جامعة أبو بكر بلقايد

UNIVERSITÉ DE TLEMCEN

Pan African University
Institute of Water
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Institute of Water and Energy Sciences (Including Climate Change)

# MODELING SUBSURFACE DRAINAGE TO CONTROL WATER-TABLES IN SELECTED AGRICULTURAL LANDS IN SOUTH AFRICA

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***Academic Year: 2016-2017***

## DECLARATION

I **Taguta Cuthbert,** hereby declare that this thesis represents my personal work, realized to the best of my knowledge. I also declare that all information, material and results from other works presented here, have been fully cited and referenced in accordance with the academic rules and ethics.

Signature:

Student:  Date: 05 September 2017

# DEDICATION

*To the Taguta Family, Where Would I be Without You?*

*Continue to Shine!*

*My son Tawananyasha and new daughter Shalom, may you grow to heights greater than mine!*

## ABSTRACT

Like many other arid parts of the world, South Africa is experiencing irrigation-induced drainage problems in the form of waterlogging and soil salinization, like other agricultural parts of the world. Poor drainage in the plant root zone results in reduced land productivity, stunted plant growth and reduced yields. Consequentially, this hinders production of essential food and fiber. Meanwhile, conventional approaches to design of subsurface drainage systems involves costly and time-consuming in-situ physical monitoring and iterative optimization. Although drainage simulation models have indicated potential applicability after numerous studies around the world, little work has been done on testing reliability of such models in designing subsurface drainage systems in South Africa's agricultural lands. This study investigated the occurrences of shallow water-tables South Africa's agricultural lands as well as the applicability of drainage simulation models in optimized designing and evaluating performance of subsurface drainage systems as means for controlling water-tables in cropped fields in South Africa. The study also used tried and tested models to assess the effectiveness of existing drainage systems that were designed by conventional means. Three models (DrainMod, EnDrain and WaSim) were tested and compared to recommend the most appropriate model considering local conditions.

It was observed that Makhathini irrigation scheme is suffering from shallow water-tables, although the trend is decreasing in some blocks due to a drainage system that was introduced in them. EnDrain model performed very well in simulating subsurface drainage system dynamics, as shown by the good agreement between observed and simulated drain discharges ($R^2$ = 0.81), comparably better than DrainMod and WaSim especially during validation. The existing drainage systems at Breede proved to be effective in lowering water-table to levels that maintain optimum crop yields. Therefore, shallow water-tables are a reality in agricultural areas where they exist, and subsurface drainage systems can solve this problem, while simulation models can be simple and cost-effective means of designing and evaluating their performance of subsurface drainage systems. EnDrain, which is user-friendly, basic and requires the least input data, is a better drainage simulation model.

Further study should focus on impacts of climate change on subsurface drainage dynamics and crop yields, as well as testing drainage simulation models at other alternative study sites with different soil and climatic conditions.

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## LIST OF ABBREVIATIONS

ARC - Agricultural Research Council

AUC - African Union Commission

CARA - Conservation of Agricultural Resources Act

CRM - Coefficient of Residual Mass

DAFF - Department of Agriculture, Forestry and Fisheries

DD - Drain Discharge

DWAF - Department of Water Affairs and Forestry

FAO - Food and Agriculture Organization of the United Nations

MAE - Mean Absolute Error

Ms - Microsoft

NWRS - National Water Resource Strategy

PAUWES - Pan African University Institute of Water and Energy Sciences (including Climate Change)

$R^2$ - Pearson's product-moment correlation coefficient

RMSE - Root Mean Square Error

RSA - Republic of South Africa

SABI - South African Irrigation Institute

SAWS - South African Weather Services

UKZN - University of KwaZulu-Natal

WRC - Water Research Commission

WTD - Water-table Depth

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# EXECUTIVE SUMMARY – ENGLISH

**Topic:** Modeling Subsurface Drainage to Control Water-Tables in Selected Agricultural Lands, South Africa

## Problem Statement

An estimated 15 to 18 % of South Africa's irrigated land is affected by waterlogging and salinization (FAO, 2016). Despite the successful application of DrainMod and WaSim subsurface drainage models at Pongola (South Africa), Malota (2012), Malota and Senzanje (2015) and Malota and Senzanje (n.d.) emphasised challenges associated with its adoptability including unavailability of reliable key data. DrainMod lacks interactive graphical user interface and process animations, which is a strength in WaSim (Hess and Counsell, 2008). Simplified models may provide a comparable degree of certainty (Bastiaanssen et al., 2007), of which simplicity is one of EnDrain model's strengths. It is therefore necessary to test other models and compare their functionality and performance with DrainMod, so as to recommend appropriate model(s) for certain conditions, such as degree of data availability. Such comparison provides planners, designers and water managers with a wide range of choice for decision support tools, as well as their appropriacy, strengths, weaknesses and special characteristics.

## Main Objective

To assess extent and causes of shallow water-tables and evaluate the reliability of applying EnDrain, DrainMod, EnDrain and WaSim in designing water-table control drainage systems in cropped fields in South Africa.

## Specific Objectives

i) To determine the extent, severity and possible drivers of shallow water-tables at the study sites.

ii) To evaluate EnDrain model's ability in simulating subsurface drainage dynamics at the study sites.

iii) To compare EnDrain, DrainMod and WaSim models and recommend the most appropriate model(s) considering performance, usability and input data requirements at the study sites.

iv) To assess performances of existing subsurface drainage systems, using DrainMod and WaSim, at the study sites.

**Literature Review – Research Gaps**

South Africa's agriculture is already suffering from waterlogging and salinization of cropped lands with some lands being abandoned due to decreased productivity. Of course, there has been increased activity in drainage modeling research in the last few years (e.g. Reinders et al., 2016a, b, c; Malota, 2012; Malota and Senzanje, 2015) but potential exists to test if other models e.g. EnDrain can be simpler and cost-effective methods to control the water-tables. For such studies to produce practically valid results, more areas with different conditions (soil, crop, climate) need to be studied, with either adequate measured or estimated soil hydraulic properties. Preferably, comparison of two or more models on similar study sites would help on choice of better model.

Furthermore, impact of climate change on agricultural drainage and crop yields need to be explored to enhance decision making and policy. Exploring appropriate drainage simulation models for design of water-table control drainage systems in South Africa's agricultural lands is necessary for present-day and future efficient production of food and fiber. Site-specific monitoring and delineation of occurrences of shallow water-tables and their causes is important, it provides physical evidence of the poor drainage problem and the possible interventions. It will also add more knowledge and value to the existing ad hoc drainage design approaches (Reinders et al., 2016a, b, c).

**Materials and Methods**

a) Study areas: Makhathini, Pongola and De Doorns.
b) Data collection: geographical coordinates, climatic (rainfall, temperature, relative humidity, solar radiation, evapotranspiration), soil properties, crop development, drainage system parameters, observed water-table depths and observed drain discharges.
c) Water-tables mapping with Surfer 14 at Makhathini.
d) Testing performance of EnDrain subsurface drainage model at Pongola: calibration and validation.
e) Assessing performance of existing drainage systems at De Doorns using EnDrain, DrainMod and WaSim models at Pongola.

f) Assessing performance of existing subsurface drainage systems at De Doorns, Breede.

**Relevancy**

a) Creating a database of cost effective and simple techniques for optimized design and evaluation of subsurface drainage systems.
b) Increased agricultural land and water productivity.
c) Safeguarding of irrigation investments.
d) Sustainable and efficient agricultural production.
e) Policy:
    - Conservation of Agricultural Resources Act (CARA) No. 43 of 1983 (CARA, 1983);
    - Irrigation Strategy for South Africa (DAFF, 2015);
    - Water Research Commission (WRC) project K5/2026//4 "Development of Technical and Financial Norms and Standards for Drainage of Irrigated Lands in South Africa.";
    - National Water Resource Strategy Second Edition 2013: Water for an Equitable and Sustainable Future (DWAF, 2013);
    - National Water Act (RSA, 1998); and
    - National Water Policy (RSA, 1997).

**Key words:** shallow, simulate, excess, model, policy

# EXECUTIF SOMMAIRE: FRENCH

**Sujet:**

MODÈLE DE DRAINAGE DE SOUS-FORCE POUR CONTRÔLER LES TABLEAUX D'EAU DANS DES TERRES AGRICOLE SÉLECTIONNÉES, AFRIQUE DU SUD

## Déclaration de problème

L'estimation de 15 à 18% des terres irriguées de l'Afrique du Sud sont affectées par l'engorgement et la salinisation (FAO, 2016). Malgré l'application réussie des modèles DrainMod et de drain de subsistance de WaSim à Pongola (Afrique du Sud), Malota (2012), Malota et Senzanje (2015) et Malota et Senzanje (n.d.) ont mis l'accent sur les problèmes liés à leur adoption, y compris l'indisponibilité de données clés fiables. DrainMod manque d'interface utilisateur interactive et d'animations de processus, ce qui est une force dans WaSim (Hess et Counsell, 2008). Les modèles simplifiés peuvent fournir un degré de certitude comparable (Bastiaanssen et al., 2007), dont la quelle la simplicité est l'une des forces du modèle EnDrain. Il est donc nécessaire de tester d'autres modèles et de comparer leurs fonctionnalités et leurs performances avec DrainMod, pour faire une recommandation de des modèles appropriés pour certaines conditions, telles comme le degré de disponibilité des données. Une telle comparaison fournit aux planificateurs, aux concepteurs et aux gestionnaires de l'eau une large gamme de choix pour les outils de soutien à la décision, ainsi que leur appropriation, leurs points forts, leurs faiblesses et leurs caractéristiques particulières.

## Objectif principal

Pour évaluer l'étendue et les causes des nappes phréatiques peu profondes et évaluer la fiabilité d'appliquer EnDrain, DrainMod, EnDrain et WaSim dans la conception des systèmes de drainage de la nappe phréatique dans les champs cultivés en Afrique du Sud.

Objectifs spécifiques

i) Déterminer l'étendue, la gravité et les éventuels conducteurs des nappes phréatiques peu profondes sur les sites d'étude.

ii) Évaluer la capacité du modèle EnDrain à simuler la dynamique de drainage subsurface sur les sites d'étude.

iii) Comparer les modèles EnDrain, DrainMod et WaSim et recommander le (s) modèle (s) le plus approprié (s) en ce qui concerne les performances, la facilité d'utilisation et les exigences en matière de données d'entrée sur les sites d'étude.

iv) Évaluer les performances des systèmes existants de drainage subsurface, en utilisant DrainMod et WaSim, sur les sites d'étude.

**La révision de la littérature - Lacunes dans la recherche**

L'agriculture de l'Afrique du Sud souffre déjà de l'engorgement et de la salinisation de terres cultivées, certaines terres étant abandonnées en cause d'une diminution de la productivité. Bien sûr, il y a eu une activité accrue dans la recherche sur la modélisation du drainage au cours des dernières années (par exemple, Malota, 2012; Malota et Senzanje, 2015; Reinders et al., 2016a,b,c;), mais il existe un potentiel pour tester si d'autres modèles, par exemple, EnDrain peut être une méthode plus simple et moins coûteuse pour contrôler les nappes phréatiques. Pour que ces études produisent des résultats pratiquement valables, il faut étudier les zones présentant des conditions différentes (sol, culture, climat), soit avec des propriétés hydrauliques adéquates du sol mesurées ou estimées. De préférence, la comparaison de deux ou plusieurs modèles sur des sites d'étude similaires aiderait à choisir un meilleur modèle.

En outre, l'impact du changement climatique sur le drainage agricole et les rendements des cultures doit être exploré pour améliorer la prise de décision et la politique. L'exploration de modèles de simulation de drainage appropriés pour la conception de systèmes de drainage de la nappe phréatique dans les terres agricoles de l'Afrique du Sud est nécessaire pour la production efficace et future d'aliments et de fibres. Le suivi et la délimitation spécifiques du site des bassins hydrographiques peu profonds et de leurs causes sont importants, il fournit des preuves physiques du mauvais problème de drainage et des interventions possibles. Cela ajoutera plus de connaissances et de valeur aux approches de conception de drainage ad hoc existantes (Reinders et al., 2016a,b,c).

**Matériaux et méthodes**

a) Domaines d'études: Makhathini, Pongola et De Doorns.

b) Collecte des données: coordonnées géographiques, climatiques (précipitations, température, humidité relative, rayonnement solaire, évapotranspiration), propriétés du sol, développement des cultures, paramètres du système de drainage, profondeurs observées de la nappe phréatique et déversements de drain observés.

c) Cartographie des tables d'eau avec Surfer 14 chez Makhathini.

d) Test des performances du modèle de drainage sous-sol EnDrain à Pongola: étalonnage et validation.

e) Comparaison des performances des modèles EnDrain, DrainMod et WaSim à Pongola.

f) Évaluation de la performance des systèmes de drainage subsurés existants chez De Doorns, Breede.

**Pertinence**

a) Création d'une base de données de techniques rentables et simples pour une conception et une évaluation optimisées des systèmes de drainage souterrain.

b) Augmentation de la productivité des terres agricoles et de l'eau.

c) Sauvegarde des investissements dans l'irrigation.

d) Production agricole durable et efficace.

e) Politique:

- L act sur la conservation des ressources agricoles (CARA) No. 43 de 1983 (CARA, 1983);
- Stratégie d'irrigation pour l'Afrique du Sud (DAFF, 2015);
- Projet de la Commission de la recherche sur l'eau (CMR) K5 / 2026 // 4 « Élaboration de normes et de normes techniques et financières pour le drainage des terres irriguées en Afrique du Sud » ;
- Stratégie nationale sur les ressources en eau Deuxième édition 2013: L'eau pour un avenir équitable et durable (DWAF, 2013);
- L Act nationale sur l'eau (RSA, 1998); et Politique nationale de l'eau (RSA, 1997).

# Chapter 1 : INTRODUCTION

This section presents an introduction to the research project. Beginning with a background of the study, the section concludes with problems and challenges that were encountered during the study.

## Chapter Outline

## 1.1 Background

Globally, 34 million hectares are salinized and approximately between 250 000 and 500 000 hectares of valuable agricultural land is lost annually due to poor drainage, thus reducing crop production potential (FAO, 2011; FAO, 2002). The problem is most prevalent in irrigated lands of semi-arid and arid zones (FAO, 2011), such as South Africa where it is irrigation-induced (Freisem and Scheumann, 2001). Poor drainage manifests as waterlogging (excess water in the soil) and salinization (excess salts in soil) in the plant root zone, and the two phenomena inevitably coexist in semi-arid and arid regions (Madramootoo et al., 1997).

Waterlogging and soil salinization in the root zone hinder plant growth and reduce crop yields. Artificial drainage on poorly drained agricultural fields is needed to reduce waterlogging and salinization, for ensuring optimum air, water and salt conditions in the root zone (Madramootoo et al., 1997). Thus, agricultural drainage is a vital water management practice that plays a key role towards sustainable and efficient agricultural production systems (Martinez-Beltran et al., 2007). Usually subsurface drainage systems are designed through physical experimentation which is expensive, time consuming, and delays decision making (Malota and Senzanje, 2015).

The soil system and associated processes is complex and non-linear (Ali, 2011). For example, the soil's saturated hydraulic conductivity varies spatially and temporally (Oosterbaan and Nijland, 1994). These processes affect crop production and there is need to optimally understand them so as to effectively manage agricultural water systems. State of the art approaches such as models attempt to simplify these systems and processes. If observed data are available to calibrate and execute innovative soil water flow simulation models, these techniques can enhance the understanding and solving of relatively complex phenomena in irrigation and drainage science and management (Bastiaanssen et al., 2007), including design and evaluation drainage systems (Reinders and Louw, n.d.).

## 1.2 Problem Statement

Out of 18 million hectares of land under cultivation in South Africa, approximately 1.6 million hectares are under irrigation. An estimated 0.26 million hectares of the irrigated land is affected by waterlogging and salinization (FAO, 2016). Moreover, these problems are increasing alongside the costs of drainage (Reinders, Senzanje, and Oosthuizen, 2014; Malota and Senzanje, 2015). Vaalharts along Orange River, Pongola in KwaZulu-Natal region, Breede River area in Western Cape and Gamtoos in Eastern Cape are experiencing drainage problems (Reinders, et al., 2016a). At Makhathini irrigation scheme, some portions of the agricultural land were deserted due to reduced productivity caused by poor drainage (Reinders et al., 2016b). Despite the successful application of DrainMod and WaSim subsurface drainage models at Pongola (South Africa), Malota (2012), Malota and Senzanje (2015), and Malota and Senzanje (n.d.) emphasised challenges associated with its adoptability including unavailability of reliable key data. Examples of such scarce data include saturated hydraulic conductivity, as well as soil water characteristics. Similar sentiments were also shared by Wang et al. (2006) and Bastiaanssen et al. (2007) on the application of agricultural water management decision support tools such as computer-based drainage design simulation models in many areas, particularly in data-scarce or poor or water-short countries. DrainMod lacks interactive graphical user interface and process animations, which is a strength in WaSim (Hess and Counsell, 2008). Simplified models may provide a comparable degree of certainty (Bastiaanssen et al., 2007), of which simplicity is one of EnDrain model's strengths. It is therefore necessary to test other models and compare their functionality and performance with DrainMod, so as to recommend appropriate model(s) for certain conditions, such as degree of data availability. Such comparison provides planners, designers and water managers with a wide range of choice for decision support tools, as well as their appropriacy, strengths, weaknesses and special characteristics.

To contribute to this existing knowledge and sustainable agricultural production, this study first assessed the occurrence of shallow water-tables at chosen sites, and then explored possibilities of using other models in drainage design for water-table control in cropped lands on selected sites in South Africa.

## 1.3 Research Questions and Objectives

### 1.3.1 Main research question

What is the temporal and spatial status of groundwater tables in selected South Africa's agricultural lands, and can the three chosen models reliably be used to design, evaluate performance of and simulate subsurface drainage dynamics for subsurface drainage systems in South Africa?

### 1.3.2 Specific research questions

i) What are the observed water-table depth extents and severities, and the possible drivers at selected sites?
ii) Can the EnDrain model reliably simulate the measured drain discharges at selected sites?
iii) Among DrainMod, EnDrain and WaSim models, which is/are the most appropriate model(s) with respect to performance, usability and input data requirements at the study sites?
iv) Can DrainMod and WaSim reliably be applied for designing and evaluating performance of existing subsurface drainage systems at alternative sites with different soils, climate and crop conditions?

### 1.3.3 Main objective

To assess extent and causes of shallow water-tables and evaluate the reliability of applying EnDrain, DrainMod, EnDrain and WaSim in designing water-table control drainage systems in cropped fields in South Africa.

### 1.3.4 Specific objectives

i) To determine the extent, severity and possible drivers of shallow water-tables at Makhathini study site.

ii) To evaluate EnDrain model's ability in simulating subsurface drainage dynamics at Pongola study site.

iii) To compare EnDrain, DrainMod and WaSim models and recommend the most appropriate model(s) considering performance, usability and input data requirements at Pongola study site.

iv) To assess performances of existing subsurface drainage systems, using DrainMod and WaSim, at the De Doorns study site.

## 1.4 Relevance to Water Policy

Water and drainage are inter-related, and so are their policy aspects. Policies comprise of activities, programmes, projects and actions at different hierarchy, therefore this research work provides information and evidence for water and drainage policy. This study is related to the following policy aspects of South Africa:

- Conservation of Agricultural Resources Act (CARA) No. 43 of 1983 (CARA, 1983);
- Irrigation Strategy for South Africa (DAFF, 2015);
- Water Research Commission (WRC) project K5/2026//4 “Development of Technical and Financial Norms and Standards for Drainage of Irrigated Lands in South Africa.”;
- National Water Resource Strategy Second Edition 2013 (NWRS 2): Water for an Equitable and Sustainable Future (DWAF, 2013);
- National Water Act (RSA, 1998); and
- National Water Policy (RSA, 1997)

## 1.5 Thesis Outline

This thesis has five chapters. Chapter 1 presents a general introduction, problem statement, objectives of the study as well as its relevance/significance to South Africa's water and drainage policies. The literature review on exploring the relevant theories and published research work is covered in Chapter 2, as well as detailed explanations of the three chosen drainage simulation models. Chapter 3 discusses the study areas, and materials and methods applied in collecting, preparing and analyzing data. Chapter 4 presents the results and discussion. Finally, the general summary, conclusions and policy implications of the study are presented, as well as the recommendations for future research.

## 1.6 General Study Approach

In line with the objectives of this study, the conceptual flow of study is shown in Figure 1.1.

## 1.7 Encountered Research Obstacles

The main obstacles encountered were logistics of the research project. I received my invitation letter for research internship from my supervisor by mid-February 2017. Originally, I was supposed to attend the research internship from 1st March 2017 to 31st July 2017 at University of KwaZulu-Natal (South Africa) but the stipends delayed in Tlemcen (Algeria) until end of March. I failed to secure the South African Study Visa from the Embassy of South Africa in Algiers (Algeria) because they needed a proof of accommodation signed and stamped by a South African landlord and Department of Home Affairs or Police, this was impossible to obtain since I was still in Algeria. A study visa was required to enable access to services and stipend offered by the host institution. As soon as I received the stipend and the flight ticket from PAUWES, I travelled to my home country (Zimbabwe) with the hope of getting the South African Study Visa easily from home than in Algeria. On arriving in Harare (Zimbabwe) at the end of April, the South African authorities told me that successful application and securing a study permit would take me another six weeks. I found this to be impractical considering that I was already a month into my internship period, and they were also requesting the signed and stamped proof of accommodation from South African side. Whilst I was considering a way forward, I was invited for another two-month internship with the West African Science Service Centre for Climate Change and Adapted Land Use (WASCAL) Competence Centre, Burkina Faso under the PAUWES-WASCAL partnership and I went there on 1st April. Whilst in Ouagadougou (Burkina Faso), I visited the South African Embassy to be told of less requirements than in Algeria or Zimbabwe. I applied and secured the study visa, then proceeded to South Africa through Zimbabwe early June 2017 after finishing the WASCAL internship.

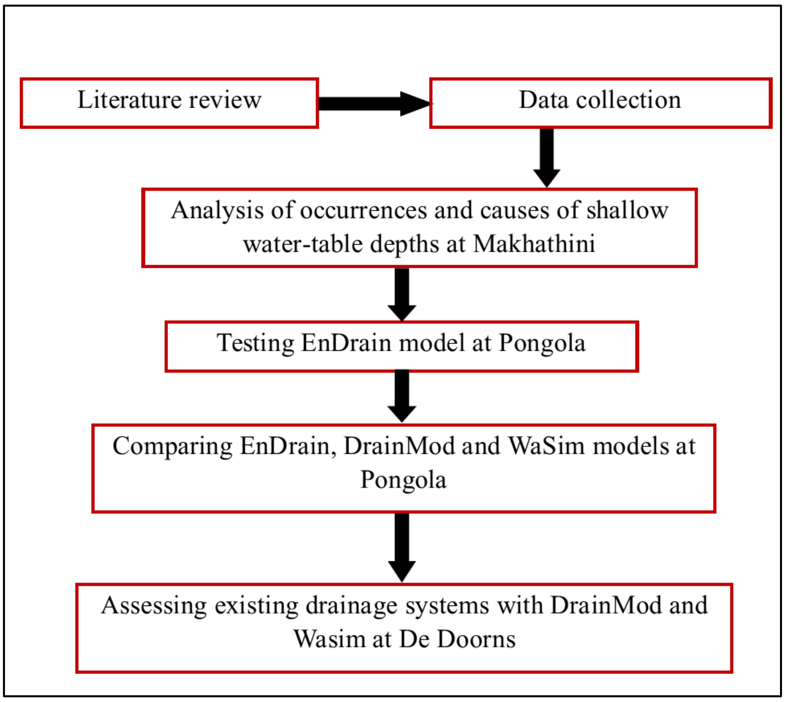



Figure 1.1: Conceptual flow of study.

My time in South Africa was relatively short, I failed to secure adequate modeling inputs data for the initially proposed three models (DrainMod, EnDrain and WaSim) and the four study sites (Breede, Pongola, Gamtoos and Vaalharts). Instead I got some minimum data for three sites (Makhathini, Pongola and Breede), which I ended up working on. This explains the differences in my proposal and the actual research work. This was my fallback position in my original research proposal under the section "1.4 Possible Obstacles" where I stated that under circumstances of time or data availability becoming strictly limiting to the extent of obstructing progress and results of the research project, either the number of study sites or the number of drainage simulation models or both factors would be reduced without compromising the overall research objective.

It also took me considerable time to get practically used to the three models since I received the data later than expected. It is highly recommended that in the future, PAUWES should play an active role in assisting students to secure travelling documents and the requisite permits to their internship hosts in time, for example study visas.

# Chapter 2 : LITERATURE REVIEW

This section presents the global and South African context of agricultural drainage as well as the basics of subsurface drainage and the relevant subsurface drainage simulation models. The section concludes with impacts of drainage, the aspects of drainage in South Africa's policy and the research gaps that motivated this study.

**Chapter Outline**

## 2.1 Drainage of Agricultural Lands

### 2.1.1 Global context

Globally, approximately 0.25 to 0.5 million hectares of productive land is lost every year due to poor drainage, resulting in reduction of food and fiber production potential (FAO, 2002; FAO, 2011). The problems of poor drainage exist or co-exist as waterlogging (when excess water displaces air in soil pores to soil saturation) and salinization (accumulation of excess salts in soil). Although the common sources of excess water are precipitation, over-irrigation, overland flow, groundwater flow, or water applied as leaching requirements (Savva and Frenken, 2002), irrigation is the primary cause of rising water-tables to the top soil (waterlogging) and the buildup of salts within the upper soil layers (salinization) in semi-arid climates where and when the precipitation is insufficient to meet the crop water requirements (Reinders et al., 2016c). Drainage problems are common in agricultural lands that are inadequately self-draining by natural means (Ritzema, 1994). Ideally, an irrigation system should timeously apply needed crop water and remove excess water to facilitate optimum soil-water conditions for plant growth as well as efficient and sustainable agriculture (McCarthy, Hubbard, and Quisenberry, 2016). The extremes of drainage problems (that is waterlogging and salinity) involve abandonment of agricultural land, as exemplified by the deserted lands of historic Chaldea, Tigris valley and Euphrates Rivers (Mesopotamia) (Malota, 2012).

### 2.1.2 South African context

South Africa lies in the semi-arid climate zone (Reinders et al., 2016b), and it is prone to irrigation-induced salinization and waterlogging. In South Africa, an estimated 15 to 18% of the total irrigated land is waterlogged and salinized, with a marked worsening of these problems alongside costs of drainage (Reinders et al., 2014; Malota and Senzanje, 2015). According to Shikwambana et al. (2014) and Reinders et al. (2016a,b,c), areas affected by drainage problems in the country include Vaalharts, Breede, Pongola, Gamtoos and Makhathini, and the problems can be attributed to:

- poor management of land (soil), water and irrigation systems,
- leaking earthen dams and irrigation furrows,
- cultivation of natural waterways,

- natural phenomena such as shallow groundwater tables and heavy rainfalls in some areas.

Some agricultural lands in South Africa were rendered unproductive and abandoned due to drainage problems (Reinders et al., 2016b) for example parts of Makhathini (Shikwambana et al., 2014), this emphasizes the severity of the situation.

### 2.1.3 Effects of poor drainage

Water logging and excessive soil salinity disturb the balance on soil-plant-air-water continuum, thus detrimentally affecting the root zone aeration and uptake of nutrients by plants, resulting in stunted plant growth and reduced yields (Reinders et al., 2016b). Associated impacts of poor drainage include:

- increased soil salinization by movement of salts with rising water-tables,
- scalding of the crops when water ponds during the summer,
- health risks arising from mosquitoes breeding in humid fields,
- delayed seed germination when excess soil water disturbs soil temperatures,
- increased activity of plant diseases and pests e.g. fungus growth,
- reduced load bearing capacity and strength of waterlogged soil which hinders building of structures, and
- increased vulnerability to compaction of waterlogged soil by animals and machines (Ali, 2011).

