SOIL WATER DYNAMICS AND RESPONSE OF COWPEA TO WATER AVAILABILITY UNDER MOISTUBE IRRIGATION

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PREFACE

The research contained in this thesis was completed by the candidate while based in the Discipline of Bioresources Engineering, School of Engineering of the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Pietermaritzburg, South Africa.

The contents of this work have not been submitted in any form to another university and, except where the work of others is acknowledged in the text, the results reported are due to investigations by the candidate.

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Dr. Aidan Senzanje

Date:

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Dr. Tafadzwanashe Mabhaudhi

Date:

DECLARATION OF PLAGIARISM

I, Edwin Kimutai Kanda declare that;

(i) This thesis except where otherwise indicated, is my original work.

(ii) This thesis has not been submitted for any degree or examination at any other university.

(iii) This thesis does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons.

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DECLARATION OF PUBLICATIONS

The following are the list of publications in this thesis.

1. Kanda, EK., Mabhaudhi, T., and Senzanje, A. 2018. Hydraulic and clogging characteristics of Moistube irrigation as influenced by water quality. *Journal of Water Supply: Research and Technology – AQUA* 67(5): 438 – 446 (Chapter 3)
2. Kanda, EK., T. Mabhaudhi and A. Senzanje, 2018. Coupling hydrological and crop models for improved agricultural water management – A review. *Bulgarian Journal of Agricultural Science*, 24 (3): 380–390
3. Kanda, EK., Niu, W., Mabhaudhi, T. and Senzanje, A. 2018. Moistube irrigation technology: A review. Submitted to *Agricultural Research*. Under review with a manuscript number AGRI-D-18-00254
4. Kanda, EK., A. Senzanje and T. Mabhaudhi. 2019. Parameterisation and testing of aquacrop model for full and deficit irrigated cowpea (*Vigna unguiculata* (L.) Walp). Submitted to *Agricultural Water Management*. Under review with a manuscript number AGWAT-2018-1361

The following Manuscripts are ready for submission to Journals

1. Soil water dynamics under Moistube irrigation
   Kanda, EK., A. Senzanje and T. Mabhaudhi
2. Soil water distribution under Moistube irrigated cowpea (*Vigna unguiculata* (L.) Walp)
   Kanda, EK., A. Senzanje and T. Mabhaudhi
3. Response of cowpea (*Vigna unguiculata* (L.) Walp) to varying water regimes under Moistube irrigation
   Kanda, EK., A. Senzanje and T. Mabhaudhi

The following papers were presented at national and international conferences

1. Kanda, EK., Senzanje, A and Mabhaudhi, T. 2018. Effect of soil texture on soil water movement under Moistube irrigation. South African National Commission on Irrigation and Drainage (SANCID) Symposium. White River, Mpumalanga, South Africa. 13th – 15th November 2018.

2. Kanda, EK., Senzanje, A and Mabhaudhi, T. 2018. Yield response of cowpea under varying water regimes under Moistube irrigation. South African Institute of Agricultural Engineers (SAIAE) Symposium and Biennial CPD Event. Durban North, South Africa. 17th – 20th September 2018.
3. Kanda, EK., Senzanje, A and Mabhaudhi, T. 2018. Simulation of soil water dynamics under Moistube irrigation. International Conference and 69th IEC Meeting of the International Commission on Irrigation and Drainage (ICID). Saskatoon, Saskatchewan, Canada. 12th – 17th August 2018.
4. Kanda, EK., Senzanje, A and Mabhaudhi, T. 2018. Moistube irrigation technology: An advancement in irrigated agriculture. 3rd Ukulinga Howard Davis Memorial Symposium. Ukulinga Research Farm, UKZN, Pietermaritzburg. 22nd – 23rd May 2018
5. Kanda, EK., Mabhaudhi, T. and Senzanje, A. 2017. Hydraulic and clogging characteristics of Moistube irrigation. South African Irrigation Institute (SABI). Cape Town, South Africa. 1st – 3rd August 2017.

In all the above papers and manuscripts, the conceptualization of the idea was done by EK Kanda (student), and A Senzanje and T Mabhaudhi (supervisors). EK Kanda conducted the research and the write up while the supervisors corrected and proof-read the manuscripts.

Niu Wenquan contributed to the manuscript in Chapter 2 by proof-reading and correcting the document as most of the articles were in Chinese. The supervisors gave the final concurrence to the manuscript.

ABSTRACT

Increasing population, urbanization and industrialization has put pressure on the irrigation sub-sector to produce more yield using less water i.e. improving crop water productivity (WP). This can be achieved through the adoption of efficient irrigation systems such as micro-irrigation. Moistube irrigation (MTI) is a relatively new technology like subsurface drip irrigation (SDI) but with a semi-permeable membrane whose nanopores emit water in response to applied pressure and soil water potential. Being a new technology, there is little information regarding its hydraulic characteristics and soil water distribution which are necessary for its design, operation and management. Furthermore, the response of crops under a variety of soils and environmental conditions under MTI has not been covered extensively. Therefore, this study aimed at determining the hydraulic and clogging characteristics of MTI. The effect of soil texture on the soil water dynamics of MTI was also determined. Finally, the response of cowpea, an important but neglected African indigenous legume, to varying water regimes under MTI was also determined. This study was based on the hypothesis that cowpea responds favourably to water regimes under MTI. The study was accomplished through laboratory, field experiments and agro-hydrological models. AquaCrop and HYDRUS 2D/3D were chosen for this study due to their reliability in predicting crop yield responses to water availability and soil water dynamics respectively. The laboratory experiments were conducted in soil bins to determine the soil water dynamics of MTI under sandy clay and loamy sand soils which were used to calibrate the HYDRUS 2D/3D model. The hydraulic characteristics were determined at a pressure of between 10 kPa and 100 kPa while the effect of suspended and dissolved solids was determined under a pressure of 20 kPa and 30 kPa. The field experiments consisted of glasshouse and tunnels to examine the response of cowpea to full and deficit irrigation of MTI with SDI as the control. The results were used to parameterise and validate the AquaCrop model. Finally, HYDRUS 2D/3D and AquaCrop were coupled to draw into the strengths of the individual models and used to simulate the water use of cowpea under MTI in two agro-ecological zones in South Africa.

The results showed that the discharge – pressure relationship of Moistube followed linear and power functions. It was also established that suspended solids had severe clogging effect than dissolved solids. In the soil bin experiment, simulated water contents closely matched ($R^2 \geq 0.70$ and RMSE ≤ 0.045 cm^3 cm^{-3}) the observed values in all the points considered for the two soil textures. The model slightly under-estimated or over-estimated the soil water content with percent bias less than 15.6%. There was no significant difference ($p > 0.05$) between the soil water distribution in lateral and downward direction for both sandy clay loam soil and loamy sand. However, the soil water content upward of the Moistube placement depth was significantly lower ($p < 0.05$) than both the lateral and downward soil water contents in loamy sand. The soil water dynamics under MTI while incorporating the root water uptake indicated that there was no significant difference between the root water uptake in SDI and MTI ($p > 0.05$). Water loss through drainage was significantly higher ($p < 0.05$) under SDI than MTI in loam while it was negligible in clay for both irrigation types. Drainage increased with increased Moistube placement depth. The interaction between the distribution of root water uptake and

the soil water distribution indicated that a suitable placement depth for cowpea under MTI was 15 cm in loam and 20 cm in clay.

There were no significant differences ($p > 0.05$) in the yield response of cowpea between MTI and SDI but the latter performed better under deficit irrigation conditions. AquaCrop model was parameterized and tested successfully under full and deficit irrigation. The results indicated the model simulated the canopy cover (CC) very well with $R^2 \geq 0.85$, RMSE ≤ 24.5%, EF ≥ 0.45, and $d \geq 0.87$. The simulated water content closely matched the observed with $R^2 \geq 0.61$, RMSE ≤ 11.3 mm, EF ≥ 0.51, and $d \geq 0.86$ indicating that the model reasonably captured the soil water dynamics. Generally, yield and biomass were simulated satisfactorily by the model with R^2 of 0.84 and 0.88, and RMSE of 282 kg ha $^{-1}$ and 1307 kg ha $^{-1}$, respectively, during parameterisation. Similarly, during model testing the model performance was very good with R^2 of 0.96 and 0.99, and RMSE of 165 kg ha $^{-1}$ and 798 kg ha $^{-1}$ for yield and biomass, respectively. The highest WP was achieved under 70% ETc (crop water requirement) and 40% ETc for yield and biomass, respectively. Having successfully calibrated and tested the HYDRUS 2D/3D and AquaCrop models, the two were used symbiotically to simulate the water use of cowpea in two environments characterized by clay and sandy soils. The crop characteristics were obtained using AquaCrop while HYDRUS 2D/3D was used to generate optimum irrigation schedules and the soil water balance. Thereafter, the water use and yield of cowpea was determined. The average grain yield and biomass were 2600 kg ha^{-1} and 10000 kg ha^{-1}, respectively, with the difference between the two sites being less than 5% under both SDI and MTI. The water use and WP varied from 315 mm to 360 mm and 0.67 to 1.02 kg m^{-3}, respectively, under the two irrigation types at the two sites considered. The WP was higher under SDI than MTI, but the differences were less than 10%. This showed that cowpea responded similarly under MTI and SDI. Further research is needed on the determination of the clogging characteristics due to fertigation. Finally, more field experiments under other environmental conditions need to be carried out to validate the results of this study.

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B	Biomass
BC	Boundary Conditions
CC	Canopy Cover
CDC	Canopy Decline Coefficient
CEF	Controlled Environment Facility
CERES	Crop Environment Resource Synthesis
CGC	Canopy Growth Coefficient
CropSyst	Cropping System simulation
CV	Coefficient of Variation
d	Willmot Index of Agreement
DAFF	Department of Agriculture, Forestry and Fisheries
DAP	Days After Planting
DI	Deficit Irrigation
E	Soil Evaporation
EC	Electrical Conductivity
EF	Nash-Sutcliffe model efficiency coefficient
ET	Evapotranspiration
ETa	Actual evapotranspiration
ETc	Crop evapotranspiration
FAO	Food and Agriculture Organization
GDD	Growing Degree Days
HI	Harvest Index
IWP	Irrigation Water Productivity
LAI	Leaf Area Index
MPS	Matric Potential Sensors
MTI	Moistube Irrigation
NRMSE	Normalized Root Mean Square Error
PBIAS	Percent Bias
R^2	Coefficient of determination
RE	Richards' Equation
RMSE	Root Mean Square Error

RUE	Radiation Use Efficiency
RWU	Root Water Uptake
SDI	Subsurface Drip Irrigation
SE	Standard Error
SEM	Standard Error of Mean
STICS	Simulator Multidisciplinary for Crop
TDS	Total Dissolved Solids
Tr	Transpiration
TSS	Total Suspended Solids
UKZN	University of KwaZulu – Natal
USDA	United States Department of Agriculture
WP	Water Productivity
WP*	Normalized Water Productivity
WUE	Water Use Efficiency
Y	Yield

1. INTRODUCTION

1.1 Improving Water Productivity Using Efficient Irrigation Methods

Rainfall distribution is increasingly becoming unreliable due to climate change. This has increased the uncertainties in rainfed crop farming. Irrigation is one option of ensuring yield stability and therefore enhancing the food security of the people who rely on agriculture as primary source of their livelihoods. However, irrigation which is the largest consumer of freshwater withdrawals is facing competition from increased domestic and industrial demand (Fereres and Soriano, 2007). This calls for prudent management of irrigation water through the adoption of efficient irrigation systems such as trickle systems.

Moistube irrigation (MTI) is a relatively new technology which operates like subsurface drip irrigation (SDI). Under MTI, water is emitted throughout the length of the Moistube semi-permeable membrane (unlike emitters in drip irrigation) in response to the system pressure and the soil water potential soil (Yang *et al.*, 2008;Qi, 2013;Yang, 2016). MTI is low pressure technology, therefore, it does not require pumping and thus minimal energy requirements since even a pressure head of 2 m can yield flows of about 0.24 ℓ $hr^{-1}m^{-1}$ (Qiu *et al.*, 2015). Another advantage is that it does not require specialized skills for operation (Lyu *et al.*, 2016).

The design and management of irrigation systems require information on the soil water distribution. Design and management aspects such as the volume of the wetted zone, spacing of emission devices, irrigation schedules, etc relies on the soil water dynamics (Lubana and Narda, 2001). Knowledge of the soil wetted volume helps in the establishment of the emitter spacing and the duration of irrigation when the wetted volume is within the root zone (Provenzano, 2007). For optimum water application to the root zone in subsurface irrigation systems, there is need to determine precisely the depth of placement of laterals and spacing of emitters to minimize percolation losses (in the case of deeper depths) or soil evaporation in the case of too shallow depths (Kandelous and Šimůnek, 2010b) . Soil water dynamics under irrigation systems depends on factors such as soil type, initial soil moisture content, system characteristics, crop type, evapotranspiration (Subbaiah, 2013), spacing, and depth of laterals (Kandelous and Šimůnek, 2010a).

Soil water dynamics under irrigation systems can be determined using field and laboratory experiments and simulation models. However, carrying out field measurements using variety of soils with variable emitter flow rates and irrigation methods to determine the soil water distribution is costly and onerous (Phogat *et al.*, 2012). HYDRUS 2D/3D is a numerical model used for the simulation of water movement and solute transport in 2D/3D variably-saturated porous media (Šimůnek *et al.*, 2006). HYDRUS 2D/3D is superior to other models because of its user-friendly Windows-based interface unlike the DOS-based numerical codes of other numerical models such as SWMS 2D and in addition it accounts for root water uptake (Šimůnek *et al.*, 2008). It has been applied successfully to simulate soil water distribution under various types of irrigation methods including drip irrigation (Kandelous and Šimůnek, 2010a) and MTI (Fan *et al.*, 2018a;Fan *et al.*, 2018b).

MTI has been applied in the production of vegetable and fruit crops in China with promising results in terms of yields and water use efficiency (WUE). For instance, a comparison between MTI and SDI in tomato production showed that the former had more or less same yield per unit area compared to the latter but a 13% higher WUE (Xue *et al.*, 2013b). A similar study by Lyu *et al.* (2016) found that MTI achieved 38% water savings than drip irrigation. In an experiment carried out by Yao *et al.* (2014), Moistube irrigated navel oranges achieved the highest yield than those under conventional irrigation and rainfed water conditions.

1.2 Cowpea: An Under-utilized Indigenous Legume

Cowpea (*Vigna unguiculata* (L.) Walp) is one of the most important legumes which falls under the category of African leafy vegetable. It is the most cultivated crop in resource scarce countries of Africa, Asia and Central America due to its ability to withstand extremely harsh environmental conditions such as high temperatures, limited water and soil fertility (Shiringani and Shimelis, 2011). It is mostly under-utilized in Southern African Countries like South Africa, unlike in West Africa where majority of the world's cowpea is produced (DAFF, 2014). It is dual-purpose crop where the grains (dry and fresh) and vegetable leaves are consumed by humans (Badiane *et al.*, 2004) and its stalk utilized as livestock fodder (Sprent *et al.*, 2009). In most parts of tropical and subtropical Africa, cowpea is grown together with other crops such as millet, sorghum and maize in a mixed farming system (Padulosi, 1997;Asiwe, 2009).

Cowpea grain is highly nutritious with about 24% protein content and therefore an alternative to animal proteins for poor households besides generating income to the producers and traders (Quin, 1997). This makes cowpea an attractive option for inclusion in cropping programmes aimed at addressing food and nutrition problems in Sub-Saharan Africa (Chivenge *et al.*, 2015). Cowpea can also be used as a medicinal plant where the leaves help in inhibiting bacterial and fungal growth (Kritzinger *et al.*, 2005).

Water is a limiting factor in cowpea production especially in water scarce regions like South Africa. Although cowpea is considered a drought tolerant crop, insufficient soil moisture at critical growth stages such as reproduction phase is detrimental to its growth and yield response (Peksen, 2007;Ahmed and Suliman, 2010). Therefore, an adequate and uniformly distributed water should be provided across the crop growth stages to prevent yield reduction or crop failure. Irrigation would help in the expansion of cowpea to other areas and thus contribute to the improvement of the livelihoods of rural households.

1.3 Modelling as a Tool for Improving Agricultural Water Management

The assessment of yield response to water can be achieved by using field or crop models. AquaCrop is one such model developed by Food and Agriculture Organization (FAO) of the United Nations to help in assessing the response of crops to environmental and farm management practices and therefore, improvement in the WP in rainfed and irrigated agriculture (Raes *et al.*, 2009). It has been applied in assessing the response of various crops to water (Vanuytrecht *et al.*, 2014). Although the model has been applied in major crops, only few studies exist on its use in under-utilized crops such as bambara groundnut, sweet potato, quinoa, taro and teff (Geerts *et al.*, 2009;Araya *et al.*, 2010;Karunaratne *et al.*, 2011;Mabhaudhi *et al.*, 2014a;Rankine *et al.*, 2015). To the best of available knowledge, AquaCrop has not been parameterized for cowpea.

Most hydrological models that are used in agriculture focus primarily on the soil physical processes and simplify the processes of transpiration, root water uptake and crop growth while crop models, on the other hand, include detailed crop development processes but are inadequate in describing root zone processes (Vereecken *et al.*, 2016). Complex crop and hydrological models require detailed or many input parameters which may not be available or are expensive to collect. On the other hand, simple and user-friendly models have limitations due to simplification of processes. Therefore, no single model can simulate satisfactorily all the outputs required for decision making in agricultural water management. Hence, it is important to integrate two or more models in such a way as to maximize and minimize on their individual strengths and weaknesses, respectively.

1.4 Research Objectives

Being a new technology, the information on the hydraulic and clogging characteristics which are important parameters in design and operation of irrigation systems is scanty. Also, there is little information on the soil water distribution under MTI for a variety of soils. Although some studies on the performance of MTI on the production of vegetables and fruits have been carried out, information on other crops under a variety of environmental conditions is unavailable. Therefore, the objectives of this study were;

(a) To assess discharge characteristics of MTI under variable operating pressure and water quality scenarios
(b) To determine the soil water distribution under MTI with respect to clay and sandy soils
(c) To evaluate the effect of soil water distribution on MTI system design for cowpea
(d) To determine the yield and water productivity of cowpea under MTI for different climatic conditions

The study was based on the following hypotheses;

a) The water flow from the Moistube has a positive relationship with operating pressure and negative relationship with suspended and dissolved solids concentration
b) The shape of the wetting pattern is symmetrical for clay and asymmetrical for sandy soil with upward and lateral movements being less than downward movement
c) The spacing and depth of placement of Moistube laterals are functions of the soil type, crop root characteristics, and Moistube flow
d) The yield and water productivity of cowpea are higher in MTI than SDI

1.5 Thesis Outline

This thesis is structured as follows: The review on Moistube irrigation is described in Chapter 2 while in Chapter 3, the hydraulic characteristics and the effect of suspended and dissolved solids on the discharge of Moistube are discussed. The soil water dynamics under MTI without crop uptake is described in Chapter 4 while the soil water distribution incorporating crop water uptake is discussed in Chapter 5. In Chapter 6, the response of cowpea to water availability under MTI is described. The parameterisation and testing of AquaCrop model for cowpea under full and deficit water conditions under MTI is described in Chapter 7. The coupling of HYDRUS 2D/3D and AquaCrop in the simulation of water use of cowpea under varying environmental conditions is discussed in Chapter 8. Finally, the conclusion and recommendations are provided in Chapter 9.

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2. MOISTUBE IRRIGATION TECHNOLOGY

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Abstract

Irrigated agriculture is under pressure to increase water use efficiency (WUE) and crop water productivity because of inter-sectoral competition for scarce water resources. The shift to micro-irrigation has improved crop quality, yield and WUE. Subsurface drip irrigation significantly reduces non-beneficial water balance components such as runoff and soil evaporation. However, the problem of water loss by deep percolation still exists in this method. Moistube irrigation is a relatively new type of irrigation method where water flows out of the Moistube nanopores as a function of soil water potential and operating pressure. It supplies water continuously to the crop at 80 – 90% of the field capacity. Therefore, it is a form of deficit irrigation. Based on the previous studies, this Chapter reviews Moistube irrigation technology by highlighting its hydraulic characteristics, crop growth and yield response, WUE, clogging characteristics and the soil water dynamics. From the review, the soil water dynamics under MTI is influenced by the soil texture, system pressure and depth of placement of Moistube laterals. The effect of water quality parameters such as suspended and dissolved solids need to be investigated further. The review also revealed that water savings and higher WUE could be achieved using MTI than conventional irrigation. There is need to investigate how other crops respond to MTI technology.

Keywords: clogging characteristics, crop yield, soil water dynamics, semi-permeable membrane, subsurface irrigation, water use efficiency

2.1 Introduction

Rainfall, as a primary source of water for agricultural production, is becoming increasingly erratic perhaps due to climate change which has led to reduction in crop yields in several parts of the world and especially in Sub-Saharan Africa (Schlenker and Lobell, 2010). In arid and semi-arid regions where rainfall is hardly enough for crop production, irrigation is the main option for ensuring food and cash crop production. However, some irrigation methods like furrow, basin, and flood among others, have low efficiencies. For instance, Ibragimov *et al.* (2007) established that an average water savings of 32% can be achieved by drip irrigation than furrow irrigation. Kahlown *et al.* (2007) found that basin irrigation requires 67% more water than sprinkler irrigation. One of the options for reducing water losses in irrigated agriculture is the adoption of efficient irrigation systems such as micro-irrigation.

Micro-irrigation technologies such as drip irrigation have gained popularity given their higher water application efficiencies. Drip irrigation can achieve water use efficiency (WUE) as high as 95% as compared to 75% which can be achieved with sprinkler irrigation systems (Locascio, 2005). The use of subsurface irrigation helps in improving the WUE by minimizing the non-beneficial water use components such as surface runoff, soil evaporation and percolation. The development in subsurface irrigation has evolved since the beginning of man's civilization through the use of buried clay pots (Bainbridge, 2001), porous subsurface clay pipes (Ashrafi *et al.*, 2002), subsurface drip irrigation (SDI) (Camp, 1998) and semi-permeable membranes utilized in Moistube irrigation (Yang *et al.*, 2008).

Micro-irrigation techniques such as drip irrigation have been studied extensively. A recent review by Lamm *et al.* (2012) highlighted the general applicability of SDI in the United States of America. It also highlighted the challenges facing its wider applicability and the opportunities arising from it. Some of the challenges included lack of clarity on depth and spacing of drip lines, crop germination and establishment, salt build up, clogging and damage by rodents. To eliminate some of the above problems, a relatively new technology (Moistube irrigation) was developed in China using nanotechnology (Yang *et al.*, 2008;Yang, 2016). This technology can be considered as an upgrade of the porous irrigation pipes which have popularly been marketed as "leaky pipe" and "soaker hose' (Yoder and Mote, 1995;Janani *et al.*, 2011). However, instead of using micro porous, the pipes are made of flexible semi-permeable membranes whose pores are in the nano scale (Yang *et al.*, 2008).

This review aimed at understanding the existing knowledge of Moistube irrigation in terms of the pressure-discharge relationships, soil water dynamics including use of models and clogging characteristics and how various crops respond to it. The review was done to provide the basis for its adoption and applicability outside China especially in areas facing water scarcity. It would also provoke more research on its characteristics which could lead to further development and refinement in design, operation and maintenance. The review was mainly conducted by searching through the articles available online especially in Google and Google Scholar using key words and phrases such as “Moistube irrigation”, “Moistube” and semi-permeable membrane irrigation”. Other articles were obtained from the manufacturer of the product.

The rest of this review is structured as follows: Firstly, a brief description of Moistube irrigation technology (MTI) is provided. Secondly, the design aspects such as the hydraulic characteristics and depth of placement are described. Thirdly, the soil water distribution in MTI is discussed. Fourthly, the response of some selected crops to water availability under MTI is described by highlighting the water savings and yield improvement as compared to conventional irrigation methods. Finally, the effect of suspended solids on the clogging characteristics of Moistube is described. At the end, conclusion including the prospects for further research is provided.

2.2 Description of Moistube Irrigation

MTI is a relatively new subsurface irrigation technology that utilizes nanotechnology where a polymeric semi-permeable membrane allows movement of water by osmosis. The semi-permeable inner layer has approximately 100,000 nanopores per square centimetre with pore diameter range of 10-900 nm (Yang, 2016;Zou *et al.*, 2017). The structure of Moistube is illustrated in Figure 2.1. Since it supplies water continuously throughout the crop growing season, MTI can be referred to as a continuous type of irrigation to distinguish it from conventional irrigation methods (Zhang *et al.*, 2015a;Yang, 2016;Sun *et al.*, 2018). Moistube flow approximates that of line-source subsurface drip irrigation (Zhang, 2013). However, instead of closely spaced emitters, water oozes from the semi-permeable membrane to the surrounding soil due to the soil water potential difference between the water inside the Moistube lateral and the adjacent soil (Yang *et al.*, 2008;Qi, 2013;Yang, 2016).

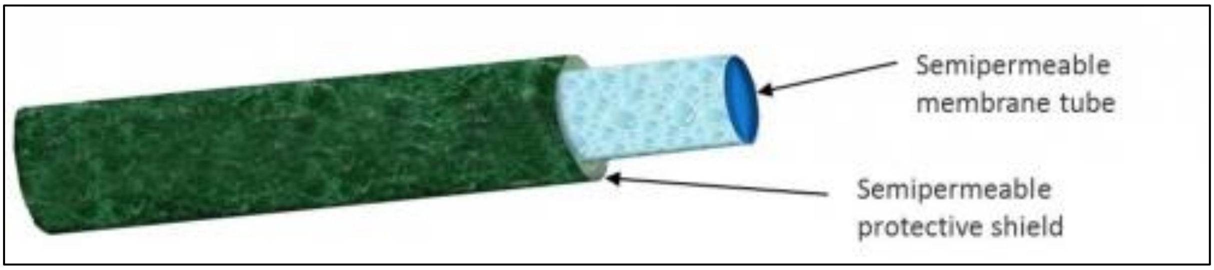

Figure 2.1: Internal structure of Moistube ((Zou *et al.*, 2017)

Being a relatively new technology having been developed less than 10 years ago, most of the applications of MTI are found in China where it has been used for the production of few vegetable, fruit, and cereal crops (Zhang *et al.*, 2017e;Zou *et al.*, 2017). Zou *et al.* (2017), described the developmental stages of Moistube irrigation technology where it has undergone three phases; first, second and third generation in terms of material and technical properties. The first generation consisted of a thin double layer nano-porous with non-woven protective outer layer. The second generation was a thick single layer nanotube with higher mechanical strength than the previous version. The third generation (which is the current product illustrated in Figure 2.2) involved improvement of the anti-clogging performance of the second generation. The semi-permeable membrane pipes have a nominal diameter of 16 mm and thickness of about 1 mm (Yu *et al.*, 2017). This would fit in the nominal sizes available for drip irrigation systems (12 mm – 24 mm) and thus the pipe network is similar.

Figure 2.2: Laying Moistube tapes

2.3 Design and Operation

The design and operation aspects of MTI are discussed in the following sub-sections in terms of the operation requirements, water flow mechanism and design aspects i.e. the depth and spacing of Moistube laterals.

2.3.1 Operation requirements

MTI is low pressure technology; therefore, it does not require pumping and thus minimal energy requirements. It can be run on gravity though overhead tanks since even a low head of 2 m can yield flows of about 0.24 ℓ hr $^{-1}$m^{-1} (Qiu *et al.*, 2015). Therefore, the technology has less operation costs and does not require specialized skills for operation (Lyu *et al.*, 2016). SDI systems operate within a pressure head range of 17 m to 27.5 m and therefore, pumping is required (Camp and Lamm, 2003).

In summary the advantages of MTI as outlined by the manufacture include more than 50% water savings, minimal energy costs (i.e. no pumping), reduced clogging, reduced maintenance cost, efficient fertilizer use and enhanced crop growth (yield and biomass), zero evaporation and minimum percolation losses (Envirogrower, 2017).

2.3.2 Water flow mechanism

The flow from Moistube occurs in two ways; besides the applied pressure, the flow also varies with respect to the soil water potential (Yang *et al.*, 2008) as described below;

a) In the absence of system pressure, Moistube discharge is a function of soil water potential. When the soil is dry, water oozes out of the Moistube until the potential difference between the two sides of the membrane is equal (when the soil approaches saturation point) when seepage reduces or stops (Figure 2.3).
b) In presence of system pressure, the flow from a Moistube lateral is linearly proportional to the operating pressure as shown in Equation 2.1 (Niu *et al.*, 2013b;Yang, 2016);

$$q = ah + b \qquad (2.1)$$

where q = emitter discharge (mℓ hr $^{-1}$m^{-1}), h = system operating pressure (m) and a, b are constants related to soil type. Niu *et al.* (2013b) found the value of a and b to be 64.8 and 25.6, respectively, for clay loam soil.

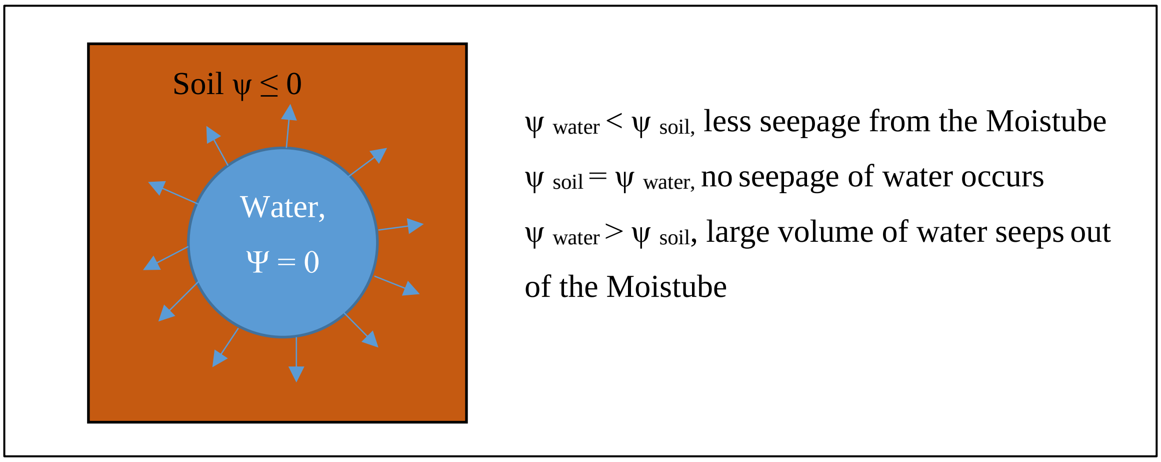

Figure 2.3: Moistube flow due to soil water potential (Yang, 2016)

A soil box experiment by Niu *et al.* (2017) established that the flow from Moistube increases slightly with response to initial soil water content and then decreases until it reaches a stable steady state after 48 hours. They also found that at zero pressure, the Moistube flow could be predicted using the initial soil moisture content and the bulk density of the soil. The study also established that the effect of soil water potential described in Figure 2.3 was weak and it lasted only for 44 hours.

A study by Qi *et al.* (2013) found that the Moistube flow in soil is 40 – 70% less than in the air due to the influence of the adjacent soil. The extent of decrease in discharge in buried emitters depends on the soil hydraulic characteristics, emitter flow rate, presence or absence of cavities around emitter outlet and the irrigation system properties (Shani *et al.*, 1996). For the same soil texture, the reduction in discharge is proportional to the emitter flow rate (Gil *et al.*, 2008). Thus, the pressure-discharge relationship in buried drip emitters is given by Equation 2.2 (Shani *et al.*, 1996);

$$q = k(h - h_s)^x \qquad (2.2)$$

where h_s = positive pressure which develop at the emitter outlet, k = emitter coefficient, x = emitter exponent, q and h are as defined in Equation 2.1

From Equation 2.1, it can be inferred that Moistube flow rate is like the laminar flow regime (exponent close to one) in a drip emitter. Therefore, Moistube flow rate is sensitive to pressure variation.

2.3.3 Spacing and depth of Moistube laterals

The main factors that affect the line spacing of irrigation pipe laterals include the soil type, installation depth and type of crop (Lamm and Trooien, 2003). The depth of lateral placement depends on soil characteristics, crop type, tilling depth, and whether the system is used for crop establishment or another irrigation method is used until the crop is established (Charlesworth and Muirhead, 2003). Some studies have been carried out to determine the suitable Moistube layouts and placement depths for some crops as described in the following paragraphs.

The depth of Moistube placement depends on the soil texture and crop type (root characteristics). In indoor soil box experiments, Niu *et al.* (2013b) found a suitable placement depth of between 15 – 20 cm for clay loam soil. A study by Zhang *et al.* (2016b) found that a placement depth of 3.5 cm performed better than 8.5 for the growth of cabbages. After analysing three depths of 10 cm, 20 cm and 30 cm, Lyu *et al.* (2016) and Niu *et al.* (2017) found the suitable placement depth for tomatoes in a greenhouse as 10 cm. However, Zhang *et al.* (2015c) found that a depth of 15 cm resulted in highest tomato yields than at 10 cm and 20 cm. Similarly, Zhang *et al.* (2015b), established that the suitable Moistube depth for tomato under plastic mulch was 15 cm with less salt deposition than at 10 cm and 20 cm. In another study, Guo *et al.* (2017) established that a placement depth of 3.5 cm for onions gave higher yields than at 7 cm. In a study to determine the growth and yield response of sunflower under MTI, Tian *et al.* (2016) found that the suitable depth was 20 cm where the crop growth and yield was significantly higher than at 10 cm. In summary, the placement depths of Moistube for a variety of crops are shown in Table 2.1

Table 2.1 Placement depth in Moistube irrigation

Crop	Placement depth (cm)	Reference
Cabbage	3.5	(Zhang *et al.*, 2016b)
Tomato	10 and 15	(Zhang *et al.*, 2015b;Zhang *et al.*, 2015c;Lyu *et al.*, 2016;Niu *et al.*, 2017)
Onions	3.5	(Guo *et al.*, 2017)
Sunflower	20	(Tian *et al.*, 2016)

In terms of lateral spacing, Moistube can be placed between rows where it serves rows of crops or in-line with the crop rows. In a study to determine the number of Moistube lines suitable for tomatoes, Lyu *et al.* (2016) established that for improved irrigation WUE, quality and yields coupled with economic considerations, one Moistube lateral per one ridge containing two rows of crops was appropriate. However, in a similar study, Niu *et al.* (2017) recommended 3 tubes serving one ridge containing 2 lines of tomatoes due to high salinization in a greenhouse. From this study, perhaps a low density of Moistube could have been recommended in open field. In fact, the three layouts considered (one, two and three Moistube lines) did not have a significant effect on the soil water distribution.

2.4 Soil Water Dynamics

The soil water distribution is necessary in the design of irrigation systems. The soil water dynamics in SDI systems depend on factors such as soil type, initial soil moisture content, emitter flow rate, the rate of water application, crop type, evapotranspiration, spacing, and depth of laterals (Kandelous and Šimůnek, 2010a;Subbaiah, 2013).

The soil water distribution in subsurface irrigation can be determined by field (or laboratory) experiments or by simulation using analytical, empirical or numerical models (Subbaiah, 2013). The following sub-sections describe the field and laboratory experiments for the determination of the soil water distribution and infiltration characteristics in MTI and also the potential for using soil water models to determine the subsurface water flow.

2.4.1 Field and laboratory experiments

The following studies have been carried out in the determination of the soil water movement in MTI. For silt loam soil, Zhang *et al.* (2014) studied the effect of initial soil moisture content on the soil water flow in MTI. In the study, 2.1%, 5.6%, 8% and 10.1% initial moisture contents were used. Infiltration rate fitted almost perfectly ($R^2 > 0.99$) the Kostiakov model as indicated in Equation 2.3. The infiltration rate decreased with time.

$$I = Kt^{\alpha} \qquad (2.3)$$

where I = infiltration rate (LT^{-1}), K = coefficient of infiltration, α = infiltration index, t = infiltration time (T). The exponent α increased with increasing initial soil water content. In general, the initial soil water content influenced the speed of the wetting front. A study by Niu *et al.* (2017) found that the initial soil moisture content had negative and significant relationship with the Moistube flow.

However, when the Moistube is installed in a vertical direction, Yu *et al.* (2017) found that the infiltration rate fitted ($R^2 \geq 0.92$) a modified Horton's empirical model (Equation 2.4). The study was conducted for three soil textures (silt loam, sandy loam and sand).

$$I = I_c + (I_i - I_c)e^{-k(t-1)} \qquad (2.4)$$

where I = infiltration capacity (LT^{-1}), I_c = final infiltration (LT^{-1}), I_i = initial infiltration (LT^{-1}) t = infiltration time ≥ 1 hour, k = infiltration constant. The infiltration rate varied with soil type. The average values of k in Equation 2.4 were 0.25, 0.18 and 0.13 in silt loam, sandy loam and sandy soil, respectively.

A study by Niu and Xue (2014) found that the rate of infiltration has a positive correlation with degree of mineralization in silt loam soil and the volume of the wetted soil was higher than in distilled water. This was confirmed by another study by Zhang *et al.* (2017c) where it was established that the speed of the wetting front increased as the degree of mineralization increased from zero (distilled water), 2 g l^{-1}, 2.5 g l^{-1} and 3 g l^{-1} then it decreased at 3.5 g l^{-1}, and 5 g l^{-1}. The study also found that the infiltration index in Equation 2.3 decreased with increasing degree of mineralization.

An experiment by Xue *et al.* (2013a) established that the soil water movement in the soil is influenced by the hydraulic head where the speed of the wetting front increased with increasing head. As illustrated in Equation 2.1, Moistube discharge is proportional to pressure. However, according to Zhang *et al.* (2015c), the effect of pressure on temporal and spatial variations was not significant. This could partly be explained by the fact that only two pressures were considered in this study and therefore the interaction between pressure and the variations in soil water content could not be analysed conclusively. When three pressure heads (1 m, 1.5 m and 2 m) were considered, Yu *et al.* (2017) established that the wetted volume increased with increasing head.

A study by Zhang *et al.* (2017a) found that bulk density influenced the soil water movement under MTI where the cumulative infiltration was lower in soil with bulk density of 1.2 g cm^{-3}

than that of 1.4 g cm^{-3}. This was consistent with studies by Zhang *et al.* (2016a) where soil infiltration decreased with increase in clay content of the soil. Yu *et al.* (2017) found that soil type had significant effect on the soil water dynamics of MTI.

Another study by Zhang *et al.* (2012) found that the downward movement of water was 10% and 17% higher than upward movement in clay loam and sandy soils, respectively. Similarly, Xie *et al.* (2014b) found that the shape of the wetted volume in sandy loam soil was symmetrical about the Moistube lateral longitudinal axis and that the soil water movement was less influenced by gravity. Therefore, the soil water distribution under MTI is slightly different from that of SDI where Cote *et al.* (2003) established that the downward movement of water is about 50% higher than upward movement in sandy soils while that of silt is symmetrical. A study by Xu *et al.* (2015) found that altering the soil physical and hydraulic characteristics through the addition of biochar significantly reduced the infiltration rate, enhanced lateral movement of water, and reduced the upward flow in MTI.

The placement depth of Moistube significantly influence the soil water dynamics and salt transport. Niu *et al.* (2017) established that low salinity and high soil water content were in the soil layer close to the Moistube lateral. Similarly, Niu *et al.* (2013b) found that the Moistube placement depth had a significant effect on the shape of the wetted soil. In this study, the horizontal water movement and the ratio of width and depth of the wetted volume decreased with increased placement depth.

The above studies show that the soil water distribution under MTI is influenced by the type of the soil, system pressure, and the placement depth. Presence of impurities such as salts in the irrigation water also influenced the water flow in the soil.

2.4.2 Simulation of soil water distribution under Moistube irrigation

Carrying out field or laboratory measurements using a variety of soils with variable flow characteristics and irrigation methods in order to determine the soil water distribution is costly and difficult (Phogat *et al.*, 2012). In the case of MTI, the main element which require adjustment is the pressure heads to achieve the desired flow. The soil water distribution in subsurface irrigation can be determined by solving the Richards' Equation (RE) for multidimensional soil water flow based on Darcy's law and the continuity equation (Subbaiah, 2013).

Moistube irrigation can be modelled as a line source form of SDI. Its soil water distribution can, therefore, be represented by a two-dimensional form of RE (Equation 2.5) (Skaggs *et al.*, 2004).

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left[K(h)\,\frac{\partial h}{\partial x}\right] + \frac{\partial}{\partial z}\left[K(h)\,\frac{\partial h}{\partial z} + K(h)\right] \qquad (2.5)$$

Where θ = volumetric water content [L^3L^{-3}], h = soil water pressure head [L], K = unsaturated hydraulic conductivity [LT^{-1}], t = time [T]; and x = horizontal spatial coordinate [L], and z = vertical spatial coordinate.

The studies on soil water dynamics described in the preceding sub-section were mostly through laboratory experiments. A study was done by Zhang *et al.* (2015a) where HYDRUS-2D model was used to simulate the soil water dynamics under MTI and SDI as control. From the study, it was found that the shape of the soil water distribution in MTI and SDI was symmetrical at initial stages of irrigation. However, after 15 hours of irrigation, the water distribution in Moistube was still symmetrical while in drip it became asymmetrical with the upward movement being less than the downward movement. In a recent study by Fan *et al.* (2018b), HYDRUS 2D satisfactorily simulated the wetting pattern dimensions under MTI with average root mean square error (RMSE) of 0.43 cm. Similarly, Fan *et al.* (2018a), found RMSE of 0.03 cm^3/cm^3, percent bias less than 10% and model efficiency of 0.955 when HYDRUS 2D was used to simulate the soil water content distribution in a vertically-inserted Moistube. It is therefore possible to determine the soil water distribution under MTI for a variety of soils and flow rates using soil water models instead of the laborious, costly and time-consuming field or laboratory experiments.

2.4.3 Spatial and temporal irrigation uniformity

In the conventional irrigation such as drip or sprinkler, water is applied after a certain interval which can range from hours to days or weeks as per the irrigation schedule and as dictated by the soil water depletion. However, MTI is designed to apply water continuously throughout the cropping season (Zhang *et al.*, 2015a;Yang, 2016). This means that the crop will be relatively water stress-free throughout the season.

