is useful in cases where the order of the observations may influence the results. Examples of these are situations when data is collected in a time sequence or in some other sequence, such as geographic area.

2.2.3 Changes in the time-series during the period: change points and trends

Changes in rainfall series can occur abruptly (step change), gradually (trend) or may take more complex forms. The (non-)existence of these changes need to be ascertained because seasonal and other short-term fluctuations (climate variability) and the lack of homogeneity in the data can lead to inaccurate methods of analysis and resulting deductions. Many methods have been suggested to characterize the behaviour of long-term weather patterns and to predict future trends. In this work the Pettitt's test (Pettitt, 1979) in SPELL-Stat time series statistical analysis program (Guzman and Chu, 1990) was used to identify change points in the time series. A change in data series having a probability above 0.8 was considered a change point. It is indicated by a green line in the plot area. These points represent years that had a possible change in the data relative to the previous years. At the identified possible breaks in the series, the data were divided at the change point by considering an equal number of data on both sides of the change point. The year corresponding to the highest probability was considered the end of the first sub-set and the year following it as the first year of the next sub-set. The tests of the stability of variances (F-test) and means (T-test) were conducted at 95% confidence level.

The Mann-Kendall (Mann, 1945; Kendall, 1975) and the Spearman's coefficient were used to explore trends in the annual time series (e.g. Suppiah and Hennessy, 1998; Rodrigo et al., 1999; Lázaro et al., 2001; Libiseller, 2002; Warburton, 2005). A brief description of the procedure used when carrying out the general Mann-Kendall (MK) test is provided below.

Considering a time-series of length n (P_i, i=1,2,…..,n), the trend can be assessed by computing the statistic S as follows:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{j-n} \operatorname{sgn}\left(P_i - P_j\right) \tag{2.4}$$

where

$$\operatorname{sgn}\left(P_i - P_j\right) = \begin{cases} 1 & if \; P_i > P_j \\ 0 & if \; P_i = P_j \\ -1 & if \; P_i < P_j \end{cases} \tag{2.5}$$

Generally, if a dataset displays a consistently increasing or decreasing trend, S will be positive or negative respectively, with a larger magnitude indicating the trend being more consistent in that direction. Under the null hypothesis H_0 that there is no trend displayed by the time series, the distribution of S is then expected to have a zero-mean and a variance expressed by Eq. 2.6.

$$\operatorname{var}(S) = \frac{n(n-1)(2n+5)}{18} \tag{2.6}$$

where n is the number of years under consideration.

For every series, the test statistic Z_{MK} is calculated as follows:

$$Z_{MK} = \begin{cases} \dfrac{S-1}{\sqrt{\operatorname{var}(S)}} & if \; S > 0 \\ 0 \quad if \; S = 0 \\ \dfrac{S+1}{\sqrt{\operatorname{var}(S)}} & if \; S < 0 \end{cases} \tag{2.7}$$

A level of statistical significance α is then chosen. A value of $Z_{1-\alpha/2}$ is determined using a standard normal distribution table. If $|Z_{MK}| > Z_{1-\alpha/2}$, the series is said to display a trend significant to α. By introducing the expected variance of S in the determination of Z, the MK test is able to reject what might appear to be trends over small periods of time that may appear to exhibit a short trend.

The Kendall test was used to evaluate trends in monthly data series. The Seasonal Kendall test (Hirsch et al., 1982) accounts for seasonality by computing the Mann-Kendall test on each of the months separately, and then combining the results. For example, January data are compared only with January, February only with February, etc.

2.2.4 Drought assessment and indices

Several indices, normally composed of continuous functions of rainfall and/or temperature, river discharge or other measurable hydrometeorological variable, have been developed to quantify drought. However, most of them are related to rainfall which is the fundamental driving force and pulsar input behind most hydrological processes (Schulze et al., 1995). Common examples of these indices include Palmer Drought Severity Index (PDSI - Palmer, 1965), Rainfall Anomaly Index (RAI - Rooy, 1965), Bhalme and Mooly Drought Index (BMDI - Bhalme and Mooley, 1980), Surface Water Supply Index (SWSI – Shafer and Dezman, 1982), Index of Moisture Adequacy (IMA – Sastri, 1993) and Aggregated Drought Index (ADI – Keyantash and Dracup, 2004). Reviews of some of these indices are found in Oladipo (1985), Smakhtin and Huges (2004) and Keyantash and Dracup (2004). These indices have been viewed as crucial in planning agricultural activities and managing associated water supply systems (Sharma, 1996) as well as in the assessment of the consequences of changes in land use so as to develop effective management strategies (Sutherland et al., 1991).

Oladipo (1985) examined and compared the performance of three drought indices viz. the PDSI (Palmer, 1965), the RAI (Rooy, 1965) and the BMDI (Bhalme and Mooley, 1980) to depict periods of different drought intensities. All the three indices appeared to be effective in detecting drought periods. The author concluded that for meteorological purposes, and when undertaking single-station analysis, simple indices with rainfall as the only input e.g. RAI perform comparatively as well as the more complicated indices in depicting periods and intensity of drought. A similar conclusion was drawn by Alatise and Ikumawayo (2007). In this study, the Rooy (1965) rainfall anomaly index (RAI), modified to account for non-normality was used to describe the annual rainfall variability. RAI is calculated for positive (Eq. 2.8) and negative (Eq. 2.9) anomalies as follows:

$$RAI = +3\left[\frac{R_a - R_e}{R_{x10} - R_e}\right] \tag{2.8}$$

$$RAI = -3\left[\frac{R_a - R_e}{R_{m10} - R_e}\right] \tag{2.9}$$

where R_a is the actual rainfall for a given year, R_e is the mean rainfall for the total length of record, R_{x10} is the mean of the 10 highest values of rainfall on record, and R_{m10} is the mean of the 10 lowest values of the rainfall on record. Tilahun (2006) found that values of RAI less than -3 were correlated with drought years.

2.2.5 Onset of sowing and risk assessment

2.2.5.1 Sowing onset definitions

In the study area, rainfall is generally expected from mid November and sowing seldom happens before this time. In addition, low temperatures result in inadequate heat units for maize growth (Fig. 2). In order to assess the suitable range of sowing dates for the "bold strategy" (early planting) the following criteria were set:

- Any date after 15th November with rainfall total of 40 mm in at least 4 days (B_{D1}) – definition 1;
- Any date after 15th November with rainfall total of 40 mm in at least 4 days without a dry spell exceeding 10 days in the next 40 days (B_{D0}) – definition 2;
- Any date after 15th November that the available soil water storage[12] exceeds 40 mm and does not drop to zero in the next 30 days (B_{W0}) – definition 3.

Similar criteria were selected for the "cautious strategy" (late planting) whereby 15th December was considered as the earliest possible sowing date and a rainfall total of 30 mm. Thus:

- Any date after 15th December with rainfall total of 40 mm in at least 4 days (C_{D1}) – definition 1;
- Any date after 15th December with rainfall total of 40 mm in at least 4 days without a dry spell exceeding 10 days in the next 40 days (C_{D0}) – definition 2;

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[12] Field capacity water storage less water storage at wilting point

- Any date after 15th December that the available soil water storage exceeds 40 mm and does not drop to zero in the next 30 days (C_{W0}) – definition 3.

The above criteria were motivated by historical information from community members, local agricultural extension officers and preliminary analysis of rainfall patterns in the study area.

2.2.5.2 Estimation of the cumulative depth

In the upper Thukela, planting depth is commonly about 10 cm (Kosgei et al., 2007). The desired wetting depth should be deeper than this depth because the top 10 cm is usually the active evaporative soil layer. A cumulative depth that will bring the top 25 cm of the soil to field capacity in up to 4 days was considered in this work. The total available soil water (TAW) for the major soils around the various stations (Table 2.1) was used to determine the amount of rainfall necessary to raise the water content from wilting point to field capacity. As values of TAW at the top 25 cm (Table 2.1) do not vary widely from one station to another, an average value of 40 mm was used, which was obtained by upgrading the TAW values by 20% (Magalavai et al., 2008) to account for losses by surface runoff, non-uniform wetting and soil evaporation. This factor was adopted as detailed field measurements were not available. In such circumstances, results from other studies on similar conditions are used but there is need to test them on a small scale for validation.

Farmers in the study area pointed out that if desired rains did not occur by mid-December, they sowed as long as the conditions are slightly above “average”. This situation was approximated to coincide with 75% of the rainfall, and thus a value of 30 mm was used for the “cautious strategy”.

2.2.5.3 Water balance determination

For the definitions that were based on soil water storage, a simple water balance module in INSTAT+ for Windows (Stern et al., 2003) was used. The Penman-Monteith approach (Allen et al., 1998) was used to estimate the crop reference evapotranspiration (E_{To}) using parameters from each weather station. After obtaining the crop reference evapotranspiration (E_{To}) from the Penman-Monteith approach (Allen et al., 1998), the respective crop factors were used to estimate the daily crop water requirements. In this study, differences in evaporation and transpiration between field crops and the reference grass surface was separated into two coefficients: a basal crop (K_{cb}) and a soil evaporation coefficient (K_e). K_{cb} represents the ratio of

E_{Tc} to E_{T0} under conditions when the soil surface layer is dry, but where the average soil water content of the root zone is adequate to sustain full plant transpiration. The majority of evaporation from soil following wetting by precipitation or irrigation is represented by the separate K_e. The total, actual $K_{c\ act}$ is the sum of K_{cb} and K_e: $K_{c\ act} = K_xK_{cb} + K_e$. K_x is a stress reduction coefficient which reduces K_{cb} when the average soil water content or salinity level of the root zone are not conducive to sustain full plant transpiration. K_{cb} and K_e range from 0-1.4 while K_x range from 0-1. K_{cact} is then multiplied by E_{To} to obtain $E_{TCactual.}$

To account for surface run-off, the effective rainfall was pre-determined as 80% of the actual measured rainfall (xref. Section 2.2.5.2).

2.2.5.4 Identification of sowing dates

For each of the eight climatic stations, Instat+ for Windows (Stern et al., 2003) was used to identify suitable sowing dates based on the criteria outlined in Section 2.2.5.1. To identify dry spell occurrence, a 'dry' day was defined as a day with rainfall less than 1 mm. In all definitions, the onset date was considered to be the date on which the criteria was first satisfied or exceeded. Because of low temperature and frost incidences after mid May (Fig. 2.2), no sowing was considered after 15th February and any potential date that occurred later than this date was unsuccessful. The maize plant stops developing when the heat units fall below 6°C.

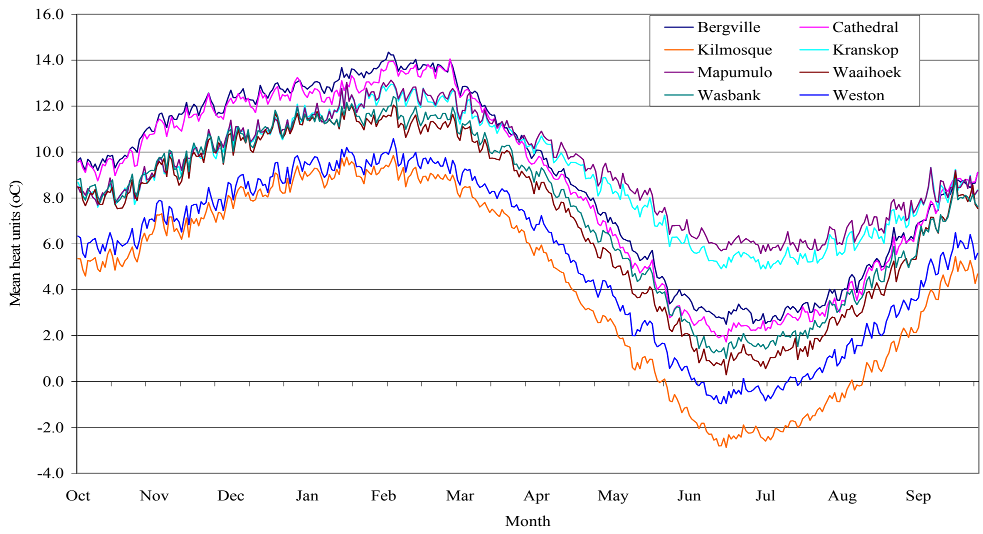

Figure 2.2: Mean heat units estimated from daily temperature data (1901–1999) in all the eight stations considered in the study. The base temperature used was 10°C

The heat units were approximated from the mean of the maximum and minimum temperature less the base temp. (10°C).

2.2.5.5 Length of season and risk assessment

The end of the season was defined as any date after 1st April that the water balance falls to zero. However, low temperatures during this time are known to cause inadequate heat units for growth (Fig. 2.2). Therefore, the end of season was set as any date after 1st April but not later than 15th May (in all stations except Mapumulo and Kranskop, located at warmer areas, whose date was set at 15th June) that the water balance fell to zero. In each year, the length of the season was calculated as the difference between the end and the successful start date.

The risk assessment was based on whether or not a successful sowing date was obtained and the length of the season. Sowing failed when the set criteria (xref. Section 2.2.5.1) were not met through out the season. Maize varieties commonly promoted by seed companies in this region require approximately 165 days to mature e.g. variety PAN 6611. However, the water and heat requirements are minimal in the last month. Thus, the risk that a season was shorter than 135 days was evaluated. All lengths of season less than 135 days led to yield reduction. In addition, an evaluation was made for a 120-day variety. In the absence of a successful sowing date the overall risk for the season was 100%. Likewise if the length of the season is less than 135 days or 90 days, then the overall risk of not achieving optimum yield was regarded 100%. Thus, it was used to reflect incidences when optimum conditions were not met.

2.2.6 Probability of rain and dry spell occurrence

A considerable number of previous studies have analyzed long-term rainfall data using stochastic models and frequency distribution functions to determine the persistence of dry or wet days. One commonly used probability model is the first order Markov chain (e.g. de Arruda and Pinto, 1980; Sivakumar, 1992; Sharma, 1996; Adiku et al., 1997; Barron et al., 2003; Mebrhatu et al., 2004; Raes et al, 2004) in which a present day's state is dependent only up to a day before. Details of its use for this purpose have been elaborated by De Arruda and Pinto (1980), Jones and Thorton (1993), Sharma (1996), Adiku et al. (1997) and Barron et al. (2003). In the present study, the first order Markov chain in the spell lengths routine of Instat+ for Windows statistical package (Stern et al., 2003) was used to compute the dry and wet spell lengths and their distributions. A ‘dry spell’ comprised any consecutive number of days with rainfall less than 1 mm (xref. Section 2.2.5.4). The probability of dry spells was calculated for a series of overlapping 30-day periods in successive 3-day intervals. The rainfall amounts on rainy days were modeled by gamma distribution.

2.3 Results and discussion

2.3.1 Data quality checks: homogeneity and normality

Table 2.2 contains the Z-values for the Thom test used to decide if the data was homogeneous or not. The time series data from all the stations are shown to be homogeneous since all the values (Z_T) are less than the critical value of 2.58 ($p \leq 0.01$). This indicated that the time series were obtained under similar conditions over the entire period, enabling any observed variability to be associated with other factors. A value of 10 was obtained from the Anderson-Darling normality test with a p-value less than 0.005. The large statistic and the low p-value indicated that the normal distribution did not fit the data very well, suggesting that the series are not normally distributed. A plot of residuals indicated that the data were slightly skewed at the tails. The same was experienced in the monthly time series. However, the Shapiro-Wilk statistic (Shapiro and Wilk, 1965) calculated for both the series did not lead to a rejection of the hypothesis of normality for any station ($p \leq 0.05$).

2.3.2 Annual rainfall: descriptive statistics, change points and trends.

2.3.2.1 Annual and monthly rainfall statistics

The descriptive statistics of the annual rainfall series for all stations are provided in Table 2.2 and Fig. 2.3. In all stations, the annual rainfall data series was considered from October to September. There was a difference in rainfall in the eight stations. The range in maximum, minimum and average rainfall was 877 mm, 708 mm and 486 mm, respectively. The mean annual maximum, minimum and average rainfall for all the stations was 1428 mm, 469 mm and 839 mm, respectively. The inter-quartile array ranged between 183.2 mm and 401.8 mm. One half of the stations viz. Cathedral Peak, Mapumulo, Kilmashogue and Kranskop, arranged in order of increasing magnitude of rainfall, had a mean annual rainfall of more than 800 mm. It is interesting to note that two of these stations (Cathedral Peak and Kilmashogue) are located at the extreme west and the other two (Mapumulo and Kranskop) are at the extreme east.

Cathedral Peak and Kilmashogue stations are located above 1500 masl which could explain the influence of elevation (Drakensberg Mountains) on rainfall. On the other hand, proximity of Mapumulo and Kranskop stations to the warm Indian Ocean could be responsible for more rainfall in these stations. The stations in between had mean annual rainfall ranging between 677 mm and 783 mm.

The classification of the Thukela Basin as ‘arid and semi-arid’ in this study is more “agronomic” rather than “climatic” as it was based on the rainfall patterns. The area receives rainfall only in summer and thus smallholder farmers can only produce crops during this period. Hence the definition the the definition is not based on Koppen zoning, but an agronomic classification.

Table 2.2: Annual maximum rainfall (R_x), minimum rainfall (R_n), mean rainfall (R_e), standard deviation (S_d), first quartile (Q_1), third quartile (Q_3), coefficient of variation (C_v), coefficient of skewness (C_s), coefficient of kurtosis (C_k), Z-values from Thom test (Z_T), Spearman's rank correlation (S_{rc}) coefficient and Mann-Kendall (Z_{MK}) test with the corresponding p-values for all the stations studied

Station name	R_x (mm)	R_n (mm)	R_e (mm)	Q_1 (mm)	Q_3 (mm)	S_d	C_v (%)	C_s	C_k	Z_T[*]	S_{rc}	Z_{MK}	p-
Weston	1113	364	677.7	577.1	770.7	116.9	25	0.45	0.21	0.3	0.54[a]	5.466[a]	0.000
Bergville	1205	334	718.2	599.5	808.1	172.2	24	0.57	0.36	-0.71	0.266[a]	2.582[a]	0.004
Mapumulo	1620	277	1008.8	854.0	1128.0	234.8	23	0.26	0.46	2.12	0.132	1.345	0.089
Waaihoek	1179	436	709.9	618.2	801.4	149.8	21	0.47	0.51	1.52	0.035	0.417	0.338
Wasbank	1361	362	782.5	669.2	893.6	177.6	23	0.2	0.31	0.91	-0.03	0.000	0.500
Kilmashogu	1436	985	839.3	720.8	964.9	180.8	22	0.32	0.37	-1.72	0.034	0.247	0.402
Kranskop	1516	403	811.3	671.1	948.9	199.0	25	0.65	1.05	1.52	0.181	1.826[a]	0.033
Cathedral	1990	594	1163.5	945.2	1347.0	304.2	26	0.32	-0.45	2.12	0.527[a]	5.520[a]	0.000

[*] Critical value for Thom's test was 2.58 at p≤0.01; [a]Trends statistically significant at p≤0.05

The Turkey's confidence interval method was used to compare the means in a one way analysis of variance. There were significant differences at p≤0.05 and p≤0.01 between rainfall in Cathedral Peak and all the other stations. This was also the case with Mapumulo, implying that Cathedral Peak station received relatively higher rainfall than all the stations suggesting that, in this case, altitude played a significant role in influencing occurrence of rainfall rather than the proximity to the ocean. There was no significant difference, at both levels, between rainfall series at stations located at 1072–1446 masl. The rainfall series at Wasbank, situated almost in the central part of the basin, had a significant difference with only Cathedral Peak and Mapumulo stations. The average coefficient of variation of the annual rainfall series was 24%, 23.6% and 23% for stations above 1500 masl, between 1072-1446 masl and at 544 masl respectively. Kranskop and Mapumulo had the highest coefficients of skewness and kurtosis, suggesting that variability decreased with altitude.

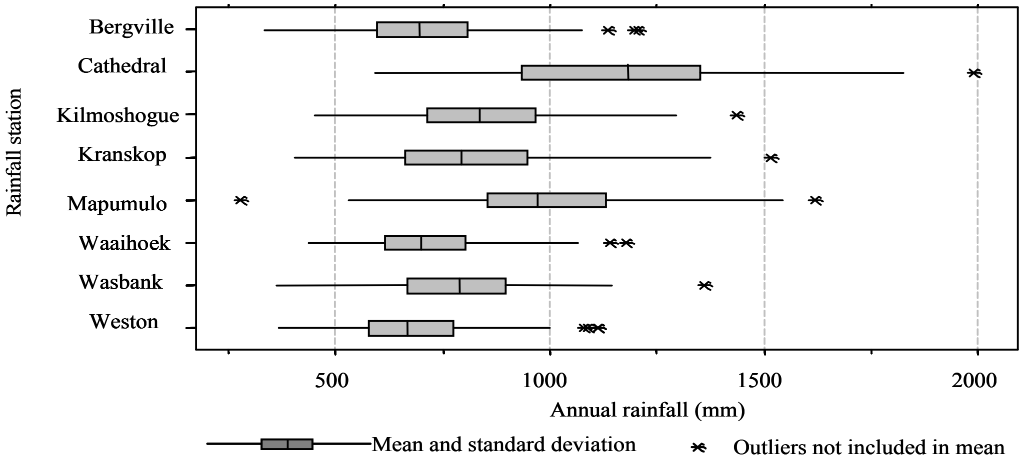

Figure 2.3: Annual rainfall characteristics (mean and standard deviation) in the eight stations from 1901-1999 data series

Table 2.3 shows the pair-wise comparison (at p≤0.05 and p≤0.01) of annual rainfall between stations.

Table 2.3: Pair-wise comparisons of annual rainfall between stations at two significant levels

p	0.01								
0.05	Station	Bergvi	Cathed	Kilma	Krans	Mapum	Waaih	Wasba	Westo
	Bergville	▨	ϕ	ϕ		ϕ			
	Cathedral	√	▨	ϕ	ϕ	ϕ	ϕ	ϕ	ϕ
	Kilmashogue	√	√	▨		ϕ	ϕ		ϕ
	Kranskop	√	√		▨	ϕ			ϕ
	Mapumulo	√	√	√	√	▨	ϕ	ϕ	ϕ
	Waaihoek		√	√	√	√	▨		
	Wasbank		√			√		▨	ϕ
	Weston		√	√	√	√			▨

√ Statistically significant at p≤0.05; ϕ Statistically significant at p≤0.01

Descriptive statistics of monthly rainfall in all stations were calculated. A summary of the monthly rainfall is provided in Fig. 2.4. On average, between April and September the mean monthly rainfall was lower than 50 mm. This period coincides with winter in the summer-rainfall region of South Africa in which the Thukela basin lies. In this region, most rainfall falls between October and March. The occurrence of peaks varied between December (Weston, Waaihoek and Kranskop) and February (Cathedral Peak). The peaks in Bergville, Kilmashogue, Mapumulo and Wasbank occurred in January. Weston and Waaihoek received their lowest rainfall in May. Of the remaining stations, June was a common month when the lowest rainfall was experienced, except at Bergville and Mapumulo where the lowest rainfall was observed in July.

Monthly rainfall variability was summarized using the coefficients of variation (CV) and the results are provided in Table 2.4. Rainfall was more variable in winter (Apr-Sept) compared to summer (Oct-Mar). Bergville, Cathedral, Waaihoek and Mapumulo stations had an average CV of 53% in summer. Weston, Wasbank, Kilmashogue and Kranskop had coefficients of 52%, 50%, 49% and 47%, respectively over this period. In winter, the average CV ranged between 112% (Mapumulo) and 141% (Bergville). Unlike summer in which the pair-wise comparison with Turkey's confidence interval method ($p \leq 0.05$ and $p \leq 0.01$) showed significant difference between all the stations except for Cathedral Peak, there were no significant differences in winter rainfall.

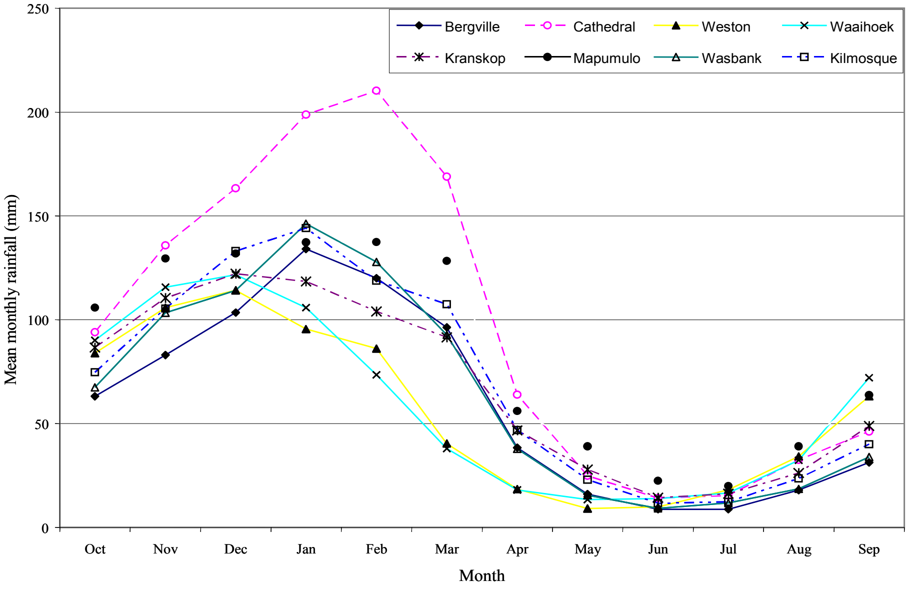

Figure 2.4: Mean monthly rainfall (1901-1999) in eight representative stations with large rainfall records in the Thukela basin

Table 2.4: Coefficient of variation (%) of monthly rainfall (1901-1999) in the eight selected station in the Thukela basin

Month/Station	Bergvi	Cathed	Weston	Waaih	Krans	Mapum	Wasba	Kilmas
October	71.2	62.7	49.4	48.9	46.4	52.9	58.2	57.7
November	54.9	60.5	45.7	42.2	42.6	48.3	49.0	48.6
December	49.3	50.4	38.7	49.5	41.8	48.2	46.6	44.8
January	44.7	43.0	48.9	51.7	44.8	43.0	41.7	44.4
February	47.6	47.4	53.2	51.6	50.7	54.9	49.7	46.6
March	52.0	51.7	74.6	74.5	55.0	68.0	54.6	50.3
April	79.7	75.0	126.7	145.6	71.0	76.4	85.9	71.1
May	145.6	105.2	171.0	167.6	147.2	126.7	123.9	118.2
June	175.7	147.9	155.0	212.5	140.5	129.0	172.4	159.2
July	173.2	210.5	133.4	141.9	160.2	133.5	166.3	155.1
August	136.6	130.5	117.0	105.1	112.8	115.5	132.0	121.4
September	133.6	104.7	65.3	55.9	122.6	91.1	112.3	104.3

2.3.2.2 Abrupt (step) changes in rainfall data.

Table 2.5 shows the specific years in which abrupt changes in the time series occurred and their respective tests of stability in the variance (F-test) and mean (T-test).

Table 2.5: Change points in the annual rainfall time series in all the stations identified by Pettitt's test and the tests of stability of variances (F-test) and means (T-test)

Station	Year[13]	F-test	T-test
Bergville	1907-1908	1.427	2.624[a]
	1925-1926	2.299	0.385
	1926-1927	2.424	0.878
	1928-1929	3.254	0.333
	1929-1930	3.612	0.328
	1942-1943	1.780	0.352
	1944-1945	4.675	1.490
	1949-1950	2.590	0.625
	1950-1951	1.980	0.147
Cathedral Peak	1906-1907	1.415	1.565
	1976-1977	2.078	0.337
Kilmashogue	1906-1907	7.407[a]	2.997[a]
	1909-1910	1.083	2.863[a]
	1911-1912	1.216	2.458[a]
	1913-1914	1.147	3.083[a]
Kranskop	1908-1909	8.488[a]	0.915
	1938-1939	3.056	0.821
	1945-1946	3.914[a]	0.382
Mapumulo	1911-1912	3.082	0.174
	1938-1939	1.347	0.810
Wasbank	1913-1914	4.763[a]	0.32
	1924-1925	2.737	3.083[a]
Weston	1906-1907	4.841	3.738[a]
	1987-1988	1.076	0.206

[a]Change point statistically significant at $p \leq 0.05$

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[13] Change point between annual rainfall values of the indicated years.

The Pettitt's test showed that the Bergville station had the highest number of change points. However, except for the test of stability of means in 1907/08, all the other tests of stability of variances and means were not significant in this station. Waaihoek was the only station that had no change point. Stations above 1400 masl (Weston, Kilmashogue and Cathedral Peak) and mainly situated in the Drakensberg ranges, had a common change point in 1906-1907. Conversely, Mapumulo and Kranskop, the two stations with lower altitudes and closer to the outlet of the basin had 1938-1939 as a common change point. Except at Kranskop where the test of stability in variances was significant in 1945-1946, all significant change points occurred before 1915. This suggests that over the past five decades of the time series, there were no significant abrupt changes. Any changes that were observed could be attributed to gradual climatic changes.

2.3.2.3 Gradual changes (trends) in annual and monthly data series

Values of the Spearman's rank correlation (S_{rc}) coefficients and the MK test are included in Table 2.2. The S_{rc} coefficients indicated a positive trend for all stations except for Wasbank. However, only Weston, Bergville and Cathedral Peak had significant trends ($p<0.05$). From the MK values obtained, all stations displayed a positive trend in rainfall except Wasbank whose annual rainfall seemed to have fluctuated uniformly about the mean. However, only four stations showed significant trends. Cathedral Peak and Weston had increasing trends in annual rainfall of about 5.5 mm.yr^{-1} while Bergville and Kilmashogue had upward trends of 2.58 mm.yr^{-1} and 1.83 mm.yr^{-1}, respectively.

The results of the 5-year moving averages are graphed in Fig. 2.5. There was a relatively similar pattern in the moving average values before 1930 after which Cathedral Peak and Mapumulo experienced increased annual rainfall. This seemed to occur in the early 1940s in the other stations. The annual rainfall in Cathedral Peak and Mapumulo differed after 1950. In general, major peaks showed a recurrence of about 10 years. This behaviour was more elaborate in the years after 1950. The troughs also depicted a similar cyclic pattern although the period was not as pronounced as the peaks.

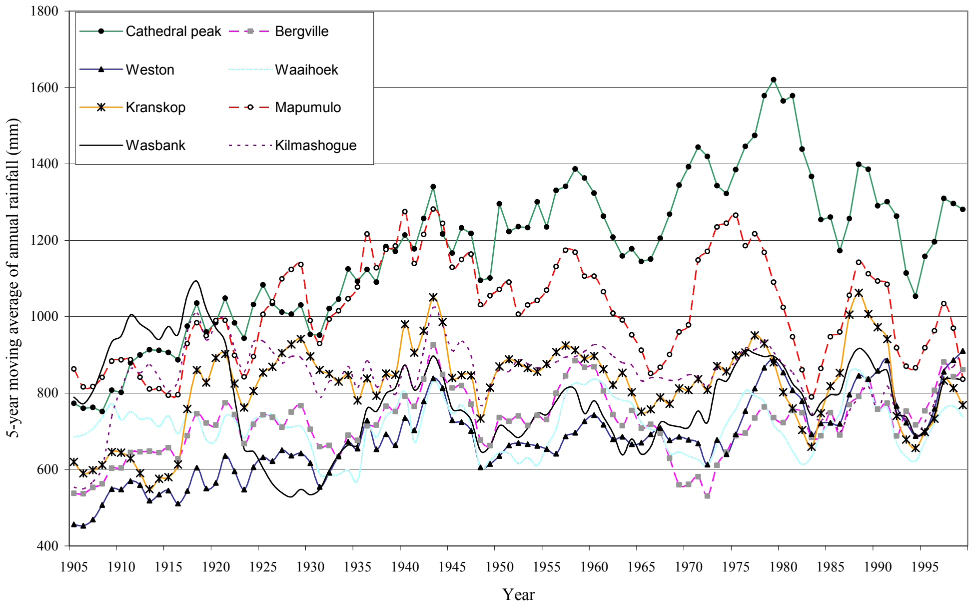

Figure 2.5: 5-year moving averages of annual rainfall from 1901-1999 for selected station in the Thukela basin

The Kendall test applied to identify trends on monthly timescales showed that in general increasing trends were experienced in summer while decreasing trends occurred in winter (Table 2.6). However, most of these trends were not statistically significant at $p \leq 0.05$. Kilmashogue, Waaihoek and Mapumulo stations revealed no statistically significant trends. Weston and Cathedral Peak had higher number of statistically significant positive trends falling mainly in January, March, November and December. Kranskop revealed statistically significant positive trends in January and October. This explains the increasing trends in annual rainfall in these three stations (Table 2.2). Bergville and Wasbank experienced statistically significant negative trends in winter. Although Bergville had a significant positive annual trend, there was no month with a statistically significant positive trend. However, two-thirds of the months revealed increasing but insignificant trends which may, through accumulation influence the annual totals.

Without regarding the level of significance, the results in Table 2.6 indicated that 5 stations experienced decreasing rainfall trends in summer. Three had negative trends in November (Mapumulo, Wasbank and Kranskop), February (Waaihoek, Wasbank and Kilmashogue) and March (Mapumulo, Waaihoek and Wasbank) while one each in December (Mapumulo) and January (Waaihoek).

Table 2.6: Monthly Mann-Kendall statistics computed from monthly rainfall records of eight stations in the Thukela basin. The p-values are provided in parenthesis

Station	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Weston	1.303	2.721[a]	3.936[a]	3.87[a]	1.569	2.742[a]	2.074[a]	-0.469	2.081[a]	0.756	0.93	0.206
	(0.0963)	(0.0033)	(0.0000)	(0.0001)	(0.0583)	(0.0031)	(0.019)	(0.3195)	(0.0187)	(0.2249)	(0.1762)	(0.4185)
Bergville	0.574	1.433	1.442	1.587	0.6137	0.8979	0.0816	-2.209[a]	-1.102	-1.39	0.585	-0.866
	(0.2829)	(0.0759)	(0.0746)	(0.0562)	(0.2697)	(0.1846)	(0.4675)	(0.0136)	(0.1353)	(0.0823)	(0.2793)	(0.1934)
Mapumulo	0.825	-0.127	-0.435	0.774	0.045	-1.421	-0.218	-1.318	-0.878	-0.5	0.85	0.65
	(0.2046)	(0.4495)	(0.3317)	(0.2195)	(0.4819)	(0.0777)	(0.4138)	(0.0937)	(0.19)	(0.3085)	(0.1978)	(0.2579)
Waaihoek	1.321	1.097	0.617	-0.181	-1.082	-1.382	0.206	-1.613	-0.8486	-1.45	-0.357	-1.186
	(0.0932)	(0.1362)	(0.2687)	(0.4280)	(0.1396)	(0.0835)	(0.4186)	(0.0533)	(0.1981)	(0.0735)	(0.3607)	(0.1179)
Wasbank	1.125	-0.49	0.314	0.191	-1.237	-2.101	-0.003	-1.044	-1.079	-1.94[a]	-0.2323	-2.041[a]
	(0.1304)	(0.3122)	(0.3766)	(0.4245)	(0.1081)	(0.0178)	(0.4988)	(0.1483)	(0.1403)	(0.0262)	(0.408)	(0.0206)
Kilmashogue	0.469	0.559	1.436	0.290	-0.810	0.296	-0.084	-1.442	0.317	0.388	1.105	-0.937
	(0.3197)	(0.288)	(0.0755)	(0.3858)	(0.2090)	(0.3835)	(0.4673)	(0.0746)	(0.3756)	(0.3491)	(0.1347)	(0.1743)
Kranskop	2.394[a]	-0.077	0.883	2.189[a]	0.559	0.112	-0.49	-1.386	-1.656	-0.941	1.321	-0.13
	(0.0083)	(0.4687)	(0.1887)	(0.0143)	(0.288)	(0.4555)	(0.3122)	(0.0829)	(0.0489)	(0.1733)	(0.0932)	(0.4483)
Cathedral Peak	2.872[a]	2.074[a]	2.452[a]	3.389[a]	3.673[a]	2.346[a]	1.128	-1.361	-0.231	-0.957	1.388	1.216
	(0.002)	(0.019)	(0.0071)	(0.0004)	(0.0001)	(0.0095)	(0.1297)	(0.0868)	(0.4087)	(0.1693)	(0.0826)	(0.1121)

[a] Statistically significant at $p \leq 0.05$

The timing of these decreasing trends could have negative impacts for small-scale rainfed maize production especially in Mapumulo (germination and grain filling-stages), Waaihoek (vegetative, tussling and grain-filling stages) and Wasbank (germination, tussling and grain-filling stages), if the monthly rainfall is lower than the monthly gross crop water requirements. Daily rainfall characteristics and field water balances would provide useful information on occurrence and severity of dry spells as described by Barron et al. (2003) and Fox and Rockström (2003).

2.3.3 Drought assessment and indices

The Rainfall Anomaly Index (RAI - Rooy, 1965) was used to investigate years that droughts were experienced. In this study a drought year was taken as any year with RAI<-3. RAI considers annual rainfall characteristics alone, while risk of failure takes into account the onset and cessation of rainfall as well as heat units. From the assessment, RAI ranged between +5.34 to -3.68 in Cathedral Peak, +0.27 to -5.36 in Bergville, -0.32 to -5.17 in Weston, +0.10 to -4.70 in Waaihoek, +2.28 to -4.92 in Kranskop, +2.95 to -5.74 in Mapumulo, +1.27 to -5.19 in Wasbank and +1.77 to -4.60 in Kilmashogue (Fig. 2.6). The stations in Fig. 2.6(a) had a mean annual precipitation (MAP) of over 800 mm while those in Fig. 2.6(b) had a MAP of less than 800 mm. There were more negative values in Fig. 2.6(b) compared to Fig. 2.6(a). Tilahun (2006) found that years having RAI<-3 correlated with annual drought. Although the study regions are not close and may not be similar, in this study values of RAI less than -3 were considered drought years. This was done to provide a comparison between stations of the frequency of yield reduction that may be expected as a result of rainfall that does not satisfy the crop water requirements. Values of RAI<-3 from all stations are shown in Table 2.7. Drought incidences varied widely in these stations. There were 50, 58 and 50 drought years in Bergville, Waaihoek and Weston, respectively. Kranskop and Wasbank had 33 and 36 drought years, respectively while both Cathedral Peak and Mapumulo each had 4 drought years. Twenty three drought years were found for Kilmashogue station. Thus, on average the drought return period was 2 years in Bergville, Waaihoek and Weston, 3 years in Kranskop and Wasbank, 4 years in Kilmashogue while it was 25 years in Cathedral Peak and Mapumulo stations. However, a good number of the drought years for most stations occurred in the first 20 years of record.

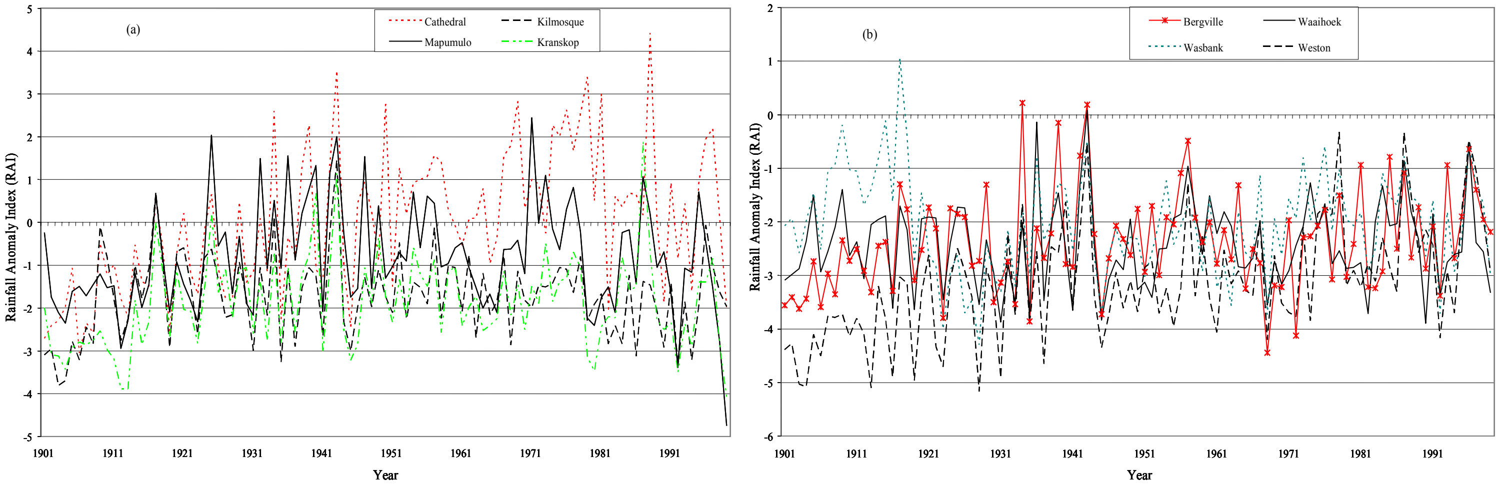

Figure 2.6: Time series of RAI for (a) Cathedral, Kilmashogue, Mapumulo and Kranskop; (b) Bergville, Waaihoek, Weston and Wasbank stations

Table 2.7: Drought occurrence derived from RAI for years with values of RAI<-3 in the eight representative stations studied in the Thukela basin

Station/Year (1900+)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33
Cathedral	■					■		■											■														
Bergville	■	■	■	■	■	■	■	■		■	■	■	■			■			■	■			■				■	■		■	■	■	■
Weston	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■		■	■	■			■	■		■	■		■
Waaihoek	■	■	■			■	■			■		■				■			■				■				■	■		■	■	■	■
Kranskop		■	■	■		■	■	■	■	■	■	■	■		■				■				■								■		■
Mapumulo												■																					
Wasbank			■			■													■		■	■	■	■	■	■	■	■		■	■		■
Kilmashogue	■	■	■	■	■	■		■				■							■				■								■		

Station/Year (1900+)	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66
Cathedral																																	
Bergville		■		■			■	■				■	■			■		■		■								■		■		■	■
Weston		■		■				■			■	■	■		■	■	■			■	■	■	■		■		■	■		■		■	■
Waaihoek		■		■			■	■				■	■	■	■		■	■	■	■	■					■					■	■	■
Kranskop		■		■				■			■	■	■												■						■		
Mapumulo																																	
Wasbank		■						■			■	■	■		■			■	■							■		■	■	■		■	■
Kilmashogue		■		■				■				■																		■			

Station/Year (1900+)	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99
Cathedral																																	
Bergville	■	■	■	■		■					■		■			■	■	■		■		■		■		■		■					
Weston		■		■	■	■		■					■		■		■			■						■		■					
Waaihoek		■	■	■	■						■	■	■	■	■	■								■		■	■	■	■			■	■
Kranskop				■									■	■										■		■		■				■	■
Mapumulo																										■						■	■
Wasbank		■		■												■	■							■		■		■					■
Kilmashogue		■														■		■		■				■		■		■					

Therefore, it was important to consider the distribution of the drought years to make useful inferences. This was summarized in Fig. 2.7. The 99 years of data were subdivided into four window periods viz. 1901-1925, 1926-1950, 1951-1975 and 1976-1999.

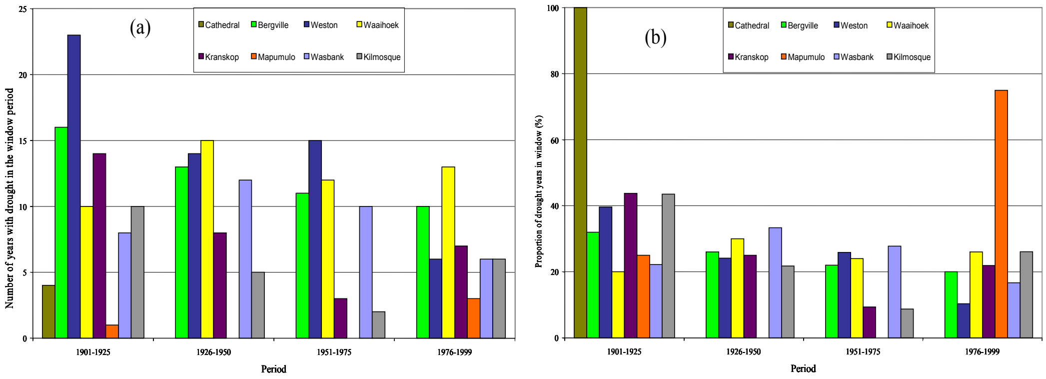

Figure 2.7: Distribution of drought years: (a) drought years in window period; (b) proportion of drought years in window relative to the total drought years in the station

For each station, Fig. 2.7(a) illustrates the percentage of drought years relative to the number of years in the window period. During the window period 1901-1925, 92% of the years were drought years in Weston. Bergville and Waaihoek had drought $\geq 40\%$ of the entire record. It was only in the 1901-1925 window period that Cathedral Peak had drought years (Fig. 2.7(b)). In addition to this window period, Mapumulo experienced drought years only during the 1976-1999 window period. There was no consistency in drought occurrence although five stations (Waaihoek, Bergville, Wasbank, Kilmashogue and Kranskop) experienced a decline of drought years in the 1951-1975 window period compared to the 1926-1950 window period. Except for Wasbank, all these station had an increase in drought years in the last window period (1976-1999). In Mapumulo 25% of the drought years happened in this window whereas the remainder was observed between 1976 and 1999. The rest of the stations experienced drought years following no particular pattern ranging from 9-44% of the total number of years considered.

The distribution of drought years, although analyzed in an annual time step, could provide an indication of the success of crop production systems. However, the crop water requirements for annual crops differ from one growth stages to another and some stages are more sensitive to water stress as compared to others. The success of maize production in rainfed agriculture partly depends on the onset of rains which determines the sowing dates. In the Thukela basin, the available soil moisture content and heat units are the main factors that influence performance of maize production after germination.

2.3.4 Onset of sowing and risk assessment

The potential start dates of sowing estimated using the three identified onset definitions (Section 2.2.5.1) are shown in Table 2.8 and Table 2.9 for the "bold" (early) and "cautious" (late) sowing strategies. Years that sowing failed (Table 2.8 and Table 2.9) were the years whose potential date of sowing occurred later than 15th February (Section 2.2.5.4). There were fewer years of failure in the 1951-1999 window compared to the 1901-1950 window which also had a higher variability in the estimated sowing dates. In over 30% of the time, sowing failed in Kranskop, Waaihoek and Weston for both strategies. More years of failure were found with the definition of sowing that considered dry spells. This indicated that dry spells play a significant role in determining the success of sowing in the Thukela basin. The probability of rain and dry spells of various lengths are shown in Fig. 2.8(a) – 2.8(d) and Fig. 2.9(a) – 2.9(d). The water balance definition provided for early sowing dates in approximately 60% of the time compared to the definition that considered dry spells. This underscores the need to consider soil hydraulic properties in such analyses. Regions with soils having good water holding capacities are likely to store more water, thus cushioning the potential negative effects that may be caused by dry spells.

On average, the "bold strategy" (November 15th) resulted in potential sowing dates which were about 3 weeks earlier than the "cautious strategy" (December 15th) in all the considered sowing definitions, although the amount of rainfall considered was lower (30 mm) than that adopted in defining dates in the "bold strategy" (40 mm). This situation suggests that even as the rainfall season progressed, the daily increment in its amount was not substantial. Fig. 2.4 shows that daily rainfall in December across all stations compared to that received in November was only about 1 mm more which may not have made any significant difference in considering a later date for sowing. In addition the probability of dry spells increases towards the end of December in most of the stations considered in this study (Fig. 2.8(a) – 2.8(d) and Fig. 2.9(a) – 2.9(d)), which delays further or diminishes the possibility of a successful sowing date. The dry spells were computed for a series of overlapping 30-day periods in successive 3-day intervals.

Table 2.8: Mean sowing dates, length of growing season and the risk of sowing for the periods 1901-1950 and 1951-1999 for the "bold strategy"

Station	Successful sowing date, B_{D1}[1]					Successful sowing date, B_{D0}[2]					Successful sowing date, B_{W0}[3]				
	No. of years sowing failed*	Start of season		Season length		No. of years sowing failed*	Start of season		Season length		No. of years sowing failed*	Start of season		Season length	
		Mean start	Std. error	Mean length	Std. error		Mean start	Std. error	Mean length	Std. error		Mean start	Std. error	Mean length	Std. error
Bergville[a]	9	21-Dec	4.2	111.3	4.5	13	25-Dec	4.5	107	4.9	14	30-Dec	5.2	100.6	5.2
Bergville[b]	1	14-Dec	3.1	116.6	3.6	4	19-Dec	3.5	111.4	3.8	3	22-Dec	3.5	107.3	4.3
Cathedral[a]	4	11-Dec	3.3	139.4	3.9	6	12-Dec	3.2	139.1	3.9	4	16-Dec	4.1	134.9	4.6
Cathedral[b]	2	04-Dec	2.4	155.3	3.4	3	04-Dec	2.1	154.1	3.4	2	08-Dec	3.7	151.2	4.4
Kilmashogue[a]	3	14-Dec	3.3	139.6	3.9	6	14-Dec	3.4	141.9	4.3	3	11-Dec	3.8	142.8	4.6
Kilmashogue[b]	2	14-Dec	2.4	155.3	3.4	4	14-Dec	3.1	135.7	4.2	3	05-Dec	3.0	144.4	4.4
Kranskop[a]	16	11-Dec	3.3	153.2	6.3	17	11-Dec	2.9	155.0	6.2	14	01-Dec	3.5	162.0	5.9
Kranskop[b]	3	10-Dec	3.2	149.0	5.8	8	10-Dec	3.0	155.2	5.7	3	28-Nov	2.5	161.8	5.4
Mapumulo[a]	12	11-Dec	4.1	171.5	6.6	16	11-Dec	2.9	179.4	5.7	5	30-Nov	2.9	179.2	5.0
Mapumulo[b]	3	09-Dec	2.8	165.9	5.6	6	09-Dec	3.0	167.9	5.3	3	21-Nov	1.6	183.9	4.5
Waaihoek[a]	20	16-Dec	4.2	115.1	4.6	25	16-Dec	4.6	115.2	5.0	17	23-Nov	5.4	109.4	5.3
Waaihoek[b]	1	09-Dec	2.6	120.0	2.8	6	12-Dec	2.7	116.5	3.1	1	08-Nov	3.4	120.8	3.5
Wasbank[a]	17	18-Dec	4.7	123.6	5.3	20	18-Dec	4.5	127.6	5.3	5	24-Dec	4.5	122.3	4.8
Wasbank[b]	2	11-Dec	3.3	132.2	4.0	7	15-Dec	3.4	127.7	4.3	1	05-Dec	3.4	137.8	4.1
Weston[a]	18	19-Dec	4.5	119.1	5.4	21	22-Dec	5.3	117.5	6.0	10	25-Dec	5.1	112.5	6.0
Weston[b]	5	13-Dec	3.1	132.0	4.4	5	15-Dec	3.1	130.6	4.6	5	11-Dec	3.5	134.3	4.4

[a,b] Denote the periods 1901-1950 and 1951-1999 respectively.

[*] Potential sowing date occurred after 15th February

[1] Any date after 15th November with a rainfall total of 40 mm in at least 4 days.

[2] Any date after 15th November with a rainfall total of 40 mm in at least 4 days without a dry spell exceeding 10 days in the next 30 days.

[3] Any date after 15th November that the water balance exceeds 40 mm in at least 4 days and does not drop to zero in the next 30 days.

Table 2.9: Mean sowing dates, length of growing season and the risk of sowing for the periods 1901-1950 and 1951-1999 for the “cautious strategy”

Station	Successful sowing date, C_{D1}[1]					Successful sowing date, C_{D0}[2]					Successful sowing date, C_{W0}[3]				
	No. of years sowing failed*	Start of season		Season length		No. of years sowing failed*	Start of season		Season length		No. of years sowing failed*	Start of season		Season length	
		Mean start	Std. error	Mean length	Std. error		Mean start	Std. error	Mean length	Std. error		Mean start	Std. error	Mean length	Std. error
Bergville[a]	13	10-Jan	4.5	88.8	3.5	19	10-Jan	2.9	90.0	3.9	18	14-Jan	3.4	85.1	3.4
Bergville[b]	2	01-Jan	2.3	93.7	3.3	10	04-Jan	2.5	94.3	3.4	5	04-Jan	2.5	90.8	3.6
Cathedral[a]	5	02-Jan	2.2	116.6	3.6	6	04-Jan	2.3	115.5	3.6	6	03-Jan	2.6	116.7	3.8
Cathedral[b]	2	29-Dec	1.8	130.3	2.9	2	31-Dec	2.1	127.6	2.9	2	26-Dec	3.7	132.9	3.0
Kilmashogue[a]	5	05-Jan	2.4	117.0	3.8	6	05-Jan	2.5	116.8	3.6	4	31-Dec	2.5	142.8	4.6
Kilmashogue[b]	3	01-Jan	1.9	117.1	3.6	8	01-Jan	2.1	118.7	3.8	4	30-Dec	2.3	119.2	3.7
Kranskop[a]	18	01-Jan	3.0	133.3	5.9	19	02-Jan	3.1	133.0	5.9	19	27-Dec	3.0	141.0	6.0
Kranskop[b]	6	06-Jan	2.3	122.5	5.6	11	06-Jan	2.5	124.7	6.0	5	28-Dec	2.2	133.1	5.5
Mapumulo[a]	15	06-Jan	2.9	147.4	5.4	20	06-Jan	2.7	154.1	5.1	7	26-Dec	2.4	153.4	4.7
Mapumulo[b]	5	01-Jan	2.2	143.7	5.4	8	04-Jan	2.6	141.7	6.0	4	22-Dec	1.7	151.9	5.3
Waaihoek[a]	23	04-Jan	2.8	95.5	4.1	32	04-Jan	2.8	98.8	4.2	21	05-Jan	3.8	96.9	4.1
Waaihoek[b]	1	30-Dec	2.0	99.3	2.0	10	31-Dec	2.1	98.5	2.4	3	31-Dec	2.4	97.7	2.5
Wasbank[a]	19	11-Jan	3.0	100.3	5.0	26	11-Jan	3.0	105.4	5.2	6	09-Jan	2.8	105.7	4.1
Wasbank[b]	2	01-Jan	2.2	115.5	3.5	11	01-Jan	1.9	110.8	3.8	2	29-Dec	2.2	114.4	3.5
Weston[a]	21	10-Jan	2.5	93.8	3.4	25	14-Jan	3.0	90.5	3.4	13	12-Jan	3.2	91.7	3.9
Weston[b]	5	31-Dec	2.4	114.0	3.6	8	01-Jan	2.7	113.8	3.8	8	31-Dec	2.8	114.7	4.3

[a,b] Denote the periods 1901-1950 and 1951-1999 respectively.

[*] Potential sowing date occurred after 15th February

[1] Any date after 15th December with a rainfall total of 30 mm in at least 4 days.

[2] Any date after 15th December with a rainfall total of 30 mm in at least 4 days without a dry spell exceeding 10 days in the next 30 days.

[3] Any date after 15th December that the water balance exceeds 30 mm in at least 4 days and does not drop to zero in the next 30 days.

Sowing after the season has advanced leads to short lengths of growing season because of the low heat units in May (<6°C except in Mapumulo and Kranskop). On average using the "bold strategy", the mean length of growing season with all sowing definitions was above 135 days in 50% of the stations and only 25% if the "cautious strategy" was adopted. The mean length in Bergville, Waaihoek, Wasbank and Weston does not reach 135 days in all cases. Based on RAI, most of these stations had droughts in more than half of the years considered (Table 2.7). In all cases, the standard error was approximately half the 95% confidence interval for the true mean sowing dates and the length of the season, suggesting that they exhibited a normal distribution. In most cases the confidence interval reflected by the width of the bars in Fig. 2.8(a) – 2.8(d) and Fig. 2.9(a) – 2.9(d), was higher in the stations that had shorter growing seasons. This may be as a result of the low probability of rainfall (p_r) which was less than 40% in these stations during this period.

Based on the sowing onset definitions, the years that sowing failed (Table 2.8 and Table 2.9) and the length of the growing season in cases where sowing was successful were used to estimate the overall risk of failure to achieve optimum yields in maize production. The probability of the length of the "active" growing season being less than either 135 days or 90 days was derived from probability plots. As an example the plot for Bergville and an illustration for Weston are shown in Fig. 2.10. It is seen that the shorter the growing season, the higher the gradient of the curve and the higher the probability of risk of failure to achieve optimum yields in maize production and vice versa. Table 2.11 contains the estimates of the risks due to failure of sowing, short growing lengths and the overall risk of maize production. A summary is provided in Fig. 2.11.

Superficially, from the mean start dates of sowing (Table 2.8 and Table 2.9) there seems to be no major differences between successful sowing dates from different onset criteria. However, a deviation of a day and a standard error of 3 days suggested that two successful dates could be up to a week apart. In Waaihoek for example, adopting the early sowing strategy, the difference in sowing dates between the water balance (S_{D2}) and the no-dry spell (S_{D1}) definitions was 23 days earlier in favour of S_{D2}. Another 10 days deviation is likely to arise considering the precision of the estimate (standard error).

There was an advance in the potential sowing date in 1951-1999 compared to 1901-1950 in all the sowing definitions. In the “bold strategy” sowing definition 1 (xref. Section 2.2.5.1, Table 2.8) the average advance in sowing dates was 4.1 days with a range of 0 to 7 days. Definitions 2 and 3 had mean advances of 3 days and 9.2 days, respectively and corresponding ranges of 0-8 days and 4 to 19 days. In the “cautious strategy” sowing definitions 1, 2 and 3 (Table 2.9) had average advances of 4.8, 4.4 and 5.6 days, respectively. The corresponding ranges were -5 to 11 days, -4 to 13 days and -1 to 12 days. Kranskop was the only station whose potential sowing dates lagged in the 1951-1999 period in relation to 1901-1950. Because definition 3 considers field water balance, the findings indicated that suitable sowing dates have shifted forward for up to 2.5 weeks in 1951-1999 compared to 1901-1950. This is an important observation in the sense that the water balance approach has shown that it is a superior method to follow over the other sowing definitions. Secondly, the *Induna* could revise the cattle calendar and livestock confined need to happen approximately a month earlier to allow for timely land preparation and sowing.

Thus, onset of rainfall is correlated with sowing. However, Kipkorir et al. (2007) observed that frequently successful germination occurs due to an early storm but seedlings do not survive too long dry periods that immediately follow. Such false starts of the season can be avoided by introducing a requirement of intolerable dry days in a certain period following the potential start date (Raes et al., 2004; Stern et al., 2003). The probability of rainy and dry days is discussed in the following section.

2.3.5 Probability of wet and dry spells

The probability of wet and dry spells was computed using routines in INSTAT+ for Windows (Stern et al., 2003). The average percent probabilities of spells are given in Table 2.10 while probabilities for each station are illustrated in Fig. 2.8 and Fig. 2.9.

There is less likelihood of dry spells in 1901-1950 compared to 1951-1999. Thus the increasing trend in annual and seasonal rainfall observed in some stations (xref. Section 2.3.2.3) could be attributed to increased intensities (xref. Chapter 2 Section 3.4.2) and/or amount of rainfall per rainy day because there was no increase in number of rainy days and the probability of rainfall was decreasing (Table 2.10).

During sowing, the range of probability of occurrence of dry spells in stations with MAP > 800 mm was 15-25% while in those with MAP <800 mm the range was 35-50% (Table 2.10). The probability of rainfall was about 40% and 35% in the two categories, respectively. The true sowing dates could be predicted with more certainty in stations with MAP higher than 800 mm.

Table 2.10: Average percent probabilities of wet and dry spells from all stations categorized according to MAP in two periods (1901-1950 and 1951-1999)

MAP		>800 mm		<800 mm	
Spells/Period		1901-1950	1951-1999	1901-1950	1951-1999
Wet spells	P_r	34.9	29.3	30.8	22.0
	P_rd	27.0	23.4	21.4	18.6
	P_rr	54.1	43.1	50.6	33.7
Dry spells	P_7-day	70.5	78.8	83.5	89.1
	P_10-day	43.8	53.6	58.9	67.1
	P_14-day	25.5	33.1	36.9	44.2

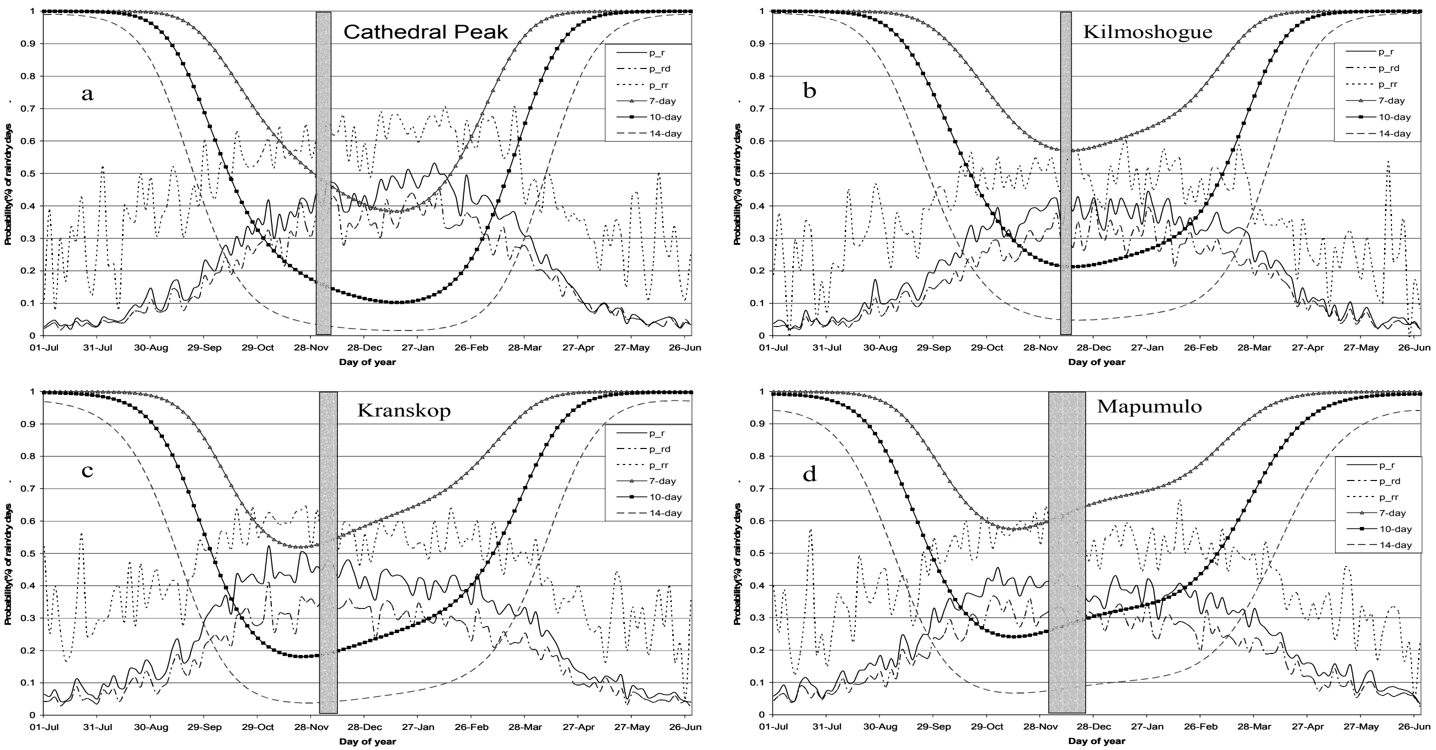

Figure 2.8: Observed average probability of rainfall occurrence on any day during the year (p_r), probability of rain if previous day was dry (p_rd) or received rainfall (p_rr), probability of dry spells exceeding 7, 10, and 14 days (7-day, 10-day and 14-day respectively) for: (a) Cathedral; (b) Kilmashogue; (c) Kranskop and (d) Mapumulo. The shaded bars indicate the mean estimated onset of sowing. The width of the bars represents the range in which the true sowing dates (estimated at 95% confidence level) lie

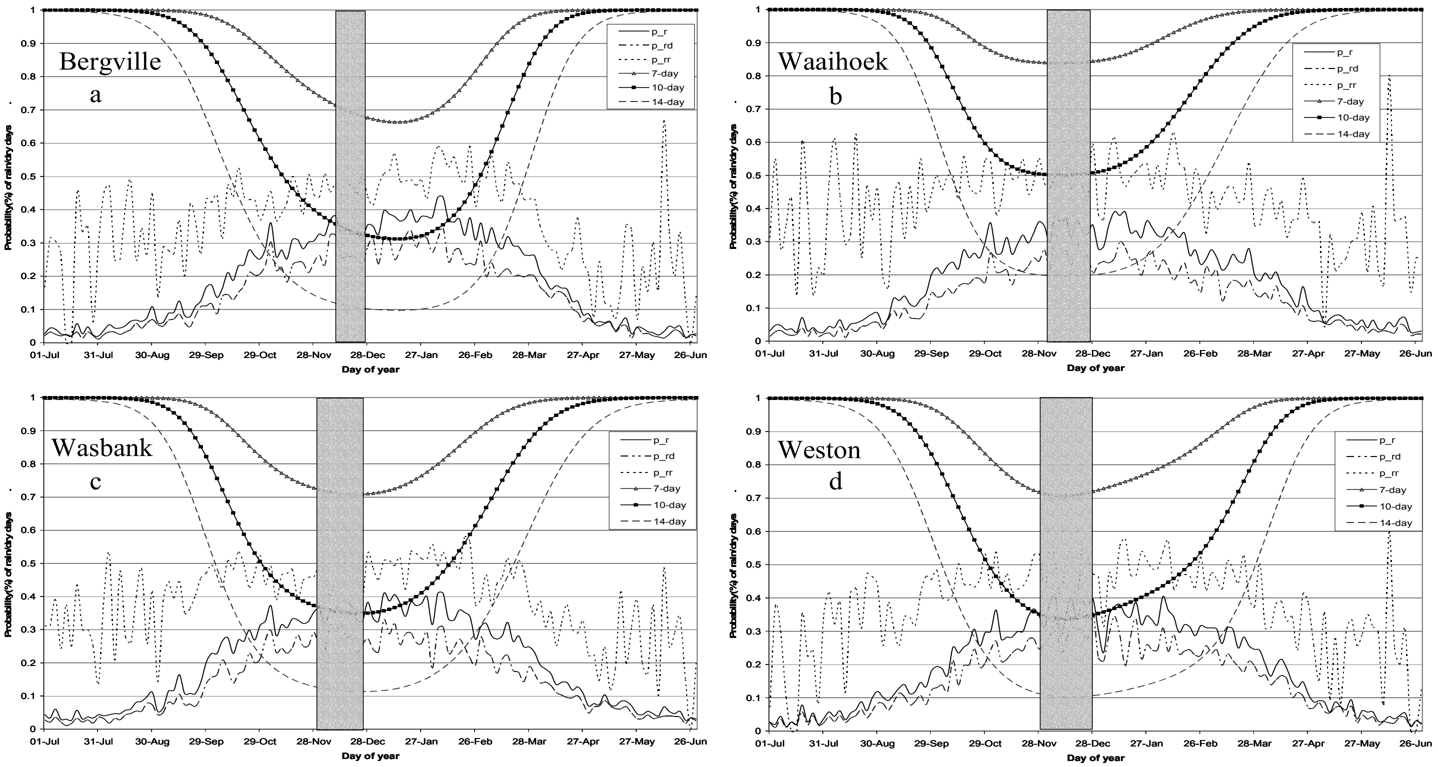

Figure 2.9: Observed average probability of rainfall occurrence on any day during the year (p_r), probability of rain if previous day was dry (p_rd) or received rainfall (p_rr), probability of dry spells exceeding 7, 10, and 14 days (7-day, 10-day and 14-day respectively) for: (a) Bergville; (b) Waaihoek; (c) Wasbank and (d) Weston. The shaded bars indicate the estimated mean onset of sowing. The width of the bars represents the range in which the true sowing dates (estimated at 95% confidence level) lie

Table 2.11: Percent probability risk of having the length of the “active” growing season less or equal to 90 and 135 days and the overall risk of maize production based on three sowing definitions and two sowing strategies

Station	Period		1901-1950			1951-1999			1901-1950			1951-1999		
	Definitions		B_{D1}[a]	B_{W0}[b]	B_{W0}[c]	B_{D1}[a]	B_{W0}[b]	B_{W0}[c]	C_{D1}[d]	C_{W0}[e]	C_{W0}[f]	C_{D1}[d]	C_{W0}[e]	C_{W0}[f]
Bergville	Risk (sowing)		18	26	28	2	8	6	26	38	36	4	20	10
	Risk (Length)	<135	78	80	78	76	80	80	96	96	96	94	95	95
		<90	27	35	39	17	21	33	54	54	49	40	40	48
	Overall risk	**<135**	**82**	**85**	**84**	**76**	**82**	**81**	**97**	**98**	**97**	**94**	**96**	**96**
		<90	**40**	**52**	**56**	**19**	**27**	**37**	**66**	**71**	**67**	**42**	**52**	**53**
Cathedral	Risk (sowing)		8	12	8	4	6	4	10	12	12	4	4	4
	Risk (Length)	<135	52	58	60	18	22	26	90	94	89	46	52	40
		<90	28	29	18	0	0	6	18	29	31	5	5	7
	Overall risk	**<135**	**56**	**63**	**63**	**21**	**27**	**29**	**91**	**95**	**90**	**48**	**54**	**42**
		<90	**34**	**38**	**25**	**4**	**6**	**10**	**26**	**38**	**39**	**9**	**9**	**11**
Kilmosque	Risk (sowing)		6	12	6	4	8	6	10	12	8	6	16	8
	Risk (Length)	<135	41	46	41	52	56	40	80	85	70	75	83	78
		<90	18	23	18	12	15	14	29	29	28	22	29	25
	Overall risk	**<135**	**45**	**52**	**45**	**54**	**60**	**44**	**82**	**87**	**72**	**77**	**86**	**80**
		<90	**23**	**32**	**23**	**16**	**22**	**19**	**36**	**38**	**34**	**27**	**40**	**31**
Kranskop	Risk (sowing)		32	34	28	6	16	6	36	38	38	12	22	10
	Risk (Length)	<135	82	86	57	45	49	22	100	100	100	69	75	56
		<90	50	55	43	14	21	9	65	69	78	31	48	24
	Overall risk	**<135**	**88**	**91**	**69**	**48**	**57**	**27**	**100**	**100**	**100**	**73**	**81**	**60**
		<90	**66**	**70**	**59**	**19**	**34**	**14**	**78**	**81**	**86**	**39**	**59**	**32**
Mapumulo	Risk (sowing)		24	32	10	6	12	6	30	40	14	10	16	8
	Risk (Length)	<135	52	61	24	23	28	8	72	86	48	36	44	8
		<90	36	49	13	8	12	0	50	72	18	15	35	0
	Overall risk	**<135**	**64**	**73**	**32**	**28**	**37**	**14**	**80**	**92**	**55**	**42**	**53**	**15**
		<90	**51**	**65**	**22**	**14**	**23**	**6**	**65**	**83**	**29**	**24**	**45**	**8**
Waaihoek	Risk (sowing)		40	50	34	2	12	2	46	64	42	2	20	6
	Risk (Length)	<135	100	100	100	78	90	60	100	100	100	96	100	100
		<90	86	100	85	12	28	25	100	100	97	25	50	31
	Overall risk	**<135**	**100**	**100**	**100**	**78**	**91**	**61**	**100**	**100**	**100**	**96**	**100**	**100**
		<90	**92**	**100**	**90**	**14**	**37**	**27**	**100**	**100**	**98**	**27**	**60**	**35**
Wasbank	Risk (sowing)		34	40	10	4	14	2	38	52	12	4	22	4
	Risk (Length)	<135	100	100	82	44	65	34	100	100	98	80	98	78
		<90	78	78	28	14	28	11	100	100	45	22	44	19
	Overall risk	**<135**	**100**	**100**	**84**	**46**	**70**	**35**	**100**	**100**	**98**	**81**	**98**	**79**
		<90	**85**	**87**	**35**	**17**	**38**	**13**	**100**	**100**	**52**	**25**	**56**	**22**
Weston	Risk (sowing)		36	42	20	10	10	10	42	50	26	10	16	16
	Risk (Length)	<135	100	100	88	72	72	62	100	100	100	89	90	95
		<90	77	92	63	21	22	22	100	100	86	28	37	42
	Overall risk	**<135**	**100**	**100**	**90**	**75**	**75**	**66**	**100**	**100**	**100**	**90**	**92**	**96**
		<90	**85**	**95**	**70**	**29**	**30**	**30**	**100**	**100**	**90**	**35**	**47**	**51**

[a] Sowing date after 15th November defined by a cumulative rainfall depth of 40 mm in a maximum of 4 days without a dry spell exceeding 10 days within the next 30 days.

[b] Sowing date after 15th November defined by only a cumulative rainfall depth of 40 mm in a maximum of 4 days..

[c] Sowing date after 15th November defined by a water balance that exceeds 40 mm in a maximum of 4 days and does not drop to zero before 30 days elapse.

[d] Sowing date after 15th December defined by a cumulative rainfall depth of 30 mm in a maximum of 4 days without a dry spell exceeding 10 days within the next 30 days.

[e] Sowing date after 15th December defined by only a cumulative rainfall depth of 30 mm in a maximum of 4 days.

[f] Sowing date after 15th December defined by a water balance that exceeds 30 mm in a maximum of 4 days and does not drop to zero before 30 days elapse.

