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Govinda Karki
South Dakota State University

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IMPACT OF SUBSURFACE DRAINAGE ON WATER YIELD FOR TYPICAL SOIL AND WEATHER IN EASTERN SOUTH DAKOTA

BY

GOVINDA KARKI

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IMPACT OF SUBSURFACE DRAINAGE ON WATER YIELD FOR TYPICAL SOIL AND WEATHER IN EASTERN SOUTH DAKOTA

This dissertation is approved as a creditable and independent investigation by a candidate for the Doctor of Philosophy in Biological Sciences degree with specialization in Agricultural and Biosystems Engineering and is acceptable for meeting the dissertation requirements for this degree. Acceptance of this does not imply that the conclusions reached by the candidates are necessarily the conclusions of the major department.

Todd Trooien, Ph. D., P.E. Date
Committee Chair

Christopher Hay, Ph. D., P.E. Date
Dissertation Advisor

Van Kelley, Ph. D., P.E. Date
Head, Department of Agricultural and Biosystems Engineering

Dean, Graduate School Date

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LIST OF ABBREVIATIONS

A	Green Ampts Constant
Ac	Albaton Silty Clay Soil
Bm	Bon Clay Loam Soil
ρ_b	Bulk Density
Cb	Clamo Silty Clay
CDO	Climatic Data Online
ET_c	Crop Potential Evapotranspiration
DES	Data Evaluation Software
DLS	Deep and Lateral Seepage
WP4C	Dew Point Potentiometer (Decagon)
D	Drainage
DC	Drainage Coefficient
DDR	Drainage Design Rate
q	Drainage flux
DI	Drainage Intensity
K_e	Effective Lateral conductivity
EhA	Egan Trent Silty Clay Soil
L	Empirical Pore Tortuosity/Connectivity
d_e	Equivalent drainage depth
ET	Evapotranspiration
M	Fillable Porosity
FAO	Food and Agricultural Organization
B	Green Ampts Constant
GDD	Growing Degree Days
HPRCC	High Plains Regional Climate Center
HkA	Houdek (Fine Loamy) State Soil
HoB	Houdek Clay Loam Soils
F	Infiltration
kPa	Kilo Pascal

l	Lateral Drainage spacing
MAE	Mean Absolute Error
Q_m	Mean Observed Value
m	midpoint water table above the drain
MnB	Moody Nora Silty Clay Soils
E	Nash-Sutcliffe Efficiency
NASS	National Agricultural Statistics Services
NCDC	National Climatic Data Center
NOAA	National Oceanic and Atmospheric Administration
NRCS	Natural Resources Conservation Service
Q_o	Observed Value
PTF	Pedotransfer Function
D_v	Percent Deviation
PEC	Performance Evaluation Criteria
PM	Performances Measures
PET	Potential Evapotranspiration
P	Precipitation
Q_p	Predicted Value
h	Pressure Head
REF- ET	Reference Evapotranspiration
RY	Relative Yield
θ_r	Residual Water Content
RMSE	Root Mean Square Error
RO/R	Runoff
K_s/K_{sat}	Saturated Hydraulic Conductivity
K_v	Saturated Vertical Hydraulic Conductivity
θ_s	Saturated Water Content
n	Shape Parameters
α	Shape Parameters
SEW	Soil Excess Water
SSURGO	Soil Survey Geographic Database

SWC	Soil Water Characteristics
SDWRI	South Dakota Water Resource Institute
SERF	South East Research Farm
S_{av}	Suction at Wetting Zone
T_r	Ticonic Series Soil
USDA	US Department of Agriculture
θ	Volumetric Water Content
WbB	Wentworth Silty Clay

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ABSTRACT

IMPACT OF SUBSURFACE DRAINAGE ON WATER YIELD FOR TYPICAL SOIL AND WEATHER IN EASTERN SOUTH DAKOTA

GOVINDA KARKI

2017

Subsurface drainage in agricultural land changes the field water balance by providing an alternate pathway for subsurface water. Determining the effects of subsurface drainage on downstream hydrology requires quantifying the components of the water balance. A number of studies have looked at the hydrological impacts of subsurface drainage. However, the effects are complex and difficult to generalize. The complex interaction involves the interrelation among variables such as soil type and properties, climate (rainfall and evapotranspiration), and drainage design configuration (drainage intensity and drainage coefficient), which all are local in nature. Additionally, most studies have been conducted in humid climates, whereas eastern South Dakota is located in a transitional dry subhumid climate. The objective of this study was to determine the impact of subsurface drainage on water yield (runoff plus drain flow) at the field scale in eastern South Dakota in terms of soil type, weather, and drainage design (drain depth and spacing). Long-term simulations were performed in DRAINMOD, a field scale deterministic process based hydrological model, to quantify each component involved in the water balance. The hydrologic outputs (daily, monthly, and yearly) of DRAINMOD were used to determine the impact of subsurface drainage for various scenarios of selected soil type, climatic condition, and drainage design that are typical for the study area. The results of the impacts of tile drainage on water yield at the field scale were presented as functions of soil, climate, and drainage design. The results showed the water yield increased with increased drainage intensity (DI) for all selected soils. The subsurface drainage amounts also increased with increased DI. The results also showed that runoff decreased with increased in DI within the same soil type. Also, the proportion of drainage to water yield increased with increased DI. Water yield decreased as saturated hydraulic conductivity increased. Improved understanding of impacts at the field scale is an important first step towards understanding the impacts of subsurface drainage on stream flow.

Chapter 1:

General Introduction

1.1 Background

Subsurface (tile) drainage was first brought to the United States (U.S.) in 1835 by a Scottish farmer named John Johnston, who is also known as “the father of tile drainage in the United States”. Extensive works of subsurface drains have been constructed to remove excess water from agriculutaral field since then. Modern subsurface drainage using perforated plastic pipes is considered instrumental to maximize profitability of crop production on poorly drained soils. Construction of surface drains and installation of subsurface drainage assist in removing excess water, thus providing favorable conditions for crop growth (Skaggs et al., 1994b). However, drainage of agricultural areas can produce some negative environmental impacts, particularly the degradation of water quality (Franz et al., 2015). Studies by Irvin and Whitely (1983) and Kladivko (2004) have shown that the hydrological response of catchment areas have been significantly altered by the installation of subsurface drainages over the past decades resulting in floods and flash floods, and changing the peak flow rate and time (Irwin and Whiteley, 1983; Kladivko et al., 2004). Research continues on contributions of improved subsurface drainage to changes in hydrological responses. The possible reasons for changes in hydrological response could be result of different inter-related variables; however intensified agricultural subsurface drainage has always been subject of considerable interest.