In an illustration by Yang (2016) in Figure 2.4, the importance of continuous irrigation is evident whereby in conventional irrigation (intermittent irrigation), the crop would suffer some form of water stress, during redistribution stage (B-D in Figure 2.4a) or water logging in case of irrigation above the field capacity. The continuous irrigation is an optimized form of intermittent irrigation. According to Zou *et al.* (2017) in intermittent irrigation methods such as drip, the soil water content in the rootzone changes with time and this affects the plant growth which subsequently affect the crop yield.

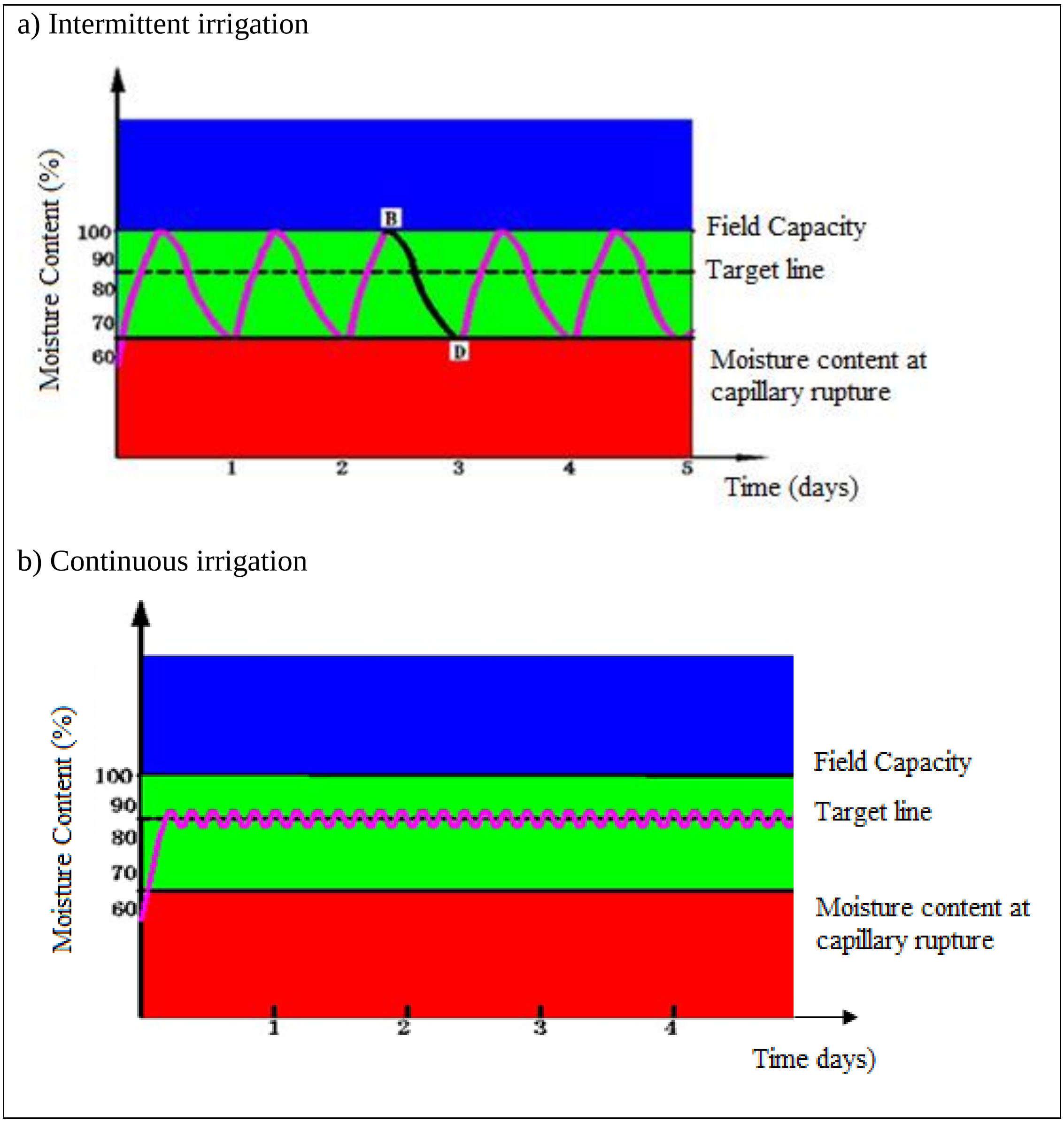

Figure 2.4 Soil moisture content (MC) curve under continuous and conventional (intermittent) irrigation (Yang, 2016).

However, continuous irrigation does not necessarily lead to improved plant growth. In a challenge to the concept of continuous irrigation, Wei *et al.* (2014) found that MTI with alternate partial rootzone drying and irrigation interval of 2 days led to improved root water absorption capacity and increase in root to shoot ratio by almost 13% than conventional MTI.

Spatial uniformity of water in the soil is important in ensuring that the crop gets the required amount of water. The distribution of water in the rootzone affects the yield response of the crop (Al-Ghobari, 2012). A study by Zhang *et al.* (2012) found that the irrigation uniformity of MTI was as high as 95% . Similarly, Zhang *et al.* (2015a) found that the uniformity of soil water distribution in MTI was 81% which was higher than in SDI. Another study by Yu *et al.* (2017) found that the soil water distribution uniformity depended on the soil texture. The study found that the average Christiansen's uniformity (CU) coefficient values were 86.7%, 85.7% and 66.9% for silt loam, sandy loam and sand, respectively. The CU values also increased with increasing pressure head with greater effect on sand than in silt loam and sandy loam.

2.5 Increasing Water Use Efficiency and Crop Yield Under Moistube Irrigation

MTI is a subsurface irrigation, and therefore, water losses due to runoff and evaporation are negligible. Since, it is a slow release kind of irrigation, deep percolation losses are minimal. As explained by Zhang *et al.* (2015a) the downward water movement under MTI is less than in SDI. These features make MTI a promising technology in arid and semi-arid areas.

A comparison between MTI and SDI for tomatoes in a greenhouse showed that the former had more or less same yield per unit area compared to the latter but a 13% higher WUE (Xue *et al.*, 2013b) . Another study by Lyu *et al.* (2016) found that MTI can achieve about 38% water savings than drip irrigation with mulch in production of tomatoes. Besides increase in total yield, the quality of the tomato in terms of fruit diameter, weight, vitamin C, soluble sugar and soluble acid ratio were 8.6%, 12%, 27%, 4.5% and 21% respectively, higher in MTI than in drip irrigation.

An experiment was carried out by Yao *et al.* (2014) to compare conventional irrigation, MTI, and rainfed water conditions. In the study, Moistube irrigated navel oranges achieved the highest leaf respiration index, photosynthetic rate, specific leave area and quantum yield. A study by Zhang *et al.* (2016b) established the water savings can be achieved in Moistube irrigation in cabbage production but the results could not be verified and thus further studies were recommended. Yin *et al.* (2017) reported 21% water savings in MTI irrigated spinach than conventional irrigation. However, Zhang *et al.* (2017e) found that maize yield decreased significantly in MTI than SDI but decreased non-significantly in wheat. In the same study, the crop WUE under MTI was not significantly different from SDI.

The higher WUE and water savings in MTI than conventional drip can partly be explained by the fact that the former supply water at 80 – 90% of field capacity (Zhang *et al.*, 2012) which is a form of deficit irrigation and thus improves crop water productivity and WUE. From the studies above, MTI is a promising technology in terms of water savings. However, validation with other crops is required and more specifically under a variety of environmental conditions.

2.6 Clogging Characteristics in Moistube Irrigation

Clogging is a major problem in micro-irrigation systems especially in SDI. The physical, chemical and bacteriological characteristics of water play a significant role in the clogging of emitters. Water sources have varying degree of suspended solids, dissolved solids and biological impurities such as algae and bacteria which are responsible for clogging emission devices in irrigation systems.

A study by Qiu *et al.* (2015) found that Moistube flow is influenced by water temperature. In the study, a unit change in temperature (^{o}C) results in 4% increase in Moistube discharge. Since it is made of elastic material, an increase in temperature may lead to increase in the dimension of the pores. This may not be the case in drip emitters where Rodríguez-Sinobas *et al.* (1999) found flowrate to be insensitive to temperature changes.

Presence of soil particles in the irrigation water cause clogging of Moistube pores. A study by Xie *et al.* (2014a) found that the sensitive particle size range which causes reduction in Moistube flow was between 0.037 mm and 0.074 mm. Similarly, Zhu *et al.* (2015) found that clogging of Moistube pores was positively correlated with soil particle concentration and the sensitive particle size range was between 0.061 mm and 0.1 mm and that under same concentration, the clogging degree decreased with increasing pressure. Another study by Qi (2013) found that if the particle size was less than 0.1 mm, the concentration of suspended solids was a significant factor in the clogging of Moistube pores. Filtration of the irrigation water is necessary to remove suspended solids and therefore, prevent clogging of the Moistube laterals.

Unlike in MTI, clogging of drip irrigation emitters have been studied extensively. Some of the recent studies on clogging of emitters due to suspended soil particles include by Bounoua *et al.* (2016) where it was established that even clay particles that pass through the filters could cause clogging of emitters as they aggregate downstream the laterals. Studies on chemical clogging has also demonstrated that precipitation of salts in irrigation water cause reduction in discharge of drip emitters. For example, Lili *et al.* (2016) found that saline water (EC = 3560 µS cm^{-1}) decreased discharge of some drip emitters to 46% after 126 hours of operation. Similarly, Liu *et al.* (2015) found a reduction in discharge of up to 85% after 35 days of drip irrigation with hard water (water hardness = 500 mg l^{-1}) and the primary component responsible for clogging was calcium carbonate. Clogging of drip emitters due to biological agents such as bacterial film in recycled wastewater has also been studied (Li *et al.*, 2009;Yan *et al.*, 2010). In these studies, the clogging occurs due to growth of bacterial slime along the flow path of the emitter.

2.7 Conclusions and Recommendations

The following conclusions can be deduced from this review

a) The discharge from Moistube is a function of the system pressure and the soil water potential. The flow is higher in the air than in the soil due to the influence of soil properties
b) The soil water dynamics is influenced by the soil type, depth of placement, system pressure and water quality.
c) MTI supplies water continuously to the crop at between 80 – 90% of field capacity throughout the cropping season
d) The technology has been applied on a few crops such as cabbages, tomatoes, onions, sunflower and oranges. These experiments have been conducted in greenhouses. From these experiments, it has been established that MTI improves the yield and WUE of crops. It has higher water savings than conventional methods such as drip irrigation.
e) Clogging due to suspended solids such as clay particles has been reported in MTI. From the results reported, suspended solids reduce the discharge from the Moistube. Therefore, the clogging characteristics in MTI is like drip irrigation.

The following are recommendations for further research arising from this review:

a) There is need to investigate further the effect of other water quality parameters, especially dissolved solids on the hydraulic characteristics of MTI.
b) The soil water distribution under different soil types and crops need to be further investigated. This could be accomplished using two-dimensional soil water models since field or laboratory experiments are costly and time consuming.

c) The suitability of MTI in other crops and environments need to be investigated by determining the growth and yield responses under different climates and soil types. This could be determined using suitable crop models such as AquaCrop or integration of crop and hydrological models.

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3. HYDRAULIC AND CLOGGING CHARACTERISTICS OF MOISTUBE IRRIGATION AS INFLUENCED BY WATER QUALITY

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Abstract

Irrigation consumes approximately 70% of total freshwater use worldwide. This necessitates the use of efficient irrigation methods such as micro-irrigation. Moistube irrigation (MTI) is a new subsurface irrigation technology where the water emits from a semi-permeable membrane of the Moistube at a slow rate depending on the applied pressure and soil water potential. There is currently limited information on the performance of Moistube tapes with respect to discharge as a function of pressure or water quality. The aim of this study was to determine the flow characteristics of Moistube tapes as a function of pressure and the effect of suspended and dissolved solids on the emission characteristics. The pressure-discharge relationship was determined within a range of 20 kPa and 100 kPa. The clogging of the Moistube was determined using water containing low, moderate and high concentrations of suspended and dissolved solids at 20 kPa and 30 kPa. The results indicated that the Moistube discharge follows power and linear functions with the applied pressure. The discharge decreased linearly over time because of clogging. The discharge decreased by 25 – 53% and 12 – 45% due to suspended solids and dissolved solids respectively. Suspended solids had a severe clogging effect on Moistube than dissolved solids. The results of this study would help in the design, operation and maintenance of MTI system.

Keywords: dissolved solids, low-pressure irrigation, micro-irrigation, nanoporous pipe, subsurface irrigation, suspended solids

3.1 Introduction

Irrigation constitutes approximately 70% of freshwater use in the world (Kulkarni, 2011). Consequently, irrigated agriculture is under pressure to increase crop water productivity. The use of subsurface irrigation helps in saving water by minimizing unproductive water loss components such as surface runoff, soil evaporation and percolation. Despite minimal water losses in subsurface drip irrigation, there is still a problem of leaching of nutrients and water, especially in light-textured soils (Cote *et al.*, 2003). In an attempt to address this problem, a new subsurface irrigation technology was developed which utilizes semi-permeable membrane to supply water continuously to the plant at a slow rate (Zhang *et al.*, 2012;Lyu *et al.*, 2016). Moistube irrigation (MTI) is a new technology which is like drip irrigation. However, instead of emitters, water emits from the semi permeable membrane of the Moistube tape depending on the applied pressure and the soil water potential of the surrounding soil. The main distinguishing feature of Moistube is its ability to supply water, in the absence of applied pressure, in response to the soil water potential (Zhang, 2013).

The main types of porous irrigation pipes, based on the pipe material, include porous clay pipes (Gupta *et al.*, 2009) and flexible porous pipes made of rubber and polyethylene (Amin *et al.*, 1998;Teeluck and Sutton, 1998;Liang *et al.*, 2009). These can further be classified based on the size of the emission pores as microporous pipes (Amin *et al.*, 1998;Teeluck and Sutton, 1998), and nanoporous where Moistube tapes belong. These pipes function as both conveyance and emission of the irrigation water. Porous pipe irrigation can be categorized as line-source trickle irrigation where the water is emitted over the entire length through closely-spaced emission devices and whose wetting pattern is a continuous strip.

Porous pipes have been applied in various parts of the world particularly in arid and semi-arid areas. They are popularly marketed as "leaky pipe" and "soaker hose' (Yoder and Mote, 1995;Janani *et al.*, 2011). Isoda *et al.* (2007) found that the water use efficiency (WUE) of porous pipes was the same as that of drip irrigation. For tomatoes grown in greenhouses in China, Xue *et al.* (2013b) found that MTI had 13% higher WUE than drip irrigation while Lyu *et al.* (2016) found water savings of 38% in MTI than drip irrigation with mulch. The higher WUE and water savings in MTI than conventional drip can be explained by the fact that the former supply water at 80 – 90% of field capacity (Zhang *et al.*, 2012) which is a form of deficit irrigation and thus improves crop water productivity and WUE. Other advantages of MTI include energy savings, low operation costs and minimal percolation losses (Lyu *et al.*, 2016).

Design and operation of an irrigation system require the knowledge of the hydraulic characteristics. Porous pipes made of elastic and flexible materials such as rubber exhibit variable permeability with respect to the applied pressure which in turn affects its emission characteristics (Liang *et al.*, 2009). The flow in a porous pipe decreases with time until a stable value is reached (Teeluck and Sutton, 1998;Liang *et al.*, 2009). There is a need for research on discharge characteristics of irrigation pipes with nanopores as emission devices. The use of nanotechnology in the manufacture of porous irrigation pipes may help in achieving partial desalinization (Madramootoo and Morrison, 2013), which is useful in the utilization of saline water in irrigation.

Water for agricultural use come from various sources such as reservoirs, municipal water supply systems, groundwater, and recycled wastewater. These water sources have a varying degree of quality which may pose problems to subsurface irrigation systems in terms of clogging of emission devices. Surface water sources contain impurities such as sand, silt and clay, and biological components like algae. Groundwater generally has high concentrations of dissolved ions such as calcium, iron, manganese, magnesium, carbonates, among others. Depending on the source and method of treatment, recycled wastewater contains organic matter, suspended solids, dissolved ions and microorganisms.

Clogging is one of the serious problems in micro-irrigation systems where it discourages the users and results in the substitution of the system with less efficient irrigation methods (Nakayama *et al.*, 2007). Emitter clogging can be classified as physical clogging due to suspended solids and organic materials, chemical clogging due to precipitates of dissolved solids and biological clogging due to algae and bacteria (Tripathi *et al.*, 2014). Besides water quality, the type of emitter also determines the degree of clogging where pressure-compensating emitters have a higher resistance to clogging than laminar flow type emitters and labyrinth type emitters with a turbulent flow (Liu and Huang, 2009). Clogging of emitters leads to poor water distribution hence limiting plant growth (Zhang *et al.*, 2017d) and thereby negatively affecting crop yields.

Despite the continued use of porous irrigation pipes, especially in the arid and semi-arid areas, there is little information on its clogging characteristics. Xie *et al.* (2014a) found that irrigation water containing soil particle sizes of between 37 μm and 74 μm can clog Moistube pores. No study has been reported on the effect of dissolved solids on the clogging of Moistube. Clogging mechanism vary with water quality and the operation parameters and are, therefore, specific to a given site.

The objective of this study was to determine discharge characteristics of Moistube as a function of operating pressure. The study also involved the determination of the effect of suspended solids and dissolved solids on the clogging characteristics of Moistube. The effect of dissolved solids on Moistube discharge is of primary importance in cases where groundwater or saline water are used for irrigation. This would help in understanding the design, operation and maintenance requirements of MTI system.

3.2 Methodology

The methods utilized in this study to achieve the objectives are explained in the following sub-sections. These included the laboratory experiments needed to establish the hydraulic characteristics in terms of pressure – discharge relationship and the clogging characteristics.

3.2.1 Pressure – discharge relationship

To determine the pressure – discharge relationship, a laboratory experiment was set up to measure the discharge from the Moistube under a pressure range of 20 kPa to 100 kPa at intervals of 10 kPa. There is no guideline on the length required for testing the discharge characteristics of porous pipes. In this study, the length of the Moistube used was 1m. The length was kept small so that friction losses are minimized (Kirnak *et al.*, 2004). The discharge was obtained by measuring the volume of water collected over 15 minutes using a 1000 ml graduated cylinder. This experiment was done in 5 replications. The duration of the experiment was 14 days.

The discharge as a function of pressure was represented by a power function illustrated in Equation 3.1 (Keller and Karmeli, 1974);

$$q = k_p h^x \qquad (3.1)$$

where q = flow rate (ℓ hr $^{-1}$m^{-1}), k_p = emitter constant, h = operating pressure (m) and x = is emitter exponent; and a linear function (Equation 3.2)

$$q = k_l h + c \qquad (3.2)$$

where k_l and c = constants while h is as defined in Equation 3.1

The power relationship in irrigation emitters helps in the characterisation of the flow regime using the value of the exponent where a value of 1 indicates laminar flow and 0.5 shows a fully turbulent flow and the intermediate values represent a partially turbulent flow (Clark *et al.*, 2007) and values below 0.5 indicate pressure compensating properties.

The porous irrigation pipes have pores whose sizes and distribution vary randomly and thus, the emission along the pipe would vary (Yoder and Mote, 1995). The emission uniformity from the Moistube was determined by measuring the flow from 20 cm segments of the lateral over a length of 1 m. This was replicated 5 times. The Moistube lateral laid horizontally but the PVC gutter sloped gently (1%) to allow for the collection of water from the segments. The experimental set-up is shown in Figure 3.1. The performance was evaluated using the coefficient of variation (CV) according to Equation 3.3 (Liang *et al.*, 2009):

$$CV = \frac{S}{\bar{q}} \times 100 \qquad (3.3)$$

where CV = manufacturer's coefficient of variation (%), S = standard deviation of discharge (ℓ hr $^{-1}$m^{-1}) and $\bar{q}$ = average discharge (ℓ hr $^{-1}$m^{-1}).

The coefficient of variation expressed in Equation 3.3 is as a result of emitter design, the material used and the precision of the manufacturing process (Capra and Scicolone, 1998).

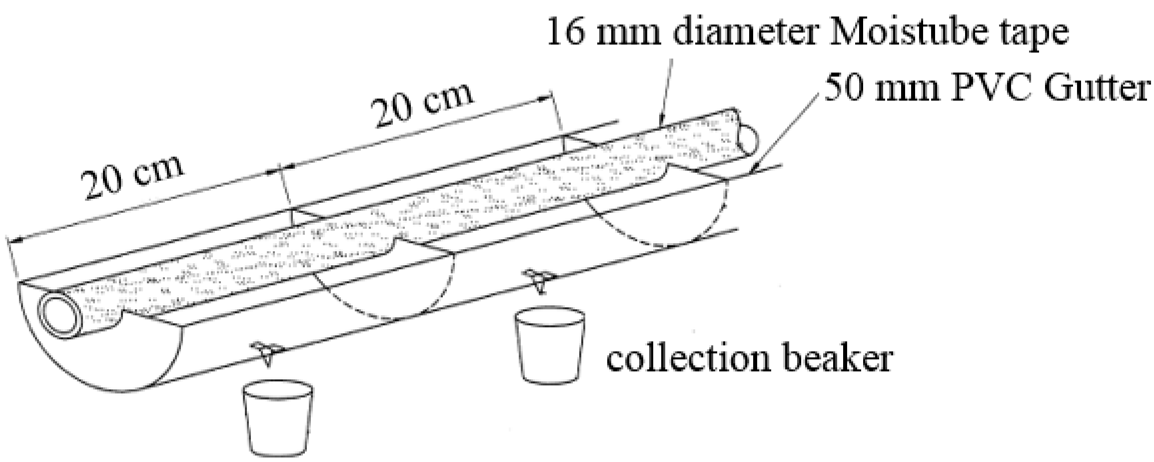

Figure 3.1 Setup for the determination of the coefficient of variation

3.2.2 Emission characteristics due to clogging

The effect of clogging due to the presence of suspended particles in irrigation water was determined by measuring the flow from Moistube at 20 kPa and 30 kPa using water containing silt and clay particles. It was not possible to determine the effect of clogging on Moistube discharge at higher pressures due to unavailability of facilities. Soil passing through a 125 µm sieve was added to tap water to achieve a concentration of 25 mg ℓ^{-1} (TS1), 75 mg ℓ^{-1} (TS2) and 150 mg ℓ^{-1} (TS3) which has a low, medium and severe clogging risk, respectively (Nakayama and Bucks (1991), as indicated in Table 3.1. Clogging due to dissolved solids was determined by adding equal proportions of calcium chloride, magnesium sulphate and sodium bicarbonate to give concentrations corresponding to low (TD1), moderate (TD2) and severe clogging risk (TD3), respectively as illustrated in Table 3.1

Table 3.1 Experiment treatments

Treatment	Clogging material	Clogging risk
T0	Tap water	Control
TS1	Suspended solids (25 mg ℓ^{-1})	Low
TS2	Suspended solids (75 mg ℓ^{-1})	Moderate
TS3	Suspended solids (150 mg ℓ^{-1})	Severe
TD1	Dissolved solids (250 mg ℓ^{-1})	Low
TD2	Dissolved solids (1000 mg ℓ^{-1})	Moderate
TD3	Dissolved solids (2500 mg ℓ^{-1})	Severe

The experimental set-up is illustrated in Figure 3.2. The experiment consisted of a 260 ℓ tank situated in stand with two platforms at 2 m and 3 m. This allowed for measurement at 20 kPa and 30 kPa. The set-up also consisted of 50 cm length Moistube replicated 4 times in a manifold arrangement. The space between the laterals was 30 cm. The discharge was measured by collecting water using 1000 mℓ graduated cylinders for 15 minutes every 24 hours for a period of 14 days. To ensure adequate mixing and suspension of the soil particles, a low-head submersible pump was placed at the bottom of the tank.

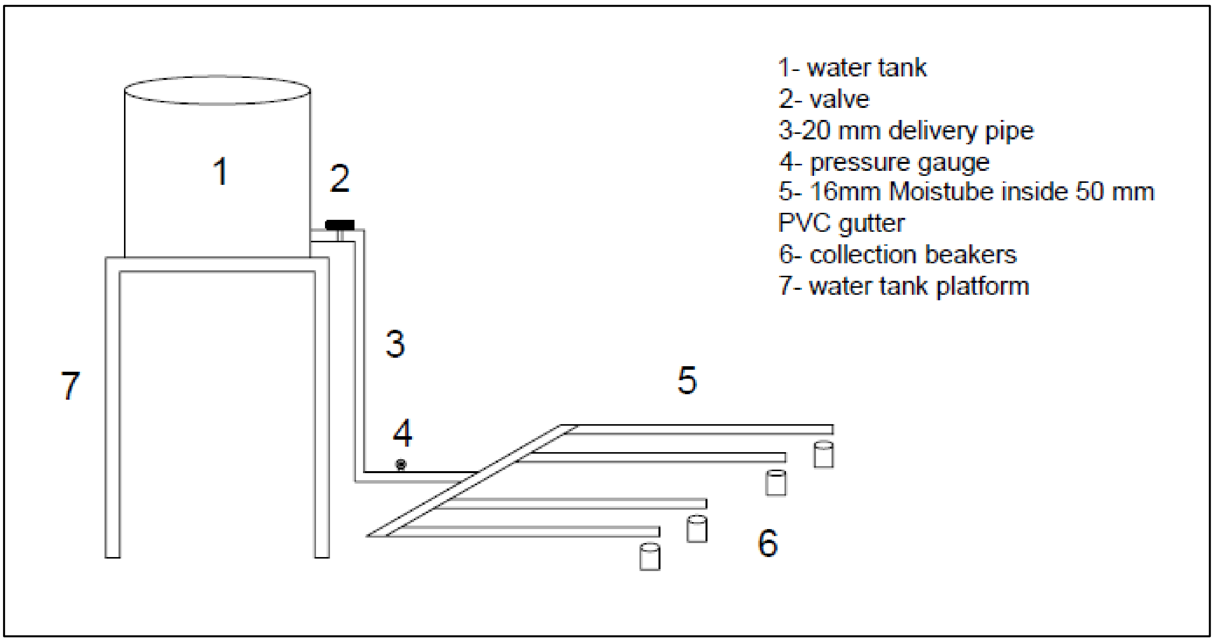

Figure 3.2 Experimental set-up

The water quality in the tank was monitored by testing periodically over the duration of the experiment to ensure that they remain within the set limits (little, moderate and severe clogging risk) and any variation adjusted accordingly. The parameters tested were total suspended solids (TSS), pH, temperature (T), electrical conductivity (EC) and total dissolved solids (TDS), which were analysed using portable handheld TSS meter from HACH industries (TSS resolutions of 0.1 at 10 – 99.9 g ℓ^{-1} and 1 at greater than 100 g ℓ^{-1}, and HI98129 combo Tester for pH/EC/TDS/temperature from Hanna Industries (resolutions: 0.01 pH, 1 µS cm^{-1}, 1 ppm, 0.1 °C). The water quality characteristics are shown in Table 3.2.

Table 3.2 Mean water quality characteristics

Treatment	pH	TDS (mg ℓ$^{-1}$)	T (^{0}C)	EC (µS cm^{-1})	TSS (mg ℓ$^{-1}$)
T0	7.8 ± 0.5	31.7± 1.6	19.2 ± 2.0	65.0 ± 2.1	
TS1	7.6 ± 0.2	32.0 ± 1.2	19.2 ± 0.6	64.8 ± 1.9	25.0 ± 4.9
TS2	7.4 ± 0.1	34.4 ± 2.9	19.7 ± 0.5	70. 0 ± 4.1	73.2 ± 4.8
TS3	7.5 ± 0.1	37.2 ±1.6	21.4 ± 0.7	74.6 ± 3.0	147.8 ±13.9
TD1	7.2 ± 0.3	269.2 ± 14.0	17.3 ± 2.1	531. 4 ± 27	
TD2	6.9 ± 0.3	1036.1 ± 218.6	15.3 ± 1.1	2060.8 ± 434.1	
TD3	7.3 ± 0.1	2480.8 ± 68.0	18.8 ± 0.8	4678.5 ± 460.4	

The effect of suspended and dissolved solids was determined by examining relative discharge over the duration of the experiment. The relative discharge was computed as in Equation 3.4

$$q_{rel} = \frac{q_i}{q_0} \times 100 \qquad (3.4)$$

where q_{rel} = relative mean discharge (%);

q_i= average discharge (ℓ hr^{-1}m^{-1}) at time, t ($0 \leq t \leq 336$) hrs and

q_0= average initial discharge obtained at the beginning of the experiment (ℓ hr^{-1}m^{-1})

The average initial discharge was the mean initial discharge of the four replicates at the beginning of the experiment.

3.2.3 Statistical analysis

The data was analysed using SPSS version 24 (IBM, New York, USA). Analysis of variance was carried out and the separation of means done by the least significant difference (LSD). The analysis was conducted at 5% significance level.

3.3 Results and Discussion

The relationship between discharge and pressure under MTI and the effect of suspended and dissolved solids on the emission characteristics of Moistube are described in the following sub-sections.

3.3.1 Pressure – discharge relationship

The discharge from Moistube under varying pressure can be represented by a power function (R^2 = 0.98) and linear function (R^2 = 0.96) as illustrated in Figures 3.3. The average discharge varied from 0.24 ℓ $hr^{-1}m^{-1}$ at 20 kPa to 1.73 ℓ $hr^{-1}m^{-1}$ at 100 kPa.

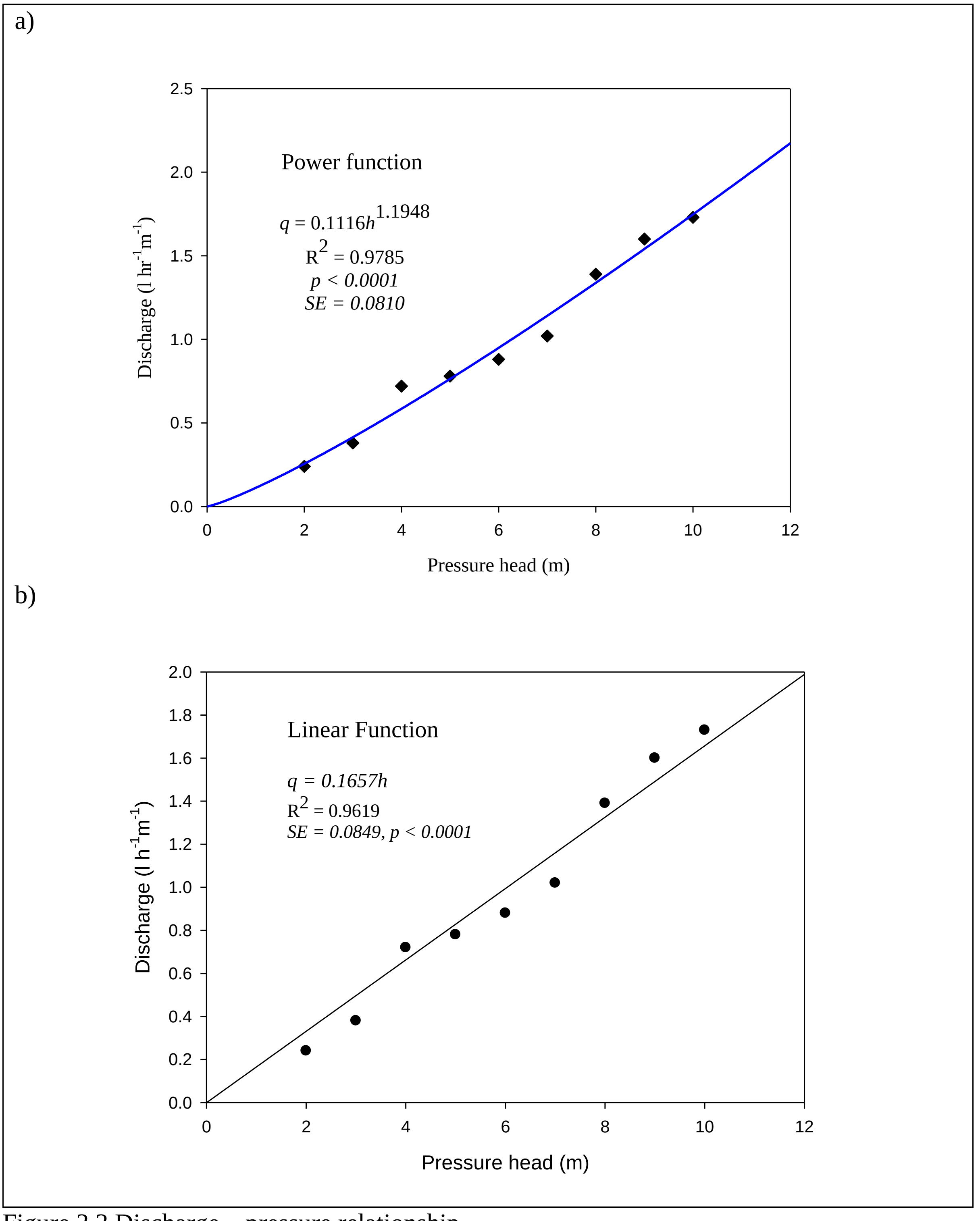

Figure 3.3 Discharge – pressure relationship

The relationship between discharge and pressure can be expressed by Equations 3.5 and 3.6

$$q = 0.1116h^{1.1948} \quad (3.5)$$

$$q = 0.1657h \quad (3.6)$$

The exponent value greater than one indicates that MTI is sensitive to pressure changes which is similar to non-pressure compensating drip emitters and, thus the length of laterals should be short (Kirnak *et al.*, 2004). The value of the exponent in Equation 3.5 shows that the flow regime is laminar (Clark *et al.*, 2007) which is explained by the linear relationship in Figure 3.3 .

The high sensitivity of discharge with pressure variation in MTI, as indicated by the exponent value greater than one, is consistent with studies carried out for porous irrigation pipes (Amin *et al.*, 1998;Liang *et al.*, 2009;Pinto *et al.*, 2014).

From Equations 3.5 and 3.6, there will be no discharge from the Moistube at zero pressure. As explained by Zhang (2013), the flow of Moistube varies with the soil water potential and the system pressure. Therefore, in the absence of pressure, the discharge will only occur when there is suction from the surrounding soil. The effect of the soil water potential is only limited to the first 44 hours as established by Niu *et al.* (2017).

3.3.2 Emission uniformity along the lateral

The coefficient of variation ranged from 4.4% to 16.1% (Figure 3.4) with an average of 11.6% which was within the acceptable range (<20%) for line-source emitters (Teeluck and Sutton, 1998). Manufacturing variation is one of the factors that affect the uniformity of an irrigation system. The results of this study demonstrate that acceptable water application uniformity can be achieved with MTI if other design factors such as lateral diameter and spacing are implemented correctly. The CV values were better than those found by Teeluck and Sutton (1998) (23.9 – 58%) and Liang *et al.* (2009) (14.3 – 48.7%) for porous plastic pipes. Yoder and Mote (1995) found the CV values in 30 cm segments of porous pipes to be within acceptable ranges. As illustrated in Figure 3.4, the CV decreased linearly (R^2 = 0.98) with increasing pressure. This can be attributed to enlargement of pores and increase in the number of active pores which were not emitting at lower pressures. Therefore, MTI can be designed and operated at pressures 50 kPa and 100 kPa where the CV values are less than 10%.

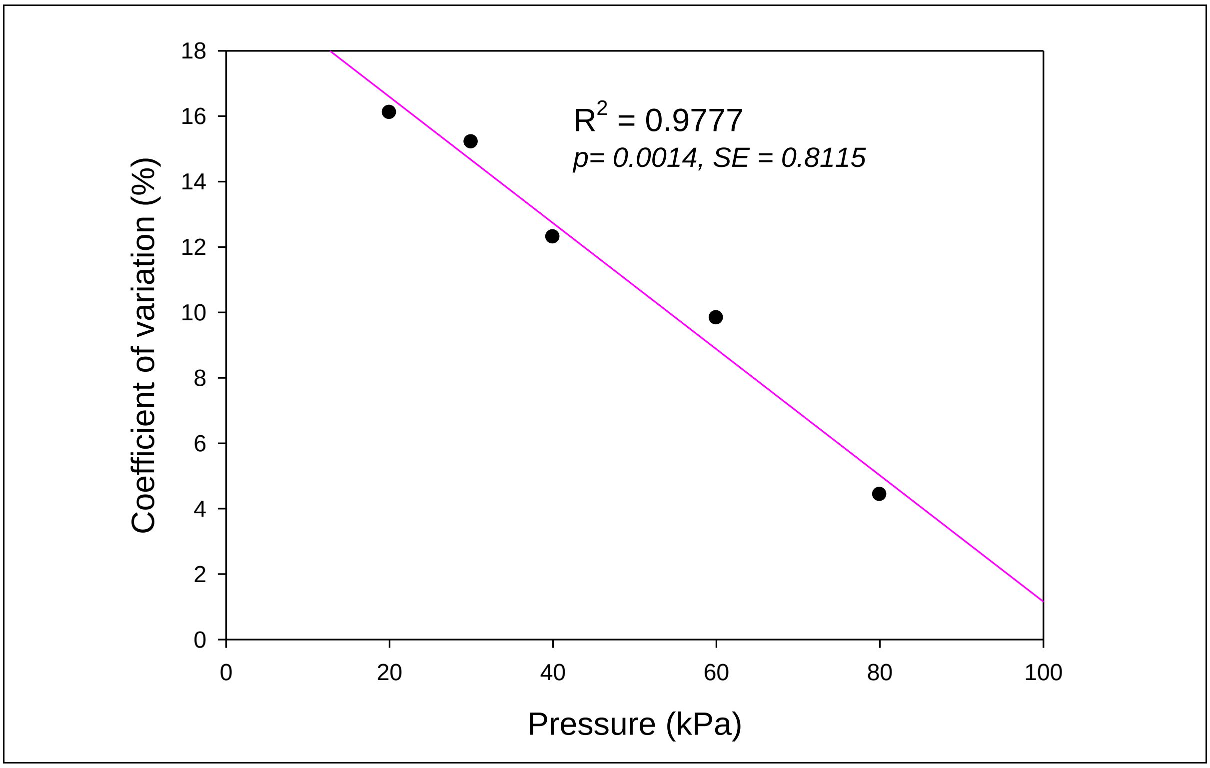

Figure 3.4 Emission variation along lateral length at varying pressure

3.3.3 Clogging effect on emission characteristics

a) Effect of suspended solids

The effect of suspended solids on Moistube discharge, as measured by the relative discharge over time, is illustrated in Figure 3.5. In some instances, such as for T0 and TS1, the discharge increases slightly in the first 24 hours. This could be attributed to the production of more effective pores as the operation time increased and as the pipe gets soaked. There was no significant difference among the discharges for the first two days ($p > 0.05$) but it became significant as the time of operation increased ($p < 0.05$) indicating the reduction of discharge because of clogging.

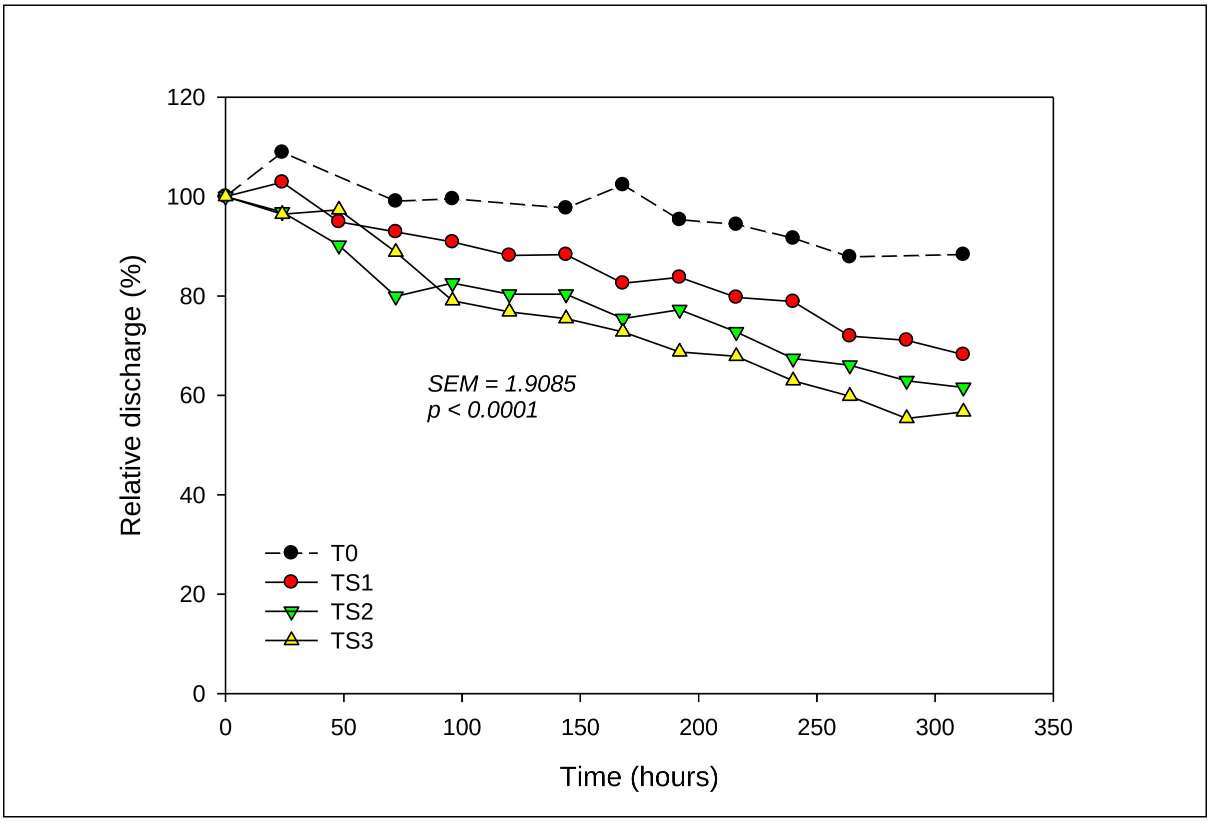

Figure 3.5 Relative discharge at 20 kPa (TSS)

The reduction in discharge from the Moistube followed a relatively linear relationship with R^2 values of 0.95, 0.93 and 0.96 for TS1 (low concentration), TS2 (moderate concentration) and TS3 (high concentration), respectively. The decrease in discharge in Moistube due to clogging is dissimilar with drip irrigation emitters where the rate of discharge declines gradually in the first few days then drastically in the latter stages.