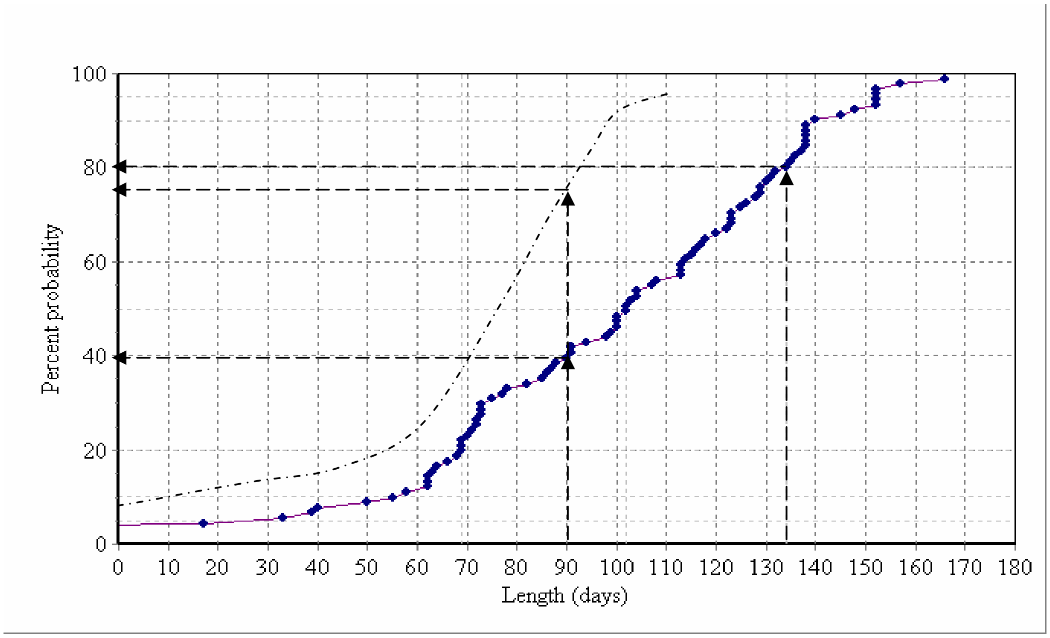

Figure 2.10: Percent probability plot of “active” length of the growing season in Bergville for the definition B_{w0} (1901-1999). The dotted line is an illustration of the probability of the “active” length of season being less or equal to 135 and 90 days in Weston for the definition B_{D1} (1901-1950)

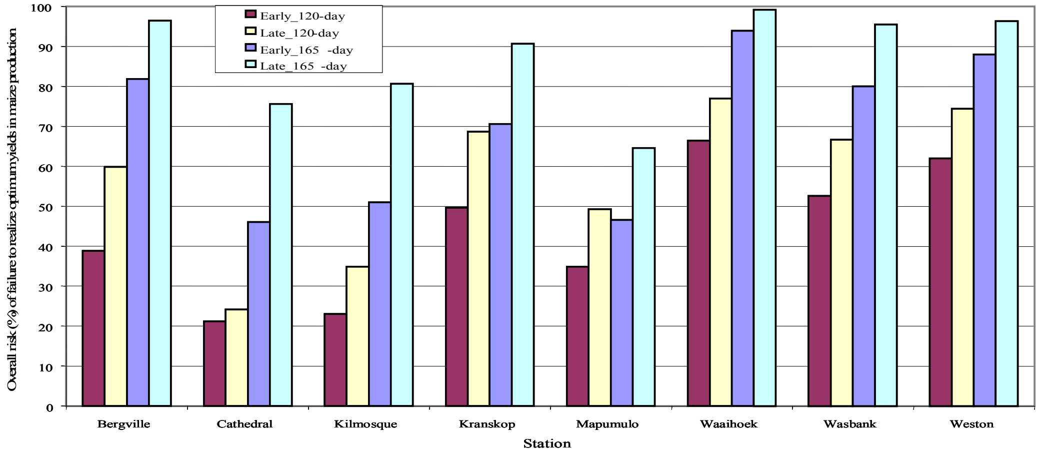

Figure 2.11: Overall risk of failure to achieve optimum yields in maize production averaged for the period 1901-1999

From the analyses, except in Mapumulo there was a reduction in maize yields or crop failure of maize with 165 days to maturity in at least 3 out of every 4 years in the Thukela basin if sowing is done after 15th December. For this variety, failure to attain optimum yields was over 95% in

Bergville, Waaihoek, Wasbank and Weston stations. These stations had the shortest growing lengths. Early sowing (15th November) using the 120-day variety gave the lowest risk although it ranged between 21% and 66%. Better rainfall (>800 mm) could have enabled Cathedral, Mapumulo and Kilmashogue to have a relatively lower risks than the other stations. Thus, over 60% of the stations considered had higher chances of reduced yields attributed to dry spells. In addition to rainfall, higher heat units towards the end of the season means that Mapumulo has the lowest risk for late sowed long duration maize varieties.

2.4 Conclusion

In this paper, a number of statistical methods were used to describe the properties of rainfall records (1901-1999) at three time scales viz. annual, monthly and daily for eight stations in the Thukela basin which was attributed to increase in the amount of rainfall per day rather than increases in rainy days. However, five stations had negative trends in monthly rainfall in some months. The seasonal amount of rainfall in all the stations is adequate for maize production and is therefore not the primary limiting factor to maize production in the Thukela Basin. However, the early season dry spells that delay sowing shortened the length of the growing season because low heat units at the end of the season do not permit optimum yiels. Thus, dry spells and temperature play a more significant role in achieving optimum crop production in the Thukela Basin. These findings suggested that inferences made from statistical properties of climatic factors based on annual or seasonal series cannot be used adequately for decision making in crop management but must be complemented with field-scale water balances at shorter time steps.

The frequency and severity of dry spells was shown to have a significant role in determining the success of sowing in the Thukela basin. The inclusion of soil hydraulic properties gave relatively earlier sowing dates suggesting that methods that improve infiltration and water holding capacity are likely to reduce the risk of failure in maize production in rainfed cropping systems. The *Induna* needs to move the livestock from the cropping areas approximately a month earlier to allow for timely land preparation and sowing as the sowing dates have advanced up to about 3 weeks. This indicated that the analyses of rainfall can result in useful information that can change certain ways of life in the society, hence potentially improving leivelihoods..

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3.0 FIELD SCALE EXPLORATION OF HYDROLOGICAL RESPONSES TO TILLAGE USING HYDROMETRIC MONITORING AND ELECTRICAL RESISTIVITY IMAGING SURVEY

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Abstract

Reliable estimates of components of the hydrological cycle are essential when addressing water availability for plant growth. These components are connected by complex interrelationships that vary in space and time and are influenced by climate and land use, among other factors. Water is a limiting resource to crop production in arid and semi-arid lands (ASALs) and is responsible for substantial yield losses annually. In-situ water harvesting techniques in the form of conservation agriculture practices have been identified and promoted as measures that can improve soil water availability and thus enhance crop yields. Tillage influences water flow paths at field scale. Quantifying hydrological fluxes enables better understanding of rainfall responses, productive and non-productive water transition processes and thus to evaluate cropping and management systems and potential downstream impacts.

This study investigated the effects of two tillage systems viz. no-till (N_T) and conventional tillage (C_T), under maize (*Zea mays L.*) production, on soil physical properties and field-scale water fluxes at four experimental sites in the Potshini catchment, South Africa during the 2005/06 - 2007/08 seasons. Each treatment in the form of a runoff plot was equipped with equipment and accessories that enabled soil moisture and runoff to be monitored. Rainfall was measured using both automatic and manual rain gauges. Soil moisture profiling using the Time Domain Reflectometry (TDR) was augmented with granular matrix sensors and an electrical resistivity tomography (ERT) imaging survey. A nearby weather station provided the necessary meteorological data. Comparisons of the rainfall responses from the two tillage systems were performed using descriptive statistics of field measurements and simulation outputs from the Parched-Thirst (PT) model.

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There were significant differences ($p<0.05$) in average bulk density from C_T plots between sites. Over 95% of the rainfall events in the study area had intensities lower than 10 $mm.h^{-1}$ and are likely to result in saturated-excess overland flow (SOF). The average cumulative runoff was 7% and 9% of seasonal rainfall in N_T and C_T treatments over the three seasons. Higher soil moisture was recorded at a depth of 60 cm in N_T treatments and at 30 cm in the C_T treatments. Significant differences ($p<0.05$) were observed in weekly soil moisture content between tillage treatments and also between seasons. Lower resistivity values were obtained in N_T plots, but did not indicate any significant difference between tillage systems. About 45% of the total soil evaporation occurred in December and January. Annually, although 67% were non-productive fluxes, N_T treatments enabled water savings of about 1% of annual rainfall compared to C_T treatments. There was a difference in both tillage systems of a factor of 3 between the observed runoff and that simulated by the Parched-Thirst (PT) model. Although there was less runoff, better infiltration and root zone moisture in N_T systems relative to C_T, these differences were not significant.

Keywords: conventional tillage; evaporation; model; moisture; no-tillage; runoff.

3.1 Introduction

The hydrological cycle is a vital link of numerous processes in hydrology, soil science, geology, ecology, meteorology and agronomy, among others. Rainfall, interception, soil moisture, runoff, total evaporation and deep percolation are some of the key components of the hydrological cycle. An important goal in agriculture is the need to optimize the use of natural resources, particularly water which is limited in arid and semi-arid areas (ASALs). Low and unstable yields characterize farming activities in these environments (Rockström and Valentin, 1997; Srivastava et al., 2004) and have been linked partly to low and erratic rainfall (Lal, 1991; Rockström and de Rouw, 1997; Postel, 1999; Rockström, 2000; Seyam et al., 2002; Gowing, 2003), poor water partitioning at field scale (Rockström et al., 1998 ; Hatibu et al., 2000; Rockström, 2003) as well as poor soils (Foth and Ellis, 1997; Klaij and Vachaud, 1999; Rockström and Falkenmark, 2000; Fox and Rockström, 2000; Lafond et al., 2006). The complementary interaction between water and nutrients could lead to poor water partitioning (primarily between soil moisture storage and transpiration) and moisture and nutrient use inefficiency (Rockström, 1999; Breman et al., 2001; Gowing, 2003; Heerink, 2005; Wichelns, 2006).

Rainfall is the major determinant of land use in dry areas where alternative sources of water e.g. for irrigation are limited. The antecedent soil moisture, soil surface characteristics (e.g. roughness, slope) and rainfall characteristics (e.g. intensity, duration) determine the path that rainwater may follow. Water that runs off after a rainfall event has been termed 'blue' water while 'green' water refers to the portion of soil water storage that is lost as total evaporation (Falkenmark, 1995; Savenije, 1999; Rockström, 2000). Jewitt et al. (2004) viewed this categorization as a promising approach that could aid the efficient management of water resources under changing land use, supporting an earlier call by Rockström and Gordon (2001) who observed that most water resources assessments focus only on about 3 % of the global hydrological cycle i.e. the proportion of water flow withdrawn from rivers without considering the dominating return flows of water vapour from rainfed crops, grasslands, forests, wetland flora, and grazing lands.

Hatibu et al. (2000) observed that water partitioning between 'green' and 'blue' water flow is dynamic since blue water formed from rainfall partitioning in a crop field upstream of a watershed may follow a series of 'green' – 'blue' flow paths before the final 'blue' water flow is determined from measurements of surface and groundwater recharge at the outlet of the catchment/basin. Furthermore, there are upstream blue water withdrawals for irrigation, household purposes and for livestock from e.g. shallow water tables, small surface and sub-surface storage systems and dams, ephemeral water ways etc that does not reach the perennial water systems where the blue water resource monitoring is generally carried out. Hence the need to quantify at field, watershed and catchment scales the actual return flows of water.

This study endeavoured to provide greater understanding of the pathways that water may follow at field scale (~100 m^2). Gerbens-Leenes and Nonhebel (2004) suggested that the hydrological system of a crop field comprise six water flows: precipitation, drainage, runoff, evaporation from the soil, transpiration from plant leaves, and irrigation as illustrated in Fig. 3.1. Flow 1 represents the total supply of precipitation (vertical) and exogenous inflow (horizontal). Flow 2 is the horizontal output of water that runs into rivers and streams (runoff), and the vertical downward flow leaving the root zone of plants to lower layers (groundwater and eventually to open water). Flow 3 represents the water evaporated from the soil and Fow 4 is the water flow that actually passes through crops as transpiration.

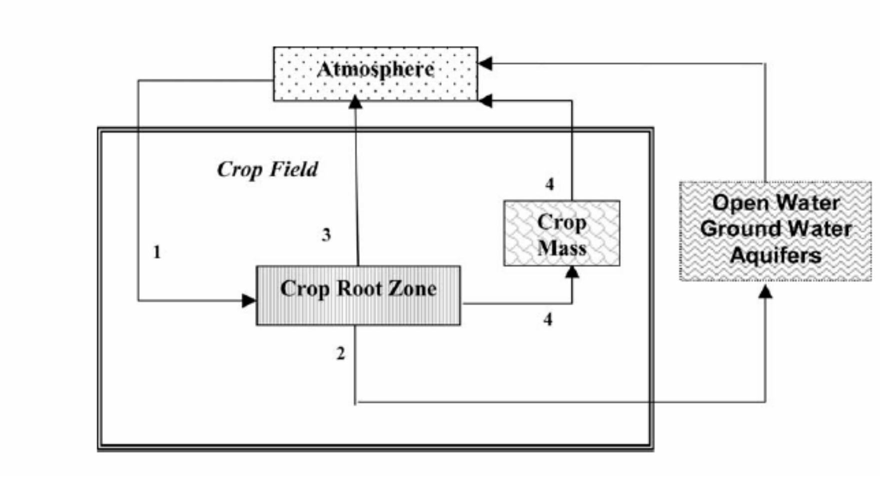

Figure 3.1: Simplified overview of the two water stocks, the 'crop root zone' and the 'crop mass' in a crop field (Gerbens-Leenes and Nonhebel, 2004)

Using hydrometric monitoring and electrical resistivity tomography (ERT) imaging, this study endevoured to determine the water stocks illustrated in Fig. 3.1.

3.2 Smallholder crop production in ASALs

At field scale, some studies have shown between 70-85% of rainfall to be non-productive water flows (Rockström, 1999) dorminated by rapid runoff to sinks, from where it is often not economical to recover for beneficial use (Hatibu et al., 2000). Runoff may occur either because the pore space is full of water and there is no longer any storage capacity (saturation-excess overland flow - SOF) or when the rainfall intensity exceeds the infiltration capacity of the soil (Hortonian overland flow - HOF). Subject to the initial moisture content, the rainfall intensity and duration, rainfall events could result in runoff that is either HOF or SOF. For example, in Potshini catchment Kosgei et al. (2007) reported that in 2005/06 season, about a quarter of the rainfall events were single-peak events with some having intensities as much as 21 $mm.hr^{-1}$ while the other events had up to five peaks and intensities lower than 2 $mm.hr^{-1}$. Therefore, it is important to identify the dominant and/or the seasonal dynamics of runoff generation processes in ASALs as they influence, for instance, the possible options to enhance water infiltration and conservation that can be adopted.

Maximizing precipitation use for rainfed agriculture in ASALs is concerned fundamentally with maximizing the productivity of the soil-plant-atmosphere system per unit of rainfall (Bennie and Hensley, 2000). Thus, knowledge of all processes that deplete the soil water storage e.g. potential total evaporation rates which has been reported to be more than twice the mean annual precipitation in South Africa (Schulze et al., 1995; Walker and Schulze, 2006) is critical. According to Williams et al. (2004), the strong positive correlation between total evaporation and ecosystem production highlights the role of water as a principal limiting resource for plant photosynthetic metabolism. As suggested by Rockström and Falkenmark (2000), vapour shifts in favour of increased transpiration water compared to evaporated water results in enhanced biomass production. It is thus relevant to distinguish water lost through direct soil evaporation from that transpired by plants to understand the biotic and abiotic factors underlying the efficiency with which water is utilized.

A number of approaches have been developed to measure directly or to derive total evaporation (evaporation and transpiration). Over a long period of time, soil evaporation and crop transpiration have generally been computed from field data, or as residuals in water balances. However, there is a need to evaluate and compare new methods before they could be reliably applied. Kite and Droogers (2000) compared 8 different methods of estimating actual evaporation and transpiration using a common database. These included field methods (e.g. FAO Penman-Monteith, large aperture scintillometer), hydrological methods (e.g. SWAP, SLURP) and remote sensing techniques (e.g. SEBAL). Their findings did not identify a superior method between the three groups as the methods showed varied temporal and spatial capabilities. The authors concluded that no single method is ideal but using a combination of methods will complement each other and prove better than any technique used alone.

Soil moisture is the residual of the transition of fluxes at the ‘crop root zone’ (Fig. 3.1) and depends on the input (Flow 1) and the depleting processes (Flows 2, 3 and 4). Knowledge of the temporal and spatial variability of moisture content in a soil provides useful insights in defining its land-use function, workability, the extent to which it can support crop growth and its potential to act as an intermediary in the hydrological cycle. O’Loughlin (1990) argued that there is no single hydrological output variable that does not primarily relate to soil moisture. According to Walker et al. (2004) the standard method of measuring soil moisture is the thermogravimetric method, a time-consuming and destructive procedure that does not allow for repetitive measurements at the same location. The authors suggested alternative measurement methods which can be automated and include neutron scattering, gamma ray attenuation, soil electrical conductivity (e.g. electrical conductivity probes, electrical resistance blocks, and electromagnetic induction), tensiometry, hygrometry (e.g. electrical resistance, capacitance, piezoelectric sorption, infra-red absorption and transmission, dimensionally varying element, dew point, and psychometric), and soil dielectric constant (e.g. capacitance and time domain reflectometry).

With regard to crop production, the availability of plant extractable soil moisture in the root zone is more critical than the frequency of occurrence of the dry spells. This makes the relationship among rainfall characteristics, seasonal crop water requirements and local soil hydraulic properties at field scale fundamental in understanding water flow paths resulting from individual rainstorms. Hence for a particular rainfall event and soil texture, in addition to the conditions on the soil surface and near-surface and catchment relief and geometry, antecedent moisture content plays a significant role in determining which path water may immediately follow: how much will infiltrate, runoff, evaporate or pond in depressions? Does the whole portion that infiltrates remain in the root zone, and by how much does it increase the moisture content? These questions have no immediate answers unless continuous observations are done.

Various tillage practices affect differently the surface and near-surface soil properties and may as well influence their hydraulic properties. Lorentz et al. (2001) argued that tillage methods influence mechanisms of lateral flow, infiltration, affect storage, redistribution and residence times of water at field scale. This could be due to changes in pore size distribution which is responsible for water infiltration, storage and transmission (Azooz et al, 1996; Moreno et al., 1997; Whilhem and Mielke, 1998; Angulo-Jaramillo et al., 2000; Lipiec et al., 2006). No-till (N_T), which entails the preparation of the immediate seed zone (Kosgei et al., 2007), has been reported to increase infiltration rate, reduce evaporation losses, increase soil water holding capacity and reduce the oxidation of organic matter (Unger and Vigil, 1998; Misika and Mwenya, 1998; Smith et al., 2001; Fowler and Rockström, 2001; Yates et al., 2006). Even though the contribution to increased infiltration and subsequently yield from N_T systems in relation to conventional tillage (C_T) systems (where 100% of top soil is inverted by ploughing) may be apparent to some, little is known about the resulting in situ hydrological properties of soils in semi-arid regions (Azooz et al., 1996; Twomlow and Bruneau, 2000) which are largely occupied by resource-poor smallholder rainfed farmers who mostly rely on hand tools and animal drawn implements for land preparation (Kosgei et al., 2007). In addition, findings from other regions cannot be universally applicable (Lal, 1989; Moreno et al., 1997) because the effect of a specific management system on water partitioning depends on the meteorological conditions at the focal site (Lampurlanés and Cantero-Martínez, 2006).

The hypothesis of this study was that, in relation to conventional tillage plots, no-tillage plots reduce run-off, hold more soil moisture and lead to higher maize yields. The objective of the study was to better understand and quantify the flow pathways of water at field scale was undertaken to provide insights into viable solutions to the chronic low yields experienced among smallholder farmers in Potshini catchment, Thukela River basin in South Africa. Attempts to quantify water flow fluxes that occur under N_T and C_T in four sites under maize (*Zea Mays L.*) production were made. By virtue of its relatively high water requirements (Cavero et al., 2000), crop losses in maize in individual seasons close to 60% have been reported in Southern Africa (Rosen and Scott, 1997 in Monneveux et al., 2006). Therefore, in catchments such as Potshini, where dry spells are common (xref. Chapter2, Section 2.3.5) and water management is internationally relevant as it forms part of a World Heritage site[14], any alteration in water flows through practices such as extensive water harvesting could have serious implication for the generation of goods and services downstream. However, interventions to enhance crop production have to be undertaken if food production and income levels which are generally very low are to be improved in the catchment (xref. Chapter 8, Section 8.3.2). Thus, each experimental site was equipped with devices to monitor the water transition processes from 2005/06-2007/08 seasons.

An attempt was made to link the measured fluxes through rainfall-runoff modeling. In this study, the Parched-Thirst (Predicting Arable Resource Capture in Hostile Environments During The Harvesting of Incident Rainfall in the Semi-arid Tropics), a process-based model which combines the simulation of hydrology with growth and yield of a crop on any number of distinct or indistinct runoff producing areas and runoff receiving areas (Young et al., 2002; SWMRG, 2006) was used. It is a distributed model, which simulates the rainfall-runoff process, soil moisture movement and the growth of a wide variety of cereals in response to daily climatic

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[14] An area may be declared a World Heritage site if it harbors natural features consisting of physical and biological formations or groups of such formations, which are of outstanding universal value from the aesthetic or scientific point of view; or geological and physiographical formations and precisely delineated areas which constitute the habitat of threatened species of animals and plants of outstanding universal value from the point of view of science or conservation; or natural sites or precisely delineated natural areas of outstanding universal value from the point of view of science, conservation or natural beauty (UNESCO, 1972).

data. It is physically based, and thus uses parameters which are measurable and do not require long series of historical data for calibration (Young et al., 2002). However, where data are difficult to obtain, three data pre-processors are available i.e a climate generator, a rainfall disaggregator and pedotransfer functions.

3.3 Materials and methods

3.3.1 Location, soils and land use

The field experimental site for this study is Potshini catchment (29.37^{0}E, 28.82^{0}S) which is located in the western headwaters of the Thukela River in the Emmaus Quaternary Catchment (V13D) in the foothills of the Drakensberg Mountains (Fig. 3.2). The field scale experiments are concentrated in an area of about 1.2 km^2. The mean annual precipitation at Potshini, measured from the SAWS[15] Bergville weather station located 7 km away, is 710 mm per annum (1901-1999). Nevertheless, this rainfall is strongly seasonal and occurs only in summer (October–March). Winter (May-September) is typically dry and is characterized by very high velocity dry winds that could have a significant effect on potential total evaporation (Fig. 3.14). The mean annual potential evaporation is approximately 1750 mm per annum (Smith et al., 2004).

Streams provide water for domestic and livestock use in the upper part of the catchment, while replenishing reservoirs for commercial farmers downstream (xref. Chapter 8, Fig. 8.1). Over the three year study period (2006-2008), extreme low stream flows occurred in between June and August in the first year while they ceased to flow in May and July in 2007 and 2008, respectively. The general topography of the study area falls gently north easterly with parallel undulating low lying mountains rising between seasonal streams. The altitude ranges from 1100 masl to about 1400 masl.

The vegetation is largely moist upland grassland that has a good early-season growth and palatability, but deteriorates rapidly during winter perhaps due to the prevailing harsh weather conditions (dry and low temperatures) and intense grazing due to a large number of livestock that are confined to a communal grazing land over summer while they graze within the

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[15] South African Weather Services

farmlands in winter. Maize is currently the main food crop produced. Smith et al. (2001) classified the soils in the study area into four major soil types[16] viz. Hutton (*Oxisols*), Avalon (Ferralsols), Estcourt (*Planosols*) and Mispah (*Lithosols*) soil patterns. However, the textural classification of the plots used was sandy clay loam with varied proportions of soil separates. Thorrington-Smith (1960) broadly classified soils in the Ladysmith-Bergville plain as of Karoo system and Beaufort series.

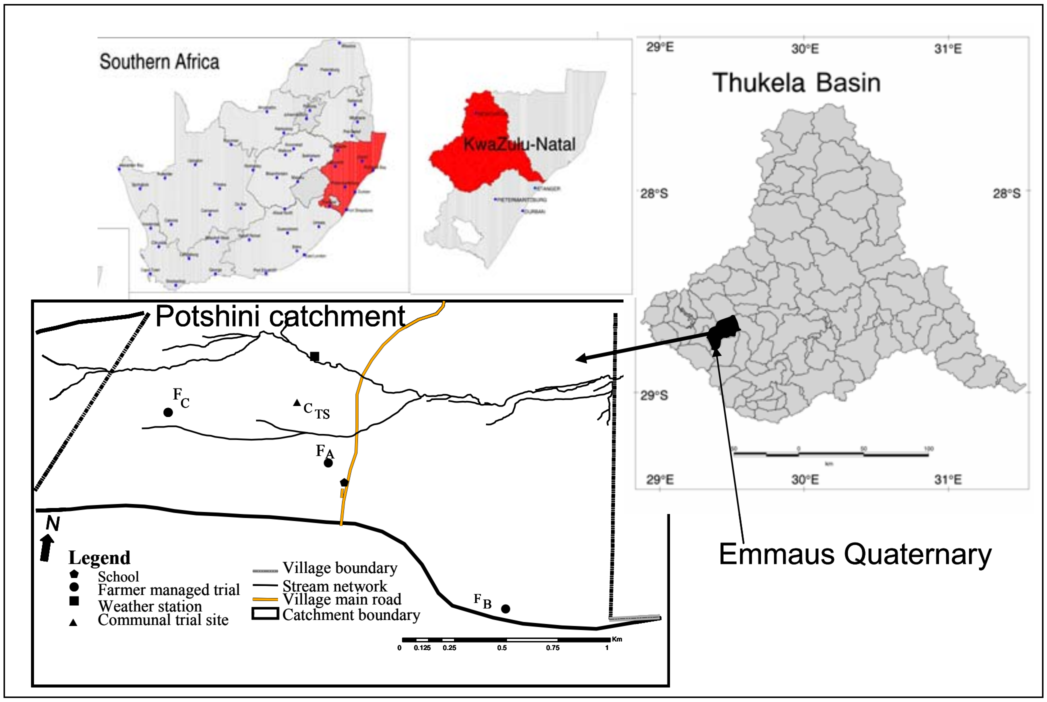

Figure 3.2: Spatial position of the Thukela basin, Emmaus Quaternary catchment and Potshini catchment experimental sites (After SSI, 2003)

3.3.2 Identification of experimental sites – the participatory approach

Unlike other research catchments in which the School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu Natal works in e.g. Wartburg (Lorentz et al., 2001) and Kruger Park (Lorentz et al., 2003), Potshini is a human settlement. This called for the involvement of the community and its institutions as well as other stakeholders e.g. government departments, municipality and NGOs from the initial preparatory stages of the study to the

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[16] FAO classification in parenthesis.

actual instrumentation and monitoring. A communication process and dialogue was initiated between the researchers and the relevant stakeholders in the catchment. This involved holding meetings with the local leaders (e.g. traditional leaders, local government officials, relevant government departmental officials etc.) and the community. A comprehensive description of the process of community engagement and stakeholder participation is provided by Kongo et al. (2008).

Once the goals and operational framework of the SSI programme (Chapter 1) were understood and accepted by all key stakeholders, having incorporated their thoughts, an existing farmers' forum (Smith et al., 2001) was used to identify possible smallholder farmers who were willing to participate in field trials. Because there was already an existing communal trial site, three more sites were identified through a process that incorporated individual farmer's willingness, community goodwill, and technical aspects. From 11 volunteer farmers, six were chosen based on the existence of a durable fence around their fields. The farmers' fields were surveyed and the slopes were found to range between 2 – 5%. Three fields having a gradient of about 3% were selected mainly because the slope of the communal trial site is at a similar range and represented the catchment relief. At each of the four sites, the experiment consisted of two tillage treatments, C_T and N_T. The three farmer-managed sites were labeled F_A, F_B and F_C while the communal (researcher-managed) trial site was designated C_{TS} (Fig. 3.1). Table 3.1 gives a summarized description of the plots.

Table 3.1: Description of the four experimental sites and depth to which soil moisture was monitored in Potshini catchment between 2005 and 2008 (Kosgei et al., 2007)

Tillage system	Plot designation	Description	Depth (cm)
Conventional tillage (C_T)	F_A_C_T	Farmer-managed site	150
	F_B_C_T	Farmer managed site	150
	F_C_C_T	Farmer managed site	150
	C_{TS}_C_T	Researcher managed site	120
No-till (N_T)	F_A_N_T	Farmer managed site	150
	F_B_N_T	Farmer managed site	150
	F_C_N_T	Farmer managed site	150
	C_{TS}_N_T	Researcher managed site	120

The soils at site C_{TS} were penetrateable to a depth of 120 cm only (e.g. Walker, 2007; Kongo and Jewitt, 2006).

3.3.3 Experimental details

3.3.3.1 Land preparation and sowing

Two tillage practices, C_T and N_T, were used in each site. No ploughing was done in the N_T treatments but instead an oxen-drawn MacGoy ripper was used to open furrows to a depth of 10 cm for planting. The ripping was done four weeks after a 3% Senator Extra-Glyphosate was sprayed at a rate of 4 liters per hectare. At planting, a similar dose of Senator Extra-Glyphosate and 0.75% Dual Gold solution at a rate of 0.8 liters per hectare was applied. Maize (cv. PAN 6611) was planted on 9th December 2005, 27th November 2006 and 29th November 2007 at a plant population of approximately 37,000 plants per hectare with an inter-row spacing of 0.9 m. Sowing commenced any date after 15th November with rainfall total of 40 mm falling in at least 4 days (xref. Chapter 2, Section 2.2.51). Weeds were controlled by hand at regular intervals twice in the season.

C_T plots were ploughed using a mouldboard ox-drawn plough to about 15 cm deep three weeks prior to planting. This was repeated a day to planting. Hand hoes were used to open 10 cm deep furrows where maize seeds were placed on the same day and at approximately the same plant population and inter-row spacing as in N_T plots. Weeding was done using hand hoes at the same time as was done in N_T plots. In all the treatments, DAP fertilizer (N=18.5%, P=8.3% and K=4.2%) was applied at a rate of 150 $kg.ha^{-1}$. Maize from all the treatments was harvested on 27th May 2006, 26th May 2007 and 5th June 2008.

All the plots were under conventional tillage until 2000 after which those which were converted to no-tillage remained so until the end of these experiments.

3.3.3.2 Soil characterization

In the 2006/07 season, soil samples were collected in May from between maize rows in the top 20 cm of each plot to determine particle size, particle density and bulk density. However, in the 2007/08, a total of twelve samples were collected from each treatment: three each from between and within maize rows at 0-20 cm and 20-40 cm depths, for the determination of bulk density. Particle size analysis was performed following the Bouyoucos hydrometer method (Anderson and Ingram, 1989; Gee and Bauder, 1986; Klute, 1986). The hydrometer was initially calibrated prior to measurements to obtain the correction factors for solution viscosity and the soil solution concentration. Sedimentation preceded sieving. The procedure outlined by Blake and Hartge (1986) was followed to determine the particle density of soil samples from the various sites. However, a 500 ml flask was used instead of a pcynometer. There was no evidence of considerable soluble solids and thus, no correction was made for total dissolved solids. Dry bulk density was determined by the core method with core dimensions 60 mm diameter by 60 mm height. The samples were weighed and re-weighed after drying for 24 hours at 105°C in an oven. In the previous seasons, only samples from 0-20 cm were analyzed.

3.3.3.3 Rainfall

Rainfall is the primary input of field scale hydrological processes. Thus, accurate measurements, especially in areas such as Potshini catchment where relief can induce variability are essential. Manual rain gauges were installed in the farmer-managed experimental sites in July 2005. The farmers were trained and enthusiastically took readings at 09h00 and 17h00 every day. A weather station with a tipping-bucket rain gauge was installed at about 100 m from site C_{TS} in November 2005 and another tipping bucket rain gauge was later located next to this site in December 2006. These complement existing automatic weather stations, one installed approximately 4 km away under the LandCare project (Smith et al., 2001) and the SAWS station at Bergville, about 7 km away.

3.3.3.4 Runoff

Each plot, in the form of a runoff plot, measured 10 m long by 2.45 m wide. Although standard runoff plots for the eligibility of the Universal Soil Loss Equation (USLE) to apply is 22.13 m long, more than 2 m wide and a slope of 9% (Wischmeier and Smith, 1978), the intention in this study was to create a controlled micro-catchment where water fluxes can be monitored and the available area was optimized for the task. Galvanized strips of sheet metal measuring 0.245 m wide and 2 m long were used to demarcate the plots by ensuring that at least 40% of its width is below the soil surface. A 15 cm glued overlap was ensured between the strips. Sheet metal was used to fabricate a trough which was secured with mortar at the sloping end of the runoff plot. A cover that only left space for runoff into the trough was fitted. Runoff generated was channeled through a 100 mm diameter polyvinylchloride (PVC) conduit whose length varied depending on the appropriate position of the tipping bucket (Fig. 3.3) which was situated at the lowest end of the runoff plot. Caution was taken to ensure that all the runoff generated within the plot and channeled through the PVC conduit reached the collecting chamber by using rubber seals at both ends of the PVC connections. Energy dissipaters were included in the collecting chamber so that the tipping process is purely as a result of the mass of the water and not influenced by the energy of the water. The rainfall intensities from historical records were used to estimate the capacity that the bucket can hold before it tips.

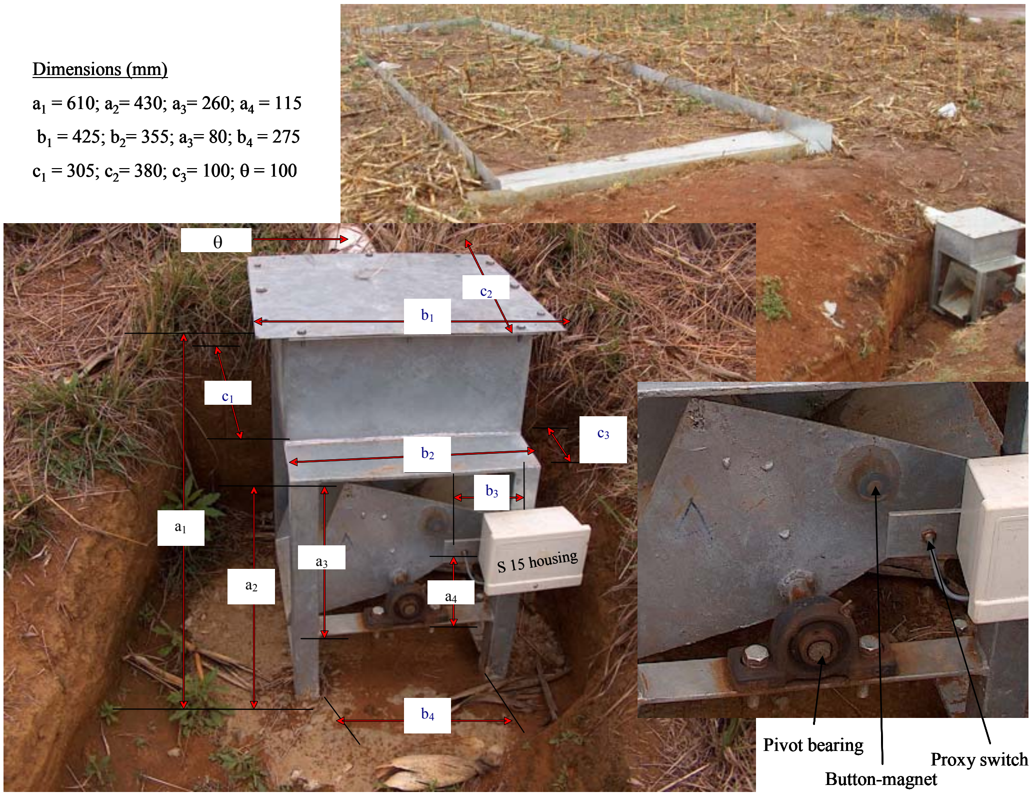

Figure 3.3: The runoff plot-tipping bucket assembly designed at the School of Bioresources Engineering and Environmental Hydrology, University of Kwa-Zulu Natal and fabricated by Troy® manufacturing (Pty) in Pietermaritzburg, South Africa

Each time the bucket tips, activation occurs between the button-magnet attached to one side of the tipping bucket (lower inset in Fig. 3.3) and the fixed proxy switch occurs which causes the proxy switch to send a logging signal to a HOBO data logger, kept in the ‘S15 housing’. All the tipping buckets were calibrated using a dynamic calibration method (Calder and Kidd, 1978; Ricchetti and Bailey, 1990) prior to the field experiments. For convenience all buckets were set to tip at a capacity of 2 liters.

3.3.3.5 Soil moisture

Walker et al. (2004) made a comparison of a wide range of in situ point soil moisture measurement techniques. They included Virrib® soil moisture sensors, Soil Moisture Equipment Corporation TRASE® buriable- and connector-type time domain reflectometry (TDR) soil moisture sensors, and a Campbell Scientific CS615 water content reflectometer. They showed that the connector-type time TDR sensor was the most accurate relative to the gravimetric measurements. In the current study, weekly readings were taken using a Time Domain Reflectometry (TDR) tube probe (IMKO TRIME-T3) from April 2005. The TDR probes have lately become popular equipment to measure in situ volumetric water content (Valente et al., 2004; Mojid and Cho, 2004; Moret et al., 2006; Greco, 2006; Tombul, 2007). These probes measure the velocity of an electromagnetic signal traveling along transmission rods. This propagation velocity is inversely proportional to the square root of the dielectric constant, which is related empirically to the soil volumetric moisture content (Topp et al., 1980). The development of this relationship advanced the rate of use of the TDR in the laboratory and in the field. Other factors that promoted its application include its small measurement volume, its relative ease of operation, and its ability to be automated and multiplexed (Tombul, 2007) as well as being a non-destructive and a versatile equipment (Mojid and Cho, 2004). Moret et al. (2006) provide more details of soil moisture measurements using the TDR.

In the Potshini catchment, each runoff plot was equipped with a 43 mm diameter acrylic access tubes that was installed to depths of 150 cm in sites F_A, F_B and F_C while at C_{TS} the maximum depth of measurement was 120 cm (xref. Table 3.1). The holes were pre-bored using a 50 mm diameter hand auger. Backfilling was carefully done to ensure that there were no air pockets between the soil medium and the tubes. The soil profile was subdivided into 5 sections of 30 cm deep. Moisture measurements were taken at the mid point of these sections i.e. 15, 45, 75, 105 and 135 cm deep. Estimates of soil moisture were based on standard calibration curves provided by the manufacturer and have not been subject to calibration at this stage because there is still a good agreement between the measured volumetric water content and the corresponding values obtained from gravimetric analyses.

To better understand moisture transitions in the soil, a nest of three granular matrix sensors (GMS, Watermark™ Soil Moisture Sensors Model 200SS, Irrometer Co., Riverside, CA), were installed at 30 cm, 60 cm and 150 cm in each plot in November 2006 to measure the soil water potential (SWP). The GMS were connected to a HOBO data logger that was set to record a SWP value every 15 minutes. Prior to installation, the GMS were calibrated against known soil water contents at the School of Bioresources Engineering and Environmental Hydrology

(SBEEH) Soil and Water Laboratory, University of KwaZulu-Natal. The soil temperature was also monitored and was used to correct the measured values of SWP as the calibration procedure was conducted at 25°C. During installation, a layer of wet soil, excavated from the location where the nest is set, was smeared around the sensors to enhanced equilibration.

The electrical resistivity tomography (ERT) provided a third approach used to investigate the effects of tillage on soil moisture storage through a single survey in July 2007. In this method, an electric current is introduced into the soil through current electrodes at the soil surface and the difference in current flow potential is measured at potential electrodes that are placed in the vicinity of the current flow (Corwin and Lesch, 2005). According to Loke (2003), low values of resistivity are associated with materials of relatively high conductance such as water, clay, salts etc, and vice versa. The RM15-D Resistance Meter System (Geoscan, 2007) with the electrodes arrangement in a pole-dipole array (Loke, 2003) was used. This array was selected because it has a good horizontal coverage for relatively small areas (Loke, 2003), such as the plots used in this study (<100 m^2). An expansion port allows the RM15-D to control multi-probe systems via the MPX15 multiplexer module (Fig. 3.4).

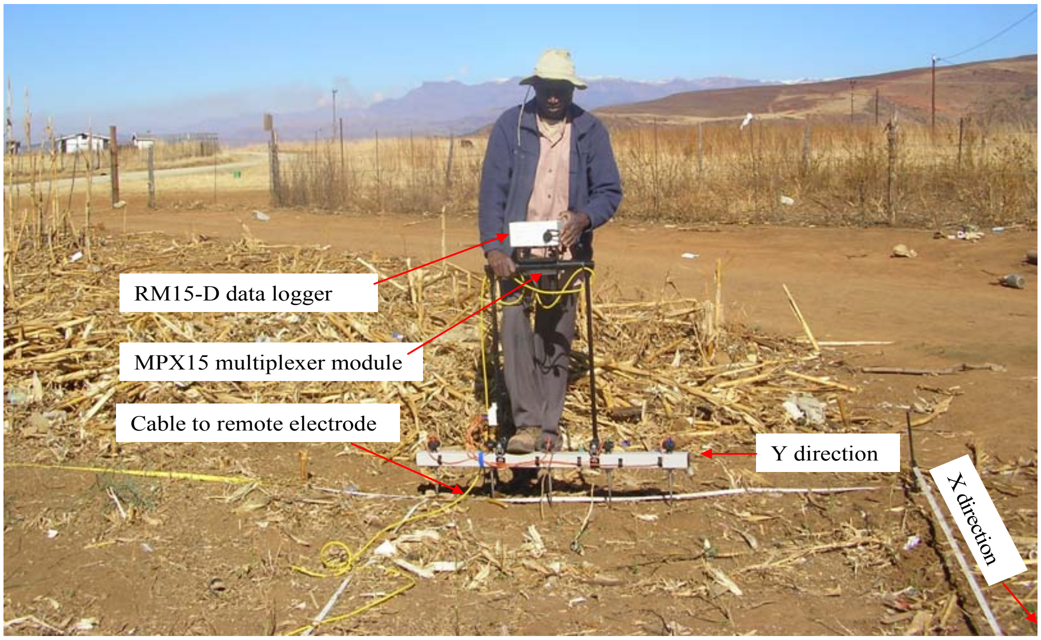

Figure 3.4: Measurement of apparent resistivity in Potshini catchment using RM15-D Resistance Meter System in July 2007

The RM15-D used had 5 electrodes spaced at 0.25 m and mounted on a 2 m frame. This configuration allowed for three depths viz. 0.25 m, 0.5 m and 1 m to be mapped consecutively at the same point. In the X direction (Fig. 3.4) a 0.5 m interval was adopted giving 20 measurements as the length of each runoff plot was 10 m. However, to obtain regular survey plans, a length of 10.5 m was considered in some sites. At the four experimental sites (F_A, F_B, C_{TS} and F_C), the length of the Y direction was 14 m, 12 m, 30 m and 20 m, respectively. The varied lengths depended on the number of plots and the distance between the treatments.

3.3.3.6 Soil evaporation and transpiration

The daily FAO Penman-Monteith approach (Allen et al., 1998) was used to estimate the grass reference crop evapotranspiration using data from a weather station situated 100 m from site C_{TS}. To estimate crop evapotranspiration, empirical crop coefficients ($K_{c)}$ were used. These coefficients vary during the growing season as plants develop, as the fraction of ground covered by vegetation changes, and as plants age and mature. K_c also varies according to the wetness of the soil surface, especially when there is little vegetation cover. Under bare soil conditions, K_c has a high value when soil is wet and its value steadily decreases as the soil dries (Allen et al., 2005). A procedure to distinguish soil evaporation from plant transpiration described by Allen et al. (1998) and Allen et al. (2005) was followed in which the actual K_c comprised of a basal crop (K_{cb}) and a soil evaporation coefficient (K_e). K_{cb} represents the ratio of evapotranspiration to reference crop evapotranspiration under conditions when the soil surface layer is dry, but where the average soil water content of the root zone is adequate to sustain full plant transpiration. The majority of evaporation from soil following wetting by rainfall is represented by the separate K_e. The FAO Penman-Monteith dual crop coefficient method (Allen et al., 1998; Allen et al., 2005) used in this study is a widely accepted approach to estimate ET. Nicolas et al., 2005[17], among other workers, have found a very close correlation between sap flow measurements and E_{To} obtained from the approach developed by Penman-Montheith. The alternative approach of using the water balance was faced with difficulties in this study. During the dry season (winter) as reported in the earlier, livestock grazed the research field and because of that some equipment were removed after harvest and re-launched after sowing. TDR probe tubes were also very loose during this time and hence soil moisture information was not accurate. At the beginning of the next season, GMS took considerable time to give realistic results. Faced with these limitations,

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[17] Nicolas, E., Torrećillas, A., Ortuño, M.F., Domingo, R., Alarćon, J.J. 2005. Evaluation of transpiration in adult Apricot trees from sap flow measurements. Agricultural Water Management 72, 131-145

the empirical crop coefficient and FAO Penman-Monteith approach was preferred to the water balance method.

3.3.4 Water balance simulation prediction using PARCHED-THIRST

The runoff-infiltration routine in PARCHED-THIRST model (Young et al., 2002, SWMRG, 2006) was used to predict surface runoff. In this routine, runoff and infiltration are calculated using the Green and Ampt (1911) equation. Runoff amount is infiltration excess, which is modified by depression storage and surface sealing. Runoff routing is based on the Soil Conservation Service (SCS) unit hydrograph (USDA, 1972). The input profile properties included crop, soil and soil surface characteristics. A maize population of 37,000 plants per hectare was used. Soil textural properties determined from laboratory samples (Section 3.3.3.2) and soil hydraulic properties estimated from field infiltration tests (xref. Chapter 4, Section 4.3.3) were inputs. An average slope of 3% for each runoff plot measuring 24.5 m^2 was used. The model was adequately calibrated for Potshini catchment, Thukela Basin (system properties) and crop, measured soil properties and soil surface conditions (profile properties). The effects of macroporosity were also considered.

3.4 Results and discussion

3.4.1 Soil textural classification and bulk densities

A summary of results from laboratory analyses of soil texture and bulk densities from different sites, tillage, depths and measurements periods are provided in Table 3.2. According to the USDA soil classification, all the sites had sandy clay loams although the proportions of sand, silt and clay were slightly varying. At the start of the season, bulk densities were higher in N_T relative to C_T treatments. This is due to the tillage of the C_T plots that loosened the soil. However, by April nearly all N_T plots had lower bulk densities at both depths. The mean bulk density between rows in the 0-10 cm depth was 1.252 and 1.262 $g.cm^{-3}$ in N_T and C_T treatments with standard deviations of 0.168 and 0.170 $g.cm^{-3}$, respectively. The corresponding average values within rows were 1.239 and 1.220 $g.cm^{-3}$ with standard deviations of 0.195 and 0.174 $g.cm^{-3}$, respectively. At 10-20 cm, the average bulk densities between maize rows were 1.323 and 1.365 $g.cm^{-3}$ in N_T and C_T with standard deviations of 0.278 and 0.192 $g.cm^{-3}$, respectively. Within the rows, the corresponding values were 1.345 and 1.359 $g.cm^{-3}$ with standard deviations of 0.170 and 0.248 $g.cm^{-3}$, respectively. This suggested than N_T had more pore space and was likely to store more water. There were significant differences ($p \leq 0.05$) in average bulk density from C_T plots between F_A and F_C as well as F_B and F_C. There were no significant differences between points of measurement (between or within rows), measurement depths nor period of measurement.

Table 3.2: Soil textural classification and bulk density measured at different periods and depths in plots under conventional and no-till systems in the Potshini catchment. Soil samples were collected from between and within the maize rows

				Bulk density								
	Classification/Period			May 2007	December 2007		February 2008		April 2008			
Site/	Soil type/Maize row			Between	Between	Within	Between	Within	Between		Within	
Tillage	Clay	Sand	Silt	0-10 cm	0-10 cm	0-10 cm	0-10 cm	0-10 cm	0-10 cm	10-20 cm	0-10 cm	10-20 cm
$F_A\_N_T$	20.6	72.2	7.2	1.072	1.121	0.932	1.212	1.170	1.059	1.154	1.064	1.229
$F_A\_C_T$				1.202	1.063	1.016	1.092	1.049	1.152	1.275	1.130	1.220
$C_{TS}\_N_T$	22.6	66.2	11.2	1.221	1.281	1.253	1.335	1.349	1.344	1.503	1.306	1.488
$C_{TS}\_C_T$				1.274	1.161	1.048	1.283	1.234	1.452	1.528	1.338	1.616
$F_C\_N_T$	25.4	65.2	8.4	1.458	1.410	1.312	1.544	1.498	1.479	1.610	1.450	1.494
$F_C\_C_T$				1.492	1.405	1.377	1.601	1.529	1.457	1.520	1.512	1.514
$F_B\_N_T$	21.2	68.3	10.5	1.147	1.120	0.968	1.112	1.114	1.180	1.025	1.055	1.169
$F_B\_C_T$				1.262	1.046	1.049	1.047	1.086	1.164	1.137	1.114	1.084

3.4.2 Rainfall

Table 3.3 describes the characteristics of rainfall events in Potshini catchment over the three seasons. The cumulative seasonal rainfall was 523, 444 and 599 during the 2005/06, 2006/07 and 2007/08 seasons, respectively. However, the amount of rainfall that occurred after sowing was 463, 336 and 541 mm, respectively in the three seasons. The total number of rainy days in each season was 71, 90 and 136 days, suggesting a decreasing average amount of rainfall per rainy day. However, the distribution of rainy days, the number of events, the average duration, the peaks and the average peak intensities were not similar (Table 3.3). The average rainfall per event was 3.19 mm, 3.19 mm and 1.63 mm in 2005/06, 2006/07 and 2007/08 seasons, respectively. The maximum monthly rainfall after sowing in 2005/06, 2006/07 and 2007/08 seasons was 153.6 mm, 96.1 mm and 160.6 mm and occurred in February, January and March, respectively. An analysis of the field scale fluxes is necessary to partition water between runoff, soil moisture storage, evaporation and transpiration. This will indicate the level of crop water deficits, if any, in each of the three seasons. Furthermore, the analysis of runoff generation between treatments could provide insights into the possible impacts on downstream generation of ecosystem goods and services.

Table 3.3: Description of rainfall events in the Potshini catchment in 2005/06 – 2007/2008 seasons

Season	Month	Rain days	Total amount (mm)	Number of events	Mean duration (h)	Mean number of peaks	Mean peak intensity (mm.h^{-1})
2005/06	November	13	59.6	37	0.5	2.8	7.7
	December	12	31.5	23	3.5	2.2	0.6
	January	15	137.7	30	3.9	2.7	2.3
	February	16	153.6	38	2.9	3.1	1.9
	March	10	110.1	24	3.9	3.3	1.9
	April	3	18.8	7	3.3	3.0	1.3
	May	2	11.4	5	3.0	3.0	0.8
2006/07	November	17	106.4	29	2.4	1.7	2.3
	December	12	76	20	1.3	1.3	4.9
	January	16	96.1	21	1.7	1.3	5.2
	February	14	53.4	19	0.7	2.0	5.2
	March	14	55	21	1.1	1.4	3.5
	April	15	57	26	1.2	1.4	3.1
	May	2	0.6	3	0.4	1.0	0.8
2007/08	November	21	57.8	70	0.6	1.1	4.8
	December	22	116.2	66	0.5	1.1	6.3
	January	20	112.6	66	0.6	1.1	4.8
	February	21	110.2	74	0.7	1.2	5.1
	March	9	160.6	17	0.5	1.1	6.5
	April	21	41.4	70	0.6	1.1	4.8
	May	22	6	6	0.5	1.1	5.3

Two sets of intensity criteria were selected to identify occasions with high intensity rainfall, which is likely to promote HOF based on the duration of the events. These were rainfall where the maximum intensity exceeded 10 mm.h^{-1} and falling for a duration of less than one hour (high intensity-short duration) and rainfall where the maximum intensity exceeded 10 mm.h^{-1} and taking longer than one hour (high-intensity-long duration). A lower value of 10 mm/hr was chosen so that both tillage systems could be accommodated. In addition, HOF occurs before the soil is saturated.

The results are summarized in Table 3.4a and Table 3.4b. From Table 3.4a, in the 2005/2006, the range of rainfall (and average) intensities exceeding 10 mm.h^{-1} falling for a period less than 1 hour was 12-39.2 (25.4) mm.hr^{-1} arising from 5 events. The corresponding values in the 2006/07 and 2007/08 were 10-42.4 (26.7) mm.hr^{-1} and 30.6-97.2 (50.3) mm.hr^{-1} from 9 and 11 events, respectively. Thus, there were more high-intensity short-duration events in the 2007/08 season compared to the previous seasons, indicating a trend of increasing intensities.

Although the proportion of time of the peak intensity to total event time ranged between 25% and 50%, the proportion of rainfall that fell within this time relative to the event total ranged between 58-72%, 41-91% and 74-99% during the 2005/06, 2006/07 and 2007/08, respectively. However, most of these events represented less than 10% of the total number of monthly events

(Table 3.3) except in December 2007, January 2008 and March 2008 when high-intensity short-duration constituted 10%, 29% and 23% of the total monthly events, respectively.

Table 3.4a: Dates and time of day in which maximum intensity exceeded 10 mm.h^{-1} and falling for a duration of less than 1 hour

Season	Date	Time	Percent of time of max. intensity	Max. intensity of event (mm.h^{-1})	Event total (mm)	Percent of rainfall at max. intensity to event total (%)
2005/06	2005/11/12	15:00-15:30	50	12.0	4.6	65.2
	2005/11/24	19:15-20:15	25	32.8	11.4	71.9
	2005/12/18	17:45-18:45	25	21.6	8.8	61.4
	2006/03/16	13:45-14:15	25	39.2	18.4	53.3
	2006/03/27	13:15-14:15	25	21.6	9.2	58.7
2006/07	2006/11/30	18:45-19:45	25	10.0	4.5	55.6
	2006/12/01	16:45-17:15	33	17.6	6.6	66.7
	2006/12/01	22:15-23:00	33	35.2	9.8	89.8
	2007/01/04	20:15-20:45	50	19.2	5.6	85.7
	2007/01/13	17:15-18:15	25	32.8	10.0	82.0
	2007/01/16	20:30-21:30	25	42.4	18.6	57.0
	2007/01/18	14:15-15:15	25	30.4	8.4	90.5
	2007/01/22	20:00-21:00	25	36.8	17.6	52.3
	2007/01/27	15:00-16:00	25	16.0	9.8	40.8
2007/2008	2007/11/01	19:00-19:45	33	69.6	26.2	88.5
	2007/12/05	22:15-23:00	33	45.0	19.0	78.9
	2007/12/11	19:45-20:30	33	97.2	43.2	75.0
	2008/01/14	19:45-20:30	33	49.2	22.0	73.6
	2008/01/15	01:45-02:30	33	30.6	10.6	87.9
	2008/01/16	18:30-19:15	33	45.6	16.8	90.5
	2008/02/23	23:15-00:00	33	40.8	19.0	71.6
	2008/03/05	21:00-21:45	33	56.0	14.2	98.6
	2008/03/06	00:00-00:45	33	30.6	11.8	86.4
	2008/03/10	22:45-23:30	33	56.4	21.6	87.0
	2008/03/30	19:15-20:00	33	31.8	12.4	85.5

Table 3.4b: Dates and time of day in which maximum intensity exceeded 10 mm.h^{-1} and where rainfall duration exceeded 1 hour

Season	Date	Time	Duration (h)	Max. intensity of event (mm.h^{-1})	Event total (mm)	Percent of rainfall at maximum intensity to event total (%)
2005/06	2005/11/28	18:30-20:15	1.75	20.0	11.4	43.9
	2005/12/06	14:45-16:30	1.75	14.4	4.4	46.4
	2006/01/19	11:45-13:15	1.50	23.2	7.4	58.4
	2006/01/26	15:15-23:45	8.50	37.6	37.8	25.4
	2006/02/23	20:30-01:00	4.50	34.4	48.2	17.8
	2006/03/02	13:15-18:00	3.75	16.0	19.0	21.1
	2006/03/16	21:30-00:00	2.50	11.2	7.0	40.0
	2006/04/17	18:00-21:45	3.75	10.0	15.8	15.8
2006/07	2006/11/02	00:00-05:30	5.50	17.6	20.6	21.4
	2006/11/12	20:45-00:00	3.25	10.0	13.2	4.90
	2006/11/13	00:00-11:30	11.5	10.4	37.8	16.3
	2006/12/30	00:00-01:30	1.50	12.0	10.2	19.6
	2007/01/30	13:45-18:45	5.00	82.4	51.2	40.2
	2007/02/01	21:15-22:45	1.50	11.2	5.6	50.0
2007/2008	2007/01/05	20:45-00:30	2.00	14.0	18.4	40.9
	2007/12/11	20:45-23-30	2.75	10.4	43.2	51.9

2008/03/22	21:00-22:45	1.75	10.0	12.2	45.6

The high-intensity long-duration events are shown in Table 3.4b. The maximum (and average) intensities were 37.6 (20.9), 82.4 (22.6) and 11 (10.5) mm.hr^{-1} in 2005/06, 2006/7 and 2007/08 seasons, respectively. The mean duration was 3.5, 5.5 and 2.75 hours, respectively. The maximum contribution of the peak intensity to the event total was 58%, 50% and 52% in the three seasons, respectively. As above, most of the events constituted less than 10% of the total number of monthly events except in April 2006, November 2006 and February 2007 where these events represented 14%, 10% and 11% of the total monthly events, respectively. When aggregated, events that could result in HOF, based on the set criteria, constituted 6.5%, 4% and 4.3% of the total rainfall events in the 2005/06, 2006/07 and 2007/08, respectively. This suggested that close to 95% of the events in the study site are likely to cause SOF. Thus, soil infiltration precedes runoff suggesting that rainfall likely to augment soil moisture irrespective of the tillage system used. However, changes in soil hydraulic properties across the season (xref. Chapter 4, 5 and 6) are likely to determine water partitioning. The following section investigates runoff generation from the observed rainfall events and could verify this finding.

3.4.3 Runoff

Responses to rainfall were varied over the three seasons mainly due to the different seasonal amount, distribution and intensities. The summary of runoff seasonal totals is provided in Table 3.5.

Table 3.5: Runoff depths (mm) and their means from four trial sites in Potshini catchment over three seasons, 2005/06-2007/08

Season	2005/06		2006/07		2007/08	
Site/Tillage	N_T	C_T	N_T	C_T	N_T	C_T
F_A	22.2	30.4	28.2	36.2	30.4	42.0
F_B	26.5	38.4	24.2	18.6	38.6	53.3
F_C	27.4	37.8	34.8	15.3	40.9	83.7
C_{TS}	30.0	42.2	29.0	23.7	33.5	42.8
Mean	26.5	37.2	29.1	23.5	35.9	55.5

A common observation in 2005/06 and 2007/08 is the lower seasonal runoff amount generated from N_T compared to the C_T treatments. These seasons had higher monthly rainfall (xref. Table 3.3) which was also relatively well distributed compared to 2006/07 season. There was a significant difference ($p<0.05$) between runoff generated from N_T and that from C_T in 2005/06 season. Significant differences were also observed in runoff from N_T between 2005/06 and 2006/07 as well as between 2005/06 and 2007/08. Similar findings were observed in C_T

treatments. For the entire period, the ratio of generated runoff from N_T to that from C_T treatments was 0.71, 1.24 and 0.65 in 2005/06, 2006/07 and 2007/08, respectively, indicating that during low rainfall seasons, runoff from C_T treatments was lower, suggesting that during such instances C_T is likely to contain higher moisture content relative to N_T. More rainfall tends to rapidly compact the loosened soil surface in C_T and thus lead to higher runoff, while much of the low rainfall amounts infiltrate into C_T relative to N_T. However, the average cumulative runoff was 7% and 9% of seasonal rainfall in N_T and C_T treatments with a standard deviation of 2.3% and 1.7%, respectively. This small difference in runoff generated from the two tillage systems could have been cause by the ripping process during planting that was applied to both treatments. In addition, the rainfall characteristics as discussed in Section 3.4.2 promote infiltration.

More runoff was generated from N_T plots at the start of the season in all the seasons considered. To illustrate this, an example is given in Fig. 3.6 for two dates in the season. This could be attributed to high surface roughness and loosened soil in the C_T plots due to ploughing. The furrows developed in this process are capable of slowing down runoff which enhances infiltration before surface sealing and compaction that reduce infiltration occur. The runoff hydrograph from N_T treatments (Fig. 3.6a) has a higher peak and of longer duration compared to that from C_T treatments, indicating that more runoff was generated. Although the cumulative rainfall of Fig. 3.6(b) is about one-third of that in Fig. 3.6(a), the peak runoff from C_T treatments is 60% of that observed in Fig. 3.6(a). The corresponding value in N_T treatments is 16%. Therefore, rainfall characteristics, antecedent moisture conditions as well as the time of occurrence of rainfall in the season influence runoff responses. Runoff is a result of other processes e.g. infiltration, interception and quick soil evaporation, characteristics of the soil surface and the near-surface play a significant role in its properties (depth and intensity). Table 3.6 contains rainfall events that were either high intensity short- or long-duration that resulted in runoff depths greater than 2 $mm.h^{-1}$.

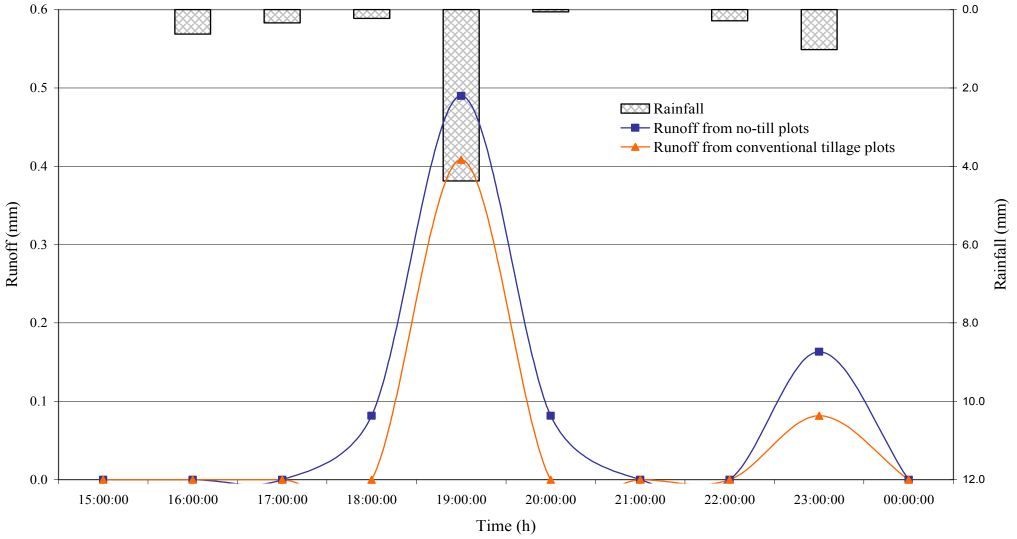

Figure 3.6a: Rainfall and runoff hydrographs on the 18th December 2006 in C_T and N_T treatments (Kosgei et al., 2007)

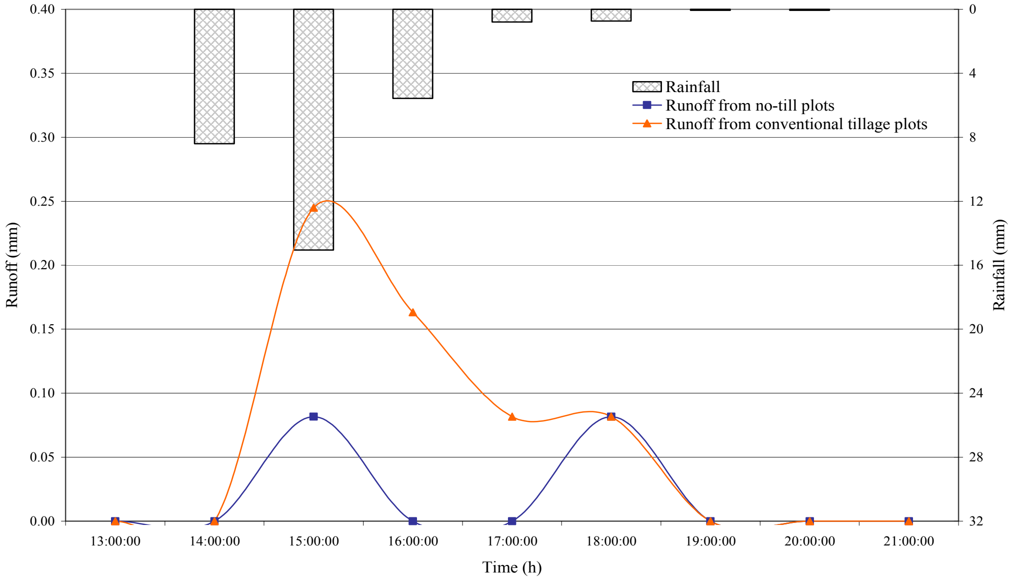

Figure 3.6b: Rainfall and runoff hydrographs on the 2nd March 2007 in C_T and N_T treatments (Kosgei et al. 2007)

Figure 3.6a and 3.6b (event based) were considered more informative than a graph of cumulative run-off because they clearly distinguished the behaviour of run-off at the start of the season and later in the season.

Table 3.6: Runoff depths exceeding 2 $mm.h^{-1}$ per rainfall event in Potshini catchment and corresponding runoff coefficients in 2005/06 – 2007/08

Treatment	Date	Time	Duration (h)	Max. rainfall intensity ($mm.h^{-1}$)	Rainfall amount responsible for runoff (mm)	Total runoff (mm)	Runoff coefficient (%)
C_T	2006/01/26	15:15-23:45	8.5	37.6	37.2	17.65	47.4
	2007/01/30	13:45-18:45	5.00	82.4	51.2	15.59	30.5
	2007/12/11	20:45-23-30	2.75	10.4	43.2	10.61	24.6
N_T	2006/01/26	15:15-23:45	8.5	37.6	37.2	19.10	51.3
	2006/11/09	17:30-23:15	5.75	7.6	47.6	13.24	27.8
	2006/11/12	20:45-00:00	3.25	10.0	13.2	6.84	51.8
	2007/01/30	13:45-18:45	5.00	82.4	51.2	13.61	26.6
	2007/11/01	19:00-19:45	0.75	69.6	26.2	6.3	24.0
	2007/12/11	20:45-23-30	2.75	10.4	43.2	11.59	26.8
	2008/03/10	23:15-00:15	1.25	6.2	21.6	2.78	12.9

Table 3.6 shows that most of the events that generated runoff greater than 2 $mm.h^{-1}$ were long-duration events (Table 3.4b). Also, only 50% of the events in Table 3.4(b) generated runoff that is greater than 2 $mm.hr^{-1}$ indicating that even though an event was regarded high-intensity (>10 $mm.h^{-1}$) as was in Table 3.4(a) and Table 3.4(b), it did not necessarily lead to higher intensities of runoff. Furthermore, some events that did not exceed 10 $mm.h^{-1}$ generated runoff which was greater than 2 $mm.hr^{-1}$. This occurred only in N_T treatments and the case in March could have been driven by higher antecedent moisture content. Tillage system has also been shown to influence runoff generation especially during the beginning of the season. For example, there were more cases of runoff above 2 $mm.hr^{-1}$ in November and December from N_T treatments which were bare at this time compared to C_T treatments that were loose after ploughing. Approximately 57% of the runoff events > 2 $mm.hr^{-1}$ in N_T occurred before the end of December compared to 33% in C_T. A regression relationship was fitted between the total runoff in Table 4 and the rainfall that caused it. For the C_T treatments, 36% (R^2=39%) of the rainfall constituted runoff while in N_T 32% (R^2=52%) of rainfall was measured as runoff for storms that led to runoff greater than 2 mm per event. This underscored the ability of N_T to generate less

runoff. However, this relationship is also affected by the duration of the rainfall events. Thus, the runoff coefficients did not show any particular pattern although in N_T, they were higher in Novermber compared to March.

3.4.4 Soil moisture

Three approaches were used to study soil moisture dynamics. These were (i) monitoring weekly using TDR, (ii) continuously monitoring SWP, and (iii) a single electrical resistivity tomography (ERT) imaging survey as described in Section 3.3.3.5.

3.4.4.1 TDR soil moisture profiling

Soil moisture was measured at five depths in all the sites except at site C_{TS} where four measurements were done because probe tubes were only 120 cm deep (xref. Table 3.1). Measurements at site F_C commenced in March 2007. Due to equipment failure, monitoring of volumetric soil moisture stopped towards the end of February 2007 and did not resume until the beginning of the 2007/08 season. Weekly volumetric soil moisture ($m^3.m^{-3}$) fluctuated depending mainly on occurrence of rainfall events and their magnitude. As expected the fluctuations were more elaborate at the top 30 cm of soil because it is an “active zone” in processes such as infiltration and evaporation. Shallow soil depths respond quickly to rainfall and also lost the moisture relatively quicker compared to greater depths. On average, more moisture was recorded at a depth of 60 cm in N_T treatments and at 30 cm in the C_T treatments. At the beginning of the season, there was more average moisture in C_T treatments at the top 30 cm in relation to N_T treatments. This observation was attributed to better infiltration as a result of loosening of the soil during ploughing. The mean seasonal volumetric moisture values are provided in Table 3.8. Fig. 3.7(a) to 3.7(c) illustrate the mean soil moisture variations in different treatments over the three seasons.

The zone weighted depth-average method (Miller et al., 2007) was used to obtain a representative moisture value for the entire depth of measurement (θ_{zone}). Thus:

$$\theta_{zone} = \frac{(d_1 * \theta_1 + d_2 * \theta_2 + d_3 * \theta_3 + \dots\dots\dots + d_n * \theta_n)}{\sum_{i=1}^{n} d_i} \tag{3.1}$$

where θ is the measured volumetric moisture content, d is the depth represented by the measured moisture, and n is the number of measurements across the profile.

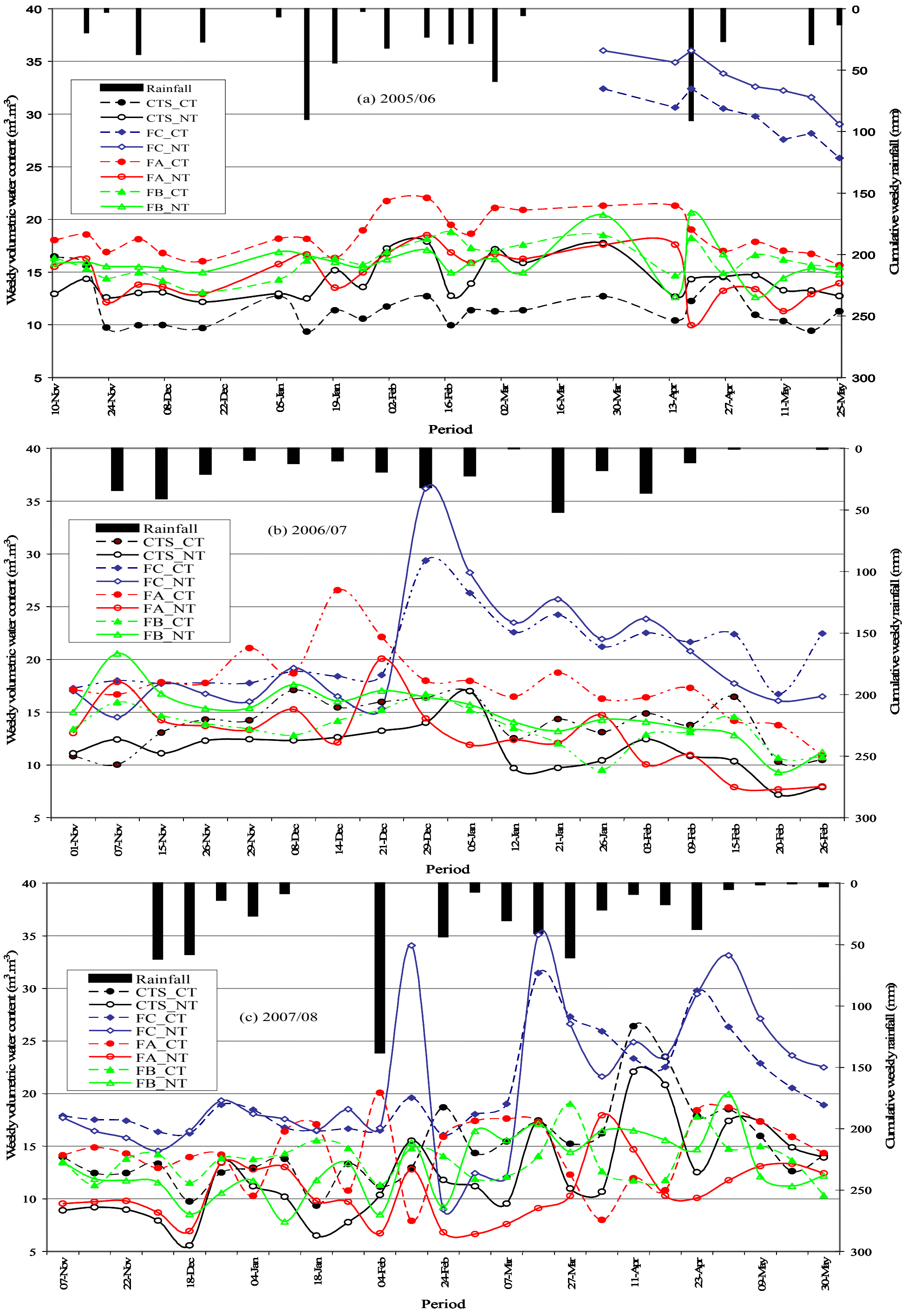

Figure 3.7: Mean variation of weekly volumetric moisture content and seasonal rainfall in (a) 2005/06; (b) 2006/07; and (c) 2007/08 seasons in Potshini catchment

Table 3.7: Mean seasonal volumetric moisture content ($m^3.m^{-3}$) in all the experimental sites in Potshini catchment. Standard deviations are provided in parenthesis

Season/Site	$F_B\_N_T$	$F_B\_C_T$	$F_A\_N_T$	$F_A\_C_T$	$F_C\_N_T$	$F_C\_C_T$	$C_{TS}\_N_T$	$C_{TS}\_C_T$
2005/06	16.16 (1.49)	15.84 (1.28)	18.57 (1.93)	14.84 (2.19)	33.28 (2.40)	29.66 (2.33)	14.19 (1.78)	11.49 (1.89)
2006/07	13.49 (1.88)	14.91 (2.52)	17.66 (3.37)	12.75 (3.26)	20.19 (5.59)	20.76 (3.49)	11.50 (2.25)	13.90 (2.34)
2007/08	13.68 (2.01)	13.13 (3.06)	14.51 (3.28)	10.61 (2.85)	20.91 (7.00)	20.44 (4.54)	14.97 (3.88)	12.25 (4.29)

From Table 3.7 and Fig. 3.7, the mean soil moisture was more variable at site F_C and least at site F_B. The response to rainfall events was also rapid at site F_C especially after several rainy months. Towards the end of the season this site consistently had higher volumetric soil moisture content. This was likely as a result of higher clay content relative to other sites (xref. Table 3.2). There was an average of 15.7%, 2.2% and 16.4% more moisture in N_T compared to C_T in plots 2005/06, 2006/07 and 2007/08, respectively. This trend is similar to the seasonal rainfall amounts over the three seasons (xref. Table 3.3). Thus, the availability of moisture and the success of crop production are directly linked with rainfall characteristics. A lower rainfall such as in the 2005/06 season had little influence on the difference in moisture between the tillage systems. However, good rains e.g. in the 2007/08 season had substantial difference in soil moisture. This suggests that there could be more water productivity benefits from N_T systems when rainfall is above a certain threshold (xref. Chapter 8, Section 8.4.2.1). This level needs to be established in order to propose better crop production management strategies for arid and semi-arid lands (ASALs) instead of just adopting what has worked elsewhere.