South Dakota is no exception in utilizing the benefits of subsurface drainage, and the number and area of subsurface drainage installations have increased for a variety of reasons (Hay, 2011). Along with increasing subsurface drainage, there are increasing concerns about the impact of subsurface drainage on the downstream hydrology and the environment. One of the recent concerns in eastern South Dakota and the Midwestern U. S. is the impact that subsurface drainage discharge has had on water quality and water yield into the Mississippi River and beyond.

1.2 Hydrological Modeling

Hydrologic systems are complex heterogenous systems and interdependent on various variables. Hydrologic process is complex process to understand in detail. Therefore, abstraction is necessary if we are to understand or control some aspects of their behavior through modeling approach. A hydrologic system model is an approximation of the actual system, and its inputs and outputs are measurable by hydrologic variables. One of the well accepted modeling tools for study of agricultural drainage system is DRAINMOD (Skaggs et al., 2012), developed at North Carolina State University. It is a process based, distributed simulation model, and has been extensively used to model the hydrology in poorly drained soils to evaluate many objective functions such trafficability, relative yield, excess soil water (SEW), and wetland hydrology.

1.3 Performance of DRAINMOD with Soil Input by Pedotransfer Function

Soil properties (saturated hydraulic conductivity, K_{sat} and soil water characteristics, SWC) are the prime inputs in DRAINMOD. The model is capable of using both direct measured soil properties and indirect methods as soil input. Direct methods of obtaining soil hydraulic properties required for hydrological models (e.g., DRAINMOD) are expensive, time consuming, and laborious compared to indirect methods. Therefore, various pedotransfer functions (PTFs) are also available for estimating the soil properties required for the model. One of the most widely used PTFs is Rosetta (Schaap et al., 2001; Schaap et al., 2004), which uses easily available soil properties (textural class, particle size distribution, bulk density, and water content at -33 kPa and -1500 kPa) to estimate water retention parameter, saturated hydraulic conductivity, and unsaturated hydraulic conductivity. Rosetta uses five different levels of input depending on the availability of information. However, only a few studies have been conducted on the possibility of using PTF-derived SWC data and K_{sat} in DRAINMOD simulation, and evaluating performance of the model. Most of those studies of using PTF in DRAINMOD were focused on humid regions and different soils than those in eastern South Dakota.

1.4 Drainage Design Rate for Eastern South Dakota

The drainage coefficient (DC) is the water removal rate of a drainage system, typically expressed in units of depth per day. Choice of a DC for drainage design is primarily dictated by weather, soils, and crop root zone depth or type of corps. The DC of a drainage system is a function of soil properties, minimum water table depth, and drainage system design. The DC associated with the optimum drain depth and spacing for maximum net return was called the drainage design rate (DDR) and has been developed for eastern United States (Skaggs et al., 2006). A simple approach for determining DDR values was first used for eastern North Carolina using DRAINMOD simulation with economic analysis (Skaggs, 2007; Skaggs and Tabrizi, 1987). Hooughoudt’s equation in DRAINMOD was used to calculate DDR (Skaggs et al., 2006) as the steady-state drainage rate associated with maximum net annual return. The results indicated this approach could be used to make reasonable estimates of the drain depths and spacing to maximize profits for given inputs. The same approach was used as an expansion study using 50-year DRAINMOD simulations to determine DDR for ten locations in the eastern USA with four different soils (Skaggs, 2007). This study suggested that the average DDR required to maximize net annual return was function of climatic factors as affected by location and soil properties, and growing season precipitation (P). The study also indicated further research would be required to validate these equations for other climatic and soil conditions. The validity of these DDR equations is unclear for a location such as eastern South Dakota that is in a transitional climate from dry sub humid to semiarid conditions.

1.5 Subsurface Drainage and Its Impacts on Hydrology

There has been much debate regarding the impact of artificial subsurface drainage on downstream hydrology since the mid 1980's due to lack of measured data (Robinson, 1990). Even though observational data are available now in many places, the debate remains because of complexity of interacting variables including drainage system soil properties, weather conditions, and crop type. There are no definitive answers whether the artificial drainage is to blame for the increased risk of downstream hydrology (peak amount and time) because most of the variables are local in nature.

There exist two schools of thought relating to the impact of subsurface drainage on hydrology: (1) Subsurface drainage increases downstream flooding because subsurface drains remove water that would be stored in the soil more quickly than it would naturally drain, and (2) Subsurface drainage reduces downstream flooding because subsurface drains allows potential surface runoff to infiltrate and be released at a slower rate increasing the travel time and thereby reducing the peak flow rates downstream (Robinson, 1990). Both schools of thought have posed reasoning to support their ideas but ultimately conclude the impact is a complex interaction of hydrologic processes and depends on local factors (Robinson and Rycroft, 1999).

The first comprehensive study was published in 1990 (Robinson, 1990) in the United Kingdom (UK). The study showed some key observations, however no definitive explanation and conclusion had been made because of the complex interactions of variables associated with the hydrologic system. The result of the study on six different fields in the UK suggested that the key factors are pre-drainage soil water condition, soil type, land use, and topography. It was observed that subsurface drainage decreased the peak flow rate in clayey soils, while it increased the peak flow rate in sandy soils. Various studies (Blann et al., 2009; Chang-xing et al., 2003; Irwin and Whiteley, 1983; Robinson and Rycroft, 1999; Skaggs et al., 1994a) found that soil type, the presence of macro pores, and surface storage are among the most dominant factors that determine whether the peak flow rate is increased or decreased. The presence of macro pores and/or surface storage increased the peak flow rates in dry summer months because of cracks in clay soils (Robinson, 1990). Climatic factors (precipitation and evapotranspiration) are other dominant factors that determine whether downstream flow increases or decreases (Basso et al., 2016). The hydrology of an agricultural field is affected by the occurrence and timing of precipitation, surface and subsurface water storage, surface runoff, infiltration, evapotranspiration, and seepage. Each of these processes is influenced by soil type, crop type, and growth stage. Drain spacing and depth, collectively termed drainage intensity (DI), is another key factor identified as modifier in hydrological response (Skaggs et al., 2005). Robinson (1990), using DRAINMOD simulations, showed that a decrease in spacing decreased the peak flow rate initially to some point and then peak flow rates increased. The drainage coefficient can also affect peak flows during large rainfall events. During large events, the subsurface storage may be filled and surface runoff will dominate (Skaggs et al., 1994a). Management practices such as mulching were observed to reduce peak flows, especially on plowed, bare soil (Robinson and Rycroft, 1999). The reduction is due to decrease in kinetic energy of rain drops hitting the soil surface, which will reduce surface sealing and increase infiltration.

