SOIL WATER DYNAMICS AND YIELD RESPONSE OF CANOLA UNDER MOISTUBE IRRIGATION TECHNOLOGY

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PREFACE

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ABSTRACT

Rainfall is becoming increasingly erratic particularly in dry areas due to climate change. Therefore, irrigation is necessary to ensure food security. Irrigation consumes large quantities of water and thus, the adoption of efficient irrigation methods is required. Subsurface drip irrigation (SDI) is an efficient irrigation system. However, water losses due to deep percolation, especially in sandy soils, is a problem. Moistube Irrigation (MTI) is a new subsurface irrigation technology which supplies water at a rate consistent with the rate of plant water uptake. This review presents the literature on SDI and MTI. The literature also describes canola production and the application of simulation models in agricultural water management. In tomato production, MTI achieved higher yields and water use efficiency than SDI. Clogging of Moistube laterals due to suspended solids have been reported. Canola in South Africa is mainly rainfed. Expanding canola production through irrigation is necessary to reduce over-reliance on imported vegetable oils. The prediction of yields and water use efficiency in agriculture is important especially in water-scarce countries like South Africa. Agro-hydrological models are useful in the assessment of management and environmental scenarios in agriculture. AquaCrop model is reliable in predicting yields for a variety of crops while HYDRUS model is good in the simulation of soil water distribution under irrigation. There is limited information on MTI with respect to discharge – pressure relationship, soil water distribution for different soils, clogging performance, and its ability to satisfy the water requirements of crops under different climatic conditions. The proposal presented in this document aims at assessing the soil water dynamics in MTI and its suitability for the growth of canola. This will be achieved through field trials, laboratory experiments, and simulation models.

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LIST OF ABBREVIATIONS

ANOVA	Analysis of Variance
APSIM	Agricultural Production Systems Simulator
B	Biomass
CC	Canopy Cover
CERES	Crop Environment Resource Synthesis
CROPGRO	Crop Growth
CropSyst	Cropping System simulation
CSM	Cropping System Model
d	Willmot Index of Agreement
DAFF	Department of Agriculture, Forestry and Fisheries
DSSAT	Decision Support System for Agrotechnology Transfer
E	Soil Evaporation
EF	Nash-Sutcliffe model efficiency coefficient
EPIC	Erosion Productivity Impact Calculator
ET	Evapotranspiration
FAO	Food and Agricultural Organization
GDD	Growing Degree Days
HI	Harvest Index
LAI	Leaf Area Index
MAE	Mean Absolute Error
MTI	Moistube Irrigation
R^2	Coefficient of determination
RE	Richards' Equation
RMSE	Root Mean Square Error
RUE	Radiation Use Efficiency
RWQM	Root Water Quality Model
SDI	Subsurface Drip Irrigation
STICS	Simulator Multidisciplinary for Crop
SWMS-2D	Simulating Water Movement and Solute transport in Two-Dimensional
Tr	Transpiration
VS2D	Variably Saturated Two-Dimensional

WOFOST	World Food Studies
WP	Water Productivity
WP*	Normalized Water Productivity
WUE	Water Use Efficiency
Y	Yield

1. INTRODUCTION

Agriculture which is the backbone of most African economies is facing uncertainties due to climate variability. Irrigation is one way of ensuring food security in case of unreliable rainfall. However, water for irrigation is facing competition from domestic and industrial sectors and thus optimizing irrigation water is of primary importance. This can be achieved through the use of efficient irrigation systems.

Moistube Irrigation (MTI), as described by Envirogrower (2016), is a new subsurface irrigation technology which supplies water at a rate consistent with the rate of plant water uptake. Therefore, it can minimize water losses due to evaporation and percolation. It uses nanotechnology where water oozes from semi-permeable membranes of the Moistube laterals to the surrounding soils. The technology, unlike drip irrigation, does not use emitters but the nanopores in the laterals allow water to flow out depending on the operating pressure and the soil water potential. This enables a continuous supply of water to the crop throughout the crop cycle, thereby, preventing crop water stress during the critical stages of crop growth.

Understanding the soil water dynamics is necessary for the design of subsurface irrigation systems (Kandelous *et al.*, 2011). The wetting pattern, which influence the spacing and depth of laterals in SDI or MTI can be determined through field measurements or by use of simulation models but the former is costly and time-consuming (Phogat *et al.*, 2012). Simulation models are less costly and, once calibrated, can be applied to a range of soil and water regimes. HYDRUS 2D/3D simulates soil water distribution for different soils and crop situations (Kandelous *et al.*, 2011).

Among the oilseed crops produced in the world, canola *(Brassica napus)* is the second largest in terms of tonnage behind soybean (Raymer, 2002). It is a genetically improved rapeseed oil with low levels of erucic acid and glucosinolate. Canola is used in the production of vegetable oil and also as a biodiesel feedstock alongside other edible oils from soybean, corn, rapeseed, palm (Koçar and Civaş, 2013), linseed, mustard, coconut and sunflower (Sims *et al.*, 2006). It has an oil content of about 40%, which is high compared to other vegetable oils such as soybean and palm both with 20% (Gui *et al.*, 2008) and sunflower with 30% (DAFF, 2011).

The demand for vegetable oils and some animal feed supplements in South Africa exceeds the production and thus, some are imported to satisfy the surplus demand (DAFF, 2011). Therefore, expanding the growing of canola beyond the Western Cape to other parts of the county through irrigation will help reduce the importation of these vegetable oils. Since irrigation consumes large quantities of water, it is prudent to produce a greater yield per unit volume of water used.

Simulation models that determine yield response to water availability are useful in optimizing water use efficiency through the improvement of crop management and production techniques (Salemi *et al.*, 2011). AquaCrop is a simple water-driven crop model that requires few input parameters but it is accurate and robust enough to simulate yield response to water for a variety of crops (Raes *et al.*, 2009; Steduto *et al.*, 2009). The model has been parameterized and tested for crops like cotton (Farahani *et al.*, 2009), maize (Heng *et al.*, 2009), quinoa (Geerts *et al.*, 2010), barley (Araya *et al.*, 2010a), teff (Araya *et al.*, 2010b), canola (Zeleke *et al.*, 2011), Bambara groundnut (Karunaratne *et al.*, 2011; Mabhaudhi *et al.*, 2014b), wheat (Salemi *et al.*, 2011), and taro (Mabhaudhi *et al.*, 2014a) among others.

There is a scarcity of information on the soil water dynamics for different soils in MTI. Also, there is limited information on the clogging resistance of Moistube laterals. The information on the pressure-discharge relationship of MTI is scanty. Finally, the performance of MTI on crops, other than tomatoes, under different climatic conditions has not been studied.

This literature review entails past studies on SDI and MTI. The main focus is on the application of simulation models to predict the soil water dynamics in subsurface irrigation and also the prediction of yield response of canola to water availability under varying climatic conditions.

This document consists of six chapters. Chapter 2 gives the literature on SDI, an overview of MTI and the application of models in predicting the soil water distribution. Canola distribution, its water requirements and growth under irrigation and various crop water productivity models are described in Chapter 3. Chapter 4 covers discussions and conclusions of the literature review. Chapter 5 gives the research proposal on soil water dynamics and evaluation of yield response of canola to water availability under MTI. The proposal includes the problem statement, objectives, methodology, expected results, budget, and work plan. Reference is provided in Chapter 6.