The difference in reduction of discharge, over the full-time range, was significant between the tap water (T0) and the other concentrations of suspended solids, between TS1 and TS2, and between TS1 and TS3 ($p < 0.05$). However, there was no significant difference between the reduction in discharge between TS2 and TS3 ($p > 0.05$). Capra and Scicolone (2007) explained that suspended solids of about 50 mg ℓ^{-1} could be considered critical level which contributes to clogging. Taking 25% reduction in discharge (75% relative discharge) as a critical measure of clogging (Niu *et al.*, 2013a), the Moistube tape could be said to be clogged after 168 hours, 216 hours, and 312 hours for TS3, TS2 and TS1, respectively. Although the relative discharge in the control (T0) did not reach critical levels during the entire duration, there is a reduction in discharge, especially after 216 hours. This could be attributed to a higher pH (7.8 ± 0.5) in the tap water (Table 3.2) which is considered to have moderate clogging effect through accelerated precipitation of dissolved ions. Liang *et al.* (2006), found that tap water, in comparison to distilled water, led to a decrease in emission rates over time from porous irrigation pipes due to clogging. However, Liang *et al.* (2009) found a decrease in emission from porous pipe even when distilled water is used which was attributed to structural changes in the pipe material.

The relative discharge at 30 kPa is illustrated in Figure 3.6. The discharge decreased with time and it passed the critical level of 75% after 144 hours, 200 hours, and 264 hours for TS3, TS2 and TS1, respectively. The decrease in discharge between all the concentrations were significant except between TS2 and TS3.

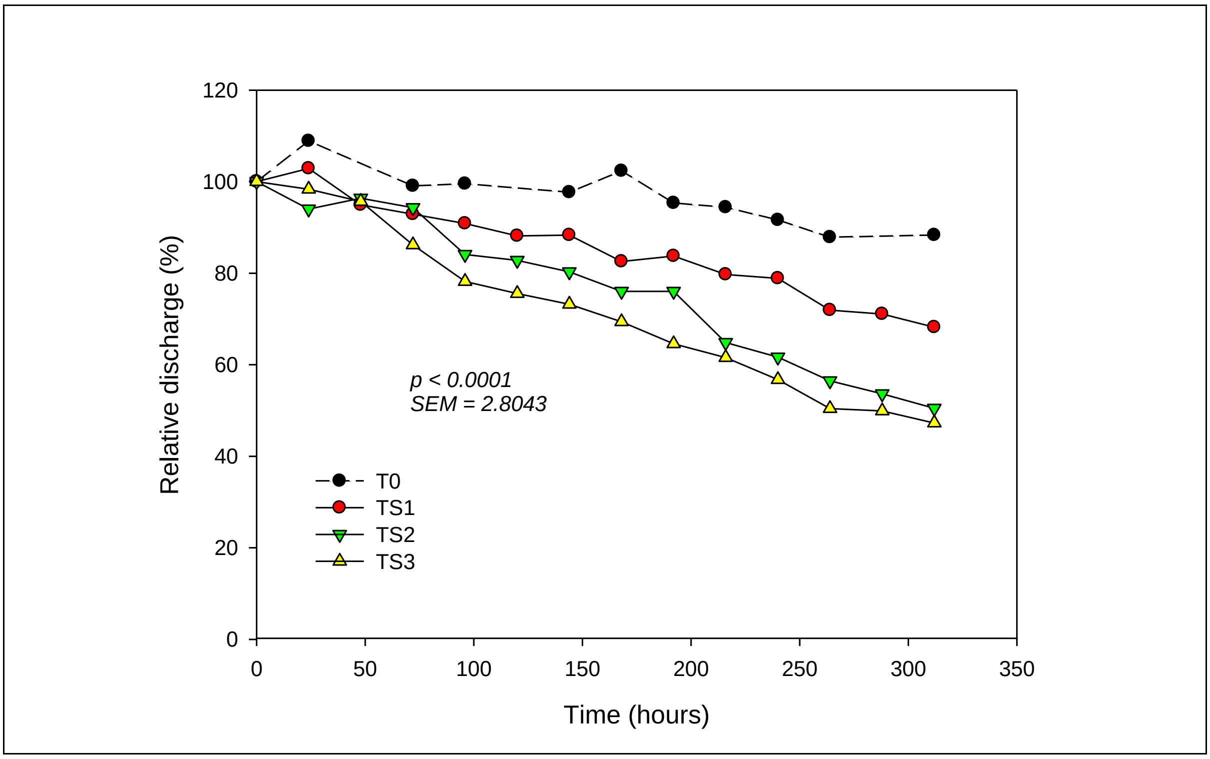

Figure 3.6 Relative discharge at 30 kPa (TSS)

The decrease in discharge over time under suspended solids at 30 kPa followed a linear relationship, as in the case with 20 kPa, with R^2 of 0.97 for both TS1 and TS2, and 0.98 for TS3.

The reductions in discharges at the end of the experiment (14 days) were 25.7%, 38.4% and 43.3% at 20 kPa, and 31.8%, 49.5% and 52.7% at 30 kPa for TS1, TS2 and TS3, respectively. The difference between the initial and final discharges was significant for all the treatments except T0 ($p < 0.05$). The reduction in discharge was higher at 30 kPa than 20 kPa. At the higher pressure, the collision of clay and silt particles increases which in turn creates coagulating effect and the relatively larger drag force makes the developed flocs unable to escape (Niu *et al.*, 2013a). Furthermore, at higher pressure, a relatively larger amount of soil particles passes through the Moistube pores because of higher discharge and consequently, the number of clogged pores is increased.

The difference in clogging characteristics at 20 kPa and 30 kPa for paired respective concentrations was not significant ($p > 0.05$). This implies that pressure had no significant effect on the clogging characteristics due to suspended solids.

b) Effect of dissolved solids

The effect of dissolved solids on Moistube discharge is presented in Figures 3.7 and 3.8 for 20 kPa and 30 kPa, respectively. The discharge increased slightly after 24 hours signifying the increase in the number of effective pores as the pipe gets soaked with water. The discharge from Moistube takes a while, especially during low pressures.

There was no significant difference among the concentrations for the first six days ($p < 0.05$). This implies that clogging process had not initiated. However, from day seven, there were significant differences among the relative discharges indicating the effect of clogging due to the precipitation of the dissolved salts. The relative discharge was above 75% in all the concentrations at 20 kPa and at TD1 (low concentration) at 30 kPa. The discharge decreased to 55% and 64% for TD3 (high concentration) and TD2 (moderate concentration), respectively at 30 kPa. There was no significant difference between the initial and final discharges for T0 and TD1 ($p > 0.05$) which signify low clogging levels. However, there was a significant difference between the initial and final discharge for TD2 at 30 kPa and TD3 at both pressures indicating clogging effect. There was no significant difference among the relative discharges at 20 kPa ($p > 0.05$). There was a significant difference between T0 (control) and both TD2 and TD1 and between TD1 and TD3 ($p <0.05$) at 30 kPa. However, the difference was not significant between T0 and TD1, and between TD2 and TD3. Previous studies on clogging of drip emitters indicated that they performed relatively worse than Moistube. Lili *et al.* (2016), found that saline water (EC = 3560 µS cm^{-1}) decreased discharge of some drip emitters to 46% after 126 hours of operation. Similarly, Liu *et al.* (2015) found a reduction in discharge of up to 85% after 35 days of drip irrigation with hard water (water hardness = 500 mg/l) and the primary component responsible for clogging was $CaCO_3$. The possible explanation for relatively less clogging of Moistube is due to the numerous number of pores per unit surface area. This, therefore, increases the time taken for a significant number to be clogged by the precipitated ions.

Dissolved solids do not cause clogging unless the ions precipitate (Nakayama *et al.*, 2007). However, in this study, precipitation was enhanced by the addition of $NaHCO_3$ which upon dissolution frees the CO_3^{2-} which in turn react with Mg^{2+} and Ca^{2+} ions from the dissolved $MgSO_4$ and $CaCl_2$, respectively. Also, the pH level of greater than 7.5 in the tap water helped in accelerating the precipitation process. Dissolved solids clog the porous irrigation pipes when the chemical precipitates flocculate around the emission pores partially or completely restricting the flow. Lili *et al.* (2016), found that the major chemical compound responsible for clogging of drip emitters was $CaCO_3$.

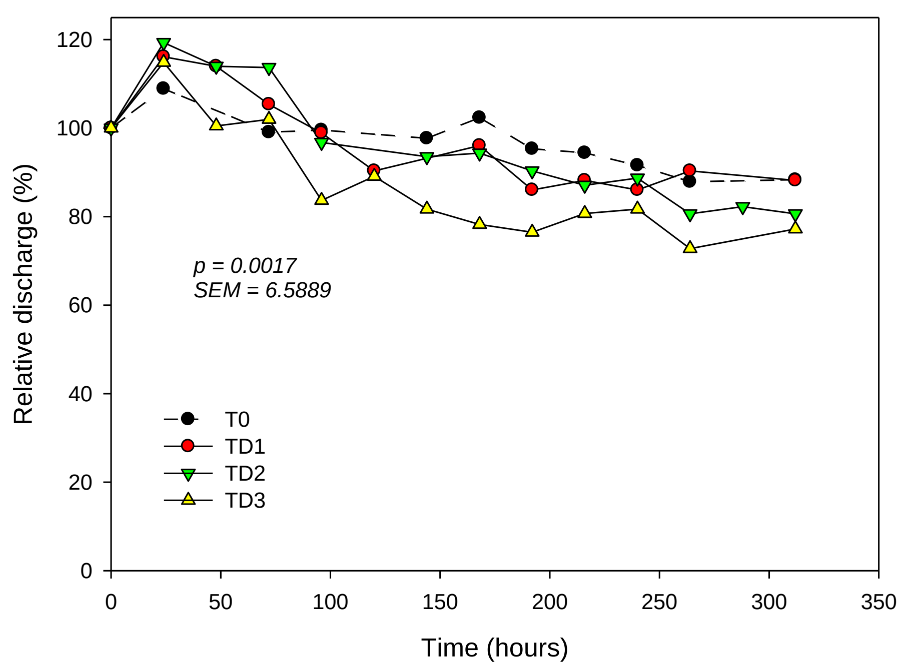

Figure 3.7 Relative discharge at 20 kPa (TDS)

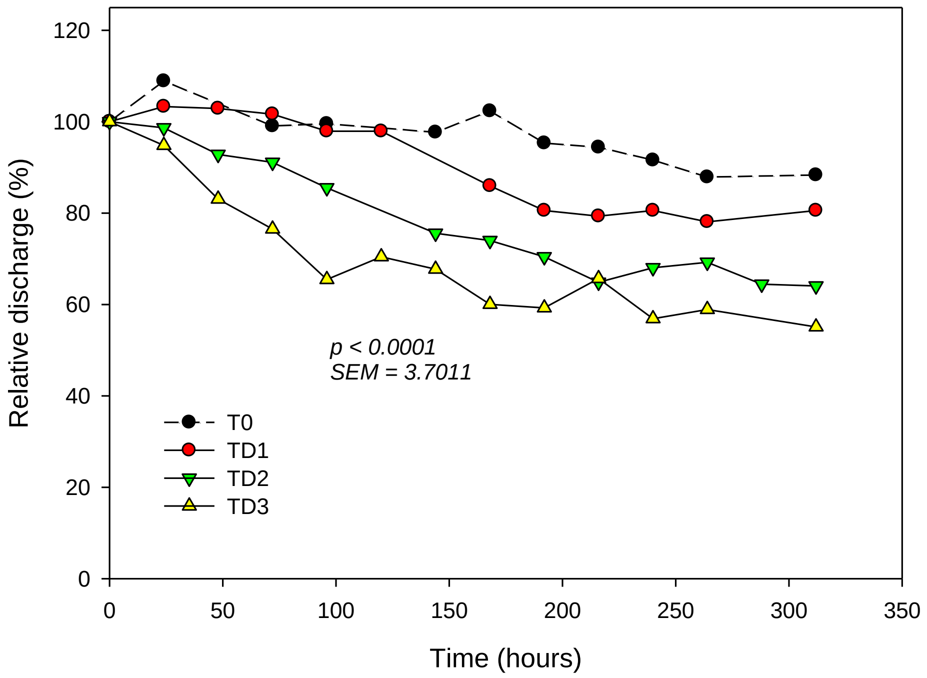

Figure 3.8 Relative discharge at 30 kPa (TDS)

The variation in clogging characteristics between the two pressures was significant for TD2 and TD3 ($p < 0.05$). This implies that pressure had an effect on the Moistube clogging. This can be explained by the fact that at 30 kPa with moderate to high concentrations, a higher amount of precipitates passes through the Moistube per unit time and some are stuck in the pores since the pressure is not high enough to push them out. However, there was no significant difference in the relative discharge of TD1 between the two pressures. This means that at low concentration of dissolved solids, the effect of pressure is negligible. The decrease in discharge followed a linear relationship at 20 kPa with R^2 of 0.66, 0.79 and 0.72 for TD1, TD2 and TD3, respectively and a good linear relationship at 30 kPa with R^2 values of 0.86, 0.93 and 0.80 for TD1, TD2 and TD3, respectively.

Multiple analysis of variance indicated that time and concentration were significant factors which affect discharge from Moistube. Discharge decreased with increasing time at varying rates because of clogging by suspended and dissolved solids. There was a significant difference between the relative discharges for suspended and dissolved solids. Suspended solids had a greater effect on clogging than dissolved solids. All the concentrations of suspended solids had a significant effect on the relative discharge while the effect of dissolved solids on the relative discharge was only significant at TD3 ($p < 0.05$). Therefore, water devoid of suspended solids should be used in MTI. In this regard, filtration systems like those of drip irrigation should be used in MTI to reduce the effect of clogging.

3.4 Conclusions and Recommendations

From the findings of this study, the following conclusions can be drawn;

1) The Moistube discharge increased with increasing pressure. The pressure discharge relationship follows linear and power functions. The exponent in the power function was greater than one indicating laminar flow regime. Therefore, the flow from Moistube is sensitive to pressure changes.
2) The manufacturing coefficient of variation decreased with increasing pressure because of the balancing or evening-out effect. The best operating pressure range for MI is between 50 kPa and 100 kPa where the CV values were less than 10%.
3) The reduction in discharge ranged from 32% to 53% because of suspended solids and 12% to 45% due to dissolved solids. Moistube laterals were relatively resistant to clogging due to dissolved solids less than 1000 mg ℓ^{-1}. Suspended solids had a significantly higher effect on reduction in Moistube flow than dissolved solids.

The CV experiment in this study was carried out over 1 m length of the Moistube. Further experiments are needed to determine the variation in discharge over longer lengths such as 3m, 6m, 10m, etc, to mimic the actual field conditions. It would also be interesting to determine the discharge variation along the length of the pipe for different land slopes to facilitate the design of suitable field layouts of the Moistube laterals.

Water quality is paramount in MTI and therefore, appropriate treatment methods for removal of suspended and dissolved solids need to be used to prevent clogging. Further research needs to be carried out under a wide range of pressures to fully understand the effect of pressure on Moistube clogging characteristics. Long-term clogging tests are needed to determine the effect of suspended and dissolved solids in a typical growing season of crops. This could be important in determining whether fertigation could be practiced in MTI without reducing the Moistube discharge.

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4. SOIL WATER DYNAMICS UNDER MOISTUBE IRRIGATION

Edwin K. Kanda, Aidan Senzanje, Tafadzwanashe Mabhaudhi

Abstract

The design and management of irrigation systems require the knowledge of soil water movement. There are few studies on soil water dynamics of Moistube irrigation (MTI) since it is a relatively new type of subsurface irrigation technology. This study aimed at determining the soil water distribution experimentally and numerically using HYDRUS 2D/3D model for two soil textures (loamy sand and sandy clay loam). The study was based on the hypothesis that soil texture influences the soil water distribution under MTI. The experiment consisted of a soil box filled with soil and Moistube, supplied with water under a constant pressure head of 60 kPa, placed at 20 cm below the top of the soil surface. The soil water was measured using MPS-2 sensors installed at depths of 5 cm, 10 cm, 15 cm, 20 cm, 30 cm, 40 and 50 cm and laterally at 10 cm, 20 cm and 30 cm. The soil water contents were measured over a period of 72 hours. The results showed that the simulated water contents closely matched ($R^2 \geq 0.70$ and RMSE ≤ 0.045 cm^3 cm^{-3}) the observed values in all the points considered for the two soil textures. The model slightly under-estimated or over-estimated the soil water content with percent bias less than 15.6%. There was no significant difference ($p > 0.05$) between the soil water distribution in lateral and downward direction for both sandy clay loam soil and loamy sand. However, the soil water content upward of the Moistube placement depth was significantly ($p < 0.05$) lower than both the laterally and downwards soil water contents in loamy sand where the soil water contents at 10 cm upward, downward and lateral after 24 hours were 0.08 cm^3 cm^{-3}, 0.23 cm^3 cm^{-3} and 0.20 cm^3 cm^{-3}, respectively. On the other hand, the corresponding values for sandy clay loam were 0.28 cm^3 cm^{-3}, 0.32 cm^3 cm^{-3} and 0.31 cm^3 cm^{-3} at 10 cm upward, downward and lateral, respectively. The simulations for wetted distance in both soil textures were also close to the observed values ($R^2 \geq 0.97$, RMSE ≤ 3.99 cm). Soil texture had a significant effect ($p < 0.05$) on soil water movement with upward movement faster in sandy clay loam than in loamy sand. The lateral and downward distances were 23 cm and 24.6 cm, respectively, for loamy sand after 24 hours. Similarly, for sandy clay loam, the lateral and downward distance was 19 cm. This should be considered in the design of MTI in terms of depth of placement and lateral spacing. The results of this study demonstrated the usefulness of HYDRUS-2D/3D model in the prediction of soil water movement for optimum design of MTI.

Keywords: HYDRUS 2D/3D, soil texture, soil water distribution, subsurface irrigation

4.1 Introduction

Competition for the scarce water resources because of increased population, urbanization and industrialization has put pressure on irrigated agriculture to improve water use efficiency (WUE) and crop water productivity (WP). WP is defined as the aggregate biomass or yield (grain, tuber, or any other useful output) produced for every unit quantity of water consumed, which can be in the form of rainfall or irrigation (Ali and Talukder, 2008). WUE, on the other hand, developed from its predecessor irrigation efficiency where the latter denotes the ratio of crop water consumption to the total amount of irrigation water applied (Heydari, 2014). One of the options for reducing water losses in irrigated agriculture is the adoption of efficient irrigation systems such as micro-irrigation. Micro-irrigation technologies have gained popularity given their higher water application efficiencies as they minimize water losses via surface runoff, soil evaporation and drainage. Moistube irrigation (MTI) is one such technology which is subsurface type of irrigation where semi-permeable membrane allow water to emit continuously throughout the length of the lateral as a function of the applied pressure and the soil water (Yang *et al.*, 2008;Yang, 2016). The review of MTI has been described in Chapter 2.

Soil water movement and distribution is necessary for the design and management of irrigation systems. Design and management aspects such as the volume of the wetted zone, spacing of emission devices, irrigation schedules, etc relies on the soil water distribution (Lubana and Narda, 2001). Knowledge of the soil wetted volume helps in the establishment of the emitter spacing and the duration of irrigation when the wetted volume is within the root zone (Provenzano, 2007).

The soil water dynamics in the case of SDI systems depend on factors such as soil type, initial soil moisture content, emitter discharge, the rate of water application, crop type, evapotranspiration, spacing, and depth of laterals (Kandelous and Šimůnek, 2010a;Subbaiah, 2013). For optimum water application to the root zone in subsurface irrigation systems, there is need to determine precisely the depth of placement of laterals and spacing of emitters to minimize percolation losses (in the case of deeper depths) or soil evaporation in the case of too shallow depths (Kandelous and Šimůnek, 2010b).

The determination of soil water distribution around an irrigation emitter can be determined using laboratory and field experiments or by using simulation models (Subbaiah, 2013). However, carrying out field measurements using variety of soils with variable emitter flow rates and irrigation methods for purposes of investigating the soil water distribution is costly and require a considerable amount of time (Phogat *et al.*, 2012). Soil water distribution models can be categorized into analytical, numerical and empirical.

Analytical methods give an exact solution, however, they are usually used to solve the water flow equations under specific conditions (Naglič *et al.*, 2012) and therefore the results need to be used as a guideline (Thorburn *et al.*, 2003). Due to non-linearity of the equation governing soil water flow, it is difficult to solve using analytical methods and in addition, the models developed are based on assumptions of soil homogeneity and uniform initial soil moisture distribution (Naglič *et al.*, 2012), simple geometries of transport domain (Subbaiah, 2013), and source configuration and thus limit their use in trickle irrigation management (Cote *et al.*, 2003).

Numerical models solve variably saturated flow problems, using finite difference, finite element, or some other kinds of boundary approximation techniques, finite volumes and reformulating the partial differential equations (Öztekin, 2002;Naglič, 2014). Numerical methods have become popular because of the limitations of analytical models which are based on numerous assumptions. Numerical models require fewer assumptions, inbuilt into them, but require considerable computing power (Cook *et al.*, 2006). However, with the recent advancement in computer technology, with fast computer speeds, numerical models have gained wide applicability (Kandelous and Šimůnek, 2010b;Naglič, 2014).

HYDRUS 2D/3D is a model used for the simulation of water movement and solute transport in 2D/3D variably-saturated porous media (Šimůnek *et al.*, 2006). HYDRUS 2D/3D is superior to other models because of its user-friendly Windows-based interface unlike the DOS-based numerical codes of other numerical models such as SWMS-2D and in addition it accounts for root water uptake (Šimůnek *et al.*, 2008). The model has been applied successfully to simulate soil water distribution under various types of irrigation methods such as furrow irrigation (Zhang *et al.*, 2013b), surface drip irrigation and SDI (Kandelous and Šimůnek, 2010b). For instance, Mante and Ranjan (2017), used HYDRUS 2D/3D in simulating the soil water contents in sandy loam under potato cultivation and found model efficiency values greater than 0.80 and percent bias less than 10%. Similarly, Patel and Rajput (2010) found root mean square errors (RMSE) and absolute error values less than 5% in the simulation of soil water content under SDI using HYDRUS 2D. Skaggs *et al.* (2004), satisfactorily simulated soil water content under drip irrigation with RMSE less than 0.04 $cm^3\ cm^{-3}$. From the studies above, it is evident that HYDRUS 2D/3D is suitable for simulating soil water distribution under irrigation systems.

MTI is a relatively new irrigation technology whose design aspects such as spacing and depth of placement under varying soil types is still under investigation as discussed in Chapter 2. This study aimed at determining the soil water dynamics of MTI under loamy sand and sandy clay loam soils using laboratory experiments and numerical simulations. It was based on the hypothesis that soil texture influences the soil water distribution under MTI. The findings of this study would aid in the understanding of the soil water distribution under MTI which would be useful in its design and management.

4.2 Materials and Methods

This study was carried out using laboratory experiments and numerical modelling using HYDRUS 2D/3D as described in the following sub-sections.

4.2.1 Laboratory experiment

The experiments were conducted in the Soil and Water Engineering laboratory of the University of KwaZulu-Natal at the Ukulinga Research Farm, Pietermaritzburg. The experiment consisted of 100 cm long, 50 cm wide and 100 cm high wooden soil box with one face made of transparent Plexiglas. The Moistube pipe was placed 20 cm below the top surface. The soil water content was measured using MPS-2 sensors installed at depths of 5 cm (T3), 10 cm (T2), 15 (T1) cm, 20 cm (D0), 30 cm (D1), 40 cm (D2) and 50 cm (D3) and laterally at 10 cm (S1), 20 cm (S2) and 30 cm (S3). The MPS- 2 sensors were calibrated in the laboratory using gravimetric measurements. The measurements were recorded every 5 mins for 72 hours. The experimental set- up is illustrated in Figure 4.1. The soil was sieved through 2 mm sieve to remove stones and gravel and placed in the soil bin gently to avoid compaction. The soil textures were loamy sand and sandy clay loam with the characteristics shown in Table 4.1.

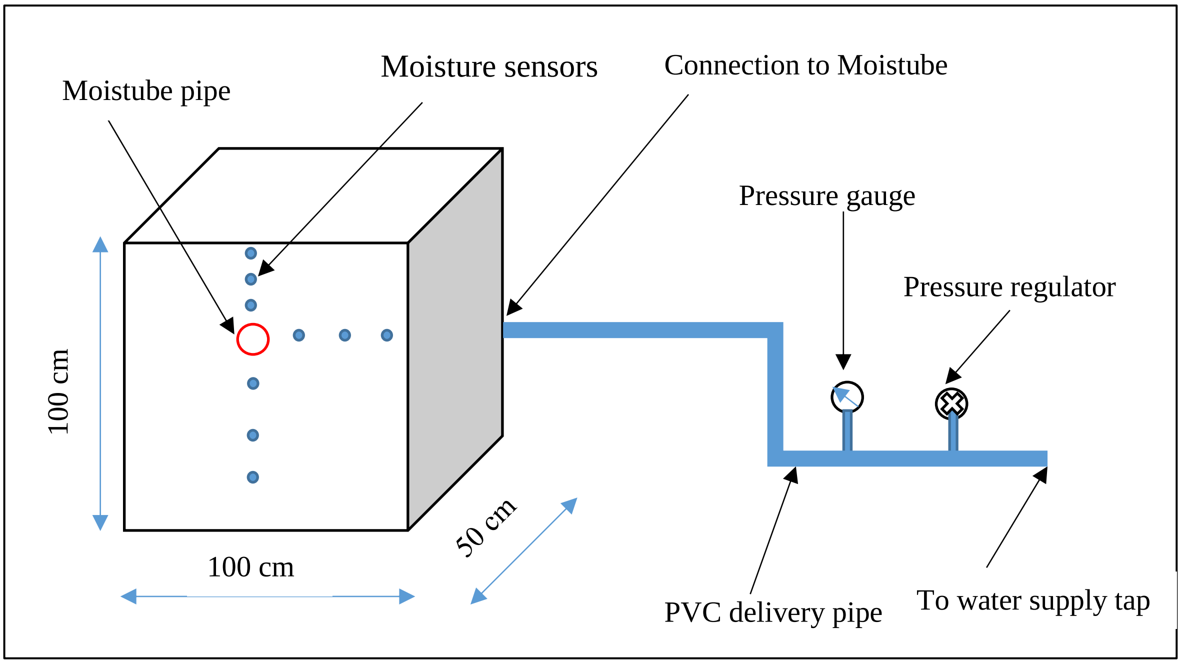

Figure 4.1 Experimental layout

Table 4.1 Soil textural characteristics

Soil textural class	Sand (%)	Silt (%)	Clay (%)	Bulk density (g cm^{-3})
Loamy sand	84.9	9.3	5.8	1.5
Sandy clay loam	62.3	12.7	25.1	1.3

4.2.2 Numerical modelling

The uniformly and variably saturated movement of water through a porous media can be described by the mixed form of the Richards' Equation as in Equation 4.1 (Šimunek *et al.*, 2007);

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x_i}\left[K(h)\left(K_{ij}^{A}\frac{\partial h}{\partial x_j} + K_{iz}^{A}\right)\right] - S(h) \qquad (4.1)$$

where θ = volumetric water content [L^{3}L^{-3}], h = soil water pressure head [L]; K = unsaturated hydraulic conductivity [LT^{-1}]; K_{ij}^{A} = elements of a dimensionless anisotropy tensor $\mathbf{K}^A$ (it is a unit matrix for isotropic media); S = general sink/source term [L^{3}L^{-3}T^{-1}] which accounts for uptake of water by the roots; t = time [T]; and x_i = spatial coordinate [L]. The first and second terms on the right side of Equation 4.1 accounts for capillarity and gravity effects, respectively (Naglič, 2014).

However, the water flow in line sources such as MTI is a two-dimensional problem and so the governing equation, assuming homogeneous and isotropic soils, is the 2D form of RE (Equation 4.2) (Skaggs *et al.*, 2004);

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left[K(h)\frac{\partial h}{\partial x}\right] + \frac{\partial}{\partial z}\left[K(h)\frac{\partial h}{\partial z} + K(h)\right] \tag{4.2}$$

where, θ, *K*, *h*, and *t* are as described in Equation 4.1 while *x*, is the horizontal space coordinate and *z*, is the vertical space coordinate.

HYDRUS 2/3D uses the Galerkin finite element technique to solve the 2D or 3D form of RE represented in Equations 4.1 and 4.2 (Kandelous and Šimůnek, 2010b). The finite element method is applied to a network of triangulated elements and the time integration is achieved through backward implicit finite difference scheme (Kandelous *et al.*, 2012).

a) Soil hydraulic parameters

Model set-up requires specification of soil hydraulic parameters in the van Genuchten Equation described by the van Genuchten-Mualem constitutive relationships as represented by Equations 4.3 to 4.5 (Skaggs *et al.*, 2004);

$$\theta(h) = \begin{Bmatrix} \theta_r + \frac{\theta_s - \theta_r}{(1+|\alpha h|^n)^m} \\ \theta_s \end{Bmatrix} \quad \begin{matrix} h < 0 \\ h \geq 0 \end{matrix} \tag{4.3}$$

$$K(h) = K_s S_e^l \left[1 - (1 - S_e^{1/m})^m\right]^2 \tag{4.4}$$

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \quad , m = 1 - \frac{1}{n} \tag{4.5}$$

where; θ = Volumetric water content [$L^3 L^{-3}$], h = soil water pressure head [L], S_e = effective saturation, θ_s = saturated water content [$L^3 L^{-3}$]; θ_r = residual water content [$L^3 L^{-3}$]; K = unsaturated hydraulic conductivity [LT^{-1}]; K_s = saturated hydraulic conductivity [LT^{-1}]; and α, *m*, *n* and *l* = empirical coefficients that affect shape parameters of the hydraulic functions.

The soil hydraulic properties were initially estimated using ROSETTA (Schaap *et al.*, 2001) with percentages of clay, silt and sand and bulk density as inputs. The saturated hydraulic conductivity was measured using constant head permeability apparatus. The initial hydraulic parameters of the two soil textures are shown in Table 4.2.

Table 4.2 Initial soil hydraulic parameters (van Genuchten-Mualem model)

Texture class	θ_r (cm^3 cm^{-3})	θ_s (cm^3 cm^{-3})	α (cm^{-1})	n	K_s *(cm day^{-1})*	l
Loamy sand	0.0486	0.3993	0.0382	2.0962	189.48	0.5
Sandy clay loam	0.0738	0.4766	0.0216	1.4119	54.67	0.5

b) Transport domain

The transport domain consisted of 100 cm by 100 cm with the Moistube lateral placed at a depth of 20 cm from the top surface. However, due to symmetry, one side was used in the simulation as illustrated in Figure 4.2. The transport domain was discretized into 2311 nodes and 4444 finite elements with finer grid around the Moistube (0.2 cm) and coarser grid (1 cm) in the remaining surface. Observation nodes were placed at co-ordinates corresponding to sensor positions as illustrated in Figure 4.1.

c) Initial and boundary conditions

The initial conditions were specified in terms of constant pressure as measured by the MPS-2 sensors. The initial pressure heads were 2000 kPa and 3000 kPa for loamy fine sand and sandy clay loam, respectively. The boundary conditions were constant flux at the location of the Moistube lateral, free drainage at the bottom boundary and no flux at the sides of the rectangular domain as indicated in Figure 4.2. The constant flux of 21.85 cm day $^{-1}$ was obtained by dividing the Moistube flow rate by the model surface area (1 cm radius located 20 cm below the top boundary) as in Equation 4.6 (Skaggs *et al.*, 2004);

$$q = \frac{flow\ \ rate}{surface\ area} \tag{4.6}$$

where q = water flux (LT^{-1})

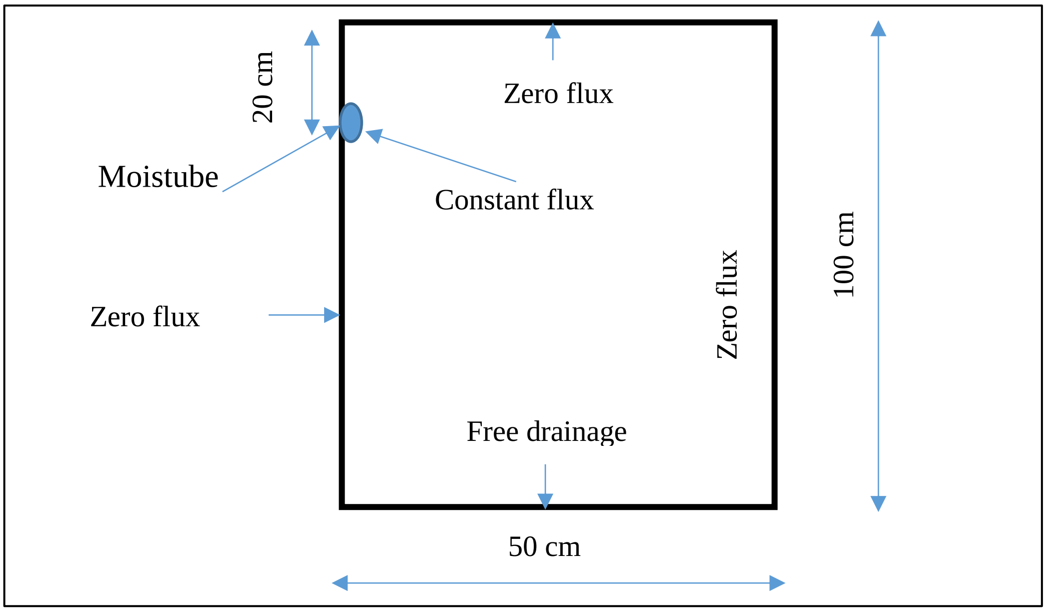

Figure 4.2 Boundary conditions

d) Model calibration and evaluation

The initial soil hydraulic properties in Table 4.2 were adjusted until the model simulations closely matched the observed soil water contents. The calibrated hydraulic characteristics are illustrated in Table 4.3.

Table 4.3 Calibrated soil hydraulic parameters (van Genuchten-Mualem model)

Texture class	θ_r (cm^3 cm^{-3})	θ_s (cm^3 cm^{-3})	α (cm^{-1})	*n*	K_s *(cm day^{-1})*	*l*
Loamy sand	0.0473	0.3796	0.0367	2.0716	178.23	0.5
Sandy clay loam	0.0736	0.4610	0.0216	1.4102	42.32	0.5

Model assessment was done using coefficient of determination (R^2), root mean square error (RMSE) and percent bias (PBIAS) as in Equations 4.7 – 4.9 (Moriasi *et al.*, 2007);

Root Mean Square Error (RMSE)

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(X-Y)^2} \qquad (4.7)$$

where; X = Observed value of the parameter being evaluated, Y= Simulated value of the parameter being evaluated, n = total number of observations and *i* = numbers 1, 2, 3 …n

Percent Bias (PBIAS)

$$PBIAS = 100 \times \frac{\sum_{i=1}^{n}(X-Y)}{\sum_{i=1}^{n} X} \tag{4.8}$$

where PBIAS is the deviation of data being evaluated, expressed as a percentage and X, Y, n and *i* are as described in equation 4.7. The lower the RMSE and PBIAS values, the better the model performance.

Coefficient of Determination (R^2)

$$R^2 = \left[\frac{n(\sum XY)-(\sum X)(\sum Y)}{\sqrt{\left[n\sum X^2-(\sum X)^2\right]\left[n\sum Y^2-(\sum Y)^2\right]}}\right]^2 \tag{4.9}$$

where X, Y, n and *i* are as described in equation 4.7

Values of R^2 greater than 0.5 indicate better model performance. A value of 1 indicate a perfect model while a value of 0 indicates a poor model.

e) Data analysis

The difference between the soil water distribution and soil water contents between the soil types was analysed using analysis of variance (ANOVA) with 95% confidence interval.

4.2.3 Scenarios

Micro-irrigation systems such as drip can be improved through adjustment of system designs and management strategies with the aim of minimizing water losses such as drainage (Cote *et al.*, 2003). Among the options of improving the performance of trickle irrigation systems, by optimizing the wetted volume, is the selection of optimum emitter flow rate taking into consideration the soil properties. Therefore, in line with the above strategy, the Moistube placement depth was maintained at 20 cm and the wetting pattern dimensions were simulated using HYDRUS -2D/3D for discharges of 0.2 ℓ $hr^{-1}m^{-1}$, 0.3 ℓ $hr^{-1}m^{-1}$ and 0.4 ℓ $hr^{-1}m^{-1}$ which corresponded to applied pressure of 20 kPa, 25 kPa and 30 kPa respectively. This was guided by the manufacturer's range of operating pressures of 20 – 60 kPa.

4.3 Results and Discussion

This section describes the soil water dynamics in terms of the soil water distribution and the wetted dimensions as influenced by soil texture and Moistube discharge rates.

4.3.1 Soil water distribution

The results of soil water content variations with time and the soil water distributions for loamy sand and sandy clay loam are shown in Figures 4.3 to 4.6. The simulated values were close to observed values in all the points considered as illustrated in Figures 4.5 and 4.6. For loamy fine sand the R^2 values were between 0.74 and 0.99 while RMSE values ranged from 0.016 cm^3 cm^{-3} to 0.045 cm^3 cm^{-3}. In sandy clay loam, the R^2 values ranged from 0.70 to 0.98 and RMSE were between 0.018 cm^3 cm^{-3} to 0.045 cm^3 cm^{-3} for all the observation points. The PBIAS values were below 15.6% in all the points considered in both soil types. The above results indicated that the model was satisfactory in predicting the water contents vertically and laterally. The model performance indicated in Figures 4.5 and 4.6 concurred with similar studies on the use of HYDRUS-2D in the simulation of soil water dynamics in SDI and MTI where RMSE values ranged from 0.01 to 0.049 (Siyal and Skaggs, 2009;Kandelous and Šimůnek, 2010b;Phogat *et al.*, 2012;Fan *et al.*, 2018b). This demonstrates the suitability of HYDRUS 2D/3D in predicting the soil water dynamics in trickle irrigation systems.

Soil texture influenced the soil water distributions. The water contents in loamy sand were significantly different in all the directions ($p < 0.05$). It was lowest in upward direction and highest in downward direction. However, in sandy clay loam, there was no significant variation in the water contents in all directions ($p > 0.05$). After 72 hours of irrigation the average water contents within 10 cm radius were 0.352 cm^3 cm^{-3} and 0.201 cm^3 cm^{-3} in sandy clay loam and loamy sand, respectively.