In general, the previous studies on impact of subsurface drainage on hydrology suggest that it is difficult to generalize the impact on hydrology because of the complexity of variables involved and limited studies. In addition, there is a study gap in quantifying the water yield caused by agricultural drainage under different scenarios of system design, soil type, and weather. With the increase in subsurface drainage in eastern South Dakota and the importance of local factors in the hydrologic responses, there is a need for research on how increased subsurface drainage impacts downstream water yield for typical soil and weather conditions available in the area. Therefore, the goal of this research is to quantify downstream water yield for different scenarios of drained conditions vs. undrained conditions under typical agricultural soil and weather conditions. While doing so, the performance of DRAINMOD, a field scale hydrological model, will also be evaluated using estimated soil hydraulic properties from pedotransfer functions (PTF).

1.6 Objectives

The goal this research is to better understand how the addition of subsurface drainage to agricultural production system alters hydrology at the field scale. Specific objectives of the study were to:

1. Evaluate the effect of measured and estimated soil hydraulic properties input in DRAINMOD.

2. Estimate the drainage design rate (DDR) for typical weather and commonly drained soils in southeastern South Dakota
3. Evaluate the imnpact of subsurface drainage on field scale water yield under typical weather on commonly drained soils in southeastern South Dakota.

1.7 Dissertation Organization

This dissertation is organized as a collection of three manuscripts with a general introduction and a general summary and conclusions. Each manuscript includes its own introduction, literature review, and methods section. Therefore, there is some redundancy in the contents.

Each manuscript addresses one of the study objectives in section 1.6. The first manuscript, titled “Evaluating the performance of DRAINMOD from measured soil properties and estimated soil properties using pedotransfer function in eastern South Dakota”, focuses on the comparison of hydrological model output by direct measured soil input vs. indirect measured soil input. The second manuscript, titled “Estimating Drainage Design Intensity for south eastern South Dakota”, estimates the drainage design rate for typical southeastern South Dakota soil and weather conditions. The final manuscript, “Impact of subsurface drainage on field-scale water yield in eastern South Dakota”, describes the impact of subsurface drainage on field-scale hydrology as a function of soil type, drainage intensity, and rainfall.

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Chapter 2:

Evaluating the performance of DRAINMOD from measured soil properties and estimated soil properties using pedotransfer functions in eastern South Dakota

2.1 Abstract:

DRAINMOD is widely used field scale hydrological model for simulating hydrology in poorly drained soils. Soil hydraulic properties are primary inputs for the model. The hydrological model predictions are most sensitive to saturated hydraulic conductivity (K_{sat}*) followed by unsaturated hydraulic properties derived from the soil water characteristic (SWC) curve, a relationship between volumetric water content and pressure head. DRAINMOD is capable of using soil hydraulic properties derived from both direct and indirect methods. Indirect methods use pedotransfer functions (PTF), which use easily available soil properties (textural class, particle size distribution, bulk density, and water content at field capacity and wilting point) to estimate water retention parameters (*θ *and h), saturated hydraulic conductivity (*K_{sat}*), and unsaturated hydraulic conductivity (*K_{usat}*) with varying levels of input. Direct methods of obtaining soil hydraulic properties required for DRAINMOD are expensive, time consuming, and laborious compared to indirect methods. A few studies have been conducted on the possibility of using PTF derived SWC data and *K_{sat} *in DRAINMOD. This study makes use of relatively newer techniques for generating SWC data using the Hyprop (Wind and Schindler evaporation method) and WP4C (dew point potentiometer) instruments. The Hyprop software includes its own PTFs for estimating saturated hydraulic conductivity (*K_{sat}*). Long term (63 year) DRAINMOD* *simulations were conducted for a study field in eastern South Dakota to evaluate DRAINMOD hydrological output using PTF derived soil properties based on NRCS soil data, and directly measured SWC curve obtained from Hyprop and WP4C and saturated hydraulic conductivity (*K_{sat}*) derived from hyprop data evaluation software (Hyprop-DES). The model was calibrated against observed water table depth, and measured SWC data and PTF derived *K_{sat}* were used in DRAINMOD under the same weather, crop, and drainage system configuration for long-term simulations. Predicted annual subsurface drainage for different soil inputs were compared with the observed and calibrated result. Both visual and statistical comparisons showed good agreement among calibrated (*C_o*) measured (*M_o*), and PTF derived (*R_o*) soil properties. The mean absolute error in annual drainage and runoff was less than 1 cm. The Nash-Sutcliffe efficiency (E) values for yearly, monthly, and daily drainage were found to be 0.99, 0.99, and 0.97 between *M_o* and *C_o* values while 0.97, 0.94, and 0.91 between *R_o* and *C_o* values. The same values for yearly, monthly, and daily runoff were found to be 0.98, 0.98, and 0.94 between *M_o* and *C_o* while 0.75, 0.75, and 0.58 between *R_o* and *C_o*. The result shows the higher agreement with calibrated values for drainage values compare to runoff. The findings of this study will be important for long-term study of drainage water management and water quality impact on watershed scale.*

2.1 Introduction:

DRAINMOD is one of the widely used field scale hydrological models for simulating hydrology in poorly drained soil, developed by Skaggs (1980) at North Carolina State University. It has been used extensively over the past 30 years to model the hydrology in poorly drained soils, and to evaluate many other objective functions such as trafficability, relative yield, amount of excess soil water (SEW_{30}), dry days, and wetland hydrology. DRAINMOD calculates surface and subsurface water balance for a thin column of soil that has a unit surface area which extends from the ground surface to the subsurface impermeable layer and is located at the midway between two tile drains. The water balance is calculated primarily at an hourly and daily time increment basis, using approximate methods with six different input such as weather, soil, crop, and system design configuration inputs (Skaggs, 1978).

Results of DRAINMOD are primarily dictated by soil hydraulic properties and evapotranspiration (ET) (Skaggs, 1980). The soil hydraulic properties used in the model are saturated hydraulic conductivity (K_{sat}), soil water characteristics (SWC) curve, drainable porosity, upward flux, and Green-Ampt parameters (Skaggs et al., 2012). All except saturated hydraulic conductivity are derived from the SWC curve within the model.

The model can use both measured and indirectly estimated soil properties. One of the precise methods of measuring water retention for developing the SWC curve in the laboratory is the combination of Hyprop (Wind and Schindler evaporation method) and WP4C (dew point potentiometer) instruments (Peters and Durner, 2008). Hyprop works well for the wet range of matric potentials, while the WP4C works well in the dry range. A combination of both methods gives the best result in generating SWC data. Moreover, hyprop and WP4C have their own data evaluation software (Schwab et al., 1985) for SWC and pedotransfer function, this uses the measured data for SWC, to estimate saturated hydraulic conductivity. It provides an alternative to field measurement of saturated hydraulic conductivity, which is time consuming, laborious and expensive.