2. MOISTUBE AND SUBSURFACE DRIP IRRIGATION

2.1 Introduction to Subsurface Irrigation

Rainfall, as a primary source of water for agricultural production, is becoming increasingly erratic due to climate change. Therefore, when there is an absence of rainfall, farmers supplement it with irrigation to ensure reliable yields and thus ensure food security. However, according to Suseela (2012), improper irrigation may waste large quantities of water, nutrients and impair the productivity of the soil. Therefore, it is necessary to adopt appropriate irrigation methods which supply the optimum quantity of water to the crop.

Water losses due to evaporation and surface runoff are minimized through the use of subsurface irrigation. 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 (Camp, 1998) and semi-permeable membranes utilized in MTI (Zhang *et al.*, 2012; Envirogrower, 2016).

2.2 Subsurface Drip Irrigation

Subsurface drip Irrigation (SDI) is a type of drip irrigation where the drip laterals are placed below the soil surface. (Camp, 1998). The general depth of SDI lateral is more than 5 cm below the soil surface (Lamm *et al.*, 2012). SDI can be a point source or a line source. Line source drip irrigation system supply water along the length of the lateral where the emissions are closely spaced or the water application patterns overlap (Naglič, 2014). In point source emitters the emission points are wider apart compared to line sources, with a general spacing of between 0.76 m and 1 m apart or according to wider plant spacing arrangement (Ayars *et al.*, 2007).

2.2.1 Lateral spacing and depth

The depth of the lateral placement , the emitter spacing, and the system pressure are important in delivering the required amount of water to the crop (Elmaloglou and Diamantopoulos, 2009). The major factors that affect the drip line spacing include the soil type, installation depth, crop type, and the reliability and amount of rainfall during the growing season (Lamm and Trooien, 2003). The depth of lateral placement depends on soil characteristics, crop type, tilling depth, and whether the SDI is used for crop establishment or another irrigation method is used until the crop is established (Charlesworth and Muirhead, 2003).The lateral should be installed in sufficient depth to prevent damage by farm machinery but shallow enough to ensure that the root zone of the crop receives adequate water while maintaining a dry soil surface (Camp and Lamm, 2003).

2.2.2 Pressure – discharge relationship

The flow from a drip emitter is a function of the operating pressure as described by Equation 2.1 (Keller and Karmeli, 1974)

$$q = kh^{x} \qquad (2.1)$$

Where q = emitter discharge [l h^{-1}], k = emitter constant, h = operating pressure [m], and x= emitter discharge exponent. The exponent x indicates the characteristics of the emitter flow regime 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. Pressure compensating emitters have exponent values very close to 0 and the non-compensating ones have values very close to 1 (Clark *et al.*, 2007).

In SDI, unlike surface drip irrigation, the soil properties affect emitter flow rate. In a saturated region, a positive pressure develops at the emitter outlet decreasing the hydraulic gradient and consequently reducing the discharge rate from the emitter as illustrated in Equation 2 (Gil *et al.*, 2008).

$$q = k\left(h - h_{s}\right)^{x} \qquad (2.2)$$

Where h_s = positive pressure [m] and q, h, k and x are as explained in Equation 2.1

The amount of decrease in emitter discharge depends on the soil hydraulic characteristics, the emitter nominal flow rate, presence or absence of cavities around the emitter outlet and the irrigation system properties (Shani *et al.*, 1996). The reduction in discharge rate from the emitter due to soil properties affects the water application uniformity (Shaviv and Sinai, 2004).

2.2.3 Emitter clogging

Clogging of the emitters is one of the main challenges in SDI (Payero *et al.*, 2005). The clogging of the emitter depends on the quality of the irrigation water. 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).

According to Payero *et al.* (2005), the following measures can be used to prevent or minimize emitter clogging. Clogging by soil particles is prevented by filtration. Chemical precipitates as a result of higher pH of the water can be prevented by injecting acid into the irrigation water. Algae and bacteria are prevented or eliminated by dosing the irrigation water with chlorine. Any small particles which pass through the filtration system are removed by periodically flushing them out from the system.

2.2.4 Advantages of subsurface drip irrigation

Some of the merits of SDI over other types of irrigation include higher water application efficiency due to wetting of a small fraction of the soil volume and minimal evaporation losses, lower energy costs because of low operating pressures, ability for utilization of wastewater since the drip lines are underground (Payero *et al.*, 2005), potential for improved yields and precise application of fertilizers (Camp, 1998). Other advantages include reduced growth of weeds due to the dry soil surface and flexibility in design and operation (Camp and Lamm, 2003).

2.2.5 Disadvantages of subsurface drip irrigation

Besides clogging of emitters discussed in section 2.2.3, some of the other disadvantages of SDI include smaller wetting pattern especially in light-textured soils which results in a smaller root zone, unseen water applications making monitoring and evaluation of irrigation difficult, reduced upward water movement, restricted root development, inflexibility in row spacing and crop rotations, high initial investment cost, and skilled labour requirements for operation and maintenance (Lamm, 2002).

Crop establishment which relies on the upward movement of water to the seed or seedling is a challenge in SDI (Charlesworth and Muirhead, 2003). Camp and Lamm (2003), suggested that if crop establishment is important and initial soil moisture is not adequate, then other surface irrigation methods can be used until the crop is established. Salt accumulation is another problem especially in areas of inadequate rainfall (Thompson *et al.*, 2009). SDI systems do not have a mechanism for leaching of accumulated salts and so this is accomplished using another surface irrigation method if rainfall is not sufficient (Hoffman and Shannon, 2007)

In soils with high permeability, gravity forces are dominant over capillary forces and therefore, leaching of nutrients and water occur quickly before plant uptake (Cote *et al.*, 2003) . Water leaching in sandy soils could possibly be minimized by scheduling multiple irrigation events per day instead of a single irrigation event (Dukes and Scholberg, 2005).

2.3 Moistube Irrigation

Moistube irrigation (MTI) is a new subsurface irrigation technology that utilizes the nanotechnology where a polymeric semi-permeable membrane allows movement of water by osmosis. The surface of the inner membrane simulates the properties of the plant tissue and thus it supplies water at a rate consistent with the rate of plant water uptake. The outer layer of the Moistube is a protective permeable polymeric material. The semi-permeable inner layer has approximately 100,000 nanopores per square centimetre with pore diameter range of 10-900 nm (Envirogrower, 2016).

MTI has a small flow of about 0.2 l hr^{-1} m^{-1} length which adjusts automatically according to the change in soil water potential (Zhang *et al.*, 2012). This means that the system has auto-regulative capability similar to buried clay pots and subsurface clay porous pipes (Bainbridge, 2001; Ashrafi *et al.*, 2002). Qiu *et al.* (2015), found that the flow from Moistube varies with pressure where at 1m head, the flow was 0.14 l hr^{-1} and 0.24 l hr^{-1} at 2 m head which shows 71% difference in flow between the two pressures. This means that the discharge is sensitive to pressure variation. Therefore, it can be inferred that the pressure-discharge relationship of MTI follows closely that of non-compensating drip emitters (Equation 2.1). MTI flow approximates that of line SDI with pores instead of closely spaced emitters (Zhang, 2013).

2.3.1 Advantages of Moistube irrigation

In addition to the water saving characteristics of SDI such as reduced soil evaporation and high water use Efficiency (WUE), MTI requires lower energy requirements (Zhang, 2015). A comparison between MTI and SDI for tomatoes in a greenhouse in China showed that MTI had more or same yield per unit area but 20% higher WUE (Xue *et al.*, 2013a). Another study by Zhang *et al.* (2012), found that irrigation uniformity of MTI is high at about 96%. Average uniformity coefficient values for SDI laterals range from 81% (Camp *et al.*, 1997) and 92% Safi *et al.* (2007).