There were significant differences ($p \leq 0.05$) in weekly soil moisture content between tillage treatments and also between seasons within the same tillage treatment. At site F_A, significant differences were observed between any two seasons and across both the treatments in a specific season. There were no significant differences in soil moisture between tillage treatments at site F_B. However, significant differences between any two seasons were found in both tillage treatments. Apart from insignificant difference between 2006/07 and 2007/08 seasons, site C_{TS} had significant differences within the same tillage treatment between the other seasons. All three seasons had significant differences in moisture content between tillage systems at this site. The 2005/06 season was the only season that a significant difference in moisture content between tillage systems was observed at site F_C. In addition, moisture content in this season was significantly different from the following seasons in each tillage system. These findings closely mirrored runoff characteristics (xref. Table 5.5) indicating that plots and seasons that generated less runoff had higher soil moisture and vice versa. However, a field scale water balance is necessary that incorporates the crop water demand and evaporation losses under the different tillage systems to be able to validate this observation, an attempt made in Chapter 8, Section 8.4.2.1.

3.4.4.2 Monitoring soil water potential

The nest of three granular matrix sensors installed at 30 cm, 60 cm and 150 cm in each plot responded differently to rainfall inputs. The calibration of the GMS was done using Kaolin/sand mix at the School of Bioresources Engineering and Environmental Hydrology (SBEEH) Soil and Water Laboratory. Three GMS, connected to a 4-channel HOBO logger, were placed inside pressure pots containing the Kaolin/sand mix. The mix was subjected to a range of pressures through a wetting and a drying cycle. Three channels of the HOBO logger recorded voltage while the 4th was connected to a temperature sensor. A plot of capillary pressure head against voltage was then plotted for each GMS. Calibration functions were then developed. A temperature correction was done if the room temperature was not 25°C. The Laboratory is still fine tuning the calibration functions and this could be the reason why this study has reported relatively higher matric potentials.

An example of the field responses on a semi-log scale is provided in Fig. 3.8. Although the sensors were installed in mid November 2006, data for the first 2 weeks were discarded because the sensors needed to equilibrate. Capillary tension fluctuated more at 30 cm depth through out the season. The frequency and amount of rainfall determined the response. Being a primary partitioning layer of rainfall among evaporation, transpiration, runoff and infiltration, this top layer was generally drier in the absence of rainfall compared to lower depths. Responses at lower depths (60 cm and 150 cm) lagged consistently. High tensions were experienced from mid February to mid March due to low rainfall and perhaps higher crop water requirements at this time that depleted soil water storage.

The data collected between November 2007 and January 2008 from the GMS were erratic. Some of the sensors remained at very high capillary tensions even when the soil moisture derived from other methods was high. However, by late February the responses were realistic. This behaviour was attributed to a marked delay in response after a long dry period that typically begins from as early as May to November in dry winters. Thus, data for the 2007/08 were considered non-representative.

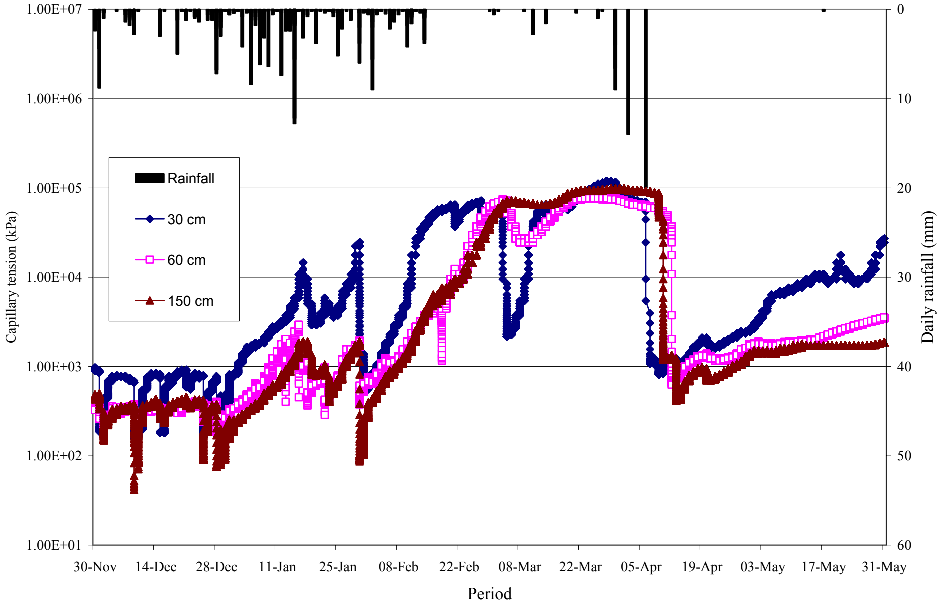

Figure 3.8: Example of the response of the granular matrix sensors at different depths to rainfall events in Potshini catchment during the 2006/07 season

The measured matric potentials were higher than expected for agricultural soils. In spite of this discrepancy, the three depths of measurement gave distinct patterns whereby the one close to the surface fluctuated most while the one at 60 cm fluctuated least perhaps because this depth acted as a transition transmitting infiltrated water (after rainfall) and soil moisture for evaporation (following a dry spell).

3.4.4.3 Electrical resistance tomography (ERT) imaging survey

The ERT imaging survey was conducted on 07/07/2007 to compare residual soil moisture contents between the two tillage systems in the Potshini catchment a using the RM15-D resistivity meter. Table 3.8 contains descriptive statistics of the measured resistivity values from RM15-D meter at the different experimental sites.

The range of resistivity values was 1130, 1000 and 850 Ω m at 25, 50 and 100 cm, respectively in N_T treatments. The corresponding values from C_T treatments were 750, 570 and 900 Ω m, respectively. The mean values were however lower in N_T in relation to C_T. Except at site F_C, there was more variability in ERT values from N_T treatments as compared to those from C_T.

There was no significant difference ($p \leq 0.05$) between resistivity values from different tillage systems in all sites except at site F_C. In general, higher resistivity values were recorded in C_T treatments. According to Loke (2003), low values of resistivity are associated with materials of relatively high conductance such as water, clay, salts etc. Thus, there is need to relate ERT measurements with at least another physical measurement.

Table 3.8: Descriptive statistics of measured resistivity values (Ω m) from different experimental sites in Potshini catchment in June 2007

Site/Tillage	Depth (cm)	Minimum	Mean	Maximum	Standard deviation
$F_A\_N_T$	25	36.90	360.50	1166.50	192.09
	50	28.26	304.35	786.57	150.86
	100	18.84	207.17	863.50	101.74
$F_A\_C_T$	25	173.49	348.78	737.90	95.19
	50	202.53	343.22	648.40	76.16
	100	226.08	318.72	452.16	52.53
$F_C\_N_T$	25	126.39	309.64	568.34	76.87
	50	94.20	190.88	383.08	51.72
	100	18.84	61.61	175.84	20.71
$F_C\_C_T$	25	181.34	402.10	691.59	87.79
	50	136.59	389.57	503.97	66.40
	100	56.52	129.62	226.08	36.04
$C_{TS}\_N_T$	25	284.17	489.40	1051.12	111.78
	50	329.70	485.73	1028.35	93.19
	100	288.88	401.26	668.82	61.33
$C_{TS}\_C_T$	25	268.47	515.01	923.95	82.76
	50	153.86	486.24	708.07	58.63
	100	131.88	379.09	963.98	55.15

In this study because the TDR was out of order at the time of this survey, the responses from the GMS at different depths at the day of the survey were used to relate the ERT measurements with the relative soil moisture in the different tillage systems. An example of the capillary tensions at site F_C is provided in Fig. 3.9. At site F_C, the mean resistivity values in the N_T treatment from Table 3.6 were 190.88 and 309.64 Ω m at 50 cm and 25 cm deep, respectively. In the C_T treatment the corresponding mean resistivity values were 389.57 and 402.10 Ω m, respectively.

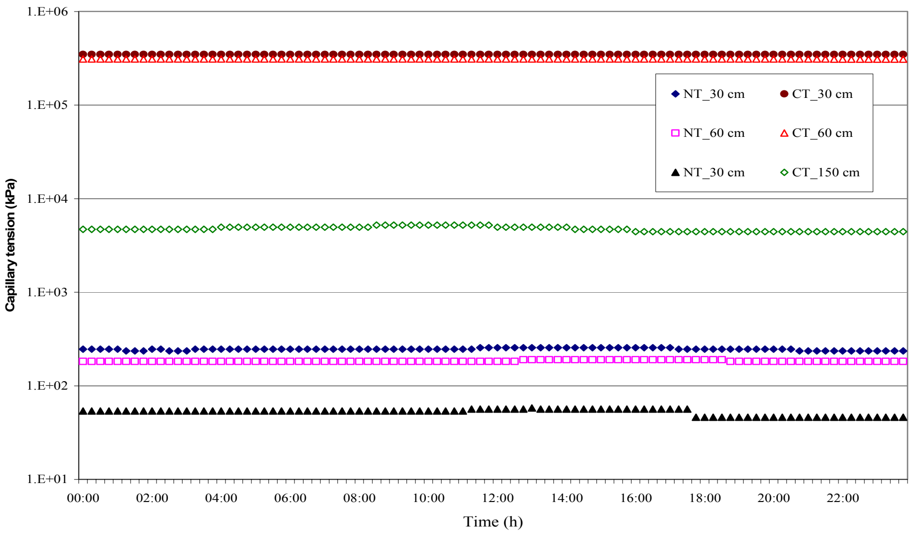

Figure 3.9: Responses from granular matrix sensors at three depths at site F_C on 07/07/2007

As illustrated by Fig. 3.9, the C_T treatment had higher capillary tensions than the N_T treatment which corresponded to the observed resistivity values. Assuming that the depth at which the resistivity values were determined (25 and 50 cm) could approximate the two top most matrix sensors (30 and 60 cm deep), it can be seen that a higher resistivity value corresponds to a higher capillary tension and vice versa in both tillage systems. This implies that the ERT mean values agreed well with the measured capillary tensions and hence the moisture status of the soil during the day of the survey. Therefore, depending on the purpose of monitoring and comparing the soil water status, both approaches are likely to yield a result having minimum disparity.

Since the other sites had relatively lower clay contents (xref. Table 2.2), the measured resistivity values were likely to be even more representative of the in-situ soil moisture at this site. The images from the various sites and depths, plotted using Surfer v. 8 software (Surface Mapping System, 2002), are provided in Fig. 3.10 to Fig. 3.13. A uniform scale of 0-1600 Ω m was used, resulting in 8 categories of resistivity values. The dotted lines show the boundaries of the runoff plots.

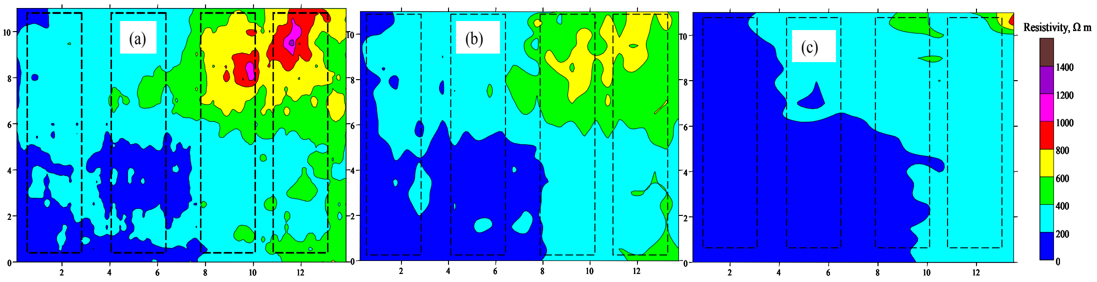

Figure 3.10: Resistivity mapping for N_T at site F_A at (a) 25 cm; (b) 50 cm; and (c) 100 cm. The dotted lines show the boundaries of the runoff plots

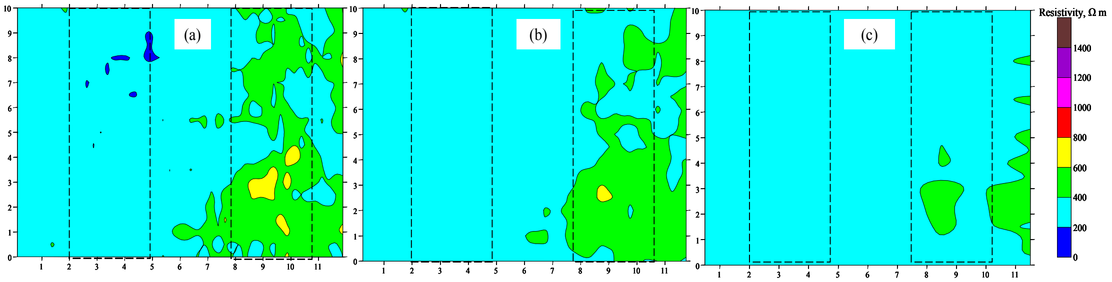

Figure 3.11: Resistivity mapping for C_T at site F_A at (a) 25 cm; (b) 50 cm; and (c) 100 cm. The dotted lines show the boundaries of the runoff plots

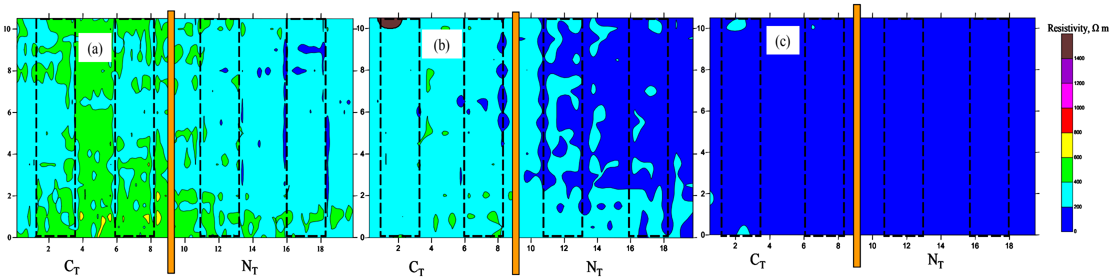

Figure 3.12: Resistivity mapping at site F_C at (a) 25 cm; (b) 50 cm; and (c) 100 cm. Mapping was done continuously at both C_T and N_T treatments; the bars separate the treatments. The dotted lines show the boundaries of the runoff plots

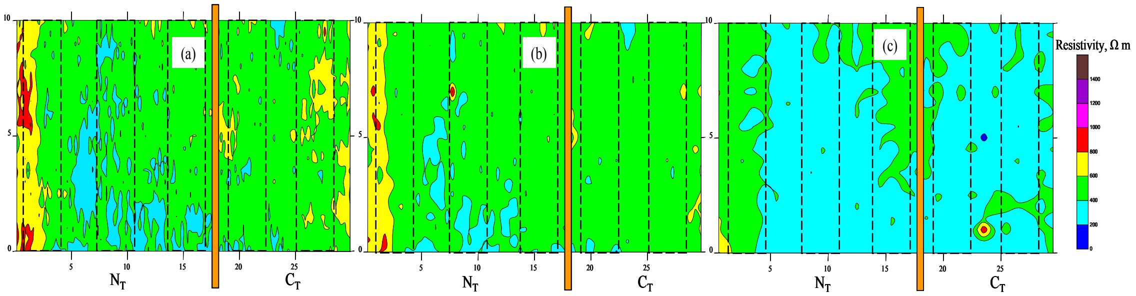

Figure 3.13: Resistivity mapping at site C_{TS} at (a) 25 cm; (b) 50 cm; and (c) 100 cm. Mapping was done continuously at both C_T and N_T treatments; the bars separate the treatments. The dotted lines show the boundaries of the runoff plots

From Fig. 3.10 to Fig. 3.13, there were generally lower resistivity values in N_T treatments which were seen as an indication of higher soil moisture retention. However, as seen from Fig. 3.10 and Fig. 3.13, some spots in N_T had higher values of resistivity. These could have been localized hard pans and/or sections where moisture depletion was greatest during the season. Irrespective of tillage system, lower depths had relatively lower resistivity values perhaps because the upper layer (<25 cm) is exposed to evaporation as the crop had already been harvested. In addition, due to the nature of the equipment (RM15-D), all crop residues had to be removed prior to the measurement, which further exposed the soil surface to evaporation.

There was more uniformity in soil moisture in C_T treatments (Fig. 3.11) in relation to N_T (Fig. 3.10) at site F_A. Values of lower resistivity in both treatments of site F_C (Fig. 3.12) coincided with the edges of the runoff plots which ran perpendicular to the furrows ripped during sowing. This suggested that the furrows concentrate water which then infiltrates into the soil. If there is a slight gradient, the water flows in the furrow but because the edge of the runoff plots acts as a barrier, it is forced to infiltrate. This also implies that ripping is capable of influencing the water partitioning process in favor of infiltration and could be used as a water conservation measure in rainfall deficient areas. At site C_{TS} (Fig. 3.13), there was no clear difference between resistivity values from C_T and N_T treatments, except for a band along the edge of N_T that consistently showed higher values of resistivity. However, this site was regarded drier than the other sites as it had higher mean resistivity values relative to the other sites in both tillage systems (xref. Table 3.5). This could be due to the shallow soils at this site that restricted the TDR probe tubes to a depth of 120 cm (xref. Table 3.1).

3.4.5 Soil evaporation and transpiration

The results of the FAO Penman-Monteith dual crop coefficient method (Allen et al., 1998; Allen et al., 2005) for the three seasons are shown in Fig. 3.14. Wind speed was also included as it plays a significant role in influencing water loss in the study area especially in winter (May-Oct) when high wind velocities are common. The total potential evaporation in the growing season was 741, 698 and 955 mm in the 2005/06, 2006/07 and 2007/08 seasons, respectively. From this, total potential soil evaporation was 415, 404 and 527 mm. Crop transpiration occurred only during summer, specifically from December to mid April, when the crop was actively growing. The corresponding total potential transpiration obtained was 326, 294 and 468 mm. This meant that the ratio of transpiration to total evaporation within the cropping period was 0.44, 0.42 and 0.49 in the 2005/06, 2006/07 and 2007/08 season, respectively.

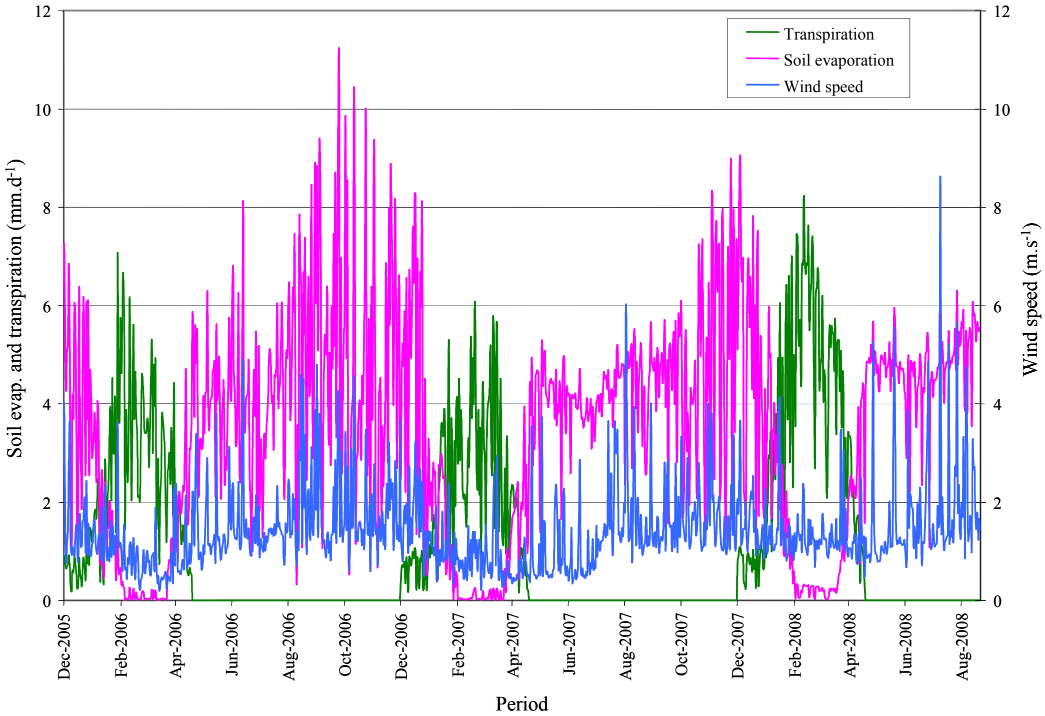

Figure 3.14: Total potential evaporation partitioned between direct soil evaporation and crop transpiration. The effect of wind speed is also illustrated

It is worth noting that about 45% of the total soil evaporation occurred at the beginning of the season i.e. December and January. Minimizing this initial loss by having crop residue on the soil surface as practiced in conservation agriculture could enable more water loss through transpiration. In addition the development of a robust rooting system is likely to result in a rapid canopy cover that will minimize direct soil evaporation in favor of plant transpiration.

Without crop production in winter, water loss through transpiration is negligible as all vegetation is dry. Thus, soil evaporation basically constitutes total evaporation. High wind speeds during this time contribute to high potential soil evaporation. The annual total potential evaporation was 1601, 1524 and 1894 mm in 2005/06, 2006/07 and 2007/08 seasons, respectively. This gives annual transpiration to total evaporation ratios of 0.2, 0.19 and 0.25 for the three seasons, respectively. Hence, over the experimental period, transpiration represented an average of approximately 45% and 22% of seasonal (cropping) and annual total potential evaporation, respectively.

Kosgei et al. (2007) observed that there is no carry-over of moisture from one season to the next because all the soil moisture, including all water from occasional low-intensity winter rainfall, evaporates in winter. Cattle quickly consume the maize residues leaving the fields bare. The total rainfall received in the winter months (Jun-Oct) was 190, 190 and 50 mm in 2005/06, 2006/07 and 2007/08, respectively. Assuming a uniform runoff coefficient in winter of 9% in both N_T and C_T treatments and negligible deep percolation, an estimated 173, 173 and 46 mm, respectively was lost as soil evaporation (xref. Section 3.3.4). Thus, total evaporation from 523, 444 and 599 mm of rainfall in the respective seasons was 486, 413 and 557 mm, respectively in N_T and 478, 404 and 545 mm, respectively in C_T treatments. During this time, transpiration amounted to 0.44, 0.42 and 0.49 of total evaporation in the three seasons. Table 3.9a contains a summary of the partitioning of water fluxes in the three years. Table 3.9b gives a summary of the data obtained from P-T model. Deep percolation was considered negligible.

Table 3.9a Summary of measured annual partitioning of water fluxes for two tillage systems in Potshini catchment between 2005/06 and 2007/2008 hydrological years

Tillage	N_T			C_T		
Year/Flux (mm)	Runoff	Soil evaporation	Transpiration	Runoff	Soil evaporation	Transpiration
2005/06	53.9	445.2	213.8	62.3	440.7	210.3
2006/07	48.2	412.5	175.5	56.7	407.3	169.7
2007/08	46.1	330.1	272.9	58.0	323.9	267.1

Table 3.9b Summary of annual partitioning of water fluxes for two tillage systems in Potshini catchment between 2005/06 and 2007/2008 hydrological years obtained from P-T model

Tillage	N_T			C_T		
Year/Flux (mm)	Runoff	Soil evaporation	Transpiration	Runoff	Soil evaporation	Transpiration
2005/06	105	263.3	94.7	119.6	280.8	62.2
2006/07	96.4	159.8	69.7	111.6	164.6	68.9
2007/08	96.1	351.8	93.2	96.7	374.6	69.6

On average 7.4, 59.5 and 33.1% of annual rainfall comprised runoff, soil evaporation and transpiration, respectively in N_T treatments. The corresponding averages in C_T plots were 8.9, 58.7 and 32.2%. Adoption of N_T reduced runoff by about 1.5%. The higher percentage of soil evaporation from N_T is as a result of the ratio method adopted in this analysis whereby soil evaporation was considered indirectly as a fraction of the infiltrated water. Higher soil moisture could stimulate a better plant canopy which may decrease soil evaporation and increase transpiration. Therefore, there is need to quantify these fluxes directly. With regard to crop production, the approximate non-productive water losses were 67% and 68% of annual rainfall in N_T and C_T treatments, respectively. Thus, in an annual basis N_T treatments enabled water savings of about 1% of annual rainfall.

3.4.6 Water balance simulation and prediction using PARCHED-THIRST (PT) model

The P-T model has two categories of inputs: system and profile properties. System properties include site (location) characteristics, climate data, number of seasons and sowing dates. Profile properties include the crop, soil properties, soil surface characteristics, area and the level of weeds. Soil properties were determined from experiments, climate data was collected from weather stations in the study area and the crop used was maize at a population of 37000 plants per hectare. From a physical inspection of each plot, the average depth of depressions was estimated and a value was entered as bund height in the soil surface characteristics. Surface sealing was considered through alteration of the measured hydraulic conductivity to account for crusting.

3.4.6.1 Soil water depth

The runoff-infiltration routine in the PT model was used to partition observed rainfall into runoff, soil moisture depth, soil evaporation and crop transpiration. The observed initial water contents in each of the treatments were used for the simulation. The predicted soil moisture depths did not agree very well with moisture depths derived from volumetric moisture contents which were measured using the TDR. Correlation coefficients obtained ranged between 0.25-0.6, with an average of 0.41. Some selected illustrations are given in Fig. 3.15.

The correlation coefficients obtained were much lower than those obtained elsewhere in the region e.g. Phiri (1998) and van der Meer (2000). The poor relationship between observed soil moisture depths and those predicted from the PT model could have been due to the use of some estimated soil hydraulic parameters e.g. wetting front suction which has been shown to have a major effect on model output (Young et al., 2002). Other hydraulic properties obtained from direct field measurements in the current study e.g. saturated hydraulic conductivity (xref. Chapter 4, Section 4.3.3), ranked by Young et al. (2002) as second in importance after area, was also regarded as difficult to be measured accurately.

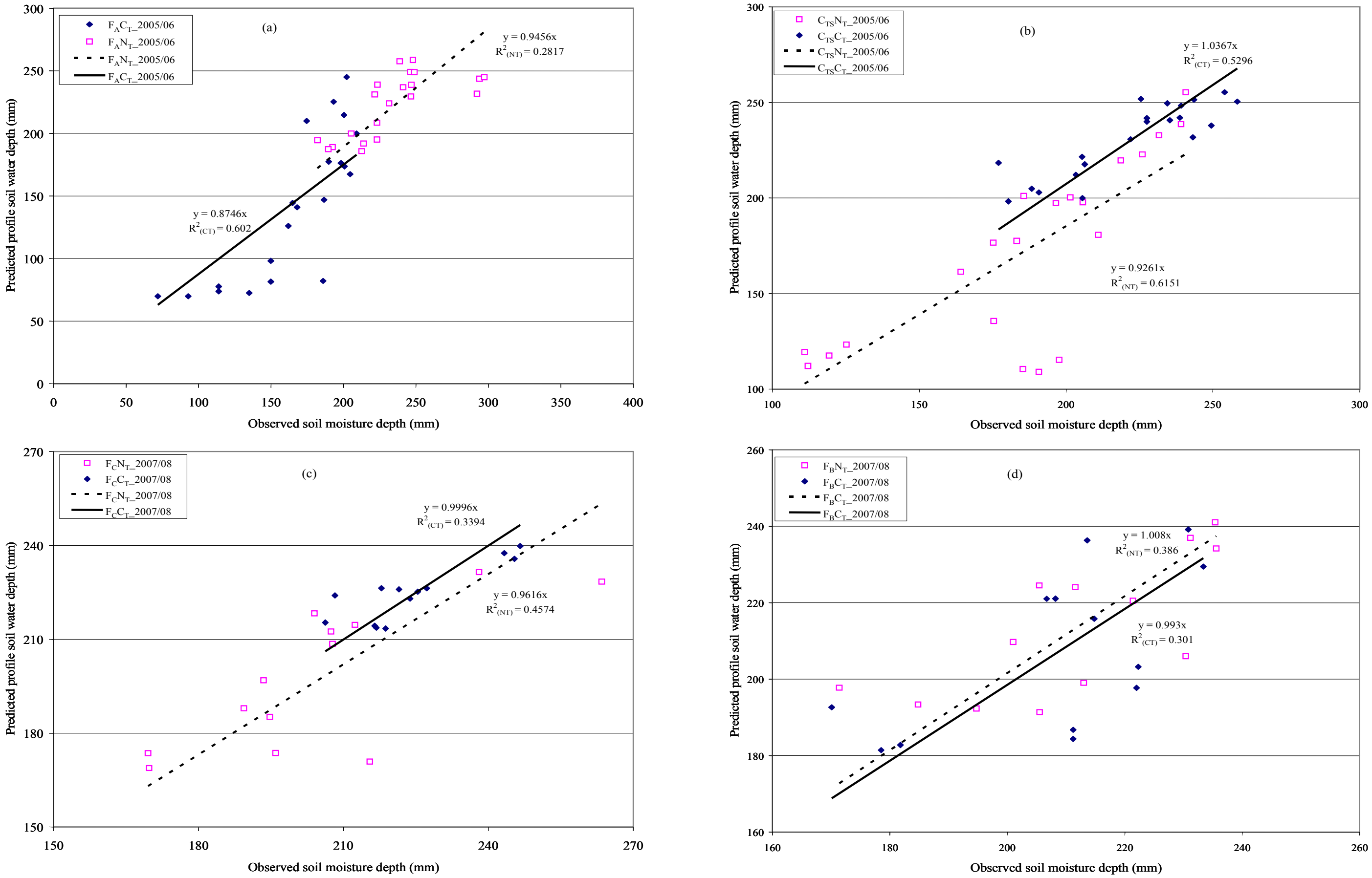

Fig. 3.15: Measured (using TDR) and predicted soil moisture depths from selected plots (a) F_A in 2005/06; (b) C_{TS} in 2005/06; (c) F_C in 2007/08; and (d) F_B in 2007/08 season

3.4.6.2 Runoff generated.

The plots used in this study did not allow run-on fluxes. Thus any measured runoff originated entirely from rain falling into the 24.5 m^2 run-off plot. The average predicted runoff from N_T treatments was 105, 97 and 96 mm in 2005/06, 2006/07 and 2007/08 seasons, respectively. The corresponding values from C_T plots averaged 120, 112 and 97 mm, respectively. The mean runoff over the three seasons was 99 mm and 109 mm in N_T and C_T treatments, respectively with corresponding standard deviations of 5.1 and 11.6. A summary is provided in Table 3.9b. There was no significant difference ($p<0.05$) in runoff between N_T and C_T. There was a difference of approximately a factor of 3 between the observed (Table 3.10) and the predicted PT model values in both treatments. An overestimation in runoff of up to 300% may have been contributed by limitations in the SCS method, including unaccounted for rainfall intensity which is an important source of variability in the methodology, lack of clear guidance as to how to vary antecedent moisture condition (AMC), the discrete unrealistic relation between Curve Number and AMC, and the fixing of the initial abstraction ratio at 0.2 (Jain et al., 2006). An example of initial abstraction is interception which is dynamic during particular rainfall events as well as at different crop growth stages.

3.4.6.3 Soil evaporation and crop transpiration.

The average simulated soil evaporation values from N_T treatments were 263, 160 and 352 mm for the 2005/06, 2006/07 and 2007/08 seasons, respectively. In C_T treatments, soil evaporation amounted to 281, 165 and 375 mm, respectively. The estimated mean crop transpiration in N_T was 95, 70 and 93 mm, respectively while in C_T, transpiration values were 62, 69 and 70 mm, respectively. There was no significant difference ($p<0.05$) between values in the two treatments nor between seasons. The relative percentages of seasonal rainfall are provided in Fig. 3.16.

The average percent of soil evaporation, crop transpiration and runoff to seasonal rainfall in N_T over the three seasons was 57%, 20% and 23% with standard deviation of 8.7%, 2% and 5.5%, respectively. The corresponding ratios in C_T plots were 60%, 15% and 25% with standard deviations of 10.2%, 4.3% and 7.7%, respectively. Thus, as seen from the field measurements, the PT model has also indicated less soil evaporation and runoff and more crop transpiration in N_T in relation to C_T. Unproductive water losses are 80% and 85% in N_T and C_T, respectively implying that N_T is capable of partitioning more water to productive use than C_T. This finding agrees with Rockström et al. (2001).

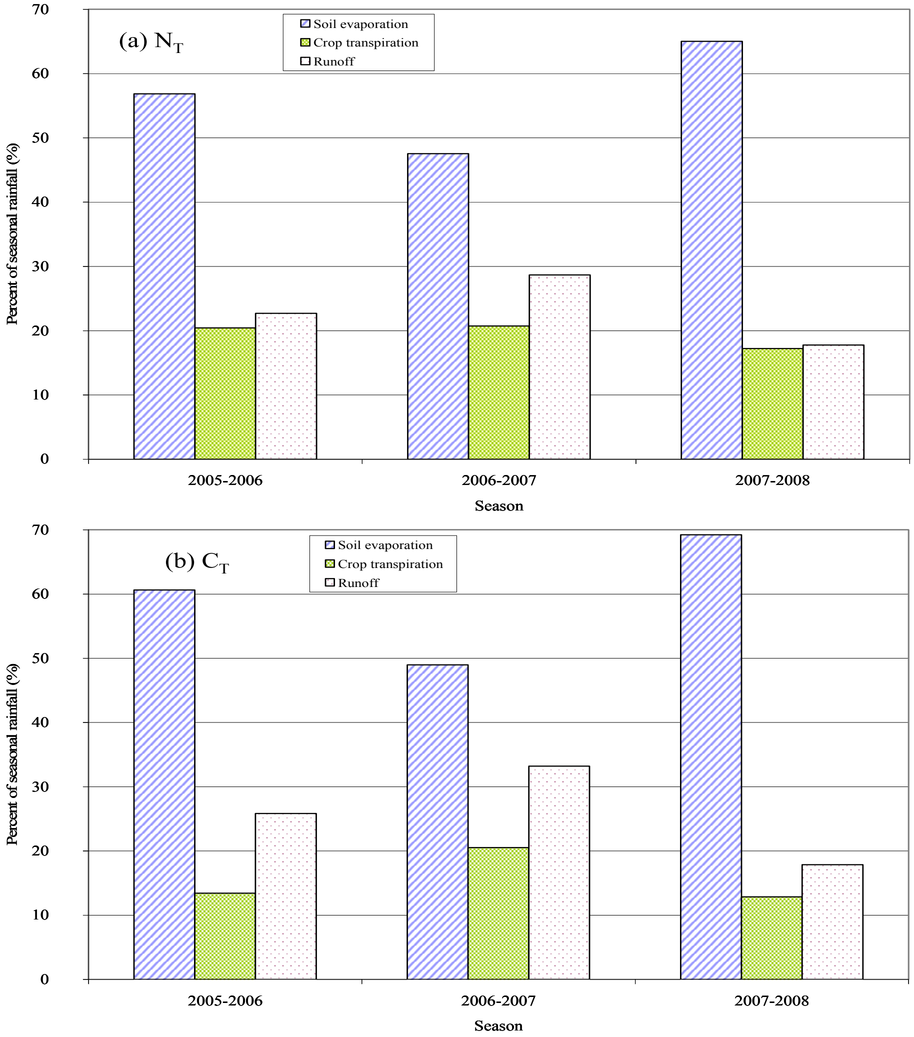

Figure 3.16: Partitioning of water fluxes obtained from the PT model in (a) N_T and (b) C_T. The fluxes are expressed as percentages of seasonal rainfall

A comparison of the variation of seasonal soil evaporation and transpiration estimated from the PT model and FAO Penman-Monteith (PM) approach is given in Fig. 3.17. At the start of the season, estimates of soil evaporation from the PT model were higher than those from PM approach. However, in approximately 20 days between December and January, the two measurements have a similar pattern. By the beginning of February, soil evaporation estimated using the PM approach is close to zero while that obtained from the PT model is about 3 mm per day. This period coincides with the onset of full canopy cover in maize and thus soil evaporation may be minimal. In all three seasons, crop transpiration from the PT model rose and declined quickly before mid December in a way that suggested that the model needed time to stabilize. The predictions of transpiration flux from the PT model were different from those from the PM approach throughout the seasons except in the last dekad of January and March. Based on the amount of disagreement, it is not possible to identify which method is most accurate. Poor simulation results from P-T model could have resulted from the model structure as it is a rainfall-runoff as well as a crop-growth model developed for more arid environments. During very wet periods (summer) the model tends to overestimate runoff and thus reduce infiltration and soil moisture storage. This then affects the modeled soil evaporation and plant transpiration and hence biomass production. Thus, direct field measurements of soil evaporation and transpiration by using for example lysimeters and/or sap flow meters, respectively are necessary to make comparisons between the measured and the model outputs and if necessary calibrate the models to improve their performance. There is a need to tailor the P-T model structure to suit the study area which is quite wet in summer and dry in winter.

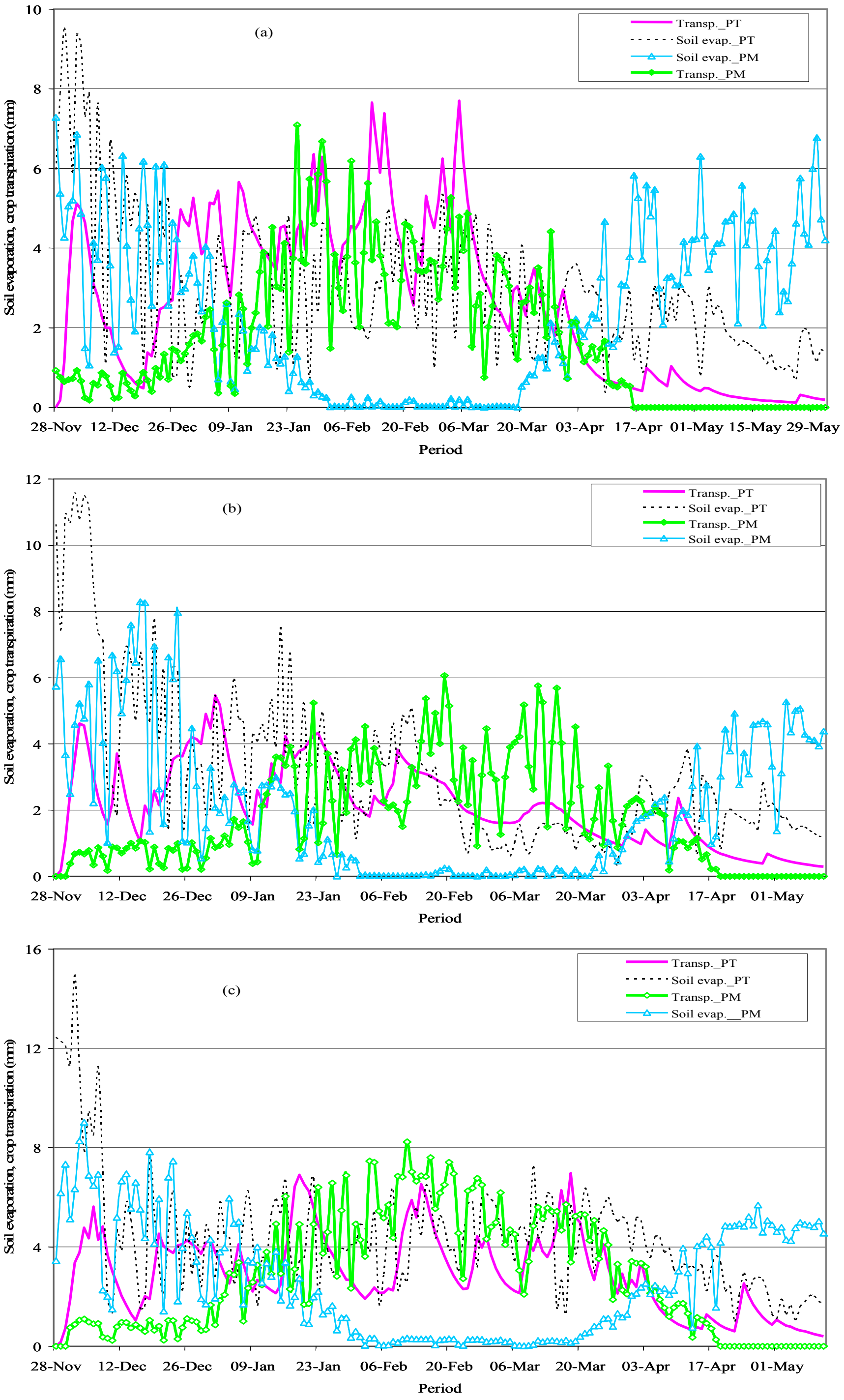

Figure 3.17: Comparison of soil evaporation and crop transpiration estimated using Parched-Thirst (PT) model and Penman-Monteith (PM) approach in (a) 2005/06; (b) 2006/07; and (c) 2007/08 seasons

3.5 Conclusion

The effects of two land preparation methods (conventional and no-till) on soil physical properties and field scale water flow paths were investigated. The tillage method used was found to influence bulk density and water partitioning. The partitioning process was mainly influenced by characteristics of rainfall events the majority of which had intensities lower than 10 mm.h^{-1}. Although there were no significantly differences ($p \leq 0.05$) in soil moisture depths, runoff depths, crop transpiration and soil evaporation between N_T and C_T, the findings suggested that N_T allowed for more infiltration, less runoff and more crop transpiration, relative to C_T.

Seasonal water savings of about 2% of annual rainfall were found in N_T treatments. However, the quantity of rainfall has to be within a certain threshold for substantial benefits to be realized. The difference is minimal during very low and very high rainfall seasons. This limit needs to be established so that in regions with seasonal rainfall lower than that, other approaches to improve soil infiltration are used rather than relying on no-tillage while no measures are required in higher rainfall areas. This study provides challenges for more field-based research to directly quantify soil evaporation, crop transpiration and deep percolation. Once quantified, model representation and performance can be improved and better inferences are likely to be made regarding water flow paths and their influence on crop production as well as possible impacts on downstream ecosystems.

Use of various techniques to monitor the fluxes complimented each other well in this study. The TDR, GMS and the ERT methods described moisture status of the soil uniformly. However, the granular matrix sensors require careful calibration against known water contents of soils similar to the ones to be investigated. They also require time to stabilize in the soil before useful readings can be obtained. Thus, it is recommended that they be re-calibrated after each season. The RM15-D meter is a useful equipment to study geophysics at small scales as used in this study. However, when the focus of the exercise is the distribution of soil moisture, resistivity values need to be related with another physical measurement because other materials present in the soil e.g. clay, salts etc influence the resistivity values. The 2-m frame on which the RM15-D meter is mounted makes it cumbersome for use when the crops are still in the field. Restricting measurements to winter months only, does not provide an opportunity to do seasonal comparisons. This study recommends further investigation into the influences of tillage on water flow directions in the soil.

The PT model simulation results did not replicate the fluxes measured or those approximated from the PM approach. This was attributed to shortcomings in the SCS method used to predict the rainfall-runoff mechanisms in the PT model. However field measurement errors, despite all attempts to minimize them, could have contributed to the discrepancy. Direct measurements of soil evaporation and crop transpiration are essential and could be used to calibrate and validate model outputs. While the work thus far has quantified hydrological processes at field scale through on-site measurements and preliminary modeling, there is need to investigate whether the increased infiltration and subsequent high moisture in the root zone contributes to higher biomass and grain yields (xref. Chapter 8, Section 8.4.2.1). In addition, it is necessary to examine the relationship between the improved infiltration and changes in soil surface and near-surface porosity (xref. Chapters 4, 5 and 6).

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4.0 DESCRIBING THE DOMINANT SURFACE AND NEAR SURFACE CHANGES IN SOIL HYDRAULIC PROPERTIES DUE TO TILLAGE. I: ESTIMATION OF STEADY-STATE INFILTRATION RATE AND HYDRAULIC CONDUCTIVITY

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Abstract

The rate of water entry into the soil determines its potential for storage thereof and thus the amount of water available for plants. In semi-arid regions where water resources are limited and not easily predictable, information on the rate of flow of water into the soil across the season is valuable. The contribution of tillage practices to soil moisture accumulation and crop yields have been widely studied. Nevertheless, the dominant drivers of processes such as infiltration and water movement are only vaguely understood. In addition, several hydrological processes cannot be fully explained on the basis of the soil moisture content per se.

A field experiment was conducted at four sites in the Potshini catchment to measure soil hydraulic properties on no-till (N_T) and to compare these with results from conventional tillage plots (C_T) at the soil surface (D_0) and at 10 cm below surface (D_{10}) in December, February and April, using double ring and tension disc infiltrometers (-0.5, -3 and -9 cm water pressure heads). Initial and final soil moisture contents were also determined at each site. The tension disc measurements were analyzed using an analytical solution of Wooding (1968) and also a numerical inversion approach using the HYDRUS-2D code coupled with a Levenberg-Marquardt parameter estimation algorithm. The classical Kostiakov, modified Kostiakov, classical Philip and modified Philip models were tested for their ability to describe infiltration rates using the data from double ring infiltrometers.

Across the season, there were relatively higher steady-state infiltration rates at depth D_{10} than at depth D_0 in both tillage systems. The estimates of hydraulic conductivity obtained from the analytical solution were between 7% and 750% higher than those obtained from the inverse

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solution, perhaps because some of the underlying assumptions were compromised. In 50% of the sites, N_T showed significantly higher hydraulic conductivity (K) compared to C_T. The modified Philip's and Kostiakov's models were recommended for routine modeling of the infiltration process on such soils.

Keywords: Double-ring, hydraulic conductivity, infiltration, model, tillage, tension disc.

4.1 Introduction

Infiltration is a complex physical process that is often difficult to accurately describe due to the isotropic and heterogeneous conditions common in agricultural lands (Chowdary et al., 2006) yet its magnitude and seasonal variations are useful in optimizing water resources in smallholder rainfed agriculture; in irrigation management; in the prediction of runoff; in minimizing erosion, and could provide indications of subsurface water recharge and contaminant transport. These are important processes that are likely to cause a chain of influences in the hydrologic cycle, making the understanding and quantification of infiltration very relevant in water resources management especially where rainfed farmers who have little capacity to mitigate moisture deficits are involved. These farmers, according to Hatibu et al. (2006) have remained at subsistence level and perpetual poverty due to uncertainties in the amount of water available at the root zone because of a combination of rainfall characteristics, poor soils and topography which causes quick runoff even before the infiltration capacity of the soil is achieved. Interventions that could improve yields in such communities need to optimize water infiltration and retention.

Soil hydraulic properties influence the entry, movement, and removal of water in the soil vadose zone. These properties include hydraulic conductivity, flux potential, sorptivity and the microscopic capillary length (Reynolds and Elrick, 2005). Tillage methods affect the soil's pore size distribution, responsible for water infiltration, storage and transmission creating a direct influence on the replenishment and depletion of soil water storage and soil biological processes important to crop response (Azooz et al, 1996; Moreno et al., 1997; Whilhem and Mielke, 1998; Angulo-Jaramillo et al., 2000; Lipiec et al., 2006). The influence of different tillage systems on soil water dynamics is not a new subject. However, mixed results have been reported e.g. the ability of no-tillage (N_T) to increase infiltration and reduce run-off (Azooz et al., 1996; McGarry et al., 2000; Kosgei et al., 2007) and increase soil water holding capacity (Whilhem and Mielke, 1998; Unger and Vigil, 1998; Misika and Mwenya, 1998; Smith et al., 2001; Fowler and Rockström, 2001; Chowdary et al., 2006). Conventional tillage (C_T) has been shown to disrupt macropore continuity and result in reduced infiltration and low hydraulic conductivity (Logsdon and Kasper, 1995; Arshad et al. 1999). However, Ferreras et al. (2000) and Pelegrin et al. (1990) obtained lower infiltration rates from N_T compared to C_T systems which was attributed to increased bulk density found in N_T soils and an increased porosity produced by tillage. Nevertheless, Logsdon et al. (1993) and Messing and Jarvis (1993) showed that the hydraulic conductivity of C_T decreased during the growing season.

Seasonal changes in various factors such as soil's bulk density, moisture regime and wetting and drying cycles affect infiltration rates. The magnitude and direction of these alterations affect the status (content and potential) of soil water and have not been investigated adequately for soils in semi-arid regions (Azooz et al., 1996; Twomlow and Bruneau, 2000; Kosgei, et al., 2007) that are largely occupied by smallholder rainfed farmers. Findings from other regions may not be universally applicable (Lal, 1989; Moreno et al., 1997) because the effect of a specific management system on water partitioning depends on the soil characteristics and meteorological conditions at each particular site (Lampurlanés and Cantero-Martínez, 2006). Root growth has been reported to block pores (Suwardji and Eberbach, 1998) implying that the type of crop and the spacing adopted could have an influence on the infiltration characteristics. Surface crusts common in tropical and subtropical regions due to raindrop impact (Casenave and Valentin, 1992; Valentin and Bresson, 1992) decrease the infiltration rate significantly because of a low surface saturated hydraulic conductivity (Šimůnek et al., 1998). These conditions underscore the need to conduct site specific sequential evaluation of changes in hydraulic properties when subjected to different tillage systems during the growing season. Indeed, Strudley et al. (2008) indicated that it is only recently that the research community is beginning to explore the dynamic temporal and spatial variability in soil physical properties and processes in the light of various management practices.

Water entry and transmission in the soil are governed by the potential gradient and hydraulic conductivity. The hydraulic conductivity depends on the soil grain size, the structure of the soil matrix and the relative amount of soil fluid (saturation) present in the soil matrix. Thus, being integrative it is a better evaluation criterion to compare the effects of tillage under different soils than solely using water retention characteristics or bulk density.

The hypothesis of this study was that the tillage system used influences soil infiltration rate and hydraulic conductivity and that there is more infiltration into N_T tillage plots compared to C_T. The main objective was to compare infiltration rates and hydraulic conductivity from infiltration data measured from N_T and C_T tillage plots at three different periods in the maize growing season.

This paper focused on the influence of repeated tillage treatments for three years on steady-state infiltration rate and hydraulic conductivity within the top 10 cm of the soil. Field-scale experiments were conducted using tension disc and double ring infiltrometers at four sites in the Potshini catchment, South Africa at monthly intervals over the maize growing season. According to Lorentz (1995) conductivity of fluids in unsaturated porous media can be estimated using mathematical models. In this study, the tension disc data was first analyzed using the classical steady-state analysis of Wooding (1968) and the derived hydraulic parameters were then compared with those obtained from numerical analysis (Šimůnek and van Genuchten, 1997). The approach proposed by Reynolds et al. (2002) was used to estimate saturated hydraulic conductivity from double ring infiltrometers. This data was further used to approximate parameters of four commonly used models viz. Kostiakov's, modified Kostiakov's, Philip's and modified Philip's models.

4.2 Materials and methods

4.2.1 Research area and experimental sites

The experiment was performed between December 2007 and April 2008 in four trial sites at the Potshini catchment (29.37°E, 28.82°S), South Africa. Rainfall, with a mean annual value of 710 mm, falls only in summer (Oct-Mar) (Kosgei et al., 2007). Smith et al. (2001) classified the soils in the study area into four major soil types[18] viz. Hutton (Oxisols), Avalon (Ferralsols), Estcourt (Planosols) and Mispah (Lithosols) soil patterns. However, the textural classification of the plots used was sandy clay loam with varied proportions of soil separates. Thorrington-Smith (1960) broadly classified soils in the Ladysmith-Bergville plain as of Karoo system and Beaufort series.

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[18] FAO classification in parenthesis.

Each of the four sites consisted of an N_T and a C_T treatment set up in the form of a run-off plot measuring 10m long by 2.45m wide. This was the third year of N_T and C_T treatments. Design details and set-up of the runoff plots are contained in Kongo and Jewitt (2006) and Kosgei et al. (2007), respectively. A summary of the four sites, their soil textural classification and mean bulk densities (xref. Chapter 3, Section 3.4.1) is provided in Table 4.1. Thus the eight plots were designated $F_A\_C_T$, $F_A\_N_T$, $F_B\_C_T$, $F_B\_N_T$, $C_{TS}\_C_T$, $C_{TS}\_N_T$, $F_C\_C_T$ and $F_C\_N_T$.

Table 4.1: Description of the four experimental sites monitored in Potshini catchment, their soil textural classification and mean bulk densities

Tillage system	Plot designation	Soil texture (%)			Mean bulk density(g.cm^{-3})	
		Clay	Sand	Silt	D_0	D_{10}
Conventional tillage (C_T)	$F_A\_C_T$	20.6	72.2	7.2	1.131	1.191
	$F_B\_C_T$	21.2	68.3	10.5	1.137	1.124
	$F_C\_C_T$	25.4	65.2	8.4	1.488	1.462
	$C_{TS}\_C_T$	22.6	66.2	11.2	1.263	1.411
No-till (N_T)	$F_A\_N_T$	20.6	72.2	7.2	1.102	1.115
	$F_B\_N_T$	21.2	68.3	10.5	1.086	1.026
	$F_C\_N_T$	25.4	65.2	8.4	1.478	1.552
	$C_{TS}\_N_T$	22.6	66.2	11.2	1.356	1.405

A MacGoy ox-drawn ripper was used to open planting furrows in N_T treatments. The ripping was done four weeks after a 3% Senator Extra-Glyphosate was sprayed at a rate of 4 liters per hectare. At planting, a similar dose of Senator Extra-Glyphosate and 0.75% Dual Gold solution at a rate of 0.8 liters per hectare was applied. Maize (cv. PAN 6611) was planted on 9th December 2005, 27th November 2006 and 29th November 2007 at a plant population of approximately 37,000 plants per hectare with an inter-row spacing of 0.9 m. Sowing was done any date after 15th November with rainfall total of 40 mm falling in at least 4 days (xref. Chapter 2, Section 2.2.5.2). Weeds were controlled by hand at regular intervals twice in the season.

C_T plots were ploughed using a mouldboard ox-drawn plough to about 15 cm deep three weeks prior to planting. This was repeated a day to planting to eliminate weeds which might have germinated so that both the treatments begin free of weeds. Hand hoes were used to open 10 cm deep furrows where maize seeds were placed on the same day and at approximately the same plant population and inter-row spacing as in N_T plots. Weeding was done using hand hoes at the same time as was done in N_T plots. In all the treatments, DAP fertilizer (N=18.5%, P=8.3% and

K=4.2%) was applied at a rate of 150 kg.ha^{-1}. Maize from all the treatments was harvested on 27th May 2006, 26th May 2007 and 5th June 2008.

4.2.2 Infiltration measurements

Infiltration measurements were done at each of the plots (Table 4.1) at depth D_0 and D_{10} in December 2007, February 2008 and April 2008. The measurements were aimed at determining the changes in hydraulic conductivity across the season. Both field and laboratory techniques and application procedures to measure hydraulic conductivity exist. Tension disc infiltrometers (Perroux and White, 1988) have recently proven useful, especially because apart from hydraulic conductivity measurements, information on the effects of macropores and preferential flow paths and soil water retention properties, superior than those from laboratory methods can also be obtained (Watson and Luxmoore, 1986; Wilson and Luxmoore, 1988; Ankeny et al., 1991; Šimůnek et al., 1998; Šimůnek et al., 1999; Angulo-Jaramillo et al., 2000; Cameira, 2003; Reynolds and Elrick, 2005; Ramos et al., 2006; Moret and Arrúe, 2007).

Angulo-Jaramillo et al. (2000) highlighted recent developments in the use of the tension disc infiltrometers. Their concluding remarks emphasized the ability of the tension disc infiltrometers to offer a simple and fast means of estimating soil hydraulic properties and structural characteristics based on infiltration measurements combined with appropriate theoretical principles or procedures. However, some of the identified limitations include errors arising from simplifying assumption of the analysis used to infer soil hydraulic properties from the measurements, problems in measurement procedures or difficult soils and the need to determine volumetric water content in equilibrium with the imposed pressure head in which errors in sampling may arise. According to Ankeny et al. (1991), the use of tension disc infiltrometers allows minimum disturbance of the soil, it is relatively rapid and functions most effectively for pressure heads close to saturation where macropores are hydraulically most active. In addition various properties of the soil are integrated beneath the infiltrometer such as the influence of local-scale heterogeneity, different soil structure and textural irregularities, preferential pathways, layering and anisotropy (Šimůnek et al., 1999).

Cylinder (ring) infiltrometers (Bouwer, 1986) have been used for decades to measure saturated hydraulic conductivity in the field. Previous workers (Bouwer, 1986; Youngs, 1987; Reynolds and Elrick, 1991; Bagarello and Sgroi, 2004; Chowdary et al., 2006) recommended the double-ring technique because the buffer ring reduces lateral movement of water from the inner ring, in which measurements are made. Ahuja (1976) reported that the effect of lateral flow on final infiltration was negligible when the diameters of the buffer and the inner rings were 0.6 m and 0.3 m, respectively. However, using an inner ring of 0.3 m diameter and a buffer ring of 0.9 m diameter eliminated the lateral flow completely.

4.2.2.1 Tension disc infiltrometer (TI) tests

The field hydraulic properties were characterized at each observation site and depth using a disc infiltrometer (Lorentz et al., 2001) constructed following the design of Perroux and White (1988) with a base diameter of 13 cm (Fig. 4.1). Such infiltrometers had been in use at the School of Bioresources Engineering and Environmental Hydrology (SBEEH), University of KwaZulu Natal since 1994. The reservoir and bubble tower are separable from the disc base. A graduated tape is attached to the reservoir. The base of the disc is covered with a nylon mesh with a bubbling pressure of about 25 cm. To achieve the desired hydraulic contact between the base of the disc membrane and the soil surface, a thin layer of commercial fine sand was applied on the soil surface.

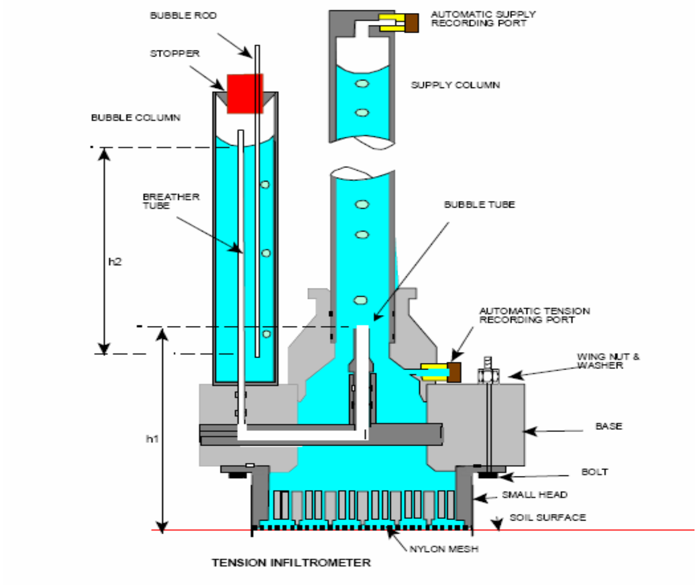

Figure 4.1: Tension disc infiltrometer (Lorentz et al., 2001) used in this study.

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Infiltration runs were performed at three pressure heads i.e. -0.5 cm, -3 cm and -9 cm at the same site. The height of the bubble tube from the base of the disc (h_1 in Fig. 4.1) was 3 cm. The pressure heads used took into account h_1. Two sets of measurements were made in each plot. The infiltration tests were conducted between rip lines in all cases. A wet to dry (0.5, 3 and 9 cm tension) sequence was adopted as this ensures a rapid advance of the wetting front hence appropriately validating the assumption of a unit gradient below the device. This sequential stepwise decrease of supply pressure head reduces the measurement errors potentially caused by hyteresis (Reynolds and Elrick, 1991). After ascertaining that the setup was stable and had no leaks, the bubble rod was opened. The time taken for water level to fall by 5 mm in the graduated reservoir was recorded manually. Measurements were repeated until infiltration rates were the same for at least four consecutive readings. After the soil surface (D_0) measurements were complete, the soil layer (0-10 cm) from the same spot was removed and infiltration measurements were repeated at a depth of 10 cm (D_{10}).

4.2.2.2 Double ring infiltrometer (DI) tests

A double ring infiltrometer test was done within a diameter of 100 cm from the tension disc test. The inner and outer diameters of the double-ring set used were 13 cm and 30 cm, respectively. The ratio of the diameter of the outer to the inner ring is more than 2 and as observed by Ahuja (1976) the flow in the inner ring was vertical. The method of measurement used was as described by Reynolds et al. (2002). The rings were pushed into the soil concentrically and parallel to the measurement surface to a depth of 5 cm with minimum soil disturbance. A steel pointer was positioned vertically at the centre of the inner cylinder with a height of 5 cm above the soil surface. The rings were then filled with water to a depth just slightly over 5 cm. Timing was started as soon as the water level in the inner ring reached the pointer. This was done simultaneously with the addition of 100 ml of water. The same amount of water was successively added and a reading taken every time the water level reached the pointer until the infiltration time did not change for five consecutive readings. At this point steady-state flow was assumed, and the steady-state infiltration was calculated from the last five measurements. Water level in the outer ring was maintained at exactly the same height as in the inner ring. Generally steady-state flow was achieved within 60 to 120 minutes.

A soil sample was collected near the measurement location to establish the antecedent moisture content. Another sample was taken after the infiltration measurement from below and also near the instrument to determine the final moisture content. These were weighed and re-weighed after drying in an oven for 24 hours at 105^0C. The procedure was repeated until there was no further change in weight. The water contents were then computed.

4.2.3 Steady-state flow and calculation of unsaturated hydraulic conductivity

After a successful set-up, timing commenced and was not stopped until steady state conditions were reached for each of the three selected tensions, noted separately, was achieved. The three sets of tension disc infiltrometer data from each measurement location were used to obtain unsaturated hydraulic conductivity K(h) and other properties. Gardner (1958) described K(h) using the following exponential function:

$$K(h) = K_s \exp(\alpha^* h) \tag{4.1}$$

where K_s is the saturated hydraulic conductivity of the porous medium [LT^{-1}], α [L^{-1}] is an empirical fitting parameter, and h [L] is the soil matric potential.

4.2.3.1 Wooding's analytical approach

Using Equation 4.1 and assuming a steady-state flow from a shallow circular pond of radius r [L], Wooding (1968) developed the following approximate solution for the steady-state infiltration rate:

$$Q(h_0) = \left(1 + \frac{4}{\alpha \pi r}\right) \pi r^2 K_s \exp(\alpha h_0) \tag{4.2}$$

where $Q(h_0)$ is the steady-state infiltration rate [L^3T^{-1}] and α [L^{-1}] is an empirical fitting parameter. The first term on the right of Eq. (4.2) represents the gravitational component of flow out of the infiltrometer and the second term represents flow due to soil capillary plus the interaction effects of gravity, capillary, and source geometry (disc radius) (Reynolds and Elrick, 2005). Eq. 4.2 necessitates two steady-state fluxes obtained with the same disc infiltrometer at different supply pressure heads (Ankeny et al., 1991), or with two infiltrometers of different diameters at the same supply pressure head (Smettem and Clothier, 1989). In this study, the method proposed by Ankeny et al. (1991) was preferred because it eliminates uncertainties that could be induced by using more than one tension infiltrometer. Methods of obtaining the unsaturated hydraulic conductivity in the middle of an interval between two successive applied pressure heads have been discussed by Ankeny et al. (1991), Reynolds and Elrick (1991), Angulo-Jaramillo et al. (2000), Šimůnek et al. (1998b),Yoon et al. (2007) and Moret and Arrúe (2007), among others. The method proposed by Ankeny et al. (1991) which fits the infiltrometer measurements by a piecewise relationship was used in this study.

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4.2.3.2 Numerical solution

The modified form of Richard's equation approximates well a radially symmetric isothermal Darcian flow in a variably saturated isotropic rigid porous medium. This equation is expressed as follows:

$$\frac{\partial \theta}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(rK\frac{\partial h}{dr} \right) + \frac{\partial}{\partial z}\left(K\frac{\partial h}{dz} \right) + \frac{\partial K}{\partial z} \qquad (4.3)$$

where θ is the volumetric water content [L^3L^{-3}], h is the pressure head [L], K is the hydraulic conductivity [LT^{-1}], r is a radial coordinate [L], z is the vertical coordinate [L] that is positive upward with z = 0 corresponding to the surface , and t is the time [T].

The following initial and boundary conditions (Warrick, 1992) apply to Eq. 4. 3:

$$\theta(r,z,t) = \theta_i(z) \quad or \quad h(r,z,t) = h_i(z) \quad t = 0 \qquad (4.4a)$$

$$\frac{\partial h(r,z,t)}{\partial z} = -1 \quad r > r_0, \quad t = 0 \qquad (4.4b)$$

$$h(r,z,t) = h_0(t) \quad 0 < r < r_0, \quad z = 0 \qquad (4.4c)$$

$$h(r,z,t) = h_i \quad r^2 + z^2 = \infty \qquad (4.4d)$$

where θ_i is the initial volumetric water content [L^3L^{-3}], h_i is the initial pressure head [L], h_0 is the imposed time variable supply pressure head [L] and r_0 is the disc radius [L].

A number of researchers (e.g. Šimůnek et al., 1996, Šimůnek and van Genuchten, 1997; Šimůnek et al., 1998a; Šimůnek et al., 1999; Angulo-Jaramillo et al., 2000; Ventrella et al., 2005; Ramos et al., 2006) have found HYDRUS-2D (Šimůnek et al., 1996), a quasi-three-dimensional finite element code, suitable to solve the above equations. In this study DISC (Šimůnek et al., 2006), a computer software package that consists of the simplified HYDRUS-2D computer program (DISCTENS), and the interactive graphics-based user interface (DISC) was used. The DISCTENS program numerically solves the Richard's equation for saturated-unsaturated water flow.

Prior to the application of the numerical solution, relationships describing the hydraulic properties of the soil have to be adopted. Leij et al. (1996) investigated the performance of five different functions and found that although the Gardener (1958) exponential function is widely used for analytical solutions, it was the least successful. Because unsaturated soil hydraulic functions developed by van Genuchten (1980) performed better, they will be used in this study. These functions are of the following form:

$$S_e(h) = \frac{\theta(h) - \theta_r}{\theta_s - \theta_r} = \frac{1}{\left(1 + |\alpha h|^n\right)^m} \qquad h < 0 \qquad (4.5)$$

$$\theta(h) = \theta_s \qquad h \geq= 0$$

$$K(\theta) = K_s S_e{}^l \left[1 - (1 - S_e{}^{1/m})^m\right]^2 \qquad h < 0 \qquad (4.6)$$

$$K(\theta) = K_s \qquad h \geq= 0$$

where S_e is the effective water content [-], K_s is the saturated hydraulic conductivity [LT^{-1}], θ_r and θ_s denote the residual and saturated water contents [L^3L^{-3}], respectively; l is a pore-connectivity parameter [-],α [L^{-1}] is an approximate equivalent to the inverse of the air-entry pressure, and n [-] and m (=1-1/n) [-] are empirical shape and pore size distribution parameters. For many soils, l was estimated to be 0.5 by Mualem (1976). This leaves five unknown parameters (θ_r, θ_s, α, n, and K_s). The hydraulic parameters in Eq. (4.5) and Eq. (4.6) represent wetting branches of the unsaturated hydraulic properties since tension disc infiltration is a wetting process (Šimůnek and van Genuchten, 1996; Ramos et al., 2006).

To obtain the desired soil hydraulic properties for multiple measurement sets using the inverse modeling approach, Šimůnek and van Genuchten (1996) proposed the minimization of the following objective function:

$$\Phi(\beta, q_1 ...., q_m) = \sum_{j=1}^{m} \left\{ v_j \sum_{i=1}^{n_j} W_{ij} \left[q_j * (ti) - q_j(ti, \beta)\right]^2 \right\} \qquad (4.7)$$

where m represents the different sets of measurements (infiltration data, pressure heads, and/or water contents), n_j is the number of measurements in a particular set, $q_j*(t_i)$ is the specific measurement at time t_i for the jth measurement set, β is the vector of optimized parameters (e.g., θ_r, θ_s, α, n, K_s, and l), $q_j(t_i, \beta)$ represents the corresponding model predictions for parameter vector β, and v_j and w_{ij} are weights associated with a particular measurement j or a measurement i within set j, respectively. Šimůnek and van Genuchten (1996), Šimůnek et al., (1999), Ventrella et al., (2005), Ramos et al. (2006) assumed that the weighting coefficients w_{ij} in Eq. 4.7 are equal to 1 suggesting that the variances of errors inside a particular measurement are all assumed to be the same. The weighting coefficients v_j, used to minimize differences in weighting between different data types, because of different absolute values and numbers of data used, is given by:

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$$v_j = \left(\frac{1}{n_j \sigma_j^{\;2}} \right) \tag{4.8}$$

In this methodology, the objective function is viewed as the average weighted squared deviations normalized by measurement variances $\sigma_j^{\;2}$. The DISCTENS code includes a Marquardt-Levenberg type parameter optimization algorithm (Marquardt, 1963) for the minimization of the objective function, Φ.

As Ankeny et al. (1991) pointed out, using tension disc data to estimate soil hydraulic properties requires either use of a single infiltrometer radius at different tensions or different infiltrometer radii at the same tension, Šimůnek and van Genuchten (1996) found that cumulative infiltration rates at one particular tension did not provide enough information to estimate more than two of the soil hydraulic parameters (i.e. θ_r, θ_s, α, n and K_s) in the model. Because unique solutions for the unknown parameters were obtained when cumulative infiltration data from multiple tensions were combined with measured values of the initial and final water contents (Šimůnek and van Genuchten, 1997), this approach was adopted in the current study. The objective function was defined in terms of the measured cumulative infiltration data at three pressure heads (-0.5 cm, -3 cm and -9 cm) and the initial and final water contents (xref. Section 4.2.2.2). Since observation errors of the measurements were unknown, the weighting coefficients w_{ij} were all assumed to be equal to unity (e.g., Ramos et al., 2006 and Šimůnek et al., 1999).

4.2.4 Analysis of double ring infiltration data

4.2.4.1 Estimation of saturated hydraulic conductivity K_s

Saturated hydraulic conductivity K_s [LT-1], was estimated for each experimental location from the one-dimensional steady-state infiltration rates following the procedure outlined by Reynolds et al. (2002). The K_s is given by:

$$K_s = \frac{q_s}{\left[\frac{H}{(c_1 d + c_2 r)} \right] + \left\{ \frac{1}{[\alpha (c_1 d + c_2 r)]} \right\} + 1} \tag{4.9}$$

where q_s [LT^{-1}] is the steady-state infiltration rate, H [L] is the depth of ponded water in the ring, $c_1 = 0.316\pi$ and $c_2 = 0.184\pi$ are dimensionless quasi-empirical constants, d [L] is the depth of ring insertion into the soil, r [L] is the radius of the inner ring, and α [L^{-1}] is the inverse soil microscopic capillary length parameter.

4.2.4.2 Fitting of infiltration models

Cumulative infiltration data from double ring infiltrometers were used to approximate parameters of four commonly used models viz. Philip's, modified Philip's, Kostiakov's, and modified Kostiakov's models. A brief description of these models is provided below.

Philip model

From Darcy's equation, for unsaturated soils a physically-based converging power series which described cumulative infiltration as a function of time was developed by Philip (1957a). Philip (1957b) further showed that the power series can be truncated to two fitting parameters which were sufficient to describe the time dependence of cumulative infiltration. For cumulative infiltration the relationship, termed the classical Philip's model is:

$$I = St^{1/2} + At \tag{4.10}$$

where I [L] is cumulative infiltration, S, is sorptivity [$LT^{-0.5}$], A is transmissivity [LT^{-1}] and t is time [T]. The expression of infiltration rate (i) is as follows:

$$i(t) = \frac{1}{2} St^{-1/2} + A \tag{4.11a}$$

According to Mbagwu (1994), sorptivity indicates the soil's ability to absorb water by matric forces during the initial stages of the infiltration process. Since it expresses the matric properties of the soil, it depends on the initial soil moisture content. The transmissivity term, A reflects the soil's ability to transmit water under the influence of gravity and has been related (Philip, 1969; Dunin, 1976) and equated (Swartzendruber and Young, 1974) to a soil's saturated hydraulic conductivity, although Collis-George (1977) and Skaggs and Khaleel (1982) pointed out that A cannot replace saturated hydraulic conductivity without incurring serious errors.

According to Kutilek and Nelson (1994), the magnitude of A in Eq. 4.11(a) comprises the hydraulic conductivity and a truncation error due to the use of fewer fitting parameters. To overcome truncation errors, a number of researchers chose to use more than two terms of the power series (e.g. Stroosnijder, 1976; Brutsaert, 1977; Swartzendruber, 1987; Kutilek and Nielsen, 1994). These are used in an expression termed the modified Philip's models. An example of the modified Philip's model is:

$$i(t) = \frac{1}{2} S t^{-0.5} \left[\frac{1}{\left\{1 + (BK_s t^{0.5})/S\right\}^2} \right] + K_s \qquad (4.11b)$$

where K_s is the saturated hydraulic conductivity $[LT^{-1}]$ and B is a constant which also corrects the effect of the force of gravity. Brutsaert (1977) proposed B values to be 1/3, 2/3, or 1. However, Kutilek and Nielsen (1994) found that a value of 1 was applicable for most practical purposes. The modified Philip's model (Eq. 4.11b), just like the classical Philip's model (Eq. 4.11a) is time dependent and provides an infinite initial infiltration and a finite steady state infiltration for large t (Lal and Shukla, 2004).