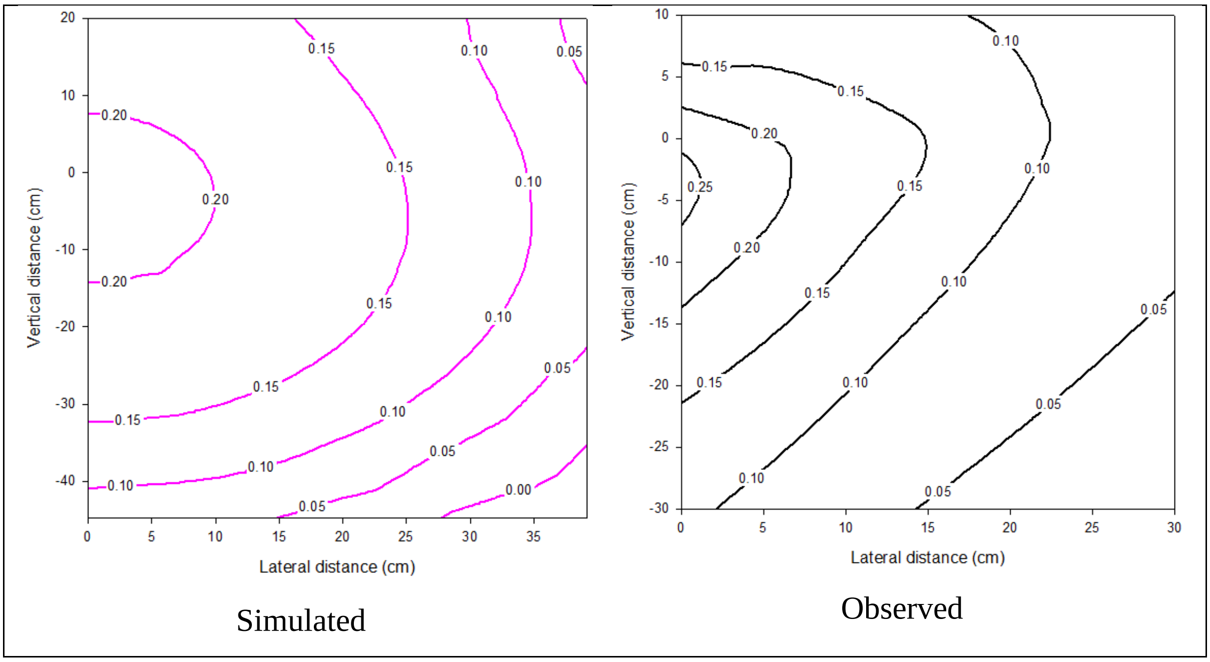

Figure 4.3 Simulated and observed soil water distribution in loamy sand after 72 hours

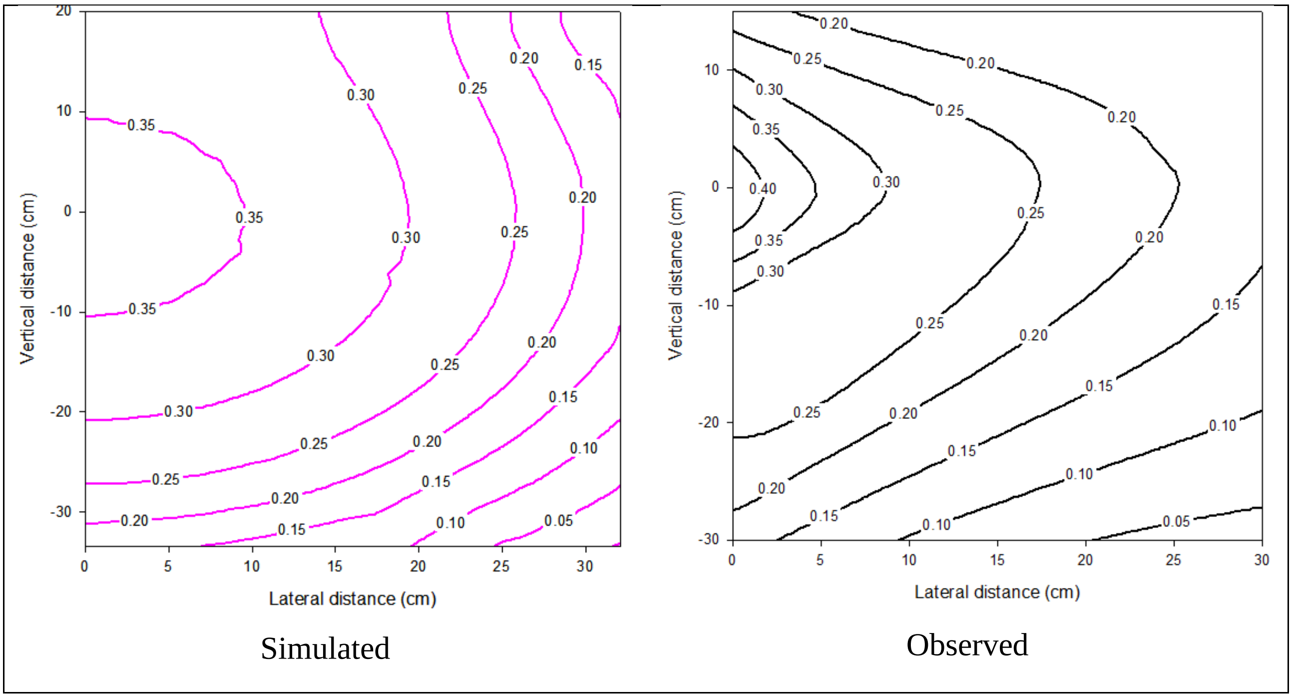

Figure 4.4 Simulated and observed soil water distribution in sandy clay loam after 72 hours

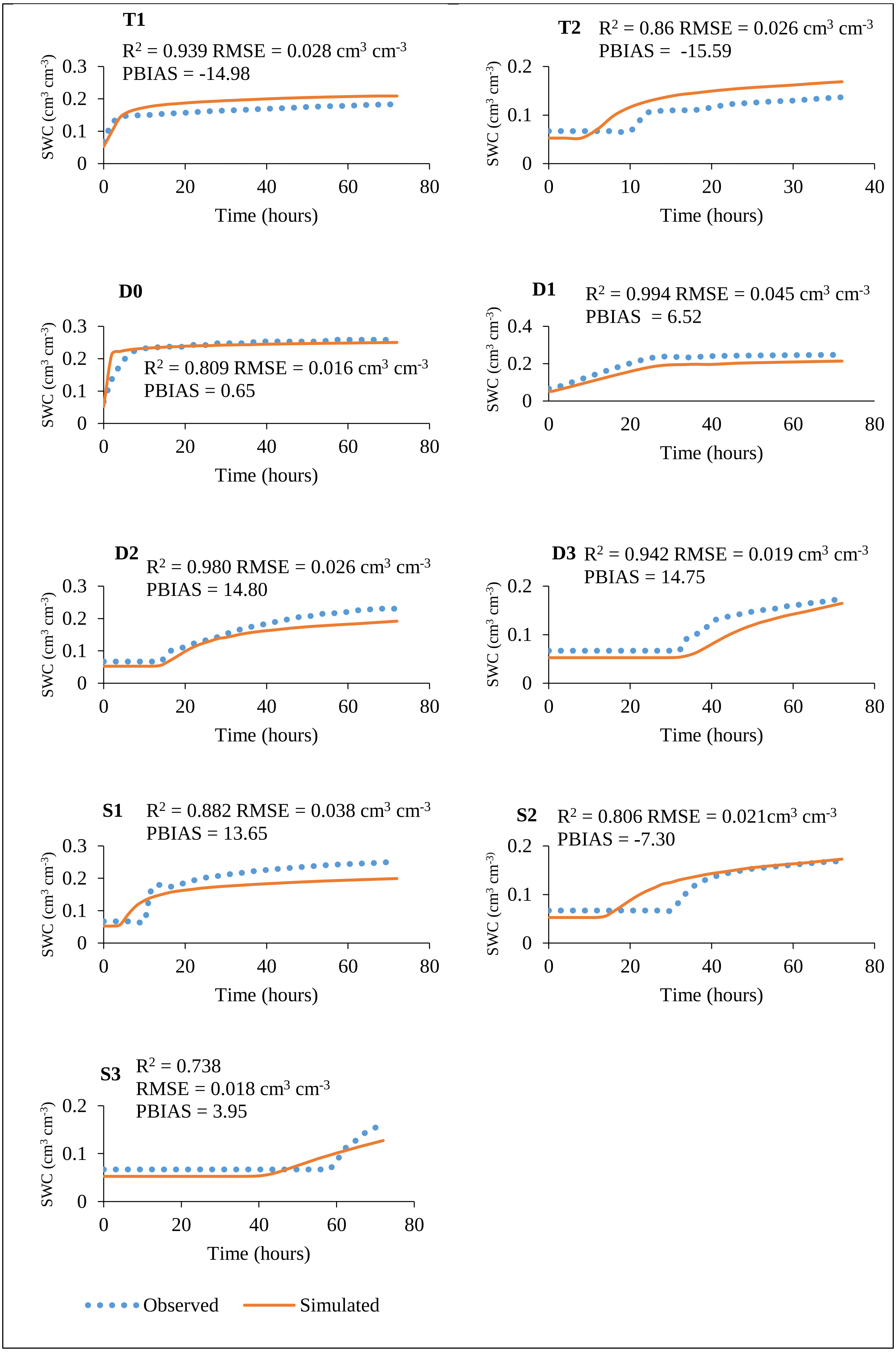

Figure 4.5 Observed and simulated soil water contents at observation nodes in loamy sand

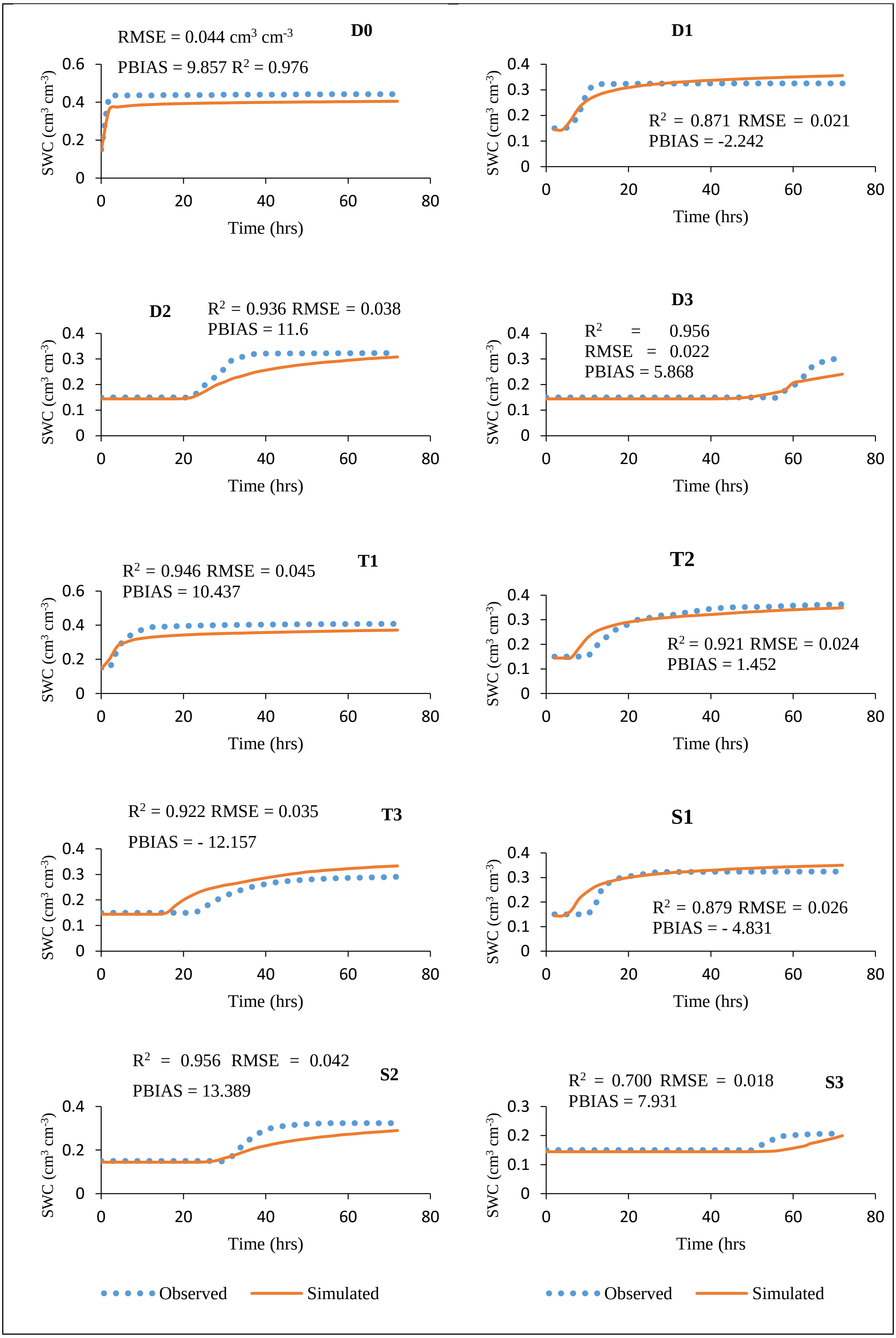

Figure 4.6 Observed and simulated water contents at observation nodes in sandy clay loam

4.3.2 Wetting pattern dimensions

The dimensions of the wetted area in terms of downward and lateral distance are shown in Figure 4.7 under the same pressure of 60 kPa. The simulated values were close to the observed values with average RMSE and R^2 values of 3.50 cm and 0.98, respectively. The model overestimated the wetting front distance by an average PBIAS of 13.56%. Therefore, the model was satisfactory in simulating the wetting pattern of MTI. In similar study on soil wetting pattern under SDI, Kandelous and Šimůnek (2010b) found that HYDRUS-2D simulated wetting dimensions satisfactorily with average RMSE value of 2.78 cm. In MTI, HYDRUS-2D simulated the wetting patterns reasonably well with RMSE of 1.1 cm and 0.43 cm in vertically installed and horizontally laid arrangement, respectively (Fan *et al.*, 2018a;Fan *et al.*, 2018b). The upward distance reached the soil surface in sandy clay loam and thus, the upward wetted distance is not presented. Fan *et al.* (2018b), found that for sandy loam, loam and silt loam soil under pressure heads of 0.6 m, 1.2 m and 1.8 m, the wetting front reached the soil surface when the Moistube placement depth was 20 cm below the soil surface.

Moistube is designed to provide water continuously unlike conventional types such as drip where water is supplied intermittently (Zhang *et al.*, 2015a;Sun *et al.*, 2018). Therefore, the wetting pattern dimensions over 24-hour period is important to determine the appropriate placement depth and spacing of Moistube laterals. From Figure 4.7, the lateral and downward distances were 23 cm and 24.6 cm respectively for loamy fine sand after 24 hours. Similarly, for sandy clay loam, the lateral and downward distance was 19 cm. Although, the wetted volume is larger in loamy sand, its average water contents were lower than in sandy clay loam. Therefore, depending on the type of the crop, the spacing of Moistube laterals should consider the soil texture as it would influence the available soil water.

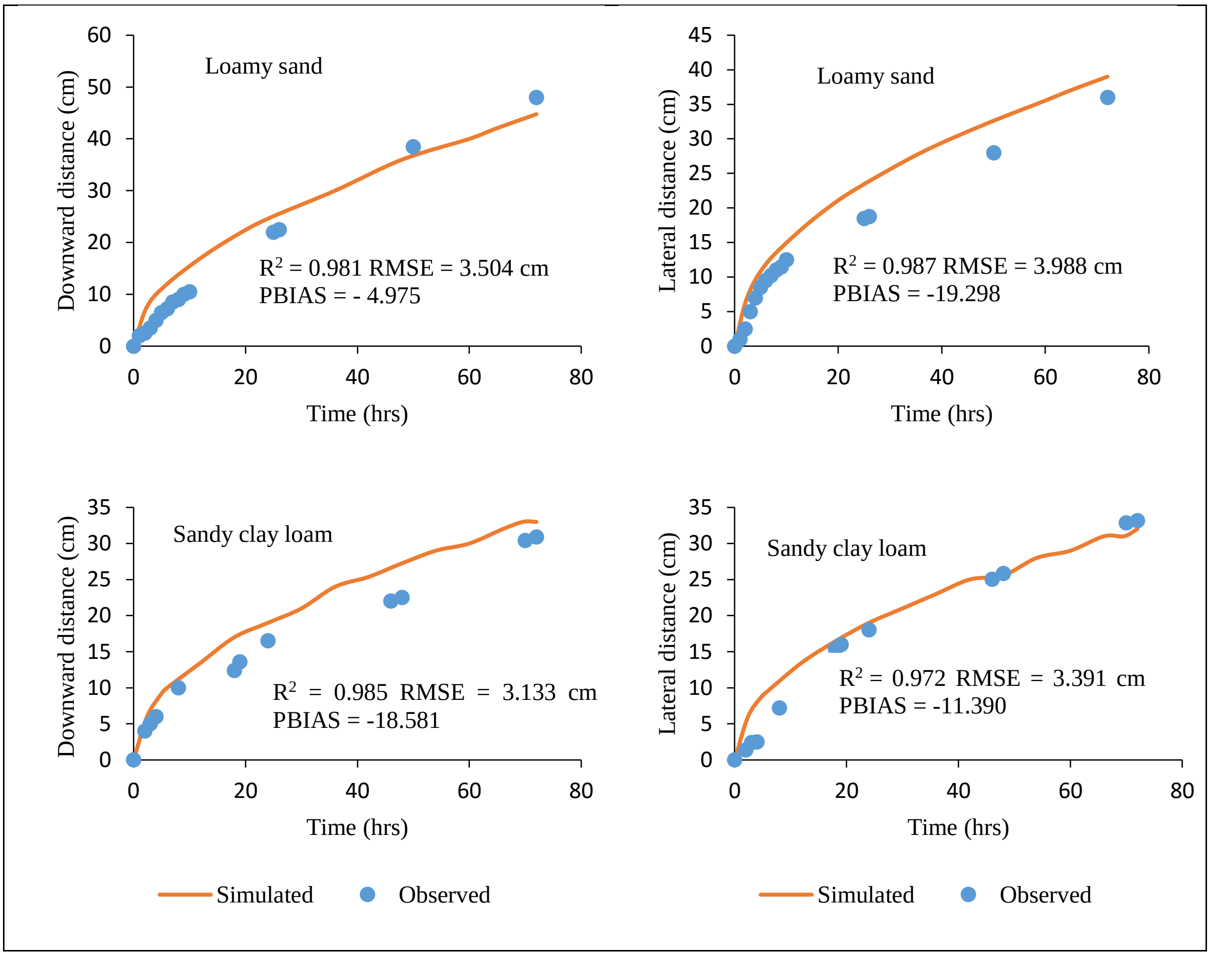

Figure 4.7 Observed and simulated wetted distances for loamy sand and sandy clay loam

4.3.3 Effect of discharge on the wetting dimensions

The results of model simulations for the wetting dimensions (upward, lateral and downward) for the two soil types are shown in Figure 4.8. The wetting dimensions increased with increasing discharge and time. This was consistent with findings by Fan *et al.* (2018b) where the soil wetting pattern under MTI was positively correlated with pressure head for a given soil texture and initial soil water content.

Soil texture significantly influenced the downward movement of water whereby after 24 hours, the downward distance was 21.4 cm in loamy sand and 16.8 cm in sandy clay loam for the discharge of 0.4 ℓ $hr^{-1}m^{-1}$. On average, the downward distance was 26% farther in loamy sand than in sandy clay loam. However, there was no significant difference ithe upward distance between the two soil textures (18.7 cm and 15.8 cm in sandy clay loam and loamy sand respectively). For a given discharge the size of the wetted volume was smaller in sandy clay loam than in loamy sand. Similar studies by Fan *et al.* (2018b) on horizontally laid Moistube and Fan *et al.* (2018a) for vertically installed Moistube found that the soil wetted volume was smaller in the finer textured soil than in the coarser-textured soil.

An optimum installation depth for subsurface irrigation systems require a balance between maintaining dry soil surface and minimizing deep percolation losses. Unlike in the previous sub-section (discharge of 0.58 ℓ $hr^{-1}m^{-1}$) where the wetting pattern reached the soil surface, the wetting pattern were all below the soil surface after 24 hours. This showed that at the Moistube placement depth of 20 cm, the operating pressure should be between 20 – 30 kPa (discharge of 0.2 – 0.4 l ℓ $hr^{-1}m^{-1}$) for these soil textures. In subsurface porous pipes Ashrafi *et al.* (2002) found that the wetting pattern geometry is sensitive to the installation depth and the irrigation amount for a given soil texture.

The wetted dimensions (upward, lateral and downward), for a given soil texture, can be represented as power function of time (Equation 4.10)

$$D = bt^c \tag{4.10}$$

where D = wetted dimension (cm), *b* = constant which depends on the discharge rate and soil type, and c = empirical constant. The value of *b* increases with increasing discharge (2.9 to 3.7 and 3.6 to 4.4 for sandy clay loam and loamy sand, respectively) while *c* is approximately the same value for the two soil textures (≈ 0.5).

Crop establishment in subsurface irrigation systems is a challenge especially in light-textured soils due to the domination of gravity than capillary forces (Charlesworth and Muirhead, 2003). For the given installation depth of 20 cm, crop establishment under MTI for sandy clay loam and loamy sand could be achieved with discharge of 0.3 ℓ $hr^{-1}m^{-1}$ and 0.4 ℓ $hr^{-1}m^{-1}$ where the upward soil water movement reached about 5 cm below the soil surface after 24 hours of water application (Figure 4.8). To allow for crop establishment under 0.2 ℓ $hr^{-1}m^{-1}$, a shallower Moistube installation depth need to be considered. However, the placement should not be too shallow to allow water to reach the soil surface as this would contribute to water losses via evaporation.

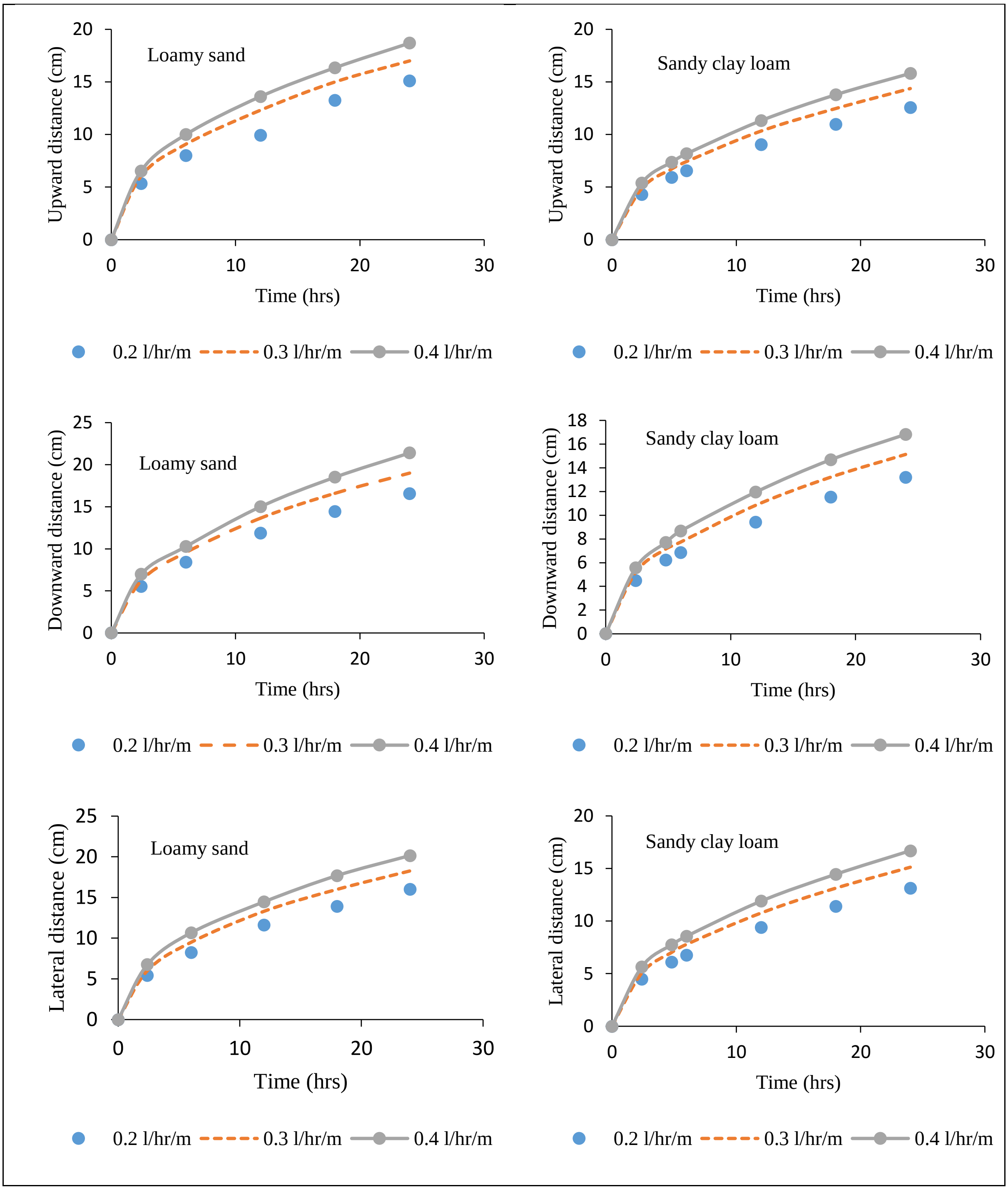

Figure 4.8 Simulated wetted dimensions under varying discharge

4.4 Conclusion

This study sought to determine the soil water dynamics of Moistube irrigation with the help of laboratory experiments and simulations with HYDRUS 2D/3D model. The simulated soil water contents were close to observed values ($R^2 \geq 0.70$, RSME ≤ 0.045 cm^3 cm^{-3} and PBIAS $\leq$ 15.6%). Similarly, the simulated wetting pattern was close with the observed values ($R^2 \geq 0.97$, RSME ≤ 3.99 cm and PBIAS ≤ 19.3%) indicating the suitability of the model in determining the soil water distribution under MTI. The use of models would overcome the challenges of using costly and time-consuming field and laboratory conditions.

The results of this study indicated that the soil water distribution in MTI depend on the soil texture and discharge. The soil water content and wetting dimensions increased with increasing discharge. The optimum depth and spacing of Moistube laterals can be obtained by varying the discharge with the aim of minimizing runoff, soil evaporation and percolation water losses. For sandy clay loam and loamy sand, a discharge of between 0.2 ℓ $hr^{-1}m^{-1}$ and 0.4 ℓ $hr^{-1}m^{-1}$ maintained a dry soil surface over 24 hours of continuous irrigation and minimized deep percolation as well when the Moistube was placed at a depth of 20 cm.

This study was carried out for two medium soil textures which are closely related with sand content above 60% and clay content less than 30%. Further research on heavy textured soils would help in understanding fully the soil water dynamics under MTI. The soil water dynamics under subsurface irrigation is also influenced by crop characteristics besides the soil texture and system parameters. Therefore, further studies are required to determine the soil water dynamics of Moistube irrigation considering root water uptake and under actual field conditions. This is covered in Chapter 5 where the soil water distribution under cowpea was determined.

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5. SOIL WATER DISTRIBUTION UNDER MOISTUBE IRRIGATED COWPEA (*Vigna unguiculata* (L.) Walp)

Edwin K. Kanda, Aidan Senzanje, Tafadzwanashe Mabhaudhi

Abstract

The determination of the soil water dynamics while considering crop evapotranspiration is necessary for optimal design and management of irrigation systems thereby minimizing water losses by soil evaporation, surface run-off and deep percolation. Moistube irrigation (MTI) is a type of technology which uses semi-permeable membrane to emit water continuously in response to the soil water potential and the applied pressure. Soil water dynamics under MTI incorporating plant water uptake has not been studied. Moreover, cowpea is a neglected but important legume which, if promoted, could help in improving the livelihoods of rural households. Therefore, this study aimed at determining the soil water distribution of Moistube irrigated cowpea. The effect of Moistube placement depth on the soil water dynamics under MTI was also determined. It was based on the hypothesis that root water uptake is influenced by the Moistube placement depth. The experiment was carried out in tunnels with MTI and subsurface drip irrigation (SDI) as a control. HYDRUS 2D/3D model was calibrated and thereafter used to simulate the soil water dynamics under 10 cm, 15 cm, 20 cm, and 30 cm Moistube placement depths in loam and clay soils. The simulated soil water contents closely matched ($R^2 \geq 0.57$ and RMSE ≤ 0.029 $cm^3\,cm^{-3}$) the observed values for both MTI and SDI. The simulation errors were less than 10% indicating that HYDRUS 2D/3D can be used in the simulation of water dynamics of irrigated cowpea. There was no significant difference between the root water uptake (RWU) in SDI and MTI ($p > 0.05$). Water loss through drainage was significantly higher ($p < 0.05$) under SDI than MTI in loam while it was negligible in clay for both irrigation types. Drainage increased with increased Moistube placement depth. The Moistube placement depth did not significantly affect the RWU in loam but increased with increased placement depth in clay up to a maximum value at 20 cm depth. The interaction between the distribution of root water uptake and the soil water distribution indicated that a suitable placement depth for cowpea under MTI was 15 cm in loam and 20 cm in clay. This would balance between soil evaporation and percolation water losses and root water uptake.

Keywords: HYDRUS 2D/3D, subsurface irrigation, root water uptake, soil water dynamics modelling

5.1 Introduction

Optimization of water use in agriculture requires better estimation of soil water dynamics by incorporating the two important processes of evapotranspiration and drainage (Shelia *et al.*, 2018). It is imperative to ensure that the water applied remains within the root zone to minimize water and nutrient losses via drainage. In subsurface irrigation systems, the optimum placement depth of drip laterals is necessary to ensure that it is neither too deep nor shallow. This requires the knowledge of the soil water dynamics.

Soil water distribution under cropped land is influenced by, among other factors, plant water uptake and the root characteristics in terms of the root length and distribution (Lubana and Narda, 2001). Root characteristics are a key driver which influence evapotranspiration and thus relevant in the process of deep percolation (Yu *et al.*, 2016). The interaction between plant roots and the soil influence the movement of water in and out of the unsaturated zone (Vrugt *et al.*, 2001). Understanding the root water extraction patterns due to root characteristics throughout the growth cycle helps in achieving effective use of water in irrigation by ensuring that water is applied where root activity is at a maximum and at a rate consistent with plant uptake (Andreu *et al.*, 1997). Root distribution is important in the design of irrigation systems and the wider concept of agricultural water management as it affects the optimal water application rates, irrigation scheduling and drainage losses (Kandelous *et al.*, 2012). Apart from soil texture, crop root characteristics determine the optimum depth of subsurface drip irrigation (SDI) laterals (Patel and Rajput, 2010).

The determination of the soil water dynamics in cropped lands under irrigation or rainfed systems can be accomplished by use of field experiments or models. Andreu *et al.* (1997), established that the soil water content varied in relation to the position of the plant roots relative to the emitter. In drip irrigation for corn, Coelho and Or (1996) found that root water uptake depended on the configuration (within the crop row or between rows) and whether the emitters were on the surface or buried. However, the field or laboratory determination of soil water distribution under a variety of soils and water regimes is costly and time consuming and therefore use of models is necessary.

HYDRUS 2D/3D has been widely used in the simulation of soil water distribution under irrigated or rainfed agricultural systems. For example, Karandish *et al.* (2017) simulated the effect of groundwater conditions on the soil water distribution in a canola field under rainfed conditions. Their study demonstrated the usefulness of simulation models in the development of optimum scenarios for crop production under shallow groundwater conditions. The model has also been used in the development of optimum irrigation schedules in drip systems for a variety of crops such as strawberry (García Morillo *et al.*, 2017). Similarly, Autovino *et al.* (2018) used HYDRUS 2D to simulate actual transpiration and soil water content in olive orchard and demonstrated the capacity of the model in designing irrigation scenarios which minimize water stress during critical crop growth stages. Egea *et al.* (2016) used HYDRUS 2D to determine the soil water dynamics and assess the effect of irrigation time on drainage loss under both full and deficit irrigation in hedgerow olive orchard field. In another study, Patel and Rajput (2010) used HYDRUS 2D to simulate the soil water distribution at different growth stages of potato which aided in the design of drip irrigation system which would minimize loss of water through drainage. Dabach *et al.* (2013) used HYDRUS 2D/3D to develop irrigation schedules of bean and bell pepper plants based on soil water status. In this study, irrigation thresholds and amounts were derived using triggered irrigation boundary condition in HYDRUS 2D/3D.

HYDRUS 2D/3D model has also been used in the determination of optimum depth of placement of drip irrigation laterals and emitters. For instance, Patel and Rajput (2008) while using HYDRUS-2D, established that the optimum depth of drip irrigation laterals for the growth of onions was 15 cm. In eggplant production a suitable placement depth of 20 cm was found in sandy loam (Ghazouani *et al.*, 2016). A similar study on eggplant by Müller *et al.* (2016) established that root density pattern had an effect on the spatial and temporal soil water distribution. This therefore implies that root water uptake needs to be considered for a better representation of the soil water distribution under irrigation. The above studies have demonstrated the ability of HYDRUS 2D/3D model in the development of optimum agricultural water management strategies.

Moistube irrigation (MTI) is designed as continuous types of irrigation where water is supplied over a 24-hour period at a slow rate. As described in Chapter 4, there are few studies on soil water dynamics under MTI (Zhang *et al.*, 2012;Niu *et al.*, 2013b;Zhang *et al.*, 2015a;Fan *et al.*, 2018b). However, no study has been done so far on the soil water dynamics in MTI under field conditions considering plant water uptake. This study, therefore, had two objectives; a) to determine the soil water dynamics of Moistube irrigated cowpea and b) to determine the effect of Moistube placement depth on soil water dynamics of Moistube irrigated cowpea. It was based on the hypothesis that root water uptake is influenced by the Moistube placement depth. This would help in determining the appropriate depth of placement of Moistube tapes in cowpea production which minimizes water losses via drainage and soil evaporation and thereby improve the water use efficiency.

5.2 Materials and Methods

This study was accomplished by field experiments and numerically using HYDRUS 2D/3D as described in the following sub-sections.

5.2.1 Tunnel experiments

a) Controlled experiment

The experiment consisted of cowpea planted in tunnels situated in the Controlled Environment Facility (CEF) at the University of KwaZulu-Natal, Pietermaritzburg (29^o 35’ S and 30^o 25’ E, 806 m a.s.l). The cowpea (mixed brown variety) was planted on 14^{th} February 2018 in rows of 50 cm and 30 cm spacing between plants giving a plant population of 66667 plants ha^{-1}. It was planted on raised beds measuring 75 cm by 11.5 m with soil layer of 0.6 m. Cowpea were planted under MTI with SDI as control with three replications. Each type of irrigation occupied one bed while the subplots representing replications were separated by 50 cm buffer. Each replication occupied a plot size of 3 m by 0.75 m. The Moistube and the drip tapes were placed at a depth of 15 cm. Phosphorous fertilizer were applied at a rate of 60 kg ha^{-1} Single Superphosphate (10.5% P) based on soil fertility tests conducted at Cedara Agricultural College. Other agronomic management practices such as weed, pest and disease control were done accordingly based on recommended best practices.

Soil water contents were obtained by converting the daily matric potentials measured using MPS-2 sensors (Decagon, Inc. USA) placed at distances of 10 cm and 20 cm away from the Moistube lateral and at depths of 10 cm, 20 cm and 40 cm. For SDI, the sensors were placed at depths of 10 cm, 20 cm and 40 cm. Gravimetric water measurements were carried out occasionally and together with volumetric measurements obtained from EC-5 sensors (Decagon, Inc. USA) used to calibrate the MPS-2 measurements (Figure A.2)

b) Ukulinga experiment

The experiment was carried at UKZN's Ukulinga Research farm. It was carried out in a 12 m by 5 m tunnel with open ends to allow free movement of air. The experiment was laid out in a split-plot design arranged in randomized complete block design with SDI and MTI occupying the main blocks. The treatments were replicated three times. Cowpea spacing was like in the tunnel experiment at CEF, but the crop was planted on 25th May 2018. Soil fertility test conducted at Cedara Agricultural College indicated that the soil did not have nutrient deficiency at Ukulinga and therefore, fertilizer was not applied. Other best management practices were carried out as appropriate.

Soil water content and Leaf Area Index (LAI) were measured weekly using PR2/6 profile Probe (Delta-T Ltd, UK) and LAI 2200 canopy analyser (LI-COR Inc. USA), respectively. The soil water contents were measured at depths of 10 cm, 20 cm, 30 cm and 40 cm.

MTI was designed to supply water continuously throughout the crop cycle. However, due to limitation in the water regulation devices, it was not possible to water the crop 24 hours in a day throughout the season but was adjusted in such a way that the crop was irrigated between 6 – 8 days and 3 – 5 days continuously every 10 days, depending on the crop water requirements, for CEF and Ukulinga experiments, respectively.

5.2.2 Numerical modelling

HYDRUS 2D/3D was used to simulate the soil water dynamics while considering plant water uptake. The procedure described in Chapter 4 was used with the modifications which are described in the following paragraphs.

The soil in the CEF tunnel was a shallow soil layer having a loam textual classification (42.3% sand, 33.3% silt, 24.4% clay) and bulk density of 1.36 g cm^{-3}. The soil at Ukulinga, on the other hand, was classified as clay (24.3% sand, 23.6% silt and 52.1% clay) with bulk density of 1.23 g cm^{-3}. The saturated hydraulic conductivity was measured using double ring infiltrometer and Guelph Permeameter (Eijkelkamp, The Netherlands). The soil water retentions parameters were estimated using ROSETTA as explained in Chapter 4 using soil texture, bulk density and the soil water contents at field capacity. The initial soil water retention characteristics are indicated in Table 5.1.

Table 5.1 Initial soil water retention characteristics (van Genuchten-Mualem model)

Texture class	θ_r (cm^3 cm^{-3})	θ_s (cm^3 cm^{-3})	α (cm^{-1})	*n*	K_s ($cm\ day^{-1}$)	*l*
loam	0.0705	0.4285	0.0114	1.4843	14.73	0.5
Clay	0.1029	0.5206	0.0195	1.3075	10.24	0.5

The values in Table 5.1 were adjusted until the simulated water contents closely matched the observed values as assessed with the help of statistical techniques described in section 5.3. The calibrated soil hydraulic parameters are illustrated in Table 5.2.

Table 5.2 Calibrated soil water retention characteristics (van Genuchten-Mualem model)

Texture class	θ_r (cm^3 cm^{-3})	θ_s (cm^3 cm^{-3})	α (cm^{-1})	*n*	K_s ($cm\ day^{-1}$)	*l*
loam	0.0655	0.4510	0.0109	1.4054	18.60	0.5
Clay	0.0980	0.5304	0.0180	1.2061	3.24	0.5

The plant water uptake is taken into account by the incorporation of the sink term as in Equation 4.1 following the empirical model developed by Feddes *et al.* (1978) . The sink term (*S*), is the amount of water extracted from the soil per unit time as shown in Equation 5.1 (Šimůnek *et al.*, 2006).

$$S(h) = \beta(h)S_p \tag{5.1}$$

Where $\beta(h)$ is the dimensionless water stress function which varies from zero to one, S_p is the potential water uptake (T^{-1}).

The potential root water uptake corresponds to the potential evapotranspiration and thus influenced by climatic parameters (Šimůnek and Hopmans, 2009). Root water uptake can be simulated as compensated or uncompensated where the former allows for water extraction in lower layers by water-stressed plants. However, in this study, compensated root water uptake was not considered since no water stress was imposed during the experiments. The model uses the two dimensional functions described in Vrugt *et al.* (2001). Since, there is no measured data on root water uptake parameters for cowpea, the root water uptake model parameters adopted were for the common bean in the HYDRUS 2D/3D database. This included critical pressure heads; P_O (pressure head below which plant roots begin water extraction), P_{Opt} which is the pressure head below which the plant roots begin water extraction at maximum possible rate, P_{2H} and P_{2L} being the high and low pressure heads, respectively, below which the maximum root water extraction is no longer possible, and P_3 which is the pressure head corresponding to wilting point (Li *et al.*, 2015). The root water distribution was assumed to vary linearly with depth. The HYDRUS 2D/3D water uptake and root parameters used in the study are indicated in Table 5.3.

Table 5.3 Root water uptake parameters based on common bean

Parameter	Value
Root water uptake	
Root water uptake model	Feddes, *et al*. (1978)
Critical pressure heads (cm)	P_O = -10, P_{Opt} = -25, P_{2H} = -750, P_{2L} = -2000, P_3 = -8000
Limiting potential transpiration rates (cm day^{-1})	r_{2H} = 0.5, r_{2L} = 0.1
Root distribution	
Maximum rooting depth, Z_m (cm)	60
Depth of maximum root density (cm)	20
Maximum rooting radius, r (cm)	20
Radius of maximum root density (cm)	10
Empirical parameters	Pz = Px = 1

The simulation domain was 25 cm (corresponding to half the row spacing) by 100 cm. The finite element mesh was discretized into 1828 triangular nodes, 175 1-D and 3479 2-D elements by using a grid size of 0.2 cm around the location of the water source (Moistube or dripper) and 1 cm on the other areas. The boundary conditions (BC) were variable flux (determined using Equation 4.6) of 0.25 cm hr^{-1} and 5.41 cm hr^{-1} under MTI and SDI, respectively. The variable flux BC was placed at 15 cm where the Moistube and drip tape were located and atmospheric BC at the top of the domain to allow for evapotranspiration fluxes. The lower boundary was free drainage while the other remaining boundaries were assigned no flux BC as shown in Figure 5.1. The soil water content at planting was the initial conditions in the model.

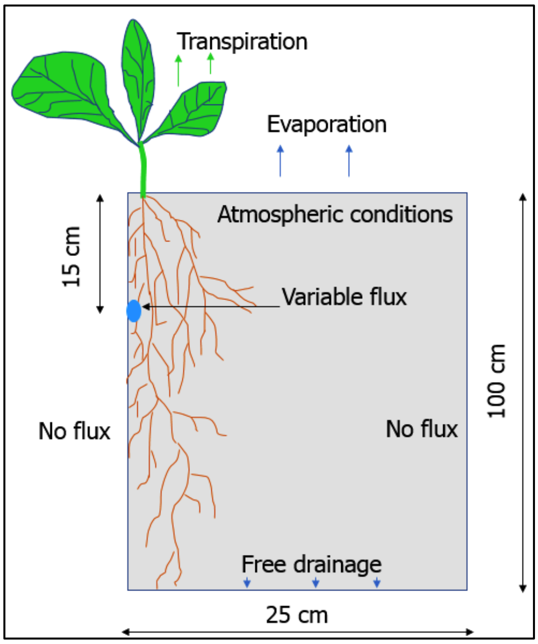

Figure 5.1 Boundary conditions

HYDRUS 2D/3D requires input of separate values of potential soil evaporation and transpiration. Therefore, evapotranspiration (ET) was split into potential transpiration (Tp) and evaporation (Ep) using Beer's law represented by Equations 5.2 and 5.3 (Šimůnek *et al.*, 2013);

$$T_p = ET_c \times [1 - \exp(-\lambda \times LAI)] \quad (5.2)$$

$$E_p = ET_c \times \exp(-\lambda \times LAI) \quad (5.3)$$

where ET_c = potential crop evapotranspiration = $ET_0 \times K_c$ (5.4)

λ = light extinction coefficient, LAI = leaf area index,

ET_o = reference crop evapotranspiration, and K_c = crop coefficients

The ET_o values were computed using FAO Penman-Monteith method described by Allen *et al.* (1998) using daily weather data from the study sites. LAI values were measured weekly using LAI-2200 canopy analyser. The light extinction coefficient for cowpea obtained by Chimonyo *et al.* (2018) was used in this study. The values for partitioned ET into Tp and Ep are indicated in Figure 5.2. The LAI values were very low during winter (Figure 5.2b) due to low temperature which inhibited most of the growth parameters and thus the Ep values were not low, as expected, during the mid-season stage.