Water loss due to downward leaching is lower in MTI than SDI especially in highly permeable soils. 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. The downward movement of water in MTI was 10% and 17% higher than upward movement in clay loam and sandy soils respectively (Zhang *et al.*, 2012). However, Zhang *et al.* (2015a), found that the downward and upward movement of water under MTI and SDI were equal at initial stages but while it was still symmetrical for MTI after 15 hours of irrigation, in SDI it became asymmetrical with the upward movement being less than the downward movement.

2.3.2 Clogging of Moistube laterals

Just like SDI where the emitters are prone to clogging, the nanopores in the Moistube lateral can be filled with particles leading to a reduction in discharge. Clogging of the Moistube was observed when water containing silt was used which led to a reduction in the outflow from the Moistube (Xie *et al.*, 2014) . This was corroborated by studies on the effect of sediment concentration on the clogging performance of Moistube where it was found that it was prone to clogging when the particle size was less than 0.1 mm (Qi, 2013) and between 0.061 mm and 0.1 mm (Zhu *et al.*, 2015).

2.4 Soil Water Dynamics in SDI and MTI

Understanding the soil water distribution is important for the design and optimization of irrigation systems (Elmaloglou and Diamantopoulos, 2009; Kandelous *et al.*, 2011). The soil water dynamics in SDI depend on factors such as soil type, initial soil moisture content, emitter flow rate, the rate of water application, crop type, evapotranspiration (Subbaiah, 2013), spacing, and depth of laterals (Kandelous and Šimůnek, 2010). In MTI it is influenced by the soil type (Zhang *et al.*, 2012), hydraulic head (Xue *et al.*, 2013b), initial soil moisture content (Zhang *et al.*, 2014), the depth of placement (Zhang *et al.*, 2015b), and the quality of irrigation water (Niu and Xue, 2014).

The soil water distribution in subsurface irrigation can be determined by field experiments or by simulation using analytical, empirical or numerical models (Subbaiah, 2013; Zhang *et al.*, 2015a). However, carrying out field measurements using a 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).

2.4.1 Soil water dynamics modelling

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). Point source SDI requires the use of the 3D form of the RE as illustrated in Equation 2.3 (Šimunek *et al.*, 2007) while line source SDI require the 2D form as illustrated in Equation 2.4 (Skaggs *et al.*, 2004). Similarly, MTI can be approximated as a line source SDI (Zhang *et al.*, 2015a).

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x_i}\left[K(h)\left(K_{ij}^{A}\frac{\partial h}{\partial x_j} + K_{iz}^{A}\right)\right] - S(h) \qquad (2.3)$$

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left[K(h)\frac{\partial h}{\partial x}\right] + \frac{\partial}{\partial z}\left[K(h)\frac{\partial h}{\partial z} + K(h)\right] \qquad (2.4)$$

Where θ = volumetric water content [L^3L^{-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 [$L^3L^{-3}T^{-1}$] which accounts for uptake of water by the roots, t = time [T], x_i = spatial coordinate [L], x = horizontal space coordinate [L], and z = vertical space coordinate.

The non-linearity of the partial differential Equations 2.3 and 2.4 makes it difficult to solve using analytical models (Cote *et al.*, 2003). This has increased the popularity of empirical and numerical models. Empirical models are derived from field observations or laboratory experiments using several methods such as regression methods, dimensional analysis and some Artificial Intelligence methods like Artificial Neural Network techniques (Subbaiah, 2013). Numerical models use finite difference, finite element, or some other kinds of boundary approximation techniques (Öztekin, 2002), finite volumes and reformulating the partial differential equations (Naglič, 2014). Numerical models are more flexible and do not require the RE to be linearized (Subbaiah, 2013).

Due to the popularity and applicability of numerical models, the following section describes some of the numerical models that have been used in simulating water dynamics in line source SDI and MTI.

2.4.2 Numerical models

Some of the numerical models that have been applied in drip irrigation include the Variably Saturated 2-D (VS2D) model (Lappala *et al.*, 1987), Simulating Water Movement and Solute transport in Two-dimensional (SWMS-2D) model (Simunek *et al.*, 1994) and HYDRUS 2D/3D model (Šimůnek *et al.*, 2006).

Ashrafi *et al.* (2002), applied VS2D model to simulate the wetting pattern of a porous clay pipe. It was validated by laboratory experiments and was found to have good agreement with observed values with modelling efficiency range of 0.75 and 0.98. The results showed that for a given soil texture, the wetting pattern depends on the depth of lateral placement and the amount of water applied. It was also found that soil hydraulic conductivity influence the soil water distribution.

A numerical model describing the water flow in SDI while taking into account the root water uptake was developed by Elmaloglou and Diamantopoulos (2009). The model solves the RE by finite difference method. Graphical visualization of the water distribution showed that the mathematical model was as good as HYDRUS 2D model. From the study, it was concluded that the soil water movement is influenced by the soil hydraulic characteristics and deep percolation was higher in light-textured soil than in heavy-textured soil.

2.4.3 HYDRUS 2D/3D model

HYDRUS 2D/3D is a model used for the simulation of water movement and solute in 2D/3D variably-saturated porous media (Šimůnek *et al.*, 2006). It uses the Galerkin finite-element method to solve the RE (Kandelous and Šimůnek, 2010). 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). Some of the applications of HYDRUS 2D/3D in line sources SDI are described in the following paragraphs.

Siyal and Skaggs (2009), investigated the soil water distribution in porous clay pipe sub-surface irrigation operating at different water pressures using HYDRUS 2D/3D. It was found that HYDRUS model matched the observed data well ($R^2 = 0.98$) in simulating the wetting pattern. The model was also used to simulate the effect of soil texture and depth of lateral placement on the soil water distribution. The operating pressure was found to exhibit a positive relationship with the wetted volume. It was also found that the installation depth affected the lateral spacing since a shallower installation depth allows water to reach the surface where horizontal movement is accelerated, thereby depicting an inverse relationship where shallower depths require larger spacing. Soil texture was found to greatly affect the shape of the wetting geometry due to its connection to soil hydraulic conductivity and water holding capacity. A greater lateral movement was witnessed in fine-textured soils which can be attributed to the effect of capillary forces which dominate gravity forces, unlike coarse-textured soils where gravity forces are predominant.

Field and numerical experiments were conducted by Kandelous *et al.* (2011) to determine the soil water distributions between two closely-spaced emitters using HYDRUS 3D. The study was aimed at validating HYDRUS 3D for modelling soil water movement using several field experiments with different installation depths and irrigation scenarios. The findings indicated that the more the overlap of wetting pattern, the less successful it was for 2D to describe the full three-dimensional subsurface irrigation processes. They concluded that in the cases where the wetting patterns overlap, 3D geometry provides reliable simulations of soil water distributions while 2D axis-symmetrical and line-source geometry can be used only before the merging of the wetting patterns and after full overlap respectively.

3. CANOLA CROP

3.1 Description and Distribution

The oilseed genus *Brassica* is a crop group belonging to the cruciferous family (Johnston *et al.*, 2002). They are among the ancient plants to be cultivated with the most of world's supply of oil being supplied by two species of *Brassica napus* L. and *B. rapa* L (Raymer, 2002). The term "canola" is a registered trademark of the Canadian Canola Association and refers to cultivars of oilseed rape that produce seed oils with less than 2% erucic acid (Raymer, 2002).