Kostiakov's model

The classical Kostiakov (1932) infiltration model was based on experimental data and its parameters contain no physical meanings (Lal and Shukla, 2004; Lei et al., 2008). The empirical model expresses cumulative infiltration, I as a function of time, t as:

$$I = Bt^{-n} \qquad (4.12a)$$

where B and n are constants. The infiltration rate is estimated from:

$$i = -nBt^{-n-1} \qquad (4.12b)$$

In Eq. 4.12(b) the initial value of the infiltration rate is infinite and as time progresses, the infiltration rate approaches zero instead of a constant (non-zero) value as is actually the case. Mbagwu (1994) suggested that this model is appropriate for expressing horizontal flows but that it is grossly deficient for vertical flows. In addition, it does not predict a final and constant infiltration rate. Thus it is not considered adequately applicable for vertical infiltration. However, this has been overcome by incorporating a maximum time range of application, $t_{max}=(B/K_s)^{1/n}$ and a coefficient, i_c which shifts the axis for infiltration rate equations and for large times infiltration approaches a finite steady state infiltration rate. Thus, the modified Kostiakov model is:

$$I = i_c t + Bt^{-n} \qquad (4.13a)$$

$$i = i_c - nBt^{-n-1} \qquad (4.13b).$$

4.3 Results and discussion

4.3.1 Cumulative infiltration

Because Wooding's analysis requires steady state infiltration rates (Ventrella, 2005) to avoid under- or over-estimation (Šimůnek et al., 1998a), all infiltration measurements were run until the time difference between four consecutive readings was constant. The infiltrometer used in this study was able to complete the infiltration tests at all the tensions without interruptions. Depending on the site, depth of measurement and period in the season the time taken to reach steady state was a minimum of about 30 minutes and a maximum of about 280 minutes. In each case the infiltration rate was high at the beginning of the test due to the lower imposed tension. Under similar conditions, plots that had lower antecedent moisture content had a rapid initial response. The gravimetric moisture content before the tension infiltrometer (TI) test (initial) and that after the TI test (final) for all sites are presented in Table 4.2. Measured bulk densities were used to convert the gravimetric to volumetric water contents.

Table 4.2: Initial and final gravimetric moisture contents (%) and soil texture for all test sites in Potshini catchment during infiltration tests done in three dates

Time done	Site	Period Till./depth	December D_0	December D_{10}	February D_0	February D_{10}	April D_0	April D_{10}
Before TI test	F_A	N_T	11.9	15.3	23.3	15.0	25.0	13.5
		C_T	14.8	18.6	20.9	16.7	22.8	11.5
	C_{TS}	N_T	11.3	9.8	14.6	15.5	13.7	14.1
		C_T	14.1	12.9	20.3	18.1	20.1	8.8
	F_C	N_T	14.0	10.2	23.8	38.6	17.2	30.1
		C_T	2.6	12.9	16.6	35.4	15.9	23.6
	F_B	N_T	6.9	7.6	10.4	15.7	26.7	16.6
		C_T	7.8	10.0	17.1	13.5	13.9	16.4
After TI test	F_A	N_T	19.5	22.2	29.1	21.3	34.2	21.7
		C_T	24.4	23.3	26.1	20.2	27.5	19.2
	C_{TS}	N_T	24.6	18.0	27.2	27.2	17.5	18.0
		C_T	25.6	18.1	26.5	22.4	26.6	15.9
	F_C	N_T	18.4	14.9	29.8	44.0	24.3	32.8
		C_T	9.2	16.4	20.4	37.1	21.9	28.2
	F_B	N_T	13.1	13.7	21.5	23.1	31.0	28.0
		N_T	16.3	18.7	24.0	21.6	24.8	25.1

The mean moisture content in N_T was 11, 18 and 20.7% in December, February and April, respectively. The mean values in C_T plots were 9.8, 18.7 and 18.1% in December, February and April. There were significant differences at $p \leq 0.05$ in initial moisture measurements in both tillage systems between December and the other instances of measurement. For the same tillage practice there were significant differences between the initial and final moisture contents in all measurements at both depths.

The volume of water that infiltrated before steady state-conditions were reached also varied. The site responses for the first one hour are illustrated in Fig. 4.2 to Fig. 4.5. Cumulative infiltration is a summation of the combined effect of capillarity and gravity. Capillary forces dominate flow at the initial stages of infiltration whereas gravitational forces become dominant when steady-state is achieved. The plots in Fig. 4.2 to Fig. 4.5 show that although the curves were similar at the initial times of infiltration, there were some differences in responses between tillage systems as well as measurement depth. In most cases, these differences were exaggerated at higher tensions and at larger t. This was interpreted as an initial indication that tillage was likely to cause differences in flow through the creation of smaller soil pores. Although sites showed variations in cumulative infiltration, the emerging trend was higher infiltration rate in C_T plots in December which became lower than in N_T by April. Due to tillage in C_T, the soil structure is loose in December but compaction ensures as the season progresses due to settlement and impact of raindrops that lead to higher bulk densities in C_T relative to N_T (xref. Table 4.1). However, this was not the case at site C_{TS} as the mean bulk density in N_T was higher than that in C_T. consequently, the infiltration envelopes at this site (Fig. 4.3) behaved differently compared to the rest of the sites since by April the envelopes from C_T treatments were higher than in N_T treatments indicating a higher volumetric intake rate.

High infiltration rate at the start of the season e.g. in December is important to rainfed farmers in semi-arid environments because this could increase the soil water to levels that guarantee germination and bridge dry spells that may follow (xref. Chapter 2, Section 2.3.5). In this regard and in circumstances where no residue is left on the soil surface in N_T treatments due to livestock grazing as is the case in the Potshini catchment, C_T is likely to be an attractive option. However, the length of time this higher infiltration is sustained, the water movement, and the water retention characteristics in the soil will influence crop growth in subsequent stages including final biomass. Thus, it is necessary to establish the dynamics of waster movement and retention throughput the season.

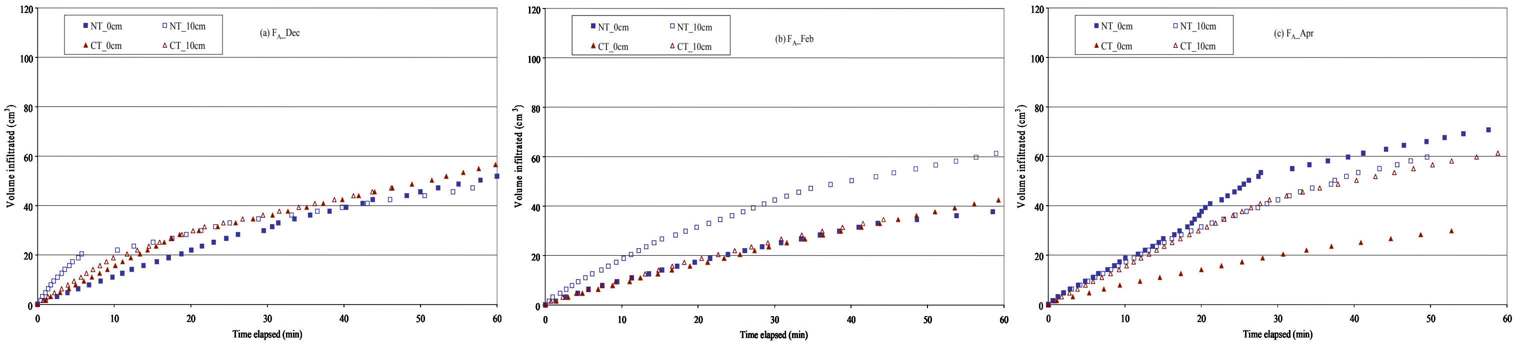

Figure 4.2: Measured cumulative tension infiltrometer curves in the first hour of infiltration on the surface and 10 cm below in N_T and C_T plots at site F_A in a) December, b) February and c) April

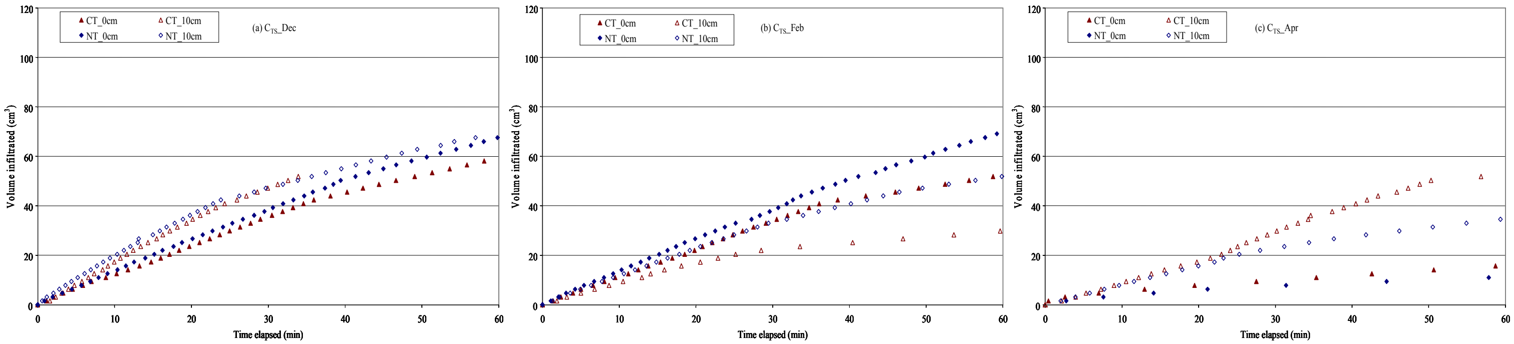

Figure 4.3: Measured cumulative tension infiltrometer curves in the first hour of infiltration on the surface and 10 cm below in N_T and C_T plots at site C_{TS} in a) December, b) February and c) April

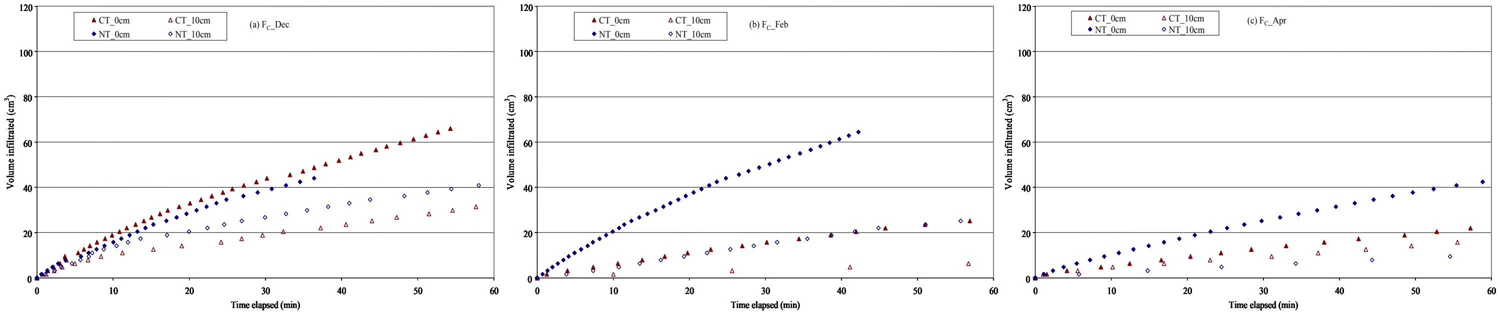

Figure 4.4: Measured cumulative tension infiltrometer curves in the first hour of infiltration on the surface and 10 cm below in N_T and C_T plots at site F_C in a) December, b) February and c) April

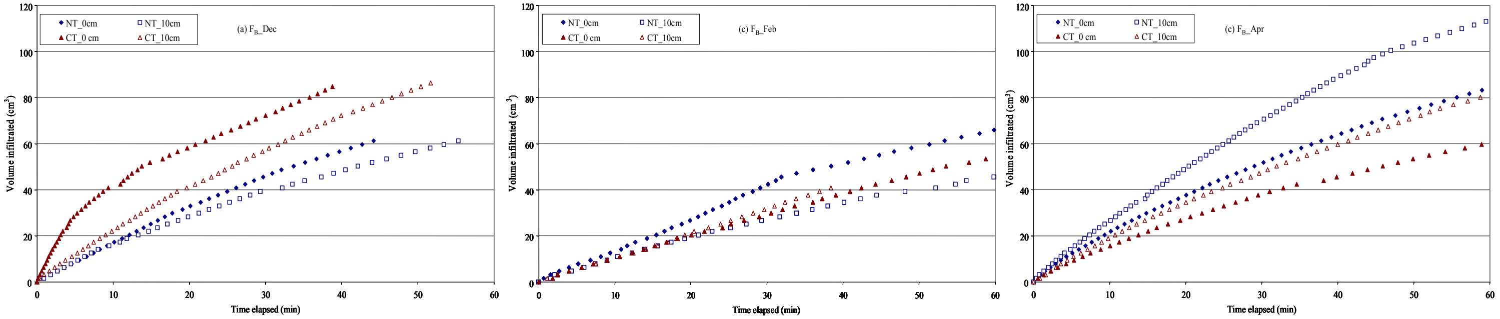

Figure 4.5: Measured cumulative tension infiltrometer curves in the first hour of infiltration on the surface and 10 cm below in N_T and C_T plots at site F_B in a) December, b) February and c) April

4.3.2 Steady-state infiltration rate

The steady state infiltration rates, q_s [LT^{-1}] of the two replicates done for each test across all sites and dates were not significantly different at $p \leq 0.05$ and averaged values were used in the subsequent sections. Steady state infiltration rates varied between tensions, sites, tillage systems, period of measurement and depths. At the specific test sites, the higher the tension used the lower was q_s. Thus, for each set of measurements the order of increasing magnitude in q_s was tension infiltrometer (TI) at 9 cm (q_{s_9}), TI at 3 cm (q_{s_3}), TI at 0.5 cm ($q_{s\_0.5}$), and double ring infiltrometer (DI) at a head of 5 cm (q_{s_DI}). Generally, the average q_s from TI were higher in December in C_T plots than in N_T plots except at site C_{TS}. This period coincided with the time when C_T plots were freshly cultivated. Nevertheless, for the other periods in the season, for different sites and depths the responses were varied. For example, site F_A had higher q_s in February in C_T plots while most of the other sites had almost equal or slightly higher q_s in N_T. The means at sites F_A and F_B had relatively lower variability. Over all sites, the average seasonal q_s in N_T and C_T from TI and DI infiltrometer are provided in Table 4.3.

Table 4.3: Mean steady-state infiltration rate (cm.min^{-1}) and the corresponding standard deviations (in parenthesis) at D_0 and D_{10} from tension disc (TI) and double ring (DR) infiltrometer measurements done during three dates in the growing season under two tillage systems in Potshini catchment.

Date		$q_{s\_0.5}$		q_{s_3}		q_{s_9}		q_{s_DR}	
		D_0	D_{10}	D_0	D_{10}	D_0	D_{10}	D_0	D_{10}
Dec	N_T	0.010	0.014	0.007	0.007	0.006	0.004	0.120	0.191
		(0.002)	(0.004)	(0.002)	(0.002)	(0.002)	(0.002)	(0.030)	(0.160)
	C_T	0.020	0.013	0.010	0.009	0.006	0.007	0.086	0.064
		(0.017)	(0.003)	(0.007)	(0.004)	(0.003)	(0.003)	(0.068)	(0.040)
Feb	N_T	0.007	0.008	0.005	0.006	0.004	0.004	0.100	0.134
		(0.002)	(0.003)	(0.002)	(0.002)	(0.002)	(0.001)	(0.086)	(0.091)
	C_T	0.008	0.006	0.006	0.004	0.005	0.004	0.166	0.075
		(0.002)	(0.005)	(0.002)	(0.001)	(0.002)	(0.002)	(0.144)	(0.061)
Apr	N_T	0.008	0.011	0.005	0.008	0.004	0.006	0.422	0.130
		(0.003)	(0.008)	(0.001)	(0.006)	(0.001)	(0.004)	(0.406)	(0.148)
	C_T	0.004	0.008	0.002	0.006	0.002	0.004	0.417	0.130
		(0.006)	(0.009)	(0.003)	(0.008)	(0.002)	(0.006)	(0.405)	(0.120)

In majority of the cases, q_s at D_{10} were higher than at D_0 in both tillage systems. Table 4.4 contains sites that had significant differences in q_s at different tensions (regular text) and measurement dates (asterisk). In all cases where there were significant differences between measurements from two tensions, a higher magnitude of q_s was always from the lower tension. For example, in December there was a significant difference between $q_{s\_0.5}$ and q_{s_3} at site F_B; the magnitude of $q_{s\_0.5}$ was higher than q_{s_3}. Italiced sites indicate the measurement date that had higher magnitude of q_s. Thus, every column in Table 4.4 with a site having an asterisk should have the same site in the same column italiced. The date when q_s was higher is then checked from column 1. The bold text shows the sites that significant differences were observed between tillage systems.

Table 4.4: Sites that displayed significant differences ($p \leq 0.05$) in q_s during the different dates of measurement in the two tillage systems in Potshini catchment

Date	Tillage		N_T				C_T			
			$q_{s\_0.5}$	q_{s_3}	q_{s_9}	q_{s_DR}	$q_{s\_0.5}$	q_{s_3}	q_{s_9}	q_{s_DR}
Dec	N_T	$q_{s\_0.5}$	F_B*,F_C*	F_B		C_{TS}, F_A	F_A*		F_A	F_A
		q_{s_3}			C_{TS}	C_{TS}, F_A				F_A
		q_{s_9}		F_B	F_C*	C_{TS}, F_A				F_A
	C_T	$q_{s\_0.5}$								
		q_{s_3}								
		q_{s_9}								
Feb	N_T	$q_{s\_0.5}$	F_B*,F_C*		C_{TS}	F_A	F_B			
		q_{s_3}	F_C			F_A				
		q_{s_9}	F_C	F_C	F_C*	F_A				
	C_T	$q_{s\_0.5}$					F_A*		F_B	
		q_{s_3}						C_{TS}*		
		q_{s_9}							F_C*	
Apr	N_T	$q_{s\_0.5}$				F_A				
		q_{s_3}				F_A				
		q_{s_9}				F_A				
	C_T	$q_{s\_0.5}$								
		q_{s_3}						C_{TS}*		
		q_{s_9}							F_C*	

* Significant difference between two measurement dates; Date with Italiced site had higher q_s .

All TI measurements in N_T at site F_A were significantly different from DI measurements across the measurement dates. This site has higher sand content (xref. Table 4.1) relative to other sites and the larger pore space may promote gravitational flow associated with DI infiltrometer. Since only one site (F_B) during one measurement date (February) and at a single tension showed a significant difference in q_s between N_T and C_T, it can be argued that tillage did not have a significant influence on steady-state infiltration rates in Potshini over the three measurement dates.

4.3.3 Soil hydraulic conductivity

According to Sephaskhan et al. (2005), infiltration rate is governed by the soil hydraulic factors such as saturated hydraulic conductivity, sorptivity, and some other empirical parameters. Thus, there was a need to investigate further these underlying factors. Hydraulic conductivity was first estimated using the analytical approached proposed by Wooding (1968) and the result compared with estimates from a numerical solution derived using HYDRUS-2D (Šimůnek et al., 1996). Saturated hydraulic conductivity was also computed. In the analytical method, K_s was estimated from DI measurements using the one-dimensional steady-state infiltration rates (q_{s_DI}) following the procedure outlined by Reynolds et al. (2002).

4.3.3.1 Analytical solution

The estimated mean hydraulic conductivity and saturated hydraulic conductivity values with their corresponding standard deviations are presented in Table 4.5. At D_0, the unsaturated hydraulic conductivity (K) was generally lower in N_T relative to C_T at the beginning of the measurement dates (i.e. in December). K increased in N_T treatments during the growing season and by April it was higher than in C_T. There was a decrease in K values as the applied tension increased. For example, in December the average K ($h_{0.5}$) from N_T treatments was 1.87 times higher than K (h_3) which was 2.02 times higher than K (h_9). The corresponding values from C_T were 2.82 and 2.54. At other dates and depths, the range of the differences was 1.80-9.80 and 1.75-2.76 times higher for -0.5 – -3 cm and -3 – -9 cm, respectively. These suggest that tillage has some considerable influence on hydraulic conductivity. However, even with continuous tillage, K ($h_{0.5}$) values are several times larger than K (h_3), indicating that sub-surface networks of water conducting soil pores may exist. As the pressure head decreased from -0.5 to -9 cm, average K (h) at both depths was found to decrease in both treatments.

At 0.5 cm tension at depth D_0, the average K in N_T was approximately 0.25, 0.4 and 2 times larger than in C_T during December, February and April measurement dates, respectively while the corresponding ratios at D_{10} were 1.2, 0.95 and 0.9. At 3 cm tension at depth D_0, K in N_T were 0.5 (0.77), 1.1 (0.86) and 1.9 (3.3) times larger than in C_T during the respective measurement dates. The ratios in brackets are for depth D_{10}. The ratios of K in N_T to C_T at 9 cm tension at the two depths were 0.44 (0.64), 0.7 (0.82) and 2.5 (3.0) in the three measurements dates.

Table 4.5: Estimated average unsaturated hydraulic conductivity (K) and saturated hydraulic conductivity (Ks) [$cm.min^{-1}$] from Wooding's analysis and the corresponding standard deviations (in brackets) at depths D_0 and D_{10} done during three dates in the growing season under two tillage systems in Potshini catchment at all the sites. The change in hydraulic conductivity between December and April is also provided.

Date/		$K_{\_0.5}$		$K_{\_3}$		$K_{\_9}$		K_{s_DI}	
tillage		D_0	D_{10}	D_0	D_{10}	D_0	D_{10}	D_0	D_{10}
NT		3.7E-3	2.5E-2	2.0E-3	2.0E-3	7.0E-4	9.0E-4	3.4E-2	4.5E-2
Dec		(7.0E-4)	(3.7E-2)	(5.0E-4)	(5.1E-4)	(5.0E-4)	(1.6E-4)	(1.4E-3)	(3.3E-2)
CT		1.5E-2	2.1E-2	4.0E-3	2.6E-3	1.6E-3	1.4E-3	3.6E-2	2.0E-2
		(3.1E-3)	(3.5E-3)	(3.5E-3)	(8.0E-4)	(1.3E-3)	(6.0E-4)	(2.9E-2)	(1.3E-2)
NT		4.3E-3	4.7E-3	1.7E-3	1.9E-3	7.0E-4	9.0E-4	9.2E-2	4.2E-2
Feb		(2.7E-2)	(3.6E-2)	(1.8E-3)	(1.8E-3)	(1.4E-3)	(1.0E-3)	(1.0E-1)	(4.2E-2)
CT		1.1E-2	4.9E-3	1.5E-3	2.2E-3	1.0E-3	1.1E-3	3.3E-2	5.1E-2
		(1.1E-2)	(1.8E-3)	(1.3E-3)	(2.0E-3)	(7.0E-4)	(1.1E-3)	(1.0E-1)	(6.4E-2)
NT		6.2E-3	3.5E-3	2.3E-3	5.0E-3	1.0E-3	1.8E-3	5.7E-2	7.6E-2
Apr		(1.3E-3)	(1.7E-3)	(6.0E-4)	(9.0E-4)	(4.0E-4)	(4.0E-4)	(2.8E-2)	(3.3E-2)
CT		2.9E-3	3.9E-3	1.2E-3	1.5E-3	4.0E-4	6.0E-4	1.3E-2	2.3E-2
		(1.6E-3)	(2.8E-3)	(7.0E-4)	(3.0E-4)	(4.0E-4)	(2.0E-4)	(1.2E-2)	(1.8E-2)
%Change	NT	68	-86	15	150	43	100	68	69
	CT	-81	-81	-70	-42	-75	-57	6	15

The increases in N_T could be attributed to improving soil structure while the decreases in C_T may be related to decreasing porosity due to rainfall impacts and soil settlement. The changes in K between December and April are also given in Table 4.5. An increase in average K in N_T plots at all tensions, except at depth D_{10} and a tension of 0.5 cm, was observed. All K measurements in C_T decreased by at least 42%. This suggested that tillage systems influences soil hydraulic conductivity which affects water entry and redistribution. Therefore, knowledge of these properties and the direction of changes induced by tillage are significant in proposing suitable farming practices in water-scarce environments. However, a seasonal field-scale water balance is necessary to compare the effects of higher K early in the season (i.e. in C_T) and later in the season (i.e. in N_T).

The average K_s values are given in Table 4.5. As expected all estimated K_s values from DI data were larger than the measured K values at 0.5 cm tension. The mean saturated hydraulic conductivity, K_s derived from DI measurements had a similar trend as K where average values in N_T increased while decreases were observed in C_T. The K_s at depth D_0 in N_T was 0.94, 2.79 and 4.39 times larger than in C_T in December, February and April, respectively. At depth D_{10}, the corresponding K_s values were 2.25, 0.82 and 3.30 times larger in N_T relative to C_T. Thus, K_s was in most cases higher in N_T suggesting a higher capacity to transmit water under saturated conditions. In semi-arid areas, soils are generally poor and rainfall is low and erratic and may occur as high intensity storms. Soils having higher K_s, such as those under N_T in this study, are likely to capture and store more water which enhances crop production.

Table 4.6: Sites that displayed significant differences ($p \leq 0.05$) in K at different tensions and K_s during the different dates of measurement in the two tillage systems in Potshini catchment

Date	Till		N_T				C_T			
			$K_{\_\_0.5}$	$K_{\_\_3}$	$K_{\_9}$	$K_{s(DR)}$	$K_{\_\_0.5}$	$K_{\_\_3}$	$K_{\_9}$	$K_{s(DR)}$
Dec	N_T	$K_{\_\_0.5}$				C_{TS}				
		$K_{\_\_3}$			C_{TS}	C_{TS}				
		$K_{\_9}$		F_B	F_B*	C_{TS}				
		$K_{s(DR)}$		F_A	F_A	$F_A{}^{*,1}$				
	C_T	$K_{\_\_0.5}$					$F_A{}^{*,1}$	C_{TS}	C_{TS}	C_{TS}
		$K_{\_\_3}$					F_A	$C_{TS}*$		C_{TS}
		$K_{\_9}$					F_A, F_C	F_B	C_{TS}	F_B, C_{TS}
		$K_{s(DR)}$						F_A	F_A	
Feb	N_T	$K_{\_\_0.5}$	F_A*	C_{TS}	C_{TS}	F_A	$F_A{}^{*,2}$			
		$K_{\_\_3}$			F_C	F_A				
		$K_{\_9}$			F_B*				C_{TS}	
		$K_{s(DR)}$				$F_A{}^{*,2}$				
					F_A	$F_A{}^{*,1}$				
	C_T	$K_{\_\_0.5}$					$F_A{}^{*,1}$			
		$K_{\_\_3}$								
		$K_{\_9}$					F_C			
		$K_{s(DR)}$								
Apr	N_T	$K_{\_\_0.5}$	F_A*	F_A						
		$K_{\_\_3}$								
		$K_{\_9}$								
		$K_{s(DR)}$			F_A	$F_A{}^{*,2}$				
	C_T	$K_{\_\_0.5}$	F_A				$F_A{}^{*,2}$		F_A	
		$K_{\_\_3}$						$C_{TS}*$		
		$K_{\_9}$							$C_{TS}*$	
		$K_{s(DR)}$								

* Significant difference between two measurement dates; Date with Italiced site had higher K or K_s. Similar superscipts indicate the particular sites that significant difference occurred.

Table 4.6 contains results from statistical analyses of hydraulic conductivity derived from Wooding's analysis for different tensions and tillage systems. Saturated hydraulic conductivity was also included in an attempt to show by how much it was different from K at the three tensions. Significant differences in K and K_s at different tensions are in regular text while significantly differences in two measurement dates are marked with an asterisk. In cases where dates coincide, a superscript has been added to identify the particular sites. Bold text shows the sites that significant differences were observed between tillage systems.

Unsaturated hydraulic conductivity at -0.5 cm revealed greater variability at depth D_0 while K at -3 cm and -9 cm showed more cases at depth D_{10}. This suggested that flow through the smallest pores in the upper layer was similar while the flow through relatively larger pores varied significantly. The reverse happened at D_{10}. As tillage directly affects the upper layer, the observed differences are likely to be as a result of the varied response from N_T compared to C_T. Fig. 4.6 illustrates the seasonal changes in average hydraulic conductivities at all sites.

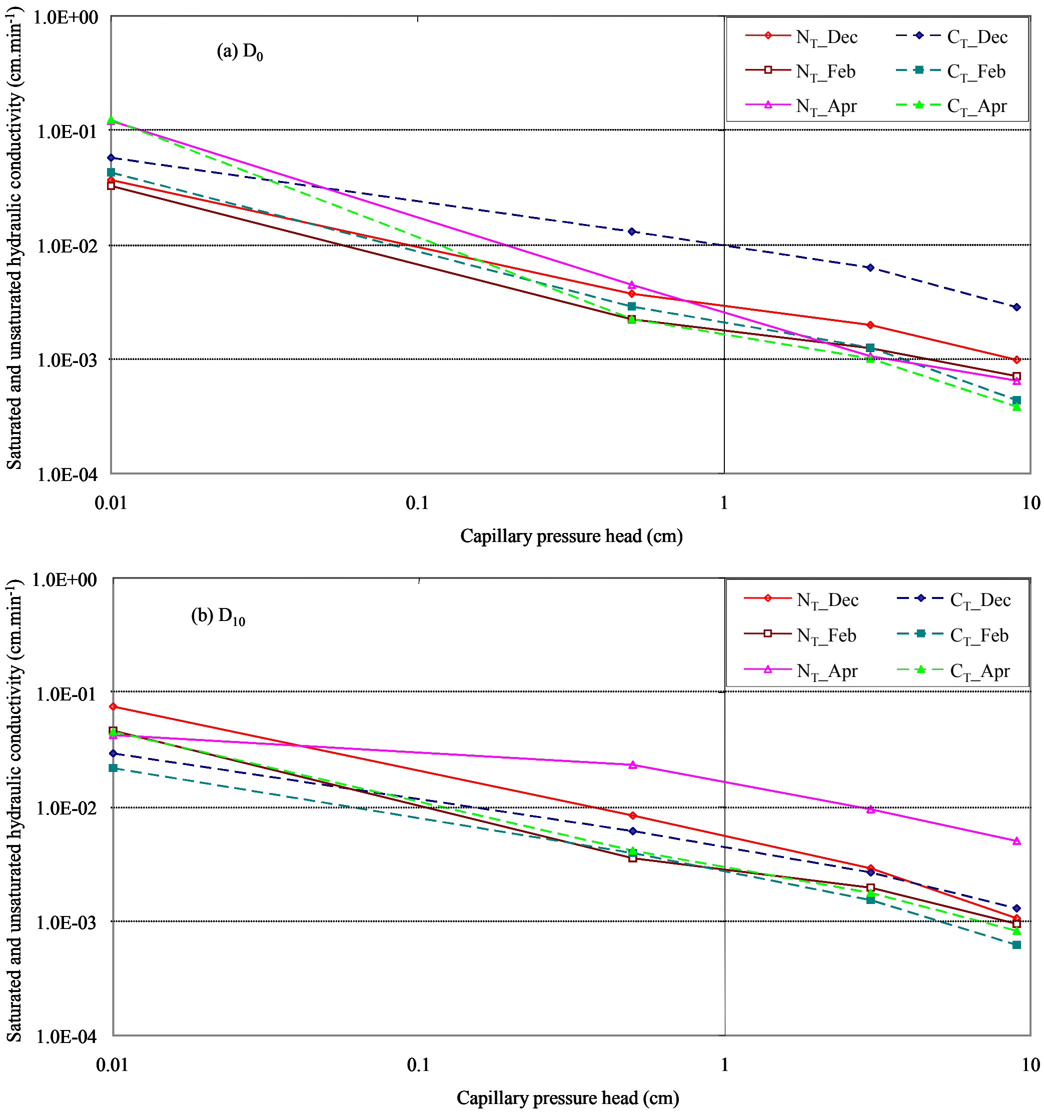

Figure 4.6: Changes in average hydraulic conductivity (K) and saturated hydraulic conductivity (K_s) with pressure head (h) under N_T and C_T systems at depths D_0 and D_{10} for the three measurement dates. Saturated hydraulic conductivity, K_s corresponds to K at capillary pressure of 0.01 cm.

Fig. 4.6 shows at that at each site the K values from the two tillage systems were not similar suggesting that tillage influenced soil properties which then affect the hydraulic properties. The hydraulic conductivity was high in C_T in December owing to ploughing. Changes in bulk density and sealing effects might have led to the rapid decline in K between December and April, specifically in C_T. Saturated hydraulic conductivity, represented by capillary pressure head of 0.1 cm, was not significantly different between tillage systems as well as measurement dates.

4.3.3.2 Numerical solution using HYDRUS-2D

In this study the objective function was defined in terms of tension disc cumulative infiltration data, and the initial and final moisture contents. The flow domain was discretized into 1073 triangular elements using DISC model (Šimůnek et al., 2006). Although DISC provided finer meshes, this was regarded a good compromise between solution precision and the required computing capacity. All the optimizations converged under 120 iterations. The average fitted van Genuchten-Mualem (VGM) model parameters and their standard deviations are provided in Table 4.6. These parameters were residual water content (θ_r), saturated water content (θ_s),α, n, and saturated hydraulic conductivity (Ks). The adopted discretization scheme resulted in mass balance errors of 0.33%, 0.27%, 0.51% and 0.19% at sites F_A, C_{TS}, F_C and F_B, respectively which were considered insignificant. Ventrella et al. (2005) and Šimůnek et al. (1998b) reported mass balance errors of less than 0.3% and 0.1% respectively which were lower than found in this study. However, they had more supply tensions with relatively smaller intervals between tension settings. The regression coefficient (R^2) was 0.99 at F_A and F_C while at C_{TS} and F_B it was found to be 0.98.

The fitted mean θ_r from all sites was 0.0012 $cm^3.cm^{-3}$. The highest value (0.0026 $cm^3.cm^{-3}$) was recorded at site F_C. The proportional values from other sites to the value observed at F_C were 28%, 8% and 51% at sites F_A, C_{TS} and F_B, respectively suggesting that θ_r was very small. The difference between sites was not significant. However, significant differences at depth D_{10} between tillage systems occurred in all cases except between February and April. Although Ventrella et al. (2005) fixed θ_r at 0.15 $cm^3.cm^{-3}$, as seen in this study, it can be set at zero (e.g. Šimůnek et al., 1998; Ramos et al., 2006) without inconsistencies in the optimization. However, the efficiency of the optimization may be compromised. The mean θ_s values from the two depths in N_T plots were 0.178, 0.278 and 0.252 $cm^3.cm^{-3}$ in December, February and April, respectively. The corresponding values in C_T plots were 0.195, 0.236 and 0.231 $cm^3.cm^{-3}$. Higher values of θ_s in N_T plots compared to C_T plots occurred apart from in December indicating that ploughing improved θ_s. However, this effect was not persistent through out the season suggesting that there were changes in soil physical properties that affected the soil pore volume and/or geometry. At depth D_0, there were significant differences ($p<0.05$) in θ_s between December and February observations in N_T plots.

In December at depth D_0, the VGM fitting parameter α that scales the conductivity and retention functions (Ventrella et al., 2005), measured 0.02, 0.007, 0.02 and 0.021 cm^{-1} at C_{TS}, F_C, F_B and F_A, respectively in N_T treatments. The corresponding values in C_T were 0.019, 0.025, 0.023 and 0.03 cm^{-1}, respectively. This indicated a decrease in air-entry pressure head ($1/\alpha$) in C_T (tilled soils) which could explain the observed higher steady-state infiltration rate, hydraulic conductivity and the final volume of water that infiltrated. These findings agree with Stothoff (1997) who found that decreasing the air-entry pressure while holding all other parameters at a fixed level tends to increase both the average moisture content and the average net infiltration flux for homogeneous media. The time frame which infiltration occurs may also be altered by changes in α. The 63% average increase in α (Table 4.7) in N_T is directly linked to tillage practice and is likely to have contributed to the relatively improved θ_s and K_s observed in N_T at later dates. The α values obtained in this study were within the range of values obtained from similar soils (Ramos et al., 2006; Ventrella et al., 2005; Šimůnek et al., 1999). The only significant differences in this study were between December and February measurements at depth D_{10} in C_T plots.

In the three measurement dates, the average of the shape parameter n in N_T treatments was 1.407, 1.277, 1.267 and 1.344 at F_A, C_{TS}, F_C and F_B, respectively while the corresponding values from C_T were 1.372, 1.408, 1.211 and 1.329. There were no significant differences between the fitted n values from N_T and C_T data. In N_T plots at depth D_0, n decreased by an average of 7% between December and April while in C_T an increase of 29% was observed. Lower n increases infiltration and could have contributed to the observed increase in K_s, in N_T treatments. This indicates that the tillage system practiced affects the parameters of the VGM model and thus the soil hydraulic properties.

Table 4.7: Fitted average van Genuchten-Mualem (VGM) model parameters: residual water content (θ_r), saturated water content (θ_s),α, n, saturated hydraulic conductivity (Ks) and unsaturated hydraulic conductivities at the three tensions in all the sites. The standard deviation of each parameter is provided in brackets. The percent change between December and April of each parameter is also given

Date/Tillage	Depth	θ_r	θ_s	α	n	K_s	$K(h_{0.5})$	$K(h_3)$	$K(h_9)$
Dec NT	D0	0.00E+00	1.85E-01	1.69E-02	1.39E+00	1.60E-03	9.00E-04	6.00E-04	3.00E-04
		(0.0000)	(0.0517)	(0.0065)	(0.1576)	(0.0010)	(0.0004)	(0.0002)	(0.0001)
	D10	0.00E+00	1.41E-01	3.89E-01	9.98E-01	2.40E-03	1.40E-03	8.00E-04	4.00E-04
		(0.0000)	(0.0917)	(0.7341)	(0.6723)	(0.0003)	(0.0002)	(0.0002)	(0.0001)
CT	D0	3.00E-04	2.12E-01	1.54E-02	1.36E+00	2.80E-03	1.50E-03	9.00E-04	5.00E-04
		(0.0005)	(0.0440)	(0.0104)	(0.1795)	(0.0026)	(0.0016)	(0.0009)	(0.0005)
	D10	2.10E-02	1.78E-01	1.30E-02	1.53E+00	7.00E-04	4.00E-04	3.00E-04	1.00E-04
		(0.0248)	(0.0321)	(0.0090)	(0.4001)	(0.0013)	(0.0008)	(0.0005)	(0.0002)
Feb NT	D0	0.00E+00	2.71E-01	3.53E-01	1.04E+00	3.20E-03	1.10E-03	5.00E-04	2.00E-04
		(0.0000)	(0.0380)	(0.6778)	(0.7323)	(0.0038)	(0.0012)	(0.0004)	(0.0001)
	D10	0.00E+00	2.86E-01	3.26E-01	9.57E-01	2.00E-03	9.00E-04	5.00E-04	2.00E-04
		(0.0000)	(0.1037)	(0.6164)	(0.6377)	(0.0018)	(0.0008)	(0.0004)	(0.0002)
CT	D0	5.00E-04	2.23E-01	1.86E-02	1.27E+00	1.90E-03	8.00E-04	4.00E-04	2.00E-04
		(0.0010)	(0.0313)	(0.0093)	(0.0585)	(0.0016)	(0.0005)	(0.0002)	(0.0001)
	D10	8.00E-04	2.50E-01	1.03E-02	1.35E+00	7.00E-04	2.00E-04	1.00E-04	1.00E-04
		(0.0015)	(0.0777)	(0.0095)	(0.3023)	(0.0006)	(0.0002)	(0.0001)	(0.0001)
Apr NT	D0	8.00E-04	2.62E-01	1.62E-02	1.21E+00	1.80E-03	9.00E-04	7.00E-04	6.00E-04
		(0.0015)	(0.0782)	(0.0043)	(0.0685)	(0.0010)	(0.0005)	(0.0003)	(0.0002)
	D10	3.65E-02	2.42E-01	1.86E-02	1.30E+00	2.70E-03	1.30E-03	7.00E-04	4.00E-04
		(0.0000)	(0.0461)	(0.0097)	(0.0896)	(0.0020)	(0.0010)	(0.0005)	(0.0002)
CT	D0	3.00E-04	2.49E-01	1.28E-02	1.28E+00	1.20E-03	6.00E-04	4.00E-04	2.00E-04
		(0.1450)	(0.5537)	(0.0086)	(0.6866)	(0.0006)	(0.0006)	(0.0678)	(0.0003)
	D10	0.00E+00	2.13E-01	1.92E-02	1.23E+00	2.70E-03	1.20E-03	7.00E-04	4.00E-04
		(0.1360)	(0.5292)	(0.0074)	(0.6470)	(0.0006)	(0.0003)	(0.0003)	(0.0001)
Average %change NT	D0	-	28	63	-7	23	-12	-23	-22
CT		-	45	24	29	-9	-11	-4	-7
NT	D10	-	30	-37	10	-19	-23	-19	-17
CT		-	9	22	-7	95	100	150	178

The estimated saturated hydraulic conductivity (K_s) values in N_T plots averaged 0.0033, 0.0043 and 0.0035 cm.s^{-1} in December, February and April, respectively while the respective C_T values were 0.0029, 0.0022 and 0.0029 cm.s^{-1}. The different sites had seasonal mean values of 0.0034, 0.0029, 0.0023 and 0.0041 cm.s^{-1} at F_A, C_{TS}, F_C and F_B, respectively. There were no significant differences between estimated K_s values at depth D_0 and also between depth D_0 and depth D_{10}. However, there were significant difference between estimated K_s in N_T and C_T in December at depth D_{10}. The mean changes in unsaturated hydraulic conductivities at the three tensions were negative for all tillage systems and depths except at depth D_{10} in C_T plots which showed higher increases at -9 cm pressure head. This could be because conventional tillage promotes development of small pores that drain quickly especially at lower depths such as this case which may not be affected by intensive compaction and/or surface sealing.

In N_T treatments at depth D_0, the estimated K_s values from the analytical approach (xref. Section 4.3.1.1) were 21, 300 and 31% higher than obtained from the VGM model in December, February and April, respectively. At depth D_{10}, they were 21, 31 and 64%. In C_T treatments the corresponding values were 365, 145 and 53% at depth D_0 while at D_{10} they were 759, 167 and 7% higher. Fig. 4.7 and Fig. 4.8 compare unsaturated hydraulic conductivity functions estimated with the numerical approach (Table 4.6) with those obtained from the analytical method (Table 4.4) at all the sites. In many cases, Wooding's analysis showed higher K especially at -0.5 cm pressure head. This discrepancy may have resulted from a compromise of the underlying assumptions which include a requirement of a homogeneous soil profile. In addition, the actual steady-state flux may not have been reached in the tests, a necessity for the analytical method. Similar divergences were reported by Šimůnek et al. (1999) and Ventrella et al. (2005).

Hydraulic conductivity, K fluctuated differently from one site to another. In December at depth D_0, two sites (F_B and F_C) showed higher values of K in C_T treatments but not at sites F_A and C_{TS}. At site F_A (Fig. 4.7a), K declined in all tests except in C_T plots at depth D_0 where the value of K was higher in February relative to December and April. The K in April in C_T treatments at this site was lower relative to N_T at both depths. A similar trend in K at depth D_0 in C_T treatments was observed in the remaining sites (Fig. 4.8) although at site C_{TS} the lowest estimated value of K was in February.

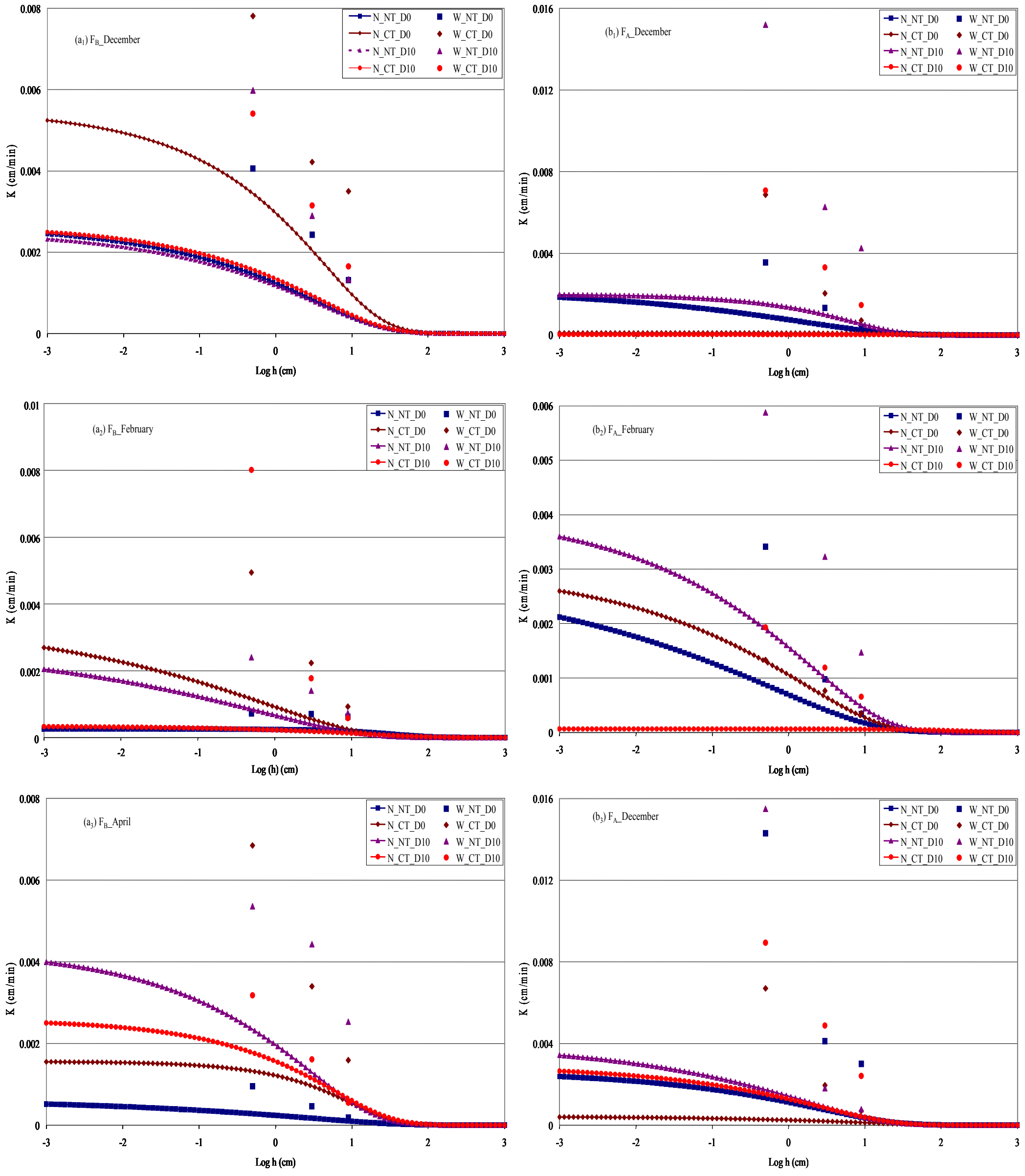

Figure 4.7: Unsaturated hydraulic conductivities estimated using numerical inversion and Wooding's analytical solution for particular pressure heads at site: a) F_B and b) F_B the three measurement dates (Legend: N = numerical; W = Wooding's)

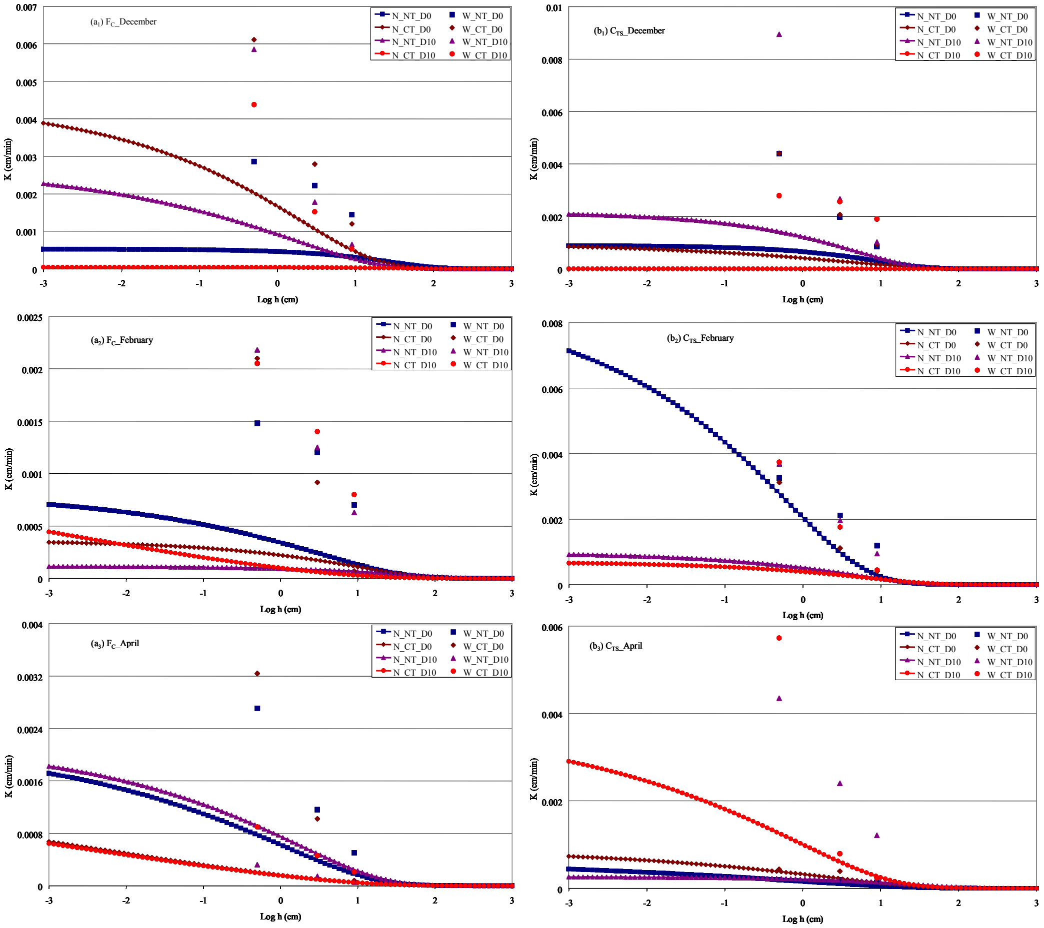

Figure 4.8: Unsaturated hydraulic conductivities estimated using numerical inversion and Wooding's analytical solution for particular pressure heads at site: a) F_C and b) C_{TS} the three measurement dates (Legend: N = numerical; W = Wooding's).

By April, higher values of K at in N_T treatments at depth D_{10} were obtained in 75% of the sites suggesting that greater impact of no-tillage was experienced at lower depths and not at the surface. However, as shown in Fig. 8(b_3) higher values of K were obtained from C_T plots, an indication that no-tillage is not recommended at site C_{TS}. Conversely by April site F_C, illustrated by Fig. 4.8(c_3), showed higher K in N_T relative to C_T suggesting that no-tillage is suitable at this site. The remaining sites had mixed results.

There were differences between the measured and fitted cumulative infiltration at the beginning of the infiltration tests in all cases. The differences at the start of the tests could have been due to the model initialization. Higher deviations were also observed at changing points when the tension was adjusted to a higher value. Compared to the observed values, the VGM model overestimated cumulative infiltration at the lower tension (0.5 cm) and underestimated at the highest tension (9 cm). Under all circumstances, the largest deviations were about 11%, 0.9% and 7% of the total infiltration volume at 0.5, 3 and 9 cm tensions, respectively. These error margins were higher than the 0.5% of the total infiltration volume reported by Šimůnek et al. (1998b) from tests that lasted over 24 hours and infiltrated over 800 cm^{-3} on sandy subsoil. Their range of tensions was 0.1 and 11.5 cm using a dry to wet sequence.

4.3.4 Philip's and Kostiakov's model parameters

The fitted Philip's model parameters were sorptivity (S) and transmissivity (A). In addition to S, the modified Philip's model includes saturated hydraulic conductivity (K_s) and a constant, B. Kostiakov's model parameters are two constants, B and n. The modified Kostiakov's model includes a term "i_c" that enables infiltration rates to approach a finite value at long t. Table 4.8 and Table 4.9 show the summary statistics of the fitted classical and modified Kostiakov's and Philip's model parameters, respectively. Most of the values of Kostiakov's term "n" were consistently less than one found in other studies (Mbagwu, 1990; Mbagwu, 1994) although Gosh (1985) argued and proved mathematically that it could be greater than unity.

Philip's terms "K_s" was higher in C_T plots in December and February but lower in April as compared to those observed in N_T plots. The term "S" increased in C_T from December to April indicating that the soil was progressively becoming denser. Although Brutsaert (1977) suggested values of 1/3, 2/3 or 1 while Kutilek and Nielsen (1994) recommended a value of 1 for the modified Philip's term "B", values greater than one were obtained in this study. This implied that the influence on infiltration rate of the first term on the right hand side of Eq. 4.11(b) was lower and thus suggests that water transmission under the influence of gravity was more dominant than that due to matric forces, a condition normally expected when a steady-state infiltration is reached. Hence, the modified Philip's model mimics the physical system better than the classical model.

Table 4.8: Average values and standard deviations (in brackets) of the fitting parameters of Kostiakov's and Philip's model using infiltration data of three dates from four test sites in Potshini catchment (Subscripts K = Kostiakov's; P = Philip's)

Date/Tillage		Depth	B_K	n_K	R^2_K	S_P	A_P	R^2_P
Dec	NT	D_0	0.10	14.99	0.97	0.60	0.96	0.97
			(0.38)	(0.36)	(0.03)	(1.04)	(0.11)	(0.04)
		D_{10}	139.68	-0.91	0.96	0.31	0.14	0.89
			(271.55)	(0.08)	(0.03)	(0.20)	(0.09)	(0.08)
	CT	D_0	14.99	-0.60	0.97	0.29	0.13	0.92
			(27.61)	(0.95)	(0.45)	(0.14)	(0.12)	(0.04)
		D_{10}	1.63	-0.84	0.98	0.22	0.18	0.94
			(2.08)	(0.93)	(0.06)	(0.17)	(0.27)	(0.05)
Feb	NT	D_0	3.67	-0.75	0.98	0.67	0.12	0.93
			(6.26)	(0.27)	(0.02)	(0.47)	(0.06)	(0.07)
		D_{10}	0.62	-0.75	0.96	0.38	0.09	0.93
			(0.82)	(0.29)	(0.04)	(0.25)	(0.10)	(0.07)
	CT	D_0	5.71	-0.96	0.98	0.39	0.10	0.93
			(10.17)	(0.06)	(0.01)	(0.44)	(0.04)	(0.05)
		D_{10}	0.19	-0.72	0.97	0.30	0.06	0.95
			(0.15)	(0.35)	(0.02)	(0.29)	(0.05)	(0.01)
Apr	NT	D_0	6.30	-0.89	0.97	0.27	0.17	0.89
			(8.41)	(0.17)	(0.02)	(0.19)	(0.17)	(0.08)
		D_{10}	2.95	-0.56	0.96	0.55	0.08	0.89
			(2.05)	(0.76)	(0.04)	(0.50)	(0.11)	(0.08)
	CT	D_0	0.34	-0.71	0.98	0.43	0.13	0.95
			(0.51)	(0.46)	(0.02)	(0.09)	(0.13)	(0.03)
		D_{10}	5.09	-0.84	0.96	0.34	0.05	0.89
			(9.83)	(0.76)	(0.27)	(0.04)	(0.05)	(0.50)
Average %change	NT	D_0	190	-43	0	-136	-23	-4
	CT		-78	17	0	-17	5	2
	NT	D_{10}	138	-21	1	33	-23	0
	CT		124	1	-1	26	-39	-3

Table 4.9: Average values and standard deviations (in brackets) of the fitting parameters of modified Kostiakov's and modified Philip's model using infiltration data of three dates from four test sites in Potshini catchment (Subscripts MK = modified Kostiakov's; MP = modified Philip's)

Date/Tillage	Depth	i_{cMK}	B_{MK}	n_{MK}	R^2_{MK}	Ks_{MP}	S_{MP}	B_{MP}	R^2_{MP}
Dec NT	D0	0.10	0.22	-0.79	0.93	0.09	2.07	9.79	0.77
		(0.06)	(0.50)	(0.49)	(0.06)	(0.14)	(1.14)	(133.34)	(0.38)
	D10	139.45	0.15	-0.16	0.78	0.15	0.37	0.79	0.80
		(271.51)	(1.58)	(0.09)	(0.18)	(0.31)	(0.54)	(0.12)	(0.37)
CT	D0	14.75	0.16	-0.18	0.80	0.16	0.48	3.22	0.80
		(27.20)	(0.24)	(0.49)	(0.33)	(0.13)	(0.24)	(5.54)	(0.29)
	D10	1.46	0.22	-0.11	0.86	0.08	0.70	4.76	0.88
		(1.58)	(0.09)	(0.18)	(0.31)	(0.54)	(0.12)	(0.37)	(0.07)
Feb NT	D0	3.39	0.33	-0.34	0.89	0.12	0.73	0.29	0.91
		(6.18)	(0.24)	(0.27)	(0.09)	(0.02)	(0.460	(0.45)	(0.07)
	D10	0.41	0.18	-0.15	0.89	0.12	0.55	1.61	0.90
		(0.69)	(0.07)	(0.12)	(0.17)	(0.09)	(0.36)	(0.09)	(0.12)
CT	D0	5.48	0.72	0.37	0.69	0.15	1.99	77.89	0.69
		(10.04)	(0.98)	(0.65)	(0.07)	(0.07)	(1.38)	(100.32)	(0.11)
	D10	0.07	0.29	0.58	0.77	0.09	5.17	-100.13	0.76
		(0.07)	(0.17)	(0.36)	(0.12)	(0.09)	(5.67)	(350.45)	(0.11)
Apr NT	D0	6.07	0.22	-0.17	0.80	0.23	0.45	1.44	0.82
		(8.27)	(0.07)	(0.25)	(0.10)	(0.04)	(0.12)	(1.36)	(0.09)
	D10	2.13	19.44	0.19	0.88	0.06	2.40	295.85	0.83
		(2.56)	(16.04)	(1.40)	(0.07)	(0.06)	(3.09)	(590.10)	(0.02)
CT	D0	0.23	0.15	-0.08	0.78	0.11	1.60	10.46	0.80
		(0.33)	(0.21)	(0.47)	(0.16)	(0.15)	(1.76)	(15.93)	(0.16)
	D10	4.94	0.18	-0.22	0.82	0.08	0.74	5.74	0.84
		(9.71)	(0.12)	(0.34)	(0.06)	(0.06)	(0.96)	(10.36)	(0.06)
Average %change NT	D0	168	8	-53	-7	63	-52	150	4
CT		-79	135	-214	0	-35	147	116	1
NT	D10	160	550	-116	6	-16	193	190	2
CT		343	-3	-383	-2	1	276	-155	-2

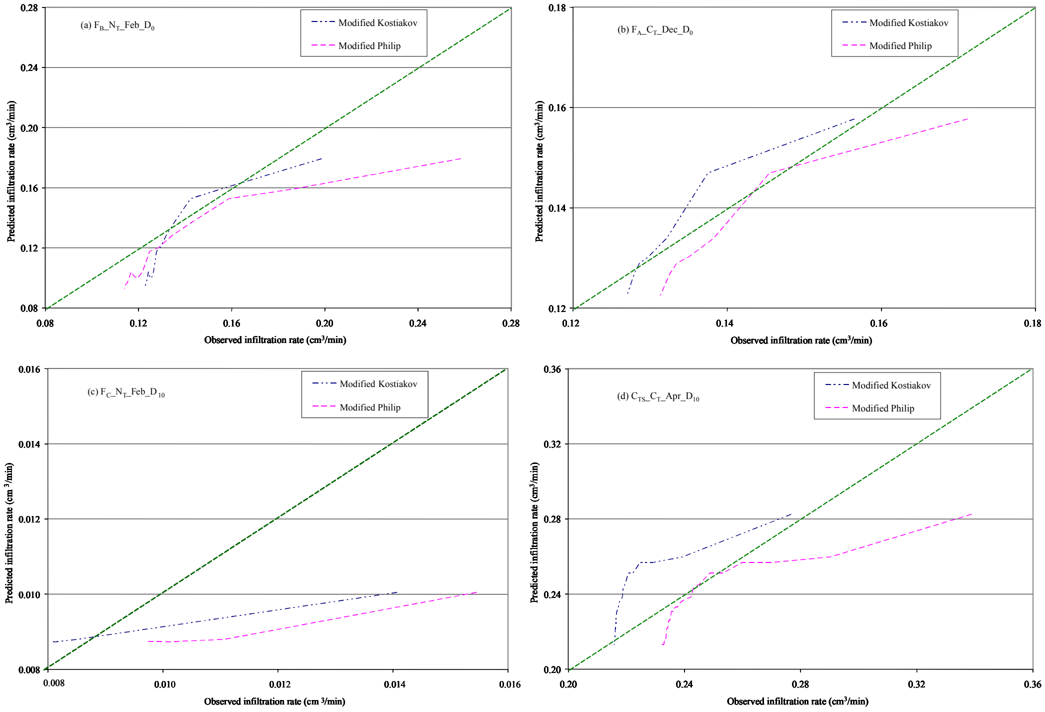

Figure 4.9: Examples of measured and fitted infiltration rates using data from double ring infiltrometer at selected sites, dates and depths in Potshini catchment

Values of the constants (n and B) in classical and modified Kostiakov's models were not significantly different ($p \leq 0.05$) suggesting that the classical model could underestimate infiltration since the term "i_c" is not included, whose value (*xref. Table 4.9*) cannot be neglected without serious errors. This suggests that the modified Kostiakov's model would represent the infiltration process better than the classical Kostiakov's model.

The mean infiltration rates for the examples shown in Fig. 4.9(a-d) were 0.234, 0.119, 0.132 and 0.009 $cm^3.min^{-1}$ at F_B, F_A, F_C and C_{TS}, respectively. The means of the infiltration rates were significantly different ($p \leq 0.001$) at all sites except between F_A and C_{TS}. In all cases predicted infiltration rates from modified Kostiakov's model were higher than those from modified Philip's model except at the final stages at site F_B (Fig. 4.9a). Apart from the example from site F_C, modified Philip's model predictions were lower than the observed values while the reverse occurred for modified Kostiakov's model. The absolute mean deviations in modified Kostiakov's model in the selected sites were 0.017, 0.008, 0.001 and 0.014 $cm^3.min^{-1}$ while those of modified Philip's model were 0.019, 0.011, 0.003 and 0.012 $cm^3.min^{-1}$ in sites F_B, F_A,

F_C and C_{TS}, respectively. These deviations were not significantly different and thus any of these models is recommended for routine modeling of infiltration process on such soils.

A comparison was made between K_s estimates from modified Philip's model and that derived from steady-state infiltration rates (Eq. 4.9) and HYDRUS-2D. A summary is provided in Table 4.10.

Table 4.10: Number of times the modified Philip's model estimated K_s exceeded that derived from steady-state infiltration rates and HYDRUS-2D at three infiltration test dates at two depths in Potshini catchment

		Steady-state K_s		HYDRUS-2D K_s	
Date	Depth	N_T	C_T	N_T	C_T
December	D_0	6	7	274	230
	D_{10}	3	4	53	28
February	D_0	7	3	119	105
	D_{10}	3	4	245	304
April	D_0	2	1	130	173
	D_{10}	2	3	562	530

The modified Philip's model estimates were higher than that derived from the two approaches although the magnitudes varied widely. The estimates were closer to those obtained from the approach proposed by Reynolds et al. (2002) than those from numerical optimization.

4.4 Conclusions

The influence of tillage on soil hydraulic properties was investigated through comparison of steady-state infiltration rates and hydraulic conductivities derived from tension disc and double ring infiltrometer data. Tension disc data were further analyzed using analytical and numerical analyzes to derive hydraulic properties of the two tillage systems. Loosened soil structure in C_T plots enabled higher steady-state infiltration rates and hydraulic conductivities in December. This however changed in February and April. In 50% of the sites, N_T showed significantly higher hydraulic conductivity compared to C_T. At site C_{TS}, higher values of K were obtained from C_T plots, an indication that no-tillage is not recommended at this site. However, site F_C had higher K and thus suitable for no-till. Hence, determination of soil hydraulic properties can be used as a decision making tool for the adoption of specific tillage practices. In general, infiltration rates at 10 cm below the surface were higher than on the surface in both tillage systems.

The saturated hydraulic conductivity obtained by Wooding's analytical method was higher than that obtained from the numerical estimation by up to 750%. Data from double ring infiltrometers were further used to fit parameters to four commonly used models. Similarly the K_s obtained from the modified Philip's model were higher than that derived from the analytical and the numerical methods. These discrepancies could be attributed to the different theoretical curves adopted and their sensitivity to assumptions such as soil homogeneity and the attainment of steady-state infiltration rates. The hydraulic parameters predicted using modified Philip's and Kostiakov's models had the least deviations with observed data and were thought to be able to represent the physical environment better than the classical Models. Thus, they were recommended for use in modeling of infiltration process on such soils.

The observed different responses in infiltration that led to different fitted parameters were likely to have been caused not only by tillage, but a combination of several factors. For example, the difference in proportions of clay, silt and sand could have influenced the response to water at different sites. Bulk density is also affected by soil textural properties. Thus, further analyses are required to establish the relationships between infiltration and soil physical properties. The important soil physical factors influencing the fitting parameters of the four infiltration models should also be identified. These are investigated in Chapter 5.

4.5 References

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5.0 DESCRIBING THE DOMINANT SURFACE AND NEAR SURFACE CHANGES IN SOIL HYDRAULIC PROPERTIES DUE TO TILLAGE. II: EVALUATION OF THE INTERACTIONS BETWEEN SOIL INFILTRATION AND SOIL CHARACTERISTICS

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Abstract

Soil plays an important role partitioning rainfall to infiltration, runoff and evaporation. The interaction between soil physical characteristics and soil management affects these processes and determines the amount of water potentially available for plant growth, an important factor in determining the success of crop production, especially among smallholder rainfed farmers in semi-arid environments. A study was undertaken during the 2007/2008 maize (Zea Mays L.) growing season at Potshini Catchment, South Africa with the aim to identify, quantify and compare the interactions between selected soil physical factors and hydraulic properties in two tillage systems (no-tillage and conventional tillage) after three years under the same land use system. Double ring infiltrometer (DI) and tension disc infiltrometer (TI) at -0.5 cm, -3 cm and -9 cm water pressure heads were used to measure the steady state infiltration rates on the surface (D_0) and 10 cm below the surface (D_{10}) in December, February and April. These measurements were then used to estimate soil hydraulic properties.

Using descriptive statistics, various comparisons were made between soil hydraulic properties derived from the two tillage systems. The hydraulic conductivity and selected soil physical characteristics were studied using Principal Component Analysis (PCA) and the relationships between the properties extracted with coinertia analysis. In addition, the relationships between model parameters fitted with van Genuchten-Mualem (VGM), Kostiakov and Philip models and soil physical properties were investigated through correlation techniques.

Different infiltration responses were observed from the tillage systems, period in the season, site and depth of measurement. Clay content, bulk density and moisture content showed negative

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correlation with hydraulic conductivity (K) while sand content was positively correlated. Silt content was positively correlated to K at the start of the season but by April it was negatively correlated. On a seasonal basis, the correlations of K were not significantly different between tillage systems. However, the comparisons based on date of measurement showed statistically significant differences between tillage systems in infiltration data collected using TI. Approximately 75% of the significantly different cases occurred at -3 cm and -9 cm water pressure heads. Over 60% of these differences involved measurements done in December and April. Bulk density, affected by ploughing was identified as the soil physical property that influenced K significantly. Fitted parameters were also affected by the seasonal changes in soil physical and hydraulic characteristics. It was concluded that tillage affects soil physical properties which consequently influence the soil's hydraulic responses.

Keywords: Double ring, hydraulic conductivity, PCA, tension disc, tillage.

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5.1 Introduction

A soil's textural composition, structure and surface characteristics play a significant role in determining the amount of water that infiltrates into the soil. In semi-arid environments where rainfall is erratic and unreliable, successful crop production systems are found in areas with soils capable of maximizing infiltration and water retention. Surface crusts common in tropical and subtropical regions on loamy and sandy soils (Casenave and Valentin, 1992; Valentin and Bresson, 1992) decrease infiltration rate significantly because of a low saturated hydraulic conductivity (Šimůnek et al., 1998). Other factors that indirectly influence water entry into the soil include rainfall characteristics (intensity, amount and distribution) (Valentin and Bresson, 1992) and root growth (Suwardji and Eberbach, 1998). This suggests that the interactions between soil physical characteristics (e.g. texture and structure) and soil management (e.g. tillage, cropping systems) affect soil infiltration and its water holding capacity.

Many authors (e.g. Moreno et al., 1997; Whilhem and Mielke, 1998; Arshad et al., 1999; Petersen et al., 2001; Pagliai et al., 2004; Lampurlanés and Cantero-Martínez, 2006; Ndiaye, et al., 2007) have investigated the effects of tillage on soil structural and hydraulic properties. A review of field measurements of soil hydraulic properties using tension disc and double ring infiltrometers was performed by Angulo-Jaramillo et al. (2000) while Strudley et al. (2008) provided a comprehensive review of literature on the causes, quantification and prediction of the effects of tillage practices on dynamically evolving soil hydraulic properties. Unfortunately most of these studies focused on the two extremes of primary tillage i.e. tractor mounted mouldboard plough and no-till management systems in large scale agriculture. In sub-Saharan Africa where smallholder rainfed farmers constitute the majority of people engaging in agriculture, inadequate resources and undulating topography necessitate the use of hand hoes and/or ox-drawn implements. Previous studies in the region on tillage practices (Twomlow, 1994; Misika and Mwenya, 1998; Auerbach, 1998; Kayombo et al., 1999; Hatibu et al., 2000; Fowler and Rockström, 2001; Barron, 2004; Smith et al., 2004; Ngigi et al., 2006) have dwelt on seasonal water productivity gains with little or no consideration of changes in soil physical and/or hydraulic properties. The common finding was improved yields attributed to an increased infiltration and water retention. Although this finding is laudable, clear relationships between soil infiltration, soil physical properties and other hydraulic properties are seldom understood. Furthermore, Mbagwu (1994) observed that information on the soil physical properties that influence the fitting parameters of many models is not readily available causing difficulties in establishing the physical basis of such models and/or refining the models so as to have a sound physical and theoretical footing. This study attempted to fill these knowledge gaps.

According to van Es et al. (1999), tillage and its temporal effects on soil hydraulic properties were greatest for medium to fine textured soils. In addition, except for initial dates where high infiltration rates were observed from minimum tillage treatments, Logsdon et al. (1993) reported inconsistent results across other measurement dates. These observations support Strudley et al. (2008), Moreno et al. (1997) and Lal (1989) who argued that site specific evaluations were necessary because there was no single blueprint of tillage practices that can be universally applicable. For example, Kosgei et al. (2007) observed that in-situ water harvesting by way of no-tillage in Potshini catchment could ensure increased moisture if complemented with presence of residue cover (mulch). However, this is currently not possible because livestock feed on the all the maize residue during winter leaving the soil bare at the beginning of the cropping season. In this study area, from four experimental sites where infiltration tests were conducted in 2007/2008 maize (*Zea Mays L.*) growing season (xref. Chapter 4), 50% of the sites under no-till (N_T) showed significantly higher hydraulic conductivity (K) compared to plots under conventional tillage (C_T). Nonetheless, K values were higher in December in C_T plots. This period coincided with the time when C_T plots were freshly cultivated. The responses were varied on other dates in the season, for different sites and depths.

This paper report findings of a study at Potshini Catchment in South Africa aimed at understanding better the effects of tillage systems on soil hydraulic characteristics in smallholder rainfed agriculture and to further establish the relationships among these properties and some selected soil physical properties. The objective of this study was to assess the interaction between soil physical properties and the measured hydraulic properties and to investigate whether these physical properties could be explained by tillage practice. The hypothesis of this study is that tillage systems induce changes in soil physical properties which in turn influence their hydraulic characteristics. Thus the study focused on the relationships between:

- Hydraulic conductivity and tillage practices;
- Hydraulic conductivity and soil texture;
- Fitted soil hydraulic parameters and selected soil physical properties; across the maize growing season.

The structure and strength of the relationships are important parameters that need to be established to identify the dominant relationships. Tasks such as these often require the use of multivariate analyses (Dray et al., 2003) because a number of soil parameters have to be linked to infiltration measurements which may have been derived from a number of approaches, sites, depths and/or dates. Among the available methods include canonical correlation analysis (Hotelling, 1936), principal component analysis (PCA) with instrumental variables (Rao, 1964), coinertia analysis (Dolédec and Chessel, 1994) and canonical correspondence analysis (ter Braak, 1986). In this study, PCA and coinertia analyses were used.

Data were gathered from double ring infiltrometers (DI) and tension disc infiltrometers (TI) in December, February and April during the 2007/2008 growing season and were used to estimate the hydraulic conductivity in December, February and April (xref. Chapter 4). The measurements were taken both at the soil surface (D_0) and 10 cm below surface (D_{10}). The important soil physical factors influencing the fitting parameters of four commonly used models viz. classical Kostiakov's, classical Philip's, modified Kostiakov's and modified Philip's models, were identified using DI infiltration data. In addition the relationship between soil physical properties and van Genuchten Mualem (VGM) model parameters was investigated.

5.2 Methodology

5.2.1 Field site, soil analyses and infiltration tests

Data for this study were obtained from an on-going research in Potshini catchment which has a broad objective of investigating the potential hydrological impacts and induced changes on soil properties resulting from potential widespread adoption of rainwater harvesting (Roskström et al., 2004). The Potshini research site (29.37^{0}E, 28.82^{0}S) is located in the western headwaters of the Thukela River at the foothills of the Drakensberg Mountains. The field scale experiments are concentrated in an area of about 1.2 km^2 and have been in place since 2005. The trials were established in the form of runoff plots measuring 10 m by 2.45 m at slopes of about 3% (Kosgei et al., 2007; xref. Chapter 3, Section 3.3.3.4). A tipping bucket at the lower end of each plot was used to measure runoff while soil moisture was monitored at five depths using a Time Domain Reflectometry (TDR) tube probe (IMKO TRIME-T3). This was supplemented with a nest of three granular matrix sensors (GMS, Watermark™ Soil Moisture Sensors Model 200SS, Irrometer Co., Riverside, CA), installed at 30 cm, 60 cm and 150 cm in each plot in November 2006 to measure the soil water potential. A brief description of the sites and soil texture and mean bulk densities are summarized in Table 4.1.