### 2.1.4 Drainage – The remedy

Drainage problems in affected areas can be rectified by artificial drainage (commonly termed 'drainage' or 'agricultural drainage') which is the removal of excess water from the ground surface and the regulation of the water-tables in the soil (FAO, 2007). Agricultural drainage is mainly meant to conserve the soil and enhance crop production (Reinders et al., 2016b). Soil conservation is key to long-term sustainable agriculture while enhanced crop production optimizes crop yields. This is achieved by facilitating a suitable root environment that enhances development of roots, decomposition of organic matter, favorable salinity content in the root zone as well as optimum land productivity (FAO, 2007; Ali, 2011). Associated benefits from agricultural drainage include:

- increased availability and accessibility of soil air and plant nutrients,
- reduced prevalence of toxic compounds and salts in the soil,
- increased availability of essential nitrogen,
- extended period of cultivation,
- improved conditions for crop germination and early development,
- improved timeliness of field operations,
- reduced soil compaction and improved workability (Savva and Frenken, 2002; FAO, 2007; Ali, 2011).

Artificial drainage is either surface or subsurface. Surface drainage system removes excessive water on the land soil surface, while subsurface drainage system controls the water-table levels and salt balances in the soil profile (Ritzema, 1994; USDA-NRCS, 2001).

## 2.2 Subsurface Drainage

The key parameters for subsurface drainage design include the drain depth ($D_d$), drain spacing (L), drain pipe diameter, recharge (R), hydraulic conductivities (K), hydraulic head at midpoint (h), drain discharge (Q), design water table-depth ($D_w$) and depth to the impermeable layer ($D_i$); These parameters are all inter-related (FAO, 2007), and are shown in Figure 2.1.

FAO (2007) provides general preliminary ranges of drain depth and spacing for specific climatic regions and soil types. Because the involved parameters are inter-related and dependent, subsurface drainage systems are usually designed using iterative relationships or functions such as the Hooghoudt equation (Hooghoudt, 1940). Historically, optimization of the subsurface drainage design parameters has been accomplished by the experimental monitoring of water-table depth while manipulating drain depth and spacing, which has proved to be costly both to set up and run the test plots. The physical monitoring of groundwater table fluctuations requires a significant amount of time, this delays timely decision-making in agricultural water management systems (FAO, 2007; Malota and

Senzanje, 2015). This calls for developing and testing simple and time-saving techniques for subsurface drainage design, such as nomographs, models and computer applications.

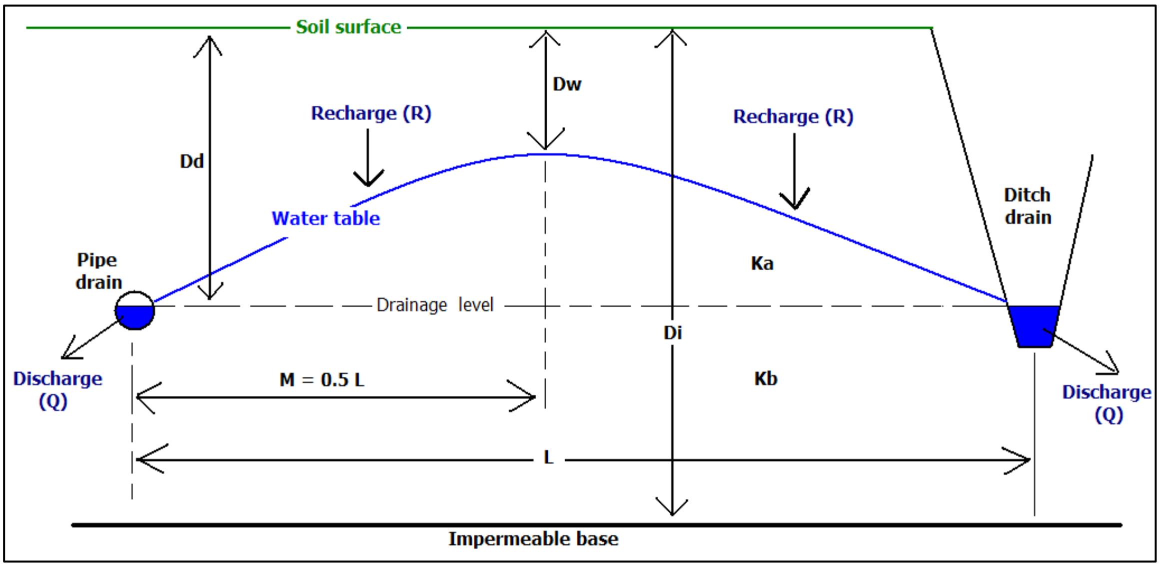



Figure 2.1: Geometry of subsurface drainage system by pipes or ditches (Wikipedia, 2017).

### 2.3 Application of Models in Agricultural Drainage

Computer-based models are increasingly becoming popular useful tools for design and evaluation of subsurface drains. During establishment of drainage systems to control water-tables and soil salts levels in agricultural lands, the design process is a key initial step because agricultural drainage systems are long term investments. It is during the design phase that the performance of the drainage system should be predicted under several likely present and future water management scenarios for appropriate sizing of the system components. This implies that drainage requirements have to be derived from the surplus water being applied by the irrigation infrastructure. In arid and semi-arid climates, this adds more complications to the process due to the dynamic behavior of the ground water table within a single irrigation season (Skaggs, 1990), coupled to the complex soil-water system (Reinders et al., 2016b). This has led to widespread research in agricultural drainage in the past years, particularly the development of better approaches, techniques and methods of designing and evaluating drainage systems in irrigated areas, such as models and simulators. Examples of developed drainage models include DrainMod (Skaggs, 1978), EnDrain (Oosterbaan, 1996), SaltMOD (Oosterbaan, n.d.), and WaSim (Hess et al., 2000), to assist in the design of new drainage systems as well as the prediction of their performance and evaluation of effectiveness of existing drainage systems. These models combine and enhance the understanding of key complex systems such as hydrological, hydraulic and soil system (Bastiaanssen et al., 2007). Models are able to simulate subsurface drain discharge and water-table trends in a broader diversity of conditions than those normally feasible through monitoring, this facilitates timely decision-making concerning normally difficult problems (Wang et al., 2006). Additional abilities in other models include animated simulations (WaSim), plotting water-table shape in soil profile (EnDrain), and predicting effect of drainage on yield and nitrogen losses (DrainMod). Marked progress in using models in designing drainage systems has occurred in many countries such as Australia (Yang, 2008), India (Hirekhan et al., 2007), Egypt (Abbott et al., 2001) and USA (Skaggs et al., 2012), with little to tell in South Africa. Reported works in South Africa have been done with DrainMod and WaSim for Pongola (Malota, 2012; Malota and Senzanje, 2015, Malota and Senzanje, n.d.) and EnDrain for Breede (Reinders et al., 2016a,b,c). In their large numbers, drainage simulation models differ in simplicity, ease, input data requirements, user-friendliness, reliability and flexibility in the range of water management situations that can be simulated (Hirekhan et al., 2007; Hess and Counsell, 2008; Skaggs et al., 2012).

The following sections give an overview of three common drainage models namely EnDrain, DrainMod and WaSim. These were selected because of their reputations regarding user-friendliness, simplicity, reliability and ease of availability.

## 2.4 EnDrain Model

### 2.4.1 Model background

EnDrain is a computer program developed by Oosterbaan (n.d.) for computing the drain flow, hydraulic head, drain spacing as well as plotting the curve described by water-table level. EnDrain can be applied in pipe drains or open ditches, with an option to include or exclude the entrance resistance resulting from water seeping into the drain. EnDrain is applied in designing subsurface drainage systems on rain-fed or irrigated agricultural land for controlling waterlogging, water-table, salinity and soil's humidity. Such drainage systems are necessary for reclaiming, remediating, rehabilitating and restoring waterlogged and saline soils (Oosterbaan, n.d.). EnDrain program is freeware (http://www.waterlog.info/endrain.htm).

In EnDrain, the computations of drainage system parameters are based on two concepts:

- the new Energy balance equation of groundwater flow (Oosterbaan et al., 1996) which calculates the energy flux by integrating the product of the hydraulic potential and the flow velocity, and
- the Darcy formula combined with water-balance (continuity) or conservation of mass equations.

EnDrain accommodates the presence of three different soil layers with different hydraulic conductivities and permeabilities: one layer above and two below drain level. The last two layers can also have individual horizontal and vertical permeabilities (Oosterbaan, n.d.). Basically, EnDrain has five tabs: Intro, Figure, Input, Output and Graphics. Intro and Figure tabs describe the program while the Input tab gives the interface for the variable input parameters that the program needs in order to execute and calculate results. The Output and Graphics tabs display the results in a text and graphical form, respectively.

### 2.4.2 Model components

EnDrain program contains four subprograms:

- DarSpac: calculates the drain spacing using the Darcy equation,
- DarCond: calculates the equivalent hydraulic conductivity of the soils between the drains using the Darcy equation,
- HydHead: calculates the shape of the water-table between drains using both the Darcy and the Energy balance equation, and
- DarDisc: calculates the drain discharge using the Darcy equation.

### 2.4.3 Input data

EnDrain input data is mainly soil properties, with few exceptions belonging to climate / hydrology, drainage / crop system and hydraulics. Figure 2.2 and Table 2.1 show and define the variables used in EnDrain.

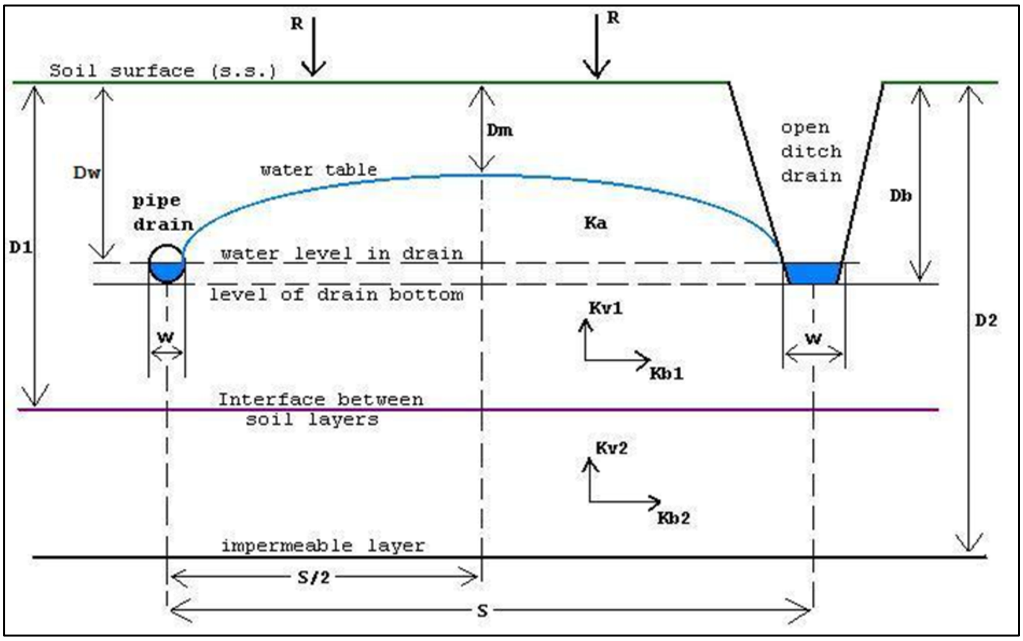



Figure 2.2: Variables used in the EnDrain model (http://www.waterlog.info/endrain.htm).

### 2.4.4 Outputs

After execution, EnDrain provides the outputs including:

- drain spacing,
- mid-way hydraulic head,
- mid-way water-table depth,
- drain discharge,
- equivalent hydraulic conductivity, and
- plot of water-table level (y-axis) variations with distance from the drain (x-axis), showing the shape of the water-table in between successive drains (Oosterbaan, n.d.).

### 2.4.5 Strengths of EnDrain

From Table 2.1, it is apparent that EnDrain has few input data requirements as compared to other drainage simulation models like DrainMod and WaSim. EnDrain is basic, simple, user-friendly and easy to use.

### 2.4.6 Limitations of EnDrain

EnDrain is an event-based model, one can simulate the drainage for only one day or event at a go. It cannot run long term or multiple simulations in one go. For multiple-event simulations, e.g. an ordinary year, one has to simulate the first day, record the results and go to the next day, that is equivalent to 365 simulations!

Currently, EnDrain doesn't have user guides or technical manuals, not even detailed guides in the "Help" tab. This imposes difficulties to users, especially for the first time. Few published literature exists on the application of EnDrain, this implies limited information for comparison of results for new studies.

### 2.4.7 Applications of EnDrain

Reinders et al. (2016c) conducted a study on the application of EnDrain in Breede, Western Cape (South Africa). They used EnDrain to compare two scenarios: (i) original drainage system design specifications computed from conventional methods, and (ii) a drainage system installed by farmer contrary to original design specifications. In the first case, the EnDrain-simulated drain discharge and water-table depth results (6.19 mm/day and 1 m respectively) agreed with original design specifications by the Department of Agriculture (6.1 mm/day and 1 m, respectively) at a spacing of 60 m. On the other scenario where a farmer installed the drainage system using 100 m spacing instead of the required 60m, the program results confirmed the shortcomings in controlling drain discharge and water-table depth. Instead of 6.19 mm/day and 1 m respectively if the subsurface drainage system were installed as originally designed, the program simulated 2.45 mm/day and 0.36 m, respectively, for the drainage system deliberately wrongly installed by farmer. These results indicate the potential applications of EnDrain in planning new drainage systems and evaluating performance of existing ones.

Valipour (2012) and, Tiwari and Goel (2015) studied sensitivity of EnDrain output to the input parameters. Both agreed that EnDrain is more sensitive to depth of water level in drain, although Tiwari and Goel (2015) reported the drain spacing having a similar sensitivity effect. Halbac-Cotoara-Zamfir (2010) used EnDrain to calculate drain spacing for soils with excess humidity in Bihor County, Western Romania. Comparing the Darcy and the Energy balance methods, results indicated that using the Energy balance method in EnDrain yields deeper water-table depths or wider spacing between drains, as compared to the Darcy equation. Overall, the outlined limitations in the previous section discourage the application of EnDrain. However, EnDrain was selected for this study because of minimum data requirements, simplicity and ease of use.

Table 2.1: Definition of variables and symbols used in the EnDrain model, refer to Fig 2.2 (Reinders et al., 2016c; EnDrain model 'input' tab).

| Variable | Definition | Units |
|---|---|---|
| R | Time average recharge or discharge | m/day |
| $D_1$ | Depth to bottom of first layer below soil surface | m |
| $D_2$ | Depth to bottom of second layer below soil surface | m |
| $D_w$ | Depth of water level in drain below soil surface | m |
| $D_b$ | Depth of drain bottom below soil surface | m |
| E | Entrance resistance at the drain | day/m |
| W | Maximum width of water body in the drain | m |
| $K_a$ | Hydraulic permeability, above drain level | m/day |
| $K_{b1}$ | Horizontal permeability, first soil layer | m/day |
| $K_{v1}$ | Vertical permeability, first soil layer | m/day |
| $K_{b2}$ | Horizontal permeability, second soil layer | m/day |
| $K_{v2}$ | Vertical permeability, second soil layer | m/day |
| $D_m$ | Depth of water-table midway between drains (time average) | m |
| S | Spacing between the parallel drains | m |

## 2.5 DrainMod Model

### 2.5.1 Model background

The latest version of DrainMod is V6.1.105 (April 2013). DrainMoD is a process-based, distributed, field- and watershed-scale hydrologic simulation model, which was developed to simulate the effects of drainage and other similar water-table management systems on drainage flows, groundwater table behaviors, and yields in poorly drained and artificially drained lands with shallow water-tables (Skaggs, 1980; Skaggs et al., 2012). The DrainMod model computes water balances (on time scales of hour and day) to predict groundwater fluctuations, drain discharges and drainage water salinity levels, for both field- and watershed scales. It uses functional algorithms to predict hydrologic components (infiltration, subsurface drainage, surface runoff, evapotranspiration, vertical and lateral seepage, water-table depth, and drained or water-free pore space in the soil profile). DrainMod program is freeware (http://www.bae.ncsu.edu/soil_water/drainmod/download.html).

DrainMod model is based on a water balance for a unit-area section of soil that stretches from the impermeable layer to the soil surface, being situated halfway between parallel drains. The water balance for a time increment $\Delta t$ may be expressed as:

$$\Delta V_a = D + ET + DLS - F$$ Equation 2.1

where $\Delta V_a$ is the change in the water-free pore space or air volume (cm), $D$ is drainage from (or sub-irrigation into) the section (cm), $ET$ is evapotranspiration (cm), $DLS$ is deep and lateral seepage (cm), and $F$ is infiltration (cm) entering the section (Skaggs et al., 2012).

In DrainMod, daily water-table depths at specific drain spacing are computed from the modified steady state Hooghoudt equation (Hooghoudt, 1940):

$$q = \frac{8K_{sat2}d_e h + 4K_{sat1}h^2}{L^2}$$ Equation 2.2

Where: $q$ is the drain discharge (mm/day); $L$ is the drain spacing (m); $K_{sat1}$ and $K_{sat2}$ are the saturated soil hydraulic conductivities (m/day) for soil layers above and below the drains, respectively; $d_e$ is the equivalent depth to impermeable layer (m); and $h$ is the hydraulic head mid-way between two drains (m) (Skaggs et al., 2012).

### 2.5.2 Model components

The model components include precipitation, infiltration, surface drainage, subsurface drainage, sub-irrigation, evapotranspiration, soil water distribution and rooting depth (Skaggs, 1980); they are all part of the water balance illustrated in Figure 2.3.

### 2.5.3 Input data

The input data needed for DrainMod model include climatic data, drainage system parameters, soil properties, crop, and trafficability parameters, as detailed in Table 2.2.

### 2.5.4 Outputs

The outputs of DrainMod include predicted water-table depth, drain discharge, infiltration and runoff; at daily, monthly and annual time steps. Other optional outputs include yields, nitrogen losses, wet stresses and dry days.

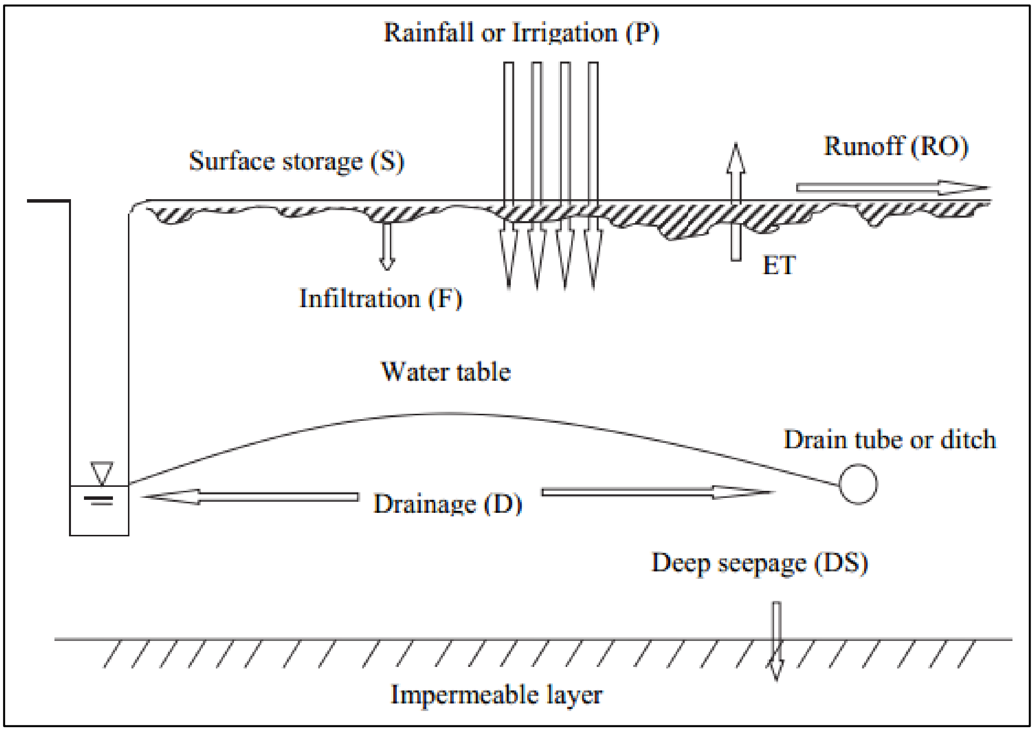



Figure 2.3: Water balance system and its components, with drainage to ditches or drain tubes (Malota, 2012).

### 2.5.5 Strengths of DrainMod

DrainMod has a comprehensive combined user guide and technical manual, as well as a detailed interactive "Help" facility in the program or online. It is able to run multiple scenarios and long-term simulations simultaneously.

### 2.5.6 Limitations of DrainMod

DrainMod has to be tested first for local conditions before use in irrigated arid or semi-arid regions (DrainMod “Help” facility). It requires relatively many data input requirements which are rarely adequate as measured (Skaggs, 1980; Skaggs 2012), and the procedures for data preparation are discouragingly many and complex for amateurs.

Table 2.2: Input data for DrainMod model (Skaggs et al., 2012).

| **Data type** | **Description** |
|---|---|
| Daily climatic | Rainfall (precipitation) (mm) |
| | Reference evapotranspiration (mm/day) |
| | Temperature – daily maximum and minimum (°C) |
| Drainage system | Design WT depth (m), hydraulic head (m) and drain discharge (mm/day) |
| | Effective drain radius (m), drain spacing (m), drain depth (m), drain material type, |
| | Depth to impermeable layer (m), drainage coefficient (mm/day) |
| | Maximum surface storage (cm), drain filter material |
| Soil | Type, saturated hydraulic conductivity (m/day), soil layer depths (m) |
| | Soil water characteristics (cm vs $cm^3/cm^3$) |
| | Green-Ampt infiltration parameters (A and B) versus water-table depth ($cm^2$/hr and cm/hr respectively) |
| | Maximum upward flux versus water-depth |
| | Drained volume versus water-table depth |
| Crop and trafficability | Maximum effective rooting depth (m) |
| | Effective rooting depth vs time distribution for crop (m) |
| Irrigation | Amount of irrigation water application (mm/day) |

### 2.5.7 Applications of DrainMod

Several studies were conducted to study the application of DrainMod in predicting drain discharge and crop yields to investigate the effectiveness of subsurface drainage systems in agricultural lands. The reliability of DrainMod in simulating water-table depths and subsurface drain discharge has been tested with success in many locations around the world for various conditions such as climates, soils, water management scenarios and crops. Results from tests in Australia (Yang, 2008), Purdue (Wang et al., 2006), South Africa (Malota and Senzanje, 2015), Sweden (Salazar et al., 2008), Quebec (Dayyani et al., 2009), Iowa (Singh et al., 2006); and North Carolina (Skaggs et al., 2012) show the model's reliability in simulating water table-depths and drain discharges. This motivated its selection for this study.

However, Sinai and Jain (2006) in Jordan Valley, Israel, reported failure of DrainMod to predict water-table depths in four out of five identical drainage plots studied. Further investigations suggested that the large anomalies were due to deep lateral seepage caused by site slopeness, soil conditions and closeness to Jordan River (Sinai and Jain, 2006). This indicates that DrainMod's reliability can be enhanced if attention is paid to site conditions.

## 2.6 WaSim Model

### 2.6.1 Model background

The Water balance Simulation model (WaSim) was developed by HR Wallingford and Cranfield University (Hess and Counsell, 2008). WaSim is a computer-based package for simulating the soil water content in the root zone and water-table depths in response to different agricultural water management strategies and environmental scenarios. The different management strategies can be drainage designs and water management practices, while examples of the environmental scenarios are weather data, soil types and cropping patterns. The WaSim model is based on a one-dimensional daily three-layer soil water balance. WaSim program is freeware (http://www.skyeinstruments.info/index_htm_files/WaSim%20-%20Water%20balance%20model.htm). The components of the water balance are shown in Figure 2.4.

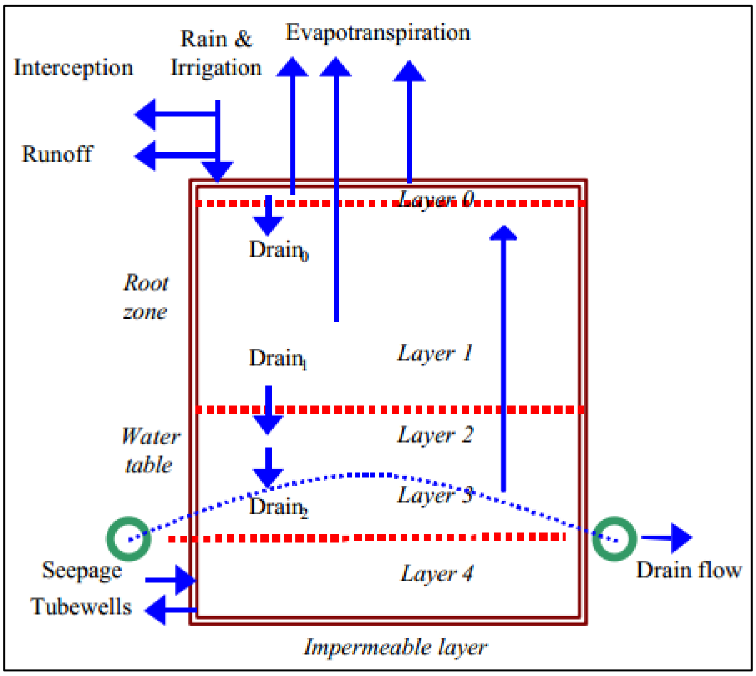



Figure 2.4: Overview of the water balance used in WaSim (Hess and Counsell, 2008)

WaSim aims to simulate the soil water storage and rates of input (infiltration) and output (evapotranspiration and drainage/deep percolation) of water as affected by climate (rainfall), irrigation and seepage (where relevant). The upper and lower boundaries are the soil surface and the impermeable layer, respectively. The computed deep percolation becomes an input into a water-table model, which then predicts the likely drainage requirements under given rainfall or irrigation scenarios (Abbott et al., 2001; Hess and Counsell, 2008).

WaSim's notable abilities and attribute include:

- running on a daily time-step,
- simulating up to 30 years,
- specifying up to 3 crops in rotation,
- simulating water-table in drained or un-drained environments,
- running as an unsaturated water balance simulation model, with drainage / water-table and salinity options switched off.

### 2.6.2 Model components

Two modules embedded in WaSim are DRAINSPACE module to design drain spacing, and WaSim-ET module to calculate reference evapotranspiration from weather station data (Cranfield University, 2016).

The algorithms used in WaSim model's water balance include:

- crop and mulch cover fractions,
- available water and soil water deficit,
- actual and potential transpiration,
- root zone deficit,
- interception loss,
- runoff estimation,
- mid-drain water table height/depth and,

- drain flow.

### 2.6.3 Input data

The WaSim model requires input data such as climatic, drainage system, soil, crop and irrigation, as shown in Table 2.3.

### 2.6.4 Outputs

WaSim numerical and graphical outputs include:

- mid-drain water-table depth,
- drain discharge, being seasonal (Hess and Counsell, 2008).

### 2.6.5 Strengths of WaSim

WaSim has relatively little data requirements. It has a technical manual, offline "Help" facility and user guide for supporting users. WaSim simulations are animated and this helps users in following track of the modeling process. Designed for training purposes, WaSim is basically simple and user-friendly.

Table 2.3: Input data for WaSim model (Hess et al., 2000; Abbott et al., 2001; Hess and Counsell, 2008)

| **Data type** | **Description** |
|---|---|
| Daily climatic | Rainfall (mm), reference evapotranspiration (mm/day) |
| Drainage system | Mid-drain water-table depth (m), depth to impermeable layer (m) |
| | Drain diameter (m), drain spacing (m), drain depth (m) |
| Soil | Type, saturated hydraulic conductivity (m/day), |
| | Soil saturation moisture content ($cm^3/cm^3$), |
| | Permanent wilting point moisture content ($cm^3/cm^3$) |
| | Field capacity moisture content ($cm^3/cm^3$), leaching efficiency (%) |
| Crop | Crop rooting depths (at planting and maximum) (m) |
| | Crop cover (maximum, mulch cover, crop coefficient at full cover) (%) |
| | Maximum ponding depth (cm), Kc for ponding |
| | Transpiration factors |
| Irrigation | Irrigation water amount (mm), lateral seepage (where relevant) |

### 2.6.6 Limitations of WaSim

There is little published literature on use of WaSim, and this is a challenge when users want to interpret or compare their results. It is recommended to test the model for site-specific conditions, hence the need for calibration and validation (Reinders et al., 2016a).