The historical account of oilseed rape as described by Przybylski and Mag (2002) is as follows. The *Brassica* genus was first produced in India some four thousand years ago but it was produced in large scale in Europe in the thirteenth century. It is believed that the oilseed rape shares the same common ancestry with wild mustard (*Sinapsis*), radish (*Raphanus*) and arrugala (*Eruca*). Due to their higher concentrations of euric acids and glucosinolates, these early varieties were considered to have the potential of causing health problems. The current canola species types include *Brassica rapa*, found in western Canada, *B. napus*, grown in Europe, Canada, and China, *B. juncea*, mostly in India, China, and Australia, and *B. carinata* found in Ethiopia (Booth and Gunstone, 2004).

Among the oilseed crops produced in the world, canola is second largest in tonnage after soybean (Raymer, 2002; Booth and Gunstone, 2004) and third vegetable oil crop after soybean and palm (Booth and Gunstone, 2004). Apart from it being used as a vegetable oil, canola can also serve as biodiesel feedstock like other available oilseed crops such as soybean, corn, sunflower, castor oil, olive, coconut and palm among others (Sims *et al.*, 2006; Koçar and Civaş, 2013). It has a higher oil content than other vegetable oils such as soybean and palm (Gui *et al.*, 2008).

In South Africa, canola was introduced in the early 1990s and thus it is relatively new when compared to other oil crops like the sunflower. The majority of the canola cultivars that are being cultivated in the Western Cape belong to the species *Brassica napus.* It is mainly grown in Western and Southern Cape as a winter crop while in the other regions, it is produced through irrigation in the summer (DAFF, 2010). Table 3.1 indicates area under canola production in South Africa (DAFF, 2014).

Table 3.1: Area under canola production (DAFF, 2014)

Year	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Area (10^3 ha)	4.6	40.2	32	33. 2	38.1	38.1	34.8	44	44	72
Quantity (10^3 ton)	32	44.2	36.5	38.2	30.8	40.4	36.9	59	80	112

3.2 Canola Water Requirements and Irrigation

Water requirements for oilseed crops closely follow the canopy formation and evaporation conditions (Aiken and Lamm, 2006). During the first stages of growth, canola demands little water and water requirement increases with vegetative and root growth until flowering (peak water use period) and decreases as the crop ripens (Tesfamariam, 2004). Canola requires a minimum of 300 mm of rainfall ,which generally occurs between April and October in canola growing zone in South Africa, in order to realize a yield of 2000 kg ha^{-1} (DAFF, 2010), otherwise, it has to be supplemented with irrigation. Canola extracts water from the soil up to a depth of 165 cm although, 92 – 95% of the total water extraction on the soil surface above a depth of 119 cm (Nielsen, 1997) and the maximum extraction is at a depth of 45 cm (Zeleke *et al.*, 2014).

3.2.1 Effect of water stress on canola growth and yield

Water stress and high temperature during critical growth stages negatively affect biomass and yield production of canola. Water stresses during flowering and seed filling stages affect the formation of seeds and therefore lower the harvest index (HI) which consequently lead to yield reduction (Johnston *et al.*, 2002).

Water stress of rapeseed during reproductive stages leads to reductions in yield and other components associated with yield such as oil content (Ahmadi and Bahrani, 2009; Khalili *et al.*, 2012). In South Africa, Tesfamariam *et al.* (2010), found that canola was utmost sensitive to water stress during the flowering stage. In this study, water stress during seed filling stage reduced the crop maturity by 127 Growing Degree Days (GDD) while water stress induced at flowering postponed crop maturity by 114 GDD. A similar study by Istanbulluoglu *et al.* (2010), in Turkey, also found the yield to be vulnerable to water stress during the flowering period.

3.2.2 Irrigation and its effect on canola growth and yield

Irrigation can be applied to satisfy the water needs for canola in areas with inadequate rainfall (supplemental irrigation) or to meet the full water requirements in dry areas when rainfall is unavailable. Owing to the competing nature of water use, prudent water management strategies are necessary especially in water scarce regions. Irrigation, being the largest component of water use, requires concerted efforts to improve the WUE in crop production. Geerts and Raes (2009), suggested one way of improving WUE is using limited irrigation at specific stages when the crop is not sensitive to water stress.

In areas of sufficient water supply, it is advisable to irrigate canola based on crop water demand for the whole growing season while in regions with scarce water resources, the crop can be water stressed during grain filling or vegetative stage so as to achieve high WUE (Tesfamariam *et al.,* 2010). In water scarce conditions it is advisable to apply irrigation water at the flowering period (Istanbulluoglu *et al.*, 2010).

Supplemental irrigation during critical growth stages of flowering and seed filling increases biomass and yield of canola (Faraji et al., 2009; Dogan et al., 2011). This could be attributed to supplemental irrigation lengthening the flowering period and increasing the total number of pods and seeds produced per plant (Abbasian *et al.*, 2011).

3.3 Crop Water Productivity Modelling

3.3.1 Water productivity and water use efficiency

Water for irrigation is increasingly becoming scarce and therefore, there is the need to produce more yields while at the same time minimizing the water used i.e. increasing crop water productivity (WP). Water productivity is the ratio of the net positive returns from crops, fisheries, domestic animals among others to the volume of water dispensed (Molden et al., 2010). More specifically crop WP is 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). Water use efficiency (WUE) 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). In some studies, the two terms are used interchangeably.

There are two ways of improving the WUE in agriculture, as per Wallace (2000). The first way is by allowing a large fraction of the water resource to be transpired and the second way is increasing the ratio of transpiration to water use. The first category involves engineering, hydrological and agronomical techniques which include reducing storage and conveyance losses in irrigation systems and reservoirs, runoff losses, soil evaporation, and deep percolation losses. The second category involves plant physiologists, plant breeders, and plant geneticists.

Assessing the WUE and WP in agriculture is achieved through examining water consumption of crops and the yield response to various water regimes through field or laboratory tests which are, however, costly and labour intensive (Geerts and Raes, 2009). The use of models is less costly and can be applied to a wide variety of environmental and management conditions. There are several crop models which are used to simulate WP and WUE. Based on the crop growth engines, crop models can be classified as carbon-driven, solar radiation-driven and water-driven models (Todorovic *et al.*, 2009). Sub-sections 3.3.2 – 3.3.4 briefly describe these models with a specific focus on their applications to simulate yield responses of canola to water availability.

3.3.2 Carbon-driven models

Todorovic *et al.* (2009), describe carbon-driven models as those that base crop growth on the assimilation of carbon by the crop during the photosynthesis process. In this modelling approach, the growth processes and phenology development are controlled by temperature, radiation, and carbon dioxide concentration. Examples of carbon-driven models include the crop models belonging to the Wageningen group such as World Food Studies (WOFOST) model among others (Bouman *et al.*, 1996; van Ittersum *et al.*, 2003) and Crop Growth (CROPGRO) model (Jones *et al.*, 2001) which is incorporated in the Decision Support System for Agrotechnology Transfer (DSSAT).

Carbon-driven models have a hierarchical structure in which the model is organized into levels where the higher-level responses is an aggregate combination of lower-level processes such as plant cells and organs, and thus, the model structure could be said to be dynamic, hierarchical, state-variable based, explanatory and deterministic (Bouman *et al.*, 1996).