Alternatively, various other pedotransfer functions (PTFs) are also available for estimating soil properties, both SWC and K_{sat}, required for DRAINMOD. One of the most widely used PTFs is Rosetta (Schaap et al., 2001; Schaap et al., 2004), which uses more readily available soil properties (textural class, particle size distribution, bulk density, and water content at -33kPa and -1500kPa) to estimate water retention parameters, saturated hydraulic conductivity, and unsaturated hydraulic conductivity. Rosetta uses five different levels of input (H1: United States Department of Agriculture (USDA) textural class; H2: H1 plus percent sand, silt, and clay; H3: H2 plus dry bulk density; H4: H3 plus water content at suction -33kPa; H5: H4 plus water content at -1500kPa).

United States Department of Agriculture, Natural Resources Conservation Service (USDA, NRCS) maintains the Soil Survey Geographic Database (SSURGO) that contains soil data collected by the National Cooperative Soil Survey (NCSS) over the course of a century, and is an attractive option for estimating soil hydraulic properties from PTFs. Few studies have been conducted on the possibility of using PTF-derived SWC data and K_{sat} in DRAINMOD simulation and evaluating performance of the model. A study in Iowa was conducted to determine which level of selected soil information would have been sufficient to use with DRAINMOD in predicting subsurface drainage volumes (Qi et al., 2015). The result showed that Rosetta in combination with SSURGO offers quick and robust way to derive soil hydraulic properties to simulate long term DRAINMOD in predicting subsurface drainage.

Another more detailed study was performed in Sweden that compared the simulated hydrologic output in DRAINMOD with four years of observed data (Salazar et al., 2008). The study used Rosetta-estimated K_{sat} using different complexity levels of soil information for a coarse textured soil with low water holding capacity and high K_{sat}. In 2009, a study was performed to evaluate the accuracy of twenty-four PTFs for predicting K_{sat} for US soils (Abdelbaki et al., 2009). The functions were divided into three groups according to their input requirements and results were ranked according to their performance in predicting K_{sat} for the entire soil's database and for each textural class in the US. In 2010, the study was extended to assess the feasibility of running DRAINMOD with PTF-predicted soil hydraulic parameters (Abdelbaki and Youssef, 2010). The PTFs selected for the study were the best ranked from the study in 2009 (Abdelbaki et al., 2009). This study also showed the excellent agreement between observed and simulated overall drainage outflows in conventional and control drainage system compared to measured soil input, while the result showed some variation in drainage flow under conventional drainage system with Rosetta soil input.

Most of the studies on the feasibility of using PTFs in DRAINMOD were focused on humid regions with different soils and climate than eastern South Dakota. SWC and K_{sat} in those studies were PTF derived. The purpose of this study was to evaluate the feasibility of running DRAINMOD simulations with Rosetta-estimated soil properties (SWC and K_{sat}) and compare them with those derived from soil water characteristic curves from Hyprop and WP4C instruments and K_{sat} from Hyprop DES-PTF. The performance of model output in predicting growing season drainage was also checked for its sensitivity to soil properties (K_{sat} and suction head) by altering inputs by a known percentage and noting the deviation in hydrological output. The predicted drainage and runoff volumes using Rosetta-derived soil properties were compared with calibrated values obtained from field-measured soil SWC and PTF-derived K_{sat}.

2.2 Methods:

2.2.1 DRAINMOD

DRAINMOD (Version 6.1) was selected for this study. DRAINMOD is a field scale, process based, distributed simulation model (Skaggs et al., 2012). It was developed by Dr. Wayne Skaggs in the Biological and Agricultural Engineering Department at North Carolina State University. It has been used extensively over the past 30 years to model the hydrology in poorly drained soils and to evaluate many other objective functions such as trafficability, relative yield, SEW_{30}, dry days, and wetland hydrology. DRAINMOD calculates surface and subsurface water balances for a thin column of soil that has a unit surface area which extends from the ground surface to the subsurface impermeable layer and is located midway between two subsurface drains. The water balance is calculated on an hourly or daily time increment basis, using approximate methods based on weather, soil, crop, and system design configuration inputs (Skaggs, 1978). The two governing water balance equations for the surface and subsurface are:

$$\Delta V = D + ET + DLS - F \qquad (1)$$

$$P = F + S + RO \qquad (2)$$

where,

ΔV is change in water free pore space, D is drainage, ET is evapotranspiration, DLS is deep and lateral seepage, F is infiltration, P is precipitation, S is change in volume of water stored on surface, and RO is runoff. All are in the same units of depth. Each of these components is calculated using approximation methods which allow DRAINMOD to run long-term simulations very quickly. DRAINMOD (Version 5.0 and higher) is capable of incorporating the effect of freezing, thawing and snowmelt (Luo et al., 2000). These versions (5.0 and higher) are also capable of simulating nitrogen and carbon cycles in shallow water table soils and the effects of drainage and drainage water management practices on nitrogen losses in drainage. The model inputs for DRAINMOD are soil properties, weather, drainage system characteristics, and crop-related parameters. Additional parameters are required to consider the effect of freezing, thawing, and snowmelt. Details of parameters can be found elsewhere for DRAINMOD (Luo et al., 2000), and predicting field hydrology with DRAINMOD (Luo et al., 2001).

2.2.2.1 Subsurface Drainage

DRAINMOD uses the steady state Hooughoudt equation (3) when the water table is between the drain depth and the soil surface. The Hooghoudt equation includes Dupuit-Forcheimer (D-F) assumptions (lateral flow in the saturated zone only) and assumes an elliptical water table.

$$q = \frac{4\mathrm{k}_e m\,(2d_e+m)}{L^2} \qquad (3)$$

where,

q is drainage flux (cm/hr.), d_e is the equivalent drainage depth of the impermeable layer below the drain (cm), m is the mid-point water table height above the drain (cm), K_e is effective lateral hydraulic conductivity (cm/hr.), and L is the lateral spacing between the drains (cm), (Figure 2.1).