### 2.6.7 Applications of WaSim

Abbott et al. (2001) used field data from Mariut Experimental Station, Egypt, to evaluate the use of WaSim for simulation of controlled drainage scenarios in comparison with conventional drainage. In Haryana (India), Hirekhan, Gupta, and Mishra (2007) evaluated capability of WaSim to predict drainage behavior for non-drained (Mundlana) and drained (Sampla) conditions in a semi-arid monsoon climate. The results from both studies in Egypt and India indicated adequate agreement between WaSim-simulated drainage parameters and observed field data including water-table depths and drain discharges. This shows that WaSim acceptably represents the drainage processes occurring in the field and it is a potentially acceptable tool to design, develop and evaluate drainage systems and agricultural water management strategies for different situations. WaSim was selected for this study because of its promising potential of applicability, and its simplicity, ease and user-friendly animated graphical interface.

## 2.7 Overview of EnDrain, DrainMod and WaSim

To summarize, the overview of input data requirements for EnDrain, DrainMod and WaSim is given in Table 2.4.

Table 2.4: Overview of input data requirements for EnDrain, DrainMod and WaSim (Reinders et al., 2016c, Skaggs et al., 2012, Hess et al., 2000; Abbott et al., 2001; Hess and Counsell, 2008).

| | **Model** | | |
|---|---|---|---|
| **Data Type** | **EnDrain** | **DrainMod** | **WaSim** |
| Climatic / weather | No | Yes | Yes |
| Drainage system | Yes | Yes | Yes |
| Soil properties | Yes | Yes | Yes |
| Cropping system | No | Yes | Yes |
| Irrigation | No | Yes | Yes |
| Observed water-table depth or drain discharge | Yes | No | No |

From Table 2.4, it is apparent that EnDrain requires less input data than DrainMod and WaSim.

## 2.8 Need for Pedotransfer Functions (PTFs) for Generating Data for Models

### 2.8.1 Background

Running drainage simulation models requires basic soil hydraulic parameters such as soil water characteristics curve, hydraulic conductivity, and soil water content at saturation and lower limit (Skaggs et al., 2012). The reliability of input parameters such as site-specific soil data greatly affects the application and performance of models such as DrainMod (Qi et al., 2015). Most subsurface drainage simulation models are not easily applicable to daily water management situations since they require detailed and specific soil and climate data which are usually unavailable in agricultural areas (Yang, 2008). Measuring such detailed site-specific soil hydraulic parameters is costly in terms of time and cost (Salazar et al., 2008; Qi et al., 2015). Fortunately, there exist alternative means such as pedotransfer functions (PTFs) to obtain soil hydraulic parameters. By definition, PTFs are equations or algorithms for estimating advanced properties from basic soil information, where and when such advanced properties are difficulty to measure or avail (Pachepsky and van Genuchten, 2011). PTFs range from simple lookup tables that give hydraulic parameters according to textural class to complex computer program models. In practice, PTFs are indirect approaches of predicting soil hydraulic parameters from basic soil data. The basic soil properties commonly used as input parameters in pedotransfer functions include particle size distribution, soil texture, porosity or bulk density, limited water retention data, mineralogical properties and organic matter/carbon content (Schaap et al., 2001; Wosten et al., 2001; Pachepsky and van Genuchten, 2011). There are numerous PTFs to predict soil hydraulic properties (Abdelbaki and Youssef, 2010) but ROSETTA is the most common (Salazar et al., 2008; Qi et al., 2015).

### 2.8.2 Rosetta

Rosetta is a computer program which uses five hierarchical PTFs for estimating van Genuchten (1980) water retention parameters and saturated hydraulic conductivity, as well as unsaturated hydraulic conductivity parameters according to van Genuchten (1980) and Mualem (1976). The hierarchy in ROSETTA's PTFs allows the prediction of van Genuchten water retention parameters and the saturated hydraulic conductivity using the following hierarchical sequence of input data:

- soil textural class,
- sands, silt and clay percentages,
- sand, silt and clay percentages and bulk density,
- sand, silt and clay percentages, bulk density and a water retention point at field capacity, and
- sand, silt and clay percentages, bulk density and water retention points at field capacity and permanent wilting point (Schaap et al., 2001).

Rosetta can be used as a standalone program or as embedded in other computer programs such as HYDRUS-1D. Rosetta Lite is a version of the Rosetta program incorporated into the HYDRUS-1D model, it is used for estimating soil hydraulic properties (Simunek et al., 2007).

#### 2.8.2.1 Rosetta hydraulic functions

The van Genuchten soil water retention function is given by:

$$\theta(h) = \frac{\theta_s + \theta_r}{\left[1 + (\alpha h)^n\right]^{1-(1/n)}} \qquad h<0 \qquad \text{Equation 2.3}$$

$$\theta(h) = \theta_s \qquad h>0 \qquad \text{Equation 2.4}$$

Where: *Θ(h)* is the measured volumetric soil water content ($cm^3/cm^3$) at the suction *h* (cm, taken positive for increasing suctions); $\Theta_r$ and $\Theta_s$ are residual and saturated soil water contents, respectively, ($cm^3/cm^3$); $\alpha$ (>0, in $cm^3$) is related to the inverse of the air entry suction, and *n* (>1) is a measure of the pore-size distribution (van Genuchten, 1980).

The Mualem (1976) pore-size distribution model is given by:

$$K \times S_e = S_e^l \left\{ \frac{\int_0^{S_e} \left[ \frac{1}{h(h)dS} \right]}{\int_0^1 \frac{1}{h(S)dS}} \right\}^2 \qquad \text{Equation 2.5}$$

Using Equations 2.3 and 2.4 above in combination with Equation 2.5 yields the van Genuchten-Mualem model given by:

$$K \times S_e = K_0 S_e^L \left\{ 1 - \left[ 1 - S_e^{\frac{n}{n-1}} \right]^{1-\frac{1}{n}} \right\}^2 \qquad \text{Equation 2.6}$$

which according to van Genuchten (1980) and Schaap et al. (2001), is then used to estimate the $K_{sat}$, $S_e$ is the effective saturation ($cm^3/cm^3$) and is computed as:

$$S_e = \frac{\theta_h - \theta_r}{\theta_s - \theta_r} \qquad \text{Equation 2.7}$$

Where $K$ is the unsaturated hydraulic conductivity (cm/day), $K_0$ is the matching point at saturation (cm/day) and similar, but not necessarily equal, to $K_{sat}$, $L$ (<0) is an empirical pore tortuosity/connectivity parameter that is usually assumed to be 0.5 (Schaap et al., 2001).

#### 2.8.2.2 Application of Rosetta

In their study for Rosetta's PTFs, Schaap et al. (2001) reported that the hierarchical models yielded better results when more predictors are used, and vice versa, although such estimations by the program can still be used when inadequate input data are available.

Studies were done in Iowa (USA) (Qi et al., 2015) and Sweden (Salazar et al, 2008) to evaluate the feasibility of using DrainMod with $K_{sat}$ and soil water characteristics curve data predicted using the PTF model, ROSETTA. Abdelbaki and Youssef (2010) assessed the feasibility of applying DrainMod using $K_{sat}$ and SWC data estimated by other PTFs on four agricultural drained sites USA. Results of the studies revealed acceptable agreement between observed and DrainMod-predicted drainage flows using ROSETTA-estimated $K_{sat}$ and laboratory-measured $K_{sat}$. This pointed to the encouraging possibility for applying PTFs to approximate soil hydraulic properties that are that are key inputs for running DrainMod model.

### 2.9 Drainage Impacts

Drainage has implications on land productivity, water productivity, water quality and the environment. Drainage enhances land productivity by improving soil health, promoting beneficial soil bacteria and maintaining favorable salt, water and air environments in the crop root zone. In similar aspect, drainage minimizes surface runoff and soil erosion. By optimizing crop yield potentials, drainage improves water productivity, that is the yield per unit water used in growing crops. This is achieved by improved water management and uptake of plant nutrients that favor crop growth. In economic terms, drainage increases farm income and financial stability. Investments in irrigation are safeguarded and sustained by drainage. By minimizing surface ponding, drainage prevents the proliferation of disease causing agents that favor humid environments, for example mosquitoes. Drainage improves trafficability of the soil for field operations, as well as lengthening growing seasons in prohibitive climates. In areas normally unfavorable for higher value crops, drainage create suitable conditions for such crops, for example fruits and vegetables. This also increases the variety of crops produced (Madramootoo et al., 1997; ICID, 2017).

By minimizing overland flow and runoff, drainage enhances water quality in streams. Drainage enhances groundwater quality by channeling away polluted water that would contaminate the groundwater aquifers below the drain pipes or ditches (Fraser and Fleming, 2001). Although it impacts positively to the environment, some environmental concerns exist. The concerns include loss of valuable wetlands and increased loss of nitrate through tile drains (Reinders et al., 2016a). Other negative impacts observed in Egypt include change of natural habitats, created water deficit for other natural plants, land subsidence, downstream water pollution and land salinization (Nasralla, 2009).

### 2.10 Drainage and South Africa Water Policy

Agricultural drainage interventions play key part in realizing many aspects of South Africa's water policy. For example, National Water Policy (RSA, 1997) gives all South African people the right to a safe and protected environment, for the good of today's and tomorrow's generations. It emphasizes on efficient, effective and sustainable use of water. Agricultural drainage systems protect both water and land resources, for long term productivity.

The Conservation of Agricultural Resources Act (CARA) No. 43 of 1983 mentions the construction and maintenance of soil conservation works (e.g. drainage infrastructure) as measures to remove excess surface and groundwater for preventing waterlogging and salinization farm lands. According to CARA (1983), such measures promote controlled utilization of the natural agricultural resources and the conservation of the soil, water and related resources in South Africa (CARA, 1983).

The Irrigation Strategy for South Africa (DAFF, 2015) emphasizes importance of surface and subsurface drainage interventions to "achieve optimum utilization of resources for sustained food security and economic returns." The strategy plans to increase irrigated land in South Africa by more than 50%, that will imply a similar increase in agricultural drainage needs.

A recently terminated Water Research Commission (WRC) project K5/2026//4 was focusing on development of guiding norms and standards for technical and financial aspects for drainage of irrigated lands in South Africa, of which drainage modeling is part of the potential technique.

In the National Water Resource Strategy (NWRS) Second Edition (DWAF, 2013), relevant themes are water resources protection and water conservation. Artificial drainage achieves the two themes by systematically removing excess water from agricultural lands, thereby preventing groundwater pollution by deep percolation. Under the section for improved rural economy, the NWRS highlights on substantial increased investment in irrigation infrastructure, with explicit mention of Makhathini Flats which is one of the study areas for this research.

In the National Water Act (RSA, 1998), it is stated that prevention of water resource pollution on the land is the sole responsibility of the owner, controller, occupant or user of the land concerned. The National Water Act states that prevention measures may include containing or preventing the movement of pollutants, with further reference to construction, purchase, acquisition, controlling, operation and maintenance of waterworks perceived to be adequate for removing the excess water from the land.

## 2.11 Research Gaps

South Africa's agriculture is already suffering from waterlogging and salinization of cropped lands with some lands being abandoned due to decreased productivity. Of course, there has been increased activity in drainage modeling research in the last few years (e.g. Malota, 2012; Malota and Senzanje, 2015; Reinders et al., 2016a,b,c) but potential exists to test if other models e.g. EnDrain can be simpler and cost-effective methods to control the water-tables. For such studies to produce practically valid results, more areas with different conditions (soil, crop, climate) need to be studied, with either adequate measured or estimated soil hydraulic properties. Preferably, comparison of two or more models on similar study sites would help on choice of better model.

Furthermore, impact of climate change on agricultural drainage and crop yields need to be explored to enhance decision making and policy. Exploring appropriate drainage simulation models for design of water-table control drainage systems in South Africa's agricultural lands is necessary for present-day and future efficient production of food and fiber. Site-specific monitoring and delineation of occurrences of shallow water-tables and their causes is important, it provides physical evidence of the poor drainage problem and the possible interventions. It will also add more knowledge and value to the existing ad hoc drainage design approaches (Reinders et al., 2016a,b,c).

# Chapter 3 : MATERIALS AND METHODS

This section elaborates the materials and methods that were used in realizing the set study objectives.

**Chapter Outline**

This chapter covers all activities and procedures followed in data collection, preparation and analysis, relevant to fulfilling the study objectives. The first part describes the study sites, namely Makhathini, Pongola and De Doorns (Breede), and their perceived suitability for this study. Initially the author had proposed to study Pongola, Vaalharts, Gamtoos and Breede but due to scarcity of key data and limited time, Vaalharts and Gamtoos were dropped and Makhathini was added.

### 3.1 Study Areas

Makhathini and Pongola are in KwaZulu-Natal Province while De Doorns (Breede) is in Western Cape Province as shown in Figure 3.1. The study areas are marked and written in red ink in the map.

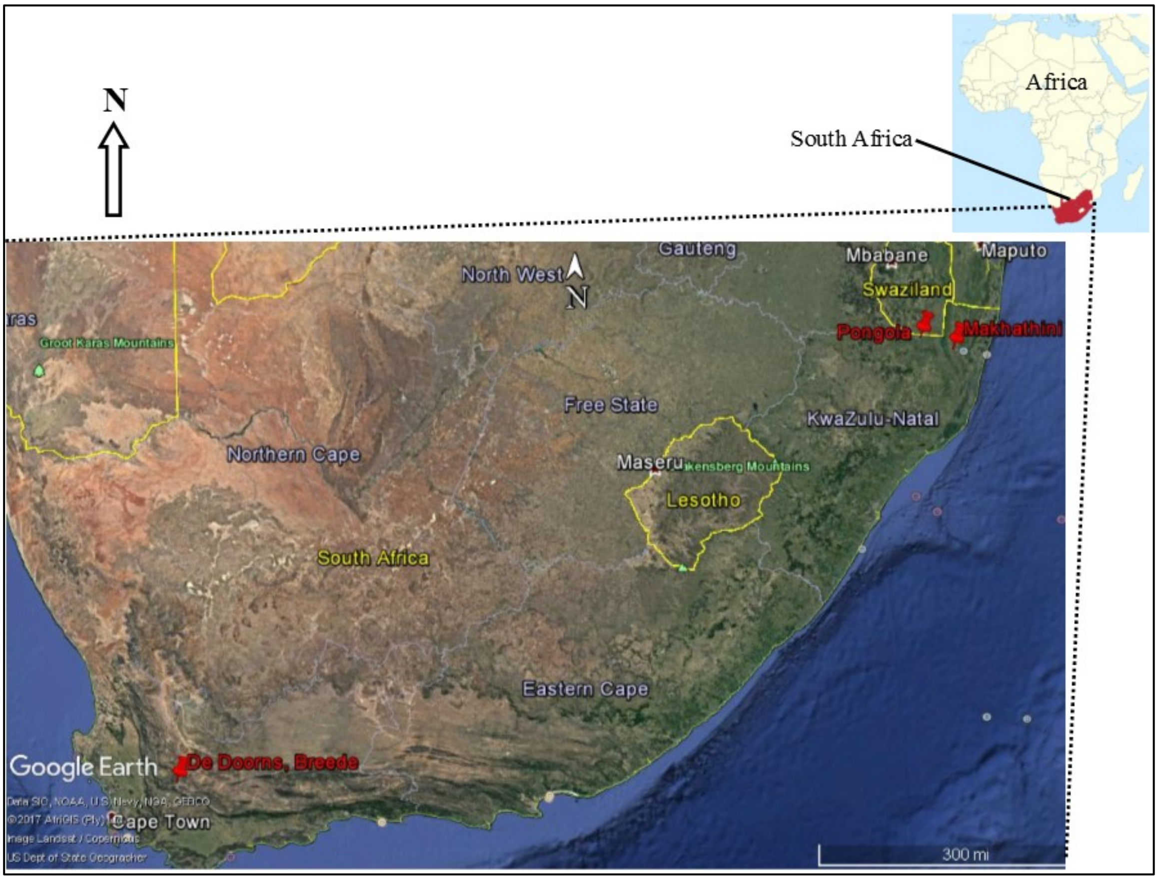



Figure 3.1: Location of the three study sites in South Africa (Google Earth Pro, 25 July 2017; Wikipedia, 2017).

### 3.1.1 Makhathini Irrigation Scheme

Makhathini is located at 27°29'5.53"S 32° 9'15.22"E, on the flood plains of the Pongola River, below the Jozini Dam in the KwaZulu-Natal Province as shown in Figure 3.2.

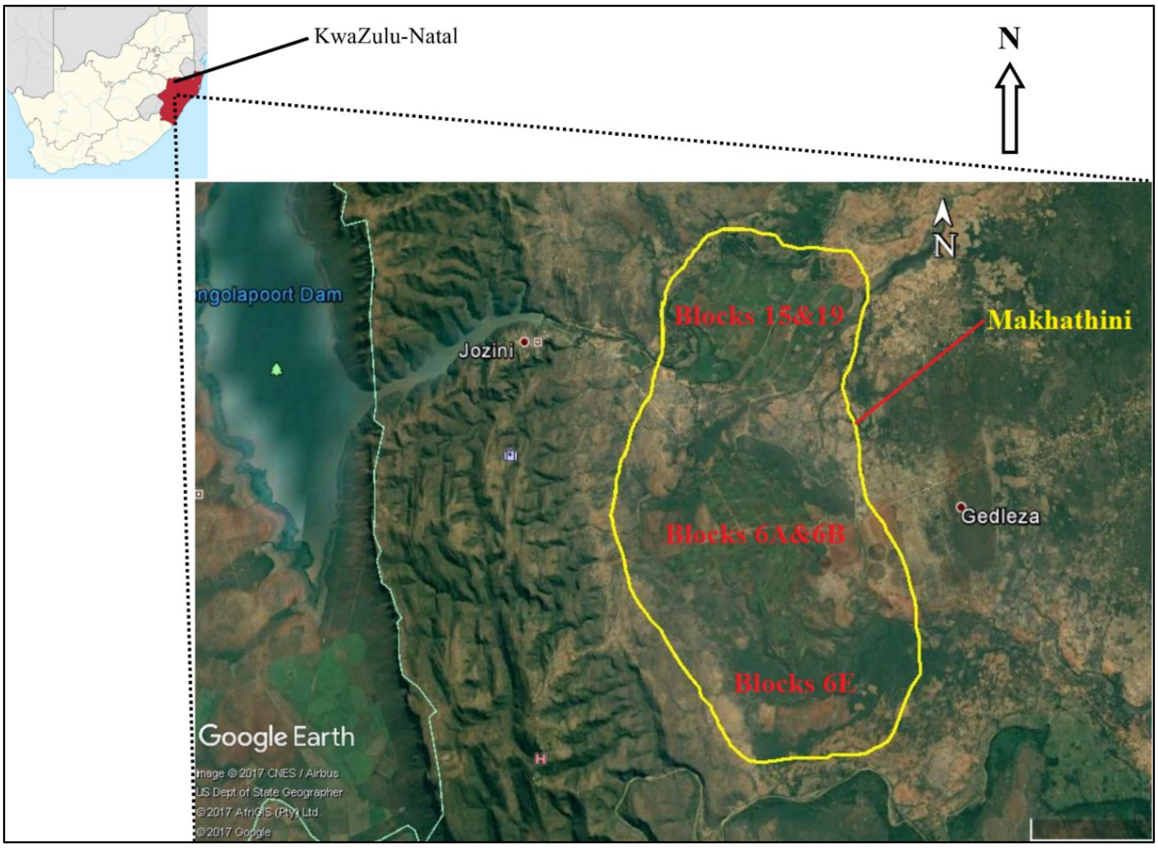



Figure 3.2: Aerial view of study site at Makhathini Irrigation Scheme (Google Earth Pro, 25 July 2017; Wikipedia, 2017).

The Makhathini study site comprises of blocks 15, 19, 6A, 6B and 6E as labelled in red in the map in Figure 3.2. The larger part of the irrigation scheme comprises of soils with a relatively high silt and clay content, at approximate values of 20% and 45% respectively. The study site is used for sugarcane production. Makhathini Irrigation Scheme covers an area of 3900 hectares, accommodating 390 farmers at approximately 10 hectares per farmer (Shikwambana et al., 2014). The wet season coincides with summer, from October to April while the winter season is dry, from May to September.

Waterlogging problems were reported on the irrigation scheme, and the causes were identified as poor irrigation management, shallow water-tables and heavy rainfalls in the area. To observe and monitor water-table fluctuations at Makhathini, the Department of Agriculture, Forestry and Fisheries (DAFF) installed 281 water-table observation points in the form of piezometers, wells and boreholes in five blocks: 6A, 6B, 12, 15 and 19. Piezometers, wells and boreholes combined are herein referred to as water-table observation points. The observation points were installed in phases but finer details about the times of installation could not be found. With respect to depth, the installed piezometers are relatively shallow and they can measure water-table depths up to four meters. Wells and boreholes are deeper than piezometers, measuring deeper than four meters, but generally boreholes go deeper than wells. Water-table depths were measured between once to twice per year for the years 2009, 2010, 2013, 2014, 2015, 2016 and 2017. When they were measured twice per year, it was deliberately just after the wet season (after maximum recharge) and at the end of the dry season (before recharge starts) (Shikwambana et al., 2014). From the perspective of this study, for the years with two seasonal observations per year, this was sufficient for analyzing seasonality trends in water-table fluctuations. But for the years with only one observation per year in the same season or month, it was sufficient to analyses water-table fluctuations between years.

The drainage problems at Makhathini resulted in some agricultural fields being deserted (Reinders et al., 2016b). According to Mjindi Farming, a contractor assigned with technical and management support of Makhathini Irrigation Scheme, a drainage ditch was completed in a section of the irrigation scheme during the period April 2012 to May 2013 (Mjindi Farming, 2013), and a technician with the DAFF confirmed that the drainage works were done in block 6E (Shikwambana et al., 2017).

### 3.1.2 Pongola Irrigation Scheme

Pongola is situated in the north-eastern side of South Africa close to the country’s border with Swaziland in the KwaZulu-Natal province, and the specific site for this study is shown in Figure 3.3. It is located at 27°21'40.69"S 31°36'57.17"E.

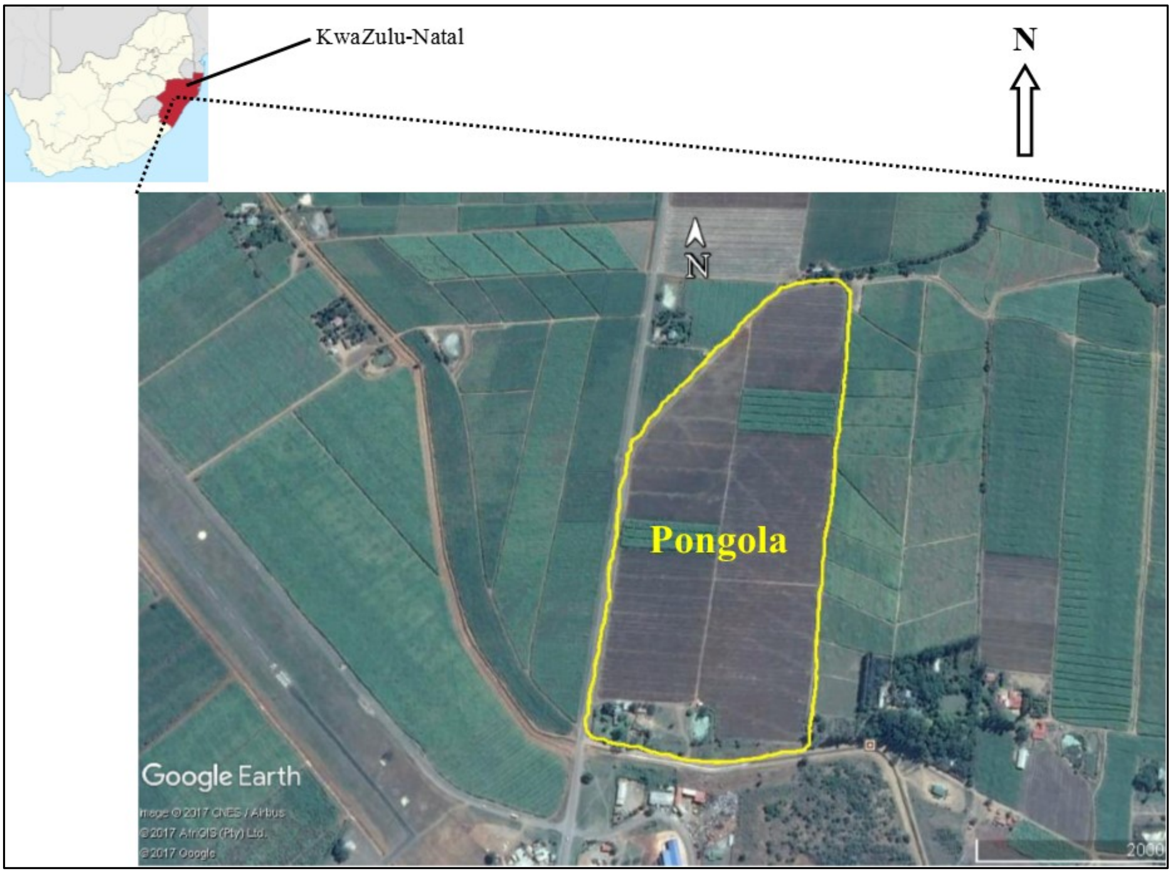



Figure 3.3: Aerial view of study site at Pongola Irrigation Scheme (Google Earth Pro, 25 July 2017; Wikipedia, 2017)

The crop grown at the study site is sugarcane, covering 32 hectares. The site has clay-loam and clay soils, the slopes are fairly gentle and the climate is arid. During April to October (winter season), sugarcane is produced mostly by irrigation, while in November to March (summer season) crops are produced by both rainfall and irrigation (Reinders et al., 2016b).

Reinders et al. (2016b) highlighted on the occurrence of drainage problems in Pongola area in form of shallow water-tables and salinization, being attributed to frequent irrigation in winter season and intense rainfalls during summer season plus base flow from the nearby Lebombo mountains. Artificial subsurface drains were installed in the 1980s, they were then recalculated and reinstalled around 2003 when shallow water-table problems persisted.

### 3.1.3 De Doorns, Breede River Irrigation Scheme

The study site is located at 33°29'05.16"S 19°37'14.80"E, lying south-west of De Doorns between the railway line and Hex River. The De Doorns site for this study is shown in Figure 3.4.