The DSSAT is an integrated computer software suite with independent models for simulating crop and soil systems, where some are radiation driven and others are carbon-driven, for simulation of various crop management strategies (Jones *et al.*, 1998). The independent programs in DSSAT enable the simulation of cropping practices for both short and long periods of time and thus, enables the assessment and prediction of the uncertainties associated with crop and farm management practices (Jones *et al.*, 2003).

DSSAT underwent some revisions predominantly in the consolidation of its cropping model, largely inspired by the modular structure of the Agricultural Production Systems Simulator (APSIM) model, which led to revision of the CROPGRO model (Jones *et al.*, 2001) and the introduction of modular DSSAT Cropping System Model (DSSAT-CSM) (Jones *et al.*, 2003). According to Jones *et al.* (2003), the DSSAT- CSM incorporates all the crop models into one code, thus allowing all the crop models to utilize the same soil model components. Also, new crops can be introduced by interfacing the new crop module in the plant module or using the crop template approach by modifying values in a species implemented in CROPCRO and this makes the CSM flexible, unlike the previous non-modular version.

CROPGRO and Root Water Quality Model (RWQM2) was adapted by Saseendran *et al.* (2010) for the simulation of the yield of spring canola. In this study, the CROPGRO-faba bean model was adapted for canola in RWQM2 for growth and yield simulation under various irrigation regimes and seasons. The grain yield simulations were good with an index of agreement (*d*) of 0.98 while biomass accumulations had *d* values ranging from 0.55 to 0.99 across the seasons.

Carbon-driven models have a very sophisticated structure due to their hierarchical nature and therefore require a detailed and substantially large number of input parameters for proper calibration which thus limits their wider applicability (Todorovic *et al.*, 2009).

3.3.3 Radiation-driven models

In this category, biomass is proportional to Radiation Use Efficiency (RUE) which is a term representing the interception of direct solar radiation by the crop (Todorovic *et al.*, 2009) . Examples include Crop Environment Resource Synthesis (CERES) model, Erosion Productivity Impact Calculator (EPIC) model, Simulator Multidisciplinary for Crop Standard (STICS) model and the APSIM model.

Radiation-driven models avoid the sub-divisions into hierarchical levels and the explanation of lower hierarchical processes which thus, results in less complex structure than carbon-driven models (Todorovic *et al.*, 2009).

APSIM was developed in Australia for the simulation of cropping systems in semi-arid and tropical areas (McCown *et al.*, 1996). The authors describe APSIM as a modular model that is used for the simulation of crop growth and yields for diverse crop management situations. It has modules grouped into biological, environmental and management (Jones *et al.*, 2001). The APSIM modelling structure consist of, among other things, modules for the simulations of the biophysical environment and the manager which is a module enabling the specification of crop management scenarios (Keating *et al.*, 2003).

The merit of APSIM is the modular framework which allows for easy linking to other component models (Keating *et al.*, 2003). This modularity increases the flexibility of APSIM and enables it to be applied in a wide range of complex farming systems (Jones *et al.*, 2001). APSIM has been applied in complex field management scenarios such as irrigation schedules, the application of fertilizers and irrigation scheduling, crop rotations, no-tillage farming and mixed cropping among others (Holzworth *et al.*, 2006).

The APSIM model was applied in the simulation of the effect of rainfall variability on canola yield and it was found that its yields varied significantly with seasonal rainfall, with high rainfall areas experiencing high yields (Farre *et al.*, 2001; Robertson *et al.*, 2004). Using APSIM, He *et al.* (2015), found that irrigation of canola produced three times more yield as compared to rainfed and also irrigation improved the yield and water productivity.

APSIM is less complex model compared to carbon – driven models but it requires specialized skills and also require detailed input parameters than water-driven models, which limits its use by a large category of users who may not have scientific and modelling skills or those users in regions which lack specialized equipment for measurement of some crop data (Holzworth *et al.*, 2006).

In general, radiation-driven models have disadvantages in that there are inconsistencies and variations in approximations of RUE in intra-crop and inter-crop species and crop groups, an unpredictable relationship of RUE between localities and seasons and unreliability in normalization of RUE for climatic conditions (Steduto and Albrizio, 2005). These demerits hamper the sturdiness and predictive ability of radiation-driven models (Albrizio and Steduto, 2005).

3.3.4 Water-driven models

In this type of models, biomass is directly proportional to the rate of crop transpiration (Todorovic *et al.*, 2009). Examples of models in this category include CropSyst (Cropping System simulation model) and AquaCrop model. CropSyst uses both water-driven and radiation-driven modelling approaches (Stöckle *et al.*, 2003). However, in CropSyst the biomass – transpiration relationship becomes unstable under low vapour pressure deficit and as a result, the radiation-driven modelling approach is the main growth engine (Bauböck, 2014). Therefore, AquaCrop is the only water driven model currently available in literature

The advantage of water-driven models over the radiation- driven models is that they allow for the normalization of WP parameter to account for climatic conditions and thus, the model becomes robust with higher extrapolative capability provided that the normalization is done through the reference evapotranspiration rate instead of vapour pressure deficit which is mostly used in radiation-driven models (Steduto and Albrizio, 2005).

CropSyst model is used for the simulation of soil water balance and demand, nitrogen demand, crop growth and development, yield, and biomass among other uses with respect to a variety of management scenarios such as irrigation and crop rotation (Stöckle *et al.*, 2003). The model is user-friendly and its conceptual nature makes it simple to use.

In assessing the comparative performance of the water-driven , carbon-driven, and radiation-driven models in the simulation of sunflower growth, Todorovic *et al.* (2009), found that although AquaCrop requires fewer input parameters, it performed similarly like CropSysts and WOFOST in the simulation of biomass and yield. Saab *et al.* (2015), found AquaCrop to be superior to CroSyst in the simulation of biomass and yield of barley. In the simulation of final biomass, the average efficiency values were 0.71 and 0.50 for AquaCrop and CroSyst respectively. The difference in the performance of the two models could be attributed to the ability of AquaCrop to account for water stress effects and dynamic harvest index, unlike CropSyst where there is more emphasis on the combined effect of water stress, radiation and fertility conditions rather than water stress only.

3.3.5 Model selection criteria

The selection of an appropriate crop model is important in modelling studies. The main factors that guide in the selection of a model include the number of input data, simplicity, wide applicability, accuracy, and the ability to determine the effect of farm practices on crop production (Priya and Shibasaki, 2001). The data required by the model should be easily available or easily measured at reasonable cost. The model structure should be simple enough to enable wide usage without the need for specialised modelling skills. AquaCrop is selected for this study due to its simple structure and low data requirements and based on the evaluation described in subsection 3.3.4. AquaCrop was developed by the Food and Agricultural Organization (FAO) to address the complexity problems associated with the previous models and present a robust, simple, accurate and user-friendly model that requires fewer input data for the simulation of potential yields of major crops such as forage, vegetable, grain, fruit and tubers among others with respect to varying water regimes (Steduto *et al.*, 2009).

3.3.6 AquaCrop model

In AquaCrop, canopy development is described as canopy cover (CC) instead of the leaf area index (LAI) like other crop models and therefore the model is simple and takes into account the variation in plant density and incomplete CC in water stress conditions (Evett and Tolk, 2009). Other notable features as outlined by Steduto *et al.* (2009) are:

(a) The partitioning of the evapotranspiration (ET) into crop transpiration (Tr) and soil evaporation (E),

(b) Developing a simpler model for canopy growth and senescence,

(c) Treating the final yield (Y) as a product of final biomass (B) and harvest index (HI), and,

(d) Dividing the effects of water stress into canopy growth, canopy senescence, Tr, and HI.