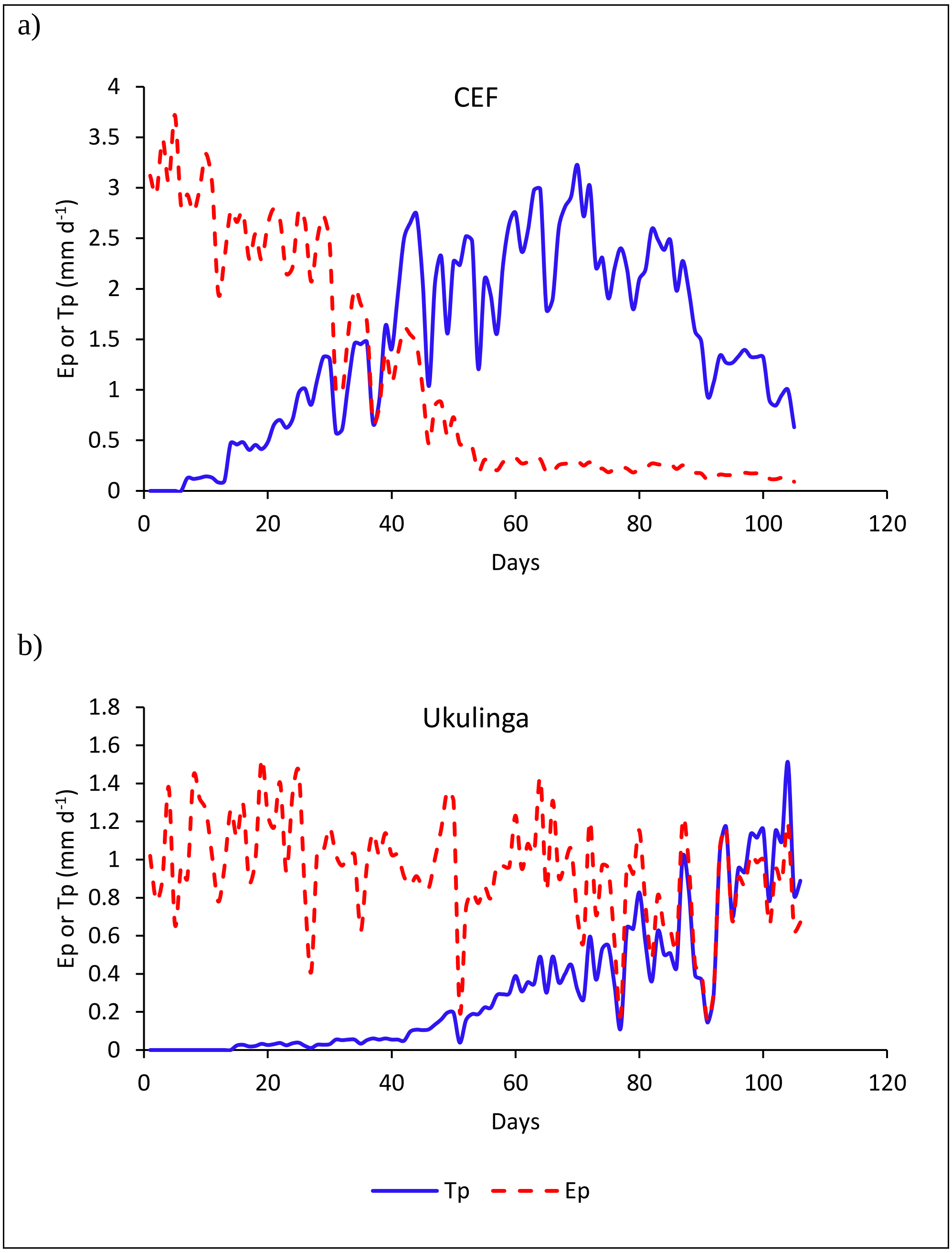

Figure 5.2 Potential evaporation (Ep) and transpiration (Tp)

Simulations were run for 100 days and 105 days for CEF and Ukulinga experiments, respectively, which were the growing periods for cowpea.

5.2.3 Effect of Moistube placement depth and soil texture on soil water dynamics

After successful model calibration and validation through the adjustment of the hydraulic properties (Tables 5.1 and 5.2) until the simulated water contents closely matched the observed values, the model was used to determine the optimum placement depth of Moistube laterals. This was obtained by simulating the soil water dynamics under four Moistube placement depths of 10 cm, 15 cm, 20 cm and 30 cm and the two soil types, i.e. clay and loam described in Table 5.2. The boundary conditions were maintained as illustrated in Figure 5.1. The atmospheric boundary conditions for CEF data was utilized for the two soil types. The root distribution parameters were the same as in Table 5.3.

The initial soil water content was obtained by solving Equation 5.5 (Selim *et al.*, 2013);

$$\theta_e = \frac{\theta_i - \theta_r}{\theta_s - \theta_r} \tag{5.5}$$

where θ_e = effective saturation θ_i = initial volumetric water content [L^3 L^{-3}], θ_s = saturated water content [L^3 L^{-3}]; and θ_r = residual water content [L^3 L^{-3}]. Selim *et al.* (2013) used θ_e values of 0.25 cm^3 cm^{-3} and 0.33 cm^3 cm^{-3} which corresponded to 54% and 70% of the average saturated soil water contents of the soils used in the study. Therefore, in the present study, 60% of the average saturated soil water contents for the two soils (Table 5.2) which gave θ_e of 0.30 cm^3 cm^{-3} was used. Therefore, the initial soil water contents were 0.18 cm^3 cm^{-3} and 0.23 cm^3 cm^{-3} for loam and clay soil, respectively.

5.3 Data Analysis and Model Evaluation

The performance of HYDRUS 2D/3D model in simulating the soil water dynamics was assessed using RMSE and R^2 as described in Chapter 4. The difference between the two types of irrigation was assessed using ANOVA at 95% confidence interval.

5.4 Results and Discussion

The model performance as assessed by comparing the observed and simulated soil water contents is described in this section as well as the root water uptake and drainage fluxes in MTI and SDI. The effect of Moistube placement depth and soil texture on the soil water dynamics is also discussed in this section.

5.4.1 Soil water content

The simulated and observed soil water contents are indicated in Figures 5.3 to 5.6. The results indicate that simulated soil water content reasonably matched ($R^2 \geq 0.68$ and RMSE ≤ 0.026 $cm^3\ cm^{-3}$) the observed values in all the points considered under MTI for both experimental sites. Similarly, the simulated water contents over the growing period closely matched ($R^2 \geq 0.57$ and RMSE ≤ 0.029 $cm^3\ cm^{-3}$) the observed values under SDI indicating satisfactory model performance. In general, the errors in the simulated soil water contents were less than 10% which indicated that HYDRUS 2D/3D can be used in simulating the soil water dynamics of cowpea under SDI and MTI. The results of the simulations in this study were consistent with other studies reported in literature on use of HYDRUS 2D/3D in the simulation of soil water dynamics of various crops under irrigation. For instance, Zhang *et al.* (2017b) reported RMSE values less than 0.029 $cm^3\ cm^{-3}$ when simulating the soil water contents of cotton under SDI and border irrigation. Similarly, Li *et al.* (2015) found an average RMSE value of 0.039 $cm^3\ cm^{-3}$ in the simulation of soil water contents in inter-cropped corn-tomato field under drip irrigation. In potato production under SDI, HYDRUS 2D simulated the soil water contents satisfactorily with RMSE of 0.012 $cm^3\ cm^{-3}$ (Mguidiche *et al.*, 2015). Phogat *et al.* (2012) reported RMSE less than 0.046 $cm^3\ cm^{-3}$ and 0.032 $cm^3\ cm^{-3}$ in the simulation of soil water contents under intermittent and continuous surface drip irrigation, respectively, of almond tree. Egea *et al.* (2016) found RMSE values of between 0.035 $cm^3\ cm^{-3}$ and 0.056 $cm^3\ cm^{-3}$ during the simulation of soil water dynamics in full and deficit irrigated orchard. Finally, Xi *et al.* (2016) reported RMSE less than 0.038 $cm^3\ cm^{-3}$ when simulating soil water contents of Chinese white poplar (*Populus tomentosa*) under SDI. The above results demonstrated that HYDRUS 2D/3D can be used reliably in the simulation of soil water dynamics of irrigated crop systems.

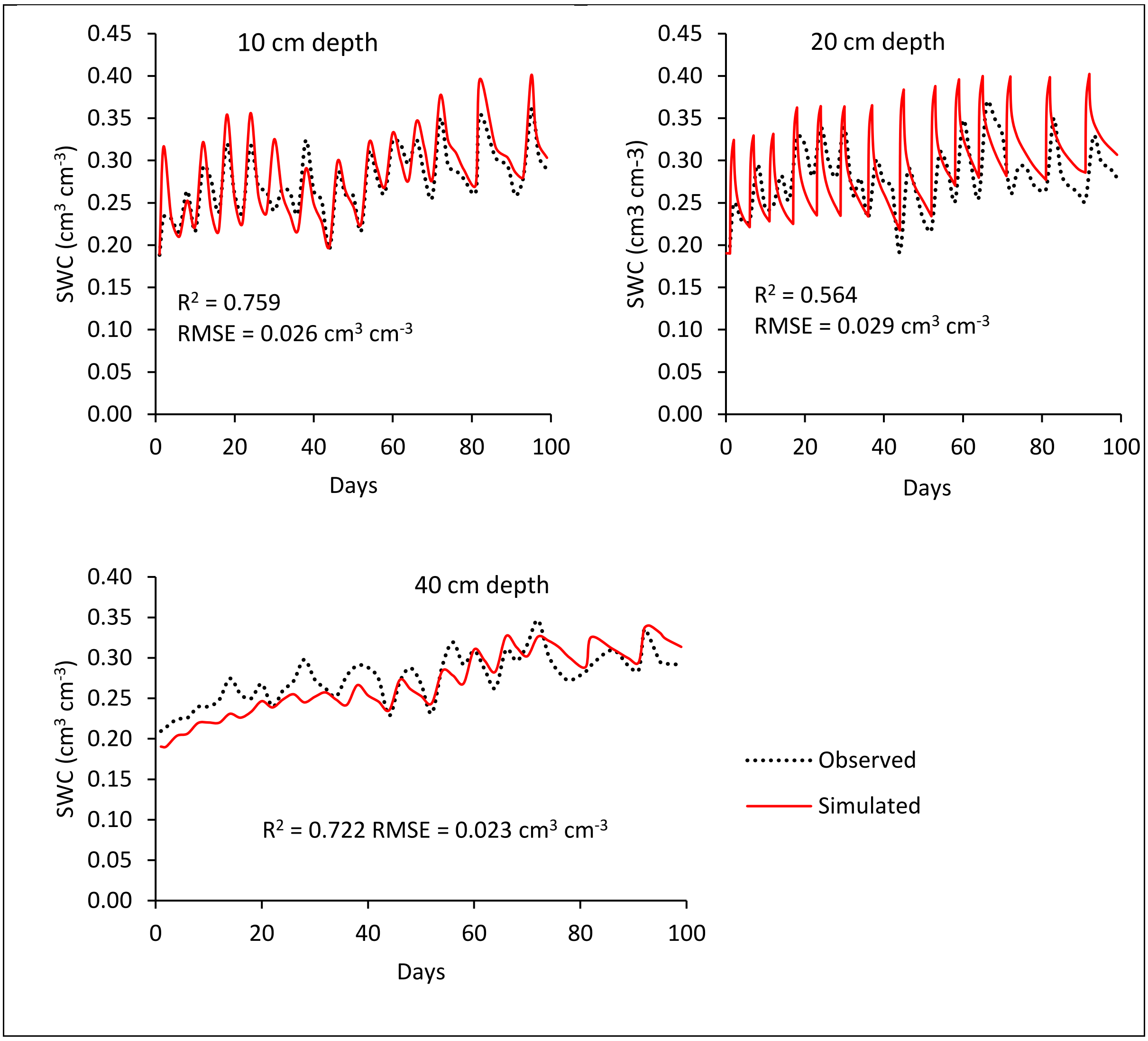

Figure 5.3 Observed and simulated soil water content under cowpea for SDI at CEF (Loam soil)

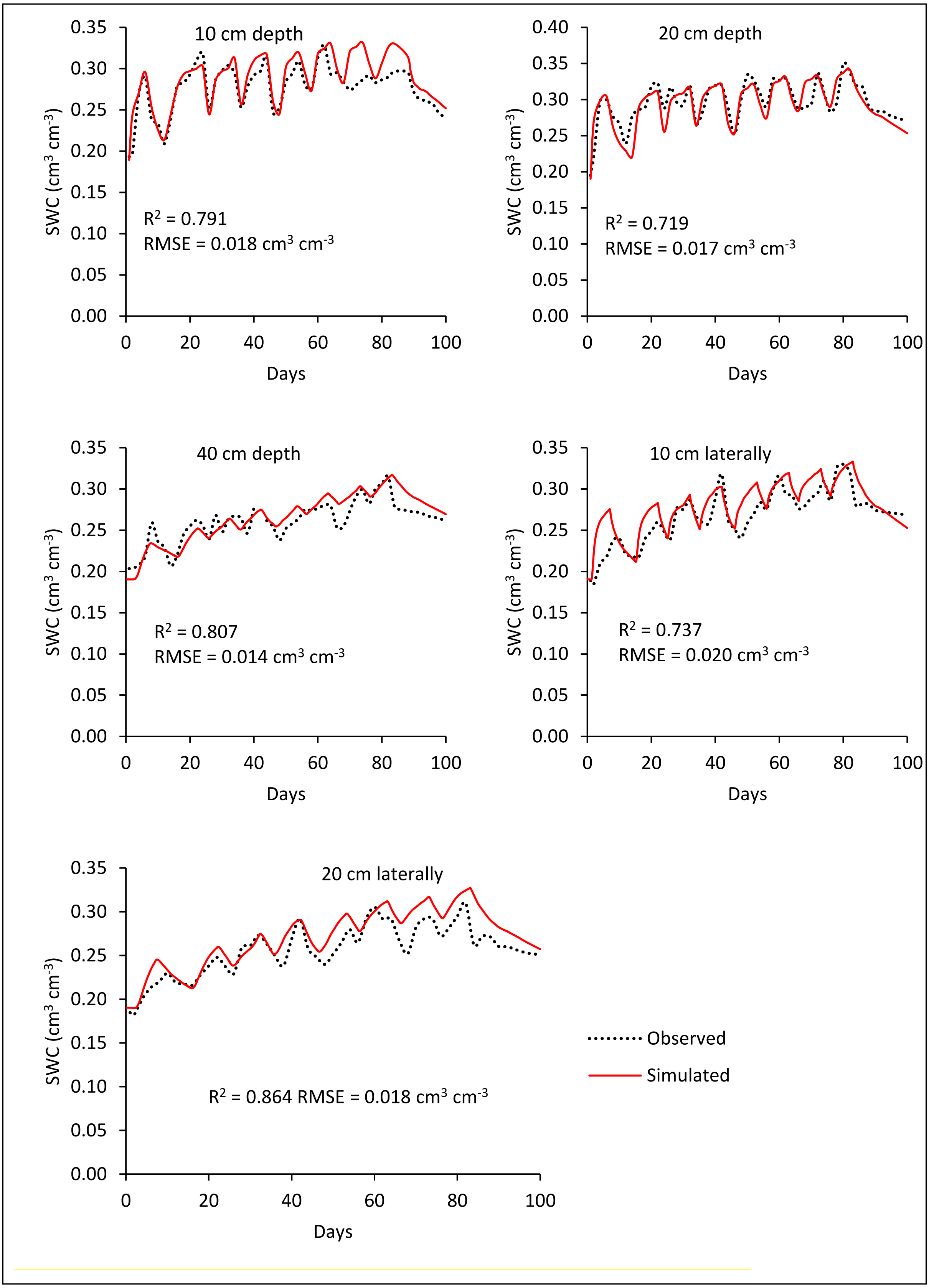

Figure 5.4 Observed and simulated soil water content under cowpea for MTI at CEF (loam soil)

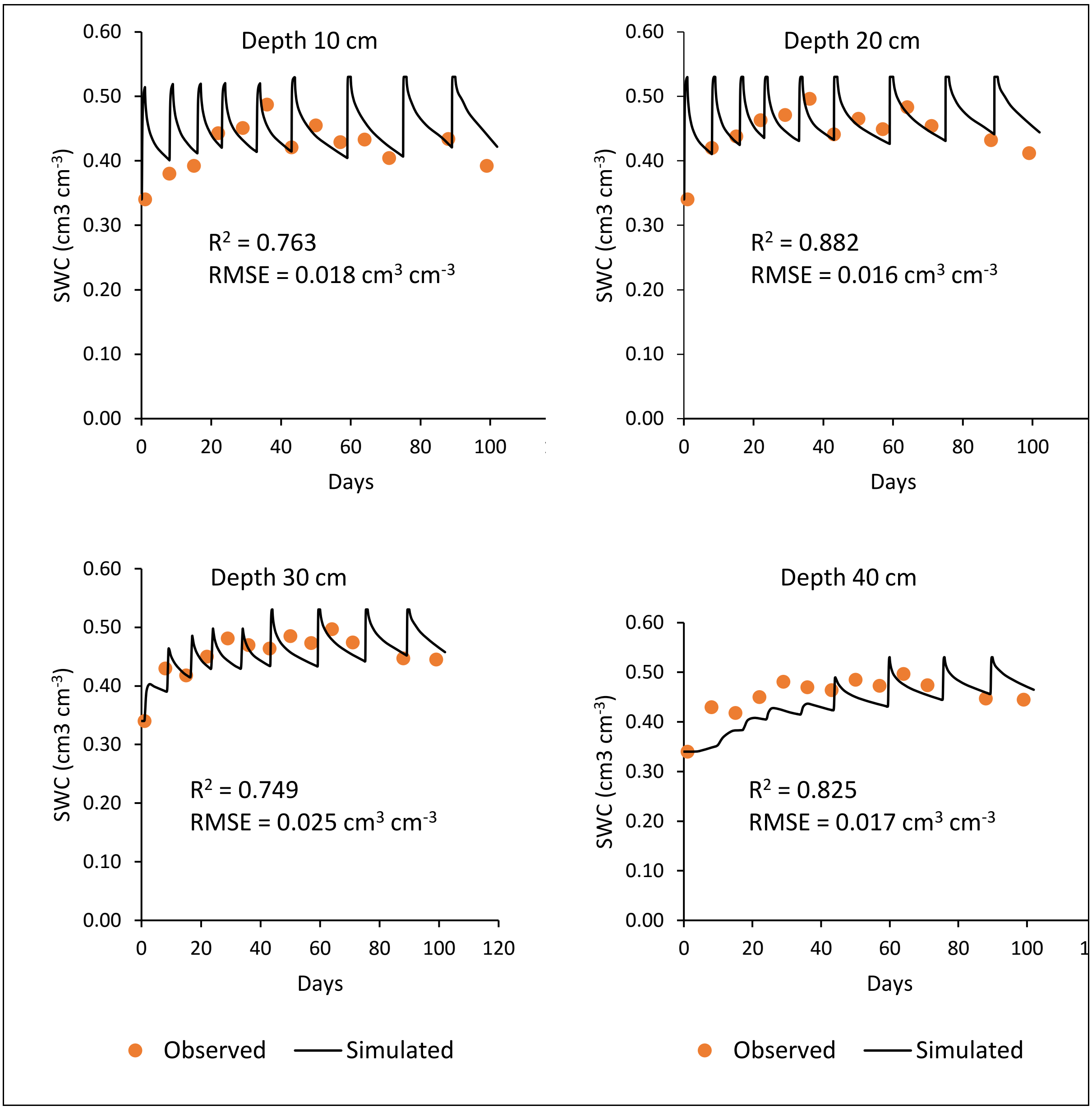

Figure 5.5 Observed and simulated soil water contents under cowpea for SDI at Ukulinga (clay soil)

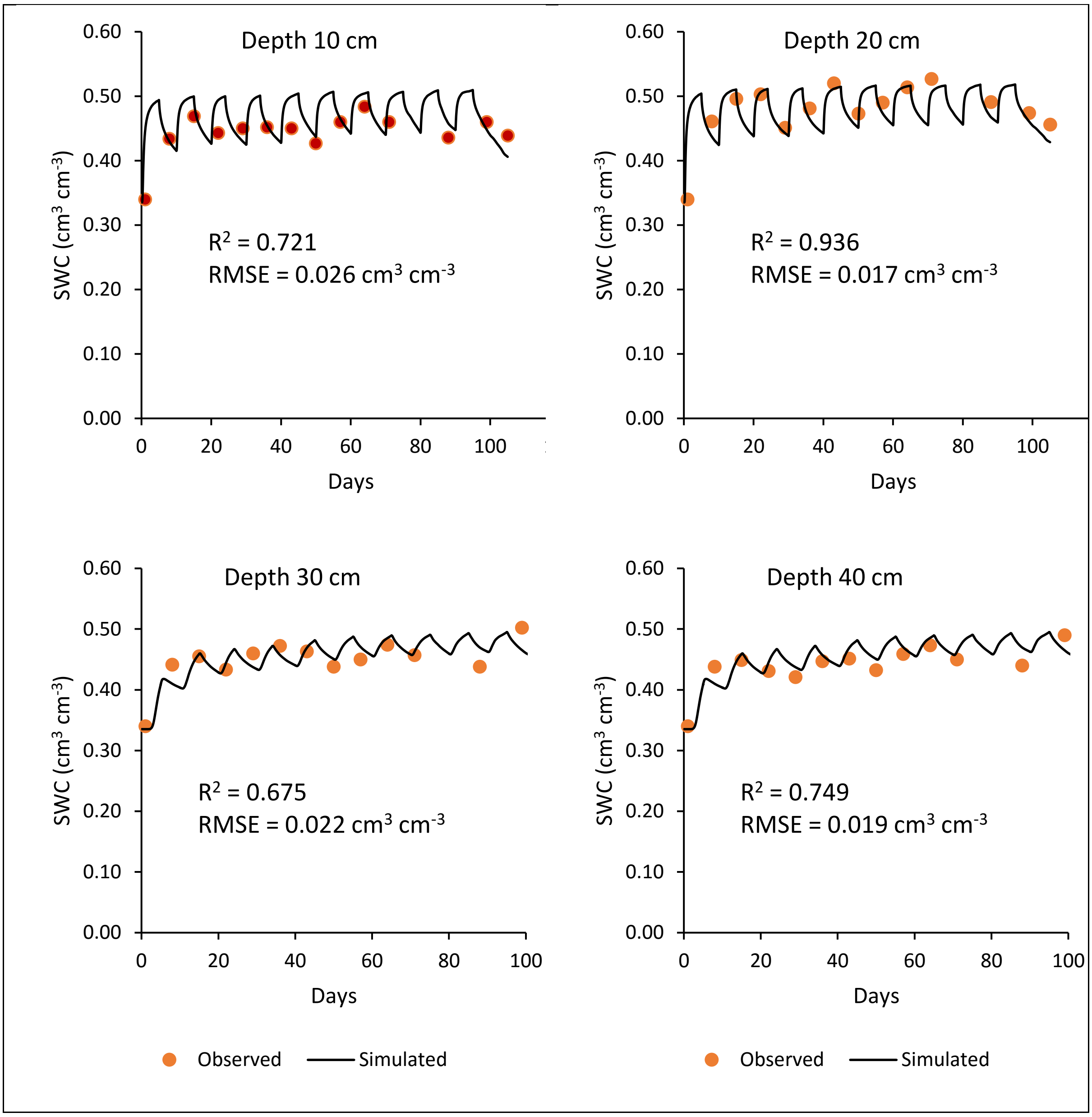

Figure 5.6 Observed and simulated soil water contents under cowpea for MTI at Ukulinga (Clay soil)

5.4.2 Soil water distribution

The soil water distribution between MTI and SDI in loam soil (CEF experiment) is illustrated in Figure 5.7. The soil water content above the Moistube/drip lateral was higher under SDI than MTI. On the other hand, the lateral movement of water was similar in both types of irrigation. However, the downward movement was slightly faster under SDI than MTI. This signifies that under SDI, there is potential for water losses through drainage. Water contents above 0.25 cm^3 cm^{-3} [≥ 80% field capacity (FC)] were within the root zone in both types of irrigation. The water contents were above and within FC about 10 cm radii from the dripper and Moistube, respectively. In clay soil, the soil water content was within the FC under MTI (Figure 5.8) but slightly above FC but below saturation under SDI. Similar results were reported by Patel and Rajput (2008) where a saturated zone was found within 9 cm radius around a SDI dripper in onion. The downward movement was faster in clay under SDI than under MTI where the soil was dry below 35 cm in the latter. The lateral movement of water was faster under SDI than MTI.

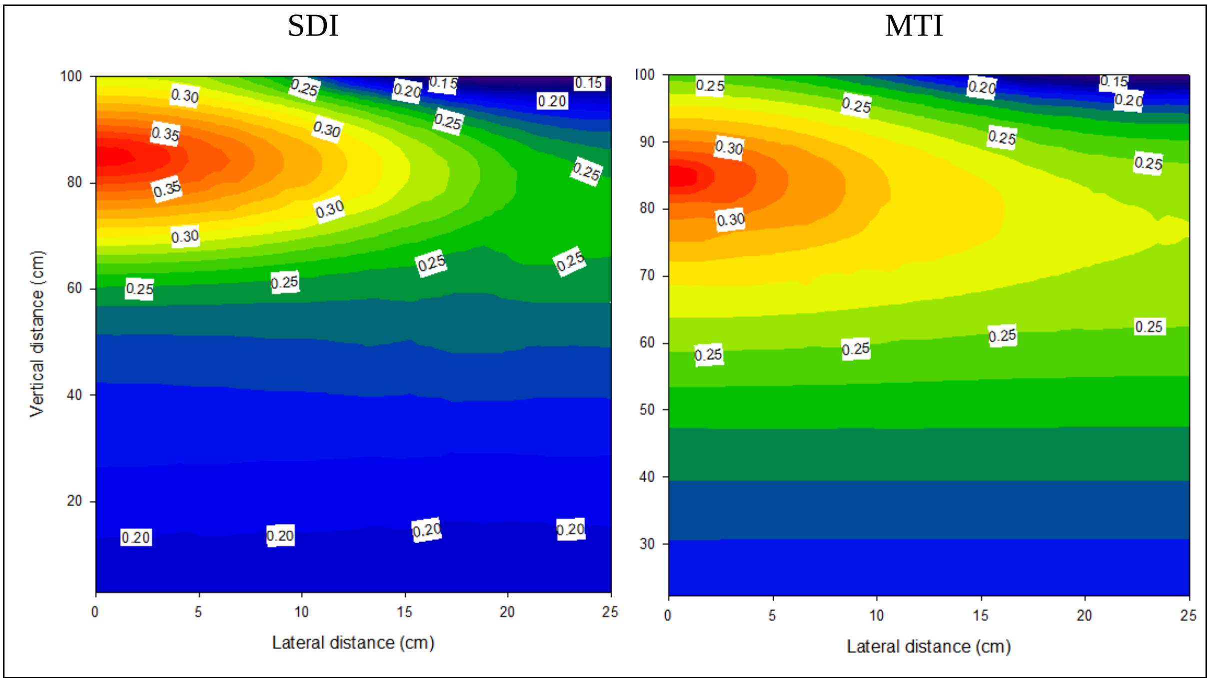

Figure 5.7 Soil water distribution in loam at Day 30

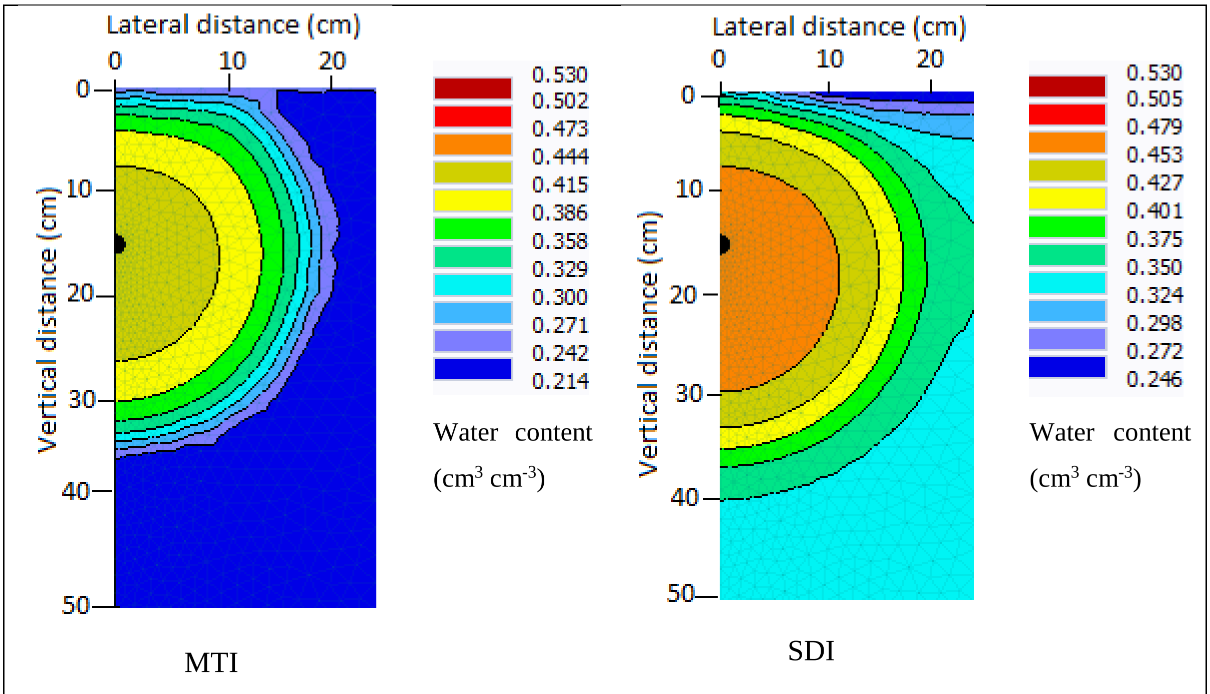

Figure 5.8 Soil water distribution in clay at Day 30

5.4.3 Root water uptake and drainage fluxes

HYDRUS 2D/3D simulates the plant water uptake as a function of the potential crop transpiration and the soil water status (Mante and Ranjan, 2017). The simulations for actual root water uptake (RWU) under SDI and MTI are shown in Figure 5.9. There was no difference in the RWU between the two types of irrigation for the CEF experiment implying that none induced water stress to the crop, since according to Deb *et al.* (2013), the RWU is relatively lower under water stress than under well-watered conditions when compensatory mechanism is not considered. Similarly, there were no significant differences between the seasonal RWU in SDI and MTI at Ukulinga trial, although towards the end MTI recorded higher values than SDI. The drainage fluxes for SDI was significantly higher ($p < 0.05$) than MTI especially after mid-season stage (Figure 5.10). Drainage was negligible at Ukulinga trials under both SDI and MTI.

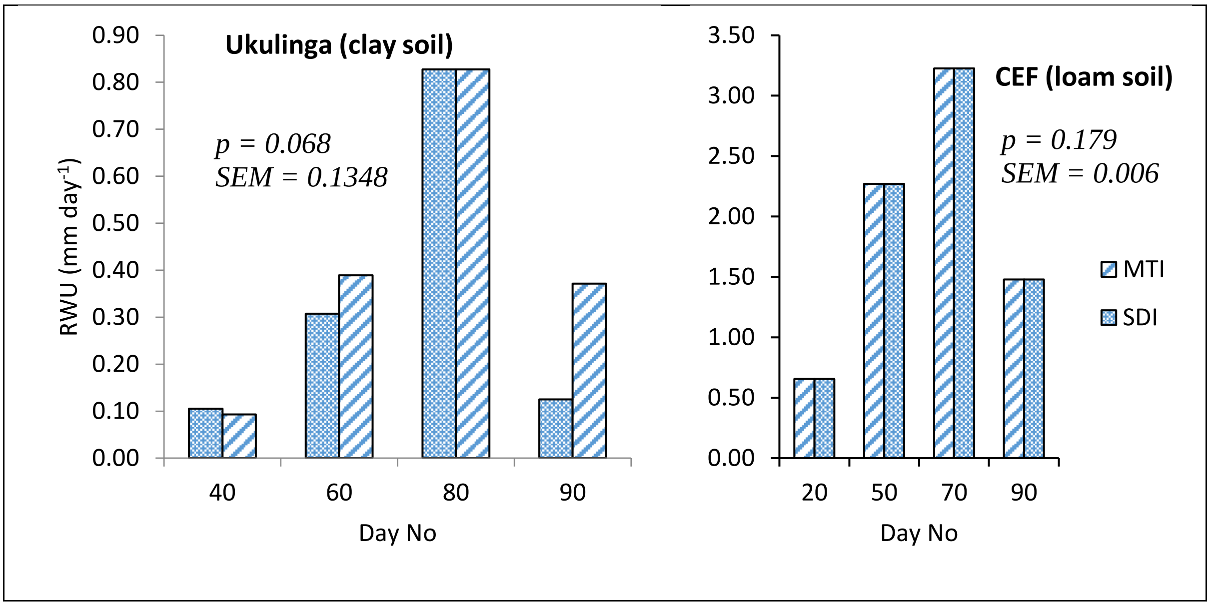

Figure 5.9 Actual root water uptake of cowpea

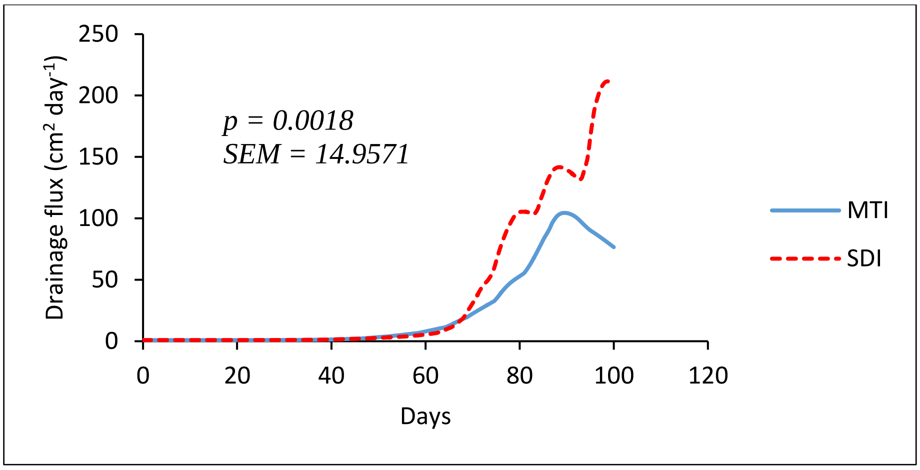

Figure 5.10 Drainage flux under MTI and SDI

5.4.4 Effect of Moistube placement depth and soil texture on soil water dynamics

The soil water distributions in loam and clay soil in 10 cm, 15 cm, 20 cm and 30 cm Moistube placement depths at Day 50 are shown in Figures 5.11 and 5.12. The soil water content above the Moistube decreased with increasing placement depth. The soil water content was within the FC within 10 cm radius under Moistube placement depth of 10 cm and 15 cm. Greatest downward movement occurred under 30 cm placement depth in loam soil which implied loss of water out of the root zone. The downward movement of water was limited in clay soil in all the four depths.

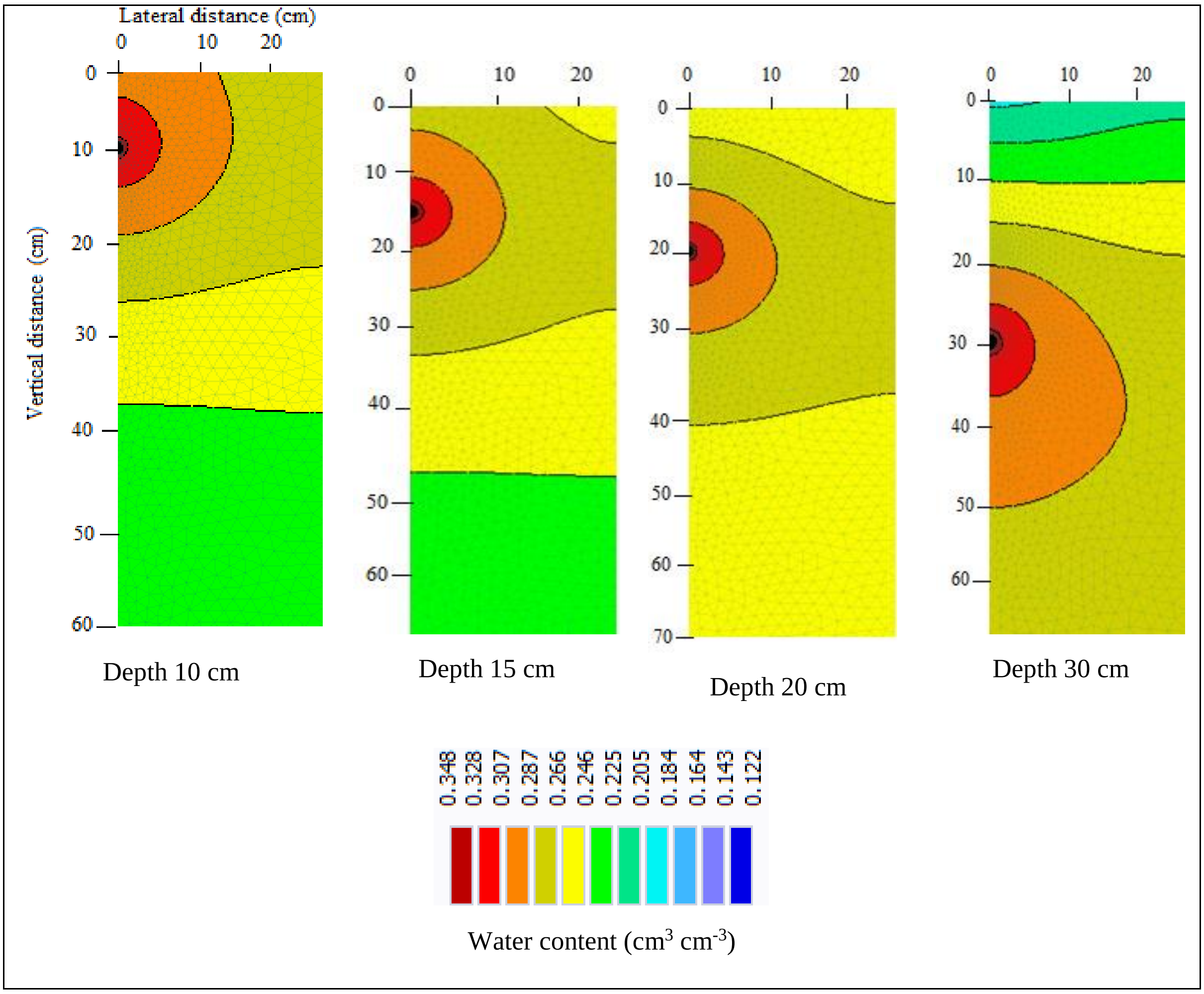

Figure 5.11 Soil water distribution in loam at different Moistube placement depths at Day 50

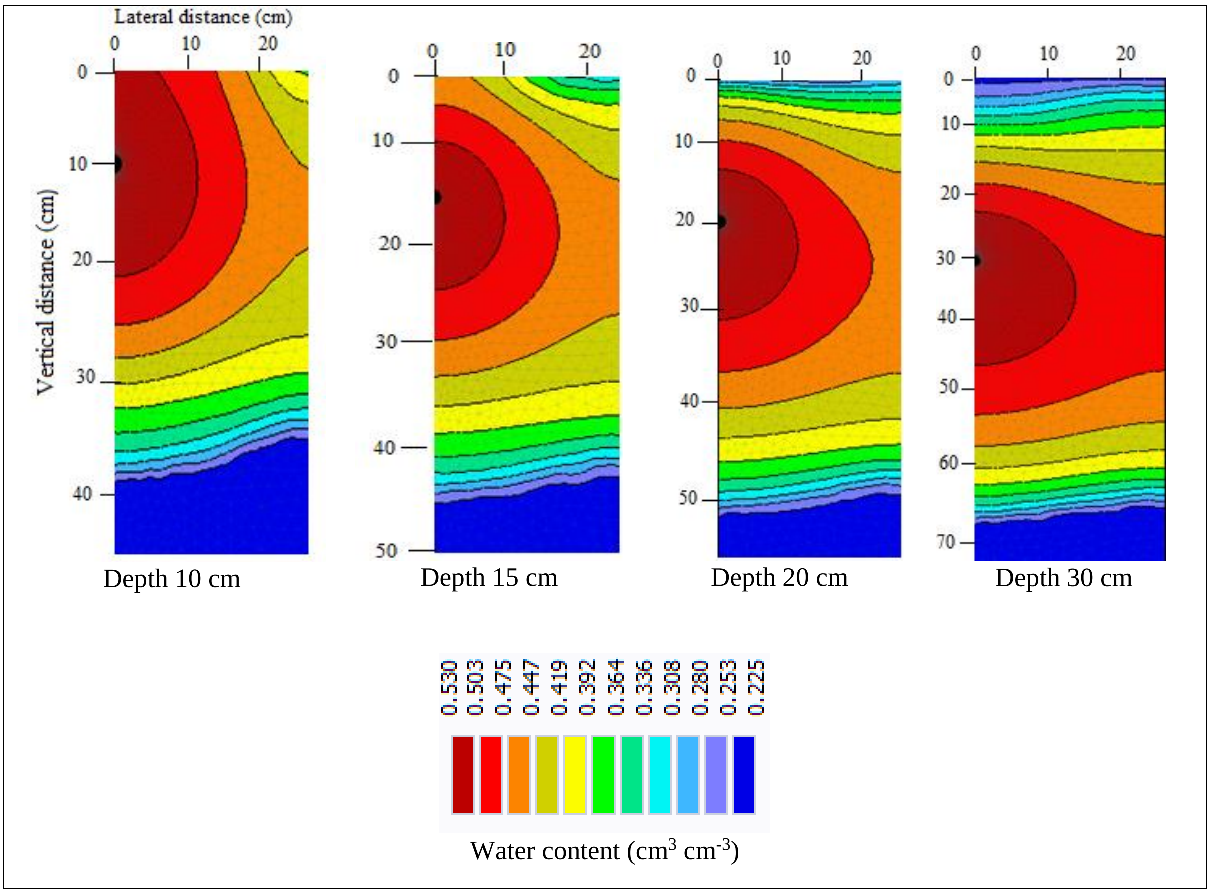

Figure 5.12 Soil water distribution in clay at different Moistube placement depths at Day 50

The distribution of roots of a particular crop influences the soil water dynamics and root water uptake distribution and water loss through deep percolation (Kandelous *et al.*, 2012). The distribution of the root water uptake under the four placement depths in loam is indicated in Figure 5.13. The maximum root water extraction occurred in the upper 20 cm of the soil layer. From the results, the soil water content (Figure 5.11) was lower in the upper 20 cm under placement depth of 30 cm and thus not suitable since the maximum root water uptake (Figure 5.13) was above the maximum water content zone. Similarly, the root water uptake distribution in clay soil was higher in the upper 20 cm of the soil (Figure 5.14). The root water uptake at placement depth of 30 cm was negligible in upper 5 cm below the surface which is attributed to low soil water content as shown in Figure 5.12.