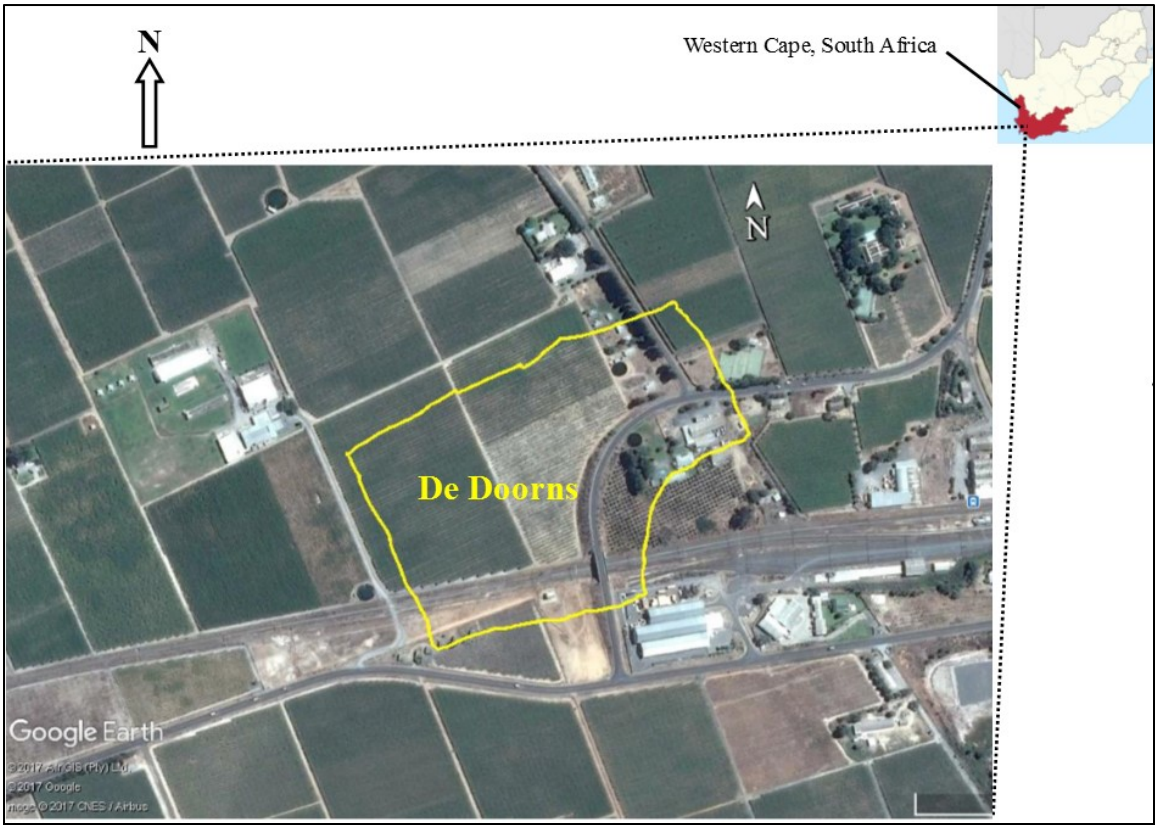



Figure 3.4: Aerial view of study site at De Doorns, Breede Irrigation Scheme (Google Earth Pro, 25 July 2017; Wikipedia, 2017).

South-east of the farm is a steep slope which feeds run-off resulting from the natural drainage patterns towards the Hex River onto the site from the south-eastern side. The surface of the terrain is rolling, leading to inconsistency in the required subsurface drain depth. The field slopeness is around 4.5% at the upper boundary, then flattening out to about 3.2%. The farmer produces Crimson seedless table grapes using 32 l/h micro sprayers for irrigation (Reinders et al., 2016b).

The climate is Mediterranean with most of the rainfall falling in winter (May to August) at an annual average of 300 - 350 mm, and irrigation is more frequent in summer months from September to April. The mean annual temperature is 17°C with maximum temperatures of 37°C occurring in summer and minimum temperatures of 0°C in winter.

At the farm, fine sand makes up most of the topsoil while loamy sand occurs on some areas. Beneath the topsoil lies a layer made of medium to coarse sand, which is more permeable than the topsoil layer. Drainage problems in Breede were highlighted by Reinders et al. (2016a,b,c).

After noticing drainage problems on site in 2002, a subsurface drainage system was designed and installed. The existing subsurface drainage system is a herringbone double sided entry system of field drains leading into a collector drain, with the main drain taking the drainage water down to the Hex River (Figure 3.5).

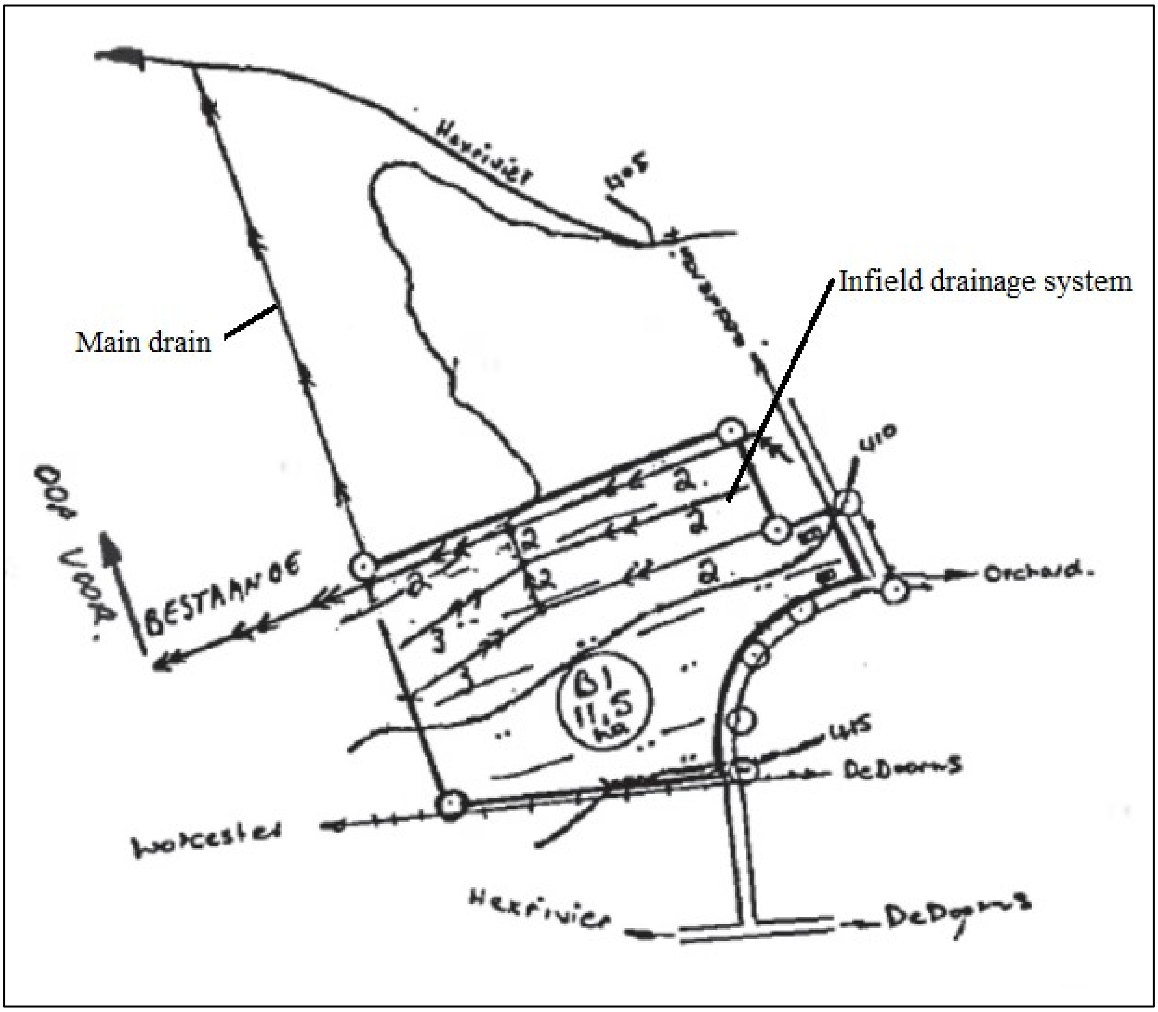



Figure 3.5: Lay-out of drainage system at De Doorns site, Breede (Reinders et al., 2016b).

The drainage system (see Figure 3.5) drains an area of 9.3 hectares, but the main drain's capacity is 42 hectares to cater for future expansions (Reinders et al., 2016b).

These three sites, namely Makhathini, Pongola and De Doorns (Breede) were finally selected and worked on because they had the minimum required data and this study was building on the previous related studies on them. For example, Makhathini and Pongola sites have operational water-table observation points such that historical water-table depth data can be obtained.

### 3.2 Data Collection and Preprocessing

The key data collected, prepared and analyzed included climatic, irrigation, soil properties, drainage system parameters, crop development stages, and observed water-table depths and drain discharges depending on availability. Further selection among the three sites to fulfill the four specific study objectives as in Sections 1.3.4 (i) to 1.3.4 (iv) was guided by availability of minimum required data.

#### 3.2.1 Makhathini

Makhathini irrigation scheme was chosen for the first specific objective:

(i) To determine the extent, severity and possible drivers of shallow water-tables at the study sites.

Historical water-tables data for the 281 water-table observation points in the blocks 6A, 6B, 6E, 15 and 19 at Makhathini (refer to Section 3.1.2 for details) for the years 2009, 2010, 2013, 2014, 2015, 2016 and 2017 was obtained from the Directorate of Water Use and Irrigation Development in the DAFF, in the form of:

- geographical coordinates of observation point (longitude, latitude and altitude), and
- observed water table depth from ground surface for particular period in a year.

As preparation, firstly the geographical coordinates data of all observation points were prepared in XYZ format in Ms Excel where X is longitude (easting), Y is latitude (northing) and Z is the altitude or elevation (meters). Secondly, the geographical coordinates and observed water-tables data for observed points in each year were prepared in XYZ format in Ms Excel where X is longitude (easting), Y is latitude (northing) but Z is the measured water-table depth (meters) for a period in each year. Sugarcane crop effective rooting depth which is also the minimum required depth of groundwater from the soil surface for optimum crop growth and development (Meyer et al., 2011) was set at 1.50 m, as recommended by Allen et al. (1998); Savva and Frenken (2002) and FAO (2017).

Monthly rainfall totals for the period January 2008 to June 2017 were obtained from SASRI Weatherweb website for the closest weather station, Makhathini Agriculture Research Council (ARC) Farm which is located at 27°25'0" S 32°12'0" E.

### 3.2.2 Pongola

Pongola was chosen for specific objectives (ii) and (iii) as given in Sections 1.3.2.2 (ii) and 1.3.2.2 (iii):

(ii) To evaluate EnDrain model's ability in simulating subsurface drainage dynamics at the study sites.

In objective (ii), EnDrain model does not need climatic and irrigation data, it runs using soil properties data, drainage system design parameters and either observed drain discharge or water-table depth (Table 2.1). Therefore, the soil, drainage system and the observed water-table depth and drainage discharge data for the periods October 1998 to September 1999 and September 2011 to February 2012 were obtained from previous work by Malota (2012), Malota and Senzanje (2015) and Reinders et al. (2016a,b,c). Refer to Table 2.1 for detailed explanation about EnDrain inputs data. The authors stated that the larger drain spacing of 90 m was used up to 2002, but then recalculated by using the Hooghoudt (1940) steady state drain spacing equation to the closer spacings of 54 m and 72 m when shallow groundwater tables problems persisted. The portion of the field dominated by clay soils has the spacing of 54 m, while the drains in the portion with clay-loam soils portion are spaced by 72 m.

(iii) To compare EnDrain, DrainMod and WaSim models and recommend the most appropriate considering performance, usability and input data requirements at the study sites.

To fulfill objective (iii), the input requirements were:

- From this current study, results from the second specific objective on performance of EnDrain at Pongola;
- Results of DrainMod's performance at Pongola for the periods October 1998 to September 1999 and September 2011 to February 2012 as reported by Malota (2012); Malota and Senzanje (2015);
- Results of WaSim's performance at Pongola for the periods October 1998 to September 1999 and September 2011 to February 2012 as reported by Malota et al. (n.d.).

### 3.2.3 De Doorns, Breede

De Doorns did not have observed water-table and drain discharge data. This study site was assigned to the fourth specific objective:

(v) To assess performances of the subsurface drainage systems existing at the study areas using DrainMod and WaSim.

There was need for comprehensive input data for DrainMod (Table 2.2) and WaSim (Table 2.3) as explained below.

### 3.2.3.1 Climatic and irrigation data

Most climatic data for the period 2005 to 2015 was obtained from the South African Weather Services (SAWS). The data was at a daily time step, and it included rainfall (mm), temperature (maximum and minimum in °C), relative humidity (%) and wind speed (m/s). Solar radiation intensity (MJ/m$^2$) data was obtained from the Global Weather Data for SWAT website (TAMU, 2017), to facilitate computation of reference evapotranspiration ($ET_0$).

To facilitate objective comparison of the drainage simulation models, the author decided to use the same values of reference evapotranspiration ($ET_0$) in DrainMod and WaSim, instead of using the different inbuilt $ET_0$ calculation methods in the models. $ET_0$ was calculated in Ms Excel by the FAO Penman-Monteith equation (Allen et al., 1998) expressed as:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$ Equation 3.1

Where $ET_0$ is reference evapotranspiration [mm day$^{-1}$], $R_n$ is net radiation at the crop surface [MJ m$^{-2}$ day$^{-1}$], $G$ is soil heat flux density [MJ m$^{-2}$ day$^{-1}$], $T$ = mean daily air temperature at 2 m height [°C], $u_2$ is wind speed at 2 m height [m s$^{-1}$], $e_s$ is saturation vapor pressure [kPa], $e_a$ is actual vapor pressure [kPa], $e_s$-$e_a$ is saturation vapor pressure deficit [kPa], Δ is slope vapor pressure curve [kPa °C$^{-1}$], $\gamma$ is psychrometric constant [kPa °C$^{-1}$].

For DrainMod, the monthly and annual heat (thermal) indices for reference evapotranspiration were determined by Thornthwaite methods (Thornthwaite, 1948) given by:

$$i = \left(\frac{t_j}{5}\right)^{1.514}$$ Equation 3.2

and

$$I = \sum_{j=1}^{12} i \quad , \qquad \text{for } t_o > 0°\text{C}; \qquad \text{Equation 3.3}$$

Where $I$ is annual heat index, $i$ is monthly heat index, $t_o$ is average temperature for a $j^{th}$ month (Thompson, 1999; Dave, 2002).

$ET_0$ correction/reduction factors for use in DrainMod were determined outside DrainMod based on geographical latitude of De Doorns study site. They were calculated by interpolation using tables of factors (Thompson, 1999) for correcting unadjusted $ET_0$ by the Thornthwaite methods. The mean monthly temperatures and precipitation used for the $ET_0$ annual heat (thermal) index and correction/reduction factors calculations were for the 11-year period 2005 to 2015.

Irrigation data was obtained from the farmers' historical records through the South African Irrigation Institute (SABI), in the form of hours of application and micro sprayer application rate (32 l/hr). The available data was for the periods 2009 (October to December), 2010 (January to April), 2011 (October to December) and 2012 (January to April). This period became the guiding period for the modeling exercises in this research study. The irrigation hours were converted to irrigation depth (mm/day) by using information from the AGRIPLAS STAT32/STAT32LH360 statojet micro sprayer specifications, such as the effective values of wetted radius, perimeter and area. Then the computed daily irrigation application depth was added to corresponding daily rainfall to obtain the total water input (gross recharge) per day which is key input into DrainMod and WaSim. For DrainMod, the Ms Excel files for daily $ET_0$, rainfall (plus irrigation) and temperatures for the given period were converted into DrainMod (.wea) format. For WaSim, the single Ms Excel file with daily values of $ET_0$ and rainfall (plus irrigation) was converted into WaSim (.cld) format. Thus, the climatic and irrigation data was ready for importing into DrainMod and WaSim for simulations.

#### 3.2.3.2 Soil data

Basic soil properties data for De Doorns, such as soil texture, soil type, soil profile, bulk density, hydraulic conductivity was obtained from previous efforts by Reinders et al. (2016a,b,c). To facilitate application of DrainMod and WaSim for De Doorns site, the basic soil properties data was used in Rosetta Lite in HYDRUS 1D (Simunek et al., 2007) to estimate the soil water characteristics for individual soil layers within the soil profile.

Rosetta Lite is a programme that is used to approximate advanced soil properties such as saturated hydraulic conductivity, soil water characteristics, in the HYDRUS 1D model. Only observed soil textural class and saturated hydraulic conductivity data were available for De Doorns, and used in Rosetta Lite. The obtained pressure head versus soil moisture content data was tabulated.

As recommended by Skaggs (1980), the soil water characteristics from Rosetta Lite were then used in DMSOILP, a DrainMod subprogram to estimate other key soil hydraulic properties such as water-table depth versus volume drained; water-table depth versus Green-Ampt infiltration parameters and water-table depth versus upward flux. For executing its tasks, the DMSOILP program contains four sub programs, which are:

- VOLDRN – prepares volume drained versus water-table depth from the soil water characteristic curves of each layer in the soil;
- MILNQRK – approximates the unsaturated hydraulic conductivities of each layer in the soil using the soil water characteristic and saturated hydraulic conductivity;
- UPFLUX – calculates steady state upward flux versus water-table depth curve from the unsaturated hydraulic conductivity function of each soil layer;
- GRNAMPT – produces Green-Ampt parameters versus water-table depth by Equations 3.4 and 3.5:

$$A = K_s \times M \times S_{av} \qquad \text{Equation 3.4}$$

and

$$B = K_s \qquad \text{Equation 3.5}$$

Where: $K_s$ is vertical saturated hydraulic conductivity (cm/hr), $M$ is fillable porosity (water content at saturation in $cm^3/cm^3$ minus water content at the desired water table depth), $S_{av}$ is the suction at the wetting front (cm). The resultant soil parameters from the DMSOILP program computations were tabulated.

Soil water pressure heads at field capacity and permanent wilting point vary with soil type (McCarthy et al., 2016), as shown in Table 3.1. These were used as guidelines for estimating WaSim soil inputs of soil moisture contents at saturation, field capacity and permanent wilting point, from the soil water characteristic data that was obtained from DMSOILP.

Other WaSim soil inputs such as drainage constant, curve number and leaching efficiency were estimated from methods and guideline values provided by Hess et al. (2000).

Table 3.1: Pressure heads for different soil types at key water retention points

| | **Head (cm, water)** | |
|---|---|---|
| **Soil type** | **Field capacity** | **Permanent wilting point** |
| Clay, clay loam | -330 | -15000 |
| Sandy | -100 | -3000 |

### 3.2.3.3 Drainage system design parameters

The parameters defined in Tables 2.2 and 2.3 of the existing drainage were used as measured by Reinders et al. (2016a,b,c).

### 3.2.3.4 Trafficability parameters

The trafficability parameters were estimated using methods recommended by DrainMod developers (Skaggs, 1980; Workman et al., 1994).

### 3.2.3.5 Crop system parameters – table grapes

The maximum effective root depth for table grapes is 1.0 to 2.0 m, with a growth period of 240 days to a full year in low latitudes areas such as De Doorns (Allen et al., 1998; Savva and Frenken, 2002; Savva and Frenken, 2001; Natural Resources Management Directorate, 2011). The majority of the roots usually occupy the top soil layer of 0.5 to 1.5 m, while normally all of the water is drawn from the top 1 to 2 m soil depth (FAO, 2017). DAFF (2012) states that grapevines take three years to produce maximum yields, and recommended harvesting time for mature grapes is from November to January. For this study, it was assumed that the grapevines are in productive stage with a 240-day growing season starting in May and harvesting in January the following year.

USDA (1993) provided means for estimating the growth stages of table grapes, as shown in Table 3.2. These were used to estimate canopy development and crop cover with time for this study. The growth of table grapes roots and change in root depth with time were estimated form typical values found by Van Zyl (1984) which are given in Table 3.3.

Table 3.2: Typical crop growth stage coefficient curve for grapes (USDA, 1993).

| Month | Day of the month | Growth coefficient | Month | Day of the month | Growth coefficient |
|---|---|---|---|---|---|
| January | 15 | 0.20 | July | 15 | 0.80 |
| February | 15 | 0.24 | August | 15 | 0.76 |
| March | 15 | 0.33 | September | 15 | 0.61 |
| April | 15 | 0.50 | October | 15 | 0.50 |
| May | 15 | 0.71 | November | 15 | 0.35 |
| June | 15 | 0.80 | December | 15 | 0.23 |
| June | 30 | 0.81 | | | |

Table 3.3: Typical root development with time for table grapes (Van Zyl, 1984).

| Month | Day of the month | Effective root depth (cm) | Month | Day of the month | Effective root depth (cm) |
|---|---|---|---|---|---|
| July | 23 | 16 | November | 7 | 93 |
| July | 28 | 43 | November | 24 | 93 |
| August | 14 | 62 | December | 5 | 93 |
| August | 29 | 86 | December | 18 | 93 |
| September | 5 | 93 | January | 9 | 111 |
| September | 10 | 93 | January | 26 | 166 |
| September | 18 | 93 | February | 21 | 146 |
| October | 23 | 93 | March | 28 | 64 |

## 3.3 Data Analysis

### 3.3.1 Spatial distribution of shallow water-tables in Makhathini

Historical water-table depths data for the periods 2009, 2010, 2013, 2014, 2015, 2016 and 2017 was prepared in XYZ format, as was explained in Section 3.2.1. The first batch of X (longitude in decimal degrees), Y (latitude in decimal degrees) and Z (altitude or elevation in meters) data in Ms Excel was imported into Surfer 14 (Golden Software, 2017) software to generate a map displaying the locations and altitudes of all the observation points. This map was meant to show topography and spatial distribution of the blocks and water-table observation points. Surfer 14 is a grid-based mapping program that applies the concept of interpolation on irregularly spaced XYZ data into a regularly spaced grid (Golden Software, 2017).

The second batch of X (longitude in decimal degrees), Y (latitude in decimal degrees) and Z (measured water-table depth in metres) data in Ms Excel was imported into Surfer 14 (GoldenSoftware, 2017) software to map the occurrence and extent of shallow water-tables for each observed period at the Makhathini study site. The water table maps were generated for all the years studied, using 1.5 m as the distinguishing depth between shallow (<1.5 m) and deep (>1.5 m) water-tables for sugarcane crop (Allen et al., 1998; Savva and Frenken, 2002; Meyer et al., 2011; FAO, 2017). Surfer 14 was then used to quantify the proportions of shallow water-table affected and unaffected areas out of the total area studied. From the monthly rainfall data obtained from the SASRI Weatherweb for Makhathini ARC Farm (SASRI, 2017), rainfall for the last hydrological year (12 months) was summed up for each period coinciding with an observed water-table depth. This was meant to study the effect of rainfall recharge on water-table depth. The results were tabulated and the trends were analyzed qualitatively.

The conceptual flow of work in assessing the occurrences and causes of shallow water-tables at Makhathini followed a general approach as outlined in Figure 3.6 with respect to the first objective of this study.

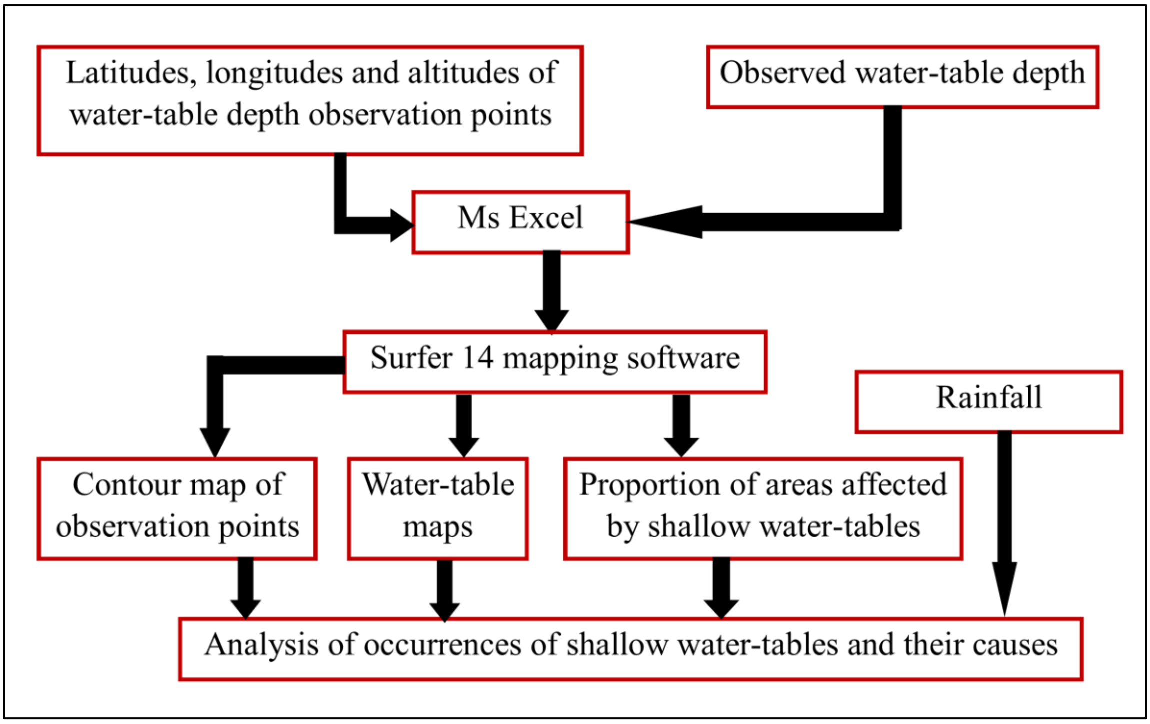



Figure 3.6: Conceptual flow of study for specific objective (i).

### 3.3.2 Modeling drain discharge using EnDrain in Pongola

Measured design parameters of the existing drainage system were reported in Malota (2012), Malota and Senzanje (2015) and Reinders et al. (2016a,b,c) as shown in Table 3.4.

Table 3.4: Current drainage system design parameters for the existing subsurface drainage systems at Pongola.

| **Parameter** | **Description** | **Measured** |
|---|---|---|
| $D_{il}$ (m) | Depth to impermeable layer from soil surface | ≈ 9.00 |
| $K_1$ (m/day) | Hydraulic conductivity of soil layer above drain | 0.98 |
| $K_2$ (m/day) | Hydraulic conductivity of soil layer below drain | 0.32 |
| q, c (mm/day, m) | Drainage coefficient and drain depth to pipe bottom | 5, 1.8 |
| a (m) | Minimum drained soil depth between drains | 1.00 |
| h (m) | Water depth above the drain, between drains | 0.80 |
| L (m) | Actual drain spacing (up to 2002) | 90.00 |
| | Actual drain spacing (from 2002) | 54.00 |

It is advisable to investigate a drainage model for its reliability in local conditions of a study site, thus the requirement for calibrating and validating the model with site specific conditions because such site-specific scenarios vary with those for which the model was originally developed from (Hirekhan et al., 2007; Reinders et al., 2016b). Model calibration is the systematic process of tuning model parameter values to yield a set of parameters which optimally minimizes differences between the estimated and observed data sets (Moriasi et al., 2007; Vaze et al., 2012). In practice, calibration involves cautiously selecting model parameter values, adjusting them within their accepted ranges, and comparing simulated output variables with observed data for prevailing set of conditions (Daggupati et al., 2015). Using the model parameters optimized during the calibration period, model validation involves running the model using the optimized parameters to demonstrate the model's ability in making sufficiently reliable simulations (Moriasi, et al., 2007).

Most of the key inputs in the EnDrain model are soil properties. To test the performance of EnDrain model, observed water-table depth was used as input, along with other relevant input data discussed in previous sections, to predict drain discharge. The predicted discharge was then compared with the observed discharge. This was all achieved through calibration and validation.

Although there is no published literature on calibration and validation of EnDrain model, other models such as DrainMod and WaSim have historically been calibrated and validated by adjusting input data including soil properties parameters such as hydraulic conductivity, to increase the agreement between simulated and observed water-table depths and drain discharge (Hirekhan et al., 2007; Skaggs et al., 2012). Some of EnDrain input data are fixed design parameters of the existing irrigation system under study, for example, depth of drainage pipe, spacing of parallel drainage pipes, drainage pipe diameter, observed water-table depth; they cannot be changed because they are the reality. This motivated the author to calibrate EnDrain by systematically adjusting the soil parameters in Table 3.6 to optimally minimize the difference of the simulated discharge from the observed discharge, as recommended by Moriasi et al. (2007), Daggupati et al., (2015) and Deelstra et al. (n.d.). Since the results from this section were to be used later in the next section for comparing performance of EnDrain, DrainMod and WaSim at Pongola, this study adopted the manual trial and error calibration method as well as the common temporal split-sample method used by Malota (2012), Malota and Senzanje (2015) and Malota et al. (n.d.). The input data for periods October 1998 to September 1999 and September 2011 to February 2012 was used for model calibration and validation, respectively. Drain depth was 1.8 m, while drain spacings were taken as 90 m and 54 m for the calibration (October 1998 to September 1999) and validation (2011 to 2012), respectively (Malota, 2102). Depth of water-table midway between drains (Dm), a key input in EnDrain to simulate drain discharges, were the observed water-table depths in Malota (2012).