The calculation scheme in AquaCrop is illustrated in Figure 3.1 and 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 taking into account 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 is a function of transpiration through the use of a conservative parameter, referred to as, normalized WP (WP*). Finally, at harvest, the yield is obtained by multiplying the simulated biomass and the modified HI.

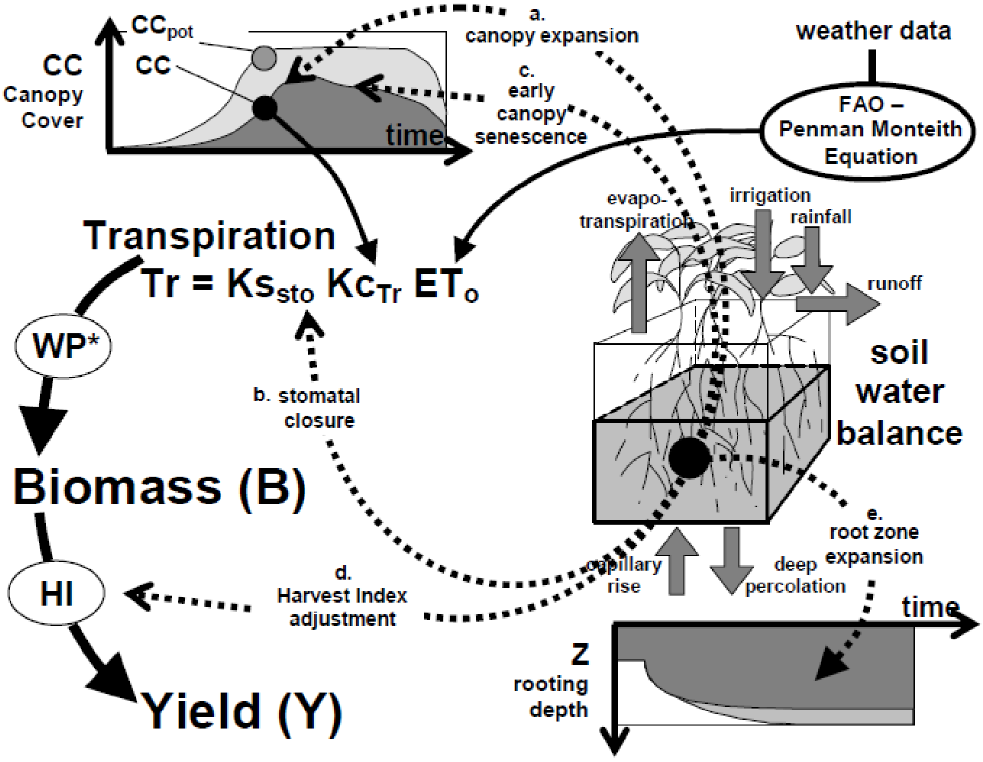

Figure 3.1: Calculation scheme in AquaCrop (Raes *et al.*, 2009).

As in other crop models, AquaCrop maintains the continuous interaction of the soil, crop and the atmosphere through its soil water balance, crop, and climate sub-models (Steduto *et al.*, 2009).

The model has been applied in the prediction of yields and biomass for various crops as stated in Chapter One. However, only one application for canola is available in the literature. Zeleke *et al.* (2011), used the AquaCrop to simulate canola yields in Australia. The model satisfactorily simulated CC development, biomass, and yield in the season where water was sufficient but overestimated biomass and yield under water stress season. Todorovic *et al.* (2009), suggested the adoption of a varying water stress function according to plant physiological responses in the growth and development of the crop instead of the simple stress coefficient in order to reduce the error in simulating crop response to water stress by AquaCrop.

AquaCrop model is poor in predicting the soil moisture content and distribution around the root zone (Al-kaisy *et al.*, 2011). This is because the simulation of water dynamics in AquaCrop is one dimensional which makes it less suitable for predicting the water flow as a result of drip irrigation which is two or three dimensional (Qin, 2015).

4. DISCUSSION AND CONCLUSION

This section covers the discussion of the literature reviewed in Chapters 2 and 3. It also provides the synthesis of the problem under study emanating from the research gaps identified.

Moistube irrigation is a modified form of SDI where instead of emitters or drippers, it has nanopores where water oozes to the soil through a semi-permeable membrane by the process of osmosis. It supplies water to the crop throughout the growing season, hence preventing crop water stress at the sensitive stages of crop growth. The technology seems to adopt the auto regulative capability similar to buried clay pots and porous pipes. MTI technology emphasises on the soil water potential as the main driver of water flow. On the other hand, the flow from the Moistube lateral pores is sensitive to pressure changes. These require further studies on pressure-discharge relationship. It would also be interesting to determine whether the flow from Moistube occurs in the absence of applied pressure.

MTI technology minimizes water losses due to evaporation and percolation and has a higher WUE than SDI. It also has a high application uniformity. This require qualification since the system is highly sensitive to pressure variation and therefore, the application uniformity will be dependent on the evenness of the field. The few studies on the use of MTI which focused on tomatoes have justified MTI as an appropriate technology in water scarce regions. However, the performance of MTI with respect to other crops is not available. Questions arise on whether the technology can support the growth of other crops whose water requirements are different from that of tomatoes considering the lower flows of MTI than in SDI.

The soil water movement in MTI is influenced by the soil water potential and system pressure. The available information on the soil water dynamics in MTI is not conclusive where one study indicates that the soil water distribution is symmetrical while another study shows that it is asymmetrical. Therefore, there is a need for further studies to clarify this phenomenon. Understanding the soil water dynamics in MTI as influenced by the soil, crop, and climatic characteristics is important for appropriate system design. Since MTI is relatively new, the current field and laboratory experiments are being conducted on trial and error basis with no clear guidelines. For example, the depth of placement of Moistube laterals for the growth of tomatoes was found by experimenting the depths of 10 cm, 15 cm and 20 cm. This means that the results obtained from those experiments are only valid for the site which was conducted and for that particular crop. Further studies are required on the soil water distribution of MTI using different soils and climate variables. This can be achieved by the use of soil water models which are less expensive than field trials.

Clogging of Moistube laterals has been reported in literature when water containing suspended particles are used. This is expected and has also been found to be a problem in SDI. It is necessary to evaluate further the clogging performance of Moistube laterals due to dissolved solids. This would be relevant in regions where saline water is used and also if fertilizers, chemicals and water are applied to the crops using MTI. Furthermore, the guidelines on irrigation water quality vary from country to country and it would be important to assess the clogging under MTI with respect to South African water quality criteria.

The application of models in irrigation water management is less costly compared to field trials. However, most models are complex and require a detailed or a large number of input parameters which may not be available or are expensive to acquire. On the other hand, simple and user-friendly models have limitations due to simplification of processes. A simple crop model like AquaCrop is good in simulating yield response to water availability but poor in simulating soil water content and distribution. HYDRUS has been proved to be reliable in predicting the soil water distribution under various irrigation methods and particularly subsurface irrigation. Despite its popularity in simulating soil water dynamics, HYDRUS is poor in simulating crop yields. It is evident that no single model can simulate satisfactorily all the outputs required for decision making in agricultural water management and hence, it is important to link crop and soil water models in such a way as to maximize and minimize on their individual strengths and weaknesses respectively.