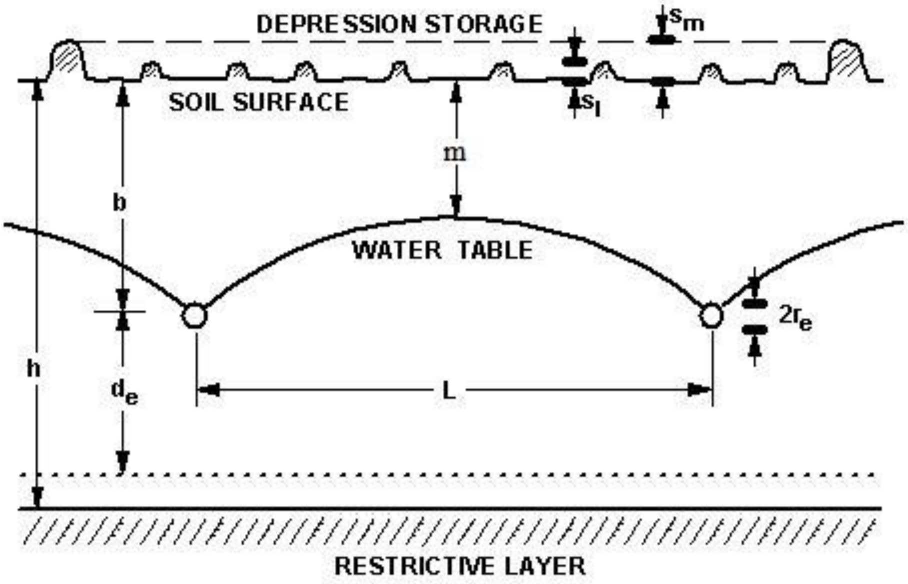

Figure 2.1 Drainage schematic for DRAINMOD (Skaggs et al., 2012)

2.2.2.2 Infiltration

Infiltration in DRAINMOD is calculated using the Green-Ampt equation (4)

$$\begin{cases} f = K_v + \frac{K_v M S_{av}}{F} \\ \quad = B + \frac{A}{F} \end{cases} \qquad (4)$$

where,

K_v is saturated vertical hydraulic conductivity, M is the fillable porosity (water content at saturation minus water content at desired water table depth), S_{av} is suction at the wetting front, F is the cumulative infiltration, and A and B are constants. Additionally, at times where rainfall is below infiltration capacity, DRAINMOD assumes that the infiltration rate is equal to the rainfall rate.

2.2.2.3 Evapotranspiration

Evapotranspiration (ET) in DRAINMOD can be estimated using either the Thornthwaite method within the model or can be given as user defined input in an input file. The Thornthwaite equation is used to calculate monthly potential evapotranspiration (PET) in the model and then converted to daily values using the method described by Thornthwaite and Mather (Thornthwaite et al., 1957). However, the Hargreaves-Samani method (Hargreaves and Samani, 1985) was used in this study as it was found to compare well with the Food and Agricultural Organization Penman-Monteith equation when using a time-step of five days or longer (Allen et al., 1998; Hargreaves and Allen, 2003). Reference evapotranspiration(Allen et al., 1998) estimated using in the REF-ET (Allen, 2000) model was multiplied using High Plains Regional Climate Center (HPRCC) crop coefficients for corn, which is based on growing degree days (GDD), and provided into the model as crop potential evapotranspiration for long term simulation. Actual ET was computed in the DRAINMOD from crop potential evapotranspiration provided in model after correction with crop coefficient as limited by soil water availability.

2.2.2 Hyprop and WP4C

Hyprop (Decagon Devices, Pullman, WA) uses the evaporation method in which continuous measurements of suction with two high-capacity tensiometers installed at different depths of soil samples are made and changes in moisture content are obtained by change in weight of soil (Schindler et al., 2010). The sample is packed in a stainless-steel cylinder to the bulk density corresponding to the field condition, and brought to saturation before measurements are taken.WP4C (Decagon Devices, Pullman, WA) is a dew point potentiometer which measures relative humidly of air above soil sample and suction is calculated. The soil sample is placed in a cup and inserted into a chamber in the WP4C, and is allowed to equilibrate to the air temperature in the chamber. Water vapor diffuses out of the soil into the air inside the chamber until the relative humidity of the air comes to equilibrium. A mirror above the sample is chilled allowing water to condense, and the temperature at which the condensation occurs is the dew point temperature. The relative humidity of the air can therefore be determined from the dew point temperature, and since the relative humidity is related to the matric potential in the soil sample, the matric potential can be determined directly from the dew point temperature measurement

Hyprop data evaluation software (Hyprop-DES) (Pertassek et al., 2011) is a computer program for analyzing data from Hyprop and WP4C experiments (Decagon Devices, Pullman, WA). Hyprop-DES provides an algorithm to fit functional relationships of the retention curve and the conductivity curve to the data. No specification of initial guesses for the parameter values is required. Seven widely used retention models are available, encompassing expressions for soils with unimodal (Van Genuchten, 1980) and bimodal (Durner, 1994; Ross and Smettem, 1993)pore-size distributions, with (Brooks and Corey, 1966) and without air-entry, and a model extension that reaches water content zero at oven dried condition(at pF scale7) (Fayer and Simmons, 1995). The retention functions are coupled to conductivity models by the classical pore-bundle models (Burdine, 1953) and (Mualem, 1976), including a film-flow component according to the models of Peters and Durner (Peters and Durner, 2008).

2.2.3 Rosetta

Rosetta (Schaap et al., 2001) is a set of pedotransfer functions which use five hierarchical surrogate soil data parameters (soil textural classes, bulk density, and moisture content at field capacity and permanent wilting point) to estimate vertical saturated hydraulic conductivity. A total of 1306 soil samples from the U.S.A. and

Europe were used to predict saturated hydraulic conductivity based on the Mualem (Mualem, 1976) pore-size model. The retention function is given by

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{[1+(\alpha h)^n]^{1-\frac{1}{n}}} \qquad (5)$$

where,

$\theta(h)$ represents the water retention curve defining the water content, θ (cm^3/cm^3), as a function of the soil water pressure head h (cm),θ_r and θ_s (cm^3/cm^3) are residual and saturated water contents respectively, while α(1/cm) and n are curve shape parameters. The equation (5) can be rewritten to yield the relative saturation (S_e)

$$Se = \frac{\theta(h) - \theta_r}{\theta_s - \theta_r} = [1 + (\alpha h)^n]^{1-\frac{1}{n}} \qquad (6)$$

The equation (6) is used in conjunction with the pore-size distribution model (Mualem, 1976).

$$K(S_e) = K_0 S_e^L \left\{1 - \left[1 - S_e^{n/(n-1)}\right]^{1-1/n}\right\}^2 \qquad (7)$$

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 the saturated hydraulic conductivity, K_{sat}. The parameter L(-) is an empirical pore tortuosity/connectivity parameter that is normally assumed to be 0.5 (Mualem, 1976). Rosetta predicts L which will be negative in most cases, although this leads to some theoretical complication, it gives better results.