Comparison of simulated and observed drain discharge was by two complementary assessments; visual and statistical. Visual assessment of agreement between simulated and observed drain discharge involved checking of notable trends, discrepancies and responses with time in the plots of (i) daily observed drain discharge (mm/day) and simulated discharge (mm/day), and (ii) cumulative drain discharge (mm) as recommended by El-Sadek et al. (2001). Once the graphs of simulated and observed drain discharges are visualized to match reasonably in closeness and trends, the results were further assessed statistically by assessing quantities of measures of performance.

In this study, the author used four quantitative statistical parameters to quantify the agreement between simulated and observed results: Pearson's product-moment correlation coefficient ($R^2$), coefficient of residual mass (CRM), mean absolute error (MAE) and root mean square error (RMSE) (Singh et al., 2006; Wang et al., 2006; Skaggs et al., 2012), given as:

$$R^2 = \frac{\left(\Sigma_{i=1}^{n}\left(O_i - \overline{O}\right)\left(P_i - \overline{P}\right)\right)^2}{\Sigma_{i=1}^{n}\left(O_i - \overline{O}\right)^2 \Sigma_{i=1}^{n}\left(P_i - \overline{P}\right)^2}$$

Equation 3.6

$$CRM = \frac{\Sigma_{i=1}^{n} O_i - \Sigma_{i=1}^{n} P_i}{\Sigma_{i=1}^{n} O_i}$$

Equation 3.7

$$MAE = \frac{\Sigma_{i=1}^{n}\left|\left(O_i - P_i\right)\right|}{n}$$

Equation 3.8

$$RMSE = \sqrt{\frac{1}{n}\Sigma_{i=1}^{n}\left(O_i - P_i\right)^2}$$

Equation 3.9

Where $O_i$ is the observed value of the *i*th observation, $P_i$ the predicted value of the *i*th observation, $n$ is the number of the observations, $\overline{O}$ = arithmetic mean of observed daily drain flow, $\overline{P}$ = arithmetic mean of predicted daily drain flow. More details on these parameters are given in Table 3.5.

Table 3.5: Statistical measures of assessing model performance during calibration and validation

| **Parameter** | **Performance measures** | **Range** | **Best** | **Interpretation** |
|---|---|---|---|---|
| $R^2$ | Quantifies agreement between the simulated and observed values | 0 to 1 | 1 with 0 intercept | 0 (no correlation), 1 (perfect correlation) |
| CRM | Overestimation or underestimate by the model | -∞ to 1 | Closer to 0 | Acceptance: within ±0.25; CRM<0: model tend to overestimate; CRM>0: model tend to underestimate |
| MAE; mm/day | Difference between the model simulations and observations | 0 to ∞ | 0 | Values closer to 0 correspond to best fit |
| RMSE; mm/day | Correlation between simulated and measured data sets | 0 to ∞ | 0 | Values closer to 0 correspond to best fit |

Table 3.6: Adjusted parameters during EnDrain calibration.

| **Parameter** | **Description and units** |
|---|---|
| $D_1$, $D_2$ | Bottom depths of 1st and 2nd layers, respectively, below soil surface (m) |
| E | Entrance resistance (day/m) |
| $K_a$ | Hydraulic permeability, above drain level (m/day) |
| $K_{b1}$, $K_{v1}$ | Horizontal and vertical permeability, respectively, 1st soil layer (day/m) |

The optimum calibrated parameters (Table 3.6) were then the input parameters during model validation (September 2011 to February 2012), where no adjustments were done. Visual assessment of plots (for daily and cumulative simulated and observed drain discharge) were done, and the statistical measures $R^2$, CRM, MAE and RMSE were evaluated again to assess performance of the model with calibrated parameters in simulating observed water-table depth.

Comparison of performance was also made between the Energy balance method and the Darcy equation method in EnDrain during both calibration and validation, by comparing their fluctuations, responsiveness and trends with respect with observed flow. EnDrain has two optional methods for simulating subsurface drainage, namely Energy balance method and Darcy method. They differ in their approaches, the Energy balance method utilizes the equation of groundwater flow (Oosterbaan et al., 1996) which calculates the energy flux by integrating the product of the hydraulic potential and the flow velocity. The Darcy method applies combination of the Darcy equation and water balance (continuity) or conservation of mass concepts. They were compared to select the most appropriate which would then be used for further comparison with DrainMod and WaSim in the third specific objective of this study. Their values of $R^2$, CRM, MAE and RMSE were also compared to infer the methods' performance. The conceptual flow of work done in this section is illustrated in Figure 3.7.

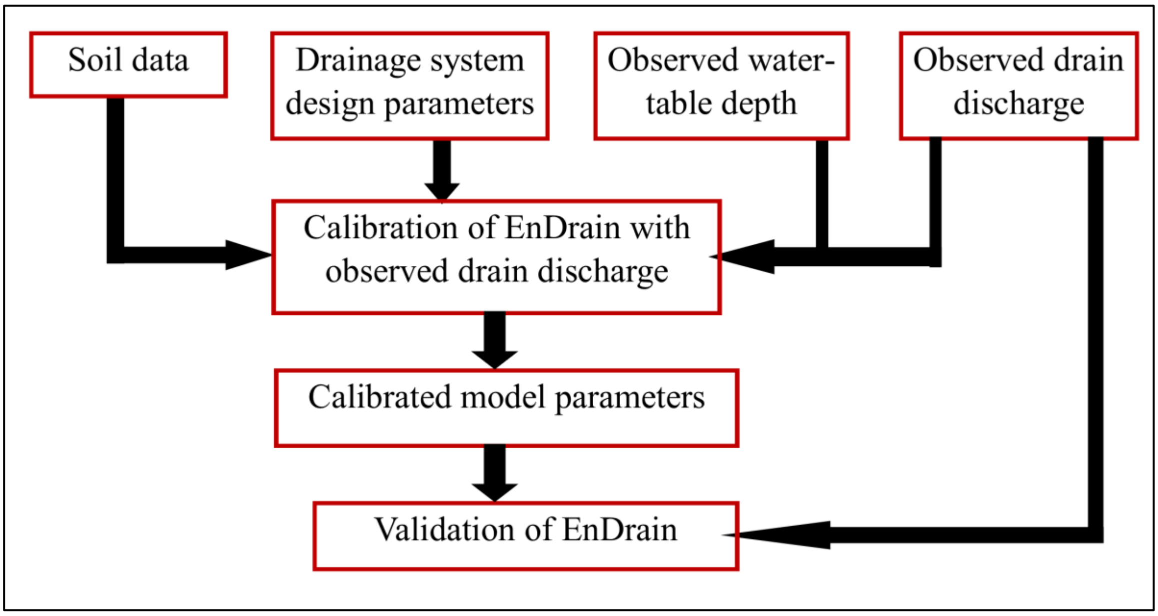



Figure 3.7: Conceptual flow of study for specific objective (ii).

### 3.3.3 Comparison of DrainMod, EnDrain and WaSim at Pongola

To recommend the most appropriate drainage simulation model, the performances of DrainMod, EnDrain and WaSim were compared for the same study site, Pongola. Results for DrainMod and WaSim at Pongola from previous work done by Malota (2012), Malota and Senzanje (2015) and Malota et al. (n.d.) were used with permission from the authors to compare with results from EnDrain from this current study (Section 3.3.2). For EnDrain, only the results from the Energy balance method were used since it was more accurate than the Darcy equation method. This comparison was important because it is often claimed that the rarely-used EnDrain is a simpler and user-friendly model compared to the widely-used DrainMod and moderately- used WaSim. Additionally, EnDrain has less input data requirements than both DrainMod and WaSim, so it is necessary to see how a model which uses less input data performs as compared to another which needs more data.

Both visual assessment and statistical analysis were used to compare and contrast the three models' performance from calibration to validation. Visual assessment was through analysis of time series plots for (i) daily observed discharge versus simulated discharge (mm/day), and (ii) cumulative discharge (mm). Statistical analysis was for statistical measures including $R^2$, CRM, MAE and RMSE. This section is illustrated in Figure 3.8.

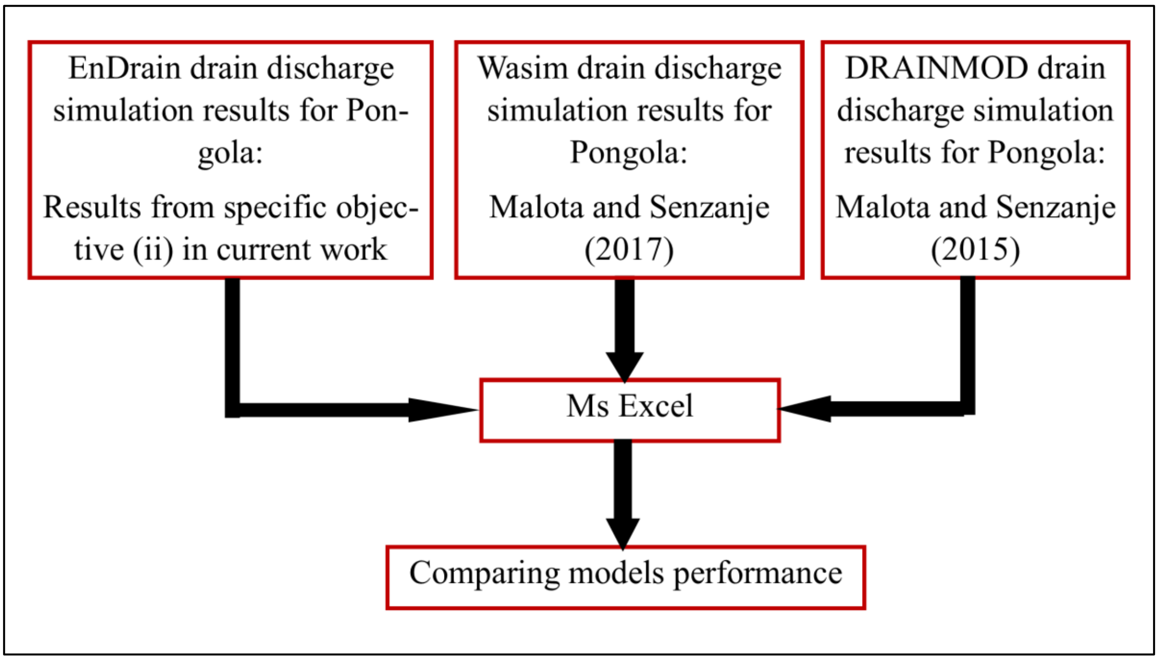



Figure 3.8: Conceptual flow of study for specific objective (iii).

### 3.3.4 Subsurface drainage simulations by DrainMod and WaSim at De Doorns site, Breede

Using input data collected and prepared in the previous Sections 3.2.3, DrainMod and WaSim were applied to simulate water-table depth and drainage discharge at De Doorns for the two periods October 2009 to April 2010 and October 2011 to April 2012. Due to lack of observed water-table depth and drain discharge data, neither calibration nor validation was done. However, the two models were assessed on their trends and responsiveness, as well as their output sum of excess water (SEW) and sum of excess water day (SED). SEW and SED are measures of crop's stress due to high water tables and excessive soil water conditions, when the water-tables encroach into the threshold (critical) rooting depth (McFarlane et al., 1989; Workman et al., 1994). SEW was computed using the equation:

$$SEWd_c = \sum_{i=1}^{n} \left( d_c - x_i \right) \qquad \text{Equation 3.10}$$

Where: $d_c$ = minimum depth (cm) beyond which a crop suffers stress due excessive soil moisture = 150 cm in this case for table grapes, $x_i$ = the water-table depth in cm on day $i$, with initial $i$ = 1 being the first day and $n$ the length of the crop growing season in number of days. SED was counted as the total number of days when the water-tables intrude into the critical crop rooting depth (McFarlane et al., 1989; Setter and Waters, 2003; Jung, et al., 2010).

Both SEW and SED are indices of waterlogging intensity (Sieben, 1964), and Moore (2001) classified waterlogging or drainage classes as well drained, moderately well drained and imperfectly drained for SEW values of less than 30, 30 to 100, and 100 to 250, respectively. Effect of drainage conditions on crop yields were commented on based on the fact that yields decreases can be observed at SEW values of greater than 100 cm-days (Sieben, 1964). Given that the effective rooting depth and minimum groundwater depth for table grapes is suggested as 1.50 m by Allen et al. (1998); Savva and Frenken (2001), Savva and Frenken (2002) and Natural Resources Management Directorate (2011), this means that the $d_c$ for this study is 150 cm. The $SEWd_c$ and $SEDd_c$ become SEW150 and SED150, they were calculated from the simulated water-table depths from DrainMod and WaSim. The interaction between a period's total rainfall plus irrigation and SEW150 was explored, as well as comparison of the SEW150 from both models for the same period. Similar interactions and comparisons were done for SED150. Comparison was also done between

(i) each model for the two periods, (ii) both models during each period, and (iii) both models during the two simulation periods. Based on the SEW and SED values, the performance of the existing subsurface drainage system at De Doorns was discussed. The workflow for this section is shown as Figure 3.9.

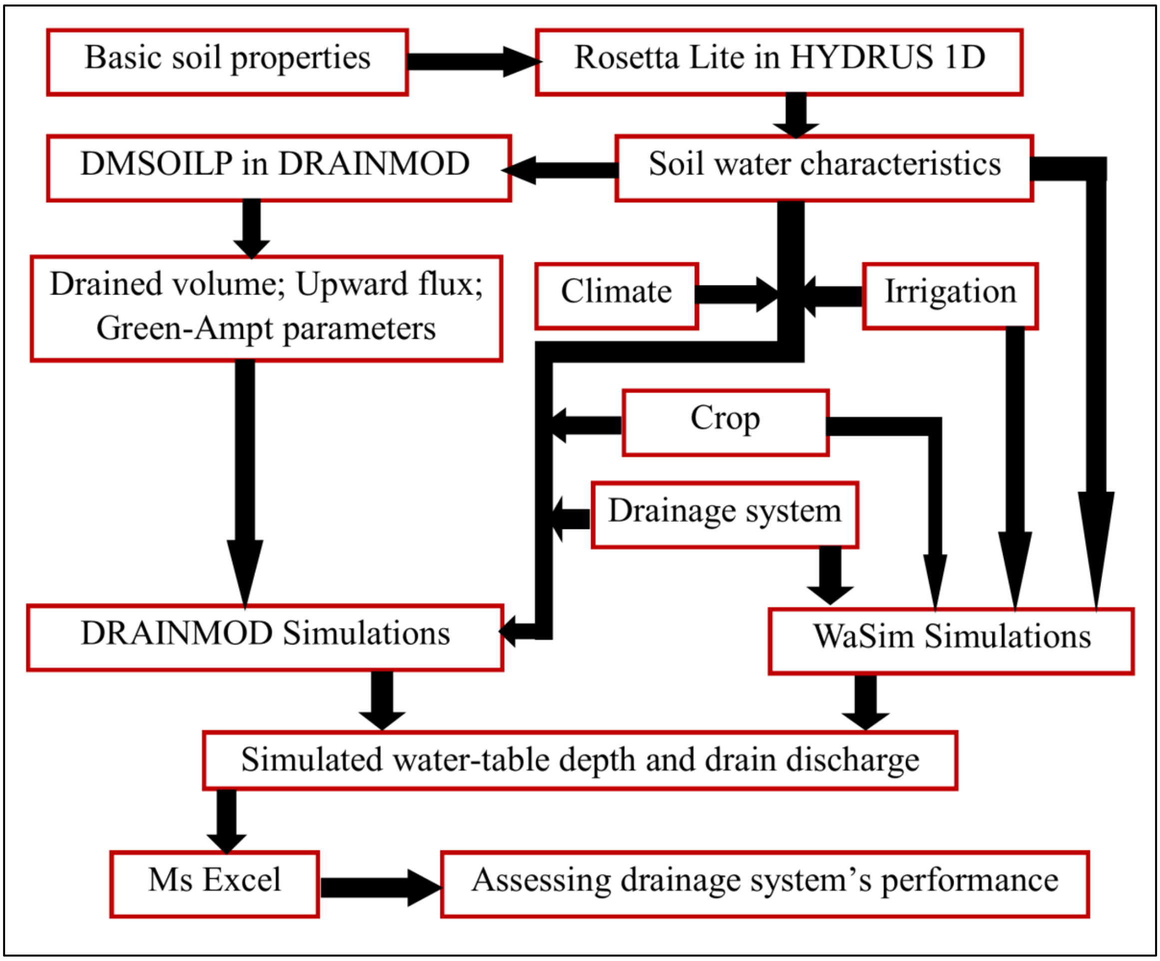



Figure 3.9: Conceptual flow of study for specific objective (iv).

# Chapter 4 : RESULTS AND DISCUSSION

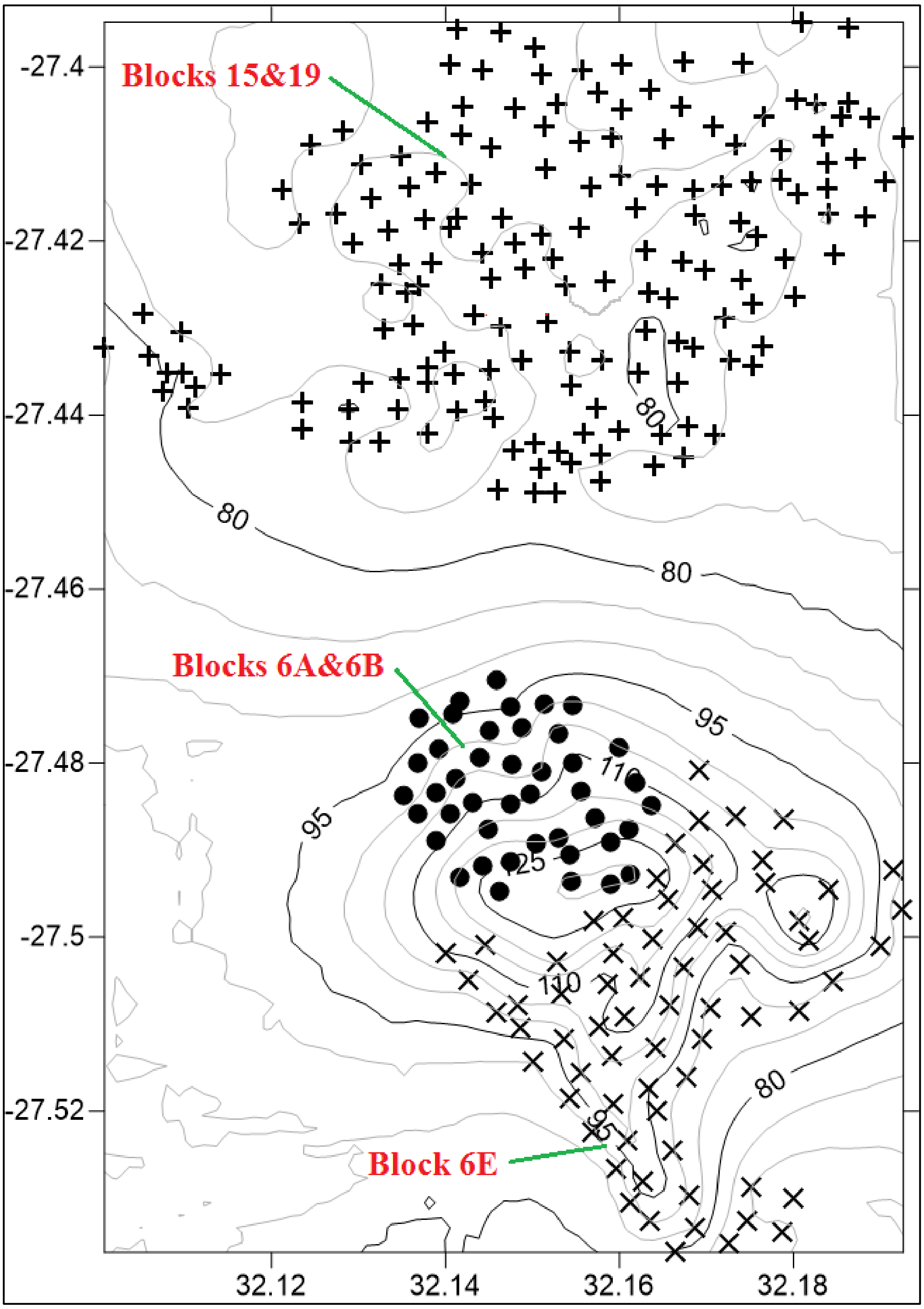
This section presents and discusses the findings from the study.

## Chapter Outline

This chapter seeks to present and discuss all the results that were obtained after collecting, preparing and analysing the data as described in the preceding sections.

### 4.1 Spatial and Temporal Distribution of Shallow Water-tables in Makhathini

Figure 4.1 shows the locations of water-table observation points on the Makhathini blocks (6A, 6B, 6E, 15 and 19) studied at the irrigation scheme.



**Key:**

| **Symbol** | **Water-table depth (m)** |
|---|---|
| + | Water table observation point in blocks 15 and 19 |
| • | Water table observation point in blocks 6A and 6B |
| x | Water table observation point in block 6E |

Figure 4.1: Map of water-table observation points on blocks 6A, 6B, 6E, 15 and 19 of Makhathini Irrigation Scheme.

The Makhathini study site comprises of blocks 15, 19, 6A, 6B and 6E as labelled in red in the map in Figure 4.1. The map (Figure 4.1) shows that blocks 15 and 19 are located at the lowest elevations than all other blocks in this study, ranging from 65 m to 87 m. Blocks 6A and 6B are located from moderate altitudes (87 m to 109 m) to higher ground (109 m to 130 m). Block 6E spans from lower altitude (65 m to 87 m) through moderate altitude (87 m to 109 m) to higher ground (109 m to 130 m).

The maps in Figures 4.2 to 4.7 show spatial and temporal variation of water-table depths for the periods 2009, 2010, 2013, 2014, 2015, 2016 and 2017. The key for interpreting the symbols and colours on the water-table maps is given.

Key for water-tables maps in Figures 4.2 to 4.7.

| **Symbol or colour** | **Water-table depth (m)** |
|---|---|
| | 0.0 to 1.5 |
| | Deeper than 1.5 |
| + | Water table observation point in blocks 15 and 19 |
| • | Water table observation point in blocks 6A and 6B |
| x | Water table observation point in block 6E |
| *Circled +, •, x | Measured for the period in question |
| *Uncircled +, •, x | Not measured for the period in question |
| +, • , x in blank background | Not measured for the period in question |

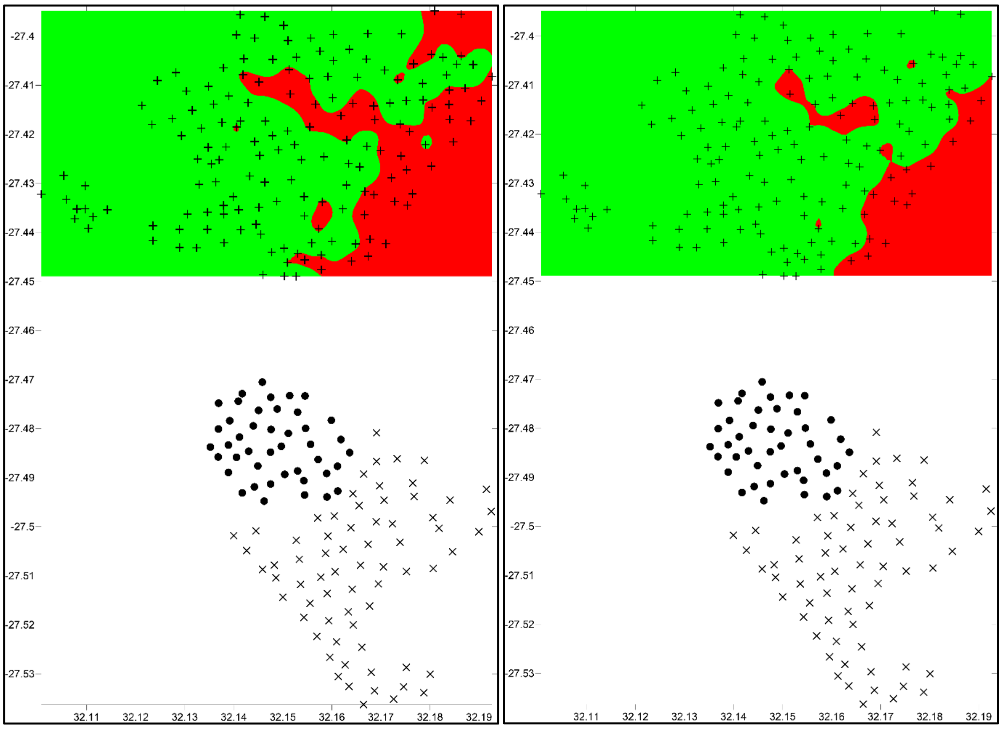



Figure 4.2: Water-table maps for Makhathini blocks 6A, 6B, 6E, 15 and 19, generated using water-table data monitored with observation points in May 2009 (left) and May 2010 (right).

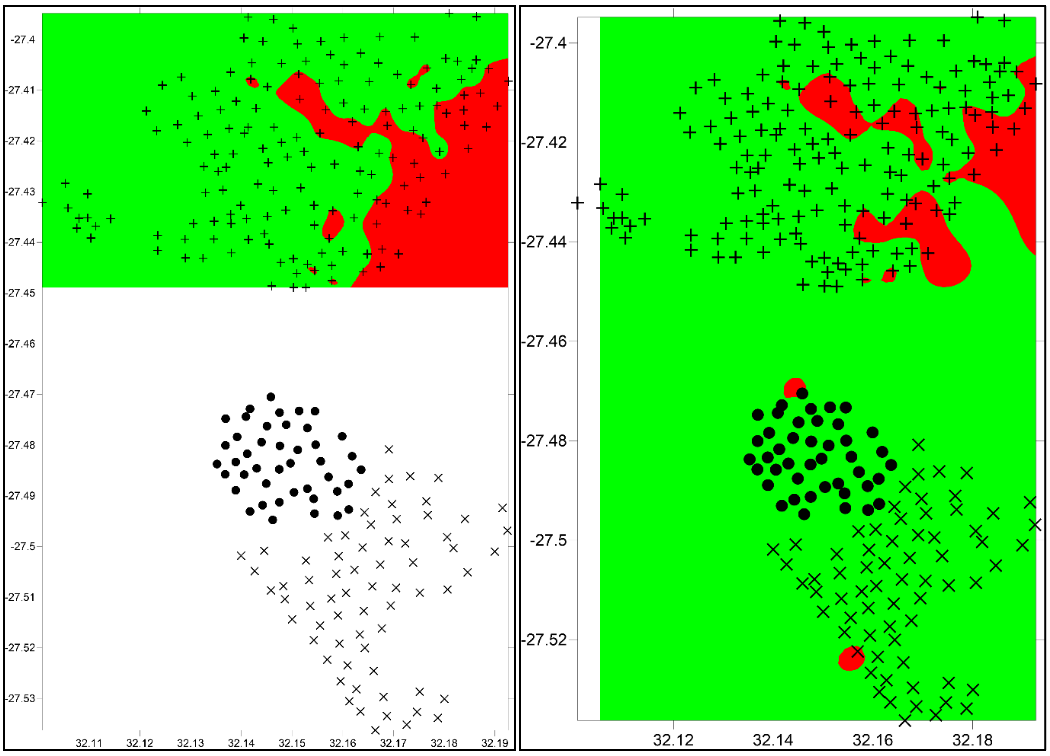



Figure 4.3: Water-table maps for Makhathini blocks 6A, 6B, 6E, 15 and 19, generated using water-table data monitored with observation points during May 2013 (left) and October 2013 (right).