Table 5.1: Description of the four experimental sites monitored in Potshini catchment between 2005 and 2008, their soil textural classification and mean bulk densities (D_0 = soil surface; D_{10} = 10 cm below surface)

Tillage system	Plot designation	Soil texture (%)			Mean bulk density(g.cm^{-3})	
		Clay	Sand	Silt	D_0	D_{10}
Conventional tillage (C_T)	$F_A\_C_T$	20.6	72.2	7.2	1.131	1.191
	$F_B\_C_T$	21.2	68.3	10.5	1.137	1.124
	$F_C\_C_T$	25.4	65.2	8.4	1.488	1.462
	$C_{TS}\_C_T$	22.6	66.2	11.2	1.263	1.411
No-till (N_T)	$F_A\_N_T$	20.6	72.2	7.2	1.102	1.115
	$F_B\_N_T$	21.2	68.3	10.5	1.086	1.026
	$F_C\_N_T$	25.4	65.2	8.4	1.478	1.552
	$C_{TS}\_N_T$	22.6	66.2	11.2	1.356	1.405

In the N_T treatments ripping was done using an oxen-drawn MacGoy implement to open furrows to a depth of approximately 10 cm for planting. In the 2007/08 season, maize (cv. PAN 6611) was planted on 28th November 2007 at a plant population of approximately 37,000 plants per hectare with an inter-row spacing of 0.9 m. Weeds were controlled initially by application of herbicides and later by hand at regular intervals twice in the season. C_T plots were prepared using a mouldboard ox-drawn plough. Hand hoes were used to open 10 cm deep furrows where maize seeds were placed on the same day and at approximately the same plant population and inter-row spacing as in N_T plots. Weeding was done using hand hoes at the same time as was done in N_T plots, although weeds were removed by hand in N_T.

After 3 years under the same treatments (N_T and C_T), infiltration measurements were conducted using TI and DI at three dates in the maize growing season (Chapter 4). Using TI, runs were performed at three consecutive pressure heads i.e. -0.5 cm, -3 cm and -9 cm at the same site. The time taken for water level to fall by 5 mm in the graduated reservoir was recorded manually. Measurements were repeated until infiltration rates were the same for at least four consecutive readings which were used to compute K through a numerical process (Šimůnek and van Genuchten, 1997) using HYDRUS-2D (Šimůnek et al., 1996) as described in Chapter 4 (Section 4.2.3.2). The inner and outer diameters of the DI set used were 130 mm and 300 mm, respectively. The rings were inserted into the soil concentrically and parallel to the measurement surface to a depth of 5 cm. A steel pointer positioned vertically at the centre of the inner cylinder indicated when 100 ml of water had infiltrated. The same amount of water was successively added and a reading taken every time the water level reached the pointer until the infiltration time did not change for five consecutive readings. At this point steady-state flow was assumed, and the K was calculated from the last five measurements using the approach suggested by Reynolds et al. (1995) (xref. Chapter 4 Section 4.2.4.1).

Soil samples were collected during the infiltration tests to determine the particle size distribution, soil bulk density and soil water content. These analyses were undertaken at the School of Bioresources Engineering and Environmental Hydrology (BEEH) Soil and Water Laboratory following procedures outlined by Blake and Hartge (1986), Anderson and Ingram (1989), Gee and Bauder (1986), and Klute (1986), among others.

5.2.2 Statistical analyses: multivariate analyses and t-tests

To determine the structure and strength of the interrelationships among the tillage practices, soil physical properties and the fitted parameters, PCA were performed using ADE-4 (Thioulouse et al., 1997). In this multivariate statistical tool the first and second factors often explain most of the variance and therefore most of the information contained in the data. Principal component analysis is performed on the symmetric covariance matrix. Results were displayed in correlation circles and factorial plans. A correlation circle shows the projection of the initial variables in the factor(s) space. When two variables are far from the center, and close to each other, they are significantly positively correlated (R^2 close to 1). If they are orthogonal, they are not correlated (R^2 close to 0). However, if they are on the opposite side of the center, then they are significantly negatively correlated (R^2 close to -1). When the variables are close to the center, it means that some information is carried on other axes. Correlation circles and factorial plans were used to describe the relationships between the derived hydraulic properties and parameters with tillage, physical and textural soil properties and the spatial (site and depth) and temporal (season) dimensions involved. The relationships between the K and the soil physical properties were extracted with coinertia analysis, a general coupling method that maximizes the co-inertia between the variables of two tables (Dray et al., 2003).

To investigate the impact of a given physical factor on K, the variance associated to the remaining factors was removed from the original data. For example, in order to evaluate the impact of clay content on K, the observed data were recalculated as if all the other variables were constant. The procedure consisted of generating a covariance matrix from data of for example silt, sand, initial water content, final water content and bulk density. Based on the principle that if two variables are uncorrelated, their covariance is zero, K was then recalculated using the eigenvectors of the covariance matrix (Jambu, 1991). In this study K data were recalculated by using the ADE-4 software (Thioulouse et al., 1997). Finally, the significance of the relationship between K and the selected soil physical properties was analyzed using t-tests for independent samples. Correlation matrices were calculated by means of STATISTICA 5.0 (StatSoft, 1995) and the results were summarized in tables.

5.3 Results and discussion

5.3.1 Hydraulic conductivity and soil physical properties

Table 5.2 contains a summary of the fitted average van Genuchten-Mualem (VGM) model parameters (θ_r, θ_s,α, n, K and K_s) and hydraulic conductivity derived from DI (K_{DI}). Although results for N_T and C_T plots varied throughout the growing season, as expected, in all cases the mean K decreased as more tension was applied.

Table 5.2: Fitted average van Genuchten-Mualem (VGM) model parameters: residual water content (θ_r), saturated water content (θ_s),α, n, saturated hydraulic conductivity (Ks) and unsaturated hydraulic conductivities at the three tensions in all the sites. The standard deviation of each parameter is provided in brackets. Included is the hydraulic conductivity from DI (K_{DI}) (Adapted from Chapter 4 Section 4.3.3.2)

Date/Till.		Depth	θ_r	θ_s	α	n	K_s	$K_{0.5}$	K_3	K_9	K_{DI}
Dec		D0									
NT			0.00E+00	1.85E-01	1.69E-02	1.39E+00	1.60E-03	9.00E-04	6.00E-04	3.00E-04	3.40E-02
			(0.0000)	(0.0517)	(0.0065)	(0.1576)	(0.0010)	(0.0004)	(0.0002)	(0.0001)	(1.40E-03)
		D10	0.00E+00	1.41E-01	3.89E-01	9.98E-01	2.40E-03	1.40E-03	8.00E-04	4.00E-04	4.50E-02
			(0.0000)	(0.0917)	(0.7341)	(0.6723)	(0.0003)	(0.0002)	(0.0002)	(0.0001)	(3.30E-02)
	CT	D0	3.00E-04	2.12E-01	1.54E-02	1.36E+00	2.80E-03	1.50E-03	9.00E-04	5.00E-04	3.60E-02
			(0.0005)	(0.0440)	(0.0104)	(0.1795)	(0.0026)	(0.0016)	(0.0009)	(0.0005)	(2.90E-02)
		D10	2.10E-02	1.78E-01	1.30E-02	1.53E+00	7.00E-04	4.00E-04	3.00E-04	1.00E-04	2.00E-02
			(0.0248)	(0.0321)	(0.0090)	(0.4001)	(0.0013)	(0.0008)	(0.0005)	(0.0002)	(1.30E-02)
Feb	NT	D0	0.00E+00	2.71E-01	3.53E-01	1.04E+00	3.20E-03	1.10E-03	5.00E-04	2.00E-04	9.20E-02
			(0.0000)	(0.0380)	(0.6778)	(0.7323)	(0.0038)	(0.0012)	(0.0004)	(0.0001)	(1.00E-01)
		D10	0.00E+00	2.86E-01	3.26E-01	9.57E-01	2.00E-03	9.00E-04	5.00E-04	2.00E-04	4.20E-02
			(0.0000)	(0.1037)	(0.6164)	(0.6377)	(0.0018)	(0.0008)	(0.0004)	(0.0002)	(4.20E-02)
	CT	D0	5.00E-04	2.23E-01	1.86E-02	1.27E+00	1.90E-03	8.00E-04	4.00E-04	2.00E-04	3.30E-02
			(0.0010)	(0.0313)	(0.0093)	(0.0585)	(0.0016)	(0.0005)	(0.0002)	(0.0001)	(1.00E-01)
		D10	8.00E-04	2.50E-01	1.03E-02	1.35E+00	7.00E-04	2.00E-04	1.00E-04	1.00E-04	5.10E-02
			(0.0015)	(0.0777)	(0.0095)	(0.3023)	(0.0006)	(0.0002)	(0.0001)	(0.0001)	(6.40E-02)
Apr	NT	D0	8.00E-04	2.62E-01	1.62E-02	1.21E+00	1.80E-03	7.00E-04	4.00E-04	2.00E-04	5.70E-02
			(0.0015)	(0.0782)	(0.0043)	(0.0685)	(0.0010)	(0.0005)	(0.0003)	(0.0002)	(2.80E-02)
		D10	3.65E-02	2.42E-01	1.86E-02	1.30E+00	2.70E-03	1.30E-03	7.00E-04	4.00E-04	7.60E-02
			(0.0000)	(0.0461)	(0.0097)	(0.0896)	(0.0020)	(0.0010)	(0.0005)	(0.0002)	(3.30E-02)
	CT	D0	3.00E-04	2.49E-01	1.28E-02	1.28E+00	1.20E-03	6.00E-04	4.00E-04	2.00E-04	1.30E-02
			(0.1450)	(0.5537)	(0.0086)	(0.6866)	(0.0006)	(0.0006)	(0.0678)	(0.0003)	(1.20E-02)
		D10	0.00E+00	2.13E-01	1.92E-02	1.23E+00	2.70E-03	1.20E-03	7.00E-04	4.00E-04	2.30E-02
			(0.1360)	(0.5292)	(0.0074)	(0.6470)	(0.0006)	(0.0003)	(0.0003)	(0.0001)	(1.80E-02)

5.3.2 Relationship between infiltration and tillage systems

The results of a PCA correlation matrix (F1-F2 axes) performed on the infiltration data is shown in Fig. 5.1. Factorial plans of tillage on the three axes are also provided.

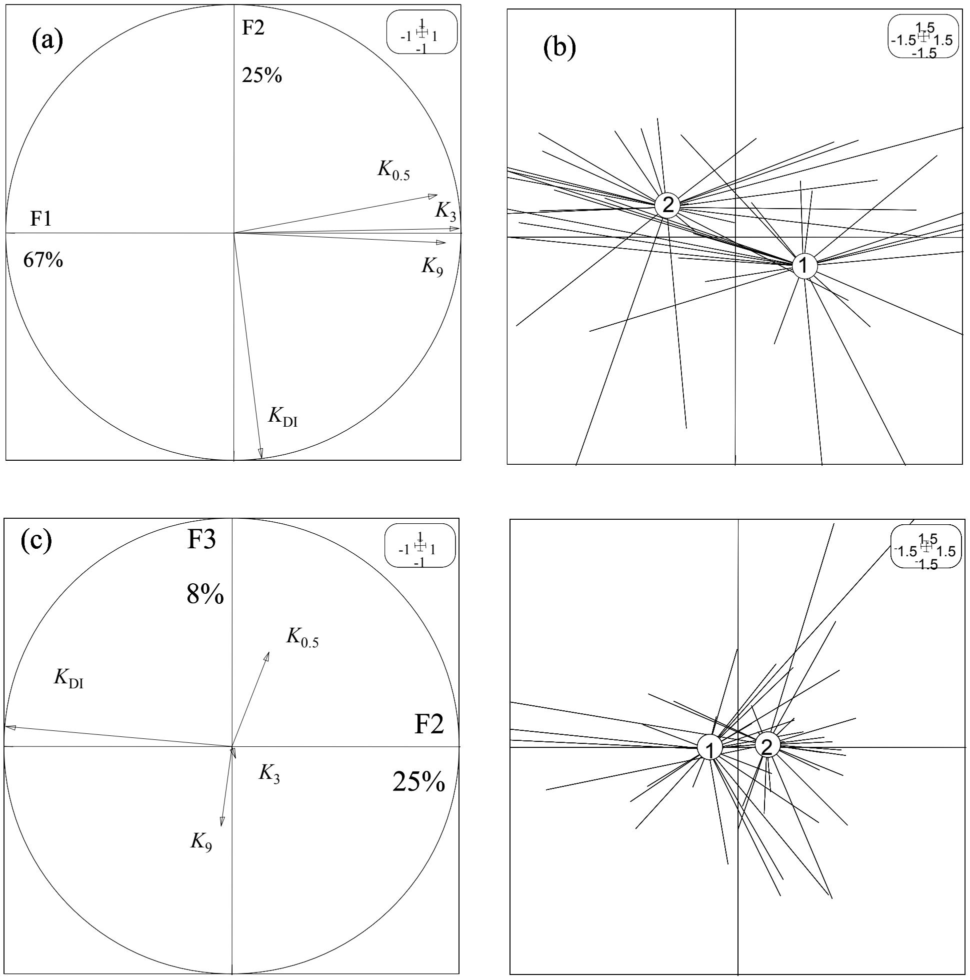

Figure 5.1: PCA correlation matrix results from the tension disc ($K_{0.5}$, K_3, K_9) and double ring infiltrometers (K_{DI}): (a) K on first and second axes (F1-F2); (b) factorial plan of tillage on F1-F2 axes; (c) K on second and third (F2-F3) axes; (d) factorial plan of tillage on F2-F3 axes. The tillage systems are represented by 1 = N_T and 2 = C_T

The first two factors of the PCA (Fig. 5.1(a)) described 92% of the variability indicating that a strong structure existed in the data. K derived from TI data at the three tensions had a strong correlation along the positive part of F1 which explained 67% of the variability. A very small proportion of the variability in this data set was explained by the F2 axis. K from DI data was represented mostly by the F2 axis. The tillage systems factorial plan on the F1-F2 axes (Fig. 5.1(b)) showed that the cluster of points from N_T treatments (1) was correlated positively with K (Fig. 5.1(a)) while the cluster of points from C_T treatments (2) was negatively correlated. Fig. 5.1(c) illustrates the relationships on the F2-F3 axes. $K_{0.5}$ and K_9 had components along the F3 axis although their influence was small as the arrows are closer to the centre of the circle. The F2-F3 axes indicated that nearly all the variability from K_{DI} was along F2 suggesting that of the total variability this data was responsible for just about 25% while the rest was due to K from TI data. The factorial plan on tillage systems (Fig. 5.1(d)) was horizontal on either side of the F2 axis with the N_T cluster (1) in the same direction as K_{DI}. However, the cluster was closer to the centre suggesting that N_T was not strongly correlated with K_{DI}. In addition, there was a reduced difference between the tillage systems (closer to each other) perhaps because these axes only explained about one-third of the variability and pointed out that the tillage systems had an influence on K_{DI} that was not statistically significant. Thus, from these observations, there was a possibility that tillage influenced more flow through smaller pores, represented by K_{TI}.

5.3.3 Relationship between infiltration and soil physical properties

From Table 5.1, the experiment sites were characterized by different proportions of the soil separates and bulk densities. These properties were likely to influence the K as shown by the factorial plans in Fig. 5.2. The cluster of points in each of the cases was distinct meaning that the observations were different from one site to another and also from one period in the season to the other. From Fig. 5.2(a), measurements in December were in the same direction as K (Fig. 5.1(a)), suggesting that at this time there was higher K when compared to February or April. This period coincided with the time when C_T plots were freshly cultivated. Nevertheless, for the other periods in the season, for different sites and depths the responses were varied. These variations may have occurred as a result of a number of factors or a combination of factors. The three main relationships investigated in this study are the effects of bulk density, clay content and tillage. The influence of the initial (M_{ci}) and final water content (M_{fi}) on K was also investigated.

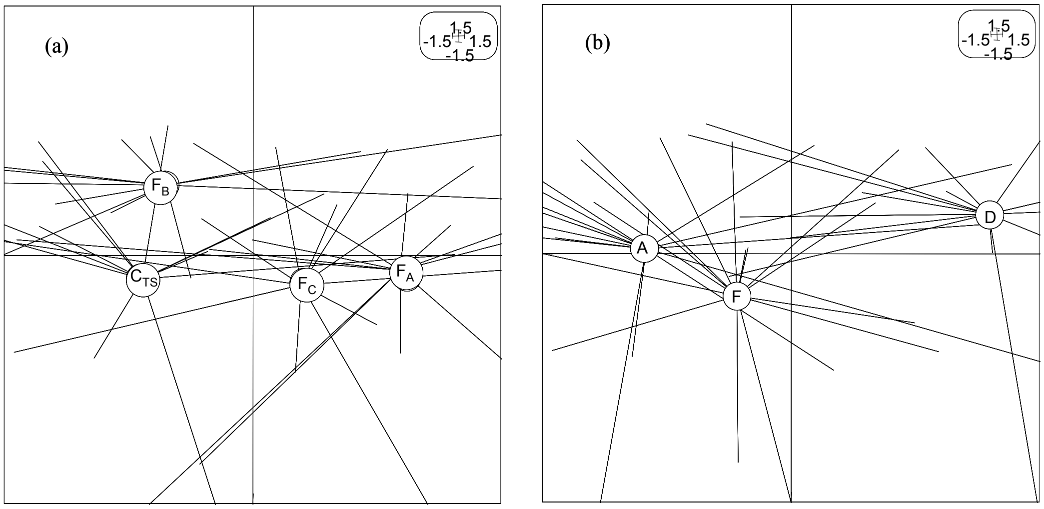

Figure 5.2: The response of hydraulic conductivity (on F1-F2 axes) as influenced by: (a) experiment sites; (b) date of experiment (D=December; F=February; A=April)

The PCA correlation matrices of some selected soil physical properties and the factorial plans of clay content and bulk density are presented in Fig. 5.3. As shown in Fig. 5.3(a) and Fig. 5.3(b), close to all the variability in bulk density and clay was explained along F1 axis as the loadings on the other axes are minimal. Clay content and bulk density negatively affected K as both were on the negative side of F1 axis since Fig. 1(a) indicated that increasing K correlated with the positive part of F1 axis. Fig. 5.3(c) and Fig. 5.3(d) show the distribution of clusters of bulk density and clay content, respectively. In all cases, the higher the B_D the lower the K. This is because the order of the codes representing B_D are increasing in the opposite direction as increasing K (Fig. 5.1(a)). This trend was similar to that depicted in Fig. 5.2(a) in which K decreased as the season advanced, indicating that the increase in B_D is likely to be the main factor that determines K. Clay content did not show a direct relationship with K in all cases although the majority of the cases (75%) indicated a similar trend as observed with B_D. One would think that the positive correlation of K with clay between 21.05-21.9% suggests that the textural combination with this range of clay improves K. This could be plausible but the F1 axis explains only 45% of the variability. In addition, site F_B with clay content of 21.2 % (Table 5.1) showed a negative correlation with K. Thus, K is likely to be influenced by a combination of factors.

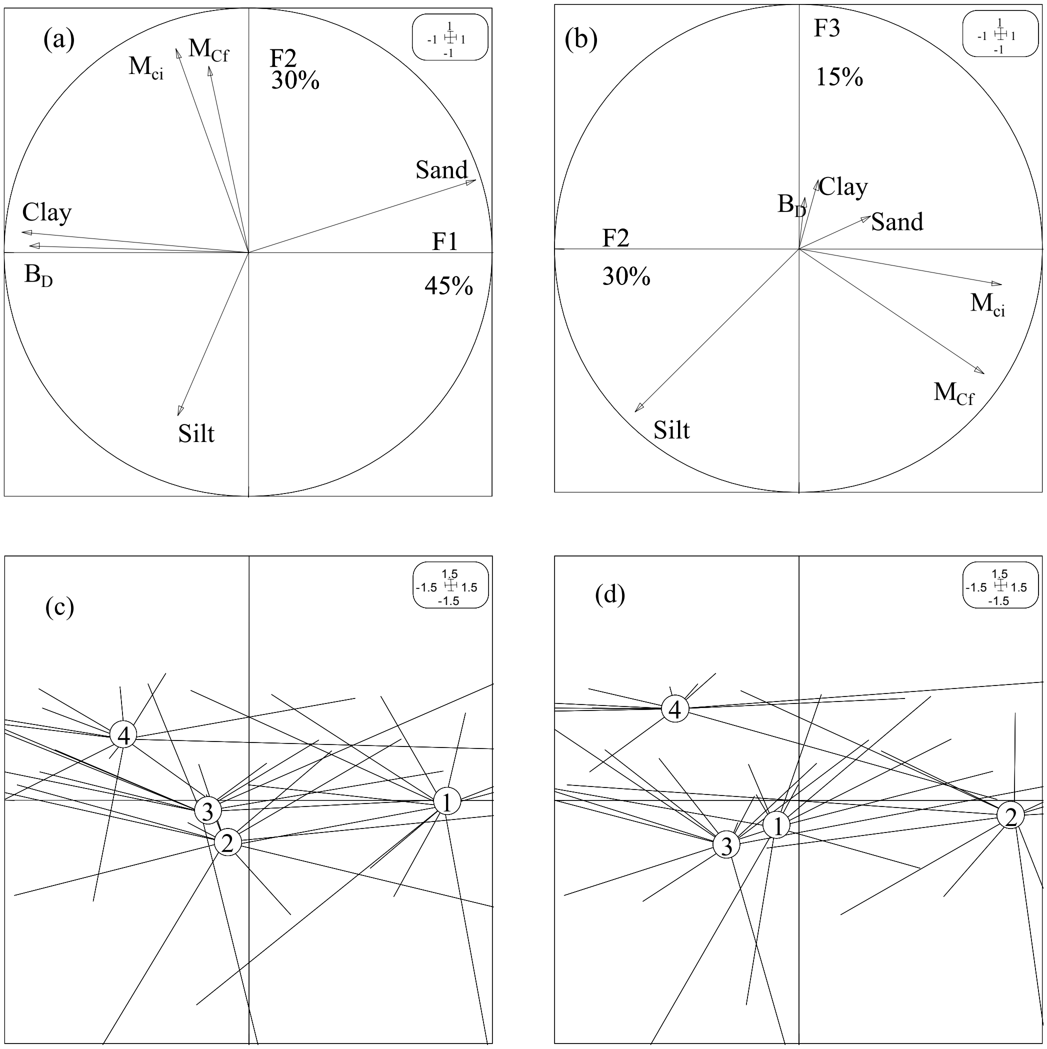

Figure 5.3: The effect of soil physical properties: (a) correlation circle on F1-F2 axes; (b) correlation circle on F2-F3 axes; (c) factorial plan on F1-F2 of bulk density ($1=B_D\leq1.107$, $2=1.107\leq B_D\leq1.252$, $3=1.252\leq B_D\leq1.481$, $4=B_D>1.481$); (d) factorial plan on F1-F2 axes of clay content ($1=C\leq21.05\%$, $2=21.05\%\leq C\leq21.9\%$, $3=21.9\%\leq C\leq23.3\%$, $4=C>23.3\%$)

To identify the extent to which these soil properties might have influenced K in the different tillage plots, three evaluation cases were carried out. The first evaluation involved projection of the measured infiltration data on all the selected soil physical properties (*Evaluation A*). This was followed by an extraction of the impact of bulk density which was done by projecting infiltration data through a matrix generated from the remaining factors (use of Table Orthonormal option of ADE-4 software, Thioulouse et al., 1997) (*Evaluation B*). A similar procedure was used to obtain the impact of clay content on K (*Evaluation C*). On a seasonal basis, the correlations between K at different tensions and from DI did not change with the projection on either bulk density or clay content. This may be as a result of the inverse relationship observed between N_T and C_T. As the season advanced, K decreased in C_T plots while the reverse occurred in N_T plots (xref. Chapter 4). These effects may have cancelled out on a seasonal time step. Further evaluations were done based on the three dates in the season during which the measurements were done. An analysis of means using STATISTICA 5.0 (StatSoft, 1995) was done to determine the significance of the identified impact. The results are given in Table 5.3.

Table 5.3: p-values from the statistical analyses of three cases of projections to identify soil physical factors affecting K (A-C = Evaluations; D_1 = Dec; D_2 = Feb; D_3 = Apr)

Parameter	$K_{0.5}$			K_3			K_9			K_{DI}		
Evaluation/Date	N_T_D	N_T_F	N_T A	N_T_D	N_T_F	N_T A	N_T_D	N_T_F	N_T A	N_T_D	N_T_F	N_T A
A_C_T_D_1	0.916	0.036*	0.007**	0.937	0.025*	0.005**	0.962	0.030*	0.008**	0.971	0.657	0.742
A_C_T_D_2	0.043*	0.994	0.845	0.023*	0.941	0.750	0.037*	0.732	0.905	0.805	0.803	0.893
A_C_T_D_3	0.007**	0.992	0.757	0.003**	0.987	0.716	0.005**	0.762	0.994	0.810	0.805	0.893
B_C_T _D_1	0.822	0.062	0.037*	0.810	0.040*	0.032*	0.758	0.044*	0.042*	0.964	0.683	0.770
B_C_T _D_2	0.052	0.866	0.658	0.026*	0.796	0.585	0.043*	0.824	0.903	0.819	0.812	0.903
B_C_T _D_3	0.065	0.780	0.973	0.030*	0.788	0.992	0.050*	0.522	0.741	0.841	0.794	0.883
C_C_T _D_1	0.986	0.075	0.027*	0.944	0.058	0.021*	0.913	0.065	0.034*	0.835	0.750	0.651
C_C_T _D_2	0.095	0.980	0.858	0.062	0.959	0.770	0.102	0.712	0.896	0.699	0.765	0.869
C_C_T _D_3	0.051	0.883	0.942	0.036*	0.862	0.945	0.053	0.631	0.806	0.483	0.540	0.648

* Significant at p=0.05; ** Significant at p=0.01

In all cases, more significantly different observations were found at 3 cm tension. The proportion was approximately 25%, 41% and 34% for $K_{0.5}$, K_3 and K_9, respectively. There were no significantly differences in K_{DI} observations. This suggested that N_T over the three years did not promote significant development of large pores but perhaps better network of smaller pores which were responsible for about 75% of the cases that the differences were significant. The projection of infiltration data on all soil physical properties (*Evaluation A*) had the highest significantly different observations while Evaluation C had the least. All significant differences at $p \leq 0.01$ occurred under *Evaluation A* and was between measurements in December and April. This suggested that there was more effect on K from a combination of soil properties, rather than on isolated cases. However, bulk density (*Evaluation B*) could have played a more significant role than clay content in influencing K due to the higher number of significant differences experienced between *Evaluation B* and *Evaluation C*. In addition there were over 60% of significantly different observations that involved measurements in December and April. Between these times, it is assumed that clay content remained constant while bulk density changed.

There were changes in the correlation matrices over the three measurement periods. The relationships are illustrated in Fig. 5.6. Bulk density remained negatively correlated in an increasing rate with K from TI data. The negative correlation between final moisture content (M_{cf}) and K at the beginning of the season was positive by the end of the season. This response was also observed with sand content. Although the silt content of the soils in the study area was only about 10%, it had a positive correlation at the beginning of the season in some cases which became negative by April. Clay content had a fluctuating negative correlation with K. The effect of sand content was equally the same as that of clay content but in the opposite direction. Neither the projection on bulk density nor clay content changed the relationships between K and the remaining properties. This was an indication that they were strongly correlated with high loadings and of the exclusion of one in the analysis does not change the result. Thus, the projection was done on both clay and bulk (*Evaluation D*).

The resulting observations illustrated in Fig. 5.7(d_1-d_3), showed that without the influence of clay and bulk density, almost all K was positively correlated with the remaining soil physical properties. There was also a marked positive correlation in K_{DI} with the remaining soil physical properties. The changes observed were linked to the absence of the effects of bulk density and clay. Because tillage affects a soil's bulk density, this study suggests that N_T systems enhance K due to the relatively lower bulk density (xref. Table 5.1).

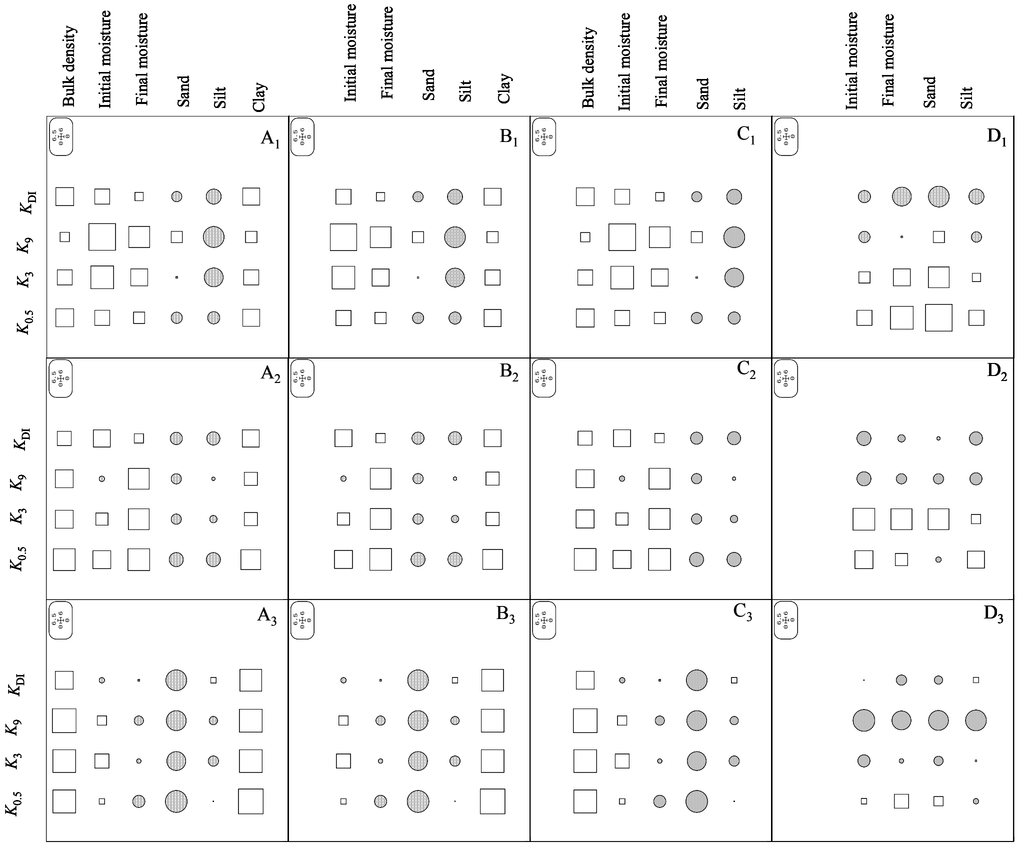

Figure 5.6: Periodic correlation matrix showing relationships between infiltration capacity and soil physical properties for: (a) Evaluation A; (b) Evaluation B; (c) Evaluation C; and (d) Evaluation D. The size of the circles (positive correlations) and the squares (negative correlations) is proportional to the degree of correlation. Subscripts 1, 2 and 3 denote the period in the season when the measurement was made (1=December; 2=February and 3=April)

5.3.4 Relationship between fitted VGM parameters and soil physical properties

Table 5.2 contains a summary of means of the fitted VGM parameters. The five parameters were saturated hydraulic conductivity (K_s), the residual and saturated water contents (θ_r and θ_s respectively) and empirical shape parameters (α and n). Except in April, the residual water content (θ_r) in C_T plots was higher than in N_T. Saturated hydraulic conductivity (θ_s) was higher in C_T plots in December but lower in the other measurement dates. Saturated hydraulic conductivity (Ks) showed a similar behaviour. Cultivation on the C_T plots was a likely cause of the observed differences. The relationship between the fitted VGM parameters and measured soil physical properties are illustrated through correlation circles in Fig. 5.8.

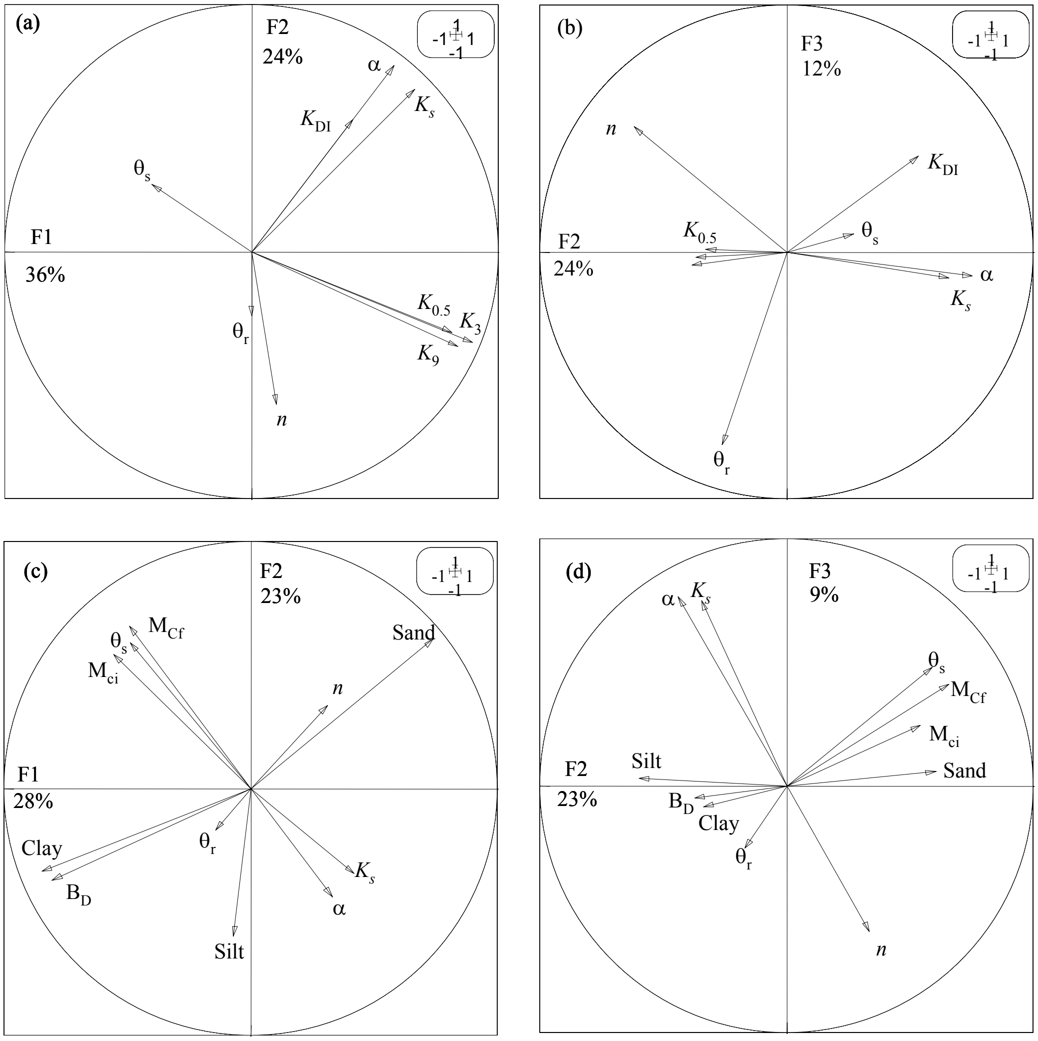

Figure 5.8: PCA correlation circles of VGM fitted parameters and: (a) K on F1-F2 axes; (b) K_c on F2-F3 axes; (c) soil physical properties on F1-F2 axes; and (d) soil physical properties on F2-F3 axes

The PCA correlation matrix performed on all the parameters fitted with van Genuchten-Mualem (VGM) model and K from DI described 36% and 24% of the variability on the F1 and F2 axes, respectively while F3 described 12% of the variability. Saturated hydraulic conductivity (K_s) and α were the only strongly positively correlated parameters. The F1, F2 and F3 axes described 28%, 23% and 9% respectively when the fitted VGM parameters were correlated with soil physical properties. Saturated water content (θ_s), initial moisture (M_{ci}) and final moisture (M_{fi}) contents correlated positively with high loadings especially on the F1-F2 axes. Residual water content (θ_r) was positively correlated with clay content and bulk density. Correlation coefficients among the selected soil physical properties and the fitted VGM parameters are given in Table 5.4.

Because of the difference in the soil separates (clay, sand and silt) in the various sites standardization was done. A statistical solution was followed that projected the matrix of VGM properties on the matrix containing the soil texture and physical properties to recalculate the VGM parameters as if the soil was the same in each site. As the three soil separates were proportions, two had to be eliminated before this projection could be done. Clay was retained in the recalculation. The analysis retained 78% of the fitted VGM table and 55% of the soil textural properties table. The significant positive correlation between the shape parameters (α and n) and K_s shown in Table 5.4 was even better after standardization (Table 5.5). However, the shape parameters, initially significantly negatively correlated were positively correlated although insignificantly after standardization. It was observed that the significantly correlated parameters were positively correlated on the F2-F3 axis (Fig. 5.3(a)-(b)). This was also true for initial moisture, final moisture and θ_s (Fig. 3(c)-(d)). However, it is important to note that for this relationship to hold, the variable should first be strongly correlated on the F1-F2 axis. Thus the PCA correlation circle is likely to provide important statistical inference that would otherwise require complicated statistical tools.

Table 5.4: Correlations among the selected soil physical properties and the fitted VGM parameters before standardization

	K_{DI}	B_D	$M_{initial}$	M_{final}	Sand	Silt	Clay	θ_r	θ_s	α	n	K_s
K_{DI}	1.00	-0.24	-0.11	0.00	0.20	0.14	-0.32^{*}	-0.16	-0.06	0.57^{*}	0.04	0.47^{*}
B_D		1.00	0.24	0.07	-0.73^{*}	0.12	0.81^{*}	0.07	0.09	-0.08	-0.33^{*}	-0.25
$M_{initial}$			1.00	0.59^{*}	-0.05	-0.31^{*}	0.26	-0.12	0.52^{*}	-0.24	-0.17	-0.18
M_{final}				1.00	0.01	-0.16	0.10	-0.02	0.92^{*}	-0.11	-0.08	-0.16
Sand					1.00	-0.54^{*}	-0.84^{*}	-0.18	-0.04	0.03	0.29^{*}	0.13
Silt						1.00	0.00	0.01	-0.14	0.20	-0.16	0.05
Clay							1.00	0.02	0.14	-0.16	-0.25	-0.20
θ_r								1.00	-0.08	-0.07	0.05	-0.10
θ_s									1.00	-0.04	-0.14	-0.08
α										1.00	-0.35^{*}	0.88^{*}
n											1.00	-0.31^{*}
K_s												1.00

* Correlations significant at $p < 0.05$

Table 5.5: Correlations among the selected soil physical properties and the fitted VGM parameters after standardization

	I_{DR}	B_D	$M_{initial}$	M_{final}	Sand	Silt	Clay	θ_r	θ_s	α	n	K_s
I_{DR}	1.00	-0.24	-0.11	-0.00	0.20	0.14	-0.32^{*}	-0.65^{*}	-0.06	0.93^{*}	0.13	0.89^{*}
B_D		1.00	0.24	0.07	-0.73^{*}	0.12	0.81^{*}	-0.07	0.09	-0.09	-0.06	-0.42^{*}
$M_{initial}$			1.00	0.59^{*}	-0.05	-0.31^{*}	0.26	-0.59^{*}	0.56^{*}	-0.38^{*}	-0.11	-0.33^{*}
M_{final}				1.00	0.01	-0.16	0.10	-0.25	1.00^{*}	-0.15	0.13	-0.27
Sand					1.00	-0.54^{*}	-0.84^{*}	-0.19	-0.03	0.01	0.40^{*}	0.18
Silt						1.00	0.00	0.06	-0.16	0.25	-0.04	0.12
Clay							1.00	0.17	0.14	-0.17	-0.48^{*}	-0.29
θ_r								1.00	-0.17	-0.41^{*}	-0.31^{*}	-0.35^{*}
θ_s									1.00	-0.19	0.16	-0.32^{*}
α										1.00	0.24	0.89^{*}
n											1.00	-0.38^{*}
K_s												1.00

* Correlations significant at $p \leq 0.05$

θ_r had very low correlation coefficients with other parameters before recalculation indicating that it could be excluded (negligible e.g. Yoon et al., 2007) in computations without significant loss in accuracy of the output. Ventrella et al. (2005) fixed the value of θ_r at $0.15m^3m^{-3}$ for clay soils at their experimental site in Southern Italy. However, after recalculation (Table 5.5), it was significantly negatively correlated with initial moisture content and K_{DI}. In total, there were 50% more significant correlations after recalculation. Thus, soil texture has an impact on the relationship between soil hydraulic and physical properties.

5.3.5 Relationship between fitted Kostiakov model and Philip model parameters and soil physical properties.

The fitted Philip's model parameters were sorptivity (S) and transmissivity (A). In addition to S, the modified Philip's model has saturated hydraulic conductivity (K_s) and a constant, B. Kostiakov's model parameters are two constants, B and n. the modified Kostiakov's model includes a term "i_c" that enable the infiltration rate to approach a finite value at long times. Table 5.6 shows the summary statistics of the fitted Kostiakov's and Philip's model parameters. The highest variability was obtained in the modified Kostiakov's "i_c" term in February (CV = 387%), followed by modified Kostiakov's "B" term in April (CV = 279%) whereas the least variability occurred in modified Kostiakov's "B" term in April (CV = 17%). The values of Kostiakov's term "n" were consistently less than one which agreed with other studies (Mbagwu, 1994; Mbagwu, 1990) although Gosh (1985) argued and proved mathematically that it could be greater than unity. Although Brutsaert (1977) suggested values of 1/3, 2/3 or 1 while Kutilek and Nielsen (1994) recommended a value of 1 for the modified Philip's term "B", a half of the mean values were found to be below 0.2 in this study.

Table 5.6: Average fitted Kostiakov's and Philip's model parameters for three periods of measurements from N_T and C_T treatments

Till-	Period	December					February					April				
age	Param.	Mean	SD	Min.	Max.	CV	Mean	SD	Min.	Max.	CV	Mean	SD	Min.	Max.	CV
N_T	A_P	0.108	0.076	0.009	0.209	0.705	4.62	5.94	0.07	18.11	1.28	69.886	194.703	-0.493	551.720	2.786
	B_K	2.143	4.441	0.069	13.040	2.073	-0.73	0.54	-1.00	0.58	0.74	-0.807	0.140	-0.999	-0.591	0.17
	B_{MK}	0.259	0.191	0.029	0.654	0.738	-4.10	6.05	-17.69	0.01	1.48	-69.69	194.64	-551.35	0.194	2.79
	B_{MP}	0.950	1.517	-0.311	4.480	1.596	0.933	280.08	0.17	79.25	2.82	0.187	0.390	-0.247	1.077	2.093
	i_c	-1.804	4.421	-12.66	0.139	2.451	0.01	0.95	-0.79	2.25	3.87	-0.470	0.511	-1.360	0.275	1.086
	K_s	0.123	0.071	0.010	0.243	0.576	0.41	0.38	0.07	1.11	0.94	0.627	0.711	0.205	2.345	1.134
	n_K	-0.752	0.257	-0.995	-0.400	0.342	0.13	0.14	0.00	0.40	1.11	0.139	0.106	0.002	0.270	0.762
	n_{MK}	-0.246	0.212	-0.629	0.002	0.859	0.07	0.05	0.01	0.13	0.64	0.190	0.118	0.015	0.337	0.624
	S_{MP}	0.638	0.414	0.033	1.364	0.650	1.43	2.28	0.24	6.97	1.60	1.217	1.207	0.224	2.916	0.992
	S_P	0.523	0.382	0.025	1.272	0.729	14.64	7.14	0.56	18.10	2.81	5.290	8.903	0.066	23.620	1.683
C_T	A_P	2.952	7.283	0.023	20.950	2.467	2.714	6.929	0.015	19.840	2.553	8.311	19.348	0.044	56.035	2.328
	B_K	-0.842	0.266	-0.996	-0.207	0.316	-0.772	0.354	-0.998	-0.032	0.459	-0.719	0.433	-0.999	0.181	0.602
	B_{MK}	-2.732	7.199	-20.52	0.172	2.636	-2.520	6.870	-19.510	0.130	2.727	-8.082	19.227	-55.520	0.072	2.379
	B_{MP}	0.507	0.691	0.121	2.178	1.362	0.161	0.161	0.007	0.463	0.996	0.191	0.085	0.055	0.300	0.445
	i_c	0.479	0.501	-0.318	1.223	1.046	-0.152	0.389	-0.565	0.342	2.567	-0.145	0.271	-0.460	0.261	1.862
	K_s	0.348	0.348	0.013	1.018	1.000	0.232	0.225	0.015	0.631	0.970	0.256	0.161	0.073	0.555	0.630
	n_K	0.079	0.049	0.008	0.147	0.629	0.092	0.098	0.003	0.297	1.073	0.155	0.185	0.001	0.556	1.195
	n_{MK}	0.104	0.076	0.009	0.217	0.733	0.119	0.115	0.003	0.332	0.972	0.118	0.104	0.009	0.297	0.881
	S_{MP}	3.581	4.185	0.151	12.510	1.169	1.168	1.388	-0.017	4.095	1.188	0.591	0.511	0.100	1.714	0.864
	S_P	11.12	5.691	6.097	21.340	2.310	8.097	12.692	0.003	33.850	1.568	3.988	5.919	0.068	14.760	1.484

Subscripts: P – Philip; MP – modified Philip; K – Kostiakov; MK – modified Kostiakov.

The changes in the fitted parameters were investigated to identify whether the variations were significant between tillage systems and dates of measurement. At depth D_0, there were fewer cases of significant difference in Philip's model parameters beween tillage systems and measurement dates. At D_{10} both "A" and "S" were significantly different in a number of cases suggesting that the hydraulic properties between the surface and this depth were different as these parameters represent initial infiltration rate and water transmission under gravity, respectively. Saturated hydraulic conductivity, K_s was similarly changed significantly in some N_T plots compared to C_T plots as well as from one date of measurement to another.

Kostiakov's fitting parameters varied significantly between tillage systems, depths and period of measurement. Kostiakov's "B" term was different between tillage systems while "n" significantly varied among seasons in the same tillage system. The term "i_c", included to enable infiltration to approach finite steady state infiltration rate at larger times, depicted more significant differences in the modified case. These variations were within and between tillage systems and also across the dates of measurement. The PCA correlation matrices between the fitted model parameters and the measured soil physical properties given in Fig. 5.7 showed that the structures were weak explaining only about 25% of the variability on the main (F1) axis.

Philip's terms "A" and "S" were negatively correlated (Fig. 5.7(a_1-b_1)) indicating that as one increases, the other decreases which is a typical field experience. The term "A" was weakly positively correlated with bulk density on F1-F2 axes and had no correlation on the F2-F3 axes suggesting that the observed changes in bulk density did not affect the variation of "A". The fitting parameters (B and n) in Kostiakov model were inversely correlated (Fig. 5.7(a_2-b_2)). However, in modified Kostiakov model the parameters were positively correlated (Fig. 5.7(c_2-d_2)). There seem to be negligible relationship between these fitting parameters and soil physical properties (B_D and K_{DI}), explaining their lack of physical meaning. The term "i_c" could not be associated with any physical property given that its loadings were very small.

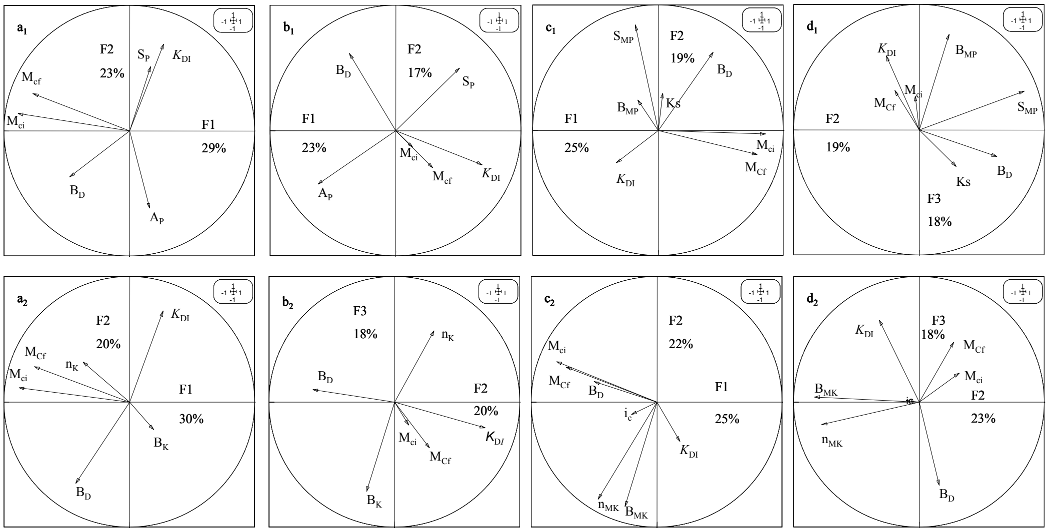

Figure 5.7: PCA correlation matrix results of soil physical properties and the fitted model parameters: (a) initial model on F1-F2; (b) initial model on F2-F3 axes; (c) modified model on F1-F2; (d) modified model on F2-F3 axes (Subcripts 1 = Philip's model; 2 = Kostiakov's model)

5.4 Summary

In the Potshini catchment, tillage systems, which change the surface conditions of the soil, showed influences on steady state infiltration rate and hydraulic conductivity (xref. Chapter 4, Section 4.2.3). According to Lampurlanés and Cantero-martínez (2006) tillage affects pore space (shape, volume and continuity of pores), residue cover and surface roughness. Thus a chain of relationships are likely to be responsible for the final/seasonal observations. For ponded infiltration tests such as those performed in Potshini, surface roughness may not play a significant role. At the beginning of the season, C_T treatments had a lower bulk density on the surface as a result of a loosened soil structure. This was responsible for higher steady state infiltration rate in C_T plots in December even when there was a likelihood of pore discontinuity due to tillage. The strong positive correlation between measurements made using the tension disc infiltrometer along the F1 axis (that explained two thirds of the total variability) indicated that the tillage effects were associated more with flow through smaller pores.

The factorial plan of tillage (Fig. 5.1), which reflects the seasonal response, related N_T with an increase in K and C_T with a decrease in K. This was associated with reconsolidation of the loosened soil structure which led to increased bulk density in C_T treatments relative to N_T treatments. Bulk density in N_T plots slightly increased and the highest value was in February suggesting that raindrop impact had some effect on porosity in both treatments. The consistently lower bulk density in N_T plots compared to C_T plots at depth D_{10} could be associated with the development of hard layers in C_T below the ploughed zone.

Soil texture was also shown to affect K. Clay content was negatively correlated withK causing sites with relatively higher clay contents to experience lower K as compared with those with higher sand content. This could be due to a difference in pore size distribution between clay and sand particles. Bulk density was shown to be significantly positively correlated with clay content. The interaction between clay content and bulk density could be responsible for highly significantly different cases ($p \leq 0.01$) against K (Table 5.3). Furthermore, the recalculation of K when the rest of the variables were projected on both B_D and clay content resulted in a higher positive correlation between K and the remaining soil properties. Saturated hydraulic conductivity (K_s) became significantly negatively correlated with θ_s only after projection. As observed by Mbagwu (1995), K_s and bulk density were negatively correlated. In this study, the correlation was significant after normalizing soil texture in all sites. The fitted VGM parameters showed no strong inclination to soil texture except for n.

The measured initial and final soil moisture contents were significantly positively correlated. Under uniform soil texture, initial moisture content was significantly negatively correlated with θ_r and positively correlated with θ_s. The final moisture content exhibited a perfect positive correlation with θ_s ($R^2 = 1$). This result suggested that under some circumstances, TI experiments could approach saturated water content depending on soil properties. The negative significant relationship between θ_r and K_s indicated that dryer soils are likely to have higher K_s and vice versa which influences the shape of the infiltration curve and thus the fitted VGM parameters. Clay did not have a significant relationship with θ_r.

Although Philip's "B" term was less than unity as recommended by a number of researchers, it fluctuated between the measurement dates and between tillage systems. Thus it was felt that in such studies that involve changes in bulk density, there is a need to use recommended values with caution. Even though there were no significant differences between tillage systems from data from DI, Kostiakov and Philip model parameters fitted from this data set showed significant differences in some cases. This was particularly observed with Philip's "A" and "S" terms which represent gravity- and matric-influenced flows, respectively. This indicated that tillage influenced the shape of the infiltration curve even when K did not change.

5.5 Conclusion

The ability of soils to capture and store water plays an important role in the success of rainfed agriculture in semi arid and arid environments. In the study area, bulk density was found to be the dominant physical property influencing hydraulic parameters. This property was also closely linked to soil texture, enabling it to exert more influence on infiltration. Because tillage systems alter the soil's physical conditions, they in turn affect the bulk density of the soil and hence water entry into the soil. However, plots that were tilled (C_T) were shown to have short term benefits as compared to N_T because of rapid reconsolidation. In N_T treatments, bulk density was lower at the end of the season when compared to the beginning. The reverse was observed in C_T plots. In addition, bulk density at depth D_{10} was not positively affected by tillage. A combination of tillage and soil physical properties led to statistically significant differences in K measured using TI. This suggested that the interactions enabled more flow through medium to smaller pores. Further analyses need to be done to investigate the contribution to total infiltration and transmission of water by these smaller pores (mesopores). In this way a better understanding of water partitioning can be reached. This thus may enable the development of suitable water management strategies for rainfed conditions.

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6.0 DESCRIBING THE DOMINANT SURFACE AND NEAR SURFACE CHANGES IN SOIL HYDRAULIC PROPERTIES DUE TO TILLAGE. III: WATER CONDUCTING POROSITY AND WATER RETENTION

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Abstract

Soil management systems affect soil porosity in ways that could influence its hydraulic properties (infiltration and storage). These effects have not been studied adequately in semi-arid environments, where rainfall is erratic and which are predominantly occupied by smallholder resource poor farmers having limited crop production options. The objective of this study was to describe the management-induced changes through the growing season in pore indices and water retention in conventional tillage (C_T) and no-till (N_T) systems after 3 years under the same treatment in smallholder farms. Infiltration measurements were undertaken with a tension disc infiltrometer in December, February and April during the 2007/2008 maize (Zea mays L.) growing season at four sites in Potshini catchment, South Africa. At each site, a wet to dry infiltration sequence corresponding to water tensions of 0.5, 3 and 9 cm was performed at the soil surface (D_0), and at 10 cm below the surface (D_{10}). The tension disc measurements were analyzed numerically using two HYDRUS-2D packages viz. DISC and RETC to derive hydraulic conductivity (K) and water retention characteristics curves (WRCC), respectively. For each site, depth and period of measurement, the K and WRCC were used to estimate several pore indices and available water content (AWC), respectively.

Tillage practices were found to affect soil hydraulic properties at all the sites, although the responses were not entirely consistent. In December, the average K values in C_T were higher in relation to N_T at depth D_0 in 75% of the sites. Significant differences ($p \leq 0.05$) in K values between measurement periods and depths were observed at some sites. In both tillage systems decreases in K between 0.5 and 9 cm tensions of over 25 times were observed between February and April, suggesting the initial presence of soil macropore networks. Regardless of tillage system, larger pores were found to represent a small proportion of total porosity but had a

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higher influence on water flow than the smaller pores. At the adopted field capacity (-330 cm), volumetric water content (θ) was higher in N_T than in C_T, by an average of 17% at two sites, while at the third site θ was higher in C_T by 13%. However, early in the season C_T had higher θ at depth D_0 at higher tensions (ϕ_ψ>2000 cm) at all sites, suggesting that crops could be sustained longer in C_T than in N_T in case of water stresses. The mean AWC, considered critical in the choice of a tillage system, was higher in N_T than C_T at depth D_{10}. However, mixed results were obtained at depth D_0. It was concluded that tillage influences soil hydraulic properties and that no-till system showed the potential to store more soil water. However, the livestock-crop production interaction remains a challenge to the potential benefits of N_T systems in the Potshini Catchment.

Keywords: Conventional tillage, no-till, porosity, tension, water content.

6.1 Introduction

Tillage is the most widely studied management practice affecting soil hydraulic properties such as hydraulic conductivity, flux potential, sorptivity and the microscopic capillary length, which represents an average soil pore size (Green et al., 2003; Reynolds and Elrick, 2005). To date, findings have been diverse with some studies showing that tillage significantly affected the number of active macropores (e.g. Petersen et al., 2001; Cameira et al., 2003; Malone et al., 2003; Nesme et al., 2005; Guo et al, 2006; Choi et al., 2007; Antonopouls and Rahil, 2007) and disrupt macropore continuity (Vervoort et al., 2001; Kutílek, 2004) while others (e.g. Azevedo et al., 1998; Droogers et al., 1998) found no significant difference in the quantity of hydraulically active macropores between different management practices. Such contradictory results add uncertainty when attempting to simulate the effects of different agricultural management systems on the movement of fluids and dissolved substances into, and through, the soil, especially in semi-arid environments where rainfall is very erratic and resource poor smallholder farmers with limited crop production options predominate.

Natural disturbances and cycles such as diurnal and seasonal changes affect soil hydraulic properties (Zhou et al. 2008). Hydraulic properties change as a result of changes in pore volume and pore size distribution over time and thus knowledge of the pore size distribution helps conceptualize the changes in the porous medium resulting from tillage (Schwartz et al., 2003). This necessitates a detailed monitoring of hydraulic properties. In addition, management practices that can improve root-zone water availability in areas arid environments like various rainwater harvesting initiatives may achieve full potential only if an in-depth understanding of the soil's response to water exist. According to Yoon et al. (2007), the behaviour of soil water is largely influenced by the distribution of various sizes of soil pores and their continuity (Kutílek, 2004). This makes their quantification an important element in understanding the dynamic processes of the movement of water and solutes in the soil. However, because of the fragile and transient nature of these pores and the lack of appropriate equipment, their characterization is difficult (Petersen et al., 2001; Messing and Jarvis, 1993). Furthermore, Yoon et al. (2007) argued that the soil porous systems are complicated, three-dimensionally structured with a variety of shapes, sizes and connectivities and the appropriate experimental equipment and conventional methods available for analyzing soil structure are costly and time-demanding.

Two experimental approaches are available for the determination of soil pore sizes and their distribution; the forced fluid intrusion and water desorption methods. Detailed descriptions of these methods are provided by Yoon et al. (2007). Lately, a tension disc infiltrometer, one of the water desorption techniques, has proven useful for quantifying the effects of macropores and preferential flow paths in the field with minimum disturbance of the soil structure (Watson and Luxmoore, 1986; Wilson and Luxmoore, 1988; Ankeny et al., 1991; Cameira, 2003; Eynard et al., 2004; Reynolds and Elrick, 2005; Ramos et al., 2006; Yoon et al., 2007; Moret and Arrúe, 2007a). According to Ankeny et al. (1991), this apparatus operates in the near-zero soil water pressure head range, where the soil pores are highly hydraulically active in the transmission of water and solutes. In this method, a sequence of steady state flow rates through the soil is measured by setting a series of tensions imposed on the soil surface. The change in water level inside the supply column may be observed manually and the time taken to fall through a prescribed height is recorded (xref. Chapter 4, Section 4.2.2.1) or automatically recorded by fitting an automatic differential pressure transducer and the drop in height of the water column after a prescribed period of time is recorded (e.g. Zhou et al., 2008). This is then converted to a volumetric inflow rate.

Both analytical (Ankeny et al., 1991; Bodhinayake et al., 2004) and numerical (Šimůnek and van Genuchten, 1996) methods are available to obtain hydraulic properties from tension disc infiltrometer data (xref. Chapter 4, Section 4.2.3). To estimate the pores sizes, the soil pores are likened to cylinders and therefore their sizes are described on the basis of "equivalent diameters"[19]. The pore radius for a given tension range is then used to compute the number of effective pores per unit area using the Poiseuille's law for flow in a capillary tube (Watson and Luxmoore, 1986; Wilson and Luxmoore, 1988; Dunn and Philip, 1991). According to Bodhinayake et al. (2004), this approach assumed a single pore size, which is likely to lead to incorrect water-conducting porosity, an unrealistic parameterization of soil properties, and poor performance of hydrological models. Other workers who voiced similar sentiments include White and Sully (1987), Ankeny et al. (1991); Reynolds et al. (1995); Reynolds and Elrick (2005); and Moret and Arrúe (2007a).

Although many studies (e.g. Ankeny et al., 1991; Logsdon et al., 1993; Cameira, 2003; Reynolds and Elrick, 2005; Ramos et al., 2006; Moret and Arrúe, 2007a) have shown that the tension disc infiltrometer is a useful tool to describe water flow through the soil profile, no further attempts have been made to relate the acquired data to pore size distribution and soil water retention that this study is aware of. Field and laboratory techniques to determine soil water retention characteristics have been documented by Bruce and Luxmore (1986) and Klute (1986), respectively. Instruments used in the field measurements have been discussed by Gardener (1986), Cassel and Klute (1986), Rawlins and Campbell (1986) and Campbell and Gee (1986), among others. In the laboratory, water retention functions are determined by establishing a series of equilibria between water in the soil sample and a body of water at known potential. According to Klute (1986), the soil water system is in hydraulic contact with the body of water through a water-wetted porous plate or medium. A single point of the retention curve is obtained when the system equilibrates and the volumetric water content of the soil is determined and paired with a value of the matric pressure head.

The hypothesis of the study was that long-term tillage systems influence pore size, pore distribution and water retention characteristics of soils. The objective of this study was to describe the management-induced temporal changes in pore size distribution and water retention in two tillage practices viz. conventional tillage (C_T) and no-till (N_T) systems which showed

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[19] According to Skopp (1981), an equivalent pore diameter is the same as that of a hypothetical cylindrical pore diameter that when saturated will pass the same flux of water as an irregularly shaped water filled pore such as is commonly found in nature.

different infiltration responses after 3 years of the same treatment (Kosgei et al., 2007; xref. Chapter 4). The specific objectives were to investigate the:

a). effects of tillage on water conducting pores and water retention; and

b). possibility of tillage-induced link(s) between hydraulic conductivity, water conducting pores and soil water retention.

6.2 Materials and methods

6.2.1 Soils

The four experimental sites, designated F_A, C_{TS}, F_C and F_B are situated in the Potshini catchment (29.37°E, 28.82°S) located in the western headwaters of the Thukela River, South Africa. Four major soil patterns[20] viz. Hutton (*Oxisols*), Avalon (*Ferralsols*), Estcourt (*Planosols*) and Mispah (*Lithosols*) soil patterns are dominant in the catchment (Smith et al., 2001). The experimental sites were concentrated in an area of about 1.2 km^2. The textural classification of the plots used was sandy clay loam with varied proportions of soil separates. Selected soil properties related to the physical and hydraulic properties (e.g. particle size, bulk density, moisture contents) were also measured (xref. Chapter 3, Section 3.3.3.2).

6.2.2 Soil measurements

At each of the four sites, steady-state infiltration measurements at the surface (D_0) and 10 cm below surface (D_{10}) were obtained using tension disc infiltrometers at three tensions: 0.5, 3 and 9 cm. A wet to dry sequence in pressure heads was adopted. The measurements were performed three times in the 2007/2008 maize (*Zea mays L.*) season at monthly intervals i.e. in December, February and April. A more detailed description of the experimental procedure, other related measurements and data processing are provided in Chapter 4.

Undisturbed core samples were taken in April from each precise site of the tension disc infiltrometer test for the laboratory determination of water retention characteristic curve. Each

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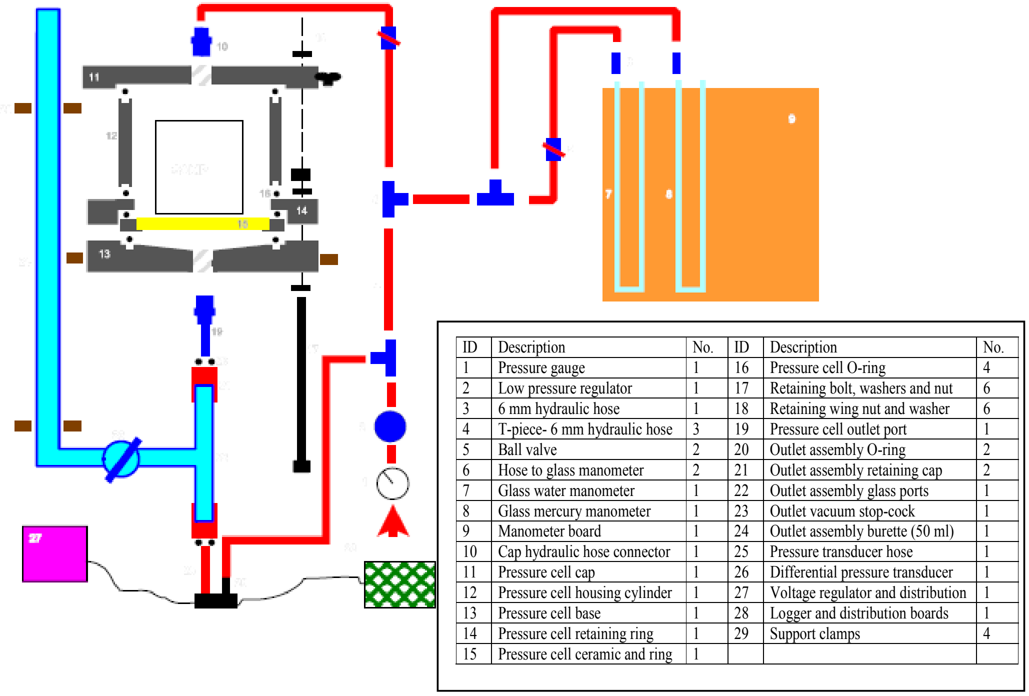
[20] FAO classification in parenthesis.

core measured 60 mm in diameter by 60 mm high. A controlled outflow method was chosen because Lorentz et al. (2001) found that this approach provided relatively accurate estimates of the characterization of soil pore structure over the range of soil moisture contents close to saturation. In addition, each point on the characteristic is determined by monitoring equilibrium of the matric pressure rather than the equilibrium of the liquid volumetric content, a procedure that enables the operator to accurately discern the time which equilibrium occurs. As a result considerable time is saved in running the test. Fig. 6.1 shows the controlled outflow cell (Lorentz et al., 2001) used in this study. The apparatus includes a data logging system to record and display the progress towards equilibrium of the matric pressure at each setting. It operates over the range water pressure range of 0 to 1000 cm.



ID	Description	No.	ID	Description	No.
1	Pressure gauge	1	16	Pressure cell O-ring	4
2	Low pressure regulator	1	17	Retaining bolt, washers and nut	6
3	6 mm hydraulic hose	1	18	Retaining wing nut and washer	6
4	T-piece- 6 mm hydraulic hose	3	19	Pressure cell outlet port	1
5	Ball valve	2	20	Outlet assembly O-ring	2
6	Hose to glass manometer	2	21	Outlet assembly retaining cap	2
7	Glass water manometer	1	22	Outlet assembly glass ports	1
8	Glass mercury manometer	1	23	Outlet vacuum stop-cock	1
9	Manometer board	1	24	Outlet assembly burette (50 ml)	1
10	Cap hydraulic hose connector	1	25	Pressure transducer hose	1
11	Pressure cell cap	1	26	Differential pressure transducer	1
12	Pressure cell housing cylinder	1	27	Voltage regulator and distribution	1
13	Pressure cell base	1	28	Logger and distribution boards	1
14	Pressure cell retaining ring	1	29	Support clamps	4
15	Pressure cell ceramic and ring	1			

Figure 6.1: Schematic of the controlled outflow cell assembly for measuring water retention characteristics of undisturbed or packed samples (Lorentz et al., 2001)

Each sample was initially fully saturated and weighed before being placed in the pressure cell housing cylinder. A circular piece of cheesecloth that fitted conveniently around and over the base of the cores was used to act as an interface and to protect the soil sample from disintegration during wetting process. After ensuring that the heights of fluid in the manometers were at the desired level and all the stopcocks fastened, the saturated porous plate was carefully placed on the base of the O-rings without trapping any air bubbles. The sample was then placed onto the porous plate, making sure that adequate hydraulic contact was established before fastening the cap.

Air pressure was applied to the cell with the out flow stopcock opened. The pressure at which drainage began was recorded. A predetermined volume of water was allowed to drain from the sample. This comprised the drainage phase and was recorded by the pressure transducer as the difference between the applied air pressure and the head of the liquid phase in the burette. The stopcock was closed and the capillary pressure was monitored over time by recording the pressure difference between the air and pore water using the differential transducer. When the transducer reading stabilized, the equilibrium pressure difference between the applied air pressure and the pore water pressure was recorded. This comprised the equilibration phase. The volume of water in the burette was then recorded. Additional points were obtained by applying successive increments of pressure until 1000 cm of pressure. The sample was then removed, weighed, dried and re-weighed.

The sample was then wetted to saturation, weighed and inserted into pressure plate apparatus set at 2000 cm of pressure. At equilibrium, when drainage ceased the pneumatic pressure in the cell is equal to but opposite sign to the matric potential. The sample was then re-weighed, wetted to saturation and re-weighed and put back into the apparatus set at a pressure of 5000 cm. After equilibrium the sample was re-weighed.

The water content at each setting of suction head was calculated as follows:

$$W_i = W_f + \frac{V_f - V_i}{M_s} \tag{6.1}$$

where:

W_i is the water content by mass at setting i (g/g);

W_f is the final water content, calculated from the wet and oven dry mass of the sample after the test is complete (g/g);

V_f is the final volume recorded in the burette after the last setting reached equilibrium (ml);

V_i is the volume recorded in the burette at setting i (ml); and

M_s is the final dry mass of the sample (g).

The volumetric water content was calculated from:

$$\theta_i = W_i \frac{\rho_b}{\rho_w} \qquad (6.2)$$

where:

θ_i is the volumetric water content at setting i ($cm^3.cm^{-3}$);

ρ_b is the dry bulk density of the soil sample ($g.cm^{-3}$); and

ρ_w is the density of water ($g.cm^{-3}$).

The capillary pressure at each setting was determined by adding the height of the column of water between the sample and the pressure transducer to the transducer reading at each setting from equilibrium.

6.2.3 Estimation of water conducting porosity

Cumulative infiltration data from 0.5, 3 and 9 cm water tensions was combined with measured values of the initial and final water contents (Šimůnek and van Genuchten, 1997) to estimate the hydraulic properties. The numerical approach (Šimůnek and van Genuchten, 1996) that uses DISC (Šimůnek et al., 2006), a computer software package that consists of simplified HYDRUS-2D programs (Šimůnek et al., 1996), was preferred to the analytical method (Wooding, 1968) because the K estimated from the latter was shown to be much higher than that from the former, suggesting that the analytical approach could have overestimated K (xref. Chapter 4). However, there is a need to do direct measurements of K to be able to discern which approach is a better estimator. The following van Genuchten-Mualem model functions (van Genuchten, 1980; Šimůnek et al., 1999) were used to approximate the hydraulic conductivity:

$$K(S_e) = K_s S_e^{\,l}\left[1-(1-S_e^{1/m})^m\right]^2 \qquad (6.3)$$

where S_e is the effective saturation [-] expressed as:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \qquad (6.4)$$

K_s is the saturated hydraulic conductivity [LT^{-1}], θ_r and θ_s denote the residual and saturated water contents [L^3L^{-3}], respectively; l is a pore-connectivity parameter [-], and m [-] is an empirical shape parameter. From a compilation of 45 soil types, l was estimated to be 0.5 by Mualem (1976). This value was adopted in this study.

The matrix flux potential ϕ_ψ [L^2T^{-1}] was defined from the derived K values at the different water pressure heads (-0.5, -3 and -9 cm) as follows:

$$\phi_\psi = \frac{K_\psi}{\alpha_\psi} \tag{6.5}$$

where ψ [L] is the applied pressure head, K_ψ [LT^{-1}] is the hydraulic conductivity and α_ψ [L^{-1}] is the slope of the ln K versus ψ curve (Ankeny, 1991).

From the classical capillary rise theory, the maximum equivalent pore radius (EPR), λ_0 [L] that remains full of water under an applied pore water pressure is defined as:

$$\lambda_0 = \frac{2\sigma}{\rho g \psi} \qquad \psi < 0 \tag{6.6}$$

where σ is the surface tension of water [MT^{-2}], ρ is the density of water [ML^{-3}], g is the acceleration due to gravity [LT^{-2}].

White and Sully (1987) defined a mean pore radius which according to Ankeny (1991) is calculated as follows:

$$\lambda_\psi = \frac{\sigma K_\psi}{\rho g \phi} \tag{6.7}$$

where ϕ is the matrix flux potential, calculated according to Eq. 6.5.

The number of λ_ψ pores per unit area of infiltration surface, N_ψ, required to produce the measured K was estimated by:

$$N_\psi = \frac{8\mu K_\psi}{\rho g \pi \lambda_\psi{}^4} \tag{6.8}$$

where μ is the dynamic viscosity of water ($ML^{-1}T^{-1}$).

The “representative mean pore radius (MPR), $\lambda_{\Delta\psi}$, for two consecutive tensions” index, was calculated as follows:

$$\lambda_{\Delta\psi} = \frac{\sigma(K_{\psi_i} - K_{\psi i-1})}{\rho g(\phi_{\psi\, i} - \phi_{\psi\, i-1})} \quad i = 1, 2, \ldots\ldots, n \qquad (6.9)$$

where $K_{\psi\, i}$ and $K_{\psi\, i\text{-}1}$ the hydraulic conductivity for two consecutive tensions and n is the number of measurements performed in a sequence.