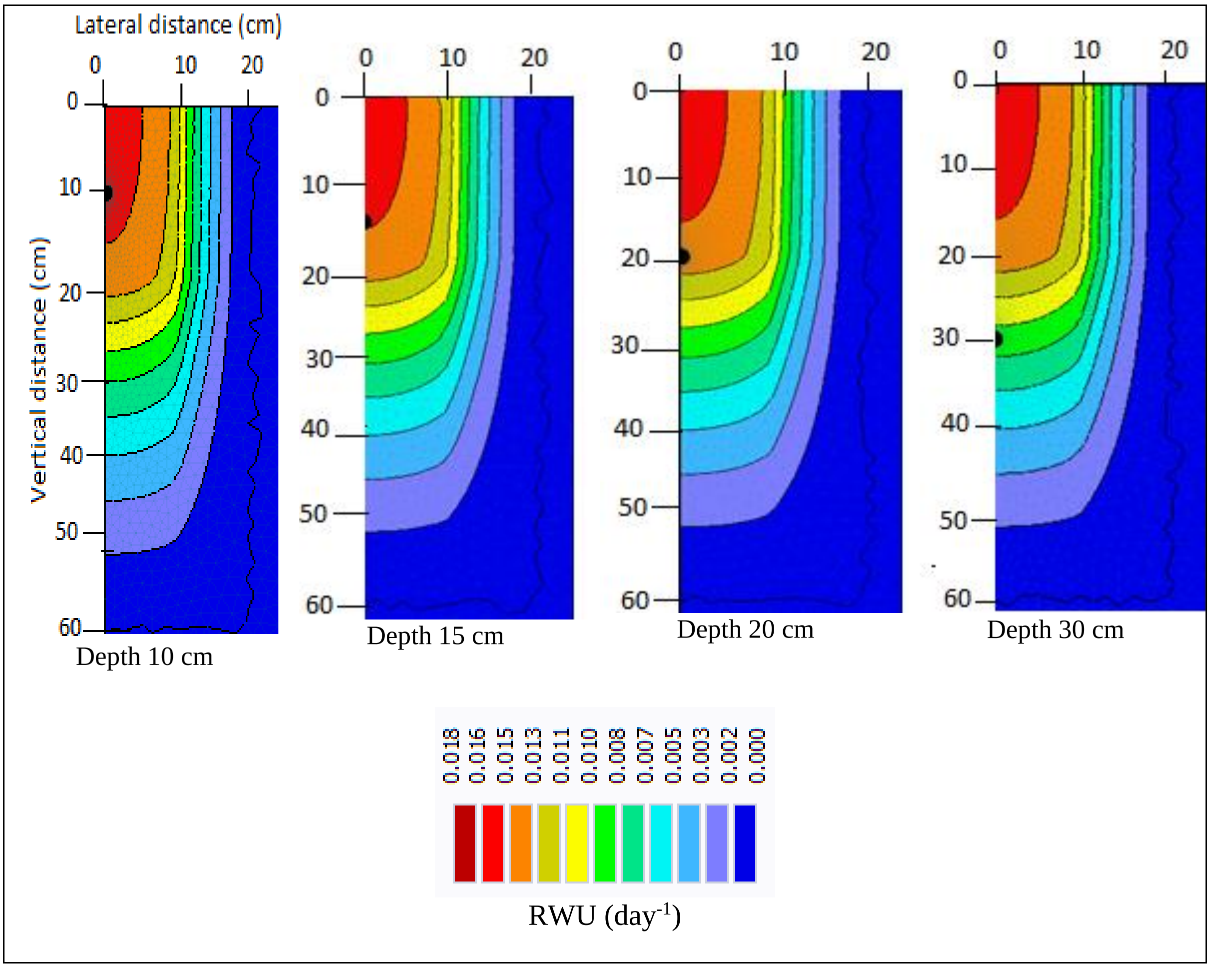

Figure 5.13 Root water uptake distributions in loam at Day 50

The root water extraction pattern illustrated in Figure 5.13 decreases in a linear pattern from the upper to lower soil layers. This could be explained as a standard root water uptake of 40%, 30%, 20% and 10% in the upper to lower soil layers, respectively during optimum water availability conditions (Steduto *et al.*, 2009). This imply that placement depths of irrigation laterals need to ensure enough water is available in the upper soil layers.

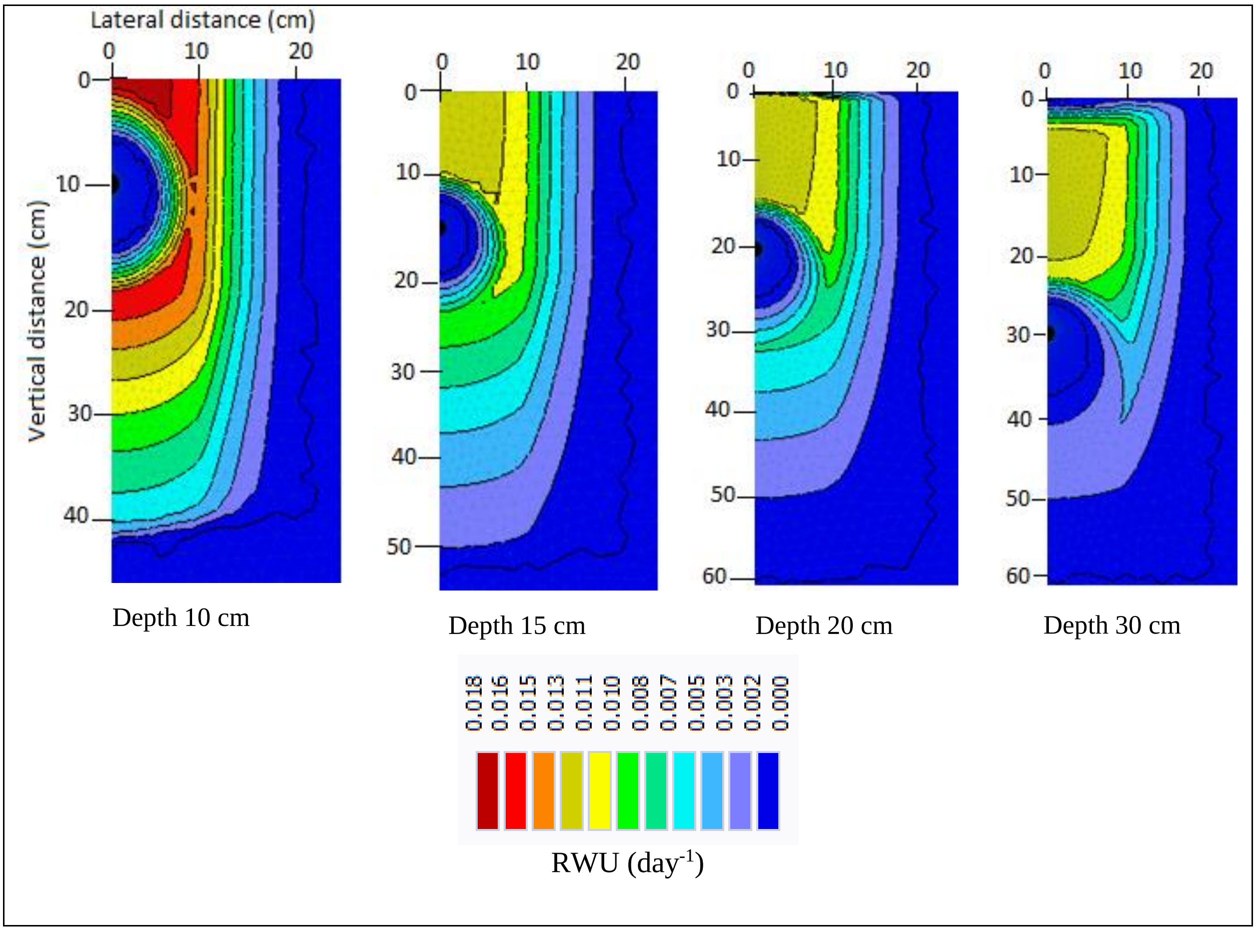

Figure 5.14 Root water uptake distribution in clay at Day 50

The seasonal water balance for the 10 cm, 15 cm and 20 cm and 30 cm Moistube placement depths were obtained from the cumulative fluxes simulated by HYDRUS 2D/3D. The proportion of drainage, evaporation and root water uptake as a percentage of the applied water is shown in Figure 5.15. In loam soil, the root water uptakes were the same for all the depths except at 30 cm where it was slightly lower. However, in clay soil, the root water uptake increased with increasing placement depth until 20 cm and declined at 30 cm. The water loss via drainage in loam soil increased with increasing placement depth. This concurred with a study by Fan *et al.* (2018b) where deeper installation depth of Moistube tapes enhanced downward movement of water. There was no difference between the drainage under 10 cm and 15 cm placement depths in loam soil. In clay soil, drainage was insignificant in all the placement depths. This was expected due to the low hydraulic conductivity in clay soil which hinders rapid downward movement. Soil evaporation increased with decrease in the placement depth. There was no significant difference in soil evaporation in loam soil at 10 cm, 15 cm and 20 cm placement depths except at 30 cm where it was significantly lower, respectively.

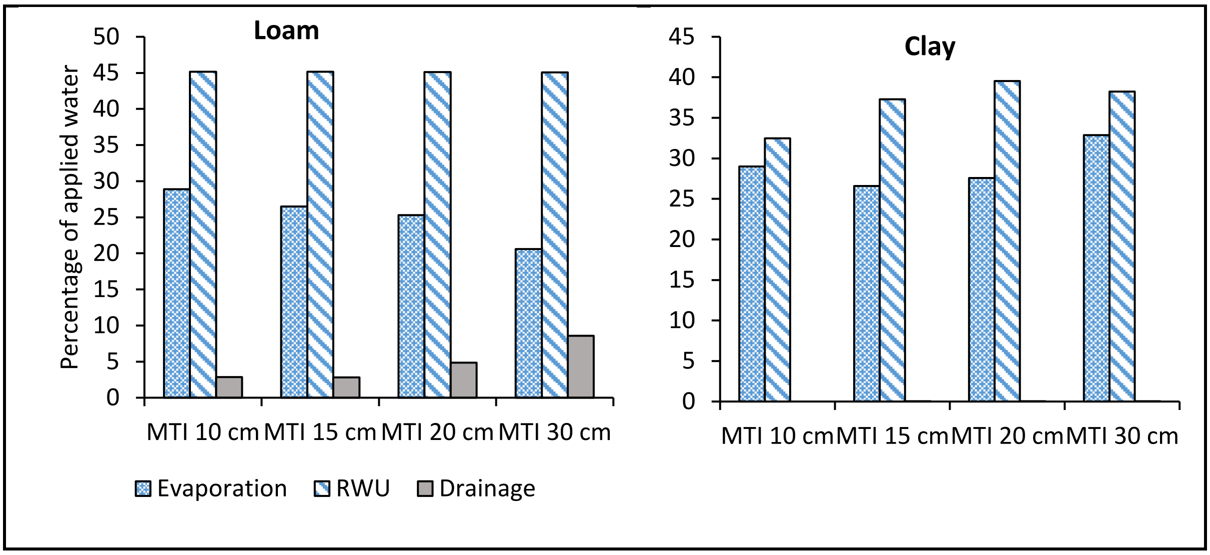

Figure 5.15 Soil water balance components under difference Moistube placement depths

The choice of the optimum placement depth in subsurface irrigation systems is based on two factors; the need to minimize water loss through evaporation and drainage while ensuring that the wetting front is close to the soil surface for crop establishment. Balancing between evaporation and drainage losses, a suitable placement depth of 15 cm could be considered ideal for cowpea under MTI in loam soil. In clay soil, 20 cm could be the suitable placement depth as it had highest root water uptake than the other depths. There are few studies on SDI on cowpea production. One such study was by DeTar (2009) where the drip laterals were placed at a depth of 26 cm.

There is no study in literature on the optimum placement depth in MTI for cowpea or any other related species. However, Moistube placement depths for few other crops are described in Chapter 2 and recap of some of the examples is provided here. The suitable Moistube placement depth for optimum tomato production in silt loam was found to be 10 cm (Lyu *et al.*, 2016;Niu *et al.*, 2017). In a study by Tian *et al.* (2016), a Moistube placement depth of 20 cm was found suitable for sunflower growth. Niu *et al.* (2013b) established that a suitable Moistube placement depth of between 15 and 20 cm in clay loam. Therefore, the choice of Moistube placement depth is influenced by the root characteristics and the soil texture (Fan *et al.*, 2018a). Generally, in subsurface irrigation systems such as drip, shallower installation depth is required in light-textured soils than heavy-textured soils (Camp, 1998).

5.5 Conclusion

The objectives of this study were to determine the soil water dynamics of cowpea under MTI and the effect of Moistube placement depth on soil water dynamics of Moistube irrigated cowpea. It was based on the hypothesis that root water uptake is influenced by the Moistube placement depth. This was achieved using field experiments and numerical simulations with HYDRUS 2D/3D.

The simulated temporal and spatial soil water contents closely matched the observed values with average R^2 of 0.78 and RMSE of 0.017 $cm^3\ cm^{-3}$ under MTI in both experimental sites. The model also satisfactorily simulated the soil water contents under SDI with average R^2 of 0.68 and RMSE of 0.026 $cm^3\ cm^{-3}$. The errors were less than 10% which indicated satisfactory model performance. The root water uptakes were similar under MTI and SDI indicating that there was no water stress over the growing period. The water movement was faster under SDI than MTI. The cumulative drainage over the growing period was significantly higher in SDI than in MTI.

The satisfactory performance of HYDRUS 2D/3D in this study indicates that it can be used to assess various design options like appropriate placement depths. The effect of Moistube placement depth on soil water dynamics in cowpea under MTI in clay and loam soil was also determined. The results indicated that soil evaporation was inversely proportional with Moistube placement depth. Drainage increased with increasing placement depth. Plant water uptake was not affected by placement depth in loam. In clay soil, on the other hand, plant water uptake increased with increase in placement depth until 20 cm but declined slightly at depth 30 cm. Therefore, the hypothesis of this study could be accepted for clay but rejected with respect to loam soil. Based on the soil water distribution, root water uptake and balancing between soil evaporation and drainage water losses, the optimum Moistube placement depth was 15 cm and 20 cm in clay and loam, respectively.

This study was limited to loam and clay soils. The soil water dynamics in other soil types, crops and Moistube discharges need to be investigated. This would give general guidelines on the appropriate placement depths in MTI. Considering that the root characteristics of cowpea were assumed, there is need for experimental determination of the spatial root distribution for accurate determination of the root water uptake. This study considered macroscopic root water uptake without compensation. Further studies need to be carried out to determine compensated root water uptake dynamics under water stress conditions. The finding in this study, indicating that the root water uptake was not significantly different under MTI and SDI was further explored in Chapter 6 where the response of cowpea under the two irrigation types was determined.

5.6 References

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6. RESPONSE OF COWPEA (*Vigna unguiculata* (L.) Walp) TO VARYING WATER REGIMES UNDER MOISTUBE IRRIGATION

Edwin K. Kanda, Aidan Senzanje, Tafadzwanashe Mabhaudhi

Abstract

Cowpea is among the neglected and underutilized indigenous legumes. Water is one of the major factors limiting cowpea production. Although, irrigation helps in stabilizing crop yields, it is the largest water consuming sector. Therefore, there is need for the adoption of efficient irrigation methods and water management practices like deficit irrigation (DI). There is lack of information on how various crops respond to MTI since it is new technology. The aim of this study was to determine the growth and yield response of cowpea to varying water regimes under MTI. It was hypothesized that there was no difference between MTI and SDI (control) and that water use efficiency of cowpea could be improved by DI strategy. The experiment was a split plot design arranged in a randomized complete block design with three replications. The water treatments consisted of full irrigation [100% of crop water requirement (ETc)], and DI of 70% ETc and 40% ETc. The results showed that water deficit had significant effect ($p < 0.05$) on time to 50% flowering where plants under 40% ETc flowered 14 days earlier in relation to plants at 100% ETc. The results further indicated that there were significant ($p < 0.05$) differences in yield components among treatments. The mean pod number per plant were 10.93, 18.70 and 24.37 while the seed number per plant were 162.1, 267.6 and 349.9 for 40% ETc, 70% ETc and 100% ETc, respectively. Grain yields were 1280 kg ha^{-1}, 2401 kg ha^{-1} and 3189 kg ha^{-1} for 40% ETc, 70% ETc and 100% ETc, respectively. There was no significant difference in yields between SDI and MTI ($p > 0.05$) in all the water treatments. However, at 40% ETc, SDI had 15% higher yield than MTI. Biomass varied significantly with the type of irrigation and water treatment ($p < 0.05$). The biomass trend was 40% ETc MTI < 40% ETc SDI < 70% ETc MTI < 70% ETc SDI < 100% ETc MTI < 100% ETc SDI. However, there was no significant differences ($p > 0.05$) between biomass under MTI and SDI at 100% ETc. There was no significant difference between MTI and SDI in water use efficiency. Generally, DI improved the water productivity of cowpea. Therefore, DI could be considered as a water management strategy in areas experiencing water scarcity.

Keywords: Biomass, deficit irrigation, indigenous legume, water use efficiency, yield

6.1 Introduction

Cowpea (*Vigna unguiculata* (L.) Walp) is one of the most important legumes grown in most parts of the world (Sebetha *et al.*, 2010). It is the mostly cultivated crop in resource scarce countries of Africa, Asia, Central and South America due to its ability to withstand extremely harsh environmental conditions such as high temperatures, limited water availability and poor soil fertility (Shiringani and Shimelis, 2011). It is also grown in European countries around the Mediterranean such as Turkey (Peksen, 2007;Basaran *et al.*, 2011). Cowpea in South Africa is cultivated in Limpopo, Kwazulu-Natal, Mpumalanga and Northwest provinces (DAFF, 2014). It can also be found in the wild in KwaZulu-Natal, Mpumalanga and Limpopo provinces (Van Rensburg *et al.*, 2007). Cowpea is nutritionally valuable in humans and animals. It is consumed as grains (dry and fresh) and vegetable leaves (Badiane *et al.*, 2004) and haulms utilized as forage for livestock (Sprent *et al.*, 2009). Cowpea grains are rich in proteins which could help in complementing the diets of majority of African households whose diets mainly consist of starch (Singh *et al.*, 2003) .

Cowpea is tolerant to limited water availability, however insufficient soil moisture at critical stages can have detrimental effect on growth and yield. Studies have demonstrated that water deficit at flowering negatively affected yields of cowpea (Anyia and Herzog, 2004a;Peksen, 2007;Ahmed and Suliman, 2010;Toudou Daouda *et al.*, 2018). However, a study by Ntombela (2012) found that water stress at vegetative stage had a higher significant effect on yield components than at flowering. In the case where the crop is stressed throughout the season, Abayomi and Abidoye (2009) found that it led to a reduction in growth and yield parameters.

From the studies above, it is evident that cowpea is sensitive to water stress especially at flowering stage. Therefore, enough soil moisture should be available at this stage to ensure yield is not reduced. Most of the cowpea production is under rainfed systems. Unavailability of rainfall or non-uniform distribution means that yields cannot be guaranteed exposing households depending on cowpea to risks of crop failure, hunger and malnutrition. Irrigation helps in stabilizing yields and acts as insurance to farmers. It also helps in growing of the crop throughout the year especially in the tropics and subtropics where temperature is conducive.

Irrigation helps in yield reliability and stabilization, but it is the biggest consumer of water resources. In arid and semi-arid areas, irrigation consumes about 70% of the total water use

(Fereres and Soriano, 2007). Irrigation sector in South Africa contributes about 60% of the total water use (Reinders *et al.*, 2010). This, therefore, requires adoption of efficient irrigation systems and prudent agricultural water management practices. Deficit irrigation (DI) is one of the main water saving irrigation strategies where volume of water applied is below the crop water requirement with the aim of maximizing economic farm output per unit volume of water (Fereres and Soriano, 2007). Adoption of efficient irrigation methods such as subsurface drip irrigation (SDI) helps in reducing the agricultural water use by minimizing the non-beneficial components such as soil evaporation, runoff and percolation (Ayars *et al.*, 1999).

Moistube irrigation (MTI) is a relatively new type of irrigation technology which originated in China. It is like SDI where instead of emitters, water flows out of the Moistube membrane as a function of applied pressure and the soil water potential. Some studies have shown that it saves more water than drip irrigation as discussed in Chapter 2. However, being a new technology, there is lack of information on how various crops respond to it. The aim of this study, therefore, was to determine the growth and yield response of cowpea to varying water regimes under MTI. This study was based on two hypotheses. First, it was hypothesized that there was no significant difference between the response of cowpea under MTI and SDI, and secondly, that water use efficiency of cowpea could be improved by deficit irrigation strategy.

6.2 Materials and Methods

The methodology adopted in this study is described in the following sub-sections. This included the description of the experimental designs and procedures as well as data collection and analysis.

6.2.1 Study area and experimental design

The study was carried out in tunnels at the Controlled Environment Facility (CEF) of UKZN, Pietermaritzbug Campus (29.58^0 S, 30.42^0 E) and UKZN's Ukulinga Research farm (29.67^0 S, 30.41^0 E.) The experiment at CEF was carried out in a glasshouse with raised beds measuring 11 m long, 0.75 m wide and 0.75 m high. The soil texture was loam (42.3% sand, 33.3% silt, 24.4%) with bulk density of 1.36 g cm^{-3}. At Ukulinga, the experiment was carried out in a 12 m by 5 m tunnel where the soil texture was clay (24.3% sand, 23.6% silt and 52.1% clay) with bulk density of 1.23 g cm^{-3}. The tunnel at Ukulinga had open ends to replicate as much as possible the field conditions with free movement of air.

The experiment was laid out in a split-plot design arranged in randomized complete block design. The main block was the irrigation type (SDI and MTI) while the sub-plots were the three water regimes replicated three times. The water regimes imposed consisted of full irrigation to meet the crop water requirement (100% ETc), and DI of 70% ETc and 40% ETc. The drip emitters and Moistube tapes were installed at a depth of 15 cm. The experimental layouts are shown in Figures 6.1 and 6.2 for CEF and Ukulinga, respectively.

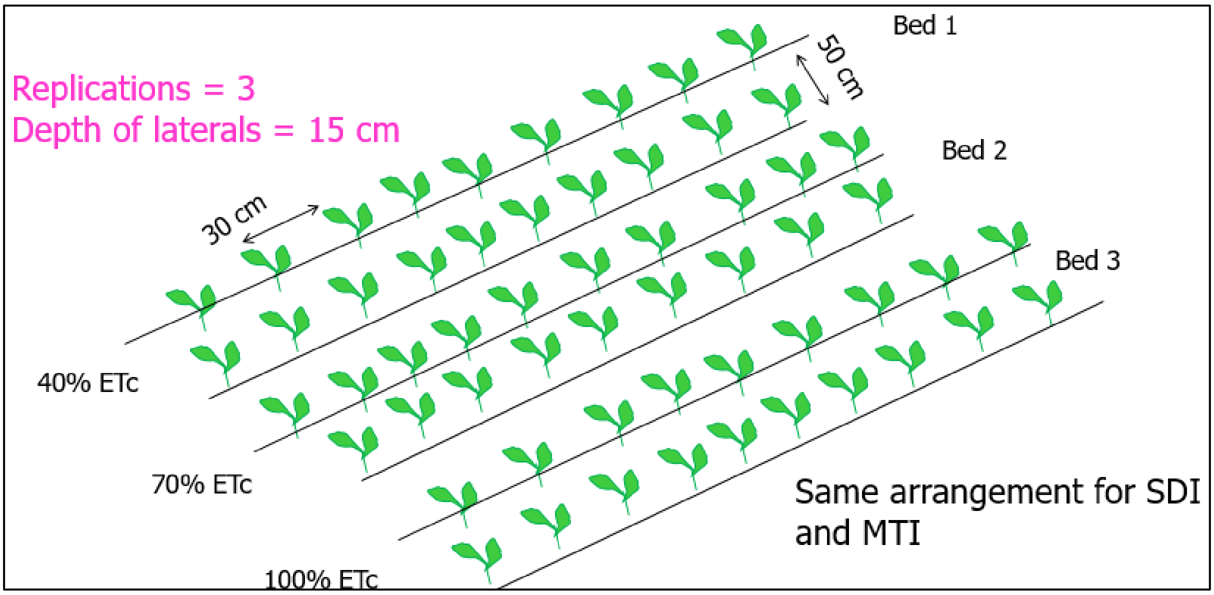

Figure 6.1 Experimental layout for CEF experiment

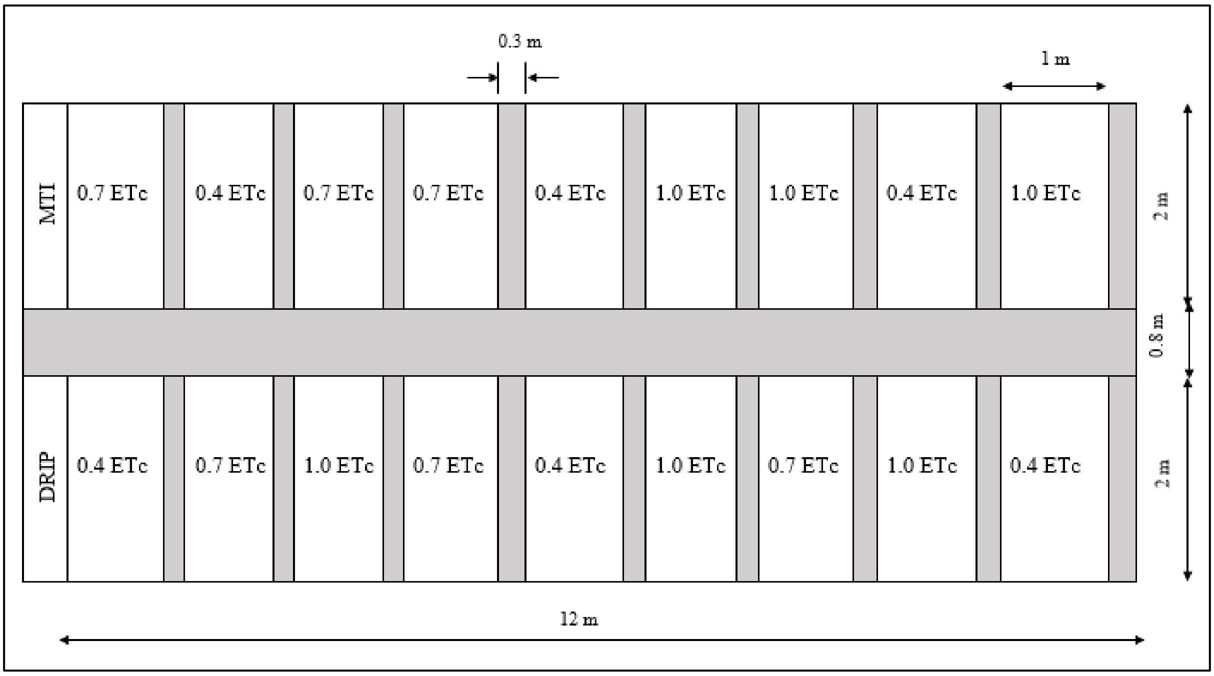

Figure 6.2 Experimental layout for Ukulinga experiment

Cowpea (brown mix variety) was planted on 14th February 2018 at CEF and 25th May 2018 at Ukulinga. The spacing was 50 cm between rows and 30 cm within rows giving a density of 66667 plants ha^{-1}. Soil fertility test conducted at Cedara Agricultural College indicated that the soil did not have nutrient deficiency at Ukulinga but soil at CEF required phosphorus at a rate of 60 kg ha^{-1} Single Superphosphate (10.5% P). The DI treatments were introduced 21 days after planting (DAP) at CEF and 30 DAP at Ukulinga when the crops were fully established. Other agronomic management practices such as weed, pest and disease control were done accordingly based on recommended best practices.

6.2.2 Determination of crop water requirements

The procedure for determination of crop water requirements was as follows;

a) The crop water requirements (ETc) for each crop growth stage were determined using potential evapotranspiration and crop coefficients as describe in Equation 5.4 (Chapter 5).
b) The net irrigation requirement (Inet) was the same ETc since rainfall was zero
c) The volume of irrigation water was computed using Equation 6.1

$$V = 10 \times \sum_{i=1}^{n} \mathrm{d} \qquad (6.1)$$

Where V = volume of water (m^3 ha^{-1}), d = irrigation depth (mm), and n = number of water applications derived from the irrigation interval.

d) The net irrigation depth was computed using Equation 6.2

$$d_{net} = \rho * (FC - PWP) * D \quad (6.2)$$

Where d_{net} = The net irrigation depth (mm), D = The depth of the root zone of the crop (mm), and ρ = allowable depletion level which was taken as 50%, FC = field capacity, PWP = permanent wilting point. The root zone was limited by the soil layer thickness which was 0.60 m and thus this was taken as the effective rooting depth.

e) The gross irrigation depth can then be calculated using Equation 6.3

$$d_{gross} = d_{net}/E_a \quad (6.3)$$

Where d_{gross} = The gross irrigation depth (mm) and E_a = The field application efficiency which was taken as 90% for both MTI and SDI.

f) The irrigation interval (T) computed using Equation 6.4

$$T = d_{ne}t/ET_c \quad (6.4)$$

Where ETc is the crop water requirement per decade

The different water regimes were applied by varying the irrigation interval in such a way that the total amount of irrigation was 100%, 70% and 40% of ETc. MTI was supposed to be continuous i.e. water applied throughout the cropping cycle but due to infrastructural challenges, the flow regulation was not sufficiently low enough to allow for continuous water application. Therefore, the water application was applied intermittently ranging from as low as 3 days continuously per decade to 8 days per decade for 40% ETc and 100% ETc, respectively.

6.2.3 Data collection and analysis

Weather data was obtained inside the tunnel using HOBO data logger sensors (Onset Computer Corporation, USA). The variables measured were temperature, relative humidity, solar radiation. Wind speed was measured using Kestrel 3000 anemometer (Nielsen-Kellerman, Inc. USA). Soil water content was measured weekly using Water Mark sensors (Irrometer Inc. USA) and MPS-2 sensors (Decagon, Inc. USA) installed at 10 cm, 20 cm and 40 cm depths. The soil water potential values obtained were calibrated using gravimetric measurements (Figure A.1). At Ukulinga, the water content was measured using PR2/6 profile probe (Delta-T Ltd, UK). Leaf area index (LAI) was measured weekly using LAI 2200 canopy analyser (LI-COR Inc. USA). Time to 50% flowering was determined by counting the number of flowered plants. Determination of yield components was done by sampling 10 plants per plot excluding border plants. All the pods were harvested from each plant and counted then shelled for yield analysis. Above ground biomass was determined by cutting each of the 10 plants per plot then weighing after air drying.

The harvest index (HI) was computed using Equation 6.5 (Cisse, 2001).

$$Harvest\ index = \frac{Grain\ yield\ (kg\ ha^{-1}}{Biomass\ (kg\ ha^{-1})} \times 100\% \qquad (6.5)$$

The reported data was analysed using ANOVA with the help of GenStat® version 18 (VSN International, Hemel Hempstead, UK). Separation of means of significant variables were done using Least Significant Differences (LSD) at 5% significance level. Correlation analysis was carried out on growth and yield components to determine the relationship between variables.

6.3 Results and Discussion

The cowpea at the Ukulinga trial facility failed to flower due to low temperatures. The night temperatures were, in most cases, very low (< 10^{o}C) which affected most of the growth parameters. The low temperatures significantly delayed time to emergence (≈15 days) and led to decline in LAI and failure of flowering. Therefore, the results reported here were for controlled experiment only.

6.3.1 Time to flowering

Water deficit affects crop growth and development by not only retarding cell division and expansion but also by altering the initiation and duration of phenological stages (Prasad *et al.*, 2008). Time to flowering is an environmental adaptive feature of most annual crops (Ishiyaku *et al.*, 2005). In the present study, the number of days to 50% flowering varied significantly across the water regimes ($p < 0.05$) as illustrated in Table 6.1. Cowpea matured earlier at 40% ETc for both MTI and SDI. MTI 70% ETc matured 5 days later than MTI 40% ETc though they were not significantly different ($p > 0.05$). Similarly, there was no significant difference between SDI at 70% ETc and MTI at 100% ETc. There was significant difference ($p < 0.05$) between SDI at 100% ETc and all the other water regimes.

Table 6.1 Time to flowering

Irrigation type	Water regime	Time to flowering (days)
Moistube	40% ETc	55.33 (2.52) [a]
Drip	40% ETc	56.67 (2.08) [a]
Moistube	70% ETc	59.67 (4.51) [a]
Drip	70% ETc	67.33 (2.08) [b]
Moistube	100% ETc	65.67 (3.06) [b]
Drip	100% ETc	74.33 (4.16) [c]
LSD (Irrigation)		3.30
LSD (ETc)		4.04
LSD (Irr x ETc)		5.72
CV (%)		5.10

Mean values in same column followed by same superscript letter do not significantly differ ($p < 0.05$) by LSD. Data in parenthesis are the standard deviations

The accelerated time to flowering due to water deficit reported in this study were consistent with those reported by Ilunga (2014) for the same variety (mixed brown) where rainfed induced water deficit led to early flowering by 7 days. Moistube supplies water to the crop at 80 – 90% of field capacity (Zhang *et al.*, 2012). This could possibly explain the non-significant difference between time to 50% flowering under 70% ETc SDI and 100% ETc under MTI. The shorter duration to flowering as a result of water deficit is considered as a drought escape mechanism in cowpea (Ehlers and Hall, 1997). However, some studies have reported delayed flowering due to water stress (Abayomi and Abidoye, 2009;Ntombela, 2012;Faloye and Alatise, 2017). The response of time to flowering under water deficit in cowpea depends on the genotype as found by Dadson *et al.* (2005) where some exhibited early flowering while others had delayed flowering.

6.3.2 Leaf area index

LAI is an important growth parameter as it signifies the extent of the assimilative capacity of a crop under existing environmental conditions (Farooq *et al.*, 2012). In the present study, the LAI varied among the treatments. Full irrigation attained a maximum LAI of 4.00 and 3.88 for MTI and SDI, respectively (Figure 6.3). The lowest maximum LAI was under MTI at 40% ETc

(2.88). There were no significance differences among drip 70% ETc (2.396 ± 1.350), Moistube 70% ETc (2.390 ± 1.100) and drip 40% ETc (2.205 ± 1.218).

The difference between the mean LAI at MTI 40% ETc (1.926 ± 1.000) and both MTI 100% ETc (2.588 ± 1.371) and SDI 100% ETc (2.205 ± 1.318) was highly significant ($P < 0.05$). This represented a decline of 25.6% under MTI at 40% ETc. These results were consistent with those reported by Souza *et al.* (2017) where LAI declined by between 13% and 47% due to water deficit. The reduction in LAI could be attributed to decreased leaf appearance rate and abscission which are considered as drought avoidance mechanism (Abayomi and Abidoye, 2009). Reduction in leaf area due to water deficit arises because of inhibited cell growth (Fathi and Tari, 2016). According to Prasad *et al.* (2008) mild water deficit causes reduction in leaf number, retarded leaf expansion rate and reduced leaf size while severe water deficit inhibits the growth of new leaves.

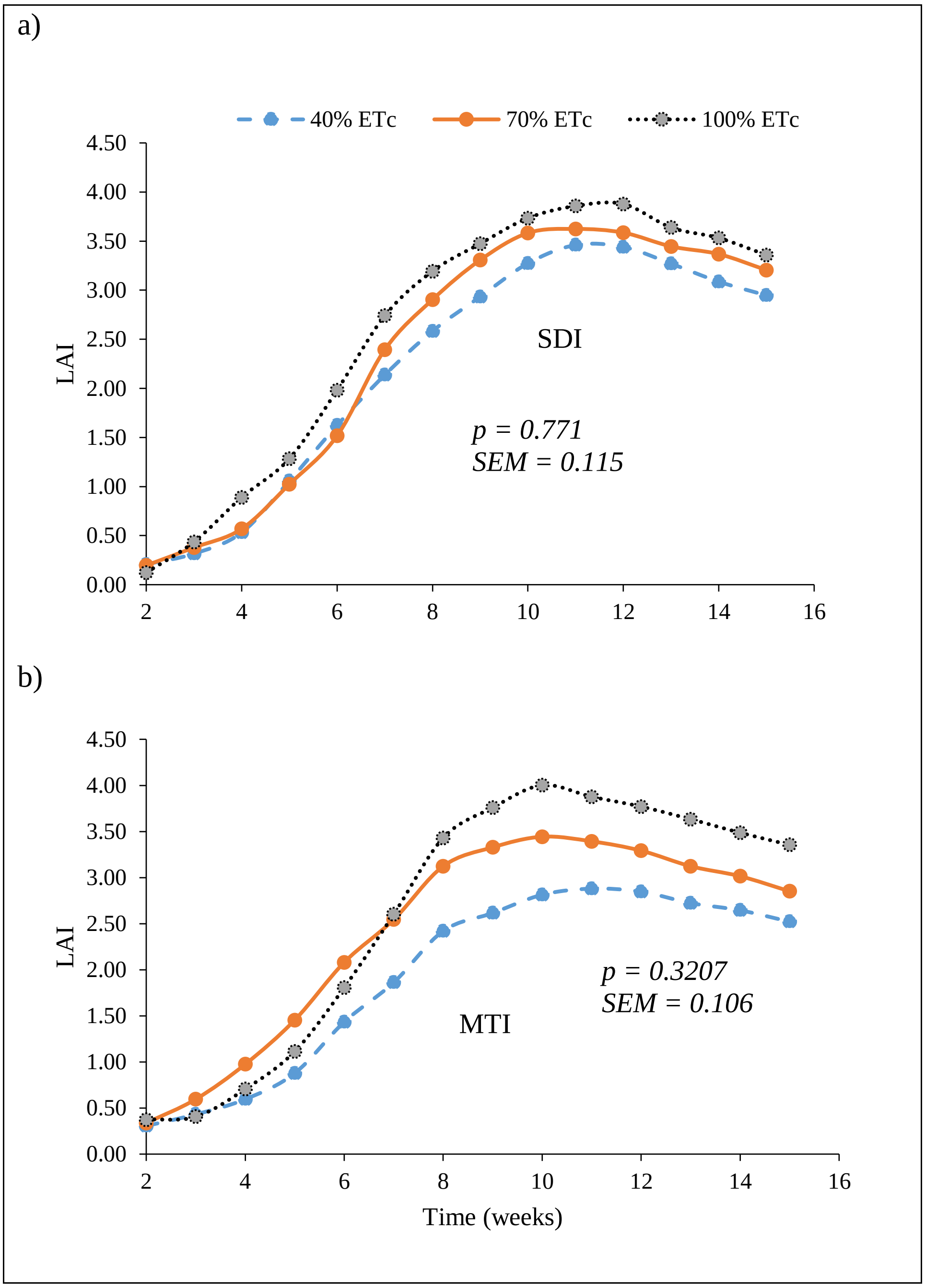

Figure 6.3 Leaf area index for different irrigation treatments (a) SDI and (b) MTI

6.3.3 Yield and yield components

The yield and yield components showed significant differences among the water regimes as illustrated in Table 6.2. There were significant differences in the number of pods and pod mass per plant among the three water regimes considered under both SDI and MTI ($p < 0.05$). The type of irrigation did not significantly affect the number of pods and pod mass ($p > 0.05$), although SDI had slightly higher number of pods (17.4%) and pod mass (22.7%) than MTI at 40% ETc. The number of seeds per plant exhibited significant variations across the type of irrigation and water regimes ($p < 0.05$). Under MTI, the seed number was significantly lower at 40% ETc than both at 70% ETc and 100% ETc. Similarly, the number of seeds at 70% ETc was significantly lower than at 100% ETc. In SDI, the seed number was significantly lower at 40% than both 100% ETc and 70% ETc but there was no significant difference ($p > 0.05$) between 70% ETc and 100% ETc. Whereas the number of seeds per plant decreased because of water deficit, the mean number of seeds per pod varied from 14 to 17 and the difference was not statistically significant ($p > 0.05$). Seed mass followed the same trend as number of seeds with significant difference ($p < 0.05$) recorded across the water regimes. The type of irrigation did not have a significant effect on seed mass per plant, but SDI performed better than MTI in all the water regimes except at 100% ETc.

The above results were similar to those found by Mousa and Qurashi (2017) where water deficit led to the decline in the number of pods per plant. Similarly, Abayomi and Abidoye (2009) found reduced pod weight and number of seeds per plant due to water deficit. In another study, Hamidou *et al.* (2007) reported an average reduction of 60% in the number of pods per plant due to water deficit. The reduction in the number of pods per plant could be attributed to lower number of flower buds and loss of flowers due to water deficit in the reproductive stage (Maleki *et al.*, 2017;Toudou Daouda *et al.*, 2018).

Biomass per plant showed significant variations with respect to water regimes ($p < 0.05$). Compared to 100% ETc, there was an average 38.5% reduction in biomass at 40% ETc in MTI. SDI recorded significantly higher ($p < 0.05$) biomass per plant than Moistube at 40% ETc and 70% ETc. However, there was no significant difference between the two types of irrigations at 100% ETc ($p > 0.05$).