From the discussions above, it is evident that information on MTI is scanty in terms of the soil water distribution for different soil types, its discharge variation with operating pressure, clogging characteristics and its ability to satisfy the water requirements of various crops for different climatic conditions.

5. RESEARCH PROPOSAL

5.1 Problem Statement

MTI is a new irrigation technology whose design parameters have not been extensively documented for various crops and environmental conditions. The current studies on MTI are being undertaken by trial and error in terms of the spacing and depth of placement of Moistube laterals. It has been applied in China for the growth of tomatoes (Zhang *et al.*, 2014; Zhang *et al.*, 2015b; Zhang *et al.*, 2015c). In these studies, it was established that the suitable depth for placement of Moistube laterals is 15 cm for the growth of tomatoes. Moreover, the results of soil water distribution in MTI shows divergence (Zhang *et al.*, 2012; Zhang *et al.*, 2015a). The presence of suspended particles in irrigation water causes clogging of Moistube laterals (Qi, 2013; Zhu *et al.*, 2015). There is the need to assess the clogging performance of Moistube laterals due to dissolved solids which could be from fertilizers and chemicals which are mostly applied together with irrigation water and also from saline water.

There is limited information on MTI in terms of its soil water distribution for different soil types, the discharge variation with pressure, the clogging resistance under different water quality conditions and its ability to meet the crop water requirements for different crops under different climatic conditions. Therefore, this research proposal aims at addressing the following questions:

a) What is the soil water dynamics of MTI in clay and sandy soils?
b) What are the discharge characteristics of MTI under varying operating pressure and water quality considerations?
c) Can the MTI flow meet the crop water requirements of canola under varying climatic conditions?
d) What is the yield and water use efficiency of canola under MTI with respect to varying climatic conditions?

5.2 Research Objectives

The study aims at assessing the soil water distribution of MTI in clay and sandy soils, the discharge variation with pressure, the clogging sensitivity, and the yield response of canola to water availability under climatic conditions of South Africa.

The specific objectives of the study are;

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

The hypotheses for this study are;

a) The shape of the wetting pattern will be symmetrical for clay and asymmetrical for sandy soil with upward and lateral movements being less than downward movement
b) The water flow from the Moistube has a positive relationship with operating pressure and negative relationship with suspended and dissolved solids concentration
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 use efficiency of canola is higher in MTI than SDI and the yields are spatially variable with climate.

5.3 Originality of the Study

This study will contribute to new and additional information on MTI in the following aspects. Firstly, it will provide new information on the pressure-discharge relationship of MTI and therefore help in understanding its sensitivity to pressure variation. Secondly, it provides new and additional information on soil water distribution of MTI for different soils. The understanding of the soil water dynamics will be relevant in MTI system design. Thirdly, this study will contribute to new information on the clogging performance of MTI under different water quality scenarios. Finally, this study will contribute to new knowledge on the ability of MTI to satisfy the water requirements of different crops under varying climatic conditions.

5.4 Methodology

This research will be conducted by laboratory experiments, field trials and modelling. The field experiment will be conducted at Ukulinga Research Farm and the laboratory experiments will be in the Agricultural Engineering Soil and Water Engineering laboratories at Ukulinga, and the Soil and Hydrology laboratory at the University of KwaZulu – Natal. The regional climate data will be obtained from the meteorological stations situated in the catchments to be studied.

Objective 1: To determine the soil water distribution under Moistube irrigation with respect to clay and sandy soils

This will be done in two parts. The first part will involve laboratory experiment to be conducted in the soil bin and the second part will be the simulation of water distribution using HYDRUS 2D/3D model.

5.4.1 Laboratory experiments

a) Soil water distribution experiment

The laboratory experiment will be conducted using soil bins of dimensions 100 cm by 100 cm x 50 cm. The soil will be excavated from Ukulinga agricultural field the soil while sand soil will be obtained from commercial vendors. The soil will be air dried and put into the soil bin. The soil in the bins will be subjected to three operating pressures of 0.5 bars (low), 1.0 bars (medium) and 2.0 bars (high) with three replications.

The Moistube will be placed at a depth of 20cm in the soil bin. Miniature tensiometers will be installed at intervals of 10 cm both vertically and horizontally from the Moistube laterals to measure the soil water potential. Moisture sensors will be installed on the side opposite the tensiometers to measure the soil water content. The initial soil water content will be determined in order to assess how it affects the soil water movement.

b) Determination of the soil characteristics

Soil samples will be obtained from the plot at Ukulinga Research Farm where the field experiment will be carried out. Undisturbed samples will be obtained from 0 – 20 cm, 20 – 40 cm, and 40 – 60 cm depths. The soil water retention characteristics will be determined using the pressure plate apparatus. The soil texture will be determined by the hydrometer method while the saturated hydraulic conductivity will be conducted by permeability apparatus. The bulk density will be analysed using the gravimetric method. The tests on sand samples will be the same as that of clay.

5.4.2 Numerical model

The simulation of the water distribution will be done using HYDRUS 2D/3D model. Model set-up requires specification of the parameters in the van Genuchten Equation described by the van Genuchten-Mualem constitutive relationships (Skaggs *et al.*, 2004);

$$\theta(h) = \begin{cases} \theta_r + \frac{\theta_s - \theta_r}{(1+|\alpha h|^n)^m} & h < 0 \\ \theta_s & h \geq 0 \end{cases} \tag{5.1}$$

$$K(h) = K_s S_e^l \left[1 - (1 - S_e^{1/m})^m\right]^2 \tag{5.2}$$

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \quad , m = 1 - \frac{1}{n} \tag{5.3}$$

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.

HYDRUS is a physical model and therefore, calibration is not necessary if all the input parameters are experimentally determined (Šimunek *et al.,* 2012). In the case where some input parameters are to be estimated, calibration will be achieved by inverse modelling as suggested by (Šimůnek and De Vos, 1999).

The model will be validated using field experiment described in sub – section 5.4.3. After validation, the model will be applied to simulate the water distribution for Moistube depths of

10 cm, 15 cm, 25 cm and 30 cm so as to enable generalization of water dynamics of MTI with respect to environmental conditions. Evapotranspiration (ET) for the catchments under consideration will be added as the input to the HYDRUS model for purposes of simulating the soil water dynamics of MTI in response to evaporative demand.

The model performance in the simulation of the soil water distribution will be assessed using graphical visualization and statistically by the Root Mean Square Error (RMSE) and coefficient of determination (R^2) as described in sub – section 5.4.4

Objective 2: To assess discharge characteristics of MTI under variable operating pressure and water quality scenarios

The effect of water quality on Moistube discharge will be determined using the water quality classification provided in the Irrigation Design Manual of South Africa which categorizes water in terms of concentration of suspended and dissolved solids, pH, dissolved oxygen, manganese, iron, hydrogen sulphide and bacteria (Burger *et al.*, 2003). However, this study will focus on suspended and dissolved solids. This will be carried out using a Moistube of 1 m length with water containing 20 mg/l, 60 mg/l, and 120 mg/l suspended solids and 200 mg/l, 600 mg/l and 1200 mg/l dissolved solids and pressure range of 10 kPa to 150 kPa. The control will be tap water (negligible suspended and dissolved solids).The outflow from the nanopores will be collected in a tray and its volume measured after fixed intervals to determine the discharge. An empirical relationship of discharge, solids concentration and pressure head will be derived. This will also serve to test the clogging performance of Moistube. This information will be useful in determining the range of concentrations of suspended solids and dissolved solids that can negatively affect the discharge of Moistube and compare with the conventional drip laterals and also help in the selection of filtration systems.