The number of $\lambda_{\Delta\psi}$ pores per unit area of infiltration surface, $N_{\Delta\psi}$, required to produce the measured K was estimated using Poiseuille's law for flow in a capillary tube as:

$$N_{\Delta\psi} = \frac{8\mu(K_{\psi\, i} - K_{\psi\, i-1})}{\rho g \pi(\lambda_{\Delta\psi})^4} \qquad i = 1, 2, \ldots\ldots, n \qquad (6.10)$$

The effective porosity, defined as the portion of the soil volume corresponding to pores with water (Cameira et al., 2003), between any two consecutive soil water tensions, $\theta_{\Delta\psi}$, was then given by the expression:

$$\theta_{\Delta\psi} = \mathrm{N}_{\Delta\psi}\pi(\lambda_{\Delta\psi})^2 \qquad (6.11)$$

According to Watson and Luxmoore (1986), Cameira et al. (2003) and Moret and Arrúe (2007a) the contribution of both macropores and mesopores to the total saturated water flux, φ, was estimated from $K_{0.5}$, K_3 and K_9, used a pair at a time, as:

$$\varphi_i(\%) = \frac{K_{\psi\, i} - K_{\psi\, i-1}}{K_s} * 100 \qquad i = 1, 2 \qquad (6.12)$$

where K_s is the saturated hydraulic conductivity. For every test the $K(\psi)$ was interpolated from the hydraulic function derived from DISC (HYDRUS-2D) using VGM characteristic curve at each pressure head. According to Malone et al. (2003) this approach assumes laminar flow, macropores are completely full and not interconnected, and turtosity and pore necks are insignificant. As a result, the resulting parameters are only equivalent values and not a true pore volume fraction.

6.2.4 Water retention characteristics

The van Genuchten model (van Genuchten, 1980) was used to describe the WRCC.

$$\theta(\psi) = \theta_r + \frac{\theta_s - \theta_r}{\left(1 + |\alpha\psi|^n\right)^m} \qquad \psi < 0 \qquad (6.13)$$

$$\theta(\psi) = \theta_s \qquad \psi \geq= 0$$

where θ (L^3L^{-3}) is the volumetric water content, ψ is the pressure head (L), θ_r and θ_s denote the residual and saturated water contents [L^3L^{-3}], respectively; α [L^{-1}], n [-] and m (=1-1/n) [-] are empirical shape parameters. Eq. 6.13 was fitted to the soil water retention data using a HYDRUS-2D component - RETC (version 6) software (van Genuchten et al., 1991).

6.3 Results and discussion

6.3.1 Hydraulic conductivity, mean pore radius (MPR) and number of pores per unit area of infiltration surface

Measurements of soil hydraulic conductivity (K) on the soil surface (D_0) and at a depth of 10 cm below surface (D_{10}) are summarized in Fig. 6.2. As expected, in all circumstances the values of K reduced as ψ decreased. The slope was higher between 3 cm and 9 cm tension compared to that between 0.5 cm and 3 cm, suggesting that the difference between the hydraulic parameters at 0.5 cm tension to those at 3 cm tension were closer as compared to the parameters between 3 cm and 9 cm. In addition, there was more variability in the observations at 0.5 cm tension than at 3 cm and 9 cm. In December, the average $K_{0.5}$ values in C_T were higher in relation to N_T at depth D_0 at all sites except F_C. The exact opposite was true at depth D_{10}. At K_3 and K_9, half of the sites had higher K in N_T relative to C_T. The higher K in C_T at this time of the season was generally attributed to the loosening of the soil surface during tillage which creates more pore space that enhances water entry and movement. In February, for ψ = -0.5 cm, K values on the surface were still higher in C_T plots at sites F_B and F_C while at $K_{9,}$ K values from C_T plots were higher at sites F_B and F_A in comparison to N_T plots. By April two sites, F_A and F_C had higher K in N_T relative to C_T. Thus, the responses had no particular trend. Similar observations were made at depth D_{10}.

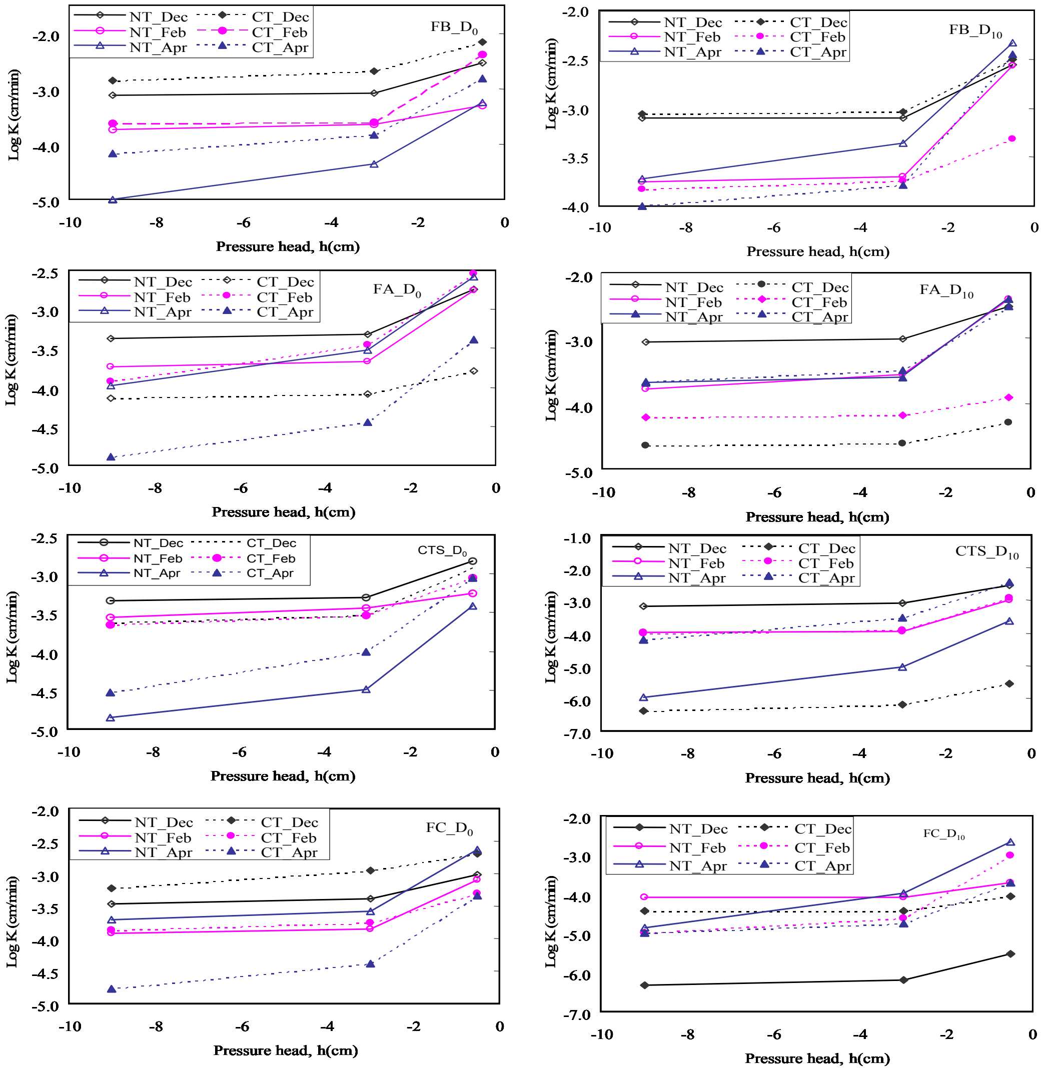


Figure 6.2: Soil hydraulic conductivity (K) vs. pressure head (ψ) relationship derived from DISC (HYDRUS-2D) using VGM characteristics for all sites during the three measurement periods) at the two depths. Pressure heads of -0.5, -3 and -9 cm water were used

Significant differences in K values between measurement periods and depths were observed at site F_C. In December, K values at depth D_0 significantly differed with values at depth D_{10} with p-values of 0.043 and 0.047 in N_T and C_T plots, respectively. In N_T plots K values at depth D_{10} in December differed significantly (p=0.037) with those obtained in February. At depth D_{10}, there was a significant difference (p=0.032) between tillage systems in December. As the tension increased from 0.5 cm to 9 cm, the mean K values decreased at both depths by an average of 16, 22 and 36 times in N_T plots in December, February and April, respectively. The corresponding values in C_T plots were 16, 21 and 32. Table 1 provides a summary of the number of times K_9 is lower than $K_{0.5}$.

Table 6.1: Number of times K values reduced as tension was increased from 0.5 cm to 9 cm

	Depth	D_0			D_{10}		
Site	Tillage	December	February	April	December	February	April
F_B	N_T	17.0	13.5	34.7	16.6	28.8	39.8
	C_T	20.9	20.9	30.2	16.6	16.6	42.7
F_A	N_T	17.0	22.9	35.5	16.6	38.0	33.9
	C_T	12.3	35.5	28.2	12.0	12.0	28.8
C_{TS}	N_T	15.1	38.0	26.3	17.4	21.4	44.7
	C_T	17.4	15.9	30.2	14.1	22.9	53.7
F_C	N_T	14.1	18.6	25.7	13.8	12.6	64.6
	C_T	25.1	14.8	30.2	12.3	44.7	21.9

The general trend from Table 6.1 is an increase in magnitude of the difference from December to April. Regardless of the tillage system, decreases in K between $K_{0.5}$ and K_9 of over 25 times were observed in February and April. This result is lower than that reported by Reynolds et al. (1995) of 79-250 times which was attributed to presence of extensive soil macropore networks. In the present study, the response due to tillage was not entirely consistent in all sites. Perhaps some sites had better macropore networks than others. This will be apparent in the following sections.

The hydraulic conductivity of a soil is influenced by sorptivity (conduction of water by capillary forces) and pore size (conduction of water by Poiseulle tube flow) and thus implies that pore dimensions and geometry plays a significant role in the overall infiltration process. Tillage has been shown to influence K. Hence, in the present study an attempt was made to capture the relationship between observed K and pore dimensions and the number of pores per unit area of infiltration surface. Because EPR defines a 'maximum' equivalent pore radius for water storage and $\lambda_{\Delta\psi}$ defines an 'average' equivalent pore radius for water transmission (Reynolds et al., 1995; Moret and Arrúe, 2007a), the latter was regarded a better estimator of water fluxes and potential storage. Average K, $\lambda_{\Delta\psi}$ and $N_{\Delta\psi}$ values are provided in Table 6.2.

Table 6.2: Average values of hydraulic conductivity (K), representative mean pore radius ($\lambda_{\Delta\psi}$) and number of $\lambda_{\Delta\psi}$ pores per unit area of infiltration surface ($N_{\Delta\psi}$) that produced the measured K

Depth	Parameter	N_T			C_T		
		Dec	Feb	Apr	Dec	Feb	Apr
D_0	$K (\times 10^{-4} cm.min^{-1})$	6.00	6.76	7.87	7.25	4.67	3.75
	$\lambda_{\Delta\psi} (\times 10^{-2} cm)$	7.92	8.01	8.15	8.46	8.19	7.88
	$N_{\Delta\psi} (\times 10^{-2}$ pores.cm$^{-2})$	8.35	2.89	2.11	2.17	2.80	2.41
D_{10}	$K (\times 10^{-4} cm.min^{-1})$	5.33	7.88	8.67	2.33	1.46	1.33
	$\lambda_{\Delta\psi} (\times 10^{-2} cm)$	7.95	8.55	9.10	6.78	5.45	4.20
	$N_{\Delta\psi} (\times 10^{-2}$ pores.cm$^{-2})$	6.79	4.97	2.91	4.80	4.93	5.29

From Table 6.2, although the response from the different sites varied, tillage had an influence on both $\lambda_{\Delta\psi}$ and $N_{\Delta\psi}$. In N_T treatments, $\lambda_{\Delta\psi}$ increased progressively from a lower value in December to a maximum in April while in C_T the maximum was observed in December. There was a corresponding decrease $N_{\Delta\psi}$ in N_T across the measurement dates while an increase was observed in C_T. This observation was similar to findings of Kooistra et al. (1984) and Malone et al. (2003) who pointed out that tillage produces disconnected macroporosity while increasing the number of smaller pores. In this study, there were no significant differences in $\lambda_{\Delta\psi}$ between tillage practices, period in the season as well as at different depths. However, significant differences in $N_{\Delta\psi}$ were observed in February from N_T plots between site C_{TS} and the rest of the sites i.e. F_B ($p<0.013$), F_A ($p<0.036$) and F_C ($p<0.014$).

6.3.2 Pore classification: macropores and mesopores

Following the procedure outlined by Ankeny et al. (1991), the applied pressure heads of -0.5, -3 and -9 cm result in mean pressure heads of -1.75 cm and -6 cm. Using the mean pressure heads and capillary theory, this study defined macropores as those pores with a pore radius >0.086 cm while mesopores as those having pore radius between 0.086 and 0.025 cm. Using this classification, the average number of $\lambda_{\Delta\psi}$ macro- and mesopores per unit area of infiltration surface ($N_{\Delta\psi}$) required to produce the measured K were estimated. A summary is provided by Fig. 6.6. In general, there was a greater number of mesopores compared to that of macropores. The maximum $N_{\Delta\psi}$ of the pores varied considerably among the field sites, depths and measurement periods. Mesopores ranged between a minimum of about 4.0×10^{-14} pores.cm^{-2} to a maximum of about 1.34 pores.cm^{-2}. Macropores ranged between 1.3×10^{-7} pores.cm^{-2} and 1.0×10^{-1} pores.cm^{-2}. These findings are similar to those of Reynolds et al. (1995) who reported considerably more mesopores in three N_T soils than in mouldboard ploughed soils.

The presence of larger $\lambda_{\Delta\psi}$ pores in N_T soils may be as a result of a greater number of persistent cracks, worm holes or root channels that gradually accumulate year-to-year as they are not destroyed by annual tillage (Reynolds et al., 1995). However, a higher silt fraction produces soil structural fragility when external stresses from weather occur because of its high content of biotic material (Cosentino and Pecorari, 2002 in Sasal et al., 2006). This could have been the situation at site C_{TS} in which by April there was higher K (Fig. 6.2) and more macropores and mesopores (Fig. 6.3) in C_T plots than at N_T plots. Thus, C_T plots at this site were regarded better from a water management perspective. Conversely, N_T is recommended for site F_A and F_C as they steadily showed more macropores and mesopores than in C_T plots. Information on soil texture is provided in Table 6.3.

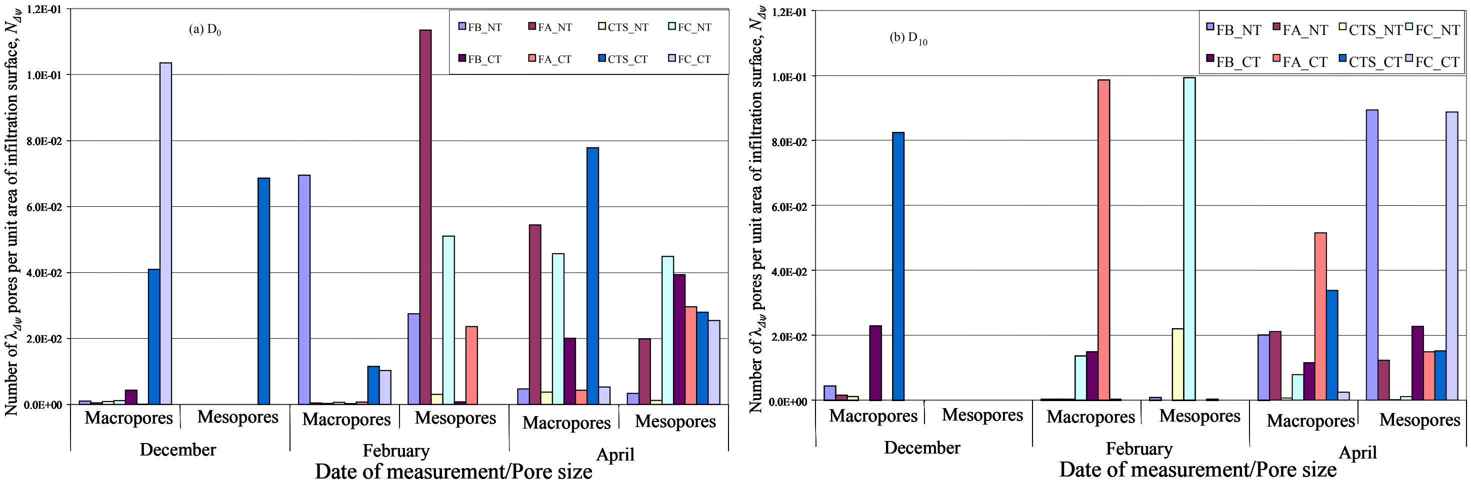


Figure 6.3: Average number of $\lambda_{\Delta\psi}$ macro- and mesopores per unit area of infiltration surface ($N_{\Delta\psi}$) required to produce the measured K at (a) depth D_0 and (b) depth D_{10} in N_T and C_T plots at the four sites in Potshini during three dates of measurement

6.3.3 Effective porosity ($\theta_{\Delta\psi}$) and contribution of macropores and mesopores to water flow (φ_i)

The pore volume occupied by the pore fluid that can circulate through the porous medium is smaller than the total pore space, and, consequently, the effective porosity is always smaller than the total porosity. In this section, effective porosity is expressed as a percentage of total porosity given in Table 6.3.

Table 6.3: Porosities from N_T and C_T plots at two depths during the three measurement periods in the four experimental sites in Potshini catchment. Soil texture at the trials sites is also included

Depth	Site	F_B		F_A		C_{TS}		F_C	
	Tillage	N_T	C_T	N_T	C_T	N_T	C_T	N_T	C_T
0 cm	December	0.537	0.568	0.555	0.578	0.483	0.532	0.397	0.400
	February	0.540	0.567	0.519	0.567	0.462	0.483	0.340	0.316
	April	0.512	0.519	0.580	0.543	0.415	0.458	0.368	0.377
10 cm	December	0.591	0.542	0.600	0.560	0.479	0.494	0.374	0.413
	February	0.561	0.535	0.531	0.529	0.428	0.415	0.325	0.362
	April	0.576	0.530	0.542	0.494	0.394	0.384	0.312	0.350
Soil texture	Sand (%)	68.3		72.2		66.2		65.2	
	Silt (%)	10.5		7.2		11.2		8.4	
	Clay (%)	21.2		20.6		22.6		25.4	

Tables 6.4(a) and 6.4(b) contain summarized values of effective porosity, $\theta_{\Delta\psi}$ (%) calculated as a percentage of total porosity for each pore class at depth D_0 (Fig. 6.4a) and D_{10} (Fig. 6.4b). In N_T plots, macropores at depth D_0 represented an average of 0.02%, 0.006% and 0.002% of the total porosity in December, February and April, respectively while mesopores constituted an average of 33.7%, 3.8% and 0.35% of the total porosity during the respective measurement periods. The corresponding average values of macropores at depth D_{10} were 0.02%, 0.003% and 0.002%, respectively and mesopores represented 32.5%, 28.5% and 1.5% of the total porosity, respectively. Under C_T plots at depth D_0 macropores constituted 0.86%, 0.006% and 0.001% while mesopores comprised 0.01%, 5.7% and 0.01% of the total porosity in December, February and April, respectively. At depth D_{10}, the average proportion of macropores to the total porosity was 1.5%, 0.004% and 0.003% in December, February and April. In these treatments the mean proportion of mesopores to the total porosity was 0.006%, 0.05% and 0.14%, respectively. As shown in Tables 6.3(a) and 6.3(b) the proportion of the pores to the total porosity in some sites was very small. In general, the results indicated that the macropores defined represented a very small proportion of the total porosity of soils in Potshini catchment

relative to mesopores. This is consistent with findings of other studies (e.g. Moret and Arrúe, 2007a; Cameira et al., 2003; Reynolds et al., 1995).

Table 6.4(a): Effective porosity between each set of consecutive soil water tensions ($\theta_{\Delta\psi}$) on the soil surface (D_0)

Tillage system	Plot	December		February		April	
		Macropores	Mesopores	Macropores	Mesopores	Macropores	Mesopores
No-till (N_T)	F_B	0.019	66.996	0.013	3.030	0.000	0.001
	F_A	0.009	26.921	0.003	5.699	0.003	0.017
	C_{TS}	0.017	33.191	0.005	1.779	0.000	0.006
	F_C	0.028	7.555	0.003	4.880	0.004	1.365
Conve-ntional tillage (C_T)	F_B	0.076	0.001	0.003	0.000	0.002	0.026
	F_A	0.000	0.002	0.004	22.749	0.000	0.002
	C_{TS}	0.770	0.000	0.009	0.000	0.001	0.005
	F_C	2.593	0.053	0.009	0.002	0.001	0.006

Table 6.4(a): Effective porosity between each set of consecutive soil water tensions ($\theta_{\Delta\psi}$) at 10 cm below surface (D_{10})

Tillage system	Plot	December		February		April	
		Macropores	Mesopores	Macropores	Mesopores	Macropores	Mesopores
No-till (N_T)	F_B	0.016	89.697	0.002	8.739	0.004	0.051
	F_A	0.024	32.818	0.003	0.146	0.003	6.111
	C_{TS}	0.023	7.495	0.002	17.539	0.000	0.000
	F_C	0.000	0.003	0.006	87.562	0.002	0.002
Conve-ntional tillage (C_T)	F_B	4.209	0.000	0.006	0.000	0.002	0.115
	F_A	0.000	0.025	0.007	0.001	0.004	0.412
	C_{TS}	1.667	0.000	0.002	0.000	0.004	0.008
	F_C	0.000	0.000	0.000	0.184	0.000	0.012

The above discussion shows that macro- and mesoporosity decrease from December to April and that the total porosity (Table 6.3) did not significantly change between the same dates. This does not explain the observed changes in K and yet in Section 6.3.1 and 6.3.2, mean pore radii were shown to increase. However, the observed increase in pore radii may not have been a physical increase in radii but perhaps a change in pore size distribution and improved geometry of the pores that resulted to continuous and less tortuous pores that increased hydraulic conductivity.

The contribution of each pore class to the total flow is illustrated in Table 6.5(a) and 6.5(b).

Table 6.5(a): The percent contribution of different pores to the total saturated water flux (φ_i) between each set of consecutive water tensions on the soil surface (D_0)

Tillage system	Plot	December		February		April	
		Macropores	Mesopores	Macropores	Mesopores	Macropores	Mesopores
No-till (N_T)	F_B	94.636	3.714	98.175	13.869	91.875	5.964
	F_A	90.571	5.528	86.389	1.687	88.348	7.381
	C_{TS}	94.171	1.342	91.692	1.535	89.071	4.542
	F_C	87.061	3.714	80.812	2.583	96.228	3.036
Conventional tillage (C_T)	F_B	88.214	11.459	85.965	0.200	89.788	5.010
	F_A	91.236	8.202	87.196	7.977	88.462	5.291
	C_{TS}	92.589	5.685	87.088	10.187	87.500	7.791
	F_C	87.845	12.087	88.674	10.773	89.366	5.159

Table 6.5(b): The percent contribution of different pores to the total saturated water flux (φ_i) between each set of consecutive water tensions at 10 cm below Surface (D_{10})

Tillage system	Plot	December		February		April	
		Macropores	Mesopores	Macropores	Mesopores	Macropores	Mesopores
No-till (N_T)	F_B	98.950	0.850	90.873	0.873	89.792	5.316
	F_A	93.409	5.682	90.707	2.854	93.084	0.877
	C_{TS}	91.921	7.895	88.306	1.008	88.605	3.233
	F_C	93.000	7.083	98.448	0.948	90.251	4.201
Conventional tillage (C_T)	F_B	96.304	2.565	90.029	9.677	94.621	1.784
	F_A	90.893	8.393	91.290	7.903	87.970	3.510
	C_{TS}	89.280	9.600	90.973	1.770	91.006	6.307
	F_C	95.714	3.878	92.930	1.440	87.100	3.850

At depth D_0 in N_T plots, an average of 93%, 89% and 91% of the water flux was conducted through macropores in December, February and April, respectively while 6.1%, 4.9% and 5.2% were the respective proportions through mesopores. In C_T plots, the percentage of water conducted through macropores in December, February and April was 90%, 87% and 89%, respectively while that conducted through mesopores was 9.4%, 7.3% and 5.8%, respectively. A similar trend was observed at depth D_{10} although macropores in C_T plots conducted an average of over 90% of the water fluxes. These results indicated that soil macropores have a higher influence on water flow than mesopores, even though they were a much smaller fraction of the total soil water-conducting porosity. Similar findings were reported by Wilson and Luxmoore (1988), Cameira et al. (2003) and Moret and Arrúe (2007a).

6.3.4 Water retention characteristics

Fig. 6.4 illustrates the measured and fitted (using RETC) water content relationships at water pressure heads of 0-5000 cm. Due to equipment breakdown, no measurements were done on all samples from C_{TS} and F_C at depth D_{10}. In most cases, the correspondence between the van Genuchten predicted and the measured values was good. The predictions were better (higher R^2) in N_T plots relative to C_T plots except at site F_A at depth D_{10}. The average absolute error on the wetter end (< 1000 cm) of the WRCC was 1.7% and 1.4% of the measured θ ($cm^3.cm^{-3}$) in N_T and C_T plots, respectively. The drier end (>2000 cm) of the WRCC was fairly predicted leading to average absolute errors of 2.5% and 2.7% of the measured θ ($cm^3.cm^{-3}$) in N_T and C_T plots, respectively.

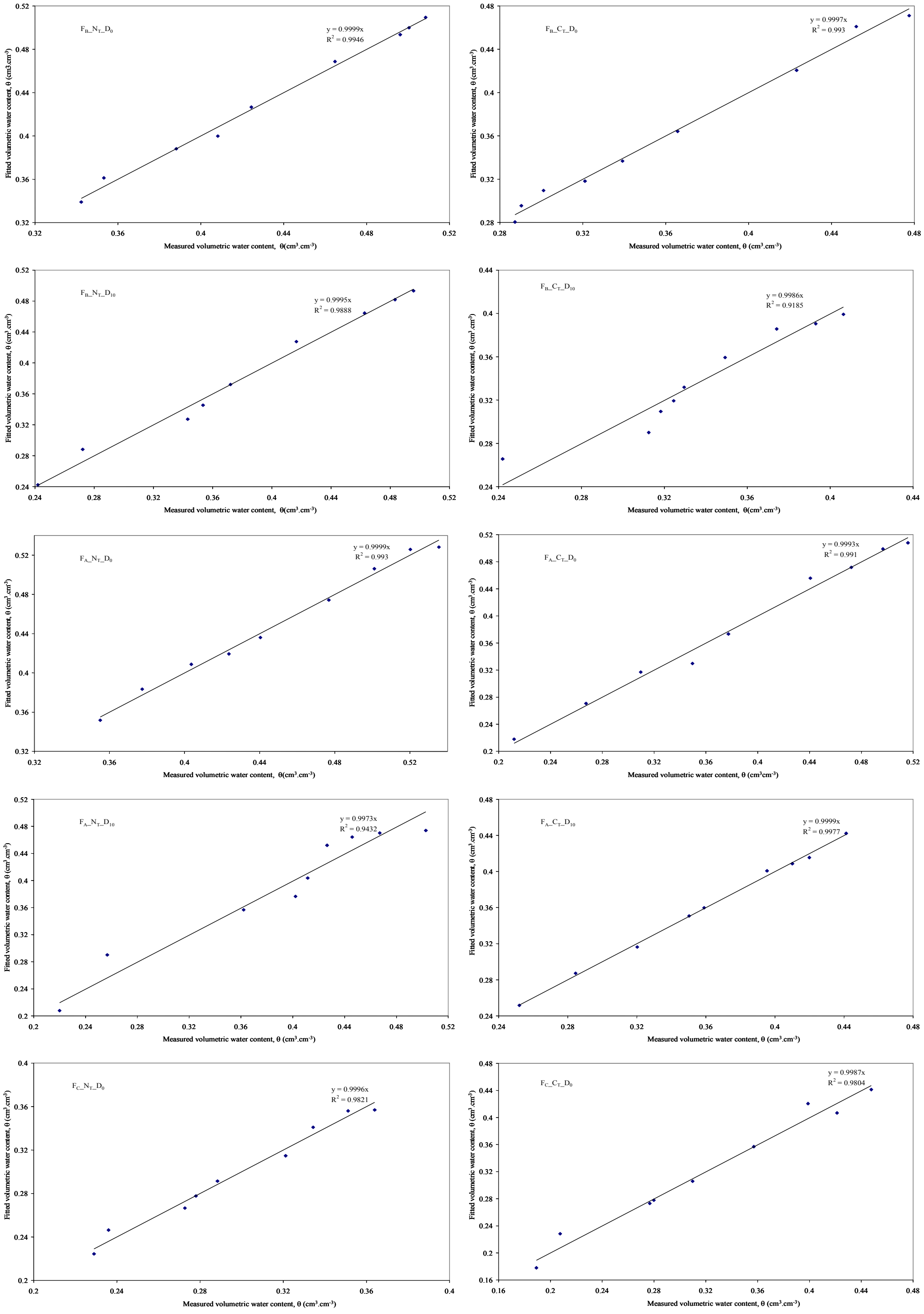


Figure 6.4: Laboratory measured and fitted water content between 0-5000 cm pressure head

Bescansa et al. (2006) argued that in semi-arid environments soils remain below field capacity for most of the growing season. However, in some areas the erratic nature of rainfall and limited arable land has necessitated crop production on poor soils and wetlands which require the extension of knowledge to water contents near-saturation (~0 cm) as opposed to the conventional approach of field capacity (-330 cm) to wilting point (-15000 cm) only. The WRCCs over the entire range fitted using RETC are provided in Fig. 6.5 - Fig. 6.7. From the varied responses, it was deduced that tillage system influences water storage.

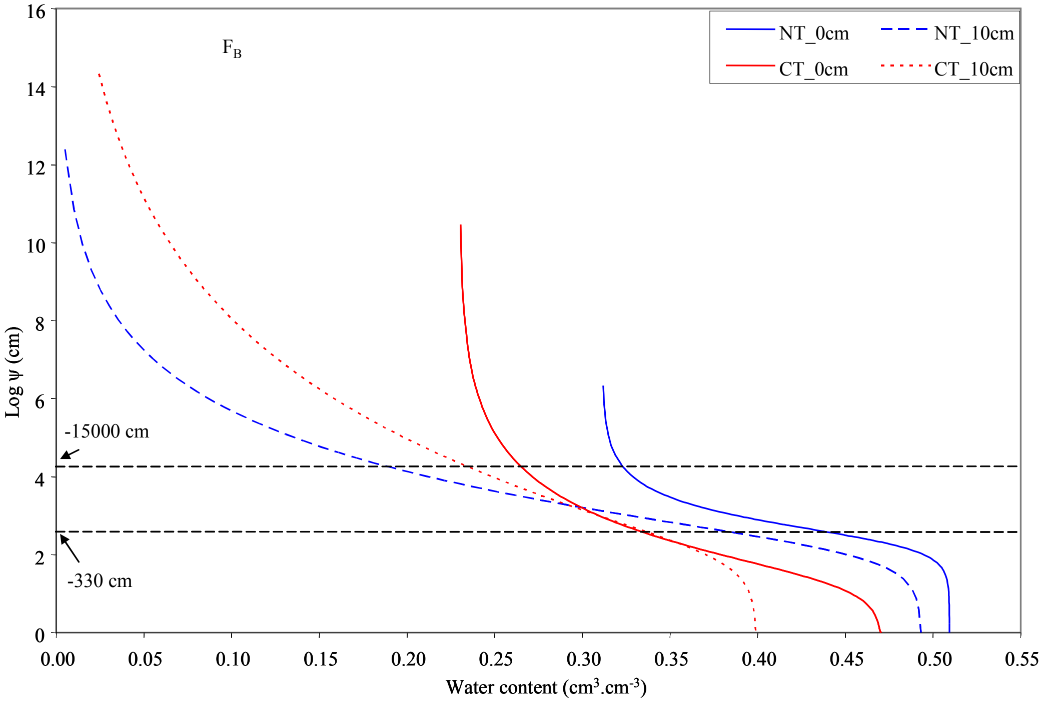


Figure 6.5: WRCCs fitted using RETC for site F_B derived from soil samples collected in April. The dotted horizontal lines show the adopted field capacity (-330 cm) and wilting point (-15000 cm)

At site F_B the two tillage systems resulted into different characteristic curves indicating that tillage influences water retention in the soil because of changes in pore properties as discussed earlier. At higher water content e.g. >0.35 $cm^3.cm^{-3}$, the water retention was much higher in N_T compared to C_T. The water content (θ) at the adopted field capacity (FC) was higher in N_T by 24.4% and 13.5% compared to C_T at depth D_0 and D_{10}, respectively (Table 6.6). This suggests that N_T treatments have a higher capacity to hold water near FC and thus, in terms of crop production, these treatments are likely to have increased biomass as compared with the C_T treatments (xref. Chapter 8) when there is adequate rainfall. At lower water content, the curve of

N_T at depth D_0 approached the adopted wilting point (-15000 cm) more rapidly than the other curves an indication that in case of early season dry spells (when plant roots are still not beyond 10 cm), plants in N_T plots will be affected most. However, if these spells occur after the plants roots are well developed and are deeper than 10 cm, their effects will affect C_T treatments more than N_T because there is still some available moisture below 0.2 $cm^3.cm^{-3}$ in N_T plots. The lowest θ at wilting point was recorded in N_T at depth D_{10} which was 20.1% lower than in C_T an indication that the available water content (AWC) was higher in N_T relative to C_T at this depth.

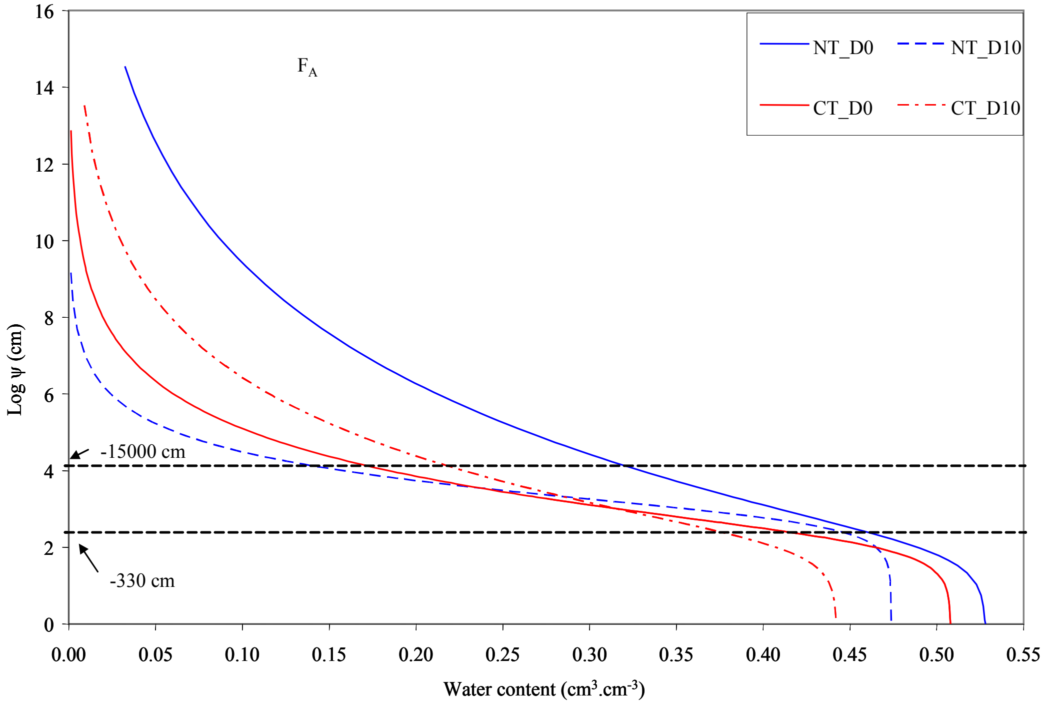


Figure 6.6: WRCCs fitted using RETC for site F_A derived from soil samples collected in April. The dotted horizontal lines show the adopted field capacity (-330 cm) and wilting point (-15000 cm)

As was the case at site F_B, N_T treatments at site F_A (Fig. 6.6 and Table 6.6) had higher θ than in C_T at both depths. At field capacity N_T had 12.1% and 16.2% higher θ at depth D_0 and at D_{10}, respectively than at C_T. Bescansa et al. (2006) reported similar findings. However, at depth D_0 there was about 47.5% higher θ at wilting point in N_T relative to C_T which indicates that N_T held more unavailable water at this depth. The reverse was observed at depth D_{10} where approximately 39.3% higher θ in C_T compared to N_T was observed. At lower θ the differences reduced and at around θ = 0.28 $cm^3.cm^{-3}$, the water retention was similar in N_T at D_{10} and in C_T

at both depths. This suggests that if θ remains at this range for a substantial period of time in the season, differences in generated fluxes and biomass between N_T and C_T could be negligible. Furthermore at this range there is no available water at depth D_0 in N_T which implies that biomass could be affected (xref. Chapter 8).

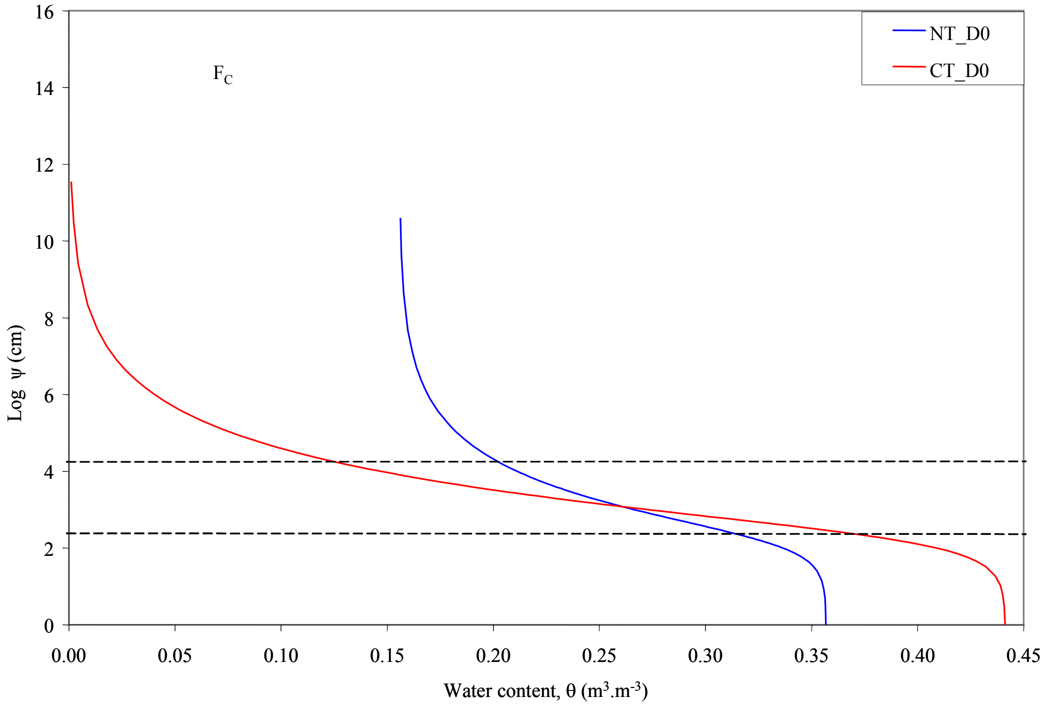


Figure 6.7: WRCCs fitted using RETC for site Fc derived from soil samples collected in April. The dotted horizontal lines show the adopted field capacity (-330 cm) and wilting point (-15000 cm)

Table 6.6: Soil water retention characteristics for three experimental sites derived from samples collected in April 2008 in Potshini catchment

Depth	Site	F_B		F_A		F_C	
	ϕ_ψ (cm) /Tillage	N_T	C_T	N_T	C_T	N_T	C_T
D_0	0	0.509	0.471	0.528	0.508	0.357	0.441
	-330	0.447	0.338	0.450	0.396	0.304	0.349
	-2000	0.360	0.294	0.383	0.269	0.246	0.229
	-15000	0.324	0.267	0.316	0.166	0.205	0.131
D_{10}	0	0.493	0.399	0.474	0.442	-	-
	-330	0.393	0.340	0.433	0.363	-	-
	-2000	0.287	0.289	0.290	0.287	-	-
	-15000	0.191	0.239	0.133	0.214	-	-

At site F_C (Fig. 6.7) where only samples at depth D_0 were analysed, at field capacity C_T had 12.9% higher θ compared to N_T. At wilting point, N_T contained 36.1% higher θ relative to C_T. The average θ at depth D_0 in N_T treatments at site F_C was significantly lower ($p<0.05$) from that at F_B and F_A. Due to equipment (flow-cell assembly) failure, the samples at depth D_{10} and those from site C_{TS} were not analyzed.

A comparison of the water contents at 0, 330, 2000 and 5000 cm tensions as affected by tillage is provided in Fig. 6.8. Table 6.6 shows that except at site F_C, the water content at saturation (~0 cm) was higher in N_T, an indication that conventional tillage lowers θ near saturation. From Fig. 11 all points to the right of the 1:1 line represent cases where θ was higher in N_T relative to C_T, and vice versa. At depth D_0, sites F_A and F_B had higher θ in N_T on the entire range of WRCCs, a suggestion that N_T systems store more water. At depth D_{10}, the θ at -2000 cm was approximately the pivot; at lower matric potential (-15000 cm) C_T had higherθ, while at -330 cm and 0 cm, higher θ was obtained in N_T. This suggested that more moisture was likely to be stored in C_T at matric potential close to wilting point, thus making them more suited to semi-arid agriculture. However, N_T had higher θ at depth D_0 at tensions higher than 2000 cm at all sites, suggesting N_T plots are likely to support a robust growth in crops than C_T treatments can. However, a decision on which system of tillage is better can only be made after estimating the plant available water content (AWC). In this study, AWC was assumed as the difference between θ at the assumed field capacity (-330 cm) and at wilting point (-15000 cm). The plant AWC at the three sites is shown in Fig. 6.9.

As seen in Fig. 6.9, the AWC was influenced by depth of measurement, tillage and site conditions (soil texture). At depth D_0, average AWC was higher in C_T relative to N_T at sites F_A and F_C. The two sites from which samples at D_{10} were analyzed showed an agreement of higher AWC in N_T compared to C_T. This was related to an improved pore size distribution of pores that does not drain fast e.g. mesopores but also presence of macropores at depth D_0 that enhance water infiltration and distribution. The 0.099 $cm^3.cm^{-3}$ and 0.218 $cm^3.cm^{-3}$ AWC values in N_T and C_T, respectively at site F_C suggested that the most appropriate method of land preparation at this site is conventional tillage whereas the other sites favoured no-till. Thus, knowledge of AWC plays a significant role in decisions regarding suitable tillage systems.

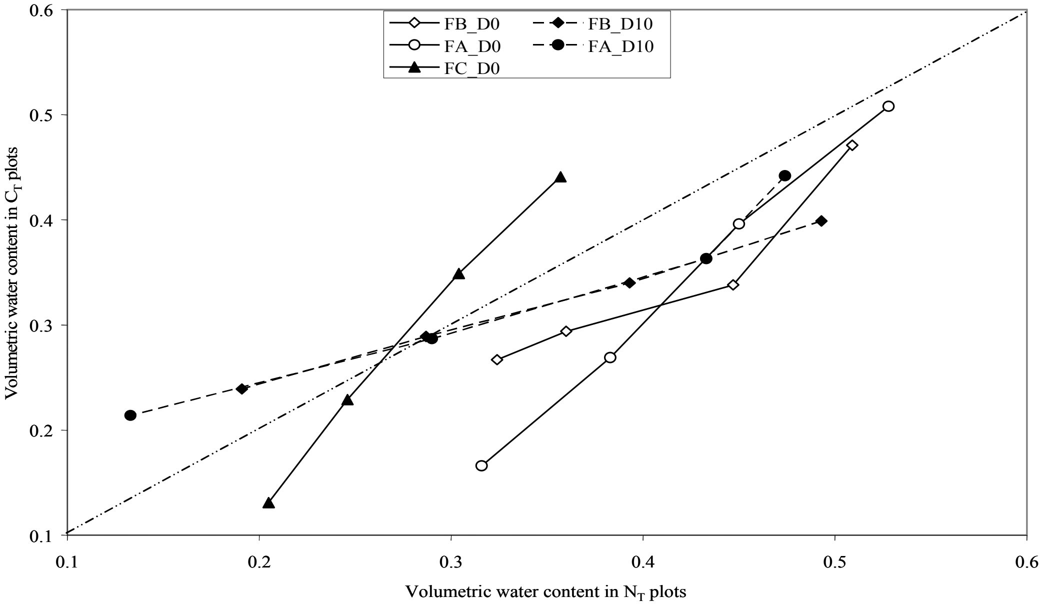


Figure 6.8: Correlation between the θ ($cm^3.cm^{-3}$) in N_T and C_T plots derived from soil samples collected in April at three sites in the Potshini catchment (at 0, 330, 2000 and 5000 cm tensions)

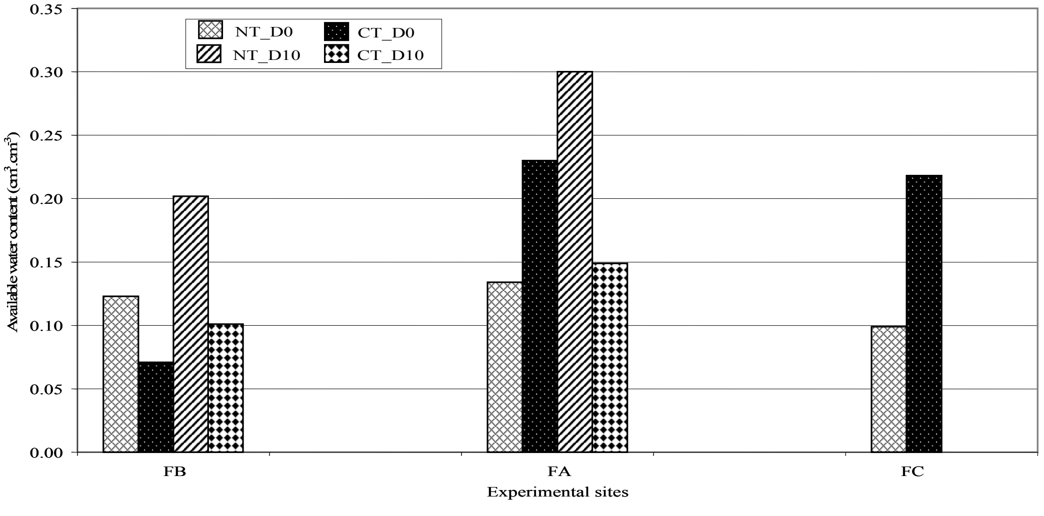


Figure 6.9: Plant available water stored in the soil ($cm^3.cm^{-3}$) at three experimental sites in Potshini catchment

A summary of the potential influence on water fluxes and plant water uptake of dominant changes to hydraulic properties resulting from tillage is given in Table 6.7.

Table 6.7: A summary of the potential influence on water fluxes and plant water uptake of dominant changes to hydraulic properties resulting from tillage. This covers results from Chapter 4 to Chapter 6.

Parameter	Influence on water partitioning and plant water uptake	CT						NT					
		December		February		April		December		February		April	
		D_0	D_{10}	D_0	D_{10}	D_0	D_{10}	D_0	D_{10}	D_0	D_{10}	D_0	D_{10}
Gravimetric soil moisture content (%)	The higher the soil moisture the higher is the potential of plant water uptake	9.83	13.6	18.73	20.88	18.18	15.08	11.03	10.73	18.03	21.2	20.65	18.58
Bulk density (g.cm^{-3})	Its increase decreases pore size thus lowers infiltration capacity and soil moisture availability	1.15	1.11	1.24	1.18	1.29	1.36	1.18	1.22	1.29	1.28	1.24	1.33
Hydraulic conductivity (x 10^{-4} cm/min)	Higher hydraulic conductivity enables higher infiltration into and transmission of water in the soil	7.25	2.33	4.67	1.46	3.75	1.33	6.00	5.33	6.76	7.88	7.87	8.67
Total porosity	The higher the total porosity the higher the possibility of having more soil moisture retained in the root zone	0.52	0.502	0.483	0.460	0.474	0.440	0.493	0.511	0.465	0.461	0.469	0.456
Average pore size (x 10^{-2} mm)	A larger pore size is likely to result in more infiltration	8.46	6.78	8.19	5.45	7.88	4.20	7.92	7.95	8.01	8.55	8.15	9.10
Average number of pores per cm^2 of area (x 10^{-2})	Depending on their sizes, a higher number of pores could either increase infiltration or water retention	2.17	4.80	2.80	4.93	2.41	5.29	8.35	6.79	2.89	4.97	2.11	2.91
Contribution of	The higher the proportion of water transmitted by	90	93	87	91	89	90	93	94	89	92	91	90

macroporosity to saturated water flux (%)	macropores the likely the higher the root zone soil moisture and available plant extractable water												
Mean monthly volumetric water content ($cm^3.cm^{-3}$)	The higher the water content the higher the likelihood that crop water requirements are satisfied	17.1		13.5		18.6		12.9		15.9		19.4	
Mean available water content ($cm^3.cm^{-3}$) in April 2008	The higher the available water content in the season the higher the chances of a better plant water uptake	-	-	-	-	0.322	0.322	-	-	-	-	0.369	0.337

Unlike the present study, many of the authors whose literature was cited obtained significantly different hydraulic properties (e.g. Watson and Luxmoore, 1986; Wilson and Luxmoore, 1988; Ankeny et al., 1991; Cameira, 2003; Eynard et al., 2004; Reynolds and Elrick, 2005; Ramos et al., 2006; Yoon et al., 2007; Moret and Arrúe, 2007a) between N_T and C_T. Most of these studies were conducted in field sites which have been under the same tillage system for over 10 years. In the current study, the two tillage systems have been practiced for only 3 years with the fields being grazed by livestock in winter (Jun-Oct). In addition, soil textural and climatic differences could have led to the results not resembling that from other regions. The difference in land preparation methods, done using ox-drawn implements in the present study as opposed to conventional machinery e.g. tractors, could also explain the variations. However, findings of Lamandé et al. (2003) which suggest that only a few new pores become effective at conditions near saturation in maize fields support the current findings.

6.4 Conclusion

In order to guide farmers towards sustainable agricultural management systems, there is a need for improved understanding of the processes responsible for changes in structural and physical properties of soil. Tillage methods used over time can change soil physical and hydraulic properties. This study compared hydraulic conductivity, total and effective porosity, water-conducting pores and the contribution of these to total saturated flux between no-till (N_T) and conventional tillage (C_T) systems at two depths. Tillage was found to influence hydraulic conductivity. Ploughing in C_T treatments in December was accompanied by a higher K. However, this was not the case in other dates of measurement. Increase in soil settling and compaction as a result of raindrop impact could have led to increase in bulk density, reflected in the decrease in total porosity that subsequently reduced K.

Better pore size distribution and connectivity of pores could have enabled N_T to realize higher K values latter in the season since there was no significant change in total porosity while on average the proportion of macropores and mesopores to total porosity declined between December and April. However, site C_{TS} had lower K at the end of the season in N_T treatments relative to C_T treatments. This was associated with a relatively higher silt fraction at this site which could have induced structural collapse because of its high content of biotic material when exposed to external stresses e.g. rainfall. Thus, an evaluation of soil textural properties is recommended prior to implementing a specific tillage system. Nevertheless, it is necessary to correlate the soil hydraulic properties against soil physical and textural characteristics to obtain more evidence regarding this observation.

Regardless of the tillage system, this study showed that macroporosity was a very small fraction of total porosity in soils of the four sites, but it had a larger influence on water flow than mesoporosity. Plants in N_T plots are likely to suffer more from water stress at the beginning of the season as compared with those in C_T plots because from the WRCCs the θ in N_T at wilting point is higher. This implies that the θ need to be maintained above this level for the plants to access water. However, in the current study area cultural practices such as mulching are not possible since all the previous season's residue is consumed by livestock, exposing the soil surface to high evaporative losses at the beginning of the season (xref. Chapter 3). This livestock-crop production interaction remains a challenge to the potential benefits of N_T systems (xref. Chapter 8). Although crops could be sustained longer in N_T than in C_T, there was more AWC in C_T at depth D_0 relative to N_T. This suggests that there is no one system that is more superior to the other and farmers could use both of the systems. However, there is a need to obtain WRCCs at several dates during the growing season to make a better judgement because knowledge of AWC plays a significant role in decisions regarding suitable tillage systems.

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7.0 STRUCTURAL AND AGROHYDROLOGICAL APPRAISAL OF RAINWATER HARVESTING STORAGE TANKS IN RURAL AREAS

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Abstract

Rainwater harvesting has resulted in widespread attention as a method for reducing the effects of dry spells and droughts common in most regions of sub-Saharan Africa (SSA), including the summer-rainfall parts of South Africa. This effort is increasingly gaining recognition in regions experiencing unevenly distributed water supplies for domestic, agricultural and industrial needs. Although the potential of rainwater harvesting is extensive, simple and economical techniques such as in-situ systems cannot provide adequate "insurance" against long dry spells. Rainwater harvesting with storage tanks (RHSTs) can bridge this gap as it is able to provide affordable water especially to smallholder agriculture, which is predicted to suffer from water shortages for food production in the near future.

However, such storage facilities require a careful assessment to guarantee their structural and agrohydrological suitability as well as to be cost-effective. In this paper the use of polythene sheet as an alternative lining material to typical building materials for underground RHSTs was explored. In the study area, runoff generation was found to be reliable for providing storage, although this may change if many farmers adopt rainwater harvesting. For the same capacity, underground water storage tanks lined with 600 µm polythene sheet were cheaper and simpler to construct compared to those built from reinforced concrete, bricks, ordinary stones or cement blocks.

Key words: crop water requirements, polythene lining, rainwater harvesting storage tanks, runoff depth, sediment load.

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7.1 Introduction

Water scarcity manifested in dry spells and droughts has had a negative effect on food production for many rural smallholder resource-poor farmers (Barron et al., 2003; xref. Chapter 2, Section 2.3.5). However, substantial yield increases derived as a result of the adoption of rainwater harvesting with storage especially during years with below average rainfall, have been reported (Barron, 2004; Barron and Okwach, 2005; Fox et al., 2005; Ngigi et al., 2005). South Africa has lagged behind the rest of Southern Africa in the adoption of runoff and rainwater harvesting systems, but there are now many calls for their evaluation and adoption of such systems. However, in-situ water harvesting approaches have been successfully implemented in parts of Free State and KwaZulu Natal provinces (Smith et al., 2004; Woyessa et al., 2006; Kosgei et al., 2007). Nevertheless, the findings summarized above highlight the need for comprehensive assessments of rainwater harvesting with storage in order to quantify potential benefits and to identify best practices, as increasing number of farmers are expected to seek information on suitable rainwater harvesting techniques to circumvent current and future water deficits. Kahinda et al. (2007) pointed out that emphasis needs to be directed towards the sizing and design details of rainwater harvesting storage tanks (RHSTs) in South Africa.

According to Fox et al. (2005), the success of any new technology is gauged by its technical and economic viability. In standard investment theory, the best investment strategy is one that brings the highest economic profit. The capital costs incurred to construct rainwater storage structures need to be as low as possible (Pacey and Cullis, 1986; Boers, 1994; Turner, 2000) since they are additional costs to smallholder farmers who may have already over-extend themselves financially to meet the cost of land preparation and inputs. Such structures also have to adequately withstand internal and external loads which may require the use of specific construction materials whose cost may be way beyond the reach of smallholder farmers.

Rainwater harvesting storage structures can be categorized based on the size, material they are made from, shape and their position relative to the ground level. They may be dams (large and small), pans, ponds or tanks. Smallholder farmers are resource constrained (*xref. Chapter 8, Section 8.3.2*) and commonly prefer farm ponds and/or tanks. The tanks may be constructed from primary building materials (e.g. bricks, stones, mortar, reinforced concrete) or acquired as finished products (e.g. plastic containers and drums). An emerging material is the plastic liner which may be used individually or in combination with other construction materials. The size of the storage tank is influenced by the supply-demand function (Section 7.3) and the accompanying cost (Section 7.5, Table 7.8). RHSTs come in different shapes. They may be cylindrical, cuboid, semi-circular, sausage-shaped, truncated cone, etc. Ngigi et al. (2005) described the commonly used type of storage in most parts of Eastern Africa as the "truncated-cone" shaped farm ponds. Further, RHSTs may be above, partially or fully below the ground level. The above-ground tanks have only the foundation constructed below the soil surface.

As the bulk of the cost of building RHSTs is taken up by construction materials, a careful analysis is necessary to ensure that affordable, reliable and sturdy structures are erected. Faber and Alsop (1976), Moita et al. (2003); Ngigi (2003), Odhiambo et al. (2005), Barron and Okwach (2005) and Ngigi et al. (2005) cautioned on water losses in the form of seepage resulting from use of inferior construction materials and/or poor workmanship. Other possible modes of structural failure common in concrete-based storage tanks include cracking that may lead to the risk of corrosive attack on the steel reinforcement (Moita et al., 2003), leaning over due to inadequate foundations, bursting (Odhiambo et al., 2005) and overturning caused by upward pressure of underground water. In some cases, failure could be propagated from exceedance of the design wall thickness or the differences in mechanical properties because of varied skills of workers, mortar density and curing conditions. These may then create unintended variations in the circumferential stresses leading to failure. However, according to Gould and Nissen-Petersen (1999), most common designs are effective, if properly constructed with good quality materials and good workmanship. However, relatively new proposals such as in this study require a craeful appraisal.

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The reliability levels of the RHSTs need to be determined in advance. Sedimentation and evaporation, if allowed, are likely to reduce the reliability of yield from surface runoff-based RHSTs. According to Odhiambo et al. (2005), many reservoirs suffer from high evaporation losses and sedimentation by virtue of their location i.e. semi-arid lands. Ngigi et al. (2005) reported evaporation and seepage losses that ranged between 0.1 - 0.3 m^3day^{-1} and 0.03 – 0.4 m^3day^{-1}, respectively and seasonally accounted for 30–50% of the total harvested runoff. Evaporative losses can be reduced by minimizing the exposed area or by providing a cover. Seepage losses can be reduced by lining the reservoir with an appropriate material. In Kenya, RHSTs are lined with polythene, mortar, rubble stones or clay (Ngigi, 2003). However, mortar sealed underground tanks often cracked and were abandoned (Ngure, 2002 in Ngigi, 2003). This could have been as a result of the long periods that the tanks remained empty. Concrete sealing worked well in other parts of Kenya, but its cost was exhobitant to many farmers. Farmers were reported to be in continuous search for seepage control methods experimenting with among other things plastic lining, butimen lining, clay lining and even competition by goats trampling. Nevertheless, seepage control has remained a major challenge in RHSTs worldwide.

In this study an assessment of the suitability of polythene lining as an alternative cost-effective method of underground rainwater storage especially in rural areas where groundwater levels fluctuate rapidly is provided and the benefits in providing a reliable water supply are highlighted through a study in the Potshini Catchment in South Africa. An analysis of appropriate linings for RHSTs is made and the process from conceptualization through design, construction and utilization of stored water is described and recommendations for the design and construction of such systems are made.

7.2 Water storage for crop production: The Potshini village

This study was carried out in the Potshini catchment (29.37^0E, 28.82^0S) located at the western headwaters of the Thukela River basin in the Emmaus district, falling within South African Quaternary Catchment V13D in the foothills of the Drakensberg Mountains, Okhahlamba municipality. The location of the research site is illustrated in Fig. 7.1. According to Taylor et al. (2001), a substantial portion of the Thukela catchment is unimproved grassland. However, the major land use is agriculture. Large tracts of land are owned by a relatively small number of commercial farmers with access to water for supplementary or total irrigation. Dry land subsistence agriculture and pastoralism are the dominant land uses in the rural areas since few of these communities have access to irrigation water from conventional sources (xref. Chapter 8, Section 8.4.2.3, Fig. 8.11). Population pressure on natural resources, especially water, is expected to increase. In particular low yields from subsistence farming as a result of frequent intra-seasonal dry spells is likely to bring more land into crop production in an area where overgrazing has created large tracts of degraded land that generates quick runoff without adequate recharge of groungwater as in the past when there was more cover. This illustrates an increasing demand for water against an increasingly declining natural supply. The situation is further complicated by environmental flow requirements that are necessary to sustain the ecosystem as enshrined in the National Water Act (DWAF, 1998). In addition, parts of the catchment lie within a declared World Heritage site, making water management in the catchment internationally relevant.

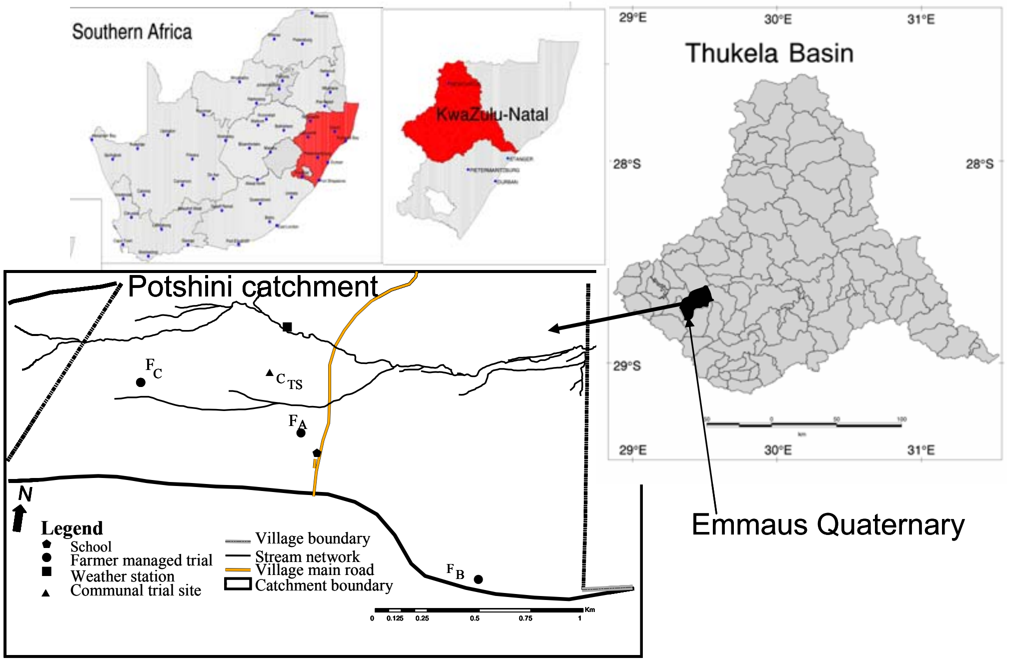

Figure 7.1: Potshini catchment relative to Emmaus quaternary catchment (V13D) and the Thukela River basin (after SSI, 2003)

Income levels in Potshini are generally very low, with over 90% of the inhabitants relying on remittances (grants and pensions) from the government (Fig. 7.2). All farmers possess small land parcels, practice subsistence agriculture, are resource-poor and have many dependents (Kosgei et al., 2007). There is a high reliance on maize and very few farmers grow pulses (Fig. 7.3a). Although the farmers do not keep formal crop production records, in a recent survey the range of maize yield in most households was estimated to be 0 – 2 tons.ha^{-1}. The absence of proper storage for this meager harvest of maize grain results in a low produce price, high post-harvest losses and food shortages that occur even before the next cropping season begins (Fig. 7.3b). These contribute to a low purchasing power in the community, as most of the household income, which in this case is largely government grants, is spent on the sourcing of food. Such a community is considered food insecure, a situation which can be eased by re-evaluation of existing and the introduction of new crop production strategies. In this case crop diversification accompanied with rainwater harvesting techniques may provide an option for improving the situation. In-situ rainwater harvesting methods have been shown to be effective in mitigating moderate intra-seasonal dry spells (xref. Chapter 3, Section 3.4.4). Rainwater harvesting with storage is able to provide "insurance" against severe and inter-seasonal dry spells. With adequate water, smallholder farmers can grow a variety of vegetables in winter, a practice common among a number of large scale farmers surrounding the Potshini catchment. In this way the annual crop production per unit land area can be increased.

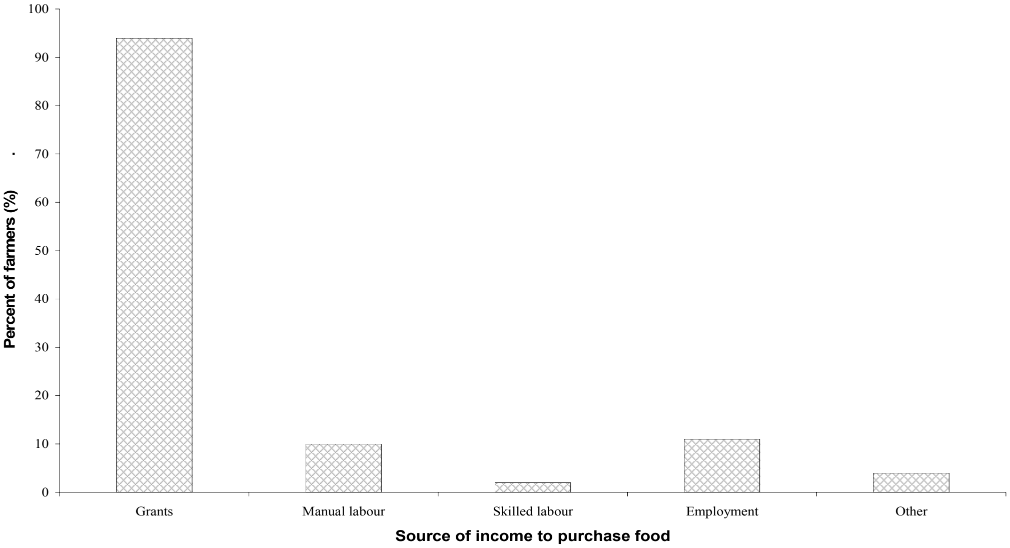

Figure 7.2: The proportion of farmers relying on various sources of income to purchase food in Potshini catchment according to a survey carried out in November 2006 (n = 105). The arithmetic sum of percentages exceeds 100% due to reliance by some farmers on multiple sources of income

Although there is an existing potential to harvest high intensity summer rainfall, there is a need to assess the seasonal reliability of runoff supply in order to establish the potential area in which crop production can be improved. Depending on the rainfall, size and nature of the identified catchment area, a decision is made on the size of the target land area, type and size of storage (De Winnar et al, 2007). The surfaces surrounding homesteads are the primary runoff generating surfaces targeted in this study. These courtyards are impervious and receive regular cleaning, thus minimizing sediments. In addition, this runoff includes that the amount of water concentrated by the roof surfaces of housing structures. Typically, this flow is a nuisance because if not well managed it might cause rills if there is adequate slope; otherwise, incidences of waterlogged and muddy surfaces occur.

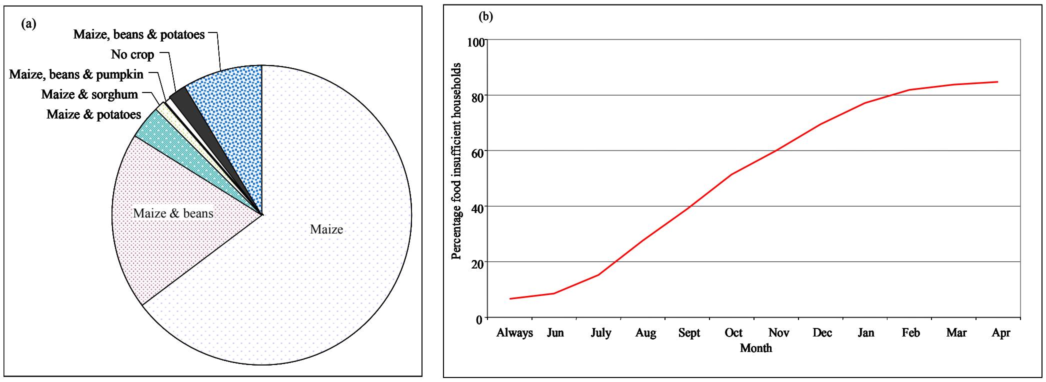

Figure 7.3: Proportion of households (a) cultivating different types of crops (b) without sufficient maize in Potshini catchment (n=105) in 2006

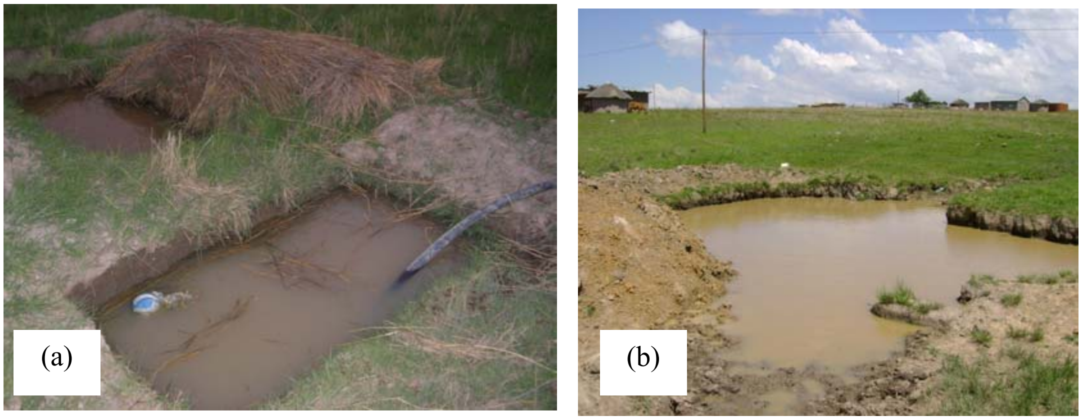

Figure 7.4: Existing attempts by farmers in Potshini catchment to provide water for homestead gardens during winter through excavations to capture a) shallow groundwater and b) runoff

In the study area, some farmers have made attempts towards sourcing water for homestead gardens by either tapping shallow groundwater (Fig. 7.4a) or by construction of small shallow unlined RHSTs (Fig. 7.4b). However, these have had little impact on household income because they are small, far from the gardens and loose water due to seepage and evaporation driven by high temperatures in summer and strong winds during winter (xref. Chapter 3, Section 3.4.5).

For rural communities such as in Potshini Catchment, the possibility of pulling efforts together to have more water through construction of a pan or dam is possible. However, the following challenges exist:

- The existing communal land is dedicated to grazing;
- Communal farming, although advocated by leading research institutions e.g. the African Centre for Food Security at the University of KwaZulu Natal, has not shown the level of success that has been achieved for example in household farming in Potshini catchment;
- Due to the spatial area of the reservoir (the depth has to be shallow because of the manual pumping used) evaporative losses will be massive. If a cover has to be provided, the cost will be exorbitant.

In South Africa, after the adoption of The National Water Act, No. 36 of 1998, previous Irrigation Boards were converted to Catchment Management Authorities (WUA). Members of the Irrigation Boards were large scale farmers and automatically became members of the WUA. Smallholder farmers are still not yet entrenched into WUAs and they are not involved in any decisions regarding water allocation. Members of the WUAs pay tariffs to extract water from the rivers but so far, they do not pay for water stored in their reservoirs (considered private water). In the current study area (Fig. 8.1) the smallholder farmers are upstream the large scale farmers and any attempts to construct dams for the smallholder farmers will likely meet resistance from downstream large scale farmers whose dams are being replenished from streams coming from the area occupied by the smallholder farmers. In addition, because of water scarcity, water permits entrenched in land ownership and competition for markets, pumping and piping water from private farms to smallholder farmers is not foreseen in the near future. Thus, rainwater harvesting at household level seems the most viable option.

7.3 Potential of RHSTs and utilization

The two important factors that determine the productivity of rainwater harvesting schemes are the reliability of the source (rainfall parameters, size and characteristics of the runoff generating surface) and the quantity of water required to fulfill the user's needs. In this case, crop water demands govern the sizing of the tank.

7.3.1 Reliability of supply

The catchment size and its characteristics determine its response to rainfall and thus the amount of runoff generated. The key catchment characteristics include topography, soils, geological properties, land-cover properties, channel network, shape and orientation. The topography controls many processes that occur in the catchment. The topographic aspect controls radiation incidence angle and terrain shading. These determine the direction of gravity flow. The topographic slope and area influence the convergence and divergence of surface-subsurface flow hence determining the availability of water. The topographic shape dictates whether overland or subsurface flow dominates. The catchment shape controls the timing and magnitude of flood pulses at the catchment outlet. These factors are important during the estimation of runoff and identification of potential RHST sites. In this study, a potential site at one of the households was identified based on runoff potential and the willingness of the farmer to participate in the venture.

The catchment area of the potential storage site was mapped using a differential GPS. The storm flow depth was estimated from the SCS model (Schmidt et al., 1987). The initial loss was taken to be 10% of the potential maximum soil water retention. The change of soil moisture storage was approximated from tables provided by the authors. The initial and final curve numbers were 71 and 72.47, respectively. The maximum potential soil moisture storage, S was then computed. The design rainfall with 80 percent exceedance probability was selected from long term rainfall records (1901-1999) at Bergville station, 7 km away from the catchment. The runoff depth, Q, was then estimated. For purposes of illustration, Table 7.1 contains these values summed into a monthly time-step.

As indicated in Table 7.1, considering rainfall with an exceedance probability of 80%, close to one quarter of the total annual rainfall occurred in January. Four months of the year were either completely dry or received rainfall that was below the set “no-runoff” threshold while another two months received less than 15 mm. An area of 0.5 ha, of which the majority was part of the courtyard (Section 7.2) was mapped as the catchment area. The modeled runoff response varied from month to month but the general behavior indicated an increase in discharge with rainfall. However, the runoff to rainfall relationship was not uniform but systematically increased to over 40% in February before it dropped suggesting the influence of antecedent moisture conditions, rainfall intensity and vegetation cover. Excluding the month of May, the average ratio of runoff to rainfall was about 30%. This was similar to values obtained for high intensity storms reported in Chapter 3 (xref. Chapter 3, Section 3.4.3, Table 3.6). Over 3 seasons, average values of 7% and 9% from no-till and conventional tillage plots, respectively were found in the maize production trials in the Potshini Catchment (xref. Chapter 3, Section 3.4.3). This was an indication that the impervious surfaces targeted in this study were suitable for rainwater harvesting.