In DRAINMOD model, a subroutine is available to convert the Rosetta output into DRAINMOD readable format and requires the following input: θ_r, θ_s α, n, L,K_0 *and* K_{sat}.

2.2.4 Study Area

The study area was located at Southeast Research Farm (SERF) near Beresford (43º4’12” N 96º55’48” W) in Clay County of South Dakota (Figure 2.2). The soil in the study area was Egan-Trent silty clay loam, (EhA, mixed, mesic pachic haplustolls). The climate in the area was classified as a transitional zone from subhumid to semi-arid conditions, with average annual precipitation (1950-2012) of 642 mm, and average annual (1950-2012) daily maximum and minimum temperature of 14.7 ºC and 1.8 ºC respectively. The field parcel was 5.75ha (14.25 acre) divided into six plots (Figure 2.2). Half of the area was conventional drainage and the other half is managed as undrained. The plots were drained separately and the drain outflow from each plot was measured in control structures that were installed in all plots to monitor the flow depth. Monitoring wells were installed in between the plots for monitoring water table depth. The observed data had been used for calibration and validation purpose.

The soil at the study area is classified as Egan-Trent series silty clay loam in the USDA, NRCS (SSURGO) database. Soil information available for this series required for the model in SSURGO is shown in (Table 2.1). Long-term (1950-2012) weather data (daily maximum and minimum air temperature, and daily precipitation) for the purpose of DRAINMOD simulation were taken from the South Dakota climate and weather station located at Centerville (station 391579), eight kimolmeters northwest of the study site. Weather data were alos used to estimate potential evapotranspiration (PET) by Hargreaves Samani (1985) method.

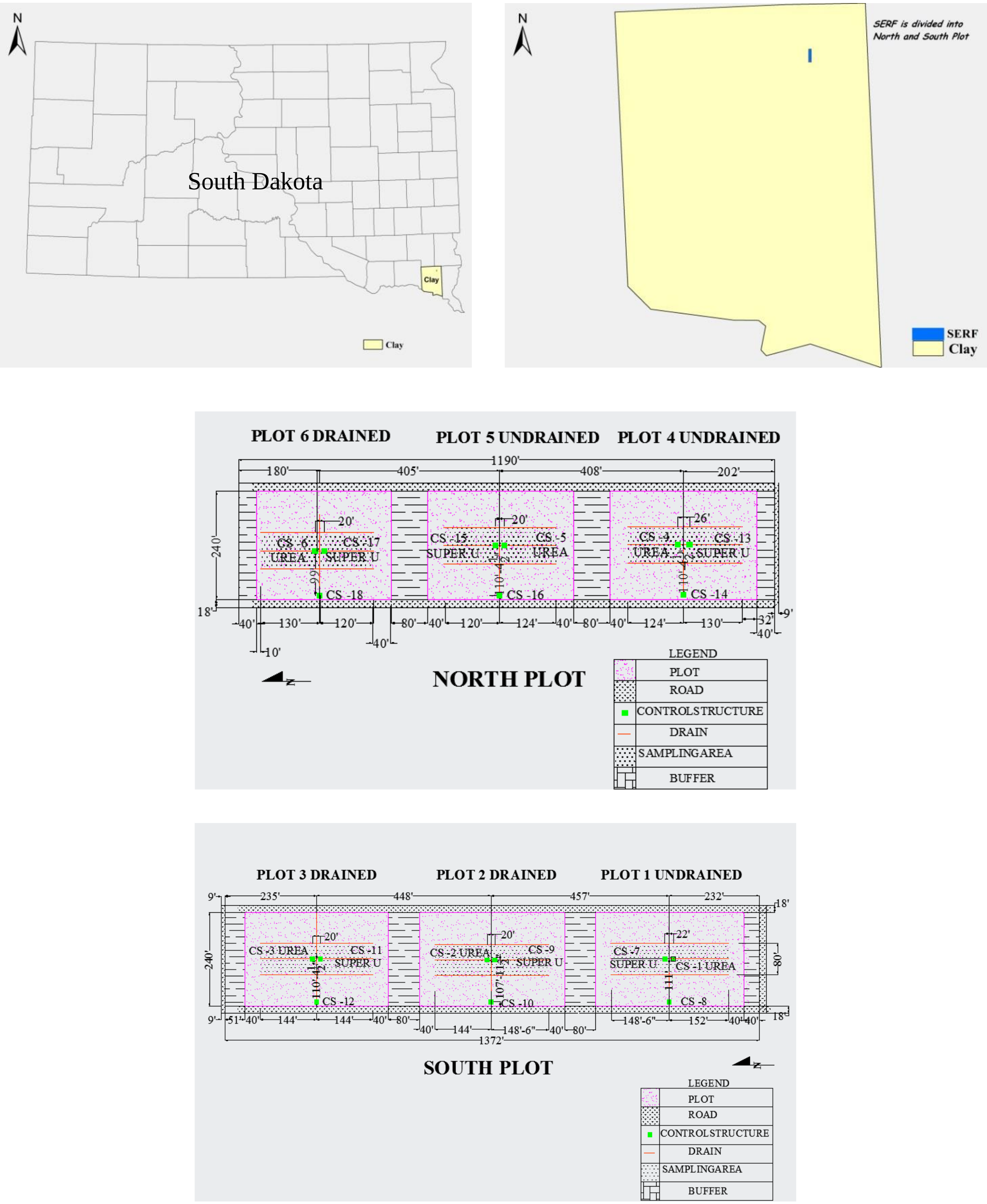

Figure 2.2 Study area

Table 2.1 Soil information from SSURGO for the study area

Component Name	Depth (cm)	Representative (K_{sat})	% of sand	% of silt	% of clay	Soil bulk density (ρ_b)	Moisture content at-33 kPa	Moisture content at -1500 kPa
		cm/hr.	%	%	%	gm/cc	%	%
EhA Egan Series (silty-Clay Loam)	0-20	3.24	6.7	62.3	31	1.20	32.7	19.6
	20-66	3.24	6.8	63.2	30	1.28	30.6	16.6
	66-86	3.24	26.4	43.6	30	1.28	30.0	15.7
	86-152	3.24	26.4	43.6	30	1.60	30.5	18.9

2.2.5 Soil Hydraulic Properties

The soil water characteristics curve was generated using hyprop-DES combining the data obtained by Hyprop and WP4C. Saturated hydraulic conductivity was obtained using the model described by Mualem (1976), a model provided within hyprop-DES. Five levels of soil information from the (SSURGO) data base were used as Rosetta input to produce the SWC data required for DRAINMOD while representative saturated hydraulic conductivity from (SSURGO) has been used for model simulation. Measured and Rosetta-generated soil hydraulic properties are shown in Figure 2.3 and Table 2.2.