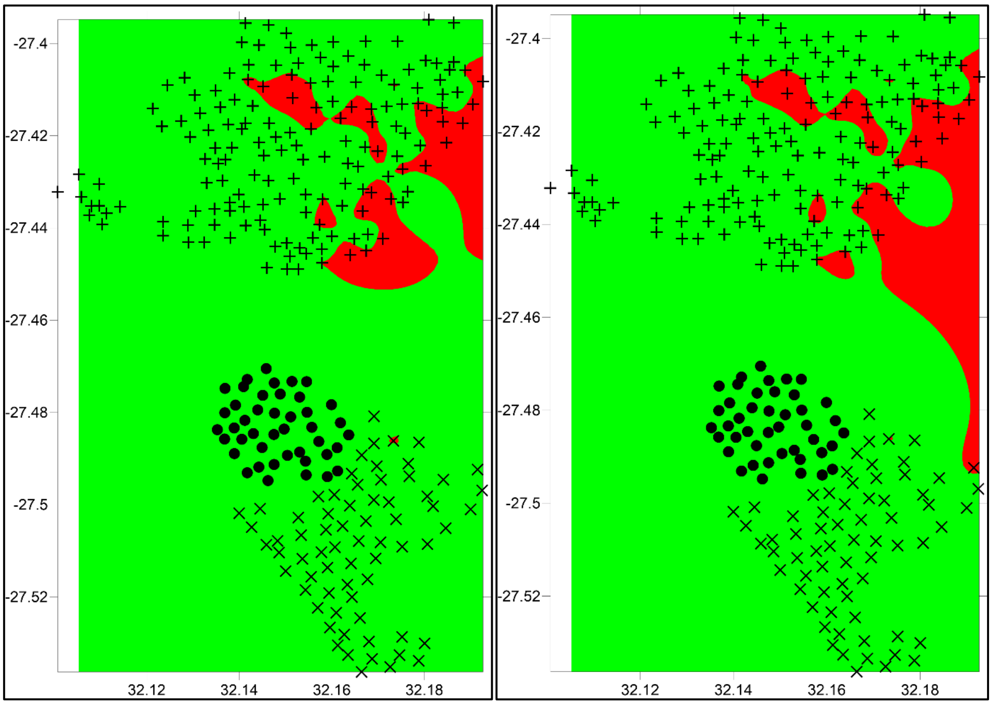



Figure 4.4: Water-table maps for Makhathini blocks 6A, 6B, 6E, 15 and 19, generated using water-table data monitored with observation points during May 2014 (left) and October 2014 (right).

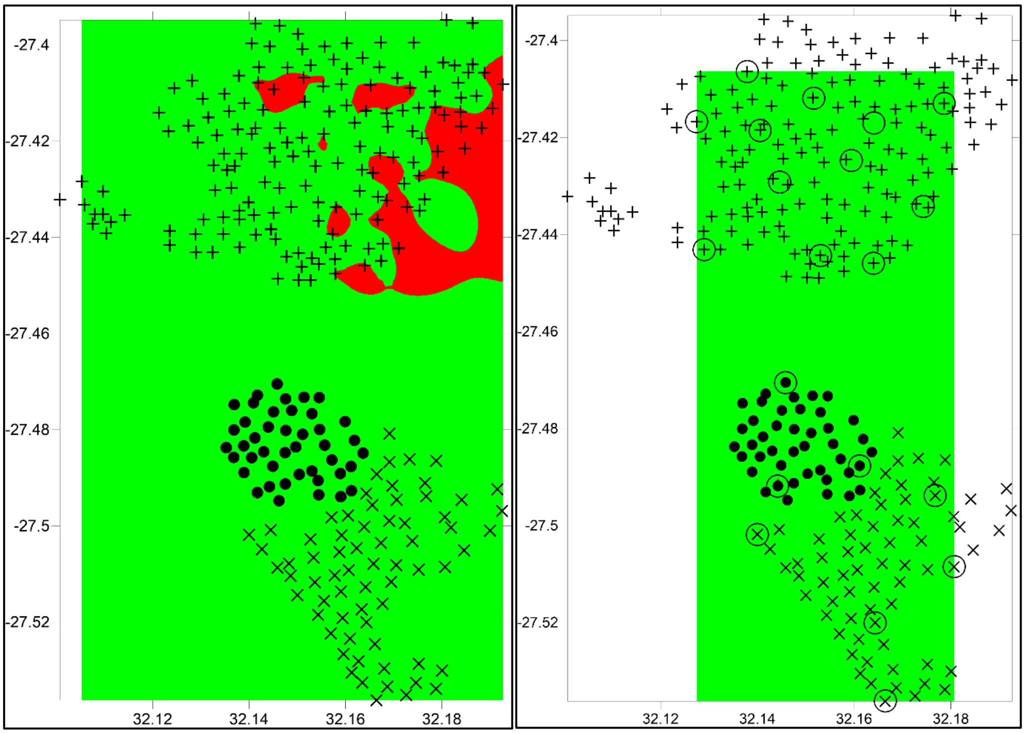



Figure 4.5: Water-table maps for Makhathini blocks 6A, 6B, 6E, 15 and 19, generated using water-table data monitored with observation points during May 2015 (left) and February 2016 (right).

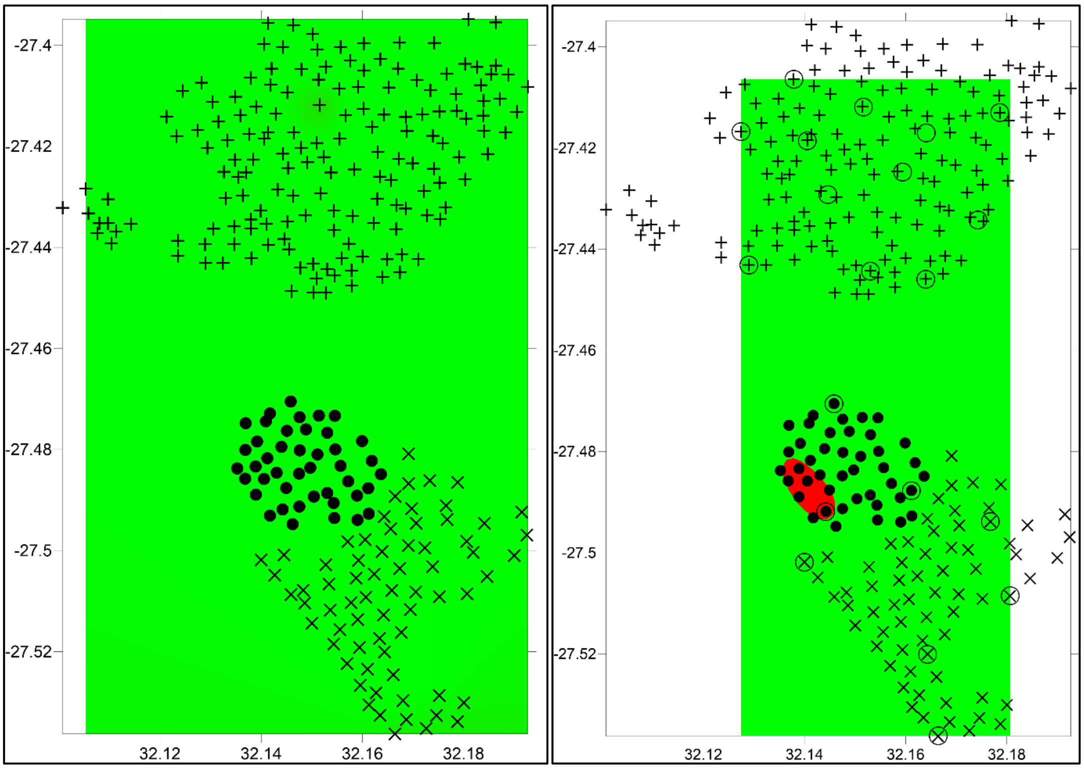



Figure 4.6: Water-table maps for Makhathini blocks 6A, 6B, 6E, 15 and 19, generated using water-table data monitored with observation points during August-September 2016 (left) and May 2017 (right).

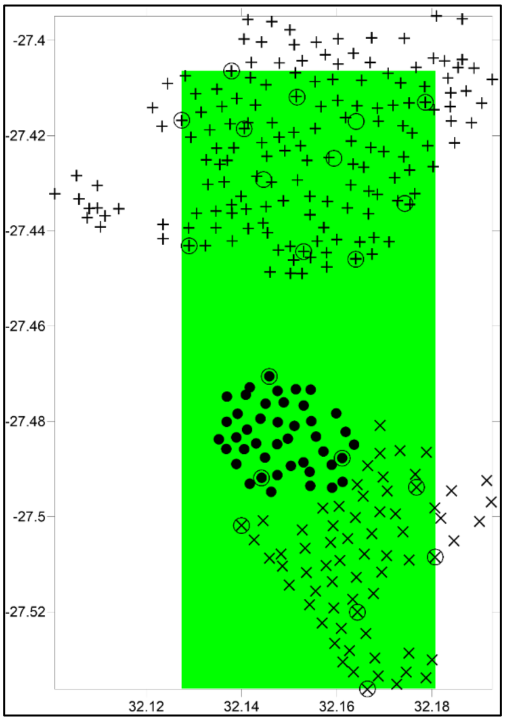



Figure 4.7: Water-table maps for Makhathini blocks 6A, 6B, 6E, 15 and 19, generated using water-table data monitored with observation points in June 2017.

The proportions of areas affected by shallow water-tables (as percentage out of the total area) as calculated in Surfer 14, and the total rainfall received in the 12 months before the period of observation are shown in Table 4.1. The respective time series plot of minimum recorded water-table depths is shown in Figure 4.8.

Table 4.1: Proportions of shallow water-table affected areas (from Surfer 14), total rainfalls for 12 months preceding the observed period and corresponding seasons (from Makhathini ARC Farm weather station) for Makhathini blocks.

| Year | Affected area, % | Rainfall in last 12 months, mm | Season |
|---|---|---|---|
| May 2009 | 25.7 | 457.2 | End of wet |
| May 2010 | 17.1 | 612.2 | End of wet |
| May 2013 | 21.9 | 740.4 | End of wet |
| October 2013 | 5.9 | 574.9 | End of dry |
| May 2014 | 6.9 | 827.8 | End of wet |
| October 2014 | 9.6 | 797.0 | End of dry |
| May 2015 | 7.0 | 515.2 | End of wet |
| February 2016 | 0.0 | 441.4 | Wet |
| August to September 2016 | 0.0 | 405.2 | End of dry |
| May 2017 | 1.1 | 562.1 | End of wet |
| June 2017 | 1.1 | 530.9 | Dry |
| Mean | 8.8 | 587.7 | |

The water-table maps in Figures 4.2 to 4.7 and information in Table 4.1 indicate that for the seven years period studied, an average of 8.8 % of the irrigated land was affected by shallow water-table depths. This value is within the range of 6 to 26% reported by Freisem and Scheumann (2001). Blocks 15 and 19 had the highest prevalence of shallow water tables, this can be attributed to downslope seepage flow from higher elevation areas, by virtue of the block's location in low-lying areas as compared to other blocks. Blocks 6A and 6B have a low occurrence of shallow water-table depths because they are located in areas of moderate to high altitudes. Block 6E has the lowest incidence of shallow water tables because it has an operational partially installed drainage system which removes excess water, and the block's bigger part is located in moderate to high ground areas. Similar trends of shallow water-tables in low-lying areas as compared to high elevation areas were reported by Malota (2012) and, Malota and Senzanje (2016) and at Pongola Irrigation Scheme, also under sugarcane crop and in the same province of KwaZulu-Natal.

Figure 8 shows trend in recorded minimum water-table depth at the Makhathini irrigation during the study period. In Figure 4.8, the green arrow shows a time period (between April 2012 and May2013) when a drainage ditch was constructed in block 6E at Makhathini irrigation scheme as claimed by Mjindi Farming (2013). Interestingly, after construction of the drainage ditch, the area affected by the shallow water-table depth fell drastically. Figure 4.8 shows a general increase in recorded minimum water-table depth, with a sharp increase evident around May 2015, which can be attributed to the effectiveness of the new drainage system in place. The coincidence is too much because the area affected by shallow water-tables continued to fall until it was almost zero while the minimum recorded water-table depth increased to deeper than one (1) metre. This implies that the drainage system was removing excess soil water resulting in lowered water-tables. Of course, the rainfall was also decreasing but not at a faster rate as area affected by shallow water-tables. The data does not sufficiently show seasonal variations in area affected by shallow water table depths, i.e. there is no clear distinction between affected areas in or at the end of either the wet and dry seasons. Generally, the area affected decreased from 2009 to 2017.

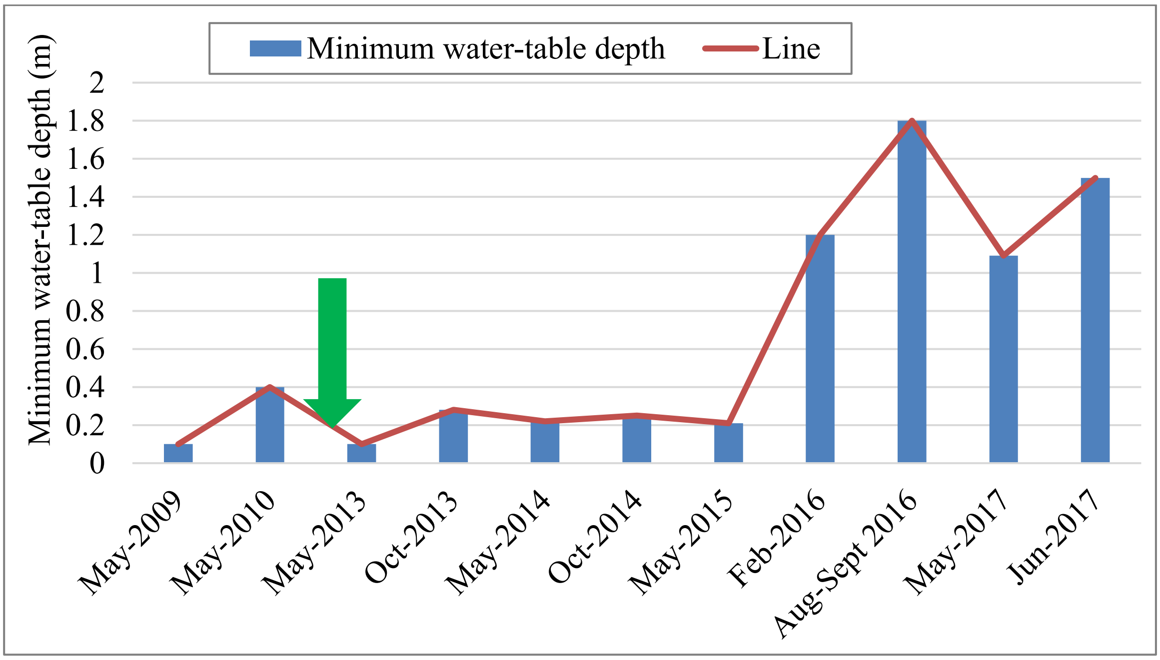



Figure 4.8: Plot of minimum water-table depths observed per period for Makhathini blocks.

These results indicate that blocks 15 and 19 need interventions to remove the excess water and lower the water-tables to facilitate optimum conditions (WTD>1.5 m) for sugarcane growth and development. Such interventions can be in form of installing optimised subsurface drainage systems.

### 4.6 Modeling Drain Discharge Using EnDrain in Pongola

Hydraulic conductivity data for Pongola as obtained from Malota and Senzanje (2015), Malota (2012) and Reinders et. al. (2016) is shown in Table 3.4.

EnDrain model calibration was done by comparing model simulated drain discharge with observed discharge for the period October 1998 to September 1999, while adjusting the parameters whose calibrated values during calibration are shown in Table 4.2.

Table 4.2: EnDrain calibrated parameters (http://www.waterlog.info/endrain.htm).

| **Parameter, symbol and units** | **Value** |
|---|---|
| Bottom depth of 1st layer below soil surface, $D_1$ (m) | 1.90 |
| Bottom depth of 2nd layer below soil surface, $D_2$ (m) | 2.30 |
| Entrance resistance, E (day/m) | 0.1 |
| Hydraulic permeability, above drain level, $K_a$ (m/day) | 1.1 |
| Horizontal permeability, 1st soil layer, $K_{b1}$ (m/day) | 0.35 |
| Vertical permeability, 1st soil layer, $K_{v1}$ (m/day) | 1 |

#### 4.6.1 EnDrain model performance during calibration

Figure 4.9 shows the time series plot of daily observed and simulated drain discharge during the calibration period.

From Figure 4.9, it is apparent that the simulated drain discharge follows the trend of the observed drainage at between moderate to high flows than at low flows. This means that the model predicts moderate to high flows better than low flows closer to 0 mm/day. Generally, the simulations from the Energy equation are underestimating drain discharge while the Darcy equation method is overestimating drain discharge. Results of further investigation by statistical analysis of measures of performance is shown in Table 4.3. The statistical measures are Pearson's product-moment correlation coefficient ($R^2$), coefficient of residual mass (CRM), mean absolute error (MAE) and root mean square error (RMSE).

Table 4.3: Statistical comparison of observed and EnDrain-simulated drain discharge during calibration.

| **Statistical parameter** | **Energy balance equation** | **Classical Darcy equation** | **Interpretation** |
|---|---|---|---|
| $R^2$ | 0.82 | 0.82 | Acceptable |
| CRM | 0.13 | -0.25 | Acceptable |
| MAE (mm/day) | 0.79 | 0.98 | Acceptable |
| RMSE (mm/day) | 1.02 | 1.31 | Acceptable |

From Table 4.3, both calculation methods in EnDrain (Energy balance equation and classical Darcy equation) showed a high correlation with observed drain discharge as indicated by the relatively high $R^2$ values of 0.82. The CRM values for both methods are within accepted ranges (Skaggs, 2012) although the Energy balance method (CRM>0) is underestimating actual drain discharge while the classical Darcy approach (CRM<0) is overestimating actual DD. Both methods are relatively reliable as indicated by low values of error (MAE and RMSE) although the Energy balance equation is more reliable than the classical Darcy equation. This is evident when the Darcy equation is giving higher errors (MAE and RMSE) than the Energy equation.

Overally, both methods (Energy Balance and Darcy) are giving results with good agreement between observed and simulated drain discharges. Comparing the $R^2$, CRM, MAE and RMSE for both methods of simulation in EnDrain, the Energy balance equation is a better predictor of the drain discharge than the Darcy equation, as shown by the stronger agreement between observed and simulated drain discharges by the former method compared to the latter. These results are similar to findings reported by Oosterbaan (n.d.) and Halbac-Cotoara-Zamfir (2010), who highlighted that application of the Energy balance method to drains results in lower water-table depths, which implies a lower drain discharge for a specific water-table depth than the Darcy equation method.

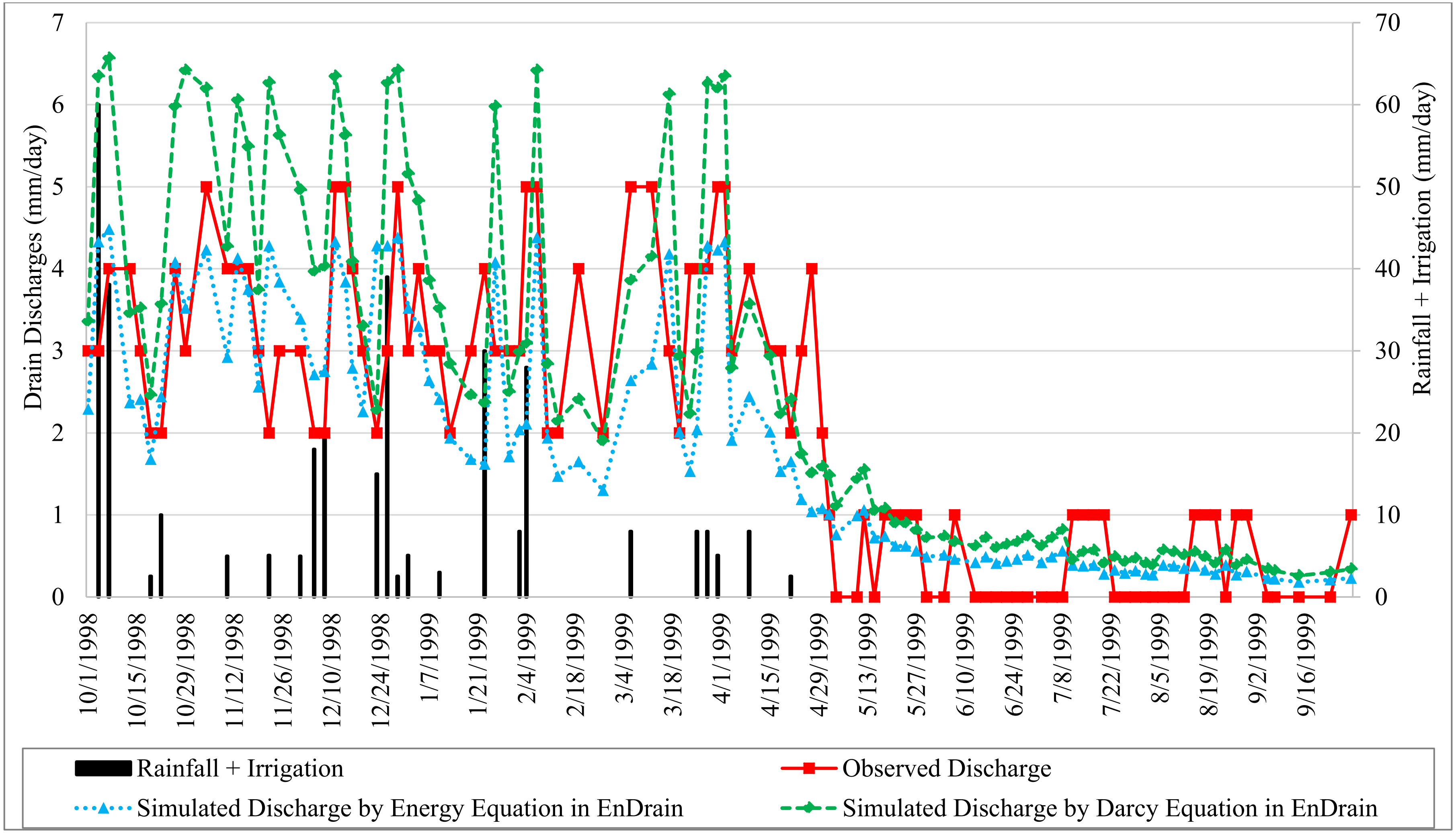



Figure 4.9: Plot of daily observed and EnDrain-simulated drain discharge trends for Pongola during model calibration (October 1998 to September 1999).

### 4.6.2 EnDrain model performance during validation

The calibrated parameters (Table 4.2) were used in EnDrain to simulate drain discharge during validation period (September 2011 to February 2012). The simulated drain discharge was compared with observed drain discharge. Figure 4.10 shows the plot of temporal variation of the observed discharge with simulated discharge.

Figure 4.10 visually shows that the simulated drain discharges are following the trends in changes in drain discharge which is a preliminary indication of a good correlation between model outputs and observed reality. The simulated and observed drain discharges are fluctuating in response to influxes of rainfall and irrigation. However, it is apparent that the Darcy equation is overestimating drain flows while the Energy equation is underestimating drain flows. The statistical measures of performance for the EnDrain model's two methods of calculation during validation are presented in Table 4.4.

Table 4.4: Statistical measures of EnDrain performance by comparison of simulated and observed drain discharge for Pongola during validation (2011 to 2012)

| **Statistical parameter** | **Energy balance equation** | **Classical Darcy equation** | **Interpretation** |
|---|---|---|---|
| $R^2$ | 0.81 | 0.80 | Acceptable |
| CRM | 0.09 | -0.11 | Acceptable |
| MAE (mm/day) | 0.24 | 0.25 | Acceptable |
| RMSE (mm/day) | 0.29 | 0.32 | Acceptable |

As highlighted in Table 4.4, both methods during validation scored in the accepted ranges of $R^2$, CRM, MAE and RMSE although the Energy equation performed better as was the case during calibration. Although both calculation methods resulted in good agreement between the observed and simulated drain discharges, the CRM values show that the Energy balance method is underestimating actual drain discharge while the classical Darcy approach is overestimating actual drain discharge. Both methods are relatively reliable as indicated by low values of error (MAE and RMSE) although the Energy balance equation is more reliable than the classical Darcy equation.

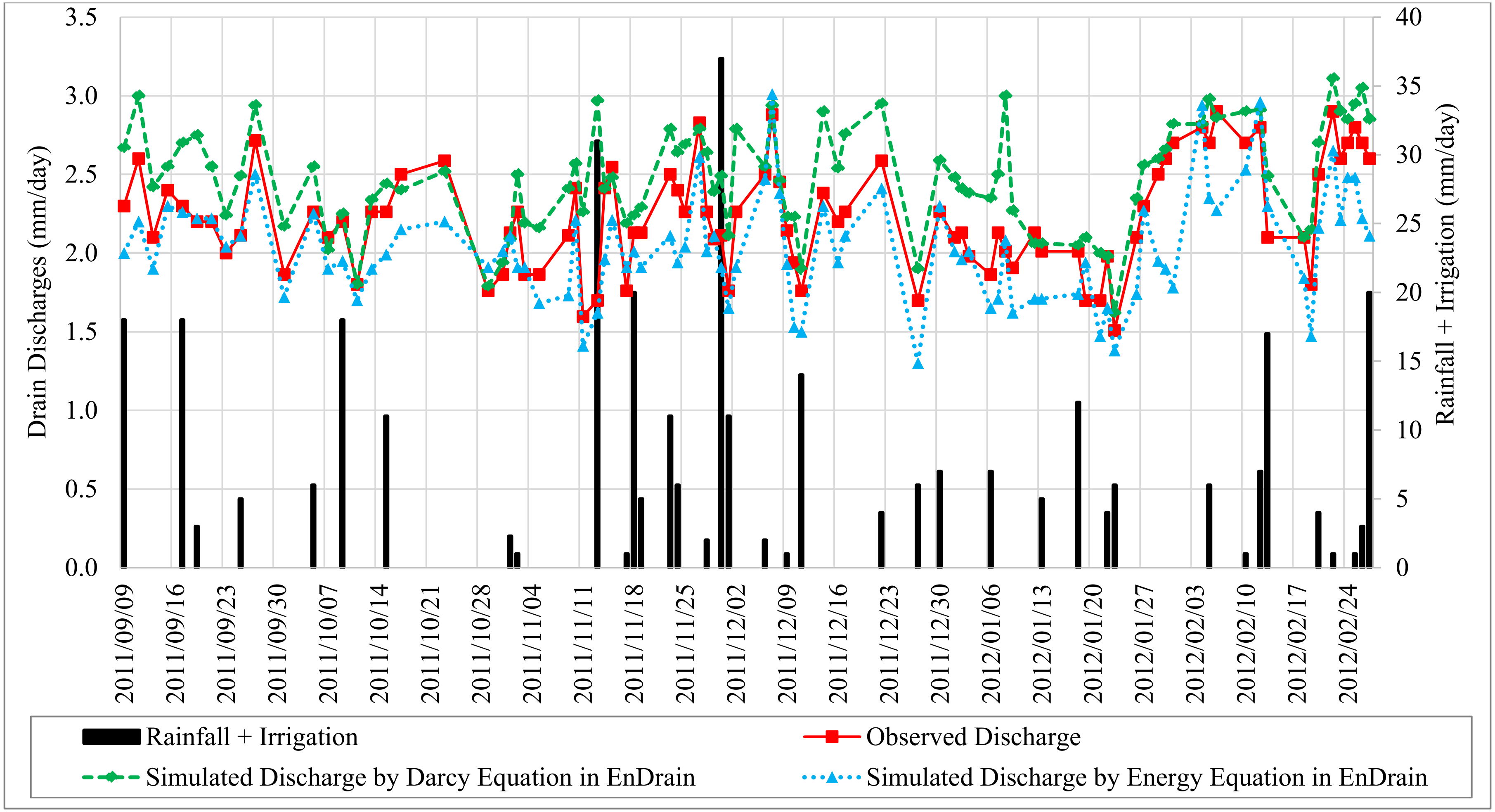



Figure 4.10: Plot of observed and EnDrain-simulated drain discharge trends for Pongola during model validation (September 2011 to February 2012)

Overall, the EnDrain performed better during validation than during calibration as indicated by the lower values of CRM and errors (MAE, RMSE) at validation. This may be attributed to different ranges of drain flows during the two periods. The correlation was a bit lower at calibration although in the same order as evidenced by the $R^2$ values (0.82 at calibration and 0.81 - 0.82 at validation).

In EnDrain, results from both calibration and validation point out that the Energy balance equation is a better drainage simulation approach than the Darcy equation. Overestimation by Darcy equation and underestimation by Energy equation agrees with reports from EnDrain developer Oosterbaan (n.d.) and another researcher Halbac-Cotoara-Zamfir (2010).