Objective 3: To evaluate the effect of soil water distribution on MTI system design for canola

HYDRUS 2D/3D model will be used to simulate the influence of installation depth and soil type on the soil wetting pattern. From the results, an appropriate depth and spacing of Moistube laterals will be determined for the growth of canola based on its water extraction characteristics, soil type and the Moistube flow rates.

Objective 4: To determine the yield and water use efficiency of canola under MTI for different climatic conditions

AquaCrop will be calibrated and validated using the field experiments which will be conducted at the University of KwaZulu – Natal, Ukulinga Research Farm where canola will be grown under MTI (refer to sub – section 5.4.3) . The model will be used to determine the yield and water use efficiency of canola.

Soil characteristics which include soil texture, hydraulic conductivity, bulk density, field capacity, wilting point, and total available water will be determined in the laboratory. Soil moisture content will be determined weekly.

The weather data will be obtained from the weather stations at Ukulinga Research Farm. The data required include daily temperature, daily rainfall, solar radiation, wind speed, and relative humidity Mean annual carbon dioxide concentration will be obtained from data from Mauna Loa observations (Hawaii). Daily potential evapotranspiration will be computed using the FAO Penman-Monteith method (Allen *et al.*, 1998).

The model will be calibrated for CC, soil water content, above ground biomass and grain yield. Canopy cover will be measured using canopy analyser LAI 2200. For canopy cover, the parameters to be adjusted include plant density, the maximum canopy at mid-season, crop phenology, the length of crop cycle and flowering. For soil water content, the parameters to be adjusted in the model are soil type and its associated features like soil horizon and the rooting depth. Calibration for yield and biomass will be done by adjusting the HI. The model will be calibrated using the data in November 2016– February 2017 growing season (summer) and validated using data to be obtained in May 2016 – August 2017 growing season (winter).

The validated model will be used to simulate yield response to water based on the climatic characteristics. Also, the WUE for each scenario will be determined. Three main climatic conditions will be considered namely semi-arid, sub – humid and humid. The main climatic variables are the evapotranspiration and rainfall. This will be achieved by linking the soil water model and the crop model. HYDRUS 2D/3D will be used to simulate the soil water content under these climatic variables together with irrigation component and used as the input to AquaCrop to predict the yields of canola

5.4.3 Field experiment

The field trial will be laid out in a randomized complete block design with three irrigation treatments. Each treatment will be replicated five times and the canola hybrid variety (Hyola 60) will be used as the experimental crop in the study. This will be conducted for two growing seasons of 2016 and 2017 for calibration and validation respectively.

The experimental plots will be 3 x 2 m with a density of 70 plants per square metre and row spacing of 300 mm as the average of the production guidelines by the Department of Agriculture, Forestry and Fisheries (DAFF, 2010). Each plot will be separated by a buffer of 1 m. The water requirement treatments will be 40% ETc, 70% ETc, and 100% ETc. The three treatments will be constant throughout the growing season. Moistube laterals will be placed in each row beneath the sowing lines at a depth of 20 cm. The control experiment will consist of SDI in the same arrangement as the MTI with the same treatments and replications.

The canopy cover, soil water content, biomass will be collected as the season progresses and total biomass, total consumptive water use and grain yield will be collected at crop maturity. Moisture profile probes will be installed at each sub-plot to measure the lateral and vertical moisture distribution.

5.4.4 Model evaluation and data analysis

The model performance will be evaluated by comparing simulated and observed canopy cover, soil moisture content, above ground biomass and yield. According to Yang *et al.* (2014), although statistical analysis is an important procedure for calibration and validation, there is no standard way on how many and which statistical techniques should be used. Moriasi *et al.* (2007), suggested a combined use of graphical, dimensionless and error indices. As per Bellocchi *et al.* (2010), evaluation statistics are complementary and so using a combination of statistical tools gives a balanced picture and allows the overall behaviour of the model to be analysed.

The statistical tools used for the assessment of the model will be the coefficient of determination (R^2), root mean square error (RMSE), Nash-Sutcliffe model efficiency coefficient (EF) and Willmot index of agreement (d).

RMSE is important as it uses the same units as observed and simulated variables and thus good for analysis (Moriasi *et al.*, 2007). The aim is to achieve a lower RMSE value. According to Heng *et al.* (2009), it is an indicator of the absolute model uncertainty. However, it cannot be used for inter-comparisons for many state variables or comparing different models (Yang *et al.*, 2014).

The coefficient, R^2, explains the percentage variation that can be of the observed data that can be explained by the model (Araya *et al.*, 2010b). A value approaching unity indicates a good model fit. It is the widely used statistical tool in the evaluation of models because it is a good indicator of accuracy through its linear regression coefficients of slope and intercept (Bellocchi *et al.*, 2010). However, it only estimates linear relationships and is not sensitive to additive and proportional differences (Yang *et al.*, 2014).

Modelling efficiency (EF) is a commonly used model evaluation technique which gives broad information about the simulated values (Moriasi *et al.*, 2007). EF values range from $-\infty$ to unity where a value between zero and unity indicates acceptable model performance. Another advantage of EF is that it is able to indicate the model performance over whole simulation period (Heng *et al.*, 2009) . However, like the index of agreement, it is more sensitive to larger deviations than smaller deviations although its larger range makes it superior (Yang *et al.*, 2014).

The Index of Agreement, *d*, is a measure of the amount prediction error and it varies from 0, indicating no agreement, and 1 , indicating perfect agreement, between measured values and the simulated values (Moriasi *et al.*, 2007). Unlike, R^2, it can identify additive and proportional differences (Yang *et al.*, 2014)

The variation among the irrigation treatments will be analysed using Analysis of Variance (ANOVA) at 95% confidence level. This will help in quantifying the effect of water stress on canola yield.

5.5 Expected Results

The expected results of this study will contribute to the:

(a) Understanding of the soil water dynamics in MTI under clay and sandy soils

(b) Design specifications for MTI for canola

(c) Understanding of canola response to water availability and climatic conditions under MTI

5.6 Budget

SN	Item Description	Quantity	Cost (R)
1	Moistube Laterals	500m	7500
2	Subsurface Drip irrigation tapes and Accessories	500m	6000
3	Pressure gauges	10	3000
4	Moisture sensors	30	6000
5	Connecting pipes	200m	3000
6	Water tank (500 L)	3	3000
7	Flow meters	20	3000
8	Soil bins	18	5400
9	Sand transport		1500
10	Small water pump	1	7500
11	Land preparation		750
12	Seeds, pesticides, herbicides and Fertilizers		6000
	TOTAL		**52650**

5.7 Work Plan

Item	**Description**	**2016**				**2017**				**2018**			
		Jan - Mar	Apr - Jun	Jul - Sep	Oct - Dec	Jan - Mar	Apr - Jun	Jul - Sep	Oct - Dec	Jan - Mar	Apr - Jun	Jul - Sep	Oct - Dec
1	Literature Review	■	■	■	■	■	■	■	■	■	■	■	
2	Proposal Development		■										
3	Laboratory Experiments			■									
4	HYDRUS calibration				■								
5	Field Experiments season 1				■	■							
6	AquaCrop calibration						■						
7	HYDRUS validation						■						
8	Field Experiments season 2						■	■					
9	AquaCrop validation and linking with HYDRUS								■				
10	Data Analysis									■			
11	Thesis draft reports										■		
12	Thesis submission and Corrections											■	■

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