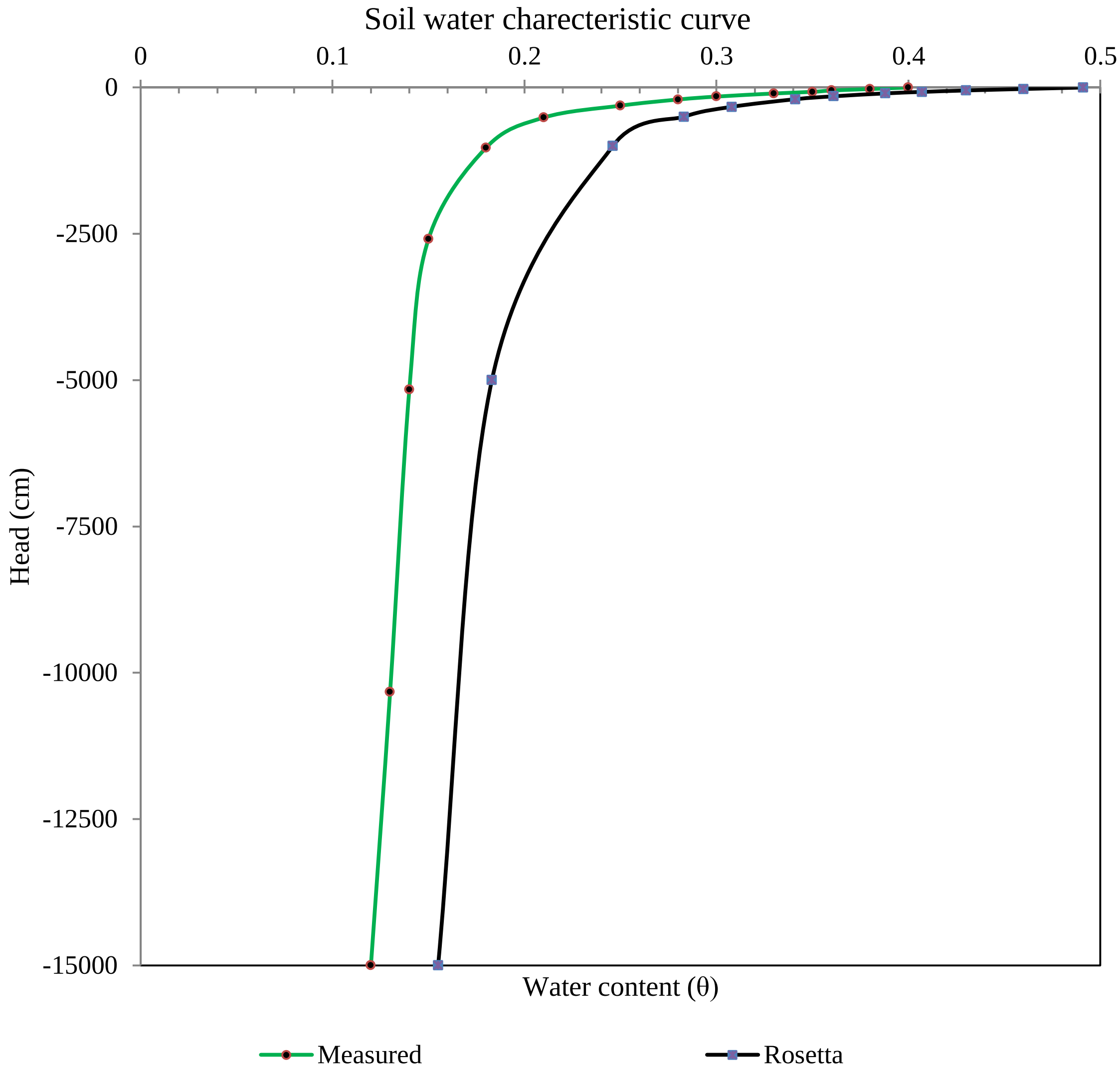

Figure 2.3 Soil water characteristics curve of the soil for study area

Table 2.2 Saturated hydraulic conductivity of the soil for the study area

Saturated Hydraulic Conductivity (K_{sat},cm/hr.)			
Rosetta derived		Estimated from hyprop	
Depth	Value of K_{sat}	Depth	Value of K_{sat}
0-43	3.24	0-20	1.74
43-71	3.24	20-45	1.74
71-119	3.24	45-110	1.74
119-132	3.24	110-152	1.74
132-152	0.97		

2.2.6 Model Simulation and Evaluation

DRAINMOD simulations were conducted for the period of 2004-2014 using measured weather data and soil hydraulic properties, and specified drainage design configuration for continuous crop. Soil temperature (freezing and thawing) was also taken into consideration in simulation. Table 2.3 and Table 2.4 list some selected DRAINMOD input parameters for drainage system design, crop production, and soil temperature. The SWC data obtained by laboratory measurement (Hyprop and WP4C) and Rosetta PTF, were used to develop water table-drained volume-upward flux relationships and Green-Ampt parameters using utilities provided in DRAINMOD separately. PET was supplied as a user defined input file. Lateral saturated hydraulic conductivity obtained from Hyprop-DES in the layers was adjusted to calibrate the model against the observed water table. Mean absolute error (MAE) was used as the objective function during the calibration process. The calibrated hydraulic conductivity values are given in Table 2.5.

Once the calibration process was completed, two sets of long term simulations (1950-2012) as shown in Table 2.6 (R_o and M_o) were performed using long term weather data, crop input, and specified drainage system design. The drainage and runoff values obtained from long-term simulations were compared with the values obtained using calibrated soil input (C_o) as shown in Table 2.5.