Table 6.2 Yield and yield components

Irrigation	Water regime	Pods $plant^{-1}$	Pod mass $plant^{-1}$ (g)	Seeds $plant^{-1}$	Seed mass $plant^{-1}$ (g)	Biomass $plant^{-1}$ (g)	Grain yield (kg ha^{-1})	Biomass (kg ha^{-1})	Harvest Index (%)	Shelling (%)
Moistube	40% ETc	10.9 (5.3) ^{a}	29.9 (19.4) ^{a}	162.1 (84.4) ^{a}	19.4 (9.1) ^{a}	85.5 (10.0) ^{a}	1280 (598) ^{a}	5701 (926) ^{a}	22.4 (9.2) ^{a}	71.23 (20.6) $^{a b}$
Drip	40% ETc	12.8 (4.9) ^{a}	36.7 (15.3) ^{a}	174.6 (59.8) ^{a}	22.8 (7.0) ^{a}	100.4 (18.9) ^{b}	1505 (462) ^{a}	6694 (1263) ^{b}	22.6 (4.8) ^{a}	66.54 (17.8) ^{a}
Moistube	70% ETc	18.7 (6.4) ^{b}	50.1 (17.6) ^{b}	267.6 (95.4) ^{b}	36.4 (9.4) ^{b}	120.2 (15.7) ^{c}	2401 (612) ^{b}	8012 (1048) ^{c}	30.1 (5.5) ^{b}	75.1 (13.0) ^{b}
Drip	70% ETc	18.5 (5.9) ^{b}	52.1 (15.8) ^{b}	315.0 (96.2) ^{c}	39.5 (10.6) ^{b}	128.9 (20.1) ^{d}	2605 (701) ^{b}	8590 (1339) ^{d}	30.5 (6.0) ^{b}	77.3 (11.8) ^{b}
Moistube	100% ETc	24.4 (7.2) ^{c}	67.8 (16.7) ^{c}	349.9 (94.3) ^{c}	48.3 (9.6) ^{c}	139.1 (18.7) ^{e}	3189 (634) ^{c}	9272 (1247) ^{e}	34.8 (5.3) ^{c}	72.4 (8.0) $^{a b}$
Drip	100% ETc	24.7 (7.4) ^{c}	67.3 (20.7) ^{c}	345.2 (101.4) ^{c}	45.8 (10.5) ^{c}	145.2 (16.5) ^{e}	3025 (695) ^{c}	9678 (1098) ^{e}	31.5 (6.2) ^{b}	70.5 (11.7) $^{a b}$
LSD (Irrigation)		1.8	5.2	9.5	2.6	5.3	88.3	350.6	1.72	2.6
LSD (ETc)		2.3	6.4	11.6	3.2	6.44	108.1	429.4	2.1	3.1
LSD (Irr x ETc)		3.2	9.0	16.4	4.6	9.11	152.9	607.2	2.9	4.4
CV (%)		24.1	24.5	23.3	20.9	15.3	20.9	15.3	17.4	13.3

Mean values in same column followed by same superscript letter do not significantly differ ($p < 0.05$) by LSD. Data in parenthesis are the standard deviations

Grain yield (kg ha^{-1}) and biomass (kg ha^{-1}) being a product of yield and biomass per plant respectively followed same trend across water regimes. Compared to SDI at 100% ETc, significant reduction in yield (57.7%) was recorded at 40% ETc under MTI while drip at 40% ETc led to a decline in yield by 50.2%. Similarly, the decline in yields at 70% ETc was 13.9% and 20.5% under SDI and MTI respectively. There was significant difference between MTI and SDI at 40% ETc. The main contributor of lower yields because of water deficit was number of pods per plant, pod mass per plant, HI and LAI which were significantly reduced under deficit irrigation. Maleki *et al.* (2017) reported a decline of between 4% and 59% in cowpea yields under water regime of 40-80% of full irrigation. Reduction in yield due to water deficit is attributed to reduced photosynthetic active radiation absorption rate by plants and reduction in radiation efficiency (Fathi and Tari, 2016). According to Prasad *et al.* (2008), water deficit generally reduces grain yields via its influence on the plant matter production prior to flowering and negatively affecting the reproduction phase of pollination.

Total biomass ((kg ha^{-1}) of cowpea followed the same trend as grain yield where MTI recorded 41% and 17% decline in biomass at 40% ETc and 70% ETc, respectively. These results were similar to those reported by Faloye and Alatise (2017) where a reduction of between 23% and 49% was recorded under water regime of between 40% and 80% of full irrigation. Water deficit leads to decline in leaf expansion, lower production of leaves and leaf senescence which ultimately decreases the biomass (Figueiredo *et al.*, 2001). Besides reduced leaf area, Anyia and Herzog (2004b) associated decline in biomass of cowpea with reduced leaf gas exchange due to water deficit.

The partitioning of biomass to grain yield, represented by HI, showed differences across water treatments and irrigation type. The highest HI was recorded at 100% ETc and the lowest at 40% ETc under MTI. The HI was significantly higher ($p < 0.05$) in MTI than SDI at 100% ETc. There was no significant difference in HI between SDI and SDI at 40% ETc and 70% ETc. Also, the HI was not significant at 70% ETc and SDI at 100% ETc. With respect to SDI, the HI was 29% lower at 40% ETc. This could be attributed to significant reductions in grain yield due to water deficit. Reduction of HI in cowpea due to water deficit was also reported by Hamidou *et al.* (2007) where a reduction of 63% was observed. Shelling percentage signifies the efficiency in which the pods are filled with grains (Mkandawire and Sibuga, 2002) . In the present study, shelling percentage was not significantly affected by water regime ($p > 0.05$).

However, Abayomi and Abidoye (2009) reported reduction in shelling percentage of cowpea due to water deficit.

Yield is a product of several components such as number of germinated plants, dry matter partitioning, seed numbers, and size of the seeds (Prasad *et al.*, 2008). There was a strong positive association between the total grain yield and number of pods per plant ($r = 0.97$), pod mass per plant ($r = 0.96$), number of seeds per plant ($r = 0.96$), biomass and HI ($r = 0.94$) as shown in Table 6.3. Among these attributes, pod mass and HI had a significant contribution to grain yield ($p < 0.05$). Total grain yield ($r = 0.85$) and biomass ($r = 0.76$) were significantly correlated with LAI ($p < 0.05$). However, yield was strongly and negatively correlated with the number of days to 50% flowering ($r = - 0.80$).

Table 6.3 Correlation analysis of growth and yield components

	Pod No.	Pod mass plant $^{-1}$	Seeds plant^{-1}	Grain yield (kg ha^{-1})	Biomass (kg ha^{-1})	Harvest index (%)	LAI	Days to flowering
Pods	1.00							
Pod mass plant $^{-1}$	0.99	1.00						
Seeds plant^{-1}	0.96	0.97	1.00					
Grain yield (kg ha^{-1})	0.97	0.96	0.96	1.00				
Biomass (kg ha^{-1})	0.98	0.98	0.98	0.98	1.00			
Harvest index (%)	0.95	0.94	0.95	0.94	0.93	1.00		
LAI	0.85	0.85	0.78	0.85	0.76	0.89	1.00	
Days to flowering	-0.83	-0.81	-0.77	-0.80	-0.71	-0.78	-0.77	1.00

6.3.4 Water use efficiency

The results of the water use efficiency (WUE), defined as the ratio of yield or biomass to volume of water applied, for SDI and MTI under the three water regimes are shown in Table 6.4.

Table 6.4 Water use efficiency for cowpea under MTI and SDI

Water regime	Water use efficiency (kg m^{-3})	
	Grain	Biomass
Moistube 100% ETc	0.916 (0.182) ^{ab}	2.664 (0.358) ^{a}
Drip 100% ETc	0.820 (0.188) ^{ab}	2.623 (0.298) ^{a}
Moistube 70% ETc	0.954 (0.243) ^{b}	3.179 (0.416) ^{b}
Drip 70% ETc	0.961 (0.259) ^{b}	3.170 (0.494) ^{b}
Moistube 40% ETc	0.790 (0.369) ^{a}	3.519 (0.411) ^{c}
Drip 40% ETc	0.860 (0.264) ^{ab}	3.825 (0.722) ^{d}
LSD (ETc)	0.093	0.169
LSD (Irrigation)	0.076	0.138
LSD (Irrigation x ETc)	0.132	0.239
CV (%)	19.2	14.8

Mean values in same column followed by same superscript letter do not significantly differ ($p < 0.05$) by LSD. Data in parenthesis are the standard deviations

Grain WUE varied significantly ($p < 0.05$) among water regimes. The highest WUE was achieved under SDI at 70% ETc but was not significantly different from MTI 70%. MTI at 40% had the lowest WUE. At 100% ETc, MTI had 11.7% higher WUE than SDI though not significantly different ($p > 0.05$). With respect to SDI, DI improved WUE by 17.3% and 4.9% under 70% and 40%, respectively. In MTI, DI improved WUE by 4.1% at 70% ETc but decreased by 17% at 40% ETc. This shows that DI at 40% under MTI is not beneficial in grain yield in relation to water consumption.

Biomass WUE showed significant variations across the three water regimes ($p < 0.05$). However, the type of irrigation did not significantly affect the biomass WUE in all the water regimes except at 40% ETc SDI where it was the highest. DI significantly improved WUE by up to 45.8% and 21.2% under 40% ETc and 70% ETc respectively. Therefore, in areas of water scarcity, cowpea can best be grown for biomass rather than grain yield. The cowpea variety used in this study (mixed brown) favours vegetative growth thus gives more biomass than grain yield (Ilunga, 2014). The results of this study were consistent with those found by Maleki *et al.* (2017) where the grain WUE was the highest at 80% of full irrigation compared to 60% and 40%. Similarly, Mousa and Qurashi (2017) reported increased WUE under water deficit imposed at various growth stages except during combination of flowering and pod filling stage where it decreased marginally. However, Ahmed and Suliman (2010) reported decreased WUE due to water deficit which was attributed to reduced photosynthetic activity.

In a nutshell, there was no significant difference in growth and yield parameters, and WUE between MTI and SDI. Zhang *et al.* (2017e) found significantly lower summer maize yields in MTI than SDI. In the same study, the yield of winter wheat was higher under SDI than MTI but not significantly different. Further, the WUE were not significantly different between MTI and SDI in both maize and wheat. In another study, Zhang *et al.* (2016c), found that SDI marginally increased WUE of summer maize compared to MTI due to the former having a 2% higher average soil moisture content over the growing season. Therefore, the crop performance under MTI and SDI is not significantly different.

6.4 Conclusion

This study sought to determine the response of cowpea to varying water regimes under MTI. It was based on two hypotheses. The first hypothesis was that the new technology (MTI) was not different from SDI in terms of crop performance. Secondly, it was hypothesized that that WUE of cowpea could be improved by DI strategy. From the study findings, majority of the growth and yield components of cowpea were not significantly different in MTI and SDI particularly under full irrigation and moderate DI. However, MTI performed poorly under 40% ETc compared to 40% SDI, especially for LAI and biomass. For both types of irrigation, water deficit negatively affected LAI and yield components. Water deficit also hastened the time to 50% flowering. This was particularly significant under MTI where the time to 50% flowering were significantly shorter under DI. At moderate DI conditions SDI was better than MTI while under full irrigation, MTI performed better in terms of grain yield, although the differences were not significantly different between the two types of irrigation. Therefore, the response of cowpea to water regimes under MTI was largely the same as that of SDI. Yield reductions of less than 20% could be achieved with 70% ETc. Therefore, the hypothesis that cowpea response under MTI was not different from SDI could be partly accepted and partly rejected based on the growth and yield parameters.

The grain WUE was improved by water deficit under SDI but only at 70% ETc under MTI. Biomass WUE was significantly improved by water deficit under both SDI and MTI. Therefore, the hypothesis that DI improves WUE of cowpea was accepted for biomass. The mixed brown variety of cowpea used in this study is highly vegetative and thus suitable for biomass production rather than grain yield. Therefore, it is best suited as leafy vegetable and fodder for human and animal consumption, respectively. This implies that DI could be a successful agricultural water management strategy in water scarce regions.

The results reported in this study was for the experiment conducted in controlled facility (CEF) during summer since the crop planted during winter at Ukulinga failed to flower. It is worth noting that majority of the experiments reported in literature on crop response to MTI was conducted under greenhouse conditions. Therefore, further studies need to be done in actual field scenario to determine the crop response to water availability under MTI. This would help in drawing conclusion on whether crops respond favourable to field conditions under MTI.

The response of cowpea under varying water regimes was conducted using field experiments. However, this is costly and time consuming. This could have been achieved using a well calibrated and tested crop model. The parameterisation and testing of AquaCrop model for cowpea is discussed in Chapter 7.

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7. PARAMETERISATION AND TESTING OF AQUACROP MODEL FOR FULL AND DEFICIT IRRIGATED COWPEA (*Vigna unguiculata* (L.) Walp)

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This Chapter is under review in *Agricultural Water Management*

Abstract

Assessment of the response of crops to varying water regimes using crop models helps in optimizing water use and improving water productivity (WP) in agriculture. AquaCrop is water-driven model used for simulating crop responses to varying environmental conditions and farm management practices. AquaCrop has not been parameterised for cowpea. Therefore, the study aimed at parameterising and testing AquaCrop under full and deficit irrigation. The experiments consisted of subsurface drip irrigation (SDI) and Moistube irrigation (MTI) with three water regimes i.e. full irrigation [100% of crop water requirement (ETc)] and deficit irrigations of 70% ETc and 40% ETc. The model was parameterised and tested under MTI and SDI experiments, respectively. The parameterisation results indicated the model simulated the canopy cover (CC) very well with $R^2 \geq 0.96$, RMSE ≤ 9.8%, NRMSE ≤ 15.5%, EF ≥ 0.90, and $d \geq 0.98$ under 100% ETc and 70% ETc. However, it simulated less satisfactorily ($R^2 = 0.85$, RMSE = 24.5%, NRMSE =37.5%, EF = 0.45, and $d = 0.87$) during testing under 40% ETc. The simulated water content, during parameterisation and testing, closely matched the observed with $R^2 \geq 0.61$, RMSE ≤ 11.3 mm, NRMSE ≤ 17.8%, EF ≥ 0.51, and $d \geq 0.86$ indicating that the model reasonably captured the soil water dynamics. The yield and biomass were simulated satisfactorily by the model with NRMSE values less than 17.1% during parameterisation. The model was very good in simulating yield and biomass with NRMSE less than 10% during testing. The highest WP was achieved under 70% ETc and 40% ETc for yield and biomass, respectively. This implied that cowpea is suitable in areas experiencing water scarcity. The above results demonstrated the ability of AquaCrop in simulating the response of cowpea to varying water regimes. Therefore, the model can be used to evaluate the response of cowpea to a variety of environmental conditions and management scenarios.

Keywords: Crop modelling, Moistube irrigation, subsurface drip irrigation, water productivity, yield.

7.1 Introduction

Rainfall in South Africa is low and unevenly distributed with about 9% translating to useful runoff making the county one of the most water scarce countries in the world (Molobela and Sinha, 2011). This makes traditionally rainfed crops such as cowpea a risky enterprise. Irrigated agriculture being the largest consumer of the available water resources is under pressure from increasing population, urbanization and industrialization (Fereres and Soriano, 2007). Therefore, producing more yields per unit volume of water, i.e improving crop water productivity (WP) is important.

Some of the main techniques for improving WP include using efficient irrigation methods and adoption of water management strategies such as deficit irrigation (Ali and Talukder, 2008). Deficit irrigation helps in improving water productivity by ensuring that all the water are in the root zone for use by the crop (Fereres and Soriano, 2007) and by making the crop to extract more water in the soil reservoirs (Hsiao *et al.*, 2007) through compensatory root water uptake mechanisms. Micro-irrigation techniques such as sub-surface drip irrigation (SDI) improves water use efficiency (WUE) by minimizing the components of water use which are not required for crop transpiration like soil evaporation, surface runoff and percolation. Moistube irrigation (MTI) is one such efficient irrigation method as discussed in Chapter 2.

Assessing the WP and WUE in agriculture is achieved by examining water consumption of crops and their response to varying water regimes through field or laboratory tests which are, however, costly and labour intensive (Geerts and Raes, 2009). Therefore, there is need for the use of crop models. Crop models can be used in the assessment of crop response to varying environmental and management conditions. They can be used to assess the scenarios which can improve WP and WUE such as deficit irrigation strategies, conservation agricultural practices like mulching, organic fertilization, zero-tillage and minimum tillage. Crop models can be classified using various criteria. One such criterion is based on the crop growth module (how the model estimates biomass from the carbon dioxide, solar radiation and water captured by the plant). Using this criterion, crop models can be water-driven, carbon-driven and radiation-driven as described by Todorovic *et al.* (2009). AquaCrop is a water-driven model developed the United Nations' Food and Agriculture Organization (FAO) to simulate the response of crops to various environmental and management practices (Raes *et al.*, 2009;Steduto *et al.*, 2009).

AquaCrop has gained popularity because it is a simple model since it does not require technical modelling skills, robust enough as it represents all the key physiological processes and require few parameters in comparison to other crop models without compromising on accuracy (Vanuytrecht *et al.*, 2014). The model has been applied in major crops, however, few studies have been done on under-utilized crops. These include quinoa, teff, taro, bambara groundnut, sweet potato and amaranthus (Geerts *et al.*, 2009;Araya *et al.*, 2010;Karunaratne *et al.*, 2011;Walker *et al.*, 2012;Mabhaudhi *et al.*, 2014b;Mabhaudhi *et al.*, 2014a;Rankine *et al.*, 2015;Bello and Walker, 2017). This study, therefore aimed at parameterising and testing AquaCrop for cowpea which is one of the neglected and under-utilized African leafy vegetables and indigenous legumes. This was done using two efficient irrigation methods in MTI and SDI. This would also determine whether the WP of cowpea could be improved by using deficit irrigation strategy.

7.2 Methodology

The process of parameterisation and testing of AquaCrop model is described in this section by highlighting the model features, field experiments and data collection procedures.

7.2.1 Model description

The main unique features of AquaCrop include (Steduto *et al.*, 2009;Vanuytrecht *et al.*, 2014);

a) simulating foliage development in the form of canopy cover (CC) instead of LAI.
b) partitioning of the evapotranspiration (ET) into crop transpiration (Tr) and soil evaporation.
c) using a simple canopy growth and senescence model, treating final yield (Y) as a product of final biomass (B) and harvest index (HI) as shown in Equation 7.2, and
d) separating the effects of water stress into canopy growth, canopy senescence, Tr, and HI.

The calculation scheme in AquaCrop as illustrated in Figure 7.2 is described by Raes *et al.* (2009) as follows. Throughout the crop cycle, the quantity of water stored in the root zone is simulated by considering water inflow and outflow from the root zone. The root zone water depletion determines the level of the water stress coefficient which ultimately affects the HI. Above ground biomass accumulation is a function of transpiration using a conservative water productivity parameter as in Equation 7.1.

$$B = WP \times \sum Tr \quad (7.1)$$

$$Y = B \times HI \quad (7.2)$$

where B = above ground biomass (kg ha^{-1}), WP = water productivity (kg m^{-3}), Tr = crop transpiration (m^3 ha^{-1}), HI = harvest index, and Y = Yield (kg ha^{-1}). The full model description is found in Raes *et al.* (2009) and Steduto *et al.* (2012).

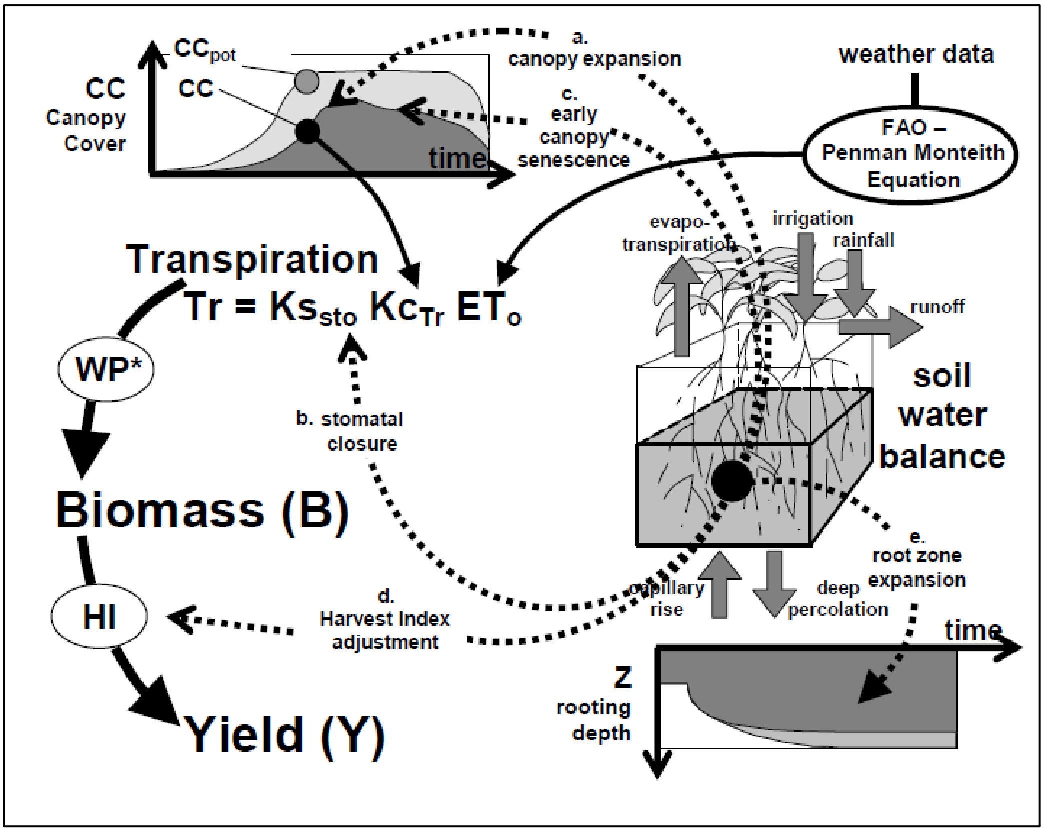

Figure 7.1 Calculation scheme in AquaCrop (Raes *et al.*, 2009)

7.2.2 Experimental design

The experimental design is as described in Chapter 6 where cowpea (mixed brown variety) was planted in a split-plot arranged in randomized complete block design involving MTI and SDI with 3 treatments of water applications (100% ETc, 70% ETc and 40% ETc) with 3 replications. The data obtained from MTI experiment was used to parameterise the model while SDI experiment was used for testing.

7.2.3 Data collection

The measurement of growth and yield parameters were done as explained in Chapter 6. The additional measurements required by AquaCrop model are explained in the following sections.

a) Crop growth parameters

Time to emergence in AquaCrop is the duration to which 90% of the seeds have emerged (Heng *et al.*, 2009). This is influenced by temperature and field preparation practices. Time to emergence was obtained by counting the number of plants that had emerged in each of the plots.

The LAI values obtained using LAI 2200 canopy analyser (LI-COR Inc. USA) described in Chapters 5 and 6 were used to compute CC using Equation 7.3 (Farahani *et al.*, 2009).

$$\mathrm{CC} = 100 \times [1 - (\exp\ (-\lambda \times \mathrm{LAI}))] \tag{7.3}$$

Where λ is the light extinction coefficient. The light extinction coefficient values for cowpea were obtained from Chimonyo *et al.* (2018) where the values varied depending on the stages of development, i.e. from 0.42 during initial to 0.62 in the grain filling stage.

The minimum root depth was obtained by measuring the seedling roots at 90% emergence. The root growth was restricted by the soil layer in the raised beds; therefore, the depth of the soil layer in the bed (0.6 m) was taken as the maximum root depth of cowpea.

b) Actual evapotranspiration

Actual evapotranspiration for cowpea over the growing period was computed using the water budget method shown in Equation 7.4 (Qin, 2015);

$$\mathrm{ET_a} = \mathrm{P} + \mathrm{I} + \mathrm{C} - \mathrm{D} - \mathrm{R} \pm\ \Delta S \tag{7.4}$$

where ET_a = actual evapotranspiration, P = rainfall, I = irrigation, C = capillary rise, R = surface runoff, D = drainage, and ΔS = change in soil water storage.

The experiments were carried out in a glasshouse and therefore, rainfall was zero. Also, capillary rise was assumed to be zero because of the raised beds. Drainage was computed from accumulating the water content above the field capacity in the soil layer. Subsurface irrigation eliminates the runoff component. Therefore, the ET_a was computed using a simplified Equation7.4 (Equation 7.5)

$$ET_a = I - D \pm \Delta S \qquad (7.5)$$

ETa ($m^3\ ha^{-1}$) was obtained by multiplying the value obtained in Equation 7.5 by 10 (Allen *et al.*, 1998).

c) Soil hydraulic properties

The soil texture was characterised as loam (42.3% sand, 33.3% silt, 24.4%) with bulk density of 1.36 g cm^{-3} with the hydraulic properties indicated in Table 7.1. The saturated hydraulic conductivity was measured using double ring infiltrometer. Field capacity, saturation and wilting point were estimated using retention data presented in Chapter 5 (Figure B.2).

Table 7.1 Soil hydraulic properties

Texture class	θ_{FC} ($cm^3\ cm^{-3}$)	θ_{WP} ($cm^3\ cm^{-3}$)	θ_{sat} ($cm^3\ cm^{-3}$)	*K_s (mm d^{-1})*	*TAW (mm)*
loam	0.315	0.160	0.458	186	155

N/B: θ_{FC} = water content at field capacity, θ_{PWP} = water content at wilting point, θ_{sat} = water content at saturation, K_s = saturated hydraulic conductivity, TAW = Total available water

d) Crop water productivity

The water productivity (WP) for grain yield and biomass was determined as the ratio of yield or biomass to actual evapotranspiration (Equations 7.6)

$$WP = \frac{\text{Grain yield or Biomass (kg ha}^{-1})}{ET_a(m^3\ ha^{-1})} \qquad (7.6)$$

7.2.4 Parameterisation of AquaCrop model

The model was parameterised using MTI data which was different from the SDI data used for testing. The procedure involved creating the following files in the model (Raes *et al.*, 2009);

a) Climate file was created consisting of ETo (computed from daily weather data), and daily minimum and maximum temperature which would induce either chilling, heat stress or optimum growth conditions.
b) Soil data file was created with the soil characteristics in Table 7.1.
c) Irrigation file was created using the irrigation events corresponding to 100% ETc (optimum water conditions) and deficit water conditions of 70% ETc and 40% ETc.

d) Initial conditions file which indicated the soil water content during planting (beginning of simulation period) was created. The average soil water content was obtained from the PR2/6 profile probe installed in the plots. Soil salinity was assumed to be zero.

e) Crop file was created as described in the following paragraphs.

There is no default cowpea in AquaCrop crop files, therefore a new grain and fruit (C4) crop was created. The model was parameterised for canopy, yield and biomass, and soil water content. The parameters adopted for cowpea are indicated in Table 7.2. These crop parameters were obtained by adjusting by trial and error some of the coefficients such as CGC, CDC, reference HI, water stress coefficients and normalized water productivity parameter (WP*) until the observed CC, biomass and yield closely matched the measured data.

Table 7.2 AquaCrop model parameters for cowpea

Parameter	Description	Value
Seedling size (cm^2)	Seedling leaf area (cm^2)	4.50
Planting density	Number of plants per hectare	66667
CC_o	Initial canopy cover at 90% emergence	0.3
Time to emergence (GDD)	Time to 90% emergence	88
Time to CCx (GDD)	Time taken to achieve maximum CC	787
Canopy senescence (GDD)	Time taken to canopy senescence	1101
Time to maturity (GDD)	Time to physiological maturity	1259
Canopy Expansion	The rate of canopy expansion	Very fast
Maximum canopy cover (%)	Consistent max canopy cover observed	90
Canopy Growth Coefficient (%day^{-1})	Units of fractional growth in CC per unit of time	16.2
Canopy Decline Coefficient (%day^{-1})	Units of fractional reduction in CC per unit of time	0.78
Length building up HI (GDD)	The time required for the Harvest Index (HI) to increase from 0 to its reference values (Hio).	288
Duration of flowering (GDD)	The number of days the crop was flowering	217
Time to flowering (GDD)	Time taken to 50% of the plants to form flowers	916
Time to maximum root depth (GDD)	Time taken for roots to reach maximum root depth	831
Minimum effective rooting depth (cm)	Root depth at 90% emergence	15
Maximum effective rooting depth (cm)	Reached, around the beginning of canopy senescence unless presence of impermeable layer	60*
Base temperature (°C)	Temp below which crop development does not progress	10
Upper temperature (°C)	Temp above which the crop development no longer increases	36
Reference Harvest Index (%)	The reference Harvest Index (HI0) is the ratio of the pod yield mass to the total aboveground biomass for non-stressed conditions	26
Water stress:		3
a) Canopy expansion Ks_{exp}	Depletion of TAW, $p_{(upper)}$	0
	$P_{(lower)}$	0.3
b) Stomata closure, Ks_{sto}	$p_{(upper)}$	0.6
c) Early canopy senescence, Ks_{sen}		0.4
	$p_{(upper)}$	
d) harvest index	Strong negative effect during flowering and due to stomata closure	
e) Shape factor	Represents the degree of response to water stress	3
WP*	WP normalized for ET_o and CO_2	15

* Limited by soil layer thickness

The seedling leaf area (4.5 cm^2) was measured destructively by sampling plants at 90% emergence. This value was used by the model to compute the initial canopy cover (CC_o). The value of CC_x obtained using Equation 7.3 and the time to reach CC_x (observed from the CC curve) was input into the model and thereafter the model determined the CGC. Time to senescence was read from the CC curve when the CC started to decline which was then input to the model for derivation of CDC. The time to flowering was defined as the time from planting to time when 50% of the plants had flowered and duration of flowering was date after 50% flowering to the date when 50% of the plants had formed pods (Brink, 1997).

The minimum root depth obtained by destructively sampling and determining the root length at 90% emergence, time to reach maximum root depth was assumed to be beginning of flowering, and the maximum root depth were entered as inputs. These were used by the model to derive the root expansion rate. The reference HI value was determined by using the value determined in Chapter 6 as the starting point and adjusting until the simulated yield closely matched the observed. A value of 26% gave good simulations of yield under optimum conditions and thus adopted as the reference HI. Default WP* of 15 g cm^{-2} was adopted for cowpea in this study. Karunaratne *et al.* (2011) used WP* of 12 g cm^{-2} for bambara groundnut.

The water stress parameters in Table 7.2 were adjusted manually to achieve the desired reduction in growth until the simulated CC reasonably matched the observed value. The base and maximum temperatures for growth of cowpea was obtained from Craufurd *et al.* (1997).

7.2.5 Model evaluation

The statistics used for evaluation of the model performance were coefficient of determination (R^2) and root mean square error (RMSE) as described in Chapter 4. The other statistical techniques used for assessing the model performance were normalized RMSE (NRMSE), Index of agreement (*d*), and model efficiency (EF) computed using Equations 7.7 to 7.9 (Yang *et al.*, 2014). These statistical indices are computed by the model automatically.

$$\mathrm{NRMSE} = \frac{\mathrm{RMSE}}{\bar{\mathrm{X}}} \tag{7.7}$$

$$d = 1 - \frac{\sum(\mathrm{Y_i} - \mathrm{X_i})^2}{\sum(|\mathrm{Y_i} - \bar{\mathrm{X}}| + |\mathrm{X_i} - \bar{\mathrm{Y}}|)^2} \tag{7.8}$$

$$\mathrm{EF} = 1 - \frac{\sum(\mathrm{Y_i} - \mathrm{X_i})^2}{\sum(\mathrm{X_i} - \bar{\mathrm{X}})^2} \tag{7.9}$$

where; Yi and Xi are simulated and observed values respectively, while $\bar{Y}$ and $\bar{X}$ are the mean of simulated and observed values, respectively.

The model performance was categorized as follows; very good when NRMSE ≤ 10%, good when 10% < NRMSE ≥ 15%, acceptable when 15% < NRMSE ≥ 20%, marginal when 20% < NRMSE ≥ 25%, and poor when NRMSE >25% (Stöckle *et al.*, 2004). EF ≥ 0 and *d* ≥ 0.75 are considered as the minimum values for crop models in simulating crop growth and yield outputs while EF ≥ 0 and *d* ≥ 0.75 while EF ≥ -1.0 and *d* ≥ 0.60 are the minimum acceptable values for soil water content (Yang *et al.*, 2014) .

7.3 Results and Discussion

This section is divided into two; parameterisation and testing. The model was parameterised and tested for canopy cover, yield and biomass, soil water content and water productivity.

7.3.1 Parameterisation

a) Canopy cover

The model was first parametrized for canopy cover (CC). The results are indicated in Figure 7.2. The model results were good ($R^2 \geq 0.96$, EF ≥ 0.86, RMSE ≤ 9.9%, NRMSE ≤ 19.6% and *d* ≥ 0.96) for all the water regimes. These results compared well with other studies reported in literature. For instance, a study by Karunaratne *et al.* (2011) found $R^2 = 0.88$ and RMSE = 14.75% for bambara groundnut. Similarly, Paredes and Torres (2017) found $R^2 \geq 0.91$ and RMSE ≤ 14.3 % for CC in vining pea.

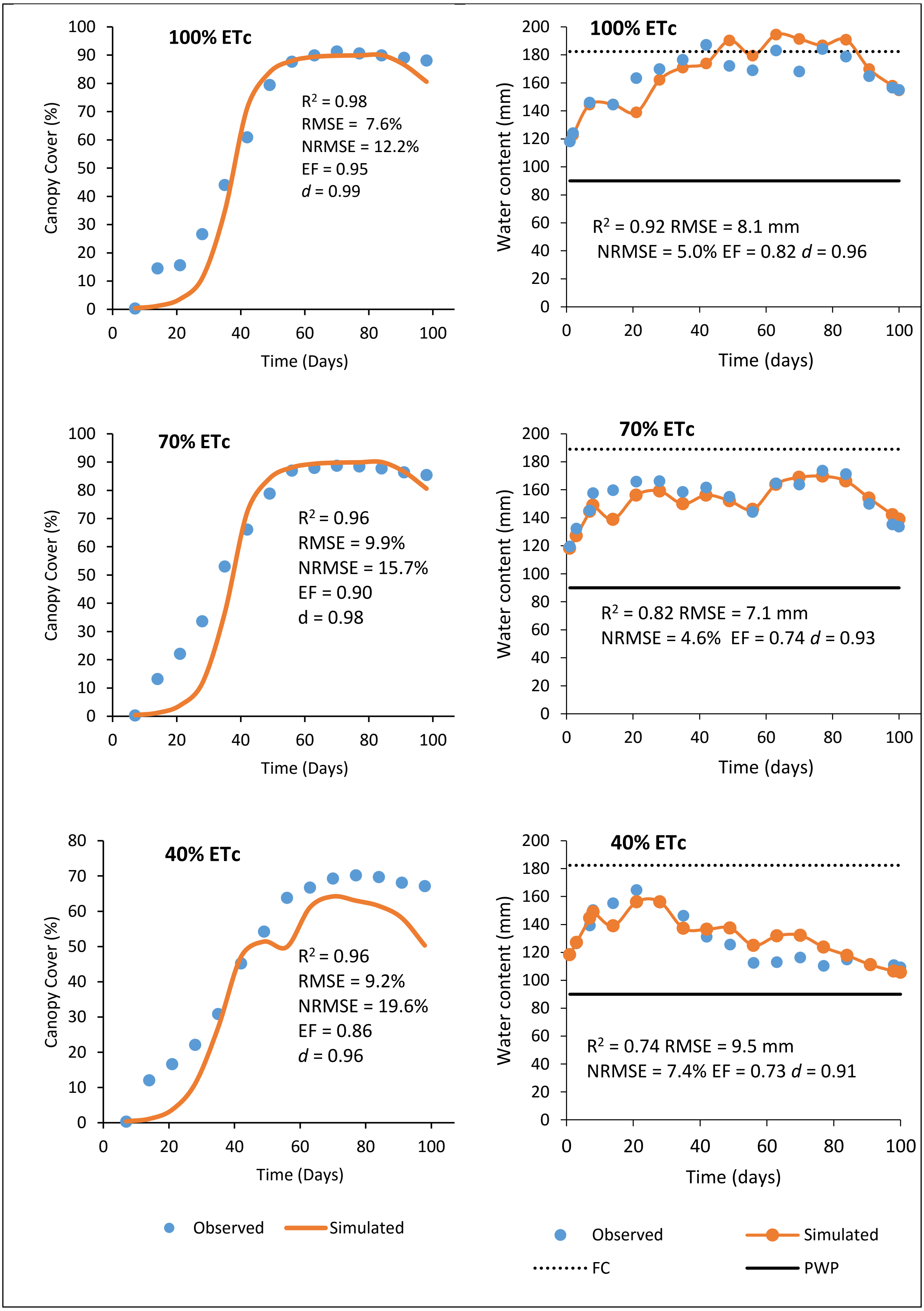

Figure 7.2 Canopy cover and soil water content for cowpea during parameterisation

b) Yield and final biomass

The observed and simulated yield and biomass are shown in Table 7.3. The model performance was good in simulating the yield (RMSE = 282.41 kg ha^{-1}, NRMSE = 12.33% and R^2 = 0.84) and reasonably in biomass (RMSE = 1307.48 kg ha^{-1}, NRMSE = 17.06% and R^2 = 0.88). The model under-estimated and over-estimated the yield under optimum and deficit water conditions, respectively. The simulated yield values matched closely the observed values at 100% ETc and 70% ETc with deviations (D) less than 16%. However, the model largely over-estimated (D ≈ 39%) the yield at 40% ETc. Nevertheless, the over-estimations were within the standard deviations of the observed data which implied that yield simulations were very good. Biomass simulations were satisfactory (D < 16%) under optimum water conditions. However, the model over-simulated biomass under water deficit conditions by up to 33%. Hadebe *et al.* (2017) reported high over-estimations (about 100%) of yield and biomass for sorghum especially during water deficit conditions. Similarly, Katerji *et al.* (2013) found deviations of up to 59% between simulated and observed biomass of maize under severe water deficit conditions The inability of AquaCrop to accurately simulate yield and biomass when water availability is low could be attributed to the possible errors in the determination of canopy senescence (Espadafor *et al.*, 2017).

Table 7.3 Observed yield and final biomass during parameterisation

Water Regime	Yield (kg ha^{-1})			Biomass (kg ha^{-1})		
	Observed	Simulated	D (%)	Observed	Simulated	D (%)
Moistube 100%	3189 (634)	2786	12.63	9272 (1247)	10715	-15.56
Moistube 70%	2401 (612)	2779	-15.55	8012 (1048)	10690	-33.42
Moistube 40%	1280 (598)	1783	-39.30	5701 (666)	7348	-28.89
RMSE (kg ha^{-1})	282.41			1307.48		

* Data in parenthesis are the standard deviations, D (Deviation) = [(Observed – Simulated) ÷ Observed] x 100

c) Soil water content

The accurate simulation of soil water balance is necessary as it drives the process of yield and biomass formation through the soil transpiration process (Vanuytrecht *et al.*, 2014) and it also influences the water stress functions in the model (Farahani *et al.*, 2009). The results for observed and simulated water content during the growing period are indicated in Figure 7.2. The water contents were satisfactorily simulated with $R^2 \geq 0.74$, RMSE ≤ 9.5 mm NRMSE ≤ 7.4%, $d \geq 0.91$ and EF ≥ 0.73.

d) Water productivity

Assessment of WP helps in the development of water management strategies aimed at addressing crop responses to climatic variables (Tsegay *et al.*, 2012). The observed and simulated WP for grain yield (WP_y) and biomass (WP_b) is shown in Table 7.4. The simulations for WP_y were very good with RMSE = 0.09 kg m^{-3}, NRMSE = 8.6% and R^2 = 0.96. Similarly, WP_b simulations were satisfactory with RMSE = 0.52 kg m^{-3}, NRMSE = 14.9% and R^2 = 0.58. Generally, the model the simulations for WP_y were good (D ≤ 9.3%) under optimum and 70% ETc conditions. However, the model over-estimated WP_y under 40% ETc.

Table 7.4 Crop water productivity for cowpea during parameterisation

Water Regime	WP_y (kg m^{-3})			WP_b (kg m^{-3})		
	Observed	Simulated	D (%)	Observed	Simulated	D (%)
Moistube 100%	1.08	1.18	-9.26	3.15	3.97	-26.03
Moistube 70%	1.14	1.19	-4.39	3.68	4.24	-15.22
Moistube 40%	0.81	1.01	-24.53	3.59	4.53	-26.18
RMSE (kg m^{-3})	0.09			0.52		

* Data in parenthesis are the standard deviations, D (Deviation) = [(Observed – simulated) ÷ observed] x 100

7.3.2 Model testing

After the model was satisfactorily parameterised, it was tested using the data obtained in the SDI experiments.

a) Canopy cover

The results of simulated CC are shown in Figure 7.3. The model performance was good under optimum and moderate water deficit conditions with R^2 ≥ 0.94, RMSE ≤ 10.5%, NRMSE ≤ 17.6%, *d* = 0.98 and EF ≥ 0.90). However, the model performance was less satisfactory (R^2 = 0.85, EF = 0.45, RMSE = 24.5%, NRMSE = 37.5% and *d* = 0.87) under 40% ETc. The model under-simulated the canopy growth under 40% ETc. In general, the model simulated rapid canopy decline rather than the gradually decreasing rate that was observed. Similarly, canopy expansion at initial stages of crop development was under-estimated by the model. In the present study the model simulated slow canopy expansion rate at initial stages than the observed values. Similar results were found by Paredes *et al.* (2015) for soybean. Similarly, the model tended to over-estimate the canopy decline which could be attributed to the indeterminate growth characteristic of cowpea with delayed canopy senescence due to water stress. Hadebe *et al.* (2017) found similar results where AquaCrop did not simulate satisfactorily the canopy decline of indeterminate sorghum genotypes. Mabhaudhi *et al.* (2014a) attributed the poor performance of AquaCrop in simulating canopy growth of taro under water deficit conditions to the model's inability to capture the steep canopy decline due to limited water availability.