### 4.7 Comparison of DrainMod, EnDrain and WaSim at Pongola

In order to compare the three subsurface drainage simulation, the observed drainage and the simulated discharges by DrainMod, EnDrain and WaSim for calibration and validation are plotted in Figures 4.11 and 4.13 respectively. The plots of cumulative observed and simulated drain discharges are shown in Figures 4.12 and 4.14, respectively. For EnDrain, the results from the Energy balance method were used since they proved to have a stronger agreement and more reliable than the Darcy equation method in the previous sections.

The plot of cumulative drain discharge (Figure 4.12) during calibration period shows that WaSim yields the highest fluxes above the observed drain discharge. Both EnDrain and DrainMod yield low fluxes than WaSim and observed drain flow. These results contrast findings by Chikhaoui et al. (2010) where DrainMod overestimated cumulative observed drain discharge. It is apparent that EnDrain and WaSim yield drain discharges that are close to the observed, than the DrainMod model.

From Figure 4.11 during calibration period, DrainMod and WaSim models appear to fluctuate to both extremes of overestimation and underestimating drainage flows at high flows, while EnDrain has higher tendency of underestimating drain discharges. At moderate flows, all models tend towards observed drain discharges. At low flows, all models slightly fail to follow the trend of actual drainage flows. This is caused by lack of recharge such as rainfall and irrigation, which are key components in the water-balance approach used by the models. Generally simulated discharge by all models is showing responsiveness to influx of rainfall and irrigation.

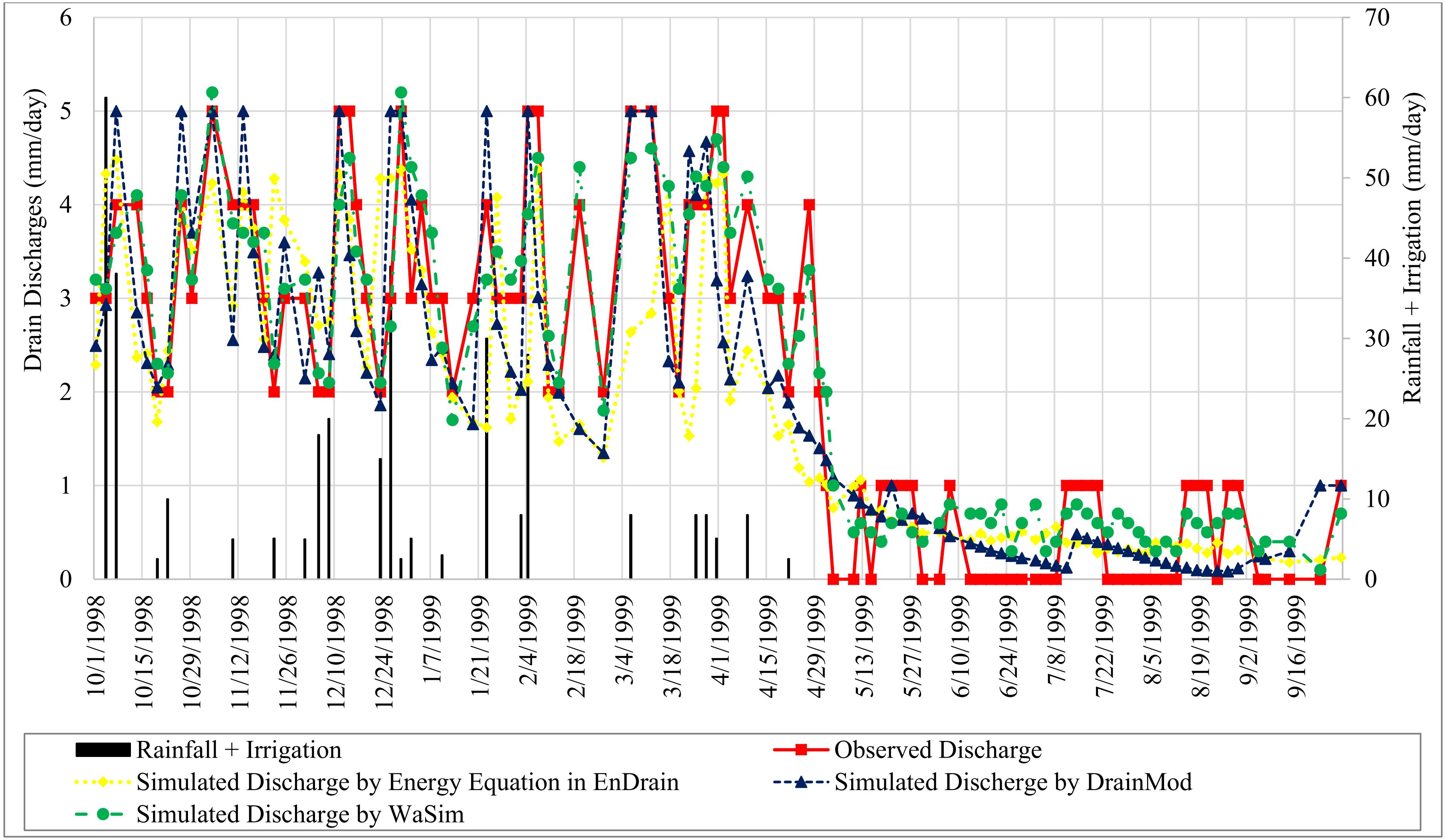



Figure 4.11: Plots of observed and DrainMod, EnDrain and WaSim-simulated drain discharge trends for Pongola during model calibration (October 1998 to September 1999).

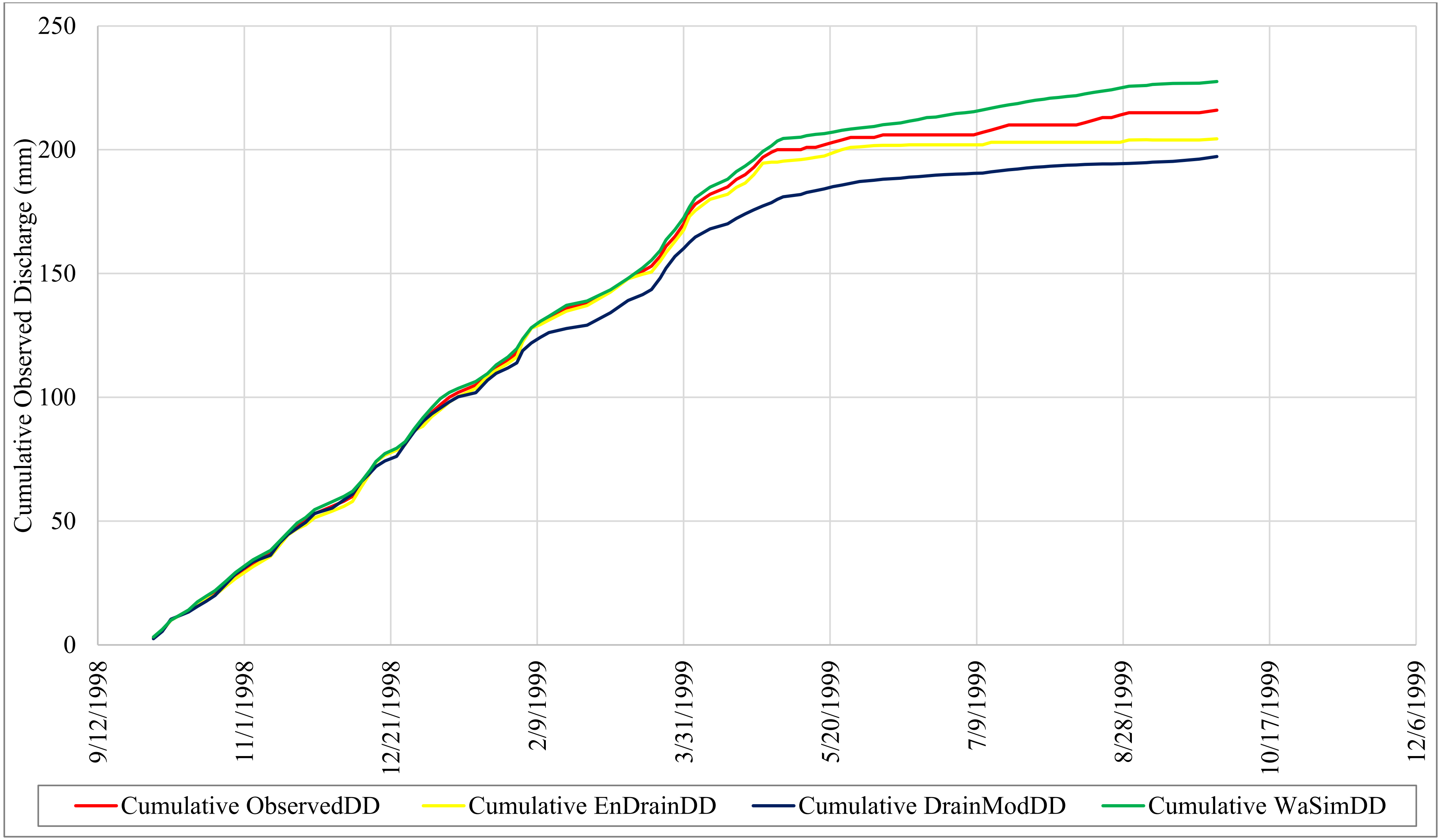



Figure 4.12: Plots of cumulative observed and DrainMod, EnDrain and WaSim-simulated drain discharge trends for Pongola during model calibration (October 1998 to September 1999).

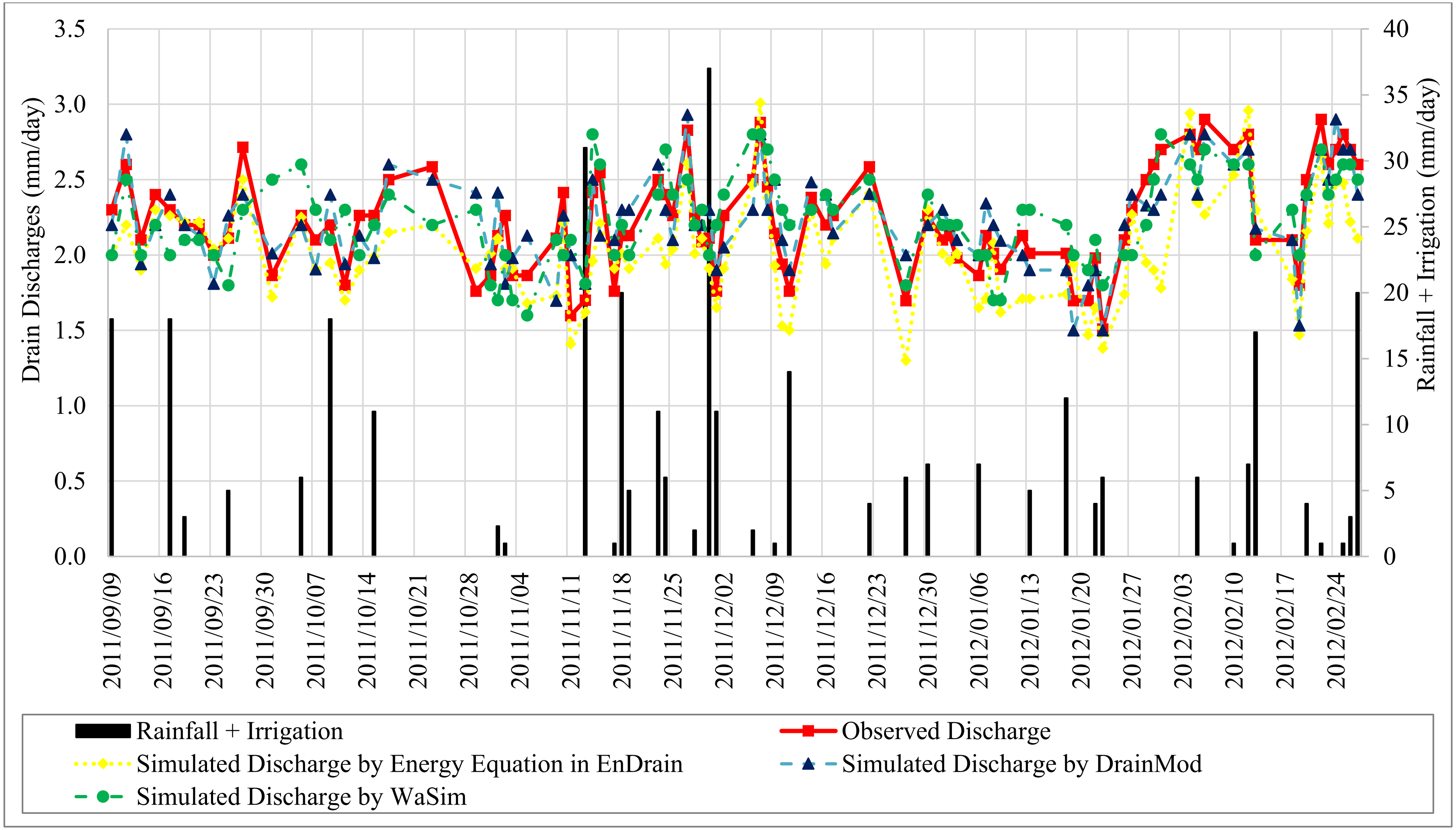



Figure 4.13: Plots of daily observed and DrainMod, EnDrain and WaSim-simulated drain discharge trends for Pongola during model validation (September 2011 to February 2012).

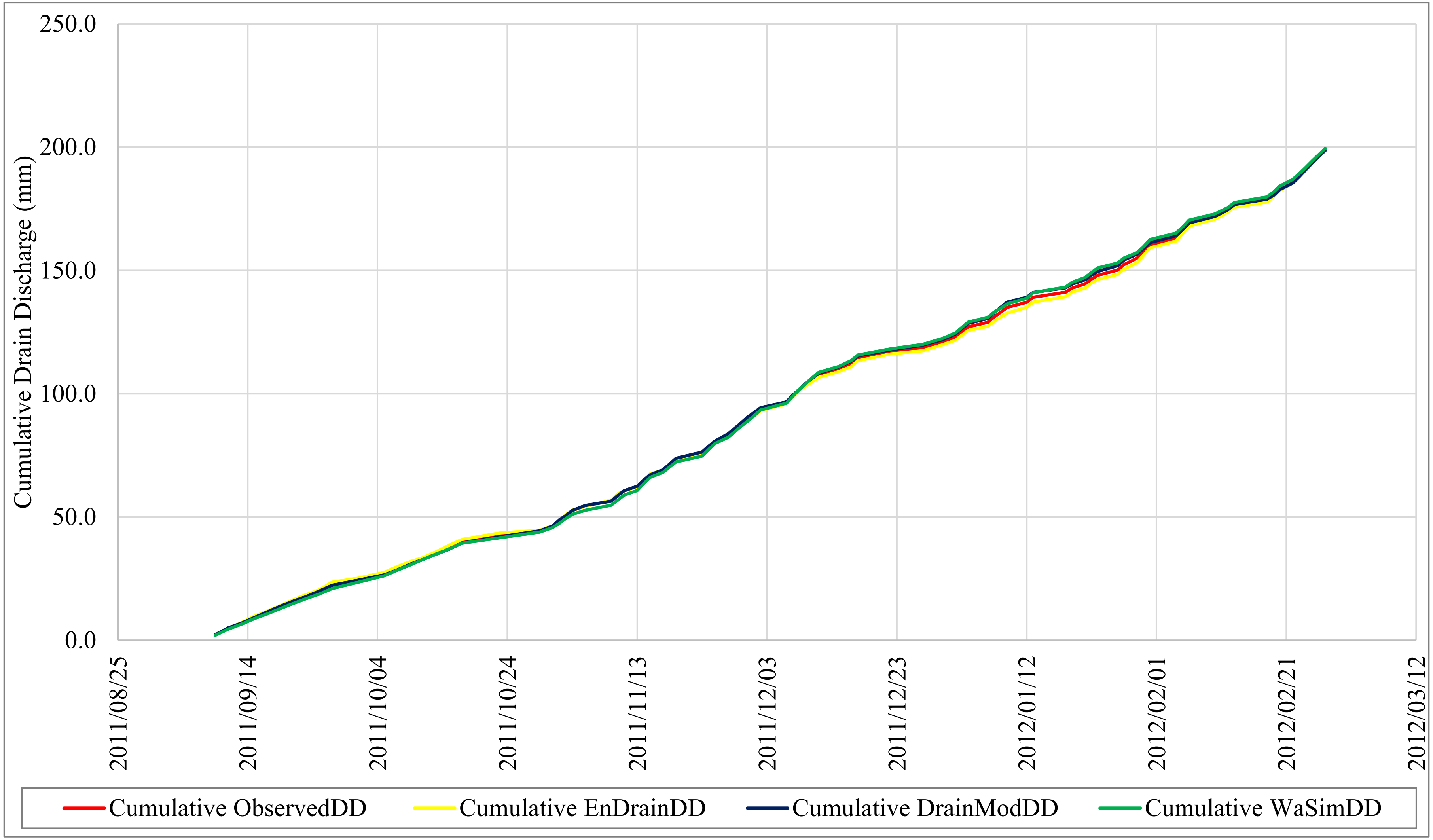



Figure 4.14: Plots of cumulative observed and DrainMod, EnDrain and WaSim-simulated drain discharge trends for Pongola during model validation (September 2011 to February 2012).

From the cumulative plot during validation (Figure 4.14), the three models' performance improved compared to the calibration period. They seem to have improved their simulation reliability, since they collapse nearly perfectly onto the line for cumulative observed discharge.

The data used for validation is in the moderate range as compared to during calibration. DrainMod and WaSim tend to alternatingly overestimate and underestimate throughout the period. EnDrain tend to be underestimating most of the time. Generally, all the models are following the trend to observed flow fluctuations, as well as showing sensitivity to incoming rainfall and irrigation. The fluctuating trend indicates the unsteady nature of observed and simulated drain discharge is a common characteristic of all three models. Further comparison of the three models is achieved by assessing the statistical measures of model performance, which are shown in Table 4.5.

Table 4.5: Statistical measures of DrainMod (Malota, 2012; Malota and Senzanje, 2015) EnDrain and WaSim (Malota et al., n.d.) performance by comparison of simulated and observed drain discharge for Pongola during calibration (October 1998 to September 1999) and validation (September 2011 to February 2012).

| **Statistical Parameter** | **Calibration** | | | **Validation** | | |
|---|---|---|---|---|---|---|
| | DrainMod | EnDrain | WaSim | DrainMod | EnDrain | WaSim |
| $R^2$ | 0.893 | 0.82 | 0.96 | 0.801 | 0.81 | 0.67 |
| CRM | 0.089 | 0.13 | 0.04 | 0.004 | 0.09 | 0.001 |
| MAE (mm/day) | 0.603 | 0.79 | 0.41 | 0.181 | 0.24 | 0.213 |

During calibration, EnDrain performed slightly poorer than DrainMod and WaSim when considering the values of $R^2$, CRM and MAE although it was predicting within accepted ranges. All three models were showed strong agreement with observed drain discharge, as well as underestimating drainage discharge (CRM>0).

During validation, all three models decreased slightly in correlation with observed drain discharge with the slightest and highest decline noted for EnDrain and WaSim, respectively. However, all three models had improved their reliability as evidenced by decreased values in CRM and MAE. A common trend for all three models during calibration and validation, it can be said that they simulate medium flows better than either too high or too low flows. This explains why they performed better during validation than calibration, because the drainage flow data was in medium range during validation. Based on these findings, where EnDrain's performance is maintained in terms of $R^2$ and improvements in error values, it seems the little-known EnDrain is more reliable and has a higher replicability than the relatively famous DrainMod and WaSim. EnDrain's performance was comparable to DrainMod and WaSim from other studies reported by Wang et al. (2006) and Hirekhan et al. (2007). Coupling this with EnDrain's relatively fewer data requirements than DrainMod and WaSim, EnDrain may be a better alternative in subsurface drainage design, modeling and assessment in data scarce situations that are common in developing countries.

## 4.8 Testing Performance of Drainage Systems at De Doorns, Breede, with DrainMod

### 4.8.1 Climatic and irrigation data

The latitude of De Doorns farm is -33°29' = 33°29'S = 33.48°.

Tables 4.6 to 4.8 show the key climatic data for this study.

Table 4.6: Mean monthly temperature ($T_{avg}$, °C) and precipitation ($P_{avg}$, mm), for De Doorns.

| Mean | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $T_{avg}$ | 24.8 | 24.4 | 22.6 | 18.7 | 15.2 | 12.1 | 11.4 | 12.3 | 14.5 | 18.0 | 20.2 | 23.0 |
| $P_{avg}$ | 9.9 | 6.8 | 4.2 | 19.4 | 33.2 | 65.0 | 43.8 | 49.4 | 17.2 | 14.4 | 41.0 | 4.6 |

Table 4.6 shows that De Doorns receives much of its rainfall during the cold winter season, while the summer is season is relatively dry. This is typical of its Mediterranean climate.

Table 4.7: Calculated monthly and annual ($I_{annual}$) heat indices for De Doorns site

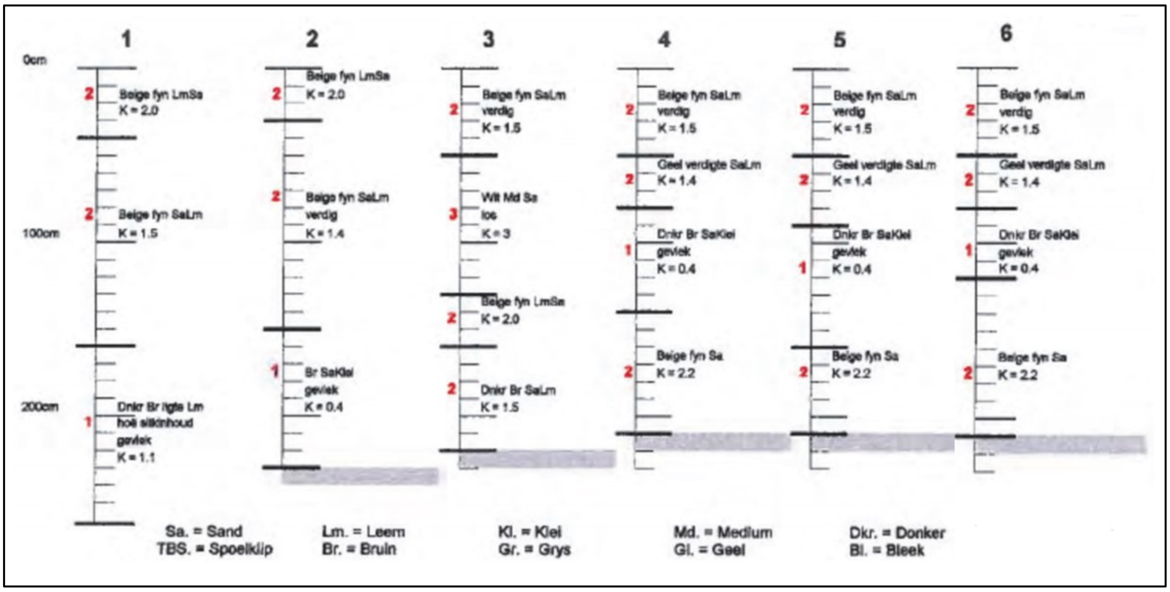
| Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | $\mathbf{I_{annual}}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 11.3 | 11.0 | 9.8 | 7.4 | 5.4 | 3.8 | 3.5 | 3.9 | 5.0 | 7.0 | 8.3 | 10.1 | **86.5** |

Table 4.8: Factors for correcting unadjusted PET by the Thornthwaite method (Thornthwaite, 1948; Thompson, 1999)

| **Lat (°S)** | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 33.48 | 1.18 | 1.12 | 1.03 | 0.95 | 0.87 | 0.83 | 0.85 | 0.92 | 1.00 | 1.08 | 1.16 | 1.20 |

### 4.8.2 Soil data

Figure 4.15 shows the soil profile at De Doorns, according to Reinders, et al., (2016b) as was inspected by means of 6 profile holes that were dug in the field. Results from analysis of the soil profile and porosities of the soil layers pointed the location of the impermeable layer, which is the ideal drain installation depth, as occurring mostly at a depth of just below 2 m.




**Key: Names from Afrikaans (Afrik) to English (Eng)**

| Afrik | Eng | Afriks | Eng | Afrik | Eng | Afrik | Eng |
|---|---|---|---|---|---|---|---|
| Spoelklip | pebble | Klei | clay | Donker | dark | Beige | beige |
| Leem | loam | Grys | grey | Bleek | pale | Verdig | compact |
| Bruin | brown | Geel | yellow | Fyn | fine | | |

Figure 4.15: Soil profile descriptions at De Doorns site, Breede (Reinders, et al., 2016b).

Table 4.9 shows the saturated hydraulic conductivities values that were determined from the soil profile hole data collected during the drainage system design, for De Doorns site (Reinders et al., 2016b).

Table 4.9: Measured saturated hydraulic conductivity by layer at De Doorns site.

| **Soil Layer** | **Position Relative to Depth of Drain** | **Thickness (cm)** | **Bottom Depth (cm)** | **Lateral Saturated Hydraulic Conductivity (m/day)** |
|---|---|---|---|---|
| 1 | Above | 120 | 120 | 4.50 |
| 2 | Above to below | 103 | 223 | 5.25 |

The estimated soil water characteristics data from Rosetta, for De Doorns are shown in Table 4.10.

Table 4.10: Estimated soil water characteristics from Rosetta Lite for De Doorns

| | **Soil water content ($cm^3/cm^3$)** | | | |
|---|---|---|---|---|
| **Head (cm)** | **Top layer** | **Bottom layer** | **Top layer** | **Bottom layer** |
| 0 | 0.426 | 0.428 | -977.0 | 0.048 |
| -23.6 | 0.306 | 0.309 | -2480.0 | 0.046 |
| -95.5 | 0.106 | 0.098 | -6280.0 | 0.045 |
| -242.0 | 0.063 | 0.060 | -7920.0 | 0.045 |
| -486.0 | 0.052 | 0.051 | -15000.0 | 0.045 |
| -774.0 | 0.049 | 0.049 | | |

The associated soil inputs for WaSim such as soil water contents at saturation, field capacity and permanent wilting point as estimated from the soil water characteristics results from Rosetta are shown in Table 4.11.

Table 4.11: WaSim soil inputs for De Doorns from Rosetta Lite.

| **Soil state** | **Soil moisture content (%)** |
|---|---|
| Saturation | 42.8 |
| Field capacity | 9.9 |
| Permanent wilting point | 4.7 |

The water table – volume drained – upward flux relationships as estimated by DMSOILP sub-utility in DrainMod are given in Table 4.12. The water-table versus Green-Ampt infiltration relationships estimated by DMSOILP sub-utility in DrainMod are given in Table 4.13.

### 4.8.3 Drainage system design

The actual drain installation spacing for De Doorns was set at 60 m, and all drainage system design parameters for De Doorns are summarized in Table 4.14.

### 4.8.4 Crop parameters – table grapes

In this study, a maximum effective rooting depth of 1.5 m was adopted since some portions of the site show significant layering and the modeling also incorporates soil water stress imposed to crops due to either excess or scarce water (Allen et al., 1998; Savva and Frenken, 2001; Savva and Frenken, 2002; Natural Resources Management Directorate, 2011). It was assumed that the crop was already producing fruits, and harvest is in January, with a growing period of 240 days. Canopy development data was adopted from (USDA, 1993), while root development data was adopted from Van Zyl (1984).

### 4.8.5 Subsurface drainage simulations by DrainMod and WaSim at De Doorns site, Breede

Figures 4.16 and 4.17 show the simulated fluctuations of water-table depths at De Doorns by DrainMod and WaSim, for the periods October 2009 April 2010 and October 2011 to April 2012, respectively. The plots of results are superimposed on the same scales for easy comparison during same period of simulation. Figures 4.18 and 4.19 show the simulated fluctuations of drain discharges at De Doorns by DrainMod and WaSim, for the periods October 2009 April 2010 and October 2011 to April 2012, respectively.