Table 7.1: Monthly estimates of daily design rainfall (P80), storm flow depth (Q), storm flow volume (Qv), peak discharge (q), sediment yield (Ysd) and volume of sediment from 0.5 ha catchment area in Potshini catchment for the rainfall record 1901-1999

Month	P_{80} (mm)	Q (mm)	Q_v(m^3)	q(m^3s^{-1})	Y_{sd} (tons)	Sed. vol.
January	93.80	39.21	123.30	0.02	0.39	0.24
February	79.00	29.00	91.22	0.02	0.28	0.17
March	68.60	22.36	70.32	0.01	0.21	0.13
April	15.20	0.30	0.95	0.00	0.00	0.00
May	0.40	0.00	0.00	0.00	0.00	0.00
June	0.00	0.00	0.00	0.00	0.00	0.00
July	0.00	0.00	0.00	0.00	0.00	0.00
August	0.00	0.00	0.00	0.00	0.00	0.00
September	5.10	0.00	0.00	0.00	0.00	0.00
October	29.40	3.36	10.56	0.00	0.03	0.02
November	48.30	11.06	34.77	0.01	0.10	0.06
December	65.40	20.42	64.22	0.01	0.19	0.11

Arid and semi-arid lands (ASALs), commonly facing acute water shortages, have soils that are highly susceptible to detachment and easily transported by agents of erosion. Although the rainfall in these areas is low, most of the events are associated with flash floods due to shallow soils, limited vegetative cover and unfavorable human activities. FAO (2001) pointed out that the reliability of water storage structures in ASALs is determined by sediment loads. Thus, it is important to estimate the sediment yield of any potential site. According to Lorentz and Schulze (1994) citing William and Berndt (1975), the Modified Universal Soil Loss Equation (MUSLE) is appropriate when considering sediment yield from individual events. The MUSLE is expressed as:

$$Y_{sd} = \alpha_{sy} (Q_v . q_p)^{\beta_{sy}} K.LS.C.P \tag{7.1}$$

where:

Y_{sd} = sediment yield from an individual event (tonnes)
Q_v = storm flow volume for the event (m^3)
q_p = peak discharge for the event (m^3s^{-1})

K = soil erodibility factor (tonne.h.N^{-1}.ha^{-1})

LS = slope length and gradient factor (dimensionless)

C = cover and management factor (dimensionless)

P = support practice factor (dimensionless); and

α_{sy}, β_{sy} = location specific MUSLE coefficients

The variables in Eq. 7.1 were obtained from the physical properties and the land use practices in the catchment. Lorentz and Schulze (1994) documented MUSLE coefficients for various land uses, slopes, storm flow volumes and peak discharge intensities in South Africa.

A sediment trap (Fig. 7.5) was constructed to eliminate the 0.75 m^3 load estimated and shown in Table 7.1. The volume of the trap is 0.15 m^3 demanding the physical removal of sediments at least five times in the year. The trap consists of three chambers each measuring 25 cm long, 50 cm wide and 40 cm deep. Energy dissipators were included in the first chamber. The wall between the first and second chambers is 2.5 cm higher than the level of water entry into the trap. The same elevation difference was maintained between the second and third chambers so that the exit level is at 7.5 cm higher than the entry level. Together with the energy dissipators the increasing level was intended to reduce the velocity of the water and encourage settling of sediments. The water flow is designed to meander in the trap as a way of further enhancing deposition. The flow velocity which may increase as a result of the constrictions is compensated by the higher eleveation of the second partition relative to the first one. A slot above the exit level was provided as an overflow facility. Two parallel 100 mm PVC pipes were used to convey the water from the sediment trap into the RHST. An inspection manhole was included mid-way between the sediment trap and the RHST.

Figure 7.5: Sediment trap and its accessories (a) construction; (b) complete trap; (c) construction of runoff conveyance channel; and (d) runoff concentration area

7.3.2 Quantity of water required

The Penman-Monteith method (Allen et al., 1998) was used to compute reference evapotranspiration (E_{To}) for the study area. The required climatological data sets were obtained from the Bergville weather station. Considering a target area of 200 m^2, the crop coefficient (K_c) approach was adopted and the crop water demand was estimated by multiplying E_{To} by the respective crop seasonal K_c. The irrigation water demand was calculated by subtracting the dependable rainfall from the crop water requirements. This was then regarded as the amount of water that needed to be stored for irrigating the area of land considered under a particular cropping pattern. During planning, the vegetables considered were cabbage, spinach, onion and tomato occupying 50%, 30%, 10% and 10% of the total area respectively. The inter-row and inter-crop spacing was 0.75 m by 0.45 m, 0.3 m by 0.15 m, 0.15 m by 0.15 m and 0.75 m by 0.3 m for cabbage, spinach, onion and tomato, respectively. The cabbage, spinach, onion and tomato varieties used matured after 135, 50, 180 and 150 days, respectively.

Table 7.2: Dekadal E_{T0}, rainfall, crop water requirements of different vegetables, the volume of water required and the volume that can be harvested and that need to be stored in Potshini catchment based on 1901-1999 climatological data from Bergville weather station. The first day of dekad 1 is 1st June

Dekad	E_{To} (mm)	Rain (mm)	Cabbage (mm)	Onion (mm)	Spinach (mm)	Tomato (mm)	Total volume	Volume generated (m^3)	Volume to store
1	16.3	0	11.1	11.1	11.1	9.5	1.3	0.0	1.3
2	19.6	0	12.9	12.9	12.9	11.0	1.5	0.0	2.8
3	30.4	0	21.3	21.3	30.4	18.2	2.9	0.0	5.7
4	32.4	0	20.1	9.7	29.8	16.8	2.6	0.0	8.4
5	40.6	0	24.7	13.0	14.1	20.7	2.3	0.0	10.6
6	41.1	0	28.8	38.9	0.0	47.3	2.6	0.0	13.3
7	45.1	0	31.6	43.2	31.6	51.9	4.2	0.0	17.5
8	35.6	0	25.5	47.4	24.9	29.0	3.4	0.0	20.9
9	53.2	0	54.9	25.5	53.2	60.2	6.1	0.0	27.0
10	46.4	0.4	48.4	54.9	46.4	53.1	5.9	0.0	32.9
11	51	0.9	53.5	48.4	51.0	58.6	6.2	0.0	39.1
12	51	3.8	49.8	53.5	0.0	54.9	3.8	0.0	42.9
13	47.4	6.7	25.2	49.8	33.2	18.1	3.3	0.0	46.3
14	49.1	6.6	1.4	30.0	34.4	18.5	2.1	0.0	48.4
15	51.8	16.1	0.0	3.8	51.8	0.0	2.2	4.0	50.6
16	50.2	25.5	0.0	10.4	50.2	0.0	2.1	22.4	48.7
17	73.9	1.6	0.0	53.2	60.2	0.0	3.4	0.0	29.7
18	57.1	21.2	0.0	21.6	0.0	0.0	0.3	12.4	30.0
Total		82.8	409.1	548.3	535.2	467.6	56.4	38.8	

The dekadal E_{To} estimates of potential evapotranspiration from Penman-Monteith model are shown in Table 7.2 for the winter period (Jun-Nov) in Potshini catchment. This window represents an unexploited potential for crop diversification and increased crop productivity in smallholder agriculture (Section 7.2). Table 7.2 also includes the derived depth, volume of crop water requirements and the net irrigated area when drip irrigation is used for the different vegetables. The proportion of the net irrigated area to the allocated area used was 0.5, 0.8, 0.7 and 0.6 for cabbage, onions, spinach and tomatoes, respectively. Due to the life cycle of spinach, three cycles are possible within the six months considered.

Although there is some rainfall from the beginning of September, runoff that could be harnessed was only realized in the last dekad of October. However, this rainfall is useful in reducing the net crop water demand. All the crop water requirements during the dry months and a bulk of it during the beginning of the rainy season have to be met by rainwater harvested and stored from the previous season. The capacity of storage required is the maximum accumulated balance between net crop water requirements and the volume of runoff replenished from rainfall. In the case considered in Potshini, the tank capacity to satisfy the water demand should be at least 50.6 m^3 (Table 7.2). To account for contingencies fixed at 5% of the required volume of water (to minimize additional costs), a RHST of 54 m^3 was considered optimal. The next step was to identify the most appropriate RHST for the site.

7.4 Tank considerations and structural design

7.4.1 Basic requirements of rainwater harvesting tanks

The following are regarded basic requirements for the reliability of RHSTs:

a) Lateral loads and hydrostatic uplift forces

The tank should be able to resist lateral loads acting on the wall. These loads include circumferential (hoop) stress and earth loads. Because various factors influence the magnitude, location and direction of the loads and forces (Fig. 7.5), there is a need to conduct a structural appraisal to identify the best combination of factors that minimize them while maximizing the benefits from the RHST. Faber and Aslop (1976) cautioned that the corners of cuboid tanks encourage build up of undesirable stresses. Thus, alternative shapes should be considered where costs can be minimized without compromising the structural strength.

A cylindrical water tank is considered as a thin-walled shell structure in the analysis of loading because the overall radius is large (usually higher than 10:1) compared to the wall thickness.

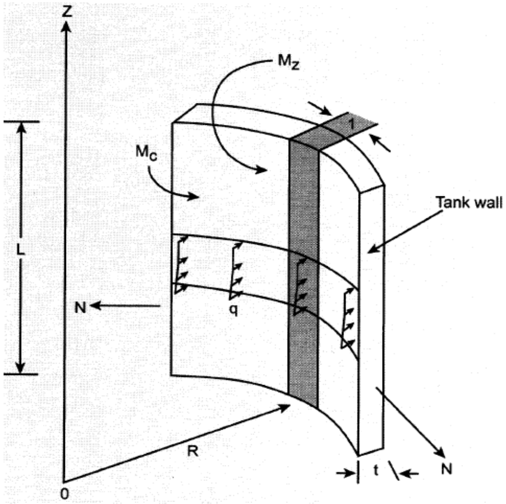

Figure 7.6: Cylindrical shell under an axisymetric load q (Godbout et al., 2003)

From Fig. 7.6, for a constant shell thickness, the uniformly distributed load on the tank wall is determined by the expression suggested by Timoshenko and Woinowski-Krieger (1959) in Godbout et al. (2003):

$$q = D\frac{d^4 w_z}{dz^4} + \frac{E_t t}{R^2} w_z \tag{7.2}$$

Where:

q = distributed applied load,

R = radius,

t = wall thickness,

E_t = elastic modulus of wall material,

w_z = radial displacement at z,

z = vertical coordinate, and

D = flexural rigidity.

Tank walls can either be joined to the base of the tank or left free to move relative to the base. The membrane theory is used to calculate the stresses in the tank wall when there are no boundary conditions (i.e. the tank walls are free to move). However, if the wall and base are monolithic (i.e. the wall and base are continuous), then the loading caused by the water pressure is counteracted by a combination of hoop and cantilever resistance. Bending, shear and hoop stresses will occur. The bending theory is used to calculate the additional loading on the tank wall. However, if the tank is in the form of a closed cylinder, longitudinal, circumferential and radial stresses do develop (Case and Chilver, 1971). These can be estimated from the variables in Eq. 7.2. The profile of the tank determines the profile of the load distribution curve as illustrated in Fig. 7.7. This provides the basis for tank selection in terms of location, shape, and the material(s) of construction.

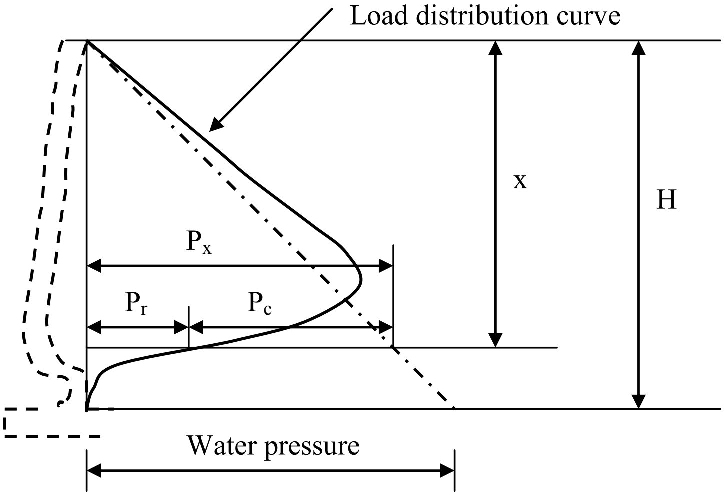

Figure 7.7: Typical load distribution for a tank with a monolithic base. P_r = portion of the load restrained by hoop stresses (radial constraints); P_c = portion of the load restrained by cantilever; P_x = total outward pressure load to be restrained; x = distance from top of tank; H = total depth of tank (After Turner 2000)

It can be seen from Fig. 7.7 that for a restrained wall, the hoop stress at the base is zero and the maximum hoop stress is experienced higher up on the wall. In the case of underground tanks, the soil takes up some of the pressure exerted by the water. However, when the tank is empty, this pressure may damage the tank especially if the wall is constrained. The load distribution curve (Fig. 7.7), is governed by the profile of the tank. Eq. 7.3 relates the tank profile to the distribution curve. All tanks with equal values of K (Eq. 7.2) have similar load distribution curves.

$$K = \frac{12H^4}{(r)^2 t^2} \tag{7.3}$$

Where:

H = height of the tank

r = radius of the tank

t = thickness of wall at foot

Another relevant load is the hydrostatic uplift force that is caused by presence of underground water. Swelling clays may also exert huge uplift forces. As these soils get wet, the clay minerals absorb water molecules causing them to expand. Conversely, drying in these soils cause shrinking that leaves large voids in the soil mass. Potentially expansive soils can be detected through laboratory investigation of their plastic properties. In this study, samples from four depths (50, 100, 150 and 200 cm) were collected and analysed at the School of Bioresources Engineering and Environmental Hydrology Soil and Water laboratory. The Atteberg's limits are shown in Table 7.3(a).

Table 7.3(a): Liquid limits, plastic limits and plastic indices of soil collected from four depths in Potshini village

Depth (cm)	Liquid limit, LL (%)	Plastic limit, PL (%)	Plastic index, PI (%)
50	39	27	12
100	42	36	6
150	46	41	5
200	51	43	8

Table 7.3(b): Categorization of potential swell based on plastic indices (Holts and Gibbs, 1956)

Category of potential swell	Liquid limit, LL (%)	Plastic index, PI (%)	Shrinkage limit, SL (%)
Low	20-35	<18	15
Medium	35-50	15-28	10-15
High	50-70	25-43	7-12
Very high	>70	>35	<11

The results of the laboratory analysis placed soils from all the depths below the "A" line in the Casagrande plasticity chart suggesting that the soil is likely to be inorganic silt or organic clays with low plasticity. Holtz and Gibbs (1956) provided a classification of potential swell based on plasticity (Table 7.3(b)). On average the soil from Potshini village can be regarded as having a low swell potential because the PI in all cases is less than 18 (Table 7.3(b)), and thus making hydrostatic uplift forces not to be a major concern in the study area. However, as shown by Kongo (2008), shallow groundwater levels rise relatively fast, there is a need to ensure that the material(s) for construction can withstand hydrostic uplift forces adequately. Deep drainage in the cropping fields was considered negligible because the trial plots used were relatively small (10m x 2.45 m).

b) Water losses

The tank's base and wall should be impervious to avoid water losses. This surface area largely determines the cost of the tank. The cost of construction materials often makes RHSTs unaffordable to many people in rural areas. Thus, it is important to investigate how and where construction materials can be reduced or cheaper options supplied. This is only possible if the magnitude of the induced forces (Section 7.4.1(a)) and their location are known. In this way, the possibility to use previously ignored and/or locally and easily available materials can be considered. It is also important for the tanks to have sturdy roofs that would prevent water losses through evaporation as well as prevent drowning and infestation. As much as possible, the tank should be built from local resources (materials and labor) with due regard not to compromise structural and seepage thresholds.

c) Sufficient water

The tank should have sufficient capacity to store enough water to meet the water requirements for the desired period (Section 7.3.2).

d) Accessories

The tank should be constructed to include accessories that eliminate or minimize sediments (Section 7.3.1) and allow for de-silting when it is due. It should also be able to deal with excess input by overflowing in a manner which doesn't damage the tank or its foundations. This flow has to be channeled carefully so as not to cause environmental degradation and/or damage to property downstream. In gravity fed systems, water abstraction points need to be incorporated within the tank's base or wall structure unless siphoning is an option. Conversely, in areas where pumping is necessary, the access into the tank may be positioned in such a way that it coincides with the entry point of a pump's suction pipe. Water losses during pumping need to be minimized as much as possible. Any water that spills should be collected or channeled away from the pumping area.

7.4.2 Structural assessment and design

This section evaluated a combination of various tank shapes, location and materials of construction to arrive at the most suitable RHST for smallholder farmers in the Potshini catchment. The design load, the maximum load at the bottom of the tank, encompassed the load due to the stored water, building materials and other incidentals. The magnitude of the design load was obtained through an assessment of loading imposed by the water stored in the RHSTs of different shapes located either above the ground or underground and made from different materials. Five wall materials (reinforced concrete, bricks, 600µm plastic, cement blocks and ordinary stones) and three roofing materials (C.I.S, LDPE and HDPE)[21] were considered for assessment.

7.4.2.1 Material(s) of construction

a) Roofing

Corrugated iron sheets, light and heavy duty plastic sheets were the evaluated roofing materials. Weld mesh supported by a few purlins was considered rather than a timber truss for the light duty plastic roofing. The heavy duty plastic sheet does not require any support as it can be securely anchored and allowed to float on top of the water. The total load from the roof structure comprise the dead loads resulting from building materials and live loads from incidentals such as wind, ice and human activities. Parker (1963) provided approximate loads of various building materials and incidental live loads (Table 7.4). To cater for safety, the design load was taken as the sum of 160% of dead loads and 140% of live loads (Case and Chilver, 1971).

Table 7.4: Loads exerted on the wall by selected building and incidental live loads (Parker, 1963)

Load	Magnitude (N/m^2)
Corrugated iron sheet (20G)	96
2”x3” white pin roof purlins spaced at 24”	24
36-50 ft span timber truss of up to ¼ pitch	192
Snow loads for up to 20^0 slope	480
Wind pressure for a pitch of up to 20^0 slope	863

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[21] C.I.S = Corrugated iron sheets; LDPE = Low density plastic liner; HPDE = High density plastic liner.

b) The wall

The properties of the wall were obtained from an analysis of the pressure due to the stored water. The pressure always applies a force perpendicular to the inside surface of the tank acting outwards; at the bottom it acts downwards. Generally, this pressure puts the tank into tension. This is unfortunate because many materials traditionally used for building and transferred to tank construction are only 10 – 20% as strong in tension as they are in compression (Turner, 2000).

Although tanks for water storage come in different shapes, cylindrical tanks are most common. However, cylindrical tanks resist all the applied loads in one plane. The tensile stress acts around the cylinder and are called 'hoop' stresses. The loads vary linearly from a minimum at the top to a maximum at the base. For unconstrained (monolithic) tanks that are considered in this study, the hoop stress is determined using the Eq. 7.5:

$$\sigma_h = \frac{\mathrm{Pr}}{t} \tag{7.5a}$$

Where:

σ_h is the hoop stress

P is the water pressure

r is the radius of the tank

t is the wall thickness

$$P = \gamma g h \tag{7.5b}$$

Where:

γ = density of water

g = Gravitational force

h = height of water

The thickness of the wall is initially assumed but verified against the rule-of-thumb against percolation i.e. 25 mm + 1/40th the depth below water level but a minimum of 100 mm is taken after analyzing the additional reinforcement and their mode of placement so that the circumferential stresses are adequately contained.

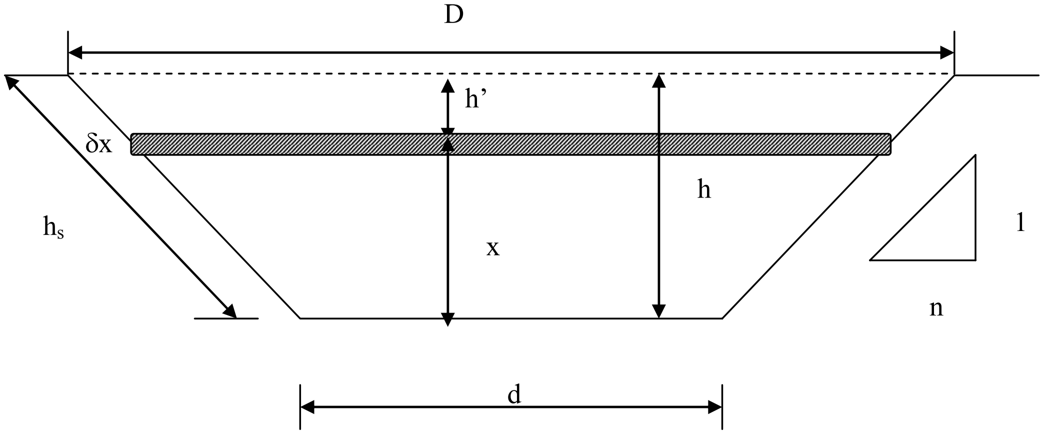

Figure 7.8: Cross-section of a “truncated-cone” shaped RHST (h_s = slanting height)

For “truncated-cone” shaped tanks (Fig. 7.8), considering an elemental area, δx, at a distance x from the base, the pressure head at this strip is h’ = (h-x) m and the radius at that point is r’ = (d/2+n*x). Thus, the hoop stress:

$$\sigma_h = \left(\gamma * g * (h - x) * \left(\frac{d}{2} + n * x \right) \right) / t \tag{7.6a}$$

At the bottom of the tank, x = 0 and h’ = h, thus:

$$\sigma_h = \left(\gamma * g * h * \left(\frac{d}{2} \right) \right) / t \tag{7.6b}$$

At the top h = x, hence:

$$\sigma_h = 0 \tag{7.6c}$$

where n is the side slope and d is the diameter.

c) Floor slab

The floor slab carries the vertical load of the water. The size and rigidity of the foundation slab are critical. If the slab is not large enough in area and not rigid enough to prevent deflection under the expected load, then excessive settlement or a bearing capacity failure could occur. In the design of the thickness of the slab, the aforementioned rule-of-thumb against percolation (Section 7.4.2.1(b)) was considered. The hydrostatic water pressure at the floor slab was computed and used to estimate the amount of steel reinforcement required. The international building code BS 8110 was used to determine the reinforcement requirements. The resulting concrete tensile stress was checked to ensure that it is within the recommended limit of 85 N/m^2

(Case and Chilver, 1971). The necessity of movement joints was also evaluated. The swell pressures were neglected since the swell potential was regarded low (xref. Section 7.4.1(a)).

7.4.2.2 Location and shape of RHSTs

Two tank shapes, cylindrical and “truncated-cone” shaped tanks were analyzed. For practical purposes, only vertical walls i.e. cylindrical tanks were considered in the assessment of above ground RHSTs.

a) Above ground cylindrical RHSTs

These are tanks whose entire wall is above the ground while only the foundation is put below the soil surface. The wall carries the entire radial water pressure (circumferential stress). This type of tank is suitable in areas where the runoff generating surface is elevated with respect to the tank position. Most above ground tanks are limited to a height of 2 m. Considering this height, to store 54 m^3, a cylindrical tank of radius, r = 2.93 m is required. No movement joint was therefore required since the floor plan of the slab is less than the recommended 6 m x 6 m (McCormack, 1997). The exposed surface area is 27 m^2 and the hydrostatic water pressure at the base of the tank is 19.62 kN. The soil and/or the floor slab of appropriate thickness should be able to withstand this pressure. The maximum circumferential hoop stress (σ_h) is 261.6 kN. The loads, thickness of the foundation and that of the wall for various materials to construct a tank of 54 m^3 is provided in Table 7.5a and 7.5b. The identified reinforcement bars are laid along the brick/stone courses.

Table 7.5a: Loads exerted by various wall materials and required equivalent steel reinforcement of above ground cylindrical 54 m^3 RHST constructed from various materials

Wall material	R-wall thickness (mm)	Thickness of other material (mm)	Total wall thickness (mm)	Horizontal bars (mm)		Vertical bars (mm)		Wall load (kN/m)
				Size	Spacing	Size	Spacing	
R-concrete	175	-	175	12	72	10	175	8.3
Brick	125	220	345	12	100	10	209	10.9
Stones	150	150	300	12	72	10	209	17.5
Cement blocks	150	220	230	12	75	10	175	9.0
Plastic liner	-	25	25	-	-	-	-	0.5

Table 7.5b: Assessment of loads exerted by various components, wall thickness and the width of foundation of above ground cylindrical 54 m^3 RHST constructed from various materials

Loads	Wall material														
	Reinforce concrete			Brick			Ordinary stone			Cement blocks			HDPE		
	C.I.S[1]	LDPE[2]	HDPE[3]	C.I.S	LDPE	HDPE	C.I.S	LDPE	HDPE	C.I.S	LDPE	HDPE	C.I.S	LDPE	HDPE
Roof load (kN/m)	1.7	1.6	0.1	1.7	1.6	0.1	1.7	1.6	0.1	1.7	1.6	0.1	1.7	1.6	0.1
Wall load (kN/m)		8.3			10.9			17.5			9.0			0.5	
Total load (kN/m)	9.0	9.9	8.4	12.6	12.5	11.0	19.2	19.1	17.6	10.7	10.6	9.1	2.2	2.1	0.6
Wall thickness (m)		0.18			0.35			0.3			0.3			0.03	
Soil stress(kN/m^2)	56.9	56.1	47.6	36.6	36.1	31.8	63.9	63.6	58.5	35.5	35.1	30.1	87.2	81.6	22
Found. width(m)	0.48	0.48	0.4	0.6	0.6	0.5	0.9	0.9	0.8	0.5	0.5	0.45	0.13	0.1	0.03

[1] Corrugated iron sheets; [2] Low density polythene; [3] High density polythene

Table 7.6a: Loads exerted by various wall materials and required equivalent steel reinforcement of below ground cylindrical 54 m^3 RHST constructed from various materials

Wall material	R-wall thickness (mm)	Thickness of other material (mm)	Total wall thickness (mm)	Horizontal bars (mm)		Vertical bars (mm)		Wall load (kN/m)
				Size	Spacing	Size	Spacing	
R-concrete	150	-	150	12	75	10	200	7.1
Brick	100	225	325	12	100	10	300	9.7
Stones	150	150	300	12	56.25	10	209	14.9
Cement blocks	125	150	275	12	75	10	209	8.7
Plastic liner	-	25	25	-	-	-	-	0.5

Table 7.6b: Assessment of loads exerted by various components, wall thickness and the width of foundation of underground cylindrical 54 m^3 RHST constructed from various materials

Loads	Wall material														
	Reinforce concrete			Brick			Ordinary stone			Cement blocks			HDPE		
	C.I.S[1]	LDPE[2]	HDPE[3]	C.I.S	LDPE	HDPE	C.I.S	LDPE	HDPE	C.I.S	LDPE	HDPE	C.I.S	LDPE	HDPE
Roof load (kN/m)	1.7	1.6	0.1	1.7	1.6	0.1	1.7	1.6	0.1	1.7	1.6	0.1	1.7	1.6	0.1
Wall load (kN/m)		7.1			9.7			14.9			8.7			0.5	
Total load (kN/m)	8.8	8.7	7.2	11.4	11.3	9.8	16.6	16.5	15.0	10.4	10.3	8.8	2.2	2.1	0.6
Wall thickness (m)		0.15			0.33			0.3			0.28			0.03	
Soil stress(kN/m^2)	58.5	57.6	47.7	35.1	34.7	30.1	55.3	54.8	49.8	37.9	37.4	32	87.2	81.6	22
Found. width (m)	0.4	0.4	0.33	0.53	0.52	0.46	0.8	0.8	0.7	0.49	0.48	0.41	0.13	0.1	0.03

[1] Corrugated iron sheets; [2] Low density polythene; [3] High density polythene

b) Below ground cylindrical RHSTs

In this study, below ground RHSTs are tanks that are constructed fully below the ground level. The soil takes up some of the water pressure. According to Vine (1982), Rankine suggested a factor, k of reduction to the normal axial load on a wall subjected to water pressure. This is expressed as:

$$k = \frac{1 - \sin\phi}{1 + \sin\phi} \qquad (7.6)$$

where, ϕ is the angle of repose of the soil material.

For sandy clay loam soils (Kosgei et al., 2007), a value of $\phi = 32^0$ was used resulting to k = 0.307. The horizontal soil pressure of a 2 m high retaining wall becomes 12.66 kN per meter length. The water pressure is reduced by this margin for all tanks with vertical walls. The net pressure used was 248.94 kN.

The exerted loads and the respective dimensions of the wall and depth of foundation are given in Table 6a and 6b. Compression forces were considered negligible.

c) Below ground "truncated–cone" shaped RHSTs

This is a tank that has a vertical cross section as shown in Fig. 7.8. Considering a tank volume of 54 m^3 the following dimensions apply:

- Bottom diameter, d = 3.95 m
- Top diameter, D = 7.9 m
- Vertical height, h = 2 m
- Slanting height, h_s = 2.6 m

Considering a side slope, n = 1, the average hoop stress acting at mid point i.e. at 1m deep is 124.34 kN. Due to the wall inclination, some of the loads due to the wall material are transmitted to the soil thus reducing the width of foundation. The corresponding soil pressure, considering the same soil properties as indicated in Section 4.3.2(b), was 8.95 kN. Thus the effective hoop stress became 115.39 kN.

The exerted loads and the respective dimensions of the wall and depth of foundation of "truncated–cone" shaped RHST are given in Table 7.7a and 7.7b. Similarly, compression forces were considered negligible.

Table 7.7a: Loads exerted by various wall materials and required equivalent steel reinforcement of below ground truncated cone 54 m^3 RHST constructed from various materials

Wall material	Thickness of R-concrete (mm)	Thickness of other material (mm)	Total wall thickness (mm)	Horizontal bars (mm)		Vertical bars (mm)		Wall load (kN/m)
				Size	Spacing	Size	Spacing	
R-concrete	67.5	-	100[a]	12	75	10	469	4.3
Brick	50	220	270	12	90	10	556	6.8
Stones	67.5	150	217.5	12	90	10	469	10.1
Cement blocks	67.5	157.5	225	12	85	10	469	7.6
Plastic liner	-	25	25	-	-	-	-	0.5

[a] Minimum wall thickness should be 100mm

Table 7.7b: Assessment of loads exerted by various components, wall thickness and the width of foundation of underground truncated cone 54 m^3 RHST constructed from various materials

Loads	Wall material														
	Reinforce concrete			Brick			Ordinary stone			Cement blocks			HDPE		
	C.I.S[1]	LDPE[2]	HDPE[3]	C.I.S	LDPE	HDPE	C.I.S	LDPE	HDPE	C.I.S	LDPE	HDPE	C.I.S	LDPE	HDPE
Roof load (kN/m)	1.7	1.6	0.1	1.7	1.6	0.1	1.7	1.6	0.1	1.7	1.6	0.1	1.7	1.6	0.1
Wall load (kN/m)		4.3			6.8			10.1			7.6			0.5	
Total load (kN/m)	6.0	5.9	4.4	8.5	8.4	6.9	11.8	11.7	10.2	9.3	9.2	7.7	2.2	2.1	0.6
Wall thickness (m)		0.1			0.27			0.22			0.23			0.03	
Soil stress(kN/m^2)	60.5	59.1	44.2	31.4	30.8	25.4	54.3	53.7	46.8	41.5	40.9	34.3	87.2	81.6	22
Found. width (m)	0.28	0.28	0.2	0.4	0.39	0.32	0.55	0.54	0.47	0.44	0.43	0.36	0.13	0.1	0.03

[1]Corrugated iron sheets; [2]Low density polythene; [3]High density polythene

Table 7.8: Bill of quantities for various 54 m^3 RHST based on materials and dimensions in Tables 7.5a – 7.7b. All the materials and labor were available locally (within Okhahlamba municipality) except for the plastic liner

Location	Shape	Roof cover	Wall material	Roof	Wall	Slab	Shutt-ering	Total (materials)	Labour (excava.)	Labour (const.)	Total (ZAR)
Above ground	Cylindrical	C.I.S	Concrete	1870	8410	3756	553	14590	300	2500	17390
			Bricks	1870	13573	3756	0	19200	300	3000	22500
			Stones	1870	14374	3756	553	20553	300	2750	23603
			Conc. Blocks	1870	9076	3756	0	14703	300	2750	17753
			Plastic liner	1870	10500	0	2500	14870	300	1500	16670
		LDPE	Concrete	1910	8410	3756	553	14629	300	2500	17429
			Bricks	1910	13573	3756	0	19240	300	3000	22540
			Stones	1910	14374	3756	553	20593	300	2750	23643
			Conc. Blocks	1910	9076	3756	0	14742	300	2750	17792
			Plastic liner	1910	9311	0	4500	13721	300	2500	18521
		HDPE	Concrete	6635	8410	3756	553	19354	300	2500	21954
			Bricks	6635	13573	3756	0	23965	300	3000	27265
			Stones	6635	14374	3756	553	25318	300	2750	28368
			Conc. Blocks	6635	9076	3756	0	19467	300	2750	22517
			Plastic liner	6635	9311	0	0	15946	300	1500	17746
Below ground	Cylindrical	C.I.S	Concrete	1870	7816	3756	553	13995	800	2000	16795
			Bricks	1870	12983	3756	0	18610	800	2500	21910
			Stones	1870	12164	3756	553	18343	800	2250	21393
			Conc. Blocks	1870	8898	3756	0	14525	800	2250	17575
			Plastic liner	1870	10500	0	0	12370	800	1500	14670
		LDPE	Concrete	1910	7816	3756	553	14035	800	2000	16835
			Bricks	1910	12983	3756	0	18649	800	2500	21949
			Stones	1910	12164	3756	553	18383	800	2250	21433
			Conc. Blocks	1910	8898	3756	0	14565	800	2250	17615
			Plastic liner	1910	10500	0	0	12410	800	1500	14710
		HDPE	Concrete	6635	7816	3756	553	18760	800	2000	21560
			Bricks	6635	12983	3756	0	23374	800	2500	26674
			Stones	6635	12164	3756	553	23108	800	2250	26158
			Conc. Blocks	6635	8898	3756	0	19290	800	2250	22340
			Plastic liner	6635	10500	0	0	17135	800	1000	18935
	Truncated cone	C.I.S	Concrete	2383	8891	2578	808	14661	500	2250	17411
			Bricks	2383	17234	2578	0	22196	500	3000	25696
			Stones	2383	12330	2578	808	18100	500	2500	21100
			Conc. Blocks	2383	11395	2578	0	16356	500	2500	19356
			Plastic liner	2383	8811	0	0	11194	500	1500	13194
		LDPE	Concrete	2513	8891	2578	808	14791	500	2250	17541
			Bricks	2513	17234	2578	0	22326	500	3000	25826
			Stones	2513	12330	2578	808	18230	500	2500	21230
			Conc. Blocks	2513	11395	2578	0	16487	500	2500	19487
			Plastic liner	2513	8811	0	0	11324	500	1500	13324
		HDPE	Concrete	11754	8891	0	808	21453	500	2250	24203
			Bricks	11754	17234	0	0	28988	500	3000	32488
			Stones	11754	12330	0	808	24892	500	2500	27892
			Conc. Blocks	11754	11395	0	0	23149	500	2500	26149
			Plastic liner	11754	8811	0	0	20565	500	1500	22565

The cost of materials was obtained from potential suppliers of the materials who also met the University of KwaZulu Natal's procurement requirements. Labor charges were based on previous experiences of similar works in rural areas in South Africa and also information from local artisans in the catchment.

7.5 Choice and construction of the suitable RHST

7.5.1 Selection of type of RHST

From the analyses, the unit volumetric cost of water (R/m^3 or US\$/m^3) for the three lowest cost of tanks considered in each category is (US$ equivalent in November 2007 is provided in parenthesis):

i). Cylindrical above ground tanks:
   - A plastic liner with a corrugated iron sheet roof ≈ 308.70 (46.35)
   - A concrete wall with an ordinary polythene roof ≈ 322.76 (48.46)
   - A concrete block wall with a corrugated iron sheet roof ≈ 328.76 (49.36)

ii). Cylindrical below ground tanks:
   - Plastic liner with a corrugated iron sheet roof ≈ 271.67 (40.75)
   - Plastic liner with an ordinary polythene roof ≈ 272.41 (40.86)
   - Concrete wall with a corrugated iron sheet roof ≈ 311.02 (46.65)

iii). Truncated below ground tanks:
   - Plastic liner with a corrugated iron sheet roof ≈ 244.33 (36.65)
   - Plastic liner with an ordinary polythene roof ≈ 246.74 (37.01)
   - Concrete wall with corrugated iron sheet roof ≈ 322.43 (48.37)

From the summary, an underground "truncated–cone" shaped tank lined with plastic and roofed with corrugated iron sheets is the cheapest option. Apart from the plastic liner, concrete as a standalone wall material is the second best probably because all the other materials used in the evaluation incorporated a reinforced concrete layer.

7.5.2 Construction procedure

As construction cost was a major concern, having considered structural requirements adequately, the cheapest tank, an underground "truncated-cone" shaped tank was adopted. The main construction steps involved were excavation to the dimensions given by Fig. 7.8, acquisition of the plastic liner, laying and securing it with a ring-beam and roofing.

7.5.2.1 Excavation

The appropriate site was identified and marked out. Digging was done using hand hoes, spades, mattocks and pick axes. The soil was moved away from the construction site using wheel barrows. A reinforced block king post was erected in the middle of the excavated hole to support the roof structure.

7.5.2.2 Laying of liner

A black polythene sheet (600 µm) welded to fit the excavated hole exactly was acquired from Hydrex (Pty) Ltd, Pretoria, South Africa (Fig. 7.9a – 7.9d). It weighed 72 kg. It was carefully laid and secured with a ring-beam made from reinforced stabilized cement blocks (Fig. 7.9f). About 3 mm fine ordinary sand was placed between the excavated soil and the liner. At the kingpost, four holes that corresponded with the reinforcement bars supporting the kingpost were punctured at the base of the liner (Fig. 7.9b). After the liner was laid, a strong adhesive was used to ensure that the remaining spaces were water-tight. Stabilized cement blocks were then placed on top of the liner (Fig. 7.9d) which were filled with concrete. According to Hydrex (Pty) Ltd, Pretoria, South Africa the liner's (600 µm) lifespan is 10-12 years. But this depends on handling during installation and de-silting.

7.5.2.3 Roof construction

Wooden posts were placed at 2 m spacing around the outer circumference of the tank to support the roof truss and the sheets. Part of the roof load is also carried by the king post. Corrugated iron sheets (Figure 7.9e – 7.9f) were used to cover the roof. This roof also acted as an additional catchment area for the tank as well as eliminating evaporation and being a safety measure by preventing animals or people from falling into the tank.

Figure 7.8: Steps of construction of an underground truncated cone RHST – a) plastic liner before being unpacked; b) marking out slots to allow for steel reinforcement in king post; c) and d) laying of liner; e) timber truss; and f) roofing with corrugated iron sheets

7.6 Conclusion

Rainwater harvesting remains a high potential source of water for agriculture and other water users and uses under current conditions of diminishing quantity and quality of water resources in a region where these are compounded by low and poorly distributed rainfall. At the moment rainwater is still free water and some governments e.g. in Kenya are in the process of enacting legislation that makes it mandatory for RHSTs to be included in any upcoming urban structures to ensure water conservation (SearNet, 2007). Although such efforts are laudible, the cost of RHSTs is still unreachable by many smallholder farmers who are hardest hit by the limitations of inadequate water as they do not have the capacity to develop conventional water sources such as boreholes and large dams. Thus, affordable storage techniques are needed.

In this study, an underground "truncated–cone" shaped tank, the use of which is reportedly growing in Eastern Africa (Ngigi et al., 2005), was found to be appropriate for the Potshini village in South Africa. This shape approximates to the 'Thai' jar tank which is reported to resist loads better than cylindrical shaped tanks (Turner, 2000). Use of underground RHSTs ensures that runoff from all areas, including those previously disregarded e.g. courtyards, ephemeral or gully flow is captured. Furthermore, the soil resists some of the water pressure, reducing the required wall thickness. In this way the overall cost of the tank is decreased.

In the Potshini catchment runoff depths from impervious courtyards were found to be adequate to support kitchen gardens of 200 m^2. Lining RHSTs with a 600 µm polythene sheet was shown from this study to be suitable and cost-effective. This finding agrees with that of Fox et al. (2005) who found out that the most economical lining material was plastic sheeting when compared to three other sealants viz. cement, rubber tarpaulin and self sealing. Structurally, polythene lining is very useful in areas such as Potshini catchment where the soil is likely to swell (Table 7.3(b)) and shallow groundwater levels rise rapidly at the beginning of the rainy season (Fig. 7.4a) because it can adjust depending on the hydrostatic pressure below it. In addition, it can be laid with ease. A corrugated iron sheet roof was constructed.

Although R 250/m^3 of water (Table 7.8) may be perceived to be high, this is a once-off expense and the only running costs are incurred during removal of sediments. Furthermore, the larger the tank the less expensive it becomes. For example, 30 m^3 reinforced concrete RHSTs and roofed with corrugated iron sheets constructed through a DWAF subsidy (Kahinda et al., 2007) cost R 433/m^3 of water in Potshini catchment compared to R 311/m^3 for the 54 m^3 constructed in this study. However, given the economic status of the community in Potshini catchment, further ways of reducing associated costs and/or engaging in profitable enterprises need to be explored. These could include use of simple treadle pumps for water delivery and growing of high value well-scheduled crops. It is only after a cost-benefit analysis that these RHSTs can be assessed to establish whether they are economically viable or not given that the initial cost is high relative to the community's ability.

As many farmers are likely to desire RHSTs in the near future, it is recommended that special attention be given to the process of design and construction of sediment collectors as local factors determine the amount and nature of the sediment loads. It is necessary that sediment removal schemes take into consideration the risk of mosquitoes breeding in the traps if the pool of stagnant water is sufficient and stands for a considerable period of time in areas where malaria is prevalent.

This study successfully used polythene as an alternative lining material for an underground RHST and was found to be cost-effective and easy to install relative to other construction materials. However, the capacity to weld plastic into different shapes is available in most urban centres in South Africa and may not be the case in other regions of SSA which presents a challenge on the use of this technology elsewhere. Thus, there is a need to evaluate the status in other regions as well as consider import costs from the nearest and/or most convenient source before making recommendations to farmers.

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8.0 FOOD PRODUCTION AND HOUSEHOLD INCOME AMONG SMALLHOLDER RAINFED FARMERS: DO BIOPHYSICAL AND POLICY INTERVENTIONS HAVE A COMMON ROLE IN ARID AND SEMI-ARID LANDS?

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Abstract

South Africa, in common with many parts of Sub-Saharan Africa (SSA), is facing increasing water shortages. Limited available water arising from a low and poorly distributed rainfall, must supply domestic, agricultural, industrial and ecosystem needs. Agricultural activities of smallholder farmers, who largely occupy arid to semi-arid areas (ASALs), are rainfall-driven as they do not have the capacity to develop conventional water sources, such as boreholes and large dams. Developing economies such as South Africa are likely to favour, in terms of water allocation, industry and mining because they are perceived to play a more significant roles in the economy. However, persistent food shortages, low income and a lack of investments resulting in high dependency levels are common among smallholder farmers in rural South Africa. Previous interventions that have been promoted to smallholders provide little buffer against dry spells and droughts and seem to suggest that ASALs are hydrologically marginal, have no significant agricultural potential and any attempts to intensify agricultural activities would lead to severe environmental degradation.

Many countries in SSA, including South Africa, have recently enacted natural resources (notably water) management and utilization legislation with more emphasis on catering for the needs of all stakeholders as well as present and anticipated water shortages. However, crop production among rural smallholder farmers has not improved, nor has the local economic revitalization and improved livelihoods that these transformations were intended to deliver. It has been suggested that if the water sector policy changes could be accompanied and augmented with reforms and strategies in the agriculture sector that directly address the plight of

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smallholder rainfed farmers with less emphasis on irrigation, more benefits are likely to be obtained.

In this paper attempts aimed at improving household food production and income through suitable rainwater harvesting and utilization technologies in Potshini catchment, Thukela basin, South Africa, are evaluated. It was found that in most years, over 80% of the community in the study area ran short of food barely four months after harvest. Rainfall amounts and distribution were most influential in governing the biomass produced. The observed yields were 67.3%, 39.5% and 79.4% of the potential grain yields in no-tillage (N_T) systems in 2005/06, 2006/07 and 2007/08 season, respectively. The corresponding values in conventional tillage (C_T) systems were 64.8%, 38.5% and 79.1% of the potential yields. There was consistently more total biomass in N_T compared to C_T treatments, although not significantly different ($p \leq 0.05$) in some cases. This suggested that N_T influences water partitioning at field scale. The Parched-Thirst (PT) model was applied in an attempt to extrapolate this study, but did not sufficiently simulate the observed biomass. Although N_T was shown to improve maize yields, its adoption was limited. Vegetable gardening was found to be a promising supplementary activity to household food and income. However, to optimize this untapped potential, it was recommended that biophysical and policy interventions skewed to address the unique constraints of resource-poor smallholder rainfed farmers must be combined.

Keywords: Biomass, gardens, policy, rainwater harvesting, yield.

8.1 Introduction

The search for solutions to insufficient food production to meet current and future human needs is one of the main challenges to humankind today. Almost 190 countries committed to the UN Millennium Development Goals (MDGs) that, among its targets, aims to reduce by half the 800 million food insecure people by the year 2015. This, in part, compels countries to enact policies that upon implementation could eradicate poverty and inequality as well as improve physical and economic access to all, at all times, to sufficient, nutritionally adequate and safe food. This is an enormous task in sub-Saharan Africa (SSA) and south-east Asia where according to Inocencio et al. (2003), 60% of the world’s food-insecure people and 75% of the world’s malnourished children live.

Although Benson (2005) argued that it is the responsibility of national governments to ensure that individuals attain food security, hunger, malnutrition and dependence was estimated to affect approximately 33 percent of the population in SSA (IAC, 2004). Because of its economic primacy over other African countries, one would assume that South Africa is better than many countries elsewhere in SSA. However, this economic strength has not been translated into easy access to food, water and other essentials in many rural communities. Approximately 2.3 million households in South Africa cannot meet their daily food requirements (De Lange, 2007). Furthermore, under-nutrition among South African children is rising (Oldewage-Theron et al., 2006) which according to De Lange (2007) has had far-reaching effects reflected not only by the children's physical impoverishment but irreversible damages on their intellectual development. In addition to biophysical challenges common among smallholder farmers that contribute to low food production, the situation in South Africa suggests inadequate conditions and/or institutions that can enable food to be secured from cash incomes or access to productive resources i.e. suitable land, adequate water and capital.

Table 8.1: Deficiencies that impact yields and possible solutions among smallholder farmers in semi-arid areas where conventional irrigation is not feasible due to resource constraints (After Rockström, 2003)

Deficiency	Causes	Management options
Low plant water availability	• Low and poorly distributed rainfall • Poor soil infiltrability and low water holding capacity • High soil evaporation losses	Soil management - Appropriate tillage - Crop rotation - Soil fertility management Water management - Water harvesting - Weed control - Mulching
Low plant water uptake capacity	• Poor rooting system • Poor vegetative growth	Soil management - Appropriate tillage - Crop rotation - Soil fertility management Crop management - Crop selection - Pest and disease management - Timing of operations

Inadequate water (Lal, 1991; Postel, 1999; Seyam et al., 2002; Rockström, 2003) and poor soils (Foth and Ellis, 1997; Klaij and Vachaud, 1999; Fox and Rockström, 2000; Rockström and Falkenmark, 2000; Lafond et al., 2006) have been commonly linked to low food production in developing countries. In addition, their complementary interaction could lead to poor water partitioning and moisture and nutrient use inefficiency (Rockström, 1999; Gowing, 2003; Heerink, 2005; Breman et al., 2001; Wichelns, 2006). The causes and possible interventions to mitigate against these crop production deficiencies are summarized in Table 8.1.

Chapter 2 and Chapter 3 investigated the frequency of occurance of dry spells and water partitioning, respectively (low plant water availability in Table 8.1) in relation to the success of maize production. The role of soil physical properties and their influence on hydraulic properties (infiltrability and water holding capacity in table 8.1) under maize production in two tillage systems (soil management in Table 8.1) were analyzed in Chapter 4-6. One water management option (water harvesting in Table 8.1) was evaluated in Chapter 7. Thus, the objective of this study was to evaluate the efficiency of the aforementioned approaches to address the deficiencies identified in Table 8.1 among smallholder farmers in Potshini Catchment, Thukela basin. The maize production trials under different tillage practices and agronomic variables were set up in summer (Nov-May) from 2001-2004 and 2005-2008 under the ARC LandCare and SSI programmes, respectively. The Parched-Thirst model (Young et al., 2002; SWMRG, 2006) was used to simulate maize (*Zea Mays L.*) production. In winter (Jun-Oct), the possibility of producing a variety of vegetables was examined. The contribution of the tailored water and agriculture sectoral reforms was also investigated and recommendations made.

8.2 National context

In South Africa, rainfall is strongly seasonal and highly irregular in occurrence. This, combined with topography results in more than 60% of the country's river flow arising from only 20% of the area (Schulze, 1997). These seasonal and regional variations in rainfall often complicate the national water balances. Backeberg (2005) claimed that over the past few years, droughts have increased in many parts of the summer-rainfall areas, including the Thukela basin (xref. Chapter 2, Section 2.3.3). The South Africa water resources statistics are summarized in Table 8.2 and Table 8.3.

Table 8.2: Water yield by source in South Africa in 2000 (After DWAF, 2000)

Sources	Million m^3/yr	%
Surface water (excluding return flows)	10,928	78.5
Groundwater	1,042	7.5
Usable return flow	1,941	14
Total	13,911	100

Though the chances of absolute water shortages may be low in South Africa (Backeberg, 2005), the aforementioned rainfall variability and the substantial reliance (92.5%) on surface water (Table 8.2), suggest a great challenge that demands efficient allocation and use of existing water resources.

Table 8.3: Water requirements by sector in South Africa in 2000 (After DWAF, 2000)

Sectors	Million m^3/yr	%
Irrigation	7,836	59.0
Urban	3,332	25.1
Rural	572	4.3
Mining and bulk industrial	756	5.7
Thermal power generation	296	2.2
Afforestation (impact on yield only)	488	3.7
Total	13,280	100

Agriculture plays an important role in income generation, food security and poverty reduction and has skewed South African water management towards the irrigation sector (Backeberg, 2005), which is the highest consumer of water (Table 8.3). However, irrigation contributes between 25 to 30 percent of gross food production which accounts for only 4–5% in terms of GDP (WRC, 2000). This amount of water allocated to the irrigation sector is likely to be reduced in the near future to pave way for domestic water supplies, as barely half of the country had been provided with domestic water services by the mid-1990's (Ralo et al., 2000). A growing global perception that water for agriculture has low value relative to other uses, perhaps because of low efficiencies in large irrigation schemes that cost huge sums of money to implement, could further jeopardize the already over exploited agricultural water. Developing economies such as South Africa are likely to favour, in terms of water allocation, e.g. electricity generation through steam turbines relative to irrigation needs because "industry" now plays a more significant role in the economy.

Rainfed agriculture, commonly linked with the deficiencies in Table 8.1 and practiced by almost all smallholder farmers due to their inability to obtain or maintain access to reliable and safe water (Hope et al., 2005), is responsible for about 20% of food production in South Africa. Although this seems low, one can only appreciate its value when compared with the cost of purchasing food from supermarket outlets which is met with a lot of financial strain. Futhermore, there is anunexploited potential to improve smallholder rainfed agriculture. However, this contribution has not received the desired recognition from policy makers and planners who instead have concentrated on conventional irrigation systems (Lankford et al., 2004) which according to Pottinger (2006) are not as efficient as small scale water harvesting projects that the author described as having reduced poverty on a much broader and more sustainable level, particularly in countries with large rural and poor populations. With rapidly growing formal and informal urban settlements and the shift towards industrialization in South Africa, water allocation for agriculture is likely to yield to higher-value urban uses, further emphasizing the significance of and the need to "upgrade" rainfed agriculture. These are formidable challenges; on one hand it is desirable to increase water allocation to domestic users and industries while on the other it is necessary to make more water available for food production. Furthermore, reserving water for environmental needs that could reduce available water resources for other existing uses by 15-20% in the country (Inocencio et al., 2003 citing Smakhtin, 2002) could lead to conflicts and violence (Lankford et al., 2004) that aggravate the problem of food security (IFPRI, 2001 in Fox et al., 2005). Another challenge is the presence of trans-boundary basins i.e. the Orange, Limpopo, Inkomati and Usutu/Pongola, shared with six neighbouring countries.

Land is regarded an important resource locally, regionally and even internationally and its possession whether individually or communally, is closely associated with one's identity in most rural communities. According to Binns and Nel (2000), the apartheid law in South Africa saw the majority of the population access less than 13% of the land surface, a state that led to environmental degradation due to its capacity being exceeded and could partly be responsible for existing social and economic disparities. Agricultural water rights from surface water are still based on ownership of land (DWAF, 1998a) and hence do not cater entirely for the interests of farmers with tiny parcels of unregistered ancestral land and landless workers, the majority of whom inhabit ASALs (Kuyvenhoven, 2004). Although this situation is being corrected with the government's initiation of redistribution of land ownership programs (Kuyvenhoven, 2004 citing Van Zyl et al., 1996; De Janvry et al., 2002), its success is yet to be recognized because of frequent stand-offs between government and the farmers who own large tracts of land. According to Malefane (2008), the government now insists that the white farmers should relinquish part of their land for "public purpose" and "public interest" as stipulated in the South African Constitution and will not compensate them the demanded "fair market price". The author pointed out that the government was committed to increase black-owned farming land from the present 4.7% to 30% by 2014. Thus, South Africa is still faced with challenges incorporating social and equity factors to accommodate the needs of previously disadvantaged communities.

While South Africa has had several water sector reforms for close to a century, a comprehensive program began after the 1994 democratization process. Backeberg (2005) provided a summary of water institutional reforms that occurred mainly after 1994. The reform process culminated into a new national water policy, a National Water Act (NWA) and a national water resources strategy intended to address existing and projected water scarcity, its deteriorating quality and environmental requirements as well as previous discriminatory laws and practices in water allocation. The new NWA, Act No. 36 of 1998 (DWAF, 1998a), made provision for water to be protected, used, developed, conserved, managed and controlled in a sustainable and equitable manner. This required a new approach to agricultural water use as NWA set four milestones that focused on smallholder farmers intended to address the inequalities resulting from past policies. These were: a) rehabilitation of existing irrigation schemes; b) determination of the development capacity of new irrigation; c) establishment of effective organizations to implement policy; and d) increased efficiency of water use. These broad objectives have detailed targets and delivery mechanisms in the water resources (DWAF, 1998b) and agriculture (NDA, 2002) policy documents, respectively. Thus, in a way the policy reforms in the water sector directly influenced the agriculture sector, but attention was only on existing and projected irrigation schemes. Smallholder farming mostly occurs in remote areas, commonly associated with hilly terrain and thus not easily accessible to rivers or streams. Thus, even though the Act provides them with water rights, technically they are unable to utilize them. Furthermore, they possess tiny unregistered ancestral land parcels that may not be consolidated and hence they may not benefit fully from the provisions of the Act.

Tailored policies that are packaged to address the immediate biophysical, social and economic resource constraints of smallholder rainfed farmers in the South African set-up are still scarce. Capacity building in a variety of aspects of crop production and water management need to be incorporated in the package. The LandCare programme (NDA, 1999), was probably a cross-cutting initiative because its goal was to optimize productivity and sustainability of resources so as to result in greater productivity, food security, job creation and a better livelihoods of rural households. In the water sector, a good example is the financial assistance programme for resource poor farmers (DWAF, 2004). According to DWAF (2007), those eligible for the support must have been previously disadvantaged, in possession of, or have access to agricultural land, have a water use authorization, except where financial assistance for acquisition of water entitlement is required, and have agricultural water use development needs and are unable to raise finance for that purpose. The farmers need to make applications to DWAF and their approval is based on meeting the basic requirements and the availability of funds.

In this paper the impact of innovative soil magement practices, soil profile moisture storage, the additional benefits of water stored in tanks and the contribution of partnerships and policies towards household food and income generation is summarized with examples drawn from the LandCare and the SSI programmes. The experiments shared the same sites except that there was an addition site (F_C) in the latter programme. The experiments were linked because the SSI programme (2005-2008 experiments) build on the findings of the LandCare programme (2001-2004 experiments) which focussed on tillage and soil fertility management. The SSI's experiments attempted to quantify water fluxes, changes in soil hydraulic properties and maize biomass on limed plots under two tillage systems. Farmers and other stakeholders in the Potshini catchment were involved in the implementation of both of these programmes.

8.3 Study area

8.3.1 Location, climate and soils

The focal research site, the Potshini catchment (29.37^0E, 28.82^0S) is situated in the western headwaters of the Thukela River. It lies in the foothills of the Drakensberg Mountains at an altitude of 1100-1400 m amsl. The higher elevation areas comprise communal grazing land. Part of the catchment is shown in Fig. 8.1. The divide between the grazing zone and cultivated area is a source of a number of seasonal streams which flow in incised gullies and provide water used for domestic purposes, livestock watering and recently gardening in the upper part of the catchment, while replenishing reservoirs for commercial farmers downstream. Although the mean annual rainfall is approximately 710 mm (Kosgei et al., 2007), it is highly erratic and falls only in summer (Oct-Mar). The mean annual potential evaporation is approximately 1750 mm per annum (Smith et al., 2004). The daily mean temperature is about 16.4^oC and the minimum and maximum temperatures recorded since 2004 are -4^oC and 34^oC, respectively.

Figure 8.1: Part of the Potshini catchment in June 2005. The main stream flows through the gully in the middle of the picture and is gauged with an H-flume slightly upstream of the dirty road running across the gully

The moist upland grassland dominant in the area has a good early-season growth and palatability, but deteriorates rapidly during winter (especially from May-Aug) due to intensive grazing and frequent occurrences of frost, which has also frustrated efforts of producing certain vegetables. Hutton (*Oxisols*) and Avalon (*Ferralsols*) soil types[22] dominate the less fertile Estcourt (*Planosols*) and Mispah (*Lithosols*) soils. However, according to Smith et al. (2001) soil acidity and a lack of sustainable farming systems are major constraints to crop production.

8.3.2 Land use and food production

Dry land subsistence agriculture and pastoralism are the dominant land uses since none of the community members have access to water for conventional irrigation, a practice common among large scale farmers who produce at least two crops per year in the immediate vicinity of the smallholder rainfed farmers in the Potshini Catchment. Per capita income levels in the catchment are generally low, about one-half of the national average (DWAF, 2001 in Taylor et al., 2001), as a large proportion of the farmers possess small land parcels, practice subsistence

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[22] FAO classification in parenthesis.

agriculture, are resource-poor and have many dependents (Kosgei et al., 2007). This has further been worsened by the HIV/AIDS pandemic which has reduced the active labor force through illness, loss of productive time while attending the sick or deaths, making many households vulnerable to hunger.

Through the SSI programme (xref. Chapter 1), one hundred and five households were interviewed in the Potshini catchment in 2006 to assess their food production and sufficiency. The average number of persons who reside in these households for over six months in a year was 700, 64% being females. The age structure of the community was 47% under 15 years, 23% between 16 and 25 years, 18% between 26 and 50 years and 12% over 50 years. These findings reflect the observation made by Kruger (2007) that:

- Children remain in rural areas in the care of relatives and friends (mainly older men and women who no longer play an active economic life);
- Young persons aged between 20-49 years migrate to the cities in search of employment;
- Rural communities consist of more women than men; and
- People who fall ill in the cities return home to be cared for.

Thus the rural community is largely made of older people and children. Considering that most of the age group of 16 – 25 years is school going, only the 26 – 50 year category are likely to be actively involved in food production. However, as observed by Kruger (2007) a large number of the persons in this category move out of the rural communities to find other opportunities in the neighboring large scale farms or in the cities. Therefore, a small proportion of the community is responsible for food production.

The unit land area per household was found to be approximately 2 ha. However, these are fragmented parcels of unfenced land that could be kilometers apart. Excluding the communal grazing ground (Fig. 8.1), the total cropped area accounted for about 68% of the total land area, while the households and other infrastructure occupied about 20%. The rest of the land was under natural pasture. However, large gullies have developed in the grazing areas and have become potential areas for runoff build up which has caused erosion in the cultivated fields. The main crop planted was maize which was common to all the respondents, except about 2% who did not cultivate any crops because they were aged and/or sick. The other crops grown, summarized in Fig. 8.2(a), are beans, potatoes, sorghum and pumpkin.

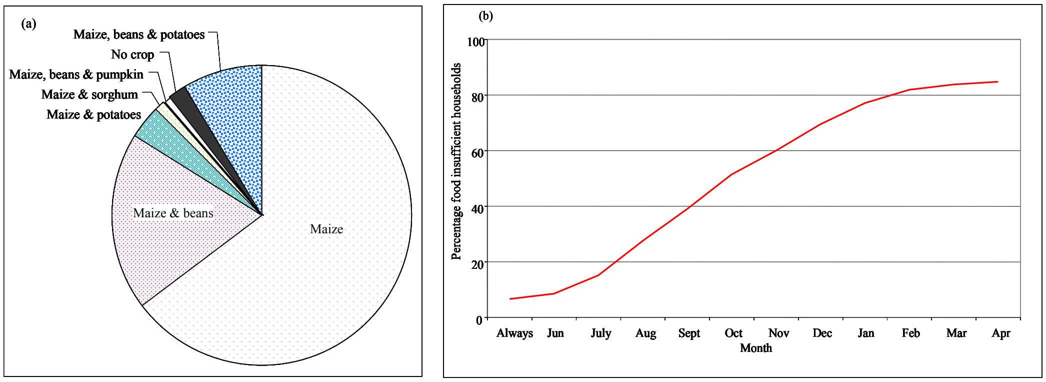

Figure 8.2: Proportion of households (a) cultivating different types of crops (b) without sufficient maize in Potshini catchment (n=105) in 2006

Although the agro-ecological zone in which the Potshini catchment is situated seems suitable for legumes such as dry beans, most of the farmers felt that seed was not readily available. However, a fair number of them acknowledged their ignorance of the crop while others cited limited land. It was not possible to establish the actual yields since over 90% of farmers never weighed their farm produce at harvest. However, a few farmers managed to estimate the general trend of maize yields which was about 1-2 tons.ha^{-1}. The respondents cited dry spells (xref. Chapter 2, Section 2.3.5) and acidic soils as major contributors to this meager yield. Nonetheless, some farmers involved in a “LandCare” programme, had adopted conservation agriculture and reported yields of over 7 tons.ha^{-1}.

About 8% of the farmers sold their maize to millers while only 1% sold beans. The sale of maize was not necessarily targeting surplus maize but rather as a consequence of improper storage structures which forced them to sell to avoid post harvest losses. Close to 85% households bought maize flour as early as November even though they had sold their own maize in July (Fig. 8.2b). Although only 2% of the respondents did not grow any crops, up to 7% indicated that they buy maize flour all the year round, suggesting that about 5% do not realize any harvest at all. Commercial farmers rented part of their modern storage bins, which a few smallholder farmers who can afford transport cost and the storage charges, utilized. This accounted for about 15% of the community who should be considered food sufficient.

Five sources of income were identified by the respondents and are used to purchase maize/maize flour. These were government remittances (94%), formal employment (11%), unskilled labor (10%), skilled labor (2%) and others (5%). The arithmetic sum of percentages exceeds 100% due to reliance by some farmers on multiple sources of income. The "other sources" included practicing traditional herbal medicine commonly known as 'Sangoma' among the Zulu community. This huge reliance on government remittances to access food indicates that this community is vulnerable to hunger and may not make meaningful investments in agricultural production unless the packages are tailored to accommodate their resource limitations.

Vegetable as well was reported by most of the households to be sourced all the year round from Bergville, a small town situated 7 km away. The main reasons cited were the lack of reliable sources of water in winter and inadequate knowledge in vegetable gardening. Only 6% of the homesteads had gardens by the end of 2004 which were all active only in summer. This suggested that the Potshini Catchment was similar to other parts of the country since NDA (2000) reported that less than 10% of households in South Africa plant food in the homestead yard. However, 52% of households in the Potshini Catchment had homestead gardens actively involved in vegetable production throughout the year by 2006. An attempt was also made to capture the main source of the gardening initiative. Two percent of the households adopted gardening from their neighborhood while 40% attributed it to the Smallholder System Innovations (SSI) in Integrated Watershed Management programme (Rockström et al., 2004) under which this study was done. The remaining 10% were sensitized through the ARC LandCare programme (NDA, 1999). These two programmes had the common goal of assessing and addressing biophysical constraints to crop production among smallholder rainfed farmers for better livelihoods and sustained ecological functioning.

8.4 Case studies

Broca (2002) argued that no country anywhere in the world would achieve food security as per the World Food Summit definition in 1996 and suggested four dimensions of food which need to be assessed. These are (i) food availability, (ii) food access, (iii) food utilization and (iv) stability of access. It is important to note that all four dimensions have to be in place before it can truly be said that an individual is food secure. In this paper, case studies which focus only on attempts to improve food availability through on-farm experimentation and crop diversification that was made possible by relevant policy interventions and building partnerships are presented and lessons from each are synthesized.

8.4.1 Bergville (Emmaus) LandCare programme

According to Smith et al. (2001), the Bergville (Emmaus) LandCare project (2000–2004) was intended to generate and diffuse new, appropriate land management technologies for local farmers in order to address soil degradation and conservation issues and to aid in solving production problems in order to increase farm productivity and income in the Bergville district of KwaZulu-Natal. Field scale experiments were performed in the Potshini Catchment at a communal trial site (Fig. 8.1). The experiments were used to determine whether a collection of technologies, based on conservation agriculture principles, could function, in a technical and biological sense, in the physical environment of the Bergville area (Smith, 2006). These included comparisons of tillage systems (conventional versus no-till), application of lime (Dolomite lime from Newcastle in KwaZulu-Natal) in various quantities and methods (0, 3, 6 and 9 tons.ha^{-1} broadcasted or applied in strips) and two levels of fertilizer (current and recommended) levels (Smith et al., 2002). Soil samples were taken from each plot at a depth of 20 cm at the end of each season for laboratory analysis of six soil cations i.e. phosphorous (P), potassium (K), calcium (Ca), magnesium (Mg), acid saturation (pH) and organic carbon (C).

Sixteen "lead" farmers, two from Potshini catchment participated in trials in their own fields aimed to improve experiential learning, improve modification and dissemination of technologies to local farmers, increase awareness among farming communities and facilitate farmer-to-farmer extension and training. These farmers, and later on their trainees (farmer-to-farmer extension approach), were provided with the necessary inputs for the 1000 m^2 plot as well as training on how to apply these inputs. Maize from both the communal and the farmer fields was harvested at the end of May in each season. At the communal trial site, costs of all input resources were recorded. The yield was regarded as the output and the income was calculated at an average rate of R900 per ton of maize for all the four seasons. The difference between the income and the input costs was considered as the benefit from the various treatments.

8.4.1.1 Results: communal trial site.

At the communal trial site, the average maize yield was 4.54, 3.88, 3.93 and 2.7 ton.ha^{-1} in the 2000/01, 2001/02, 2002/03 and 2003/04 seasons, respectively which were not significantly different. The application of lime resulted in an increase in pH, with better response from treatments where lime was applied in strips. The application of the recommended fertilizer in the non-limed plots resulted to an increase in soil pH of at least 13% by the end of the experiment. There was a strong positive correlation between pH increases and availability of Mg, an element known for its role in photosynthesis and the formation of plant tissue. The increase in Mg could have resulted in an elaborate root system and plant canopy which increased the amount of water transpired and altered the water flow paths at field scale. Thus, having favourable soil chemical properties could reduce unproductive soil evaporation losses in favour of crop transpiration and lead to a higher water productivity. However, in this study, a general decline in yields was observed through out the four seasons.

The decline in yields was linked to moisture deficits of 7 mm, 99 mm, 64 mm and 74 mm in the 2000/01, 2001/02, 2002/03 and 2003/04, respectively. Crop water deficits that occurred in February did not have severe impacts on yield compared to those that occurred in December-January or in March. The early season period (Dec-Jan) coincides with germination and initial stage while March falls in the grain-filling stage in maize having a time to maturity of over 140 days. Since the severity and timing of the dry spells (xref. Chapter 2, Section 2.3.5) play a critical role in determining the total biomass and crop yield produced per unit area, their inclusion in rainfall partitioning processes (xref. Chapter 3, Section 3.4.2-3.4.5) make them more relevant to farm management. Although there was a decline in the average yields, the lowest was still twice as much as the typical range of yield in the area. Thus, the experiment indicated that better yields can be obtained by addressing soil deficiencies.

Calculations of gross margins for the communal trial site showed that treatments in which lime and/or fertilizer were applied did not give positive returns from 2001/2002 season onwards perhaps because of the limiting moisture. This suggests that water is the primary limiting factor of crop production and verified Rockström et al. (2004) who observed that the high risk of yield reducing droughts and dry spells could be a critical factor in explaining smallholder farmers' tendency to adopt risk aversion, characterized by minimum or lack of investments in inputs, rather than production maximization strategies. It further emphasized the observation made by Hilhorst and Muchena (2000) in Hatibu and Rockström (2005) that smallholder farmers addressed crop failure due to dry spells and drought before they considered investments in soil fertility, improved crop varieties, and/or other yield enhancing inputs.

8.4.1.2 Results: Lead farmers

According to Smith (2006), the average yield in 2003/04 was 4.9 tons.ha^{-1}, compared to 3.2 tons.ha^{-1} in 2002/03, 3 tons.ha^{-1} in 2001/02 and 2.3 tons.ha^{-1} in 2000/01 (baseline). Some farmers even obtained yields of over 7 ton ha^{-1} in 2003/04, indicating increases of over 300% in relation to the baseline. The trend in yield from the lead farmers, although not identical throughout the experimental period, was positive as opposed to the result of the communal trial site. This was attributed to local soil heterogeneities and cultural practices such as weed control which farmers may have done it more frequently than at the communal site. Twomlow (1994) viewed timeliness of planting, soil hydrological properties and weed control as the most important constraints to good yields from rainfed crop production. Another factor that can contribute to low yield is a poor water-fertilizer balance. Application of the recommended fertilizer as done at the communal trial site combined with the correct liming scheme could have enhanced the development of elaborate rooting systems that created a huge demand for water that was not adequately met by the variable rainfall.

By 2003/04, 56% of the lead farmers had converted the rest of their fields to conservation agriculture. Although acknowledging the limitation of access among smallholder farmers to lime, Smith (2006) using yields of the 2003/04 season from the farmer-managed trials suggested that substantive gross margins can only be realized with intercropping and crop rotations that annually maintained liming at 1 ton.ha^{-1}. However, the author was optimistic of a continued liming programme supported by the Department of Agriculture, without which declining yields are likely to be realized. This study demonstrated that water is the primary limiting factor to improved yields in Potshini catchment although soil deficiencies also play a significant role. Due to a low rainfall, lime and fertilizer costs were responsible for negative returns. Therefore, the challenge for attaining improved yields in ASALs calls for a combination of improved land and water use techniques while general farm management practices such as timing of operations, selection of proper seed varieties etc are adhered to.

8.4.2 The Smallholder System Innovation (SSI) programme

To address the challenges of increasing food production and improving rural livelihoods, while safeguarding other critical ecological functions, the SSI programme (Rockström et al., 2004) selected the Potshini catchment based on the challenges facing smallholder rainfed farmers in Bergville such as droughts and dry spells (xref. Chapter 2, Section 2.3.5). Therefore, the programme intended to seek viable and cost-effective ways that smallholder rainfed farmers can use to mitigate these natural hazards. It also wished to capitalize on the presence and achievements of the Bergville LandCare project (Section 8.4.1) and was envisaged to compliment the work already done (Smith, 2006). One dimension of the SSI research continued with field scale experiments at four sites: the existing LandCare communal trial site (C_{TS}), the fields of the two lead farmers (F_A and F_B) from the Potshini catchment working with the Bergville LandCare project and an additional farmer's field (F_C) (*xref. Chapter 3, Section 3.3.2*). The focus of the experiments directly complimented the work done by the LandCare project, with the aim to identify and quantify the different water fluxes in conventional and no-tillage systems (Chapter 2) with the goal to provide information regarding rainfall partitioning and water productivity in summer (Nov-May).

Each of the four experimental sites was equipped with devices to monitor the water transition processes for three seasons (2005/06-2007/08). A summary of the measured parameters and various equipment and tests performed is provided in Table 8.4. More details have been provided in Chapter 3 and Kosgei et al. (2007) regarding field instrumentation, land preparation, sowing and monitoring of fluxes while Chapters 4, 5 and 6 dwelt wth infiltration responses to tillage. Random sampling (n = 5) of vegetative biomass, also referred to as Net Above Ground Primary Production (NAGPP) was performed on 27th May 2006, 26th May 2007, 15th February 2008 and 5th June 2008. The samples were analyzed in the laboratory for equivalent depth of water[23] (EWD) and dry biomass.

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[23] Amount of water contained in the maize stalks translated into a depth of water over a unit area (hectare).