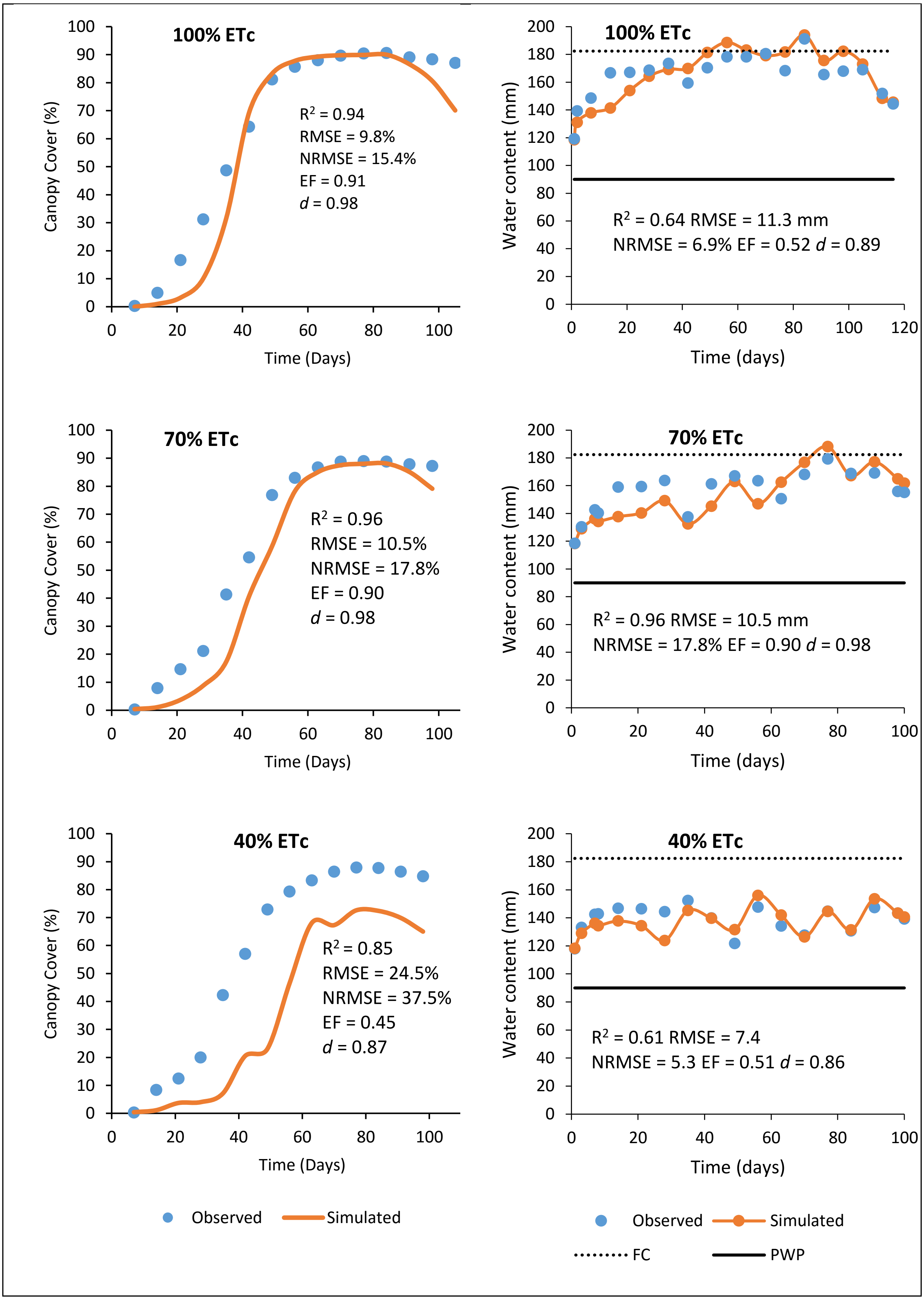

Figure 7.3 Canopy cover and soil water content of cowpea during model testing

b) Yield and final biomass

Reasonable simulation of canopy growth implies that the model can simulate final biomass and grain yield. The model performed better with the testing data than during parameterisation with deviations less than 5% under optimum and moderate water deficit conditions as shown in Table 7.5. However, the model over-estimated the yield under 40% ETc by 27.7% but it was, like in parameterisation, within the standard deviation of the observed data. The model reasonably (D ≤ 17.9%) simulated the biomass for all the water regimes. Generally, the model performed very well in simulating the yield (RMSE = 165.06 kg ha^{-1}, NRMSE = 6.9% and R^2 = 0.96) and biomass (RMSE = 798.48 kg ha^{-1}, NRMSE = 9.6% and R^2 = 0.99). These results compared favourably with those found by other researchers. In a study for bambara groundnut, Karunaratne *et al.* (2011) found R^2 = 0.78 and 0.72, and RMSE = 730 kg ha^{-1} and 360 kg ha^{-1} for biomass and yield, respectively. In South African bambara groundnut landraces, Mabhaudhi *et al.* (2014b) found RMSE of 290 kg ha^{-1} and 1700 kg ha^{-1} in simulation of yields and biomass, respectively. In soybean production, Paredes *et al.* (2015) found RMSE of about 300 kg ha^{-1} and 1050 kg ha^{-1} for yield and biomass simulations, respectively. Similarly, Paredes and Torres (2017) reported deviations ≤ 10.5% and 36% for yield and biomass, respectively, in pea. Espadafor *et al.* (2017) reported RMSE ≤ 280 kg ha^{-1} in simulating yield of dry beans.

The above results demonstrate the reliability of AquaCrop in the simulation of yields and biomass of crops including the under-utilized and neglected ones such as cowpea. Therefore, the model can be utilized in the assessment of response of cowpea to a variety of water availability scenarios.

Table 7.5 Observed and simulated yield and biomass during model testing

Water Regime	Yield (kg ha^{-1})			Biomass (kg ha^{-1})		
	Observed	Simulated	D (%)	Observed	Simulated	D (%)
Drip 100%	3025 (695)	2967	1.92	9678 (1098)	11411	-17.91
Drip 70%	2605 (701)	2489	4.45	8590 (1339)	9574	-11.46
Drip 40%	1505 (462)	1922	-27.71	6694 (1263)	7395	-10.47
RMSE (kg ha^{-1})	165.06			798.48		

* Data in parenthesis are the standard deviations, D (Deviation) = [(Observed – Simulated) ÷ Observed] x 100

c) Soil water content

The water contents reasonably matched ($R^2 \geq 0.61$, RMSE ≤ 11.3 mm, NRMSE ≤ 17.8%, $d \geq 0.86$ and EF ≥ 0.51) the observed values as indicated in Figure 7.3. EF values were greater than 0.5 which indicated reasonable model efficiencies for crop models as suggested by Yang *et al.* (2014). The model performance in simulating the soil water content in the present study were consistent with those reported by other researchers. Andarzian *et al.* (2011) reported average RMSE value of 18.5 mm in simulating the soil water content of wheat under optimum and deficit water conditions. Tsegay *et al.* (2012) reported RMSE values of between 14.42 and 18.27 mm in the simulation of soil water content for tef. Zhang *et al.* (2013a) found RMSE of between 5.7 and 22.6 mm in soil water content simulations in winter wheat. Similarly, Saab *et al.* (2014) found RSME ≤ 12.91 mm and ≤ 14.96 mm when simulating soil water content in soybean and sunflower productions, respectively, under varying irrigation amount regimes. Therefore, AquaCrop can simulate soil water dynamics with reasonable accuracy.

d) Water productivity

The observed and simulated WP for grain yield (WP_y) and biomass (WP_b) are indicated in Table 7.6. The model satisfactorily simulated WP_y with RMSE = 0.12 kg m^{-3}, NRMSE = 11.4% and R^2 = 0.99. The simulations for WP_b closely match (RMSE = 0.09, NRMSE = 2.6% and R^2 = 0.87) the observed values. However, just like during parameterisation, the model over-estimated WP_y by 26%. The model performance in the simulation of WP_b was very good with over-estimation or under-estimation of less than 5%. The under-estimation or over-estimation could be attributed to accumulation of errors in the simulation of canopy, yield, biomass, and soil water content. The results obtained in this study were consistent with other studies in literature. Kumar *et al.* (2014) found similar results for wheat subjected to saline water where the simulations were relatively poor (deviations up to 37%) under severe salt stress for non-tolerant varieties. Salemi *et al.* (2011), found better simulations of WP of winter wheat where the deviations were less than 2%.

Table 7.6 Crop water productivity for cowpea during model testing

Water Regime	WPy (kg m^{-3})			WPb (kg m^{-3})		
	Observed	Simulated	D (%)	Observed	Simulated	D (%)
Drip 100%	1.06	1.21	-14.15	3.39	3.26	3.83
Drip 70%	1.10	1.20	-9.09	3.67	3.85	-4.90
Drip 40%	0.98	1.24	-26.53	4.35	4.22	2.76
RMSE (kg m^{-3})	0.12			0.09		

* Data in parenthesis are the standard deviations, D (Deviation) = [(Observed – Simulated) ÷ Observed] x 100.

Being a first attempt at developing the crop parameters for cowpea, the data sets were not enough to allow for satisfactory determination of WP*. More experiments under a variety of climatic conditions are required to fully ascertain the reliable value of WP* for cowpea. Therefore, the value of 15 g cm^{-2} and other parameters indicated in Table 7.2 could be used as a reference point for future research

It was observed, like during parameterisation, that higher WP_y was obtained under moderate deficit condition. The highest WP_b values were obtained under 40% ETc followed by 70% ETc. This demonstrates that deficit irrigation can be considered as water management strategy in agriculture especially in arid and semi-arid lands. Cowpea variety used in this study is vegetative and therefore it can best be utilized as a leafy vegetable (where the fresh leaves are consumed) or as livestock fodder since it has higher WP_b.

7.4 Conclusion

The AquaCrop model was parameterised and tested for cowpea under full and deficit irrigation. The model was parameterised for canopy development, soil water content, yield, biomass, and water productivity using Moistube irrigation data. The parameters obtained were then used to test the model using data obtained from drip experiments. The model satisfactorily simulated canopy cover although it slightly under-estimated the initial canopy expansion for all treatments and the canopy decline during deficit irrigation treatments. This could be attributed to the indeterminate growth characteristic of cowpea where it delays senescence due to deficient water availability. The simulations for soil water content closely matched the observed values with low RMSE values. The model reasonably simulated the yield and biomass of cowpea under optimum water conditions but over-estimated under severe water deficit conditions particularly during model testing. The deviations fall reasonably close to the standard deviations of the observed data. This is the first attempt at evaluating the suitability of AquaCrop in simulating the response of cowpea (an under-utilized and neglected crop) to water availability under full and deficit water availability conditions. The results obtained in this study shows that AquaCrop can be used with reasonable accuracy, considering few data requirements and model simplicity, in the simulation of responses of cowpea to varying water regimes. Further experiments need to be carried out to fine tune the parameters developed in this study to cover other environmental conditions.

Crop models such as AquaCrop may exhibit some limitations when simulating the soil water dynamics since they adopt the tipping bucket approach in simulating the soil water flow in the vadose zone. These crop models simulate the soil water dynamics in one-dimensional whereas water flow from irrigation is a multi-dimensional problem. Therefore, it may be feasible to couple them with hydrological models which use different approach, like the Richards' Equation, in the simulation of the soil water dynamics. Chapter 8 explores the possibility of using a combination of AquaCrop and HYDRUS 2D models in the simulation of water use in cowpea.

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8. COUPLING HYDRUS 2D/3D AND AQUACROP MODELS FOR SIMULATION OF WATER USE IN COWPEA (*Vigna unguiculata* (L.) Walp)

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Abstract

Simulation of the soil water balance requires reliable representation of the main hydrological processes such as infiltration, drainage, evapotranspiration and run off. In a cropping system, the determination of the soil water balance is necessary to facilitate decisions regarding water management practices such as irrigation scheduling. This may require the coupling of hydrological and crop models. This study sought to determine the water use of cowpea under irrigated conditions in different environments of South Africa. The study considered two irrigation types, subsurface drip irrigation (SDI) and Moistube irrigation (MTI) and two environments characterized by clay and sandy soils. The study was accomplished using a hydrological model (HYDRUS 2D/3D) and AquaCrop which is a crop model. The crop characteristics were obtained using AquaCrop while HYDRUS 2D/3D was used to generate optimum irrigation schedules and the soil water balance. Thereafter, the water use and yield of cowpea was determined. The average grain yield and biomass was 2600 kg ha^{-1} and 10000 kg ha^{-1}, respectively, with the difference between the two sites being less than 5% under both SDI and MTI. The water use and water use efficiency (WUE) varied from 315 mm to 360 mm and 0.67 to 1.02 kg m^{-3}, respectively, under the two irrigation types in the two sites considered. The WUE was higher under SDI than MTI, but the differences were less than 10%. This showed that response of cowpea under MTI was not different from SDI.

Keywords: Agro-hydrological model, irrigation scheduling, soil water balance, water use efficiency

8.1 Introduction

Yield and biomass production are complex processes which rely significantly on the interaction between the soil, crop and atmosphere, and are influenced by human activities (Vereecken *et al.*, 2016). Agricultural water management practices such as irrigation scheduling require the analysis of the soil water balance to ensure that appropriate amount of water is applied to the crop. Simulation of the soil water balance needs the accurate representation of the infiltration process, runoff, drainage, root water uptake and evapotranspiration (Ritchie, 1998). Soil water balance models utilize either a simple tipping bucket approach where the only input data required include rainfall/irrigation, evapotranspiration and soil properties or those which describe soil water dynamics in a complex and rigorous way including the interactions of the various components of the system (Zhang *et al.*, 2002). In crop models, the soil water balance serves to estimate the soil water content (driver for nutrient mineralization, and gaseous exchange) and the water stress indices which drives the functioning of the plant (Brisson *et al.*, 2006)

Most hydrological models that are used in agriculture focus primarily on the soil physical processes and simplify the processes of transpiration, root water uptake and crop growth while crop models, on the other hand, include detailed crop development processes but are inadequate in describing the root zone processes (Vereecken *et al.*, 2016). Complex crop and hydrological models require detailed or many input parameters which may not be available or are expensive to collect. They also have complicated procedures which require users to have enough knowledge and skills in modelling. On the other hand, simple and user-friendly models often have limitations due to simplification of processes.

The main reason for coupling crop and hydrological models is to help in the understanding of the complex processes which cannot be represented by a single model due to their spatial and temporal dynamics. Most crop models are point scale models and therefore do not consider spatial heterogeneity. Being point-scale models, simulation of water distribution in one dimensional (vertical) and does not represent actual field scenario which comprises heterogeneous soils and slopes among other aspects. Simple models consider only some processes of the hydrological cycle and thus simplify others depending on the intended purpose of the model. Thus, two or more simple models are linked to provide a relatively accurate representation of the processes considered in the system than when individual models are used.

Coupled hydrological and crop models have been used in the simulation of various agricultural water management practices. For instance, Li *et al.* (2012) coupled WOFOST and HYDRUS 1D for modelling irrigated maize production. Soil water balance, soil water content and the groundwater depth were computed by HYDRUS 1D while carbon assimilation and partitioning were computed by WOFOST. The crop height, rooting depth and LAI computed by WOFOST were then used as inputs in HYDRUS 1D model. Akhtar *et al.* (2013) combined HYDRUS 1D and AquaCrop in the optimization of irrigation schedules for cotton. Due to the deficiency of AquaCrop in simulating capillary rise, HYDRUS 1D was used to simulate the capillary rise. AquaCrop was then used to develop optimum irrigation schedules considering the contribution by groundwater in the form of capillary rise. Finally, Shelia *et al.* (2018) coupled DSSAT and HYDRUS 1D in the simulation of the soil water balance for peanut and soybean under rainfed systems.

The popularity of HYDRUS 1D in coupling with crop models could be attributed to its use of Richards' Equation (RE) in simulating the soil water dynamics. Models that use RE perform satisfactorily in simulating soil water dynamics than those which rely on simple bucket or cascade approach. For example, Gandolfi *et al.* (2006) compared one-dimensional models that use the two approaches and found that the models that use Richard's Equation satisfactorily captured the soil water distribution better while the conceptual models using cascade approach performed poorly, especially in heavy soils.

HYDRUS 2D/3D has been applied successfully in simulating the soil water dynamics under irrigated agriculture as described in Chapters 2, 4 and 5. Similarly, AquaCrop has been applied in the simulating responses to varying environmental conditions and management practices as described in Chapter 7 and also in a review by Vanuytrecht *et al.* (2014). The popularity of these two models makes them prime candidates for agro-hydrological simulations. However, no study has been done using a combination (coupling) of HYDRUS2D and any crop model including AquaCrop. This study, therefore sought to evaluate the water use of cowpea under Moistube irrigation (MTI) under two agro-ecological zones of South Africa using a loose coupling of HYDRUS 2D and AquaCrop models.

8.2 Methodology

The description of the experimental sites and the modelling approach, development of optimum irrigation schedules and assumptions used in the study are described in this section.

8.2.1 Experimental sites

The experimental sites identified for the simulations were Ukulinga and Wartburg which belonged to 2 agro-ecological zones. The weather data for Ukulinga (2000 – 2017) was obtained from the automatic weather station situated within the Ukulinga Research Farm while for Wartburg (2015 – 2018), it was obtained from South African Sugar Research Institute (SASRI) weather web portal (https://sasri.sasa.org.za/weatherweb). The sites were chosen based on the availability of data. The descriptions of the sites are presented in Table 8.1.

Table 8.1 Description of sites

Site	Ukulinga Research Farm	Wartburg Fountain-Hill
Co-ordinates	29^{o} 40'3'' S, 30^{o}, 24'22'' E	29°27'2" S, 30°32'42" E
Altitude (m.a.s.l)	811	853
Average annual rainfall (mm)	694 [a]	750
Average temperature	25 [a]	20 [a]
Average maximum temperature	26 [a]	29 [a]
Average min temperatures	10 [a]	17 [a]
Soil type	Clay [a]	Sandy [a]
Bio-resource group	Moist Coast Hinterland [a]	Moist Midland [a]

[a] Chibarabada *et al.* (2017).

8.2.2 Modelling

The study was accomplished using light or loose coupling where the output from the first model formed the input of the second model. The two models had been calibrated and tested satisfactorily in Chapter 5 (HYDRUS 2D/3D) and Chapter 7 in the case of AquaCrop.

The modelling approach was as follows

a) AquaCrop model was used to simulate root distribution, rooting depth, partitioned potential evapotranspiration and initial irrigation schedules

b) HYDRUS 2D /3D was used to compute the soil water contents, soil water distribution, actual evapotranspiration in the form of transpiration and evaporation and the optimized irrigation schedules
c) AquaCrop was used to simulate the yield of cowpea using the optimized irrigation schedules
d) Water productivity was computed from simulated yield and actual evapotranspiration

The modelling framework is shown in Figure 8.1

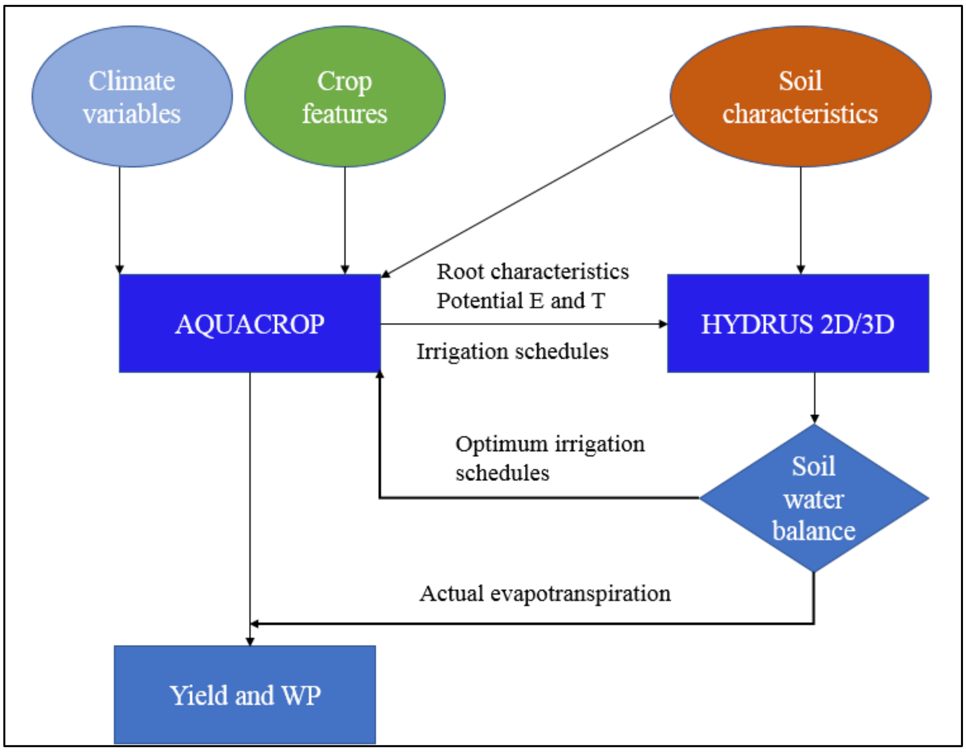

Figure 8.1 Modelling framework

The descriptions of HYDRUS 2D/3D and AquaCrop models have been provided in the preceding chapters. The boundary conditions (BC) and transport domain in HYDRUS 2D/3D were the same as in Chapter 5 except for the atmospheric and the variable flux BC which were adjusted based on the climate data and irrigation schedules for the experimental sites.

The crop data generated from AquaCrop was obtained under optimum conditions to ensure that the canopy development was not hindered by water stress. AquaCrop uses canopy development in partitioning ET to E and Tr and therefore, full canopy development is necessary so that reliable values are transferred to HYDRUS 2D/3D. The optimum water conditions were obtained by adopting the irrigation scheduling options available in the model. AquaCrop uses depth and time criteria in generating irrigation schedules. In time criterion, irrigation is applied when a certain fraction of the total available water (TAW) is depleted while a fixed amount of water is applied under the depth criterion (Geerts *et al.*, 2010). In this study, an allowable depletion of 20% and 30% of TAW for Wartburg and Ukulinga, respectively, were used and the soil water content restored to field capacity.

8.2.3 Development of optimum irrigation schedules

The optimum irrigation schedules were obtained using the triggered irrigation boundary conditions in HYDRUS 2D/3D at an observation node as described in Dabach *et al.* (2013). When the soil tension falls below the specified threshold, an irrigation is initiated (Müller *et al.*, 2016). In the present study, the observation node triggering irrigation was placed at 10 cm away from the Moistube or drip emitter. The aim is to have maximum possible root water uptake, i.e. when the irrigation amount is the same as the potential root water uptake (Dabach *et al.*, 2013). In this study, the thresholds were varied from -10 cm to -300 cm until the ratio of irrigation amount and potential root water uptake was unity. The growth stages derived by the AquaCrop model were split into two stages; the first 30 days which represented the initial growth stages and the remaining 70 days representing development to crop maturity stages.

8.2.4 Assumptions

The simulated scenarios for the two sites were based on the following assumptions

a) The planting date was in the month of October as recommended by the Department of Agriculture (DAFF, 2014). Therefore, a planting date of 15th October was used.
b) Rainfall was not considered and therefore cowpea was grown under irrigation.
c) The plant density of 66667 plants ha^{-1} was used. This corresponds to a plant spacing of 50 cm inter-row and 30 cm within row.
d) The drip and Moistube laterals were placed beneath each row.
e) The initial moisture content was at field capacity.

8.3 Results and Discussion

The irrigation thresholds and schedules, soil water balance, simulated grain yields and biomass and finally water productivity are featured in this section.

8.3.1 Irrigation thresholds and scheduling

The optimum thresholds obtained were higher (> - 200 cm) under SDI but lower (< -50 cm) under MTI. For instance, as shown in Figure 8.2, at Ukulinga, the threshold when the ratio of irrigation amount to potential transpiration was unity was at -15 cm while that for SDI was slightly above -200 cm. The low thresholds for MTI was due to the low flowrates which necessitated frequent water applications.

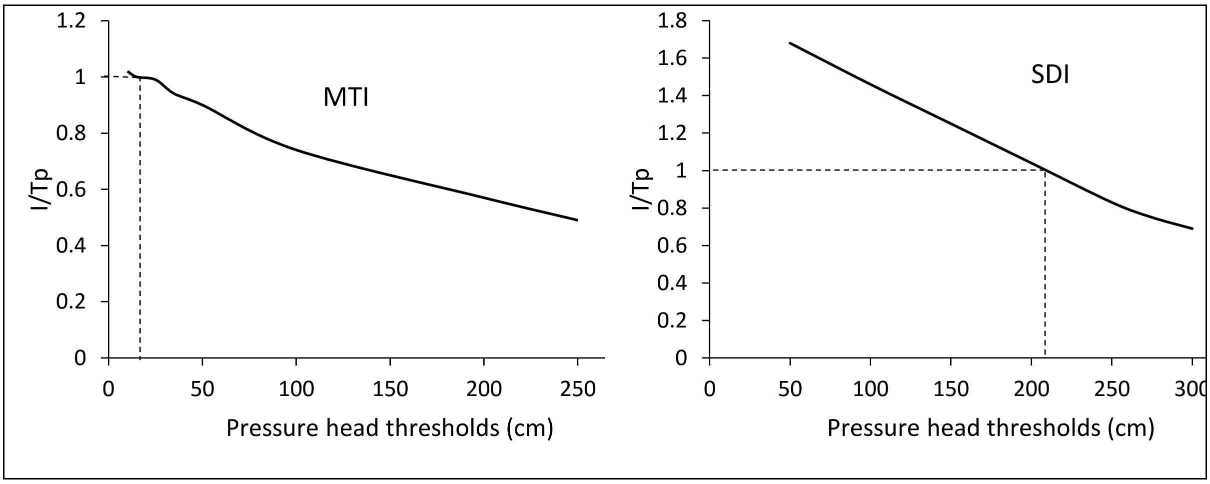

Figure 8.2 Irrigation thresholds under MTI and SDI

The optimized irrigation for MTI in Ukulinga was 7 mm at an interval of 2 days which led to a total irrigation of 336 mm. Under SDI, the irrigation consisted of two applications of 20 mm at 7 and 22 days after planting for the initial stage (first 30 days) and thereafter 25 mm after 7 days giving total of 315 mm in a season. The irrigation interval in Wartburg under MTI was 5 mm every 2 days after emergence to the 30^{th} day after planting and thereafter 9 mm every 2 days. The irrigation schedule for SDI, on the other hand, was 10 mm after every 4 days from day 6 to day 30 and thereafter 30 mm every 6 days. The last 10 days under SDI was not irrigated while under MTI 5 mm it was applied at the same rate as the initial growth stage. These accumulated to 360 mm and 355 mm under SDI and MTI, respectively.

MTI is designed as a continuous irrigation where the water is applied every day for the rest of the cropping season (Zhang *et al.*, 2015a;Sun *et al.*, 2018). However, from the results above, the optimized irrigation can be achieved by irrigating at an interval of 2 days. Similar results were found by Wei *et al.* (2014) where MTI with an irrigation interval of 2 days produced the same tomato yield as conventional MTI, but with 12% lower water use and 29% higher WUE. In another study, Yin *et al.* (2017), reported about 20% of water savings when spinach was grown under alternating irrigation interval than the conventional MTI. Therefore, in some circumstances, the crop water requirement can be met under intermittent than conventional MTI. This could be necessary especially for crops which are tolerant to limited water availability.

8.3.2 Soil water balance

The soil water balance components simulated by HYDRUS 2D/3D are illustrated in Table 8.2. The actual evapotranspiration (ETa) were higher in Wartburg than in Ukulinga. The ETa values under MTI were higher than SDI for both sides. Drainage was lower in Ukulinga possibly due to the low hydraulic conductivity of clay soil. The drainage component was about 30% lower in Wartburg under MTI than SDI. However, MTI had a marginally lower drainage in Ukulinga than SDI.

Table 8.2 Soil water balance under SDI and MTI as simulated by HYDRUS 2D/3D

Component	Ukulinga		Wartburg	
	MTI	SDI	MTI	SDI
Actual evapotranspiration (mm)	285.9	260.4	334.2	332.9
Irrigation (mm)	336	315.0	355	360
Drainage (mm)	12.6	15.1	20.8	30.3
Evaporation (mm)	46.1	47.9	82.0	77.8

8.3.3 Grain yield and biomass

The AquaCrop simulated grain yield and biomass using the optimized irrigation schedules in Ukulinga were 2662 kg ha^{-1} and 10238 kg ha^{-1}, respectively, under MTI. Similarly, under SDI the yield and biomass were 2660 kg ha^{-1} and 10232 kg ha^{-1}, respectively. This shows that under the optimum conditions, cowpea respond the same under SDI and MTI. These simulated yields were consistent with those found by Ilunga (2014) for the same cowpea variety (mixed brown) planted late August in 2013 at Ukulinga under irrigation where the observed yields were 2760 kg ha^{-1}. The deviations between the simulated and the observed in this case was 3.6%. This shows that the schedule developed in this study were satisfactory. Therefore, HYDRUS 2D/3D can be used in the development of optimum irrigation schedules and AquaCrop model used for yield estimation.

The simulated grain yield and biomass in Wartburg under MTI were 2590 kg ha^{-1} and 9993 kg ha^{-1}, respectively. Similarly, under SDI, the yield and biomass were 2625 kg ha^{-1} biomass 10097 kg ha^{-1}, respectively. There are no observed data on cowpea yields under irrigation in Wartburg. However, Chibarabada *et al.* (2017) reported cowpea yield of 1214 kg ha^{-1} under rainfed system. This indicates that irrigation could be used to improve (double) the yields of cowpea. The results of the two sites indicate that cowpea yield of about 2600 kg ha^{-1} and biomass of 10000 kg ha^{-1} could be obtained under irrigation. The yields between the two sites were not, as expected, different since non-limiting production conditions were assumed. The results could have been different under different constraints such as fertility, salinity and water deficit conditions.

8.3.4 Water productivity

The water productivity (WP) values computed from the simulated yield and ETa in Ukulinga were 0.93 kg m^{-3} and 1.02 kg m^{-3} under MTI and SDI, respectively. In Wartburg, the WUE were 0.77 and 0.79 under MTI and SDI respectively. SDI had higher WP than MTI, especially at Ukulinga. From the WP perspective, it could be said that crops which are tolerant to limited water availability perform relatively better under SDI than MTI and vice versa. This may explain the relatively higher WP of tomato, sunflower and onion under MTI than drip irrigation (Xue *et al.*, 2013b;Tian *et al.*, 2016;Guo *et al.*, 2017).

8.4 Conclusion

This study aimed at exploring the possibility of utilizing two widely applied models to predict the water use and yield of irrigated cowpea under two environments with different climate and soil characteristics. HYDRUS 2D/3D, being suited for simulating soil water dynamics, was used to generate optimized irrigation schedules and simulation of the actual evapotranspiration. AquaCrop, a prominent crop model, was used to develop the crop characteristics and the simulation of the crop yields under the two environments. This was to draw into the strengths of the individual models by using the output of one model as input in the other. This type of model linking avoided the need for programming which could not be done in this study due to limited resources.

From the simulations, the yields and biomass of cowpea were more or less the same, but SDI performed better than SDI in WP especially in Ukulinga. The results obtained indicated were close to the observed yields in Ukulinga. The water use varied from 315 to 360 mm indicating an average of 3.42 mm per day in a determinate cowpea variety maturing after 100 days. MTI could be used as intermittent irrigation, though designed as continuous irrigation, especially in crops which are tolerant to limited water availability.

The irrigation scheduling developed in this study could not be verified further with field experiments due to financial and time constraints. Further, there was no independent data on yields and biomass of cowpea under irrigated conditions, except at Ukulinga, since it is grown mostly under rainfed systems and being a neglected and under-utilized species. Therefore, more field experiments need to be conducted to validate the irrigation schedules developed and to determine the response of cowpea under irrigated conditions, particularly MTI in other environments. This should also include crop stress parameters such as deficient water and fertility, and salinity conditions.

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9. CONCLUSIONS AND RECOMMENDATIONS

9.1 Conclusions

Design, operation and management of irrigation systems require the knowledge of the soil water dynamics. The soil water dynamics in subsurface irrigation depends on, among other factors, soil type, system characteristics, depth of lateral placement and root water uptake. There is lack of clarity on some of the design aspects of MTI regarding the pressure-discharge relationship, the effect of dissolved and suspended solids on the Moistube discharge and the soil water dynamics under different soils and crop characteristics. There is scarcity of information on how various crops respond to water availability under MTI. Therefore, this study addressed the above issues as described in the following paragraphs.

The hydraulic characteristics (in terms of the pressure vs discharge relationship) and the effect of suspended and dissolved solids were studied. The results indicated that the discharge from Moistube followed a power or linear function with respect to the applied pressure. The study also established that Moistube discharge decreased with time when water containing suspended or dissolved solids was used which indicated clogging of the nano-pores. Suspended solids had a significant effect on the clogging characteristics than dissolved solids. The clogging characteristics under suspended and dissolved solids in MTI were consistent with results reported in literature for SDI. The hypothesis that Moistube discharge has a positive relationship with applied pressure and negative relationship with dissolved and suspended solids concentration was confirmed.

The effect of soil texture on the soil water dynamics under MTI was done experimentally and numerically using HYDRUS 2D/3D model. The model was calibrated for sandy clay loam and loamy sand. It was established that soil texture had significant effect on the soil water movement under MTI with downward movement being faster in loamy sand than sandy clay loam. Therefore, the hypothesis that soil texture influences the soil water dynamics under MTI was accepted. It was also found that Moistube discharge had significant effect on the soil water dynamics. Moistube discharge of between 0.2 *l* ℓ $hr^{-1}m^{-1}$ and 0.4 ℓ $hr^{-1}m^{-1}$ was found suitable when the placement depth was 20 cm for the two soil types considered.

The soil water dynamics while incorporating the root water uptake of cowpea was investigated using field experiments and numerically with HYDRUS 2D/3D. In these experiments, SDI was the control. The root water uptake between the two types of irrigation were not significantly different which implied that none induced water stress on the crop. The drainage losses were higher under SDI than MTI in loam soil (CEF experiment). The drainage losses were insignificant in clay soil (Ukulinga experiment) under both SDI and MTI. The suitable placement depth of Moistube laterals were found to be 15 cm and 20 cm in loam and clay soil respectively.

The response of cowpea, a neglected but important legume, to water availability under MTI was determined. It was established that there were no significant differences in grain yield and biomass between SDI and MTI for all the water regimes (100% ETc, 70% ETc and 40% ETc) considered. However, the time to flowering was significantly delayed under SDI at 100% ETc than MTI. The leaf area index was significantly lower under MTI at 40% ETc. Therefore, SDI performed better than MTI under deficit water conditions. Hence the hypothesis that the response of cowpea to water availability under MTI was like that of SDI was partly true. The irrigation water productivity was highest under both MTI and SDI at 70% ETc but lowest under Moistube at 40% ETc. This illustrated the improvement of water productivity under moderate water deficit conditions. Irrigation water productivity for biomass was highest under 40% ETc which indicated favourable conditions biomass production. The mixed brown variety used in this study is highly vegetative and therefore suitable as leafy vegetable (consumption of leaves) in human or animal fodder.

AquaCrop model was successfully parameterised and validated for full and deficit irrigated cowpea. MTI and SDI were used for calibration (parameterisation) and validation respectively. The model satisfactorily simulated canopy cover, water content, yield and biomass. The model tended to under-simulate the canopy expansion and canopy decline which could be attributed to the indeterminate growth characteristic of cowpea. The model over-simulated the grain yield and biomass under water deficit conditions. Generally, the under or over-simulations were within the standard deviations of the observed grain yield and biomass. This indicated that AquaCrop model can be used satisfactorily in assessing the response of cowpea to varying water regimes.

The simulation of the yield response of cowpea to optimum water conditions under MTI was simulated using a symbiotic combination of HYDRUS 2D/3D and AquaCrop models. The simulations were done for two agro-ecological zones in KwaZulu -Natal province with clay soil (Ukulinga) and sandy soils in Wartburg. It was established that MTI can best be designed as intermittent irrigation where water is applied every 2 days instead of the conventional one where water is supplied continuously. The simulated yield at Ukulinga were close to the observed yields reported in literature. This indicates that AquaCrop and HYDRUS 2D/3D could be used together for optimum irrigation water management. The yield and biomass for the two sites were similar indicating that irrigation can be used to stabilize production in in agriculture.

9.2 Recommendations

The following recommendations can be drawn from the findings of this study.

a) The effect of suspended and dissolved solids on the discharge characteristics of Moistube was carried out for 14 days. Further research is needed for a longer duration or for a typical growing period.
b) The movement of solutes need to be investigated. This could be done in conjunction with fertigation
c) The optimum placement depth of Moistube laterals need to be verified in the field to determine its effect on crop response.
d) The AquaCrop crop parameters developed in this study were obtained with data obtained under controlled environment. Therefore, further fine-tuning should be done under field conditions and other environmental and management scenarios such as soil fertility.
e) The mechanism of coupling AquaCrop and HYDRUS 2D/3D adopted in this study was simple input – output model. There is need to modify the coupling mechanism in such a way that the common processes are ‘read’ in one interface. In addition, the irrigation schedules developed were only verified for one site due to insufficient data. Therefore, these schedules or the modelling framework need to be implemented in the field, besides exploring the possibility of deficit irrigation scheduling.

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11. APPENDICES

11.1 Appendix A: Calibration of Sensors

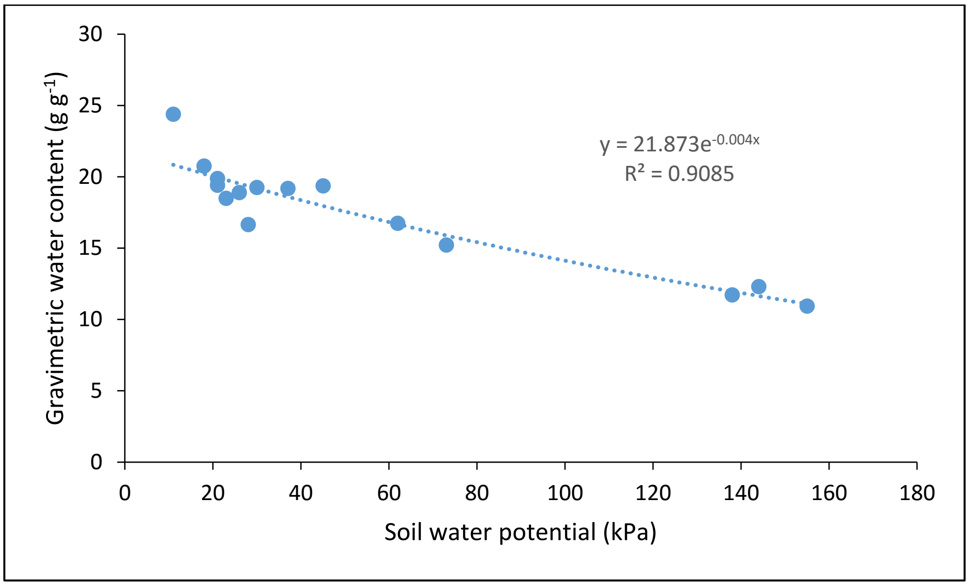

Figure A.1 Calibration for Water Mark Sensors

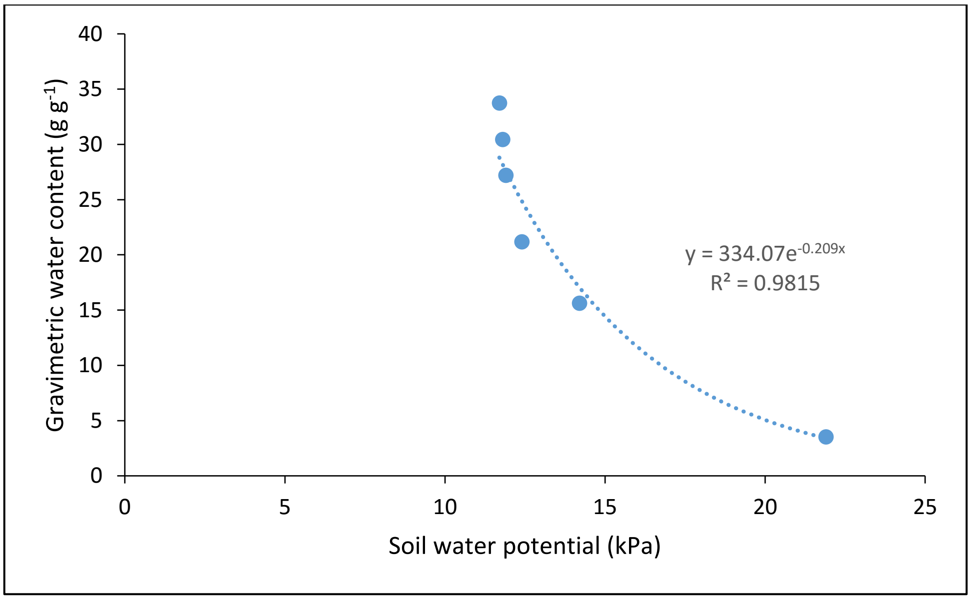

Figure A.2 Calibration for MPS2-2 sensors

11.2 Appendix B: Soil Water Retention Characteristics

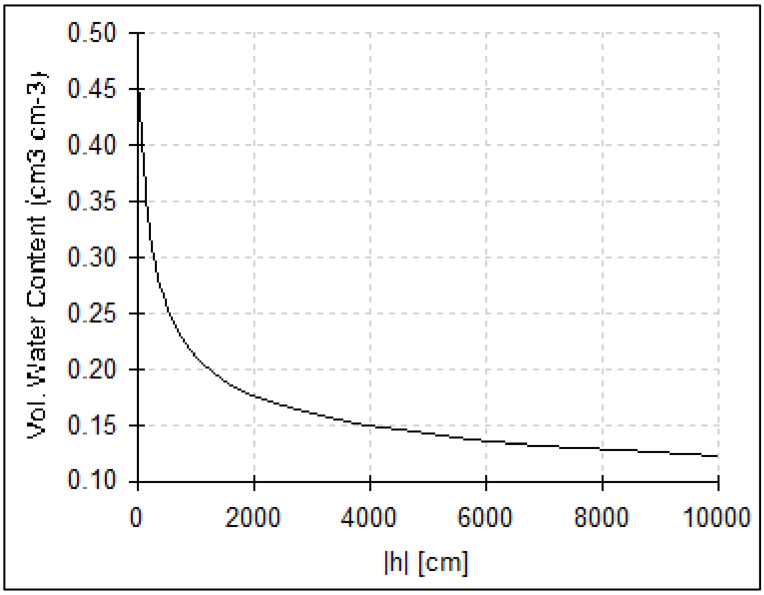

Figure B.1 Soil water retention characteristics curve for loam soil