### 4.8.5.1 Water-table depth

Figures 4.16 and 4.17 show the simulated water-table depths for the periods October 2009 to April 2010 and October 2011 to April 2012 respectively, by DrainMod and WaSim.

Table 4.12: DMSOILP program-estimated water table - volume drained – upward flux.

| Water-table depth (cm) | Volume drained (cm) | Upward flux (cm/hr) |
|---|---|---|
| 0 | 0.000 | 0.5000 |
| 6 | 0.092 | 0.5000 |
| 12 | 0.366 | 0.5000 |
| 15 | 0.572 | 0.5000 |
| 20 | 1.017 | 0.5000 |
| 25 | 1.585 | 0.5000 |
| 30 | 2.233 | 0.4670 |
| 35 | 2.952 | 0.3166 |
| 40 | 3.739 | 0.2018 |
| 45 | 4.597 | 0.1369 |
| 60 | 7.586 | 0.0421 |
| 75 | 11.20 | 0.0121 |
| 90 | 15.44 | 0.0036 |
| 120 | 25.08 | 0.0006 |
| 150 | 35.01 | 0.0002 |
| 200 | 52.35 | 0 |
| 500 | 100.0 | 0 |
| 1000 | 100.0 | 0 |

Table 4.13: Estimated Green-Ampt infiltration parameters versus water-table depth for De Doorns from the DMSOILP program.

| **Water-table depth (cm)** | **A ($cm^2$/hr)** | **B (cm/hr)** |
|---|---|---|
| 0 | 0 | 18.75 |
| 10 | 4.30 | 18.75 |
| 20 | 8.56 | 18.75 |
| 40 | 13.96 | 18.75 |
| 60 | 18.67 | 18.75 |
| 80 | 23.35 | 18.75 |
| 100 | 27.09 | 18.75 |
| 150 | 32.04 | 18.75 |
| 200 | 32.04 | 18.75 |
| 1000 | 32.04 | 18.75 |

Table 4.14: Drainage design data for De Doorns, Breede (Reinders, et al., 2016b).

| **Parameter (unit)** | **Description** | **Value** |
|---|---|---|
| $D_{il}$ (m) | Average depth to impermeable layer from soil surface | 2.20 |
| $K_1$ (m/day) | Hydraulic conductivity of soil layer above drain | 4.50 |
| $K_2$ (m/day) | Hydraulic conductivity of soil layer below drain | 5.25 |
| q (mm/day) | Drainage coefficient | 5.00 |
| b (m) | Proposed drain depth to pipe bottom | 1.80 |
| a (m) | Minimum drained soil depth between drains | 1.00 |
| h (m) | Water depth above the drain, between drains | 0.80 |
| D (m) | Depth of the impermeable layer below the drain | 0.20 |
| L (m) | Actual drain spacing | 60.00 |

Table 4.15: SEW150 and rainfall + irrigation values during period October 2009 to April 2010 for De Doorns, Breede.

| **Model** | **Mean water-table depth (m)** | | **Mean drain discharge (mm/day)** | |
|---|---|---|---|---|
| | **Oct 2009 – Apr 2010** | **Oct 2011 – Apr 2012** | **Oct 2011 – Apr 2012** | **Oct 2011 – Apr 2012** |
| DrainMod | 1.60 | 1.56 | 1.23 | 1.40 |
| WaSim | 1.47 | 1.47 | 1.78 | 1.84 |

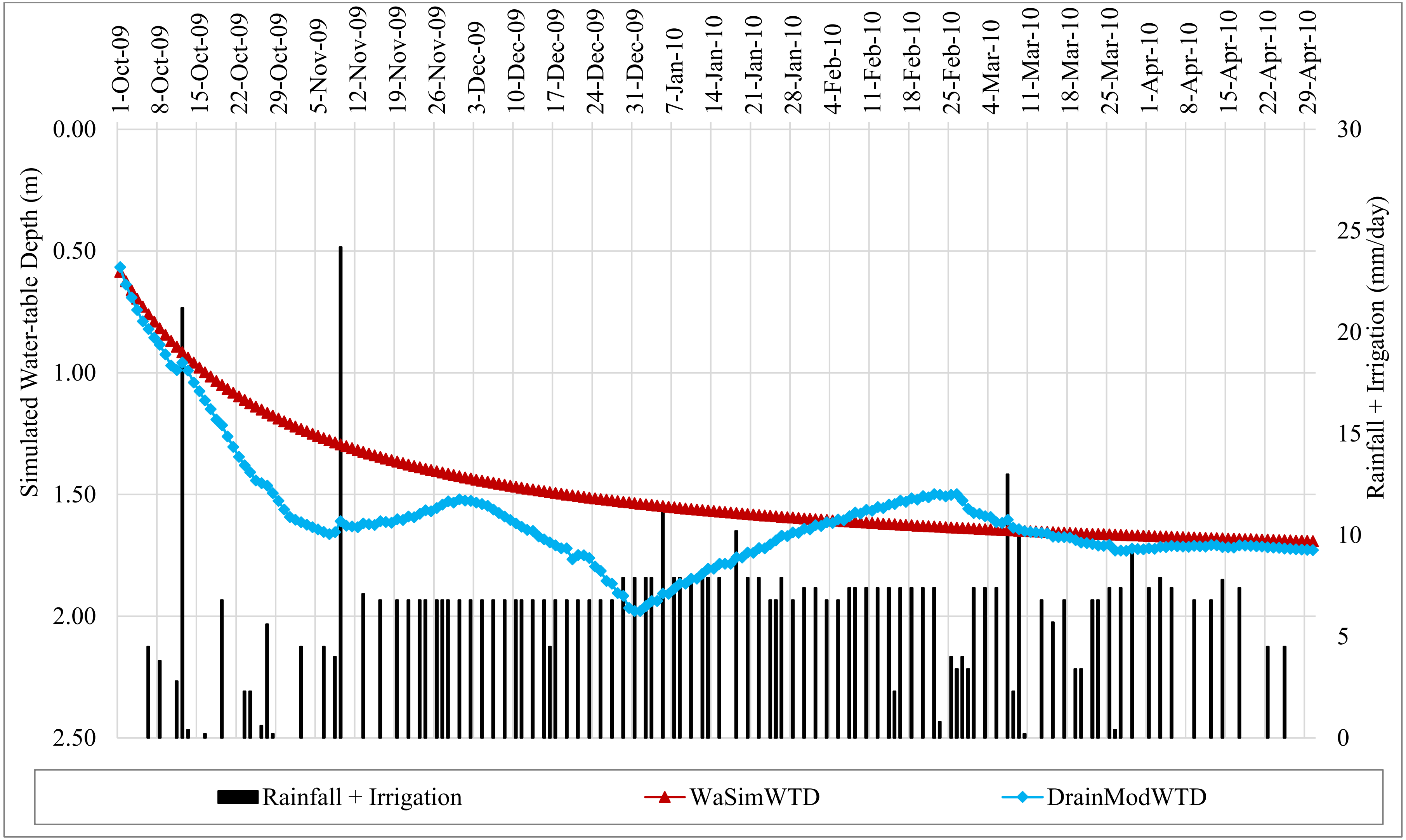



Figure 4.16: Plot of simulated water-table depth by DrainMod and WaSim at De Doorns, Breede (October 2009 to April 2010).

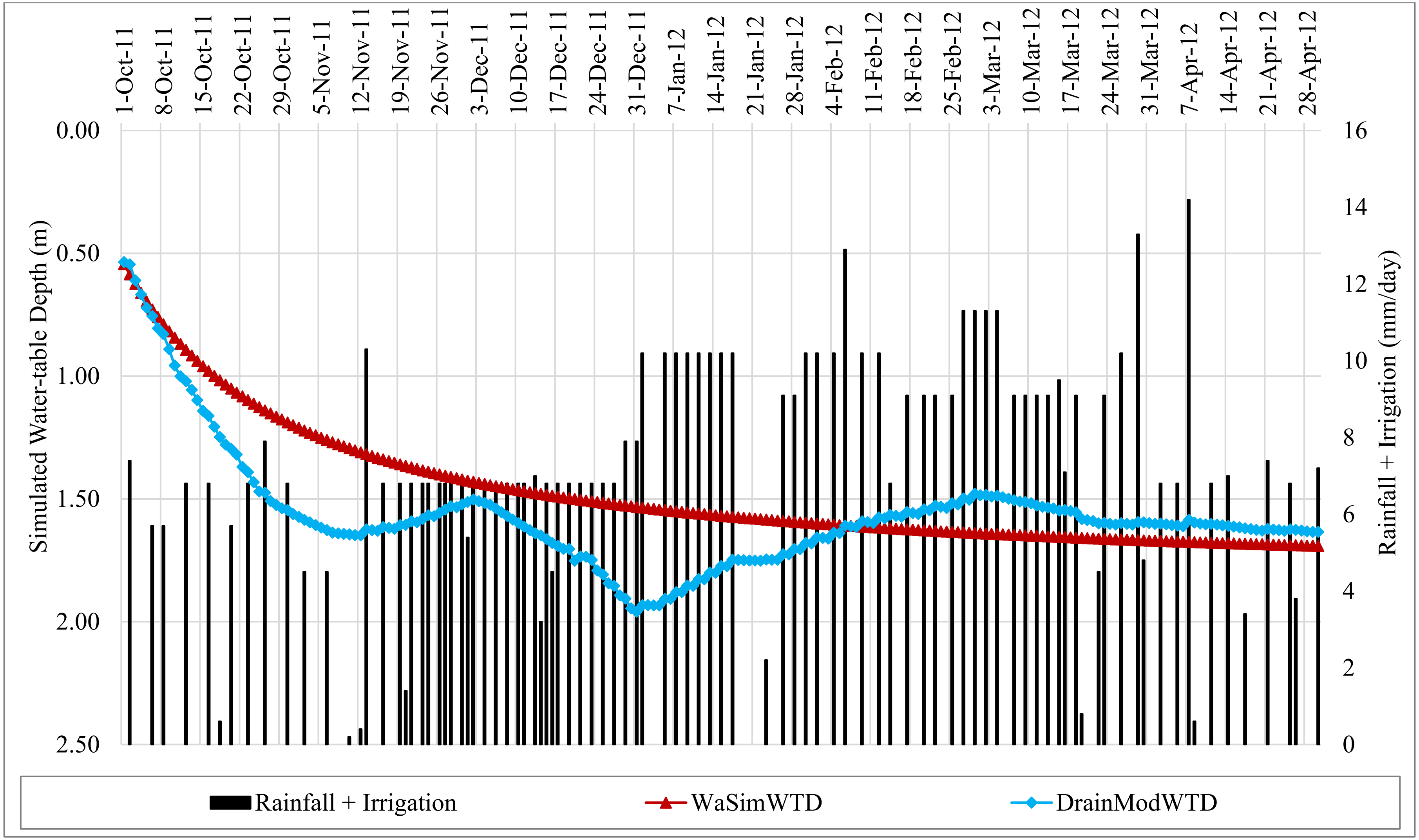



Figure 4.17: Plot of simulated water-table depth by DrainMod and WaSim at De Doorns, Breede (October 2011 to April 2011).

From Figures 4.16 and 4.17, DrainMod's simulations of water-table depth are more responsive to influxes of water input in the form of rainfall and irrigation, than WaSim. The deviations of the two models from each other at the initial stage are due to bias during model warm-up as reported by Daggupati et al. (2015) and Deelstra, et al. (n.d.) because with time they get closer to each other although WaSim tends to behave exponentially while DrainMod has tendency towards a sinusoidal pattern. Both models tend to approach a somehow constant water table depth with time. Table 4.16 summaries the values of SEW150 and SED150, with 150 cm considered as the critical water-table depth which is maximum effective root depth taken for table grapes (Allen et al., 1998; Savva and Frenken, 2002; Natural Resources Management Directorate, 2011; FAO, 2017). SEW150 and SED150 are indices of crop stress due to water excess as imposed by the performance of the existing drainage system under given local conditions. Total rainfall and irrigation for the corresponding periods are also presented.

Table 4.16: Rainfall + irrigation, SEW150 and SED150 values during period October 2009 to April 2010 for De Doorns, Breede.

| **Model** | **Total Rainfall + Irrigation (mm)** | | **SEW150 (cm-day)** | | **SED150 (day)** | |
|---|---|---|---|---|---|---|
| | **Oct 2009 – Apr 2010** | **Sept 2011 – Feb 2012** | **Oct 2011 – Apr 2012** | **Oct 2011 – Apr 2012** | **Oct 2009 – Apr 2010** | **Oct 2011 – Apr 2012** |
| DrainMod | 685.6 | 696.9 | 83.9 | 89.87 | 33 | 34 |
| WaSim | 685.6 | 696.9 | 89.2 | 95.62 | 80 | 80 |

Overall, for the same period, WaSim is yielding larger values of SEW150 and SED150. For WaSim the season October 2009 April 2010 has lower values rainfall+irrigation and SEW150, as compared to season October 2011 to April 2012 with higher rainfall+irrigation and SEW150.

Generally, WaSim has high values of SEW150 than DrainMod for both seasons. For the period October 2009 to April 2010, WaSim has a higher SED150 than DrainMod. A similar trend is observed in the period October 2011 to April 2012. The SED values for DrainMod are comparable to results from a tile form of subsurface drainage system that were reported by Jung et al. (2010) in Korea. Based on their findings, Jung et al. (2010) the tile subsurface drainage system was the best performer compared to open ditch, vinyl barrier and tube bundle systems. The SED150 values for WaSim are comparable to results from a tile form of subsurface drainage system that were reported by Verma et al. (2014) in Haryana (India). The values of SED150 for DrainMod and WaSim did not change significantly between the October 2009 to April 2010 and October 2011 April 2010, because the recharge components of rainfall and irrigation were almost the same throughout.

Given that DrainMod and WaSim were successfully applied at another location in South Africa, it can be said that the values of SEW150 and SED150 from this study show that the existing subsurface drainage systems at De Doorns are effective. Since the SED150 and SEW150 values are less than the critical 100 days, the existing subsurface drainage system at De Doorns is effective in protecting the crop from yield decreases induced by excess soil water at De Doorns, Breede (Sieben, 1964; Skaggs, 1980; Singh, Helmers, Kaleita, and Eugene, 2009). Because of the existence of the subsurface drainage systems, the De Doorns site can be classified as moderately well drained since the SEW150 values fall within 30 to 100 (Moore, 2001).

#### 4.8.5.2 Drain discharge

Figures 4.18 and 4.19 show the simulated drainage discharges for the periods October 2009 April 2010 and October 2011 April 2012 respectively, by DrainMod and WaSim.

Figures 4.18 and 4.19 show that DrainMod's simulations of drain discharge are more responsive to influxes of water input in form of rainfall and irrigation, than WaSim for both periods studied. At the initial stages of the season, the two models deviate from each other may be due to warm-up, but with time they get closer to each other although WaSim tends to behave exponentially while DrainMod has tendency towards sinusoidal. Both models tend to approach towards a somehow constant drain discharge with time.

From the two simulated periods October 2009 to April 2010 and October 2010 to April 2012, it seems like DrainMod model is limited to maximum drain flows of around 5 mm/day, unlike WaSim. DrainMod required more of certain inputs than WaSim, this include soil and crop parameter. WaSim was user-friendly because it had a graphic animated display to view simulations as they progress, with accessible controls to even pause or adjust simulation speed; facilities that are lacking in DrainMod. WaSim's graphic animated interface enhance understanding of the processes involved in the simulations by the model. The differences between DrainMod and WaSim can be attributed to their different computation algorithms and functions.

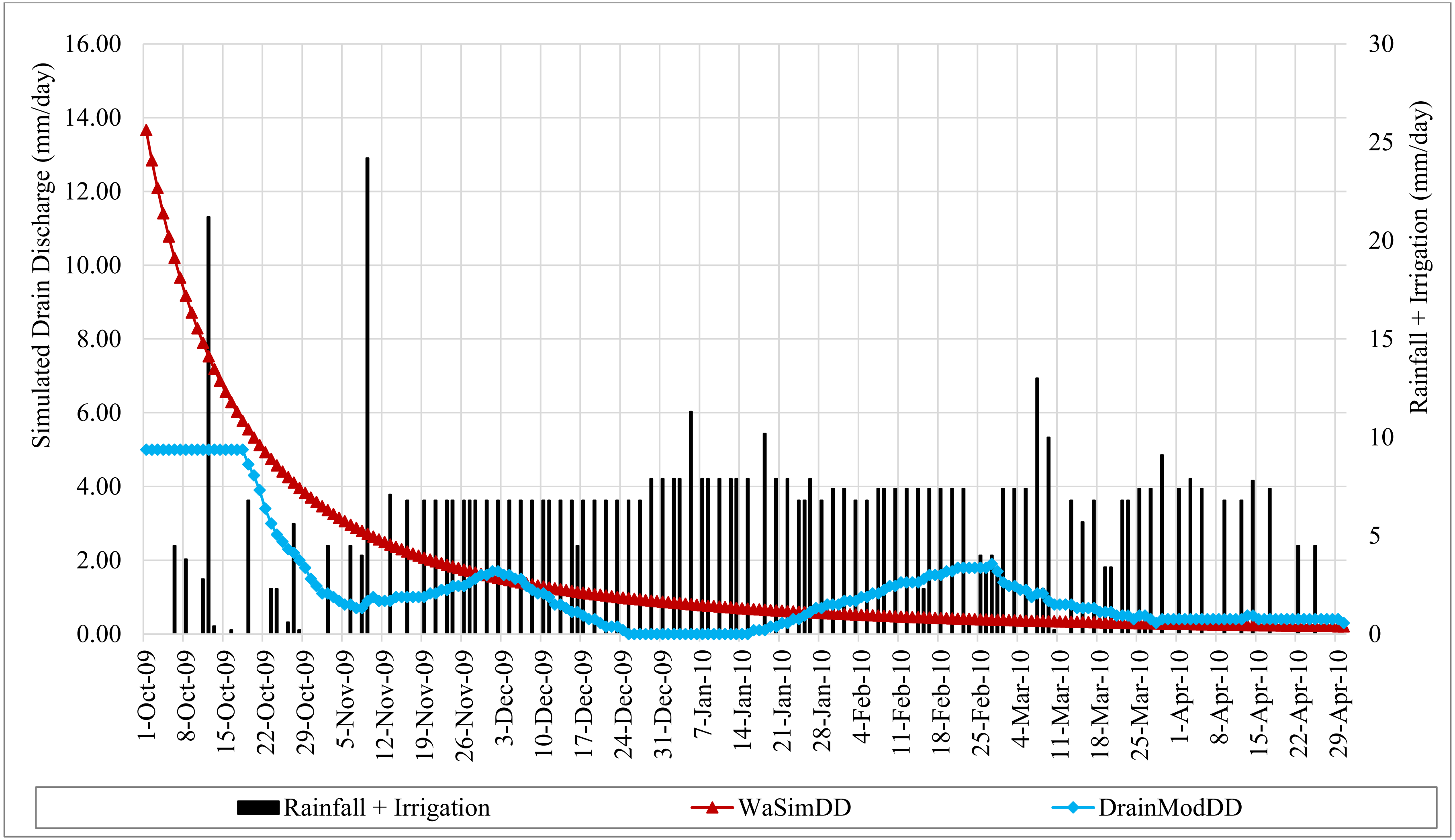



Figure 4.18: Plot of simulated drain discharge by DrainMod and WaSim at De Doorns, Breede (October 2009 to April 2010).

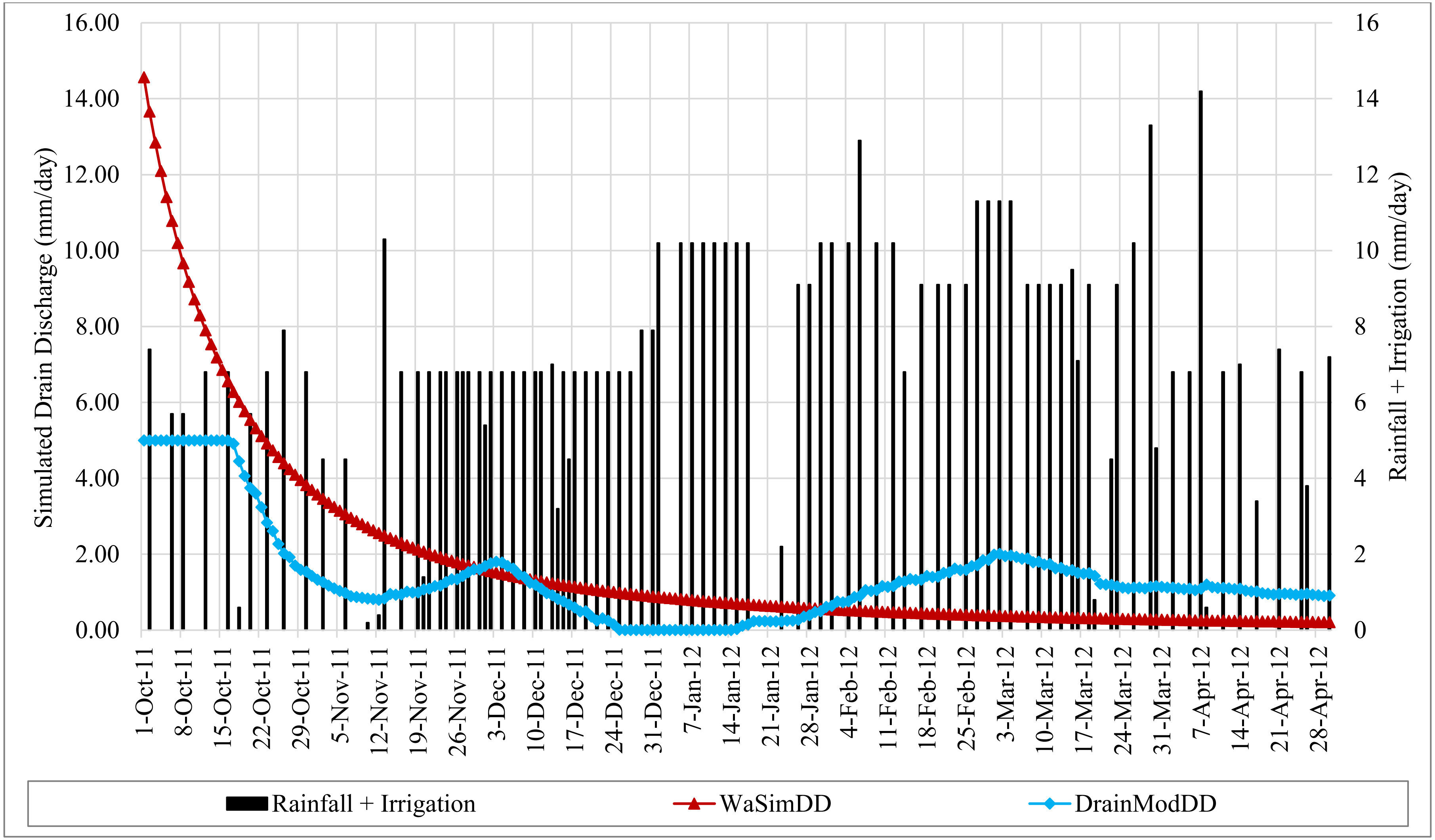



Figure 4.19: Plot of simulated drain discharge by DrainMod and WaSim at De Doorns, Breede (October 2011 to April 2012).

## Chapter 5 : SUMMARY, CONCLUSION AND POSSIBLE FUTURE RESEARCH

This section summarizes and concludes the study, as well as recommending areas of further study. The final part of the section presents the literature that was used in this study.

**Chapter Outline**

Regarding to the interaction of climate (rainfall and evapotranspiration), irrigation, soils and crops and their influence on status of water-tables and drain outflows in agricultural lands, the objectives of the work reported in this thesis were to:

- Determine the occurrences and possible causes of shallow water-tables on the Makhathini study site.
- Simulate water-table depths and drain discharges with EnDrain model at Pongola, and compare results with observed water-table depths and drain discharges.
- Compare DrainMod, EnDrain and WaSim models and recommend the most appropriate considering performance, usability and input data requirements at Pongola.
- Compare performance of DrainMod and WaSim in simulating subsurface drainage systems at De Doorns site, Breede.

## 5.1 Occurrences and Possible Causes of Shallow Water-tables

The sudden drop in trend in prevalence of shallow water-tables at some blocks in Makhathini between May 2013 and October 2013 is a result of excess water removal by a drainage canal that was constructed during the period April 2012 to May 2013. It is therefore concluded that Makhathini irrigation scheme is suffering from shallow water-tables, and subsurface drainage systems are effective remedies to the shallow water-tables problem. There is need to install similar systems on the other blocks that show high prevalence of shallow water-tables. As such, higher priority must be given to blocks 15 and 19, followed by 6A and 6B.

## 5.2 Drainage Design Capabilities of EnDrain, and Comparison with DrainMod and WaSim

EnDrain performed satisfactorily in simulating drain discharge in both calibration and validation periods ($R^2 > 0.80$) by both methods (Energy balance and Darcy). However, the Energy balance method performed better that the Darcy equation method. Thus, it is concluded that EnDrain be used to reliably design and evaluate performances of drainage systems at Pongola and other areas with similar conditions such as soils, for example the nearby Makhathini which is being affected by shallow water-tables. When using EnDrain in drainage design and evaluation, the Energy balance method must be preferred.

When compared to DrainMod and Wasim, EnDrain performed poorly during calibration but turned out to be better than the other two models during validation. Given that it has least input data requirements among the three models, EnDrain's performance here encourages its further testing and applications just like its two counterparts which are more commonly applied. It deserves similar and equal treatment and recognition, if not more. To conclude, instead of using input data-hungry models such as DrainMod and WaSim, EnDrain is a better option. Moreover, EnDrain is better because, basic, simple and user-friendly. Its input requirements are prepared by simple means.

### 5.3 Performance of Drainage System at De Doorns, Breede

Since DrainMod and WaSim were successfully applied at other location in South Africa, the simulation results at De Doorns can be considered commendable without calibration and validation. The site has an operational subsurface drainage system which is able to lower water-table depths to levels (1.50 m) that are conducive for table grapevines growth. Even towards the end of the simulation periods where there is notable increase in recharge, the drainage system is still able to perform its required functions. This indicates that artificial drainage systems can be effective interventions for controlling water-tables in agricultural lands. Therefore, it is concluded that the existing drainage systems at De Doorns is performing as expected in maintaining optimum water-tables preferred by table grapes.

### 5.4 Policy Implications of Research

From the findings of this study, the take home message for water policy-makers, advisors and stakeholders is:

- With drainage issues, it should not be out of site out of mind, there is need for frequent monitoring of water-tables in agricultural lands.
- It is evident that drainage problems are real, there is need for site-specific investigation that can lead to actions, interventions and strategy which is the implementation of policy. Construction of drainage system in Block E at Makhathini is evidence that South Africa is implementing its drainage-related policies.
- In policy, we can choose to act or not to act, but that should be a decision informed by evidence.

- Policy should advocate for and take advantage of simple, cost-effective tools such as models in agricultural water management.

- Irrigation and drainage are inseparable and they complement each other. Resources and attention must be equally invested in both, if we are to safeguard food security for ourselves and for future generations.

- There is need for a comprehensive "National Irrigation and Drainage Policy" and its documentation, to guide the actions and deliberations on development of agricultural lands with respect to drainage and its immeasurable contribution to sustainable agriculture. This proposed policy must be integrated to other policies such as water, agriculture and energy, for it to be effective.

**5.5 Future Research**

With respect to the research findings of this study, recommendations for future investigations in the study areas and South Africa in general must focus on:

- Influence of irrigation and rainfall on the observed shallow-water table trends at Makhathini.

- Impact of climate change on drainage dynamics and consequentially sugarcane yields at Pongola.

- Possibilities of adding algorithms for time series and multiple event simulation algorithms to EnDrain, a basic and simple but promising drainage simulation model.

- Possibilities and effects of automatic calibration of EnDrain, DrainMod and WaSim at Pongola.

- Comparing DrainMod and WaSim-simulated water-table depth and drain discharge with observed data at De Doorns, Breede.

- Awareness of farmers and related stakeholders on the South African drainage policy, and their perceptions on agricultural drainage issues.

- Socio-economic and environmental impacts of shallow water-tables and agricultural drainage interventions in the farming communities.

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