Table 8.4: A summary of the measured parameters and equipment used in the field and in the laboratory to monitor and explain water transitions under no-till and conventional tillage in Potshini catchment from 2005-2008

Parameter(s)	Equipment/Method	No. of stations	Measurement frequency	Remarks
Field Measurements				
Climatic parameters: Rainfall (mm); Temperature(°C); Relative humidity (%); Solar radiation (J/m^2/hr); Wind speed (m/s); Wind direction (°); and Soil temperature (°C)	Weather station	1	Continuous measurements averaged into 15-minute intervals	Installed at a convenient locations. Data from another weather station 4 km away complemented.
Rainfall (mm)	Manual rain gauges	At each experimental site	Daily	Voluntarily monitored by farmers.
Runoff (litres)	Runoff plots with tipping buckets	At every experimental plot	When bucket fills up and tips over	Equipped with event loggers to measure outflow from each study plot.
Geographic coordinates (°) and slope (%)	GPS and Theodolite	All experimental plots and selected transects	Once	Setting up runoff plots and recording terrain and geographic coordinates
Volumetric moisture content (%)	TDR and access tubes	At every experimental plot	Weekly	Measurement to a depth of up to 1.5 m; manually done.
Soil water potential (mm)	Granular matrix (Watermark®) sensors	At every experimental plot	15-minute intervals	Provide indication of moisture transitions in the soil.
Saturated water content (-)	Wetting front detectors	6 gardens	When saturation is achieved	Indicator pops out at saturation
Soil resistivity (Ω)	RM15-D resistivity meter	At all experimental plots	Once (July 2007)	Provide indication of moisture content.
Hydraulic conductivity (cm.min^{-1})	Tension disc and double ring infiltrometers	At all experimental plots	December 2007, February 2008 and April 2008.	Provide indication of water infiltration and transmission.
Laboratory measurements				
Soil textural classification	Bouyoucus method, hydrometer	At all experimental plots	Once	Sedimentation preceded sieving
Particle density (g.cm^{-3})	Blake & Hartage (1986), 500 ml flask	At all experimental plots	Once	500 ml flask used instead of pcynometer
Bulk density (g.cm^{-3})	Core rings, weighing scale, oven	At all experimental plots	December 2007, February 2008 and April 2008.	In 2007/08 season samples at 20 cm deep and within rows included
Water retention (cm^3.cm^{-3})	Weighing scale, oven, outflow cells, pressure cells	Some experimental plots	May 2008	Outflow cells failed before all samples were analyzed
Net Above Ground Primary Production (NAGPP) (tons.ha^{-1})	Weighing scale, oven,	At every experimental plot	May 2006, May 2007, February and June 2008.	NAGPP was estimated at the end of the season except in the 2007/08 season.
Grain yield (tons.ha^{-1})	Weighing scale, oven.	At every experimental plot	May 2006, May 2007 and June 2008.	Fresh weight standardized to 12.5% moisture content (Kosgei et al., 2007)

Because rainfall mainly occurs only in summer, smallholder farmers are active in crop production only during this period. This practice causes land and labour to be underutilized and thus lowers food production per unit land area. Furthermore, as indicated by the analysis of the findings from the LandCare project, maize grain yields were affected by severe intra-seasonal dry spells because the adopted in-situ water harvesting approaches are only effective to mitigate mild dry spells. Thus, the second thrust of the SSI programme was to investigate ways to provide adequate and timely root-zone moisture that could be applied whenever it is desired. Runoff based rainwater harvesting involving direct application into the soil profile or through temporary storage for supplemental irrigation was seen as an opportunity to yield stability with less risk of crop failure and could allow crop diversification e.g. vegetable gardening (xref. Chapter 7). Availability of water may also provide incentives to invest in other crop management practices that further improve yields.

This study explored the potential (supply versus demand) of runoff harvesting, soil profile storage, suitable and relatively low-cost storage tanks as well as water application methods using three innovative management approaches that occasionally overlapped. Firstly, farmer mobilization and sensitization on water harvesting for crop production commenced. To complement a needs' assessment process which was conducted through formal and informal sessions, the aforementioned survey involving 105 households was undertaken in 2006 using semi-structured interviews (Section 8.3.2) which captured the following key issues:

- Household demographic information;
- Size of land, tenure, crops grown, yields, food sufficiency;
- Awareness and/or participation in innovative initiatives e.g. water harvesting;
- Size of vegetable garden, fencing material, source of water, application method.

The second thrust involved the investigation of the potential for runoff harvesting and to identify the biophysical factors that determine suitable sites for rainwater harvesting structures. The storage capacity necessary to irrigate a garden of 200 m^2 was estimated and the use of polythene sheet as an alternative lining material to typical building materials for underground rainwater storage structures was explored and a 54 m^3 storage structure was constructed (xref. Chapter 7). De Winnar et al. (2007) utilized Geographic Information Systems as an integrating tool to store, analyze and manage spatial information that was linked to a hydrological response model to provide catchment level identification, planning and assessment of runoff harvesting sites in the Potshini catchment.

Finally, Sturdy et al. (2008) engaged farmers in garden experiments using various participatory learning and action research tools. Comparative studies of methods in which runoff was both generated within field or from an external catchment and subsequently applied directly into a conventionally tilled soil profile or trench beds were done. Various water sources and water application techniques were investigated. A series of farmer learning workshops were conducted in collaboration with a Water Research Commission (WRC) project aimed at developing training materials for water use in homestead farming systems, funded under a national policy for financial assistance to resource poor farmers (DWAF, 2004). Rural Integrated Engineering (RIE) Ltd was the approved legal entity (DWAF, 2007). Further details are provided in RIE (2008), Sturdy (2008) and Sturdy et al. (2008). The policy on financial assistance to resource poor farmers (DWAF, 2004) is seen in this study as one of the more promising tailored policies that directly engages the constraints of rainfed farmers.

8.4.2.1 Results: Maize vegetative biomass (NAGPP), equivalent water depth and grain yields.

The three seasons of field experiments were characterized by varied rainfall and weather patterns. A summary of the monthly rainfall amounts (amount that occurred after sowing), crop water requirements (CWR) and crop water deficit (CWD) is given in Table 8.5. The rainfall amounts and patterns influenced the level to which crop water requirements (CWR) were satisfied. The CWR were calculated using the FAO Penman-Monteith approach (Allen et al., 1998). On a decadal basis, the difference between observed rainfall and CWR was taken as the CWD. The results were summarized in monthly time-steps. The rainfall in May was considered not to have any influence on the CWR and CWD. All the seasons experienced some CWD in December and April, thus affecting germination and grain filling, respectively. The 2006/07 season experienced the highest cumulative CWD and also had deficits in each month. The lowest seasonal CWD was observed in the 2007/08 season.

CWR is a function of evapotranspiration which is affected by temperature and humidity, among other factors. The CWR in both the 1st and 3rd year is less than 75% that of the 2nd year. This suggests that there could have been higher heat units in the 2nd year that contributed to more growth despite the intra seasonal soil water deficit which was more pronounced in this year. There were also more rain days (71) in the 2nd year compared to those of the 1st year (56).

Table 8.5: Monthly rainfall, CWR and CWD over three seasons in Potshini Catchment

Season	Month	Rainfall (mm)[24]	CWR (mm)	CWD (mm)
2005/2006	December	31.50	169.69	138.19
	January	137.70	118.69	0.00
	February	153.60	93.79	0.00
	March	110.10	98.88	0.00
	April	18.80	104.25	85.45
Total		451.70	585.29	223.64
2006/2007	December	76.00	181.12	105.12
	January	96.10	185.28	89.18
	February	52.40	176.63	124.23
	March	55.00	149.17	94.17
	April	57.00	138.06	81.06
Total		336.50	830.25	493.75
2007/2008	December	116.20	152.88	36.68
	January	112.60	135.20	22.60
	February	110.20	110.15	0.00
	March	160.60	106.16	0.00
	April	41.40	110.56	69.16
Total		541.00	614.95	128.44

Net Above Ground Primary Production (NAGPP) and Equivalent Water Depth (EWD)

The mean NAGPP, grain yield and the total biomass are presented in Table 8.6. The total biomass was obtained by the summation of NAGPP and the corresponding grain yield. The means of the factors by which NAGPP in N_T exceeded that in C_T, illustrated in Fig. 8.3, were 1.45, 1.43, 1.58 and 1.66 in May 2006, May 2007, February and June 2008, respectively. Values below the 1:1 line in Fig. 8.3 indicate cases where there was more NAGPP in N_T compared to C_T. The magnitude of the difference is represented by the relative distance from the 1:1 line.Except at site F_C in May 2006 and February 2008 as well as site F_B in June 2008, there was consistently more NAGPP in N_T. On average NAGPP was greater by a factor of 3 in June 2008

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[24] Amount of rainfall that occurred after sowing

than in May 2007, suggesting dissimilar rainfall amounts and/or patterns (Chapter 3, Section 3.4.2). NAGPP increased by a similar margin between February and June 2008. There was a significant difference ($p<0.05$) in NAGPP between N_T and C_T at site C_{TS}. A significant difference between NAGPP measured in February and June 2008 was observed only in N_T treatments indicating that the rate of increase in NAGPP between February and June was higher in N_T than in C_T. This is attributed to more moisture retention (xref. Chapter 3, Section 3.4.4) and perhaps increase in microbial activity commonly associated with conservation agriculture practices (e.g. Arshad et al., 1990; Unger, 1991).

Table 8.6: Average NAGPP measured during harvest, grain yield and total biomass over the three seasons

Parameter	Season	2005/2006		2006/2007		2007/2008	
(Tons.ha^{-1})	Estimator/Tillage	N_T	C_T	N_T	C_T	N_T	C_T
NAGPP	Mean	6.71	5.43	7.36	5.53	24.98	15.32
	Standard Deviation	0.79	2.01	1.01	1.43	10.27	10.59
Grain yield	Mean	3.68	1.66	3.22	3.09	5.95	4.85
	Standard Deviation	1.61	0.59	1.00	0.94	1.48	2.24
Total biomass	Mean	10.39	7.09	10.58	8.62	30.93	20.17
	Standard Deviation	1.20	2.39	1.19	1.52	10.59	10.48

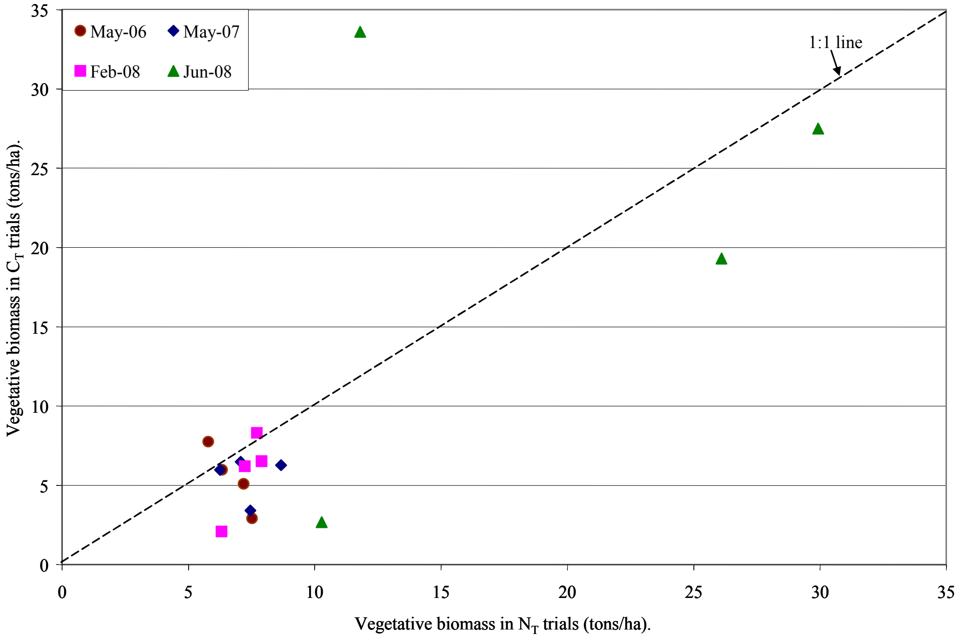

Figure 8.3: Comparison of vegetative biomass between N_T and C_T systems during the three periods

Grain yields

Grain yields for the three seasons are illustrated in Table 8.6 and Fig. 8.4. The average yields in C_T plots were 1.66, 3.09 and 4.85 tons.ha^{-1} in the 2005/06, 2006/07 and 2007/08 seasons while the corresponding mean yields in N_T plots were 3.68, 3.22 and 5.95 tons.ha^{-1}, representing yields increase factors of 2.22, 1.04 and 1.23 with respect to yields from C_T treatments. The standard deviations are provided in Table 8.6. Except in the 2007/08 season yields from C_T plots were less variable in relation to those from N_T. However, in all the three seasons, lower means were obtained from C_T treatments suggesting that use of no-tillage improves grain yields (Fig. 8.4). Values below the 1:1 line in Fig. 8.4 similarly indicate cases where there was more grain yield in N_T compared to C_T. The magnitude of the difference is represented by the relative distance from the 1:1 line.

The grain yield from both treatments varied from season to season with C_T means increasing each season while the lowest mean in N_T was obtained in 2006/07 season. Rainfall characteristics could have influenced this. For example the total rainfall between November and May was 522.7, 443.6 and 599 mm in 2005/06, 2006/07 and 2007/08 seasons, respectively.

However, the amount that fell after sowing was 463.6, 336 and 541.2 mm, respectively (xref. Chapter 3, Section 3.4.2).

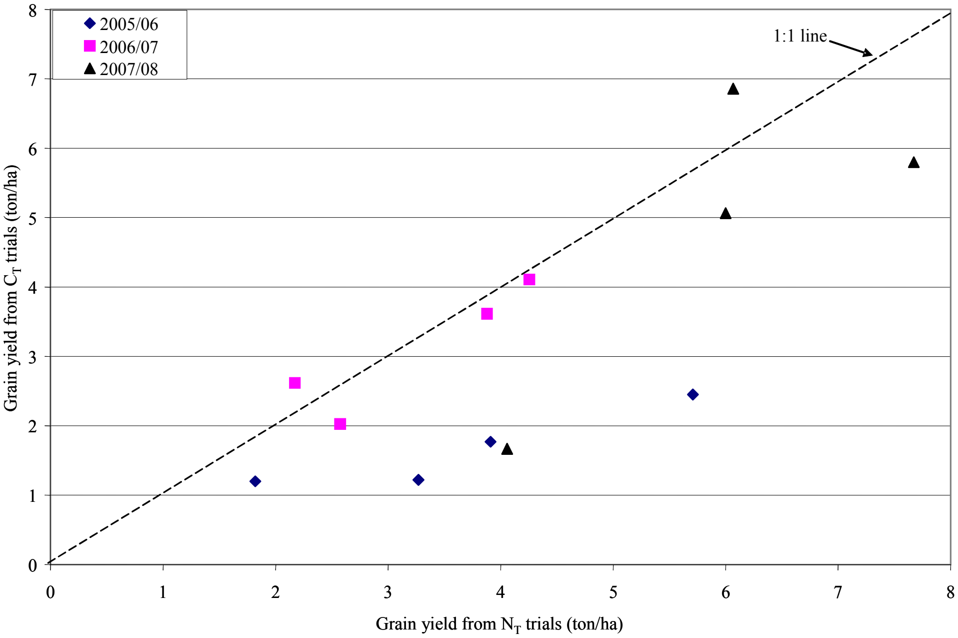

Figure 8.4: Comparison of grain yields between N_T and C_T systems during three seasons

The mean yields from N_T followed the pattern of in-season rainfall indicating that the success of no-tillage is influenced by rainfall amounts and perhaps distribution, thus the 2006/07 season having the lowest in-season rainfall led to yield from C_T being only 4% less than what was obtained in N_T. This difference could also be attributed to absence of surface sealing that inhibits infiltration which is common in ploughed soils when rainfall intensity and/or amounts are high. In fact during this season the mean runoff generated from N_T and C_T was 29.1 mm and 23.5 mm, respectively (xref. Chapter 3, Section 3.4.3). In the 2005/06 the corresponding mean runoff generated was 26.5 mm and 37.2 mm while in 2007/08 the mean values were 35.9 mm and 55.5 mm, respectively. Thus, there was potentially more moisture held in the soil in C_T treatment in 2006/07 season compared to N_T while the reverse occurred in the other seasons (xref. Chapter 3, Section 3.4.4). However, in the 2006/07 season more unproductive losses such as soil evaporation (xref. Chapter 3, Section 3.4.5) could have been responsible for the reduction in yields from C_T treatments.

N_T gave substantial increase in growth that was hard to trace back to a physical soil measurement. However, at the start of the season, there is more runoff from N_T while at later stages the runoff from C_T is higher (perhaps due to surface sealing). There are several possibilities:

- Most of the additional water retained in C_T at the beginning of the season is lost to soil evaporation;
- The balance of water retained (less runoff and soil evaporation) in N_T at this initial period is adequate for a successful germination;
- At vegetative stage, there is more biomass (higher leaf area and larger stem diameter) in N_T treatments thus reducing direct soil evaporation and since the total evaporative demand is constant, the will be an increased transpiration.
- Because of growth in relatively drier conditions as a result of higher soil evaporation and lower infiltration, C_T plots are likely to have poor root development, weak stems and leaves dry up earlier. Hence, a possibility of low biomass and grain yield.

Thus, although there is no physical soil property, there is a conversion of soil evaporation into useful transpiration (shown to be higher in N_T) and this explains the increase in growth.

Water productivity analysis

Although grain yield is the common measure of the success of farming systems, Fig. 8.3 and Fig. 8.4 show that this component of biomass is only a fraction of the vegetative biomass. Thus, it is important while evaluating the contribution of water to crop production to also consider vegetative biomass as the entire plant is utilized as animal fodder and, potentially in the second generation of cellulotic bio-fuel generation. In ASALs severe dry spells do lead to substantial grain yield reduction or even complete crop failure. These spells could occur at an advanced growth stage and failure to consider the vegetative biomass already produced results in very low or null water productivity. Water productivity in this context is a ratio of the biomass produced (tons) to the amount of water (mm) used to produce the biomass. The water productivity (WP) of grain yield (WP_g) and total biomass (WP_t) over the three seasons are illustrated in Fig. 8.5 and Fig. 8.6, respectively.

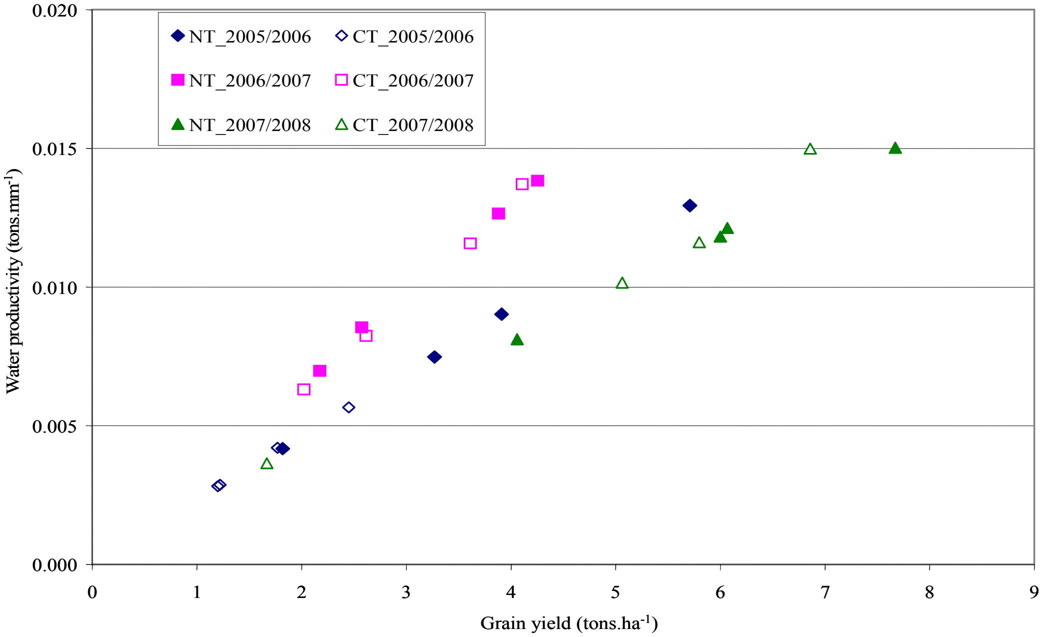

Figure 8.5: Water productivity (tons.mm^{-1}) of grain yield (ton.ha^{-1}) from four trial sites from 2005/2006 to 2007/2008 season. C_T and N_T denote conventional tillage and no-tillage, respectively

The grain yield response to net rainfall varied between sites, tillage and season. The mean WP_g in N_T treatments was 0.008 (±0.0036) tons.mm^{-1}, 0.010 (±0.0033) tons.mm^{-1} and 0.012 (±0.0028) tons.mm^{-1} in 2005/06, 2006/07 and 2007/08 seasons, respectively. The respective mean values from C_T treatments were 0.004 (±0.0013) tons.mm^{-1}, 0.010 (±0.0033) tons.mm^{-1} and 0.010 (±0.0048) tons.mm^{-1}. The 2007/08 season had higher WP_g in both tillage systems although the corresponding variability was the smallest in N_T while it was the largest in C_T in the three seasons. Interesting though was the similar mean WP_g in C_T in 2006/07 and 2007/08 in spite of differences in grain yields. This suggested that there was better utilization of net rainfall in 2006/07. There was no significant differences ($p \leq 0.05$) in WP_g from all sites in C_T treatments. However, there were significant differences in WP_g between seasons 2005/06 with both 2006/07 and 2007/08. Significant differences from N_T treatments were observed between sites F_A and F_B as well as F_A and F_C. Nevertheless, there were no significant differences between any two seasons.

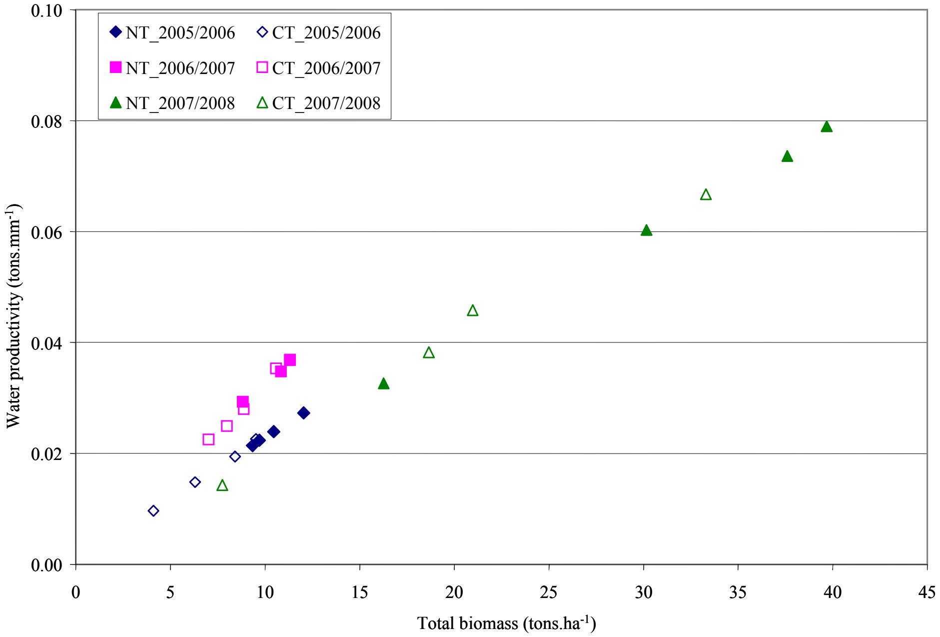

Figure 8.6: Water productivity (tons.mm^{-1}) of total biomass (tons.ha^{-1}) from four trial sites from 2005/2006 to 2007/2008 season. C_T and N_T denote conventional tillage and no-tillage, respectively

Based on the estimated WP_g and CWD in Table 8.5, and assuming that all the CWD could have contributed to increases in grain yield, an additional 1.79, 4.94 and 1.54 tons.ha^{-1} of grain could have been obtained in 2005/06, 2006/07 and 2007/08 seasons, respectively from N_T treatments. Thus, the potential yield from N_T treatments for the three years was 5.47, 8.16 and 7.49 tons.ha^{-1}, respectively. This indicates that the observed yields were 67.3%, 39.5% and 79.4% of the potential grain yields over the three seasons, respectively. In C_T treatments an additional 0.90, 4.94 and 1.28 tons.ha^{-1} could have been realized giving potential yields in these treatments of 2.56, 8.03 and 6.13 tons.ha^{-1}. The observed yields were 64.8%, 38.5% and 79.1% of the potential yields, respectively.

The water productivity based on total biomass (WP_t) was much higher in all cases as compared to WP_g. The inclusion of NAGPP generally distinguished the 2007/08 season from the previous seasons. This season had much higher NAGPP compared to the other two seasons. The mean WP_t in N_T treatments was 0.024 (±0.0026) tons.mm^{-1}, 0.034 (±0.0036) tons.mm^{-1} and 0.061 (±0.0207) tons.mm^{-1} in 2005/06, 2006/07 and 2007/08 seasons, respectively. The respective mean values from C_T treatments were 0.017 (±0.0056) tons.mm^{-1}, 0.028 (±0.0056) tons.mm^{-1} and 0.041 (±0.0216) tons.mm^{-1}. There were no significant differences ($p \leq 0.05$) in WP_t between experimental sites or tillage systems. However, significant differences were observed between the following seasons in N_T treatments: 2005/06 and 2006/07; 2005/06 and 2007/08; and 2006/07 and 2007/08. The only significant difference in WP_t from C_T treatments was between 2006/07 and 2007/08 seasons.

In Chapter 3 Section 3.4.4, there was evidence of more seasonal moisture retention in N_T treatments relative to C_T treatments and as discussed above, there was a significant difference between NAGPP measured in February and June 2008 only in N_T. This growth increase was attributed to more moisture retention since all factors remained the same in the two tillage treatments. More biomass reflects increased transpiration which indicated that water was not limiting. In addition there was no visible confining material in N_T that could have held water which was not tillage related.

Crop response to additional moisture

The findings above underscored the ability of N_T systems to capture and store more moisture relative to C_T and hence result in higher WP. Doorenbos and Kassam (1979) proposed an empirical relationship illustrating a crop yield response to available water which has been used to study the additional amount of moisture attributed to conservation tillage e.g. Ngigi et al. (2006). The additional moisture storage is reflected as increased crop water use and thus the incremental grain yields (Eq. 8.1).

$$\theta_s = \frac{\left(1 - \frac{Y_{CT}}{Y_{NT}}\right)}{K_y - \left(1 - \frac{Y_{CT}}{Y_{NT}}\right)} \qquad (8.1)$$

where θ_s is the additional soil moisture storage (%), Y_{CT} and Y_{NT} are maize yields from conventional and no-tillage treatments, respectively. K_y expresses the effect of soil moisture deficit on yield and varies with crop stage. However, a weighted yield response factor for the entire season in maize was approximated to be 1.25 (Doorenbos and Kassam, 1979). According to Ngigi et al. (2006), this additional moisture indicates the part of rainfall that was captured and stored within the root zone by virtue of a better tillage system and thus represents the percentage of runoff reduction from croplands that adopt the particular tillage practice.

Using the same approach but considering WP_t instead of WP_g as used by Ngigi et al. (2006), the average θ_s was 40.2%, 18.6% and 47.0% in 2005/06, 2006/07 and 2007/08 seasons, respectively. The measured runoff reduction due to adoption of N_T was 28.8%, -23.8% and 35.3% in the three seasons, respectively (xref. Chapter 3, Section 3.4.3). This suggested that θ_s cannot be equated to the runoff reduction but rather is influenced by the amount of water that infiltrates into the soil. As seen in 2006/07, there was 18.6% additional moisture, yet there was more runoff from N_T relative to C_T. Thus, θ_s should be treated as a measure of both infiltrated water and the efficiency by the plants to utilize moisture and should be related to total biomass rather than grain yield alone. This could result from synergistic interaction whereby good soil structure in N_T enables a robust rooting system that creates good canopy which in turn reduces soil evaporation as well as increasing the amount of water transpired.

Parched-Thirst (PT) model simulation of vegetative biomass and grain yield

The crop growth model (PARCH), a sub-model of the PT model was used to simulate maize vegetative biomass and grain yields under both N_T and C_T systems. The sub-model uses a daily time step to simulate crop growth. On each day, the resources of light, water and nutrients are converted into assimilated matter. In this study, light and water were the limiting factors to growth as nutrients were kept constant. Climatological parameters and rainfall data used were obtained from a weather station within the research site. The rainfall-runoff process was simulated as infiltration excess with infiltration being determined using the Green and Ampt (1911) equation (xref. Chapter 3, Section 3.4.6). The input profile properties included crop, soil and soil surface characteristics. A maize population of 37,000 plants per hectare was used. Soil textural properties determined from laboratory samples and soil hydraulic properties estimated from field infiltration tests (xref. Chapter 4 and Chapter 6) were inputs. An average slope of 3% for each runoff plot measuring 24.5 m^2 was used.

The means and standard deviations of NAGPP, grain yield and total biomass predicted using the PT model are provided in Table 8.7. In all seasons, the simulated statistics from N_T were higher than those from C_T. The ratios of NAGPP from N_T to that from C_T were 1.59, 1.89 and 1.81 in 2005/06, 2006/07 and 2007/08 seasons, respectively. The grain yield was 1.80, 1.92 and 1.92 times more in N_T relative to C_T over the three seasons while the corresponding ratios of total biomass were 1.62, 1.90 and 1.83, respectively. This showed that in the model, the soil hydraulic parameters are modified by tillage and in this case N_T enabled more water infiltration and storage which led to more biomass relative to C_T. Thus, the predicted trend in NAGPP was similar to the observed.

Table 8.7: Average NAGPP, grain yield and total biomass over the three seasons obtained from the PT model simulation

Parameter	Estimator	2005/2006		2006/2007		2007/2008	
(Tons.ha^{-1})		N_T	C_T	N_T	C_T	N_T	C_T
NAGPP	Mean	18.28	11.48	7.23	3.82	17.34	9.59
	Standard Deviation	6.05	6.56	3.57	3.52	7.02	6.43
Grain yield	Mean	3.15	1.75	2.78	1.45	5.82	3.03
	Standard Deviation	1.43	1.13	1.40	1.25	2.56	2.05
Total biomass	Mean	21.44	13.23	10.02	5.27	23.16	12.62
	Standard Deviation	7.47	7.67	4.97	4.77	9.58	8.47

A comparison between the measured and the simulated grain yields and total biomass is shown in Fig. 8.7. There was a relatively better agreement (Fig. 8.7a) between the predicted and the measured grain yields from N_T treatments (R^2=0.71) as compared to the relationship in C_T (R^2=0.39). An even poorer relationship was obtained in both tillage systems when predicted total biomass was plotted against the observed values (Fig. 8.7b). This suggested that the PT model is not very accurate in predicting NAGPP. Good estimates of NAGPP were obtained during low rainfall seasons e.g. 2005/06 when the mean error margin was 1.77% and 30.92% in N_T and C_T plots, respectively. However, the NAGPP during the relatively higher rainfall 2007/08 season was underestimated by the PT model. Thus, the PT model seems to be more applicable to drier conditions than the current research area. In addition, because it is both a rainfall-runoff and crop growth simulation model, it is being constrained by the amount of runoff generated as well as the biomass produced. Hence it is not easy to fully optimize the simulation which leads to low values of R^2. However, as indicated in Chapter 3 (Section 3.2), the PT model combines the simulation of hydrology with growth and yield of a crop on any number of distinct or indistinct runoff producing areas and runoff receiving areas, thus making it more applicable for water productivity studies such as in this case.

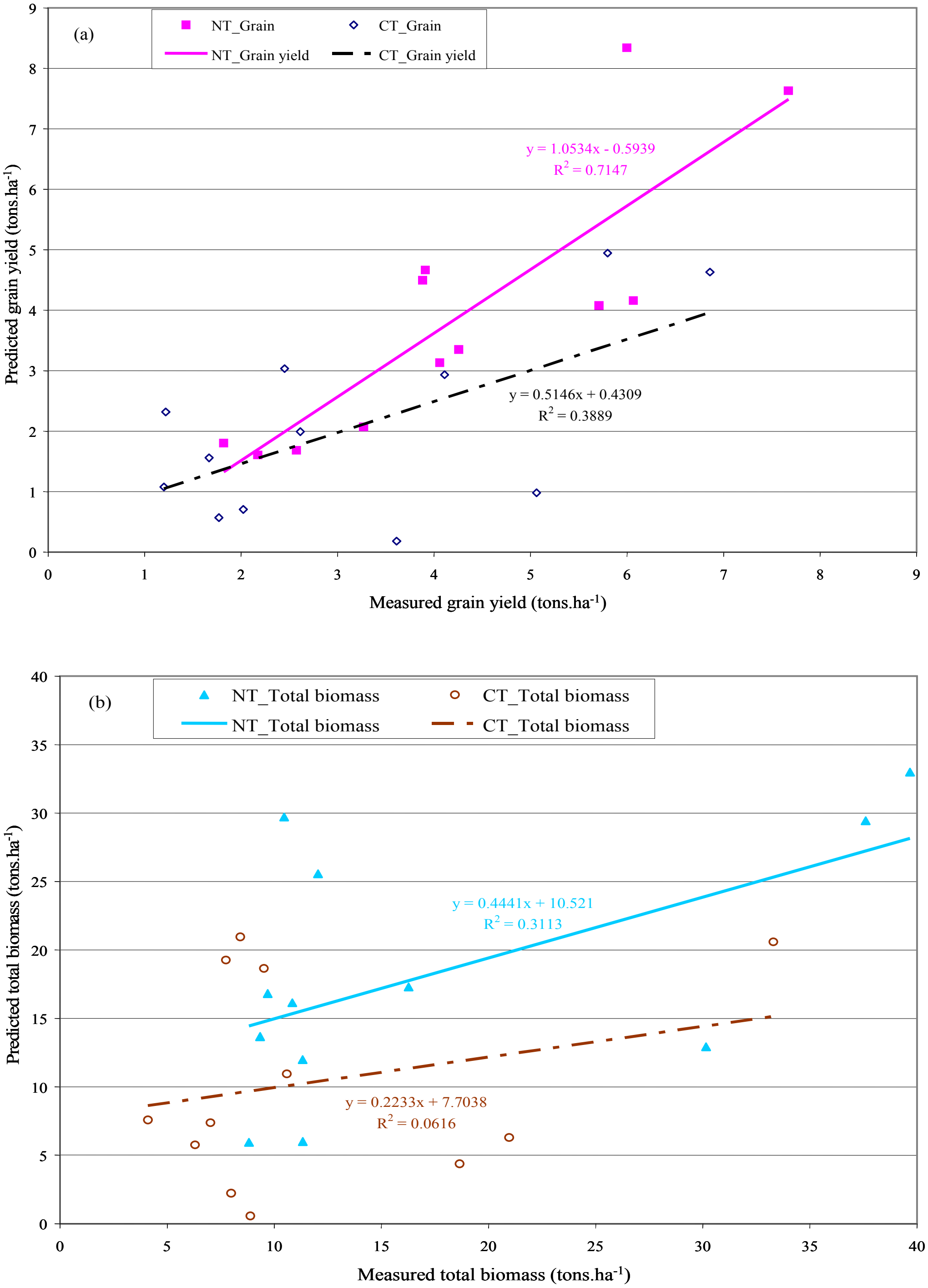

Figure 8.7: (a) Predicted versus measured grain yield; (b) predicted versus measured total biomass in N_T and C_T treatments from 2005/06 to 2007/08 season in Potshini catchment

The input parameters into P-T include measure soil properties e.g. hydraulic conductivity which was different in N_T and C_T. Using these properties the rainfall-runoff routine in P-T partitions the same rainfall into soil water storage, evaporation, transpiration and runoff. Thus, although it did not result to the same measured values of runoff or measured soil water content it differentiated runoff and soil water between N_T and C_T. Using the available radiation and the partitioned soil water, P-T differentiated yield between N_T and C_T. Thus P-T could be suitable for comparative studies.

8.4.2.2 Results: Runoff harvesting and utilization

As shown in Section 8.2.2, there is a high dependency on maize in Potshini and over 80% of the households have to source it externally only a few months after harvesting. Vegetables were reported by most of the respondents to be sourced all the year round from Bergville. Lack of reliable sources of water in winter and inadequate knowledge of vegetable gardening were the main reasons cited. By the end of 2004, only 6% of the homesteads had gardens all active only in summer. Some of these homesteads made attempts towards sourcing water for winter vegetable gardening by either tapping shallow groundwater or by excavating small shallow depressions that held a few hundred litres of water (xref. Chapter 7, Section 7.2).

This component of the study investigated the possibility of introducing runoff harvesting storage structures from impervious courtyards and roofs of thatch and corrugated iron sheets. An underground tank of about 54 m^3 lined with polythene was designed and constructed at one of the homesteads in Potshini (xref. Chapter 7, Section 7.5). This was used to water vegetable trials in an area of 200 m^2. The area occupied by cabbages, tomatoes, potatoes, spinach and onion was 80, 40, 40, 20 and 20 m^2, respectively. Part of the garden is shown in Fig. 8.8. A drip irrigation system with button drippers was used to irrigate vegetables in normal beds and in trench beds. Moisture profiling was only undertaken in blocks with cabbages (Brassica oleracea var. Drumhead) although the other vegetables were similarly drip-irrigated. The cabbages were planted at an inter-plant and inter-row spacing of 45 cm and 60 cm, respectively and matured after 140 days.

Two moisture probe tubes, 60 cm deep, were installed in each bed, one within the vegetable row and another between the rows. Laterals fitted with button-type drippers were laid along each row. The trench beds were prepared by excavating the soil to a depth of 60 cm and repacking with the aim of improving its porosity. The normal beds were ploughed to a depth of about 15 cm using hand hoes. Soil moisture was measured using a TDR every three days at 10 cm, 30 cm and 50 cm depths representing the 0-20 cm, 20-40 cm and 40-60 cm profiles, respectively. Generally, irrigation was applied after 60% depletion or when indications of water stress were observed. Thus, the frequency was increased towards maturity. The available water per meter depth of soil type used was estimated at 120 mm. The active soil profile for vegetables was considered to be 60 cm. Thus the lowest allowable soil moisture depth was 28 mm, which corresponded to a volumetric moisture content of about 21% in the current soils.

Figure 8.8: Various vegetables irrigated using water harvested and stored in an underground tank at one of the households in Potshini catchment. Inset: tank and treadle pump

Water from the sub-terrainean tank was pumped using a treadle pump into a 250-litre raised plastic tank (Fig. 8.8) from where it was distributed through a main line feeding several laterals by gravity. The supply head was approximately 2 m. Filters at the suction side of the pump and immediately before the main line were used to eliminate dirt. Irrigation started with a small amount of water, but was applied twice a week. This was because the roots of the vegetables were still shallow and applying lots of water at once could have been wasteful. The amount of irrigation water applied was measured using a graduated scale attached to the inner wall of the tank. A rainfall event of 30 mm in the second week of September which occurred after 20 mm-irrigation, supplemented the crop water requirements and greatly increased the soil moisture. The applied water and weekly average soil moisture variation from the four tubes monitored for 20 weeks are illustrated in Fig. 8.9.

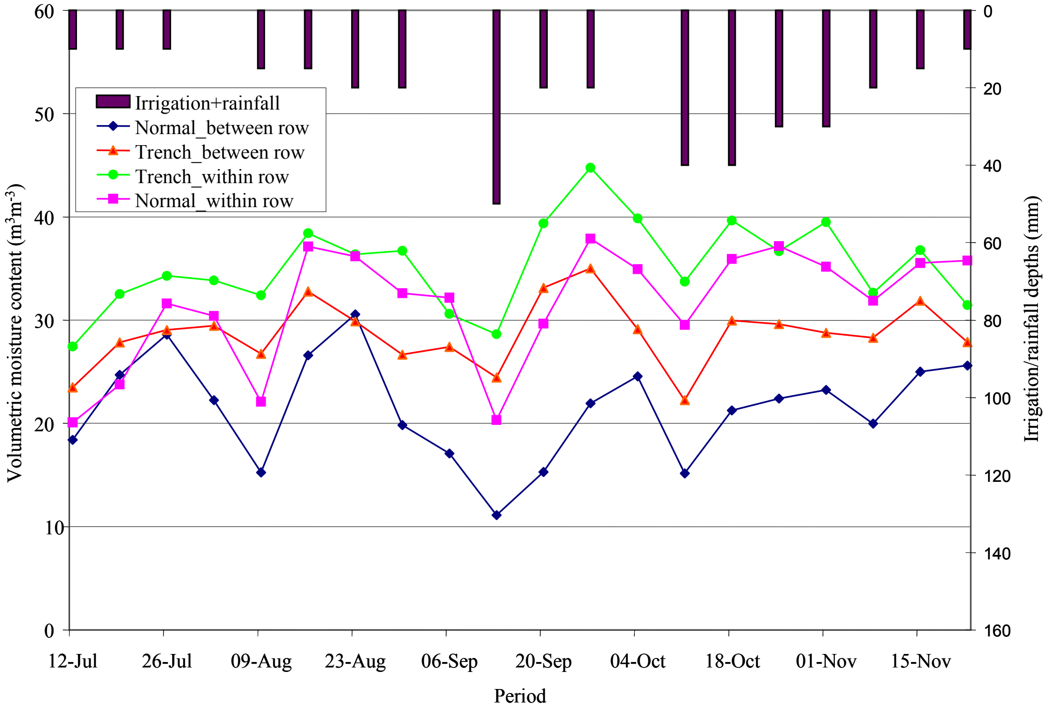

Figure 8.9: Mean volumetric soil moisture variation under different watering systems in Potshini catchment. The bars indicate rainfall events

Irrigation water was only applied along the rows. The amount of irrigation water applied to the cabbages was 375 mm distributed as follows: 30, 70, 90, 110 and 75 mm in July, August, September, October and November, respectively. The mean soil moisture was 17.64%, 14.34%, 15.74% and 10.72% from probe tubes in the trench bed within row (T_W), trench bed between rows (T_B), normal bed within row (N_W) and normal bed between rows (N_B), respectively. The lower soil moisture between rows showed that drip irrigation systems effectively provided water to the root zone. Although the same amount of water was applied, the trench beds had higher soil moisture relative to the normal beds suggesting that they had a better water holding capacity. There was more moisture fluctuation in the normal beds compared to the trench beds and in all cases except once, the moisture measure at T_W was always above 30%. Thus, the trench beds are likely to be more useful in ASALs where infiltration and storage of water from rainfall needs to be optimized. There were significant differences ($p \leq 0.05$) in volumetric moisture contents between all the treatments except between T_B and $N_{W.}$ This suggested that there was better moisture distribution in the trench beds which enabled measurements between rows to be insignificantly different from those within the rows in normal beds.

At maturity, the cabbages were harvested continuously when need arose. The vegetables were being consumed by the household as well as sold to community members. However, at harvesting the weight of the heads was taken using a hand scale. The average weight per head from the trench bed was 2.52 (±0.38) kg while that from normal bed was 2.28 (±0.14) kg. The additional moisture retention in trench beds produced relatively higher yield. Therefore, using trench beds resulted in approximately 20 $kg.mm^{-1}$ of rainfall per hectare more yield, compared to normal beds. From cabbages alone, about R500.00 was obtained from sales after satisfying the household vegetable needs.

The other vegetables produced simultaneously with cabbages were onion, spinach, tomatoes and potatoes which used 450, 300, 375 and 250 mm of irrigation water, respectively. This indicated that from the 1900 mm tank capacity and subtracting the 30 mm contribution from rainfall, the tank had a balance of 300 mm at the end of the season. However, from the rainfall some runoff was collected and thus the balance was more than 300 mm. This amount of water could have produced another crop. Thus, in winter months that have rainfall, water requirement of the crop in the field is supplemented and more water is collected into the storage tank.

8.4.2.3 Results: Participatory capacity building and stakeholder engagement

Training on the use of the harvested water was identified by the farmers as a prerequisite to the water harvesting efforts. Being a genuine and timely concern, with the assistance from the local Department of Agriculture, a comprehensive training curriculum was drawn up and implemented by the outreach component of SSI programme spearheaded by Farmer Support Group (FSG) of the Centre of Environment, Agriculture and Development, University of KwaZulu-Natal. This farmer mobilization and sensitization precipitated into formation of two Farmer Learning Groups in early 2007. Due to the type of issues these groups considered, which were not only related to agriculture but touching on their livelihoods as a whole, they became known as Farmer Life Schools (FLS). Farmers were immediately enthusiastic and Sturdy et al. (2008) engaged them further in garden experiments using various participatory learning and action research tools. The FSG provided additional financial and marketing training and assisted farmers to secure markets for their vegetables in Bergville. A stock taking exercise in mid 2007 showed that the FLS members began to develop their gardens using whatever resources available.

Figure 8.10: Various types of fencing materials used for gardens in the Potshini catchment: (a) grass and poles; (b) corrugated iron sheets and poles; (c) wood; and (d) pieces of metal standards and mesh

The sizes of the gardens varied widely with the largest being about 150 m^2. Most of the gardens were having an area of about 60 m^2. The gardens were fenced with a wide range of materials (Fig. 8.10). Many households desired a fence made from poles and mesh and reinforced with standards. This was seen as secure from livestock and poultry. However, due to inadequate resources, the majority (29%) fenced it with poles and thatch. Nevertheless, these gardens proved to be warmer during extremely low temperatures and also the grass acted as a windbreak. This allowed sensitive crops like tomatoes to be planted.

A common problem faced by the most of the farmers is the durability of their fences. Poles and thatch were damaged by wild fires in winter while the others were easily pushed aside by cattle grazing within the cropping fields in winter. Therefore the efforts of having crop production through out the year may not be sustainable unless proper fencing is secured. As shown in Section 8.2.2, a large proportion of the community relies on government remittances and may not be able to purchase the necessary fencing materials. This remains a challenge even when the community is equipped with knowledge and skills in vegetable production.

Water for irrigation was obtained from a number of sources. These included community boreholes, seasonal streams, underground tanks, shallow wells and roof-tanks. A summary of the relative number of households using each source is provided in Fig. 8.11. About 45% of the homesteads relied on water from seasonal springs that dry up by late July.

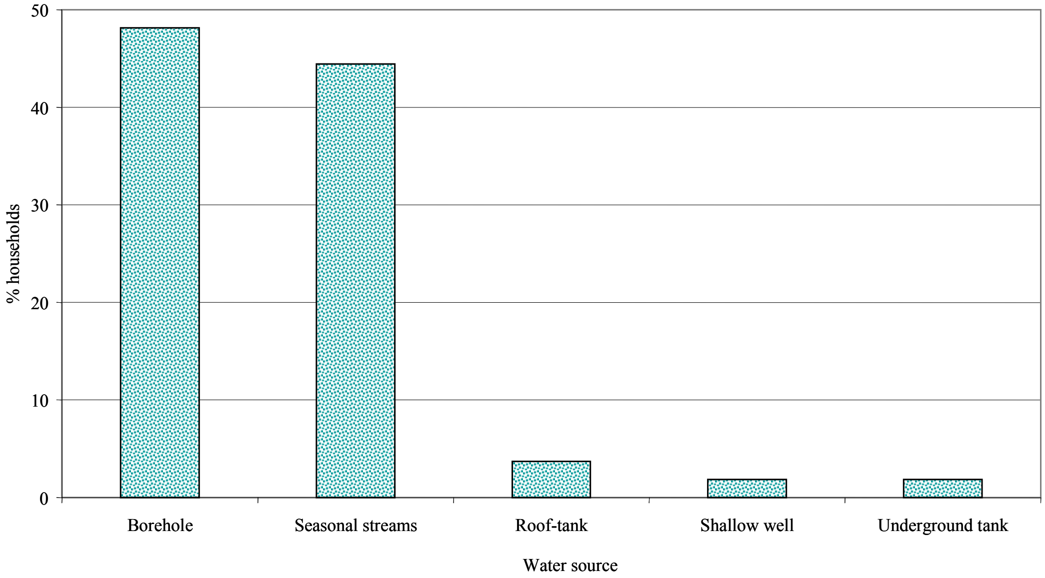

Figure 8.11: Relative proportion of households utilizing a particular water source for watering gardens in Potshini catchment (n=40) by 2006

Except for the underground tanks, roof-tanks and the shallow wells, the other sources are community resources that are not intended for use for agricultural purposes. Thus, developing alternative sources of water through harvesting of rainwater from ignored sources such as ephemeral and gully flows as well as roofs of structures was seen as a way of providing water for crop production when the resource is scarce and to avoid conflicts in the community as well.

However, as stated earlier, financial resources required to put up such structures are not readily available within the community.

Faced with these challenges, whilst it has been shown that the potential of water harvesting and utilization is immense and could have major benefits for rural livelihoods, the SSI programme through the FSG engaged some of its collaborators and stakeholders to provide financial support to this community so as to implement the tested technologies. Through its policy on financial support for smallholder irrigation farmers (DWAF, 2004), the Department of Water and Forestry (DWAF) in conjunction with a Water Research Commission (WRC) project developing learning materials for water use in homestead farming systems, funded the construction of three underground tanks of capacities ranging from 25 – 30 m^3. Each tank was worth about R 22,000 (Kahinda et al., 2007). The households provided manual labor during excavation. Support to fund more tanks through this policy is promised. Further reading regarding the implementation of this financial support in Potshini can be accessed in RIE (2008), Sturdy (2008) and Sturdy et al. (2008).

The Okhahlamba municipality, in which the Potshini catchment lies, was approached and supported the FLS with fencing material for 20 gardens measuring 200 m^2 each. The fencing material comprised of posts, chain links and standards (Fig. 8.12a). The FLS members provided labor to construct the 20 homestead gardens. The remaining FLS members who did not receive fencing materials are to benefit in the next financial year. This partnership between the SSI programme with DWAF, WRC and the Okhahlamba municipality as well as other players e.g. the Department of Agriculture demonstrated the great extent to which viable technologies can contribute to livelihoods of resource-poor communities when financial support to put up the necessary infrastructure is available. There was a "great leap", whereby farmers who never had the opportunity to produce vegetables from their own gardens (not even in summer) but purchased it through out the year, instead earned some income. The FSG assisted members of the FLS to secure markets for their vegetables in Bergville. For a household of 7 persons the community approximates a monthly expenditure of R250.00 on vegetables. Without considering gifts that is a way of life in this community, with proper planning each household could make a gross income of R25.00 per day. De Lange (2006) reported a daily income of R6.46 from vegetable sales in rural South Africa without considering household consumption. The author made the following remarks that are also applicable in the current study:

- The daily income seems to be low until it is compared with the statement that “half of South Africans survive on R20.00 per day” ; and
- Without the gardening initiatives the communities do not have an easy access to vegetables for household consumption and thus no pathway out of malnutrition and stunted growth among pre-scholars.

Figure 8.12: The “great leap” – from a thatched fence to the market (a) FLS members collecting fencing material provided by Okhahlamba municipality; (b) well protected vegetables; (c) farm-gate sales; and (d) FLS members taking their produce to supermarket outlets at Bergville (Photos (a) and (b) courtesy of Michael Malinga – FSG)

In addition, although this is a gross income, it is considered an effective use of labor because during winter, there is hardly any economic activity and therefore there is no opportunity cost involved. The essence of targeting a 200 m^2 garden was to first satisfy household vegetable needs. However, as shown above a family could make an average gross income of R 25.00 per day from selling the surplus vegetables. Since the market is not entirely external, this income is expected to decline if other farmers in the study area adopt gardening. What won’t change is that the household will be self sufficient of variety vegetables, saving expenditure on vegetables and having an improvement in the quality of diet. Therefore vegetable production is practical among rural smallholder farmers and is capable of increasing household incomes, even if it is only "virtual" (i.e. able to produce just enough for household consumption).

8.5 Discussion

8.5.1 Diversity of agriculture in the South African context

Royen and Sigwele (1998) identified the relationship between the agriculture sector and other sectors in the economy together with the way in which it is treated in the political process as the factors that determine the contribution of the sector in the economic transformation of a country. Depending on a country's core economic sectors and its level of development, the authors highlighted four phases in which agriculture can operate based on the direction of flow of resources (mainly labor and finances): (i) phase 1 – the majority of a country's revenue is extracted from agriculture; (ii) phase 2 – agriculture as key generator of economic growth; (iii) phase 3 - integrating agriculture into the economy; and (iv) phase 4 - agriculture in industrial economies. In South Africa, the contribution of agriculture to the economic transformation of the country can be said to be mainly visible in the first three phases, though at varying levels, where 90% of the country's food is grown by commercial farmers but contributing only 12% to the GDP.

To build a productive agriculture for smallholder farmers such as those in the Potshini catchment requires that resources be devoted to the agriculture sector itself (phase 1). Although people are engaged in the sector throughout the year, the turn-over is very low and most of the time they do not have adequate financial resources. For example, according to Modi et al. (2006), many rural households cannot afford to buy vegetables or the inputs required to grow them, despite the continued urge from health workers to increase vegetable consumption. Similarly, improved crop production initiatives such as rainwater harvesting with storage introduced in the Potshini catchment have been challenged directly by poverty. Although many households acknowledged the major role that gardening could play in boosting food availability, small grass-thatched gardens being watered from a community borehole more than 200 m away may not provide tangible benefits especially if the most profound problem, the lack of fencing and the funds to purchase these, persists. Intensive management of resources such as water, fertilizer and land as well as crop selection is also necessary for continued returns. These skills are often lacking among the smallholder farmers.

However, there is evidence of linkages of the agriculture sector with emerging industrial and service sectors among commercial farmers (phase 2). The government in conjunction with the private sector is also striving to develop more efficient labour and financial markets that link the urban and rural economies (phase 3). However, the previously disadvantaged communities face competition for scarce resources, markets, goods and services, as they now compete on the same footing with large scale farmers who may be well endowed and also have access to credit and subsidies. Due to their low purchasing power, smallholder farmers have been naturally relegated and have gradually developed a dependency syndrome. They look upon the government and other political institutions for the provision of very basic amenities. Some have opted to work as unskilled laborers in large scale farms instead of utilizing the same labour on their own parcels of land. Often the little cash earned is used to purchase the same food they produce, but at higher prices from supermarket outlets. However, at times due to climatic uncertainties, smallholder farmers pursue risk aversion strategies and do not invest at all in crop production. Therefore, there is a need for policy guidelines with credit, training and marketing services support, that may propel smallholder agriculture to the higher phases identified by Royen and Sigwele (1998).

Kuyvenhoven (2004) suggested three policy-related strategies that could hasten the movement from the current phase to higher phases of a community such as the one at the Potshini catchment. These are asset (land) redistribution towards the less privileged, creation of rural employment linkages and generation of non-resource based rural employment. Land lease markets were seen as an alternative to the land redistribution programs that have been characterized by difficulties since land can find the most efficient users without any change in ownership. These sentiments were earlier expressed by Marsden (1995) who argued that there was a need to develop flexible forms of land tenure such as short-term leases and contracting as they permit opportunities for outsiders to acquire rights. Although Olper (2007) claimed that owning land provides different externalities at both the economic (i.e. access to credit, risk propensity) and socio-political level (i.e. social status, political power), in the Potshini catchment the existing land resources have not been fully optimized as demonstrated in the case studies in Section 8.4.

Therefore, as the relevant authorities engage in ensuring equitable distribution of resources through legislation, transfer of assets and capacity building of smallholder farmers, this study supports the introduction of more, as well as strengthened policies tailored to the unique circumstances of smallholder rainfed farmers. The necessary policy, institutional and structural transformations should be formulated and implemented with considerations of the HIV/AIDS epidemic. Drimie (2003) pointed out that this scourge not only affects the productivity of the infected, but also diverts the labour of the household and extended family away from other productive and reproductive activities as they care for the sick. In that study, affected households fell below the social and economic threshold of vulnerability and 'survivability', leaving the survivors - mainly the young and elderly - with limited resources.

8.5.2 Adoption and up-scaling of viable technologies

The research in Potshini utilized modern techniques, instrumentation as well as a participatory process that culminated in strong partnerships from which the community has so far obtained tangible benefits. These include knowledge, skills, institutions, collaborators, financiers and infrastructure, among others. No-tillage systems have been shown in this study to promote infiltration and storage of water in the soil throughout the growing season and this improved and stabilized crop yields. However, several challenges face its adoption and up-scaling. Some of the reasons given by the members of the community as well as gathered during this work are:

- Additional input costs required for no-till systems (herbicides, fertilizer and equipment) are beyond the reach of majority of farmers who prefer to use ox-drawn implements for land preparation and weeding. In addition the recommended planters for no-till systems were not functioning well and so the process became labor intensive. In some cases C_T treatments performed better than N_T suggesting that these approaches have to be customized to cater for specific situations.
- When herbicides were not applied at the right time, weeds out-competed the crops for water and nutrients leading to lower yields relative to conventional approaches.
- Livestock fed on all plant residues leaving the soil surface bare and compacted. Residue is useful in suppressing weeds and reducing early season soil evaporation. The compacted soil surface promotes surface runoff at the expense of soil infiltration. As a result more runoff was observed from no-till systems early in theeach season.

- Without proper storage, increased maize yields did not guarantee more food or funds to the household because hired storage is costly and maize is generally a low value crop.
- Some recommended legume inter-crops e.g. Soybeans have an unpleasant taste while Lab-lab beans could not mature by the time maize was harvested (as seen in Fig. 8.1, the communal trial still had patches of green matter during winter).
- During the implementation of the LandCare programme some farmers were given financial incentives for participation and the labor provided. This induced a perception that the project was an income generating venture rather than a technology transfer process.

Livestock provide manure that enhances soil nutrients, and are used for field operations e.g. ploughing, weeding and transportation of produce as well as sources of income when these services are hired out. Furthermore, livestock is a crucial social asset that is used as bride-price (labola) during marriage in the community. Sales of livestock also mitigate cash shortages for purchasing food. Therefore, livestock production remains an important enterprise in the community and its co-existence with viable technologies e.g. no-tillage systems needs to be enhanced.

Storage facilities provide the farmers with an opportunity to manage the water application method, quantity and schedule of application. The rainwater harvesting appraisal (xref. Chapter 7) evaluated several construction materials and recommended the use of polythene as an alternative lining material which was suitable for areas with rapid fluctuations of shallow groundwater. Although the cost of the tank was influenced by materials of construction, the cost per unit volume of water decreased with increasingvolume. For example, a 30 m^3 reinforced concrete tank roofed with corrugated iron sheets cost R122/m^3 more than the 54 m^3 polythene lined tank roofed with iron sheets. Depending on the crops selected, the area irrigated by these tanks when full at the end of summer ranged from 150-250 m^2. More area can be commanded if rain is available in winter. As observed, the cost of these storage structures and fencing materials is mostly out of reach of the smallholder farmers in the community, and thus their construction and use is expected to depend on whether external support is available or not.

Suitable feedback mechanisms of research findings are necessary if the focus and depth of science as well as livelihoods are expected to change. After analyses, it is always important to provide the relevant information to the right stakeholder.The depth of detail depends on the objective of the study being conducted. The feedback given to farmers is not the same as that published in scientific journals. Perhaps previous studies did not realize anticipated changes because the correct kind of information was not passed to farmers. In this study, the information regarded pertinent to be passed to the farmers included tested crop productivity improving measures, ways to eliminate unnecessary loss of production inputs and approaches of soliciting for infrastructural support. This study recommended continued support to more farmers so as to put up durable fencing and water harvesting storage tanks because the existing potential of improving production by way of crop diversification is largely unexploited.

8.5.3 Contribution to household food production and income generation

Based on the findings reported herein, the following are considered key contributions of the SSI programme and its stakeholders to household food production and income generation in the Potshini catchment:

- The study demonstrated that ASALs should not be dismissed as hydrologically marginal areas for crop production but that optimization of biophysical resources (e.g. land, water etc) and socio-economic variables (e.g. labor and capital) could result in significant agricultural improvements and that intensification of agricultural activities can occur without causing environmental degradation.
- Farmers have been made aware of the benefits of crop diversification and a variety of vegetables that do well in the catchment.
- Continuous crop production. Farmers have always believed in large tracts of land but the use of their small parcels continuously through out the year was appreciated as equivalent to having more land that is only active partly in the year.
- By participating in hydrological monitoring of components such as rainfall, farmers realized the importance of timeliness of farming activities and are able to plan with certainty operations such as sowing and weeding that are affected by antecedent soil moisture conditions.
- Ripping during sowing, both in no-tillage or conventional tillage, was shown to enhance infiltration. Trench beds also indicated the ability to store more moisture relative to normal beds. Diversion of runoff into cropping fields or into storage tanks from pathways

and impervious courtyards was also introduced. All these initiatives increased crop production.

- Introduction and capacity building of community institutions e.g. FLS which have the potential to evolve into local cooperative societies that could handle marketing of produce, among other responsibilities.
- Strong linkages between the community and government departments, Okhahlamba municipality and other key stakeholders were established. To date these have become channels through which farmers present their requests and also receive responses. The Okhahlamba municipality has included the Potshini community as a bidder for their annual finances. The DWAF have revised their policy on financial support to smallholder farmers based on experiences in Potshini.

8.6 Conclusion

No-tillage systems do promote infiltration and storage of water in the soil throughout the growing season and thus improves crop yields. However, when rainfall is lower than a certain threshold, the yield from conventional tillage could be higher. Therefore, these approaches need to be customized to cater for specific biophysical situations. Opportunities to produce vegetable in winter were challenged by inadequate water, fencing materials and knowledge and skills. Storage facilities provided an opportunity to manage the water application method, quantity and schedule of application. This unexploited potential was found to be tenable only if external support to resource poor farmers is provided through provision of materials or funds to construct the necessary infrastructure. The long-term support was seen to have more impact if entrenched into policies that address the unique conditions of smallholder resource-poor rainfed farmers. Therefore, the combination of viable biophysical and policy interventions is viewed as the key to increased household food production and incomes in the Potshini catchment and among communities having similar biophysical and socio-economic constraints.

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9.0 CONCLUSIONS, RECOMMENDATIONS AND FURTHER RESEARCH NEEDS

The majority of rural people in South Africa, in common with other parts of SSA, rely heavily on rainfed agriculture for their food supply. Typically, this is characterized by yields that are often below 1 ton.ha^{-1}. A low and highly variable rainfall, poor soils and inadequate capacity to develop alternative water sources have been identified as some of the primary causes of the low crop production. However, there is also a growing realization that an untapped potential exists in smallholder rainfed agriculture which, if explored with suitable techniques, is likely to improve household food and incomes, even in farming systems hosted in water scarce regions, but that this requires effective management of the limited production resources (e.g. land, water, capital and labour). Of these, water has been identified as the single most important limiting factor to crop production in SSA. Thus, the general objective of this study was to identify suitable, innovative and affordable techniques (water system innovations – WSIs) that integrate soil and water management within a framework that links climate, soil properties and crop water requirements so as to effectively manage the effects of water stress on crop growth.

In the first instance, there was a need to understand the long-term rainfall characteristics of the study area in order to identify the most suitable WSIs for smallholder dryland farmers in the Thukela Basin. Analyses of daily rainfall data from eight stations (Chapter 2) and comparison of 1901-1950 and 1951-199 daily rainfall records showed that the basin has experienced increasing rainfall in some parts. This was attributed to more rainfall per rain day as dry spells were found to have increased in all the eight stations considered. Early-season dry spells effectively reduced the length of the growing season, as the planting date is constrained by low heat units at the end of the season which results in high probability levels of reduced maize yields. The rainfall analysis showed that most of the areas in the Thukela Basin experience yield impacting droughts and dry spells, in some cases once in every two years. This high recurrence of dry spells has caused some farmers to refrain from crop production as they view it as a consumer of time and resources without returns and instead prefer to do manual labour at local large scale farms. Based on the results of this analysis, it is recommended that, in order to increase the possibilities of better yields, the early-season dry spells should be mitigated through interventions that maximize infiltration and soil water storage, but which are affordable to the farmers. Consideration of soil hydraulic properties in addition to rainfall when analysing sowing criteria suggested relatively earlier sowing dates, implying that methods that improve infiltration and water holding capacity early in the season are likely to reduce the risk of failure in maize production in rainfed cropping systems. However, this study recommends that to estimate the overall risk of maize production adequately, future work needs to include all intra-seasonal dry spells, not only those in the early-season.

Among smallholder farmers focused in this study, maize was identified as the single most grown crop in the Thukela Basin. As shown, there is a high risk of failure to achieve optimum yields even with short duration varieties. This study recommends diversification of summer crops to include legumes e.g. dry beans, root crops e.g. potatoes and oil crops e.g. sunflower. This should be accompanied by a gradual shift in eating habits from the typical inclination to maize to other foods so long as nutritional requirements are adhered to. These crops can also generate much more household income than maize. Thus, the Department of Agriculture needs to provide the prerequisite training of farmers and conduct demonstrations of the suggested crops and other suitable options.

The study highlighted that a shift towards sowing approximately 2.5 weeks earlier in some stations during the 1951-1999 window, compared to the 1901-1950 period, means that livestock need to be moved out of the fields earlier than before to allow for land preparation and timely sowing. As this decision is vested upon the village authority headed by the Induna and is largely informal, this finding if adopted could be one of few written regulations for this leadership organ which is backed by scientific research.

One commonly used approach that has been shown to enhance soil moisture is in-situ rainwater harvesting. In this study, no-tillage (N_T), a form of in-situ rainwater harvesting, was compared with conventional tillage (C_T) systems through monitoring of field-scale water balances (Chapter 3), changes in soil hydraulic properties (Chapters 4-6) and biomass production (Chapter 8). The use of various techniques to monitor the fluxes complimented each other well in this study. The TDR, GMS and the ERT methods described moisture status of the soil uniformly. However, the GMS require careful calibration against known water contents of soils similar to the ones to be investigated. They also require time to stabilize in the soil before useful readings can be obtained. A period of two weeks was regarded adequate for stabilization after installation. However, after a long dry period in winter it took up to 2 months before the readings from GMS became realistic. Thus, for soils such as those in Potshini, re-calibration after each season is recommended. From the ERT measurements, ripping was shown to influence water flow paths in both tillage systems. There is a need to investigate whether the flow direction of water in the soil is also affected. Thus, future research needs to investigate this local anisotropy. Use of electrical techniques and equipment e.g. the ABEM Terrameter Systems and adopting a square array with electrode spacing of less than 50 cm is likely to give desirable detail because ripping is only done to a depth of 10 cm.

The water partitioning process was found to be influenced by characteristics of rainfall events and the soil surface conditions. The ERT measurements indicated that ripping influenced the water flow pathways. However, it was not possible to quantify its contribution to soil moisture enhancement as a standalone technique because there were no treatments without ripping. Thus, farmers are advised to use this technique with a tillage system of choice. Some farmers in the study area have innovatively used rippers for weeding in their C_T plots. In the same way as done during ploughing, the ox-drawn ripper is used to work the soil between the maize rows. This results in shallow furrows that could improve infiltration in the remaining part of the season and perhaps obtain the same benefits as those desired from N_T treatments. Thus, it is recommended that future research into the transitions of fluxes and the changes in soil physical and hydraulic properties under this practice is undertaken

There were no significant differences ($p \leq 0.05$) in water fluxes between N_T and C_T, but the findings suggested that water flow paths are affected by the tillage method and that N_T allowed for more infiltration, less runoff, less soil evaporation and more crop transpiration. The short period in which the treatments were practiced could have contributed to the lack of major differences between the treatments. However, most of the rainfall events (Chapter 3) were of low intensity and while N_T plots had more runoff at the start of the season, there was less from C_T. Towards the end of the season the reverse occurred. Thus, this study did not cater enough evidence that gives one tillage system more advantage over the other. In this view, extension staff need to be cautious while proposing tillage systems to farmers.

Approximately 45% of soil evaporation occurred early in the season i.e. December and January which coincides with the period when the likelihood of dry spells increases. Measures to reduce this early season moisture loss are vital because there is a need to ensure that germination is successful and that robust rooting systems develop. Furthermore, use of fertilizers could have negative effects if moisture is limited because the young plants desiccate faster when there are solutes (fertilizer) as most smallholder farmers place seed and fertilizer at the same depth contrary to when conventional planters are used. In addition, a good water-nutrient balance at the start of the season may lead to the development of a robust rooting and vegetative systems that may not be sustained due to dry spells at later stages. When crop losses of this nature occur, farmers develop a notion that fertilizers are a setback to crop production and thus adopt the typical risk aversion strategies of lack of investments to improve crop production. Nevertheless, there is an opportunity for synergistic productivity improvement between water and nutrients if dry spells can be addressed. Approaches such as mulching are encouraged. However, in the Potshini catchment, because livestock consume the entire maize residue during winter, there is no carry-over of moisture from one season to the next and since the soil is fully exposed at the beginning of the season, soil moisture losses are high. Thus, the full potential of N_T systems cannot be realized unless livestock production, which is both a socio-cultural and economic enterprise to the community, is harmonized with crop production. Therefore, this is identified as a socio-economic situation which negatively affects the adoption of a WSI. This further underscores the need to seek alternative cropping systems that co-exist with the present status rather than destabilizing a community's livelihood that has been there for a number of generations.

Yields from N_T systems were shown to be better than those from C_T systems when in-season rainfall was 463 mm (2005/06) while there was not much difference when the rainfall was either 336 mm (2006/07) or 541 mm (2007/08). Future research needs to assess the threshold minimum and maximum in-season rainfall that N_T treatments lead to higher yields relative to C_T treatments in the Potshini Catchment, so that other areas having similar soils and climatic patterns can be advised to use other water conservation methods rather than N_T, if their rainfall is not within the identified range. In this study, using N_T systems, a good rainfall season (2007/08) realized yields that were approximately 80% of the potential while a drier season (2006/07) resulted to yields which were 40% of the potential yield. The corresponding values in C_T treatments (based on the potential of N_T systems) were 65% and 38%. Thus, the success of WSIs largely depends on rainfall amounts and that dry spells are responsible for the gap between the potential and the typical yields to a greater extent than tillage practice.

In 50% of the sites, N_T treatments showed significantly higher hydraulic conductivity (K) compared to C_T treatments. However, in all cases there was a higher K in December in C_T relative to N_T treatments which was attributed to the "loosened" soil structure in C_T treatments. This explains the relatively lower runoff rates and higher soil moisture in C_T measured at this time compared to N_T treatments. The water retention characteristics also showed that C_T treatments had higher water contents close to the surface and were better than N_T treatments in mitigating early season dry spells. This observation suggests that C_T plots are likely to have a better germination and initial development relative to N_T plots. Although this benefit may be lost due to negative changes in the soil properties in C_T plots along the season, it is unlikely that substantial differences in yield in a drier or wetter season between the tillage systems can occur, which could explain the observations made in the Potshini Catchment. The soil physical property which was most influenced by tillage was bulk density. In C_T plots it increased from December to April while the reverse occurred in most N_T plots. Soil texture was also shown to influence bulk density. Thus, tillage affected the soil physical and hydraulic properties and through the analysis of these properties, some sites were recommended for N_T systems while others will perform better under C_T systems. These mixed results suggest that these approaches, which are widely advocated, should be customized to cater for specific biophysical situations and should not be blindly promoted

In a modelling study (Chapter 3), the Parched Thirst (PT) model simulation results did not replicate the fluxes measured nor those approximated from the widely used Penman-Monteith approach. This was attributed to shortcomings in the SCS method used to predict the rainfall-runoff mechanisms in the PT model. In addition, because it is both a rainfall-runoff and crop growth simulation model, it is constrained by both the amount of runoff generated as well as the biomass produced. Hence it is not easy to fully optimize the simulation which leads to low values of R^2. It is recommended that direct measurements of soil evaporation and crop transpiration which could be used to calibrate and validate model outputs are undertaken in similar studies in future.

Although in-situ rainwater harvesting techniques are relatively economical and simple to implement, their capacity to mitigate dry spells of longer duration is lower because water can only be harnessed and used during the rainy season and the amount of soil water that can be stored depends on the soil's pore space. Furthermore, the stored soil water is subjected to non-productive losses e.g. deep seepage and soil evaporation. By virtue of these limitations and the need to diversify crop production in order to increase annual crop production, an evaluation of biophysical and socio-economic conditions for rainwater harvesting with storage that mainly targeted vegetable production in winter was undertaken and reported in Chapter 7. Storage facilities provide an opportunity to manage the water application method, quantity and schedule of application. Runoff depths from impervious courtyards were found adequate to support kitchen gardens of 200 m^2. Lining storage tanks with a 600 µm polythene sheet was shown to be suitable and cost-effective. The use of treadle pumps instead of motorized pumps was considered to reduce investment costs further. Drip irrigation combined with trench beds gave higher water productivity as compared to normal beds. This was attributed to an improved porosity in the trench beds. Thus, it demonstrated the combined benefits of applying water only at the root-zone with an improved soil structure.

Despite the relatively low cost of constructing and storing water in harvesting storage tanks using polythene lining (R250 per m^3), this is still beyond the reach of the farmers in the Potshini catchment (Chapter 8). In addition, vegetable production in winter necessitated fencing to deter livestock. In this regard the participatory approach used to mobilize and sensitize stakeholders and other agencies to support these farmers to secure these infrastructures was a successful one and could be applied to similar situations worldwide. The contribution from national and local policies geared towards the needs of resource-poor farmers was immense. However, some of the implementation strategies of the national policies impose huge administrative and consultancy fees that reduce the budgetary allocation that is eventually used to develop the infrastructure. The community needs to be empowered with structures and training to implement such initiatives with minimum technical support from government departments. In this way, the unit cost of the infrastructure will be lower and perhaps more beneficiaries. Therefore, the combination of viable biophysical and policy interventions is viewed as the key to increased household food production and incomes in the Potshini catchment and among communities having similar biophysical and socio-economic constraints. This "cocktail" is likely to reverse the declining trends in food production in most parts of SSA, improve household incomes and result to better livelihoods. This is a goal envisaged by the SSI programme.

Underground storage facilities are vulnerable to sedimentation and thus special attention needs to be given to the process of design and construction of sediment collectors as local factors determine the amount and nature of the sediment loads. Sediment that get into the tank not only reduces the tank capacity but also wears pump parts and clogs drippers. In this study, replacement parts for the treadle pump used were not readily available. It is also necessary that sediment removal schemes take into consideration the risk of mosquitoes breeding in the traps if the pool of stagnant water is sufficient and stands for a considerable period of time, particularly in areas where malaria may be prevalent.

Despite the difficulties faced by smallholder farmers, this study demonstrated that ASALs should not be dismissed as hydrologically marginal areas for crop production but that optimization of biophysical resources (e.g. land, water etc) and socio-economic variables (e.g. labor and capital) could result in significant agricultural improvements and that intensification of agricultural activities can occur without causing environmental degradation. It is thus concluded that:

- droughts and dry spells are common in the Thukela Basin and their influence on sowing dates is largely responsible for the failure to realize optimum yields (Chapter 2);
- tillage practices influence soil hydraulic properties, water fluxes and crop yields. N_T showed higher seasonal K, AMC, transpiration and AWC and lower runoff and soil evaporation (Chapters 3-6, 8);
- rainfall characteristics and soil properties e.g. texture, hydraulic conductivity and prevalence of surface sealing need to be considered to decide the most appropriate tillage system as the widespread “gospel” of N_T is not necessarily valid, particularly where cover cannot be maintained through the dry season. The farmers’ capacity and willingness to procure herbicides to control weeds instead of using “available” ox-drawn equipment needs consideration.
- a rainwater harvesting storage tank lined with polythene, a treadle pump and drip irrigation system with crops in trench beds is the best combination for higher water productivity (Chapter 7);
- a real transformation of smallholder rainfed agriculture can only be possible if innovative soil and water technologies and land and water management practices are adopted, and locally adapted, in combination with soil nutrient management and timely agronomic practices (Chapter 8); and
- more benefits could be realized through the introduction of more, as well as strengthened policies tailored to the unique circumstances of smallholder rainfed farmers (Chapter 8).