Table 2.3 DRAINMOD input parameters

Description of Parameters	Value
Drain depth (cm)	110
Drain spacing (m)	24.40
Effective radius (cm)	0.51
Depth of impermeable layer from surface (m)	2
Drainage coefficients (cm/day)	0.95
Initial depth to water table (cm)	30
Maximum surface storage (cm)	1.0
Kirkham's depth (cm)	50% of maximum storage
Drainage system	Conventional
Crop Parameters	**Value**
limiting water table depth for no crop damage	30
Desired planting date (Day of year)	124 (May 4)
Length of growing season for corn	173

Table 2.4 DRAINMOD input for soil temperature

Soil temperature Parameters	Input value
Computational depth function coefficients (a)	2.5 cm
(b)	1.21
Thermal conductivity function W/m ° C (a)	0.39
W/m ° C(b)	1.33
Diurnal Phase lag of air temp	8 hrs.
Base temperature as boundary (°C)	9.11
Rain/snow dividing temp (°C)	0
Snow melt base temperature (°C)	1
Degree day coefficient (mm/day)	5
Critical ice content (cm3/cm3)	0.2

Table 2.5 Calibrated hydraulic conductivity

Depth	Calibrated hydraulic conductivity Ksat (cm/hr.)
0-20	1.74
20-43	3.24
43-109	3.24
109-152	1.74

Table 2.6 Soil parameters used as input in DRAINMOD

Soil input	Description of data
Rosetta (R_o)	Soil water characteristics curve(SWC) data and K_{sat}: Estimated from soil textural class, particle size distribution, bulk density, and water content at field capacity and wilting point)
Measured soil data (M_o)	Soil water characteristics curve(SWC) data: Measured from Hyprop and K_{sat}: Estimated from pedotransfer function provided in Hyprop –DES
Calibrated soil data (C_o)	Soil water characteristics curve(SWC) data: Measured from Hyprop and K_{sat}: Estimated from pedotransfer function in available in Hyprop-DES, and adjusted for calibration

2.2.7 Statistical Analysis

Performance measures (PMs) and corresponding performance evaluation criteria (PEC) are important aspects of calibrating and validating hydrologic and water quality models and should be updated with advances in modeling science (Moriasi et al., 2015). Certain statistical performance criteria are recommended by Moriasi et al. (2015) to measure the accuracy and performance of hydrological model.

DRAINMOD output using field measured SWC and Hyprop-DES derived hydraulic conductivity (M_0), and the best Rosetta-estimated soil input (R_0) were compared with long-term calibrated values (C_0). Yearly, monthly and daily simulated drainage outflow and runoff values were compared by calculating four statistical measures: Nash-Sutcliffe efficiency (E), normalized root mean square (RMSE), average percent deviation (Dv), and mean absolute error (MAE):

Nash-Sutcliffe Efficiency (E):

$$E = 1 - \frac{\sum_{i=1}^{n}(Q_o - Q_p)^2}{\sum_{i=1}^{n}(Q_o - Q_m)^2} \qquad (8)$$

Normalized root mean square (RMSE):

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(\widehat{Q_{pi}} - Q_{oi}\right)^2}{n}} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(error)^2} \qquad (9)$$

Average percent deviation (D_v):

$$Dv(\%) = \frac{\sum_{i=1}^{n}|Q_o - Q_p|}{\sum_{i=1}^{n} Qo} x100\% \qquad (10)$$

Mean absolute error (MAE):

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|Q_p - Q_o\right| = \frac{1}{n}\sum_{i=1}^{n}|e_i| \qquad (11)$$

where,

Q_o is the observed value, Q_p is the predicted value, Q_m is the mean observed value, Q_{pi} is the predicted value in ith observation, Q_{oi} is the observed value for the ith observation, n is the number of observations, and e_i is the average of absolute error. Nash-Sutcliffe model efficiency (E) is a way to measure the fit between the predicted and observed values and is also called dimensionless model evaluation statistics (Moriasi et al., 2007) . The E value is one the one of the major indicator of hydrological model evaluation as it is less sensitive to the extreme values due to the squared difference. The E value can range from $-\infty$ to 1. Unit value of E corresponds to a perfect match of modeled value to the observed value. Zero value of E ($E<0$) indicates that the model predictions are as accurate as the mean of the observed data, whereas E less than zero ($E < 0$) observed values would have been a better predictor than the model.

RMSE is the square root of the mean squared error, which can be interpreted easily as it has the same unit as observed the values and, is representative of the size of a typical error. It is a measure of goodness of fit. RMSE is one of the commonly used error index statistics. Lesser RMSE values indicate better model performance. Further, the correlation coefficient (r, which varies between -1 and 1) serves as a bench mark for performance evaluation. For example, if all points lie exactly on a line with positive slope, then r will be 1 and, RMSE will be zero (0). An average percent deviation provides an immediate complement to the visual inspection and describes percent deviation from the mean value. Lower values indicate a better model. MAE measures the closeness of predicted and observed values. A zero value of MAE indicates a perfect fit.

2.3 Results and Discussion:

The long-term model predictions of hydrological output (drainage and runoff) using various soil inputs and model performance are presented in this section. Also, results and discussion of sensitivity of model output due to errors in soil inputs are presented.

2.3.1 Model Simulations

Yearly, monthly, and daily predictions of DRAINMOD on drainage and runoff with measured soil properties (M_o) and PTF derived soil property (R_o) for the simulation period are shown in (Figure 2.4 through Figure 2.7, and Table 2.7). Both visual and statistical comparisons showed good agreement among C_o, M_o, and R_o. The mean absolute error in annual drainage and runoff in both comparisons is less than 1 cm. The

Nash-Sutcliffe efficiency (E) values for yearly, monthly, and daily drainage were 0.99, 0.99, and 0.97 between M_o and C_o and 0.97, 0.94, and 0.91 between R_o and C_o values. The same values for yearly, monthly, and daily runoff were 0.98, 0.98, and 0.94 between M_o and C_o and 0.75, 0.75, and 0.58 between R_o and C_o. The results show better agreement between for drainage values compared to runoff. The results also show better agreement between M_o and C_o compared to R_o, and C_o for both drainage and runoff.

According to reported performance criteria by Skaggs (2012), model performance is considered as excellent, good and acceptable for Nash-Sutcliffe efficiency (E) values of 0.75, 0.60, and 0.40. This criterion (E) indicates that model performance in predicting yearly, monthly, and daily drainage using measured and Rosetta soil input was excellent. Yearly and monthly runoff predictions of runoff were excellent while daily model performance was good. However, the Moriasi et al. (2015) criteria for model performance in flow prediction were slightly different and divided into very good, good, satisfactory, and non-satisfactory. According to the Moriasi et al. (2015) criteria, model performance for our study in predicting yearly, monthly, and daily drainage using measured and Rosetta soil input were very good. Model performance in predicting yearly and monthly runoff prediction using Rosetta was good while model performance in predicting daily runoff was satisfactory.

Our study showed RMSE values less than unity, suggesting that the model is within the acceptable range, as lesser RMSE values indicate better model performance. The result showed that RMSE values for yearly, monthly, and daily drainage between Mo and Co were 0.25, 0.08, and 0.007 cm while R_o and C_o were 0.65, 0.94 and 0.01 cm. The RMSE values for yearly, monthly, and daily runoff between M_o and C_o were 0.20, 0.06, and 0.01 cm while R_o and C_o were 0.98, 0.25 and 0.04 cm. The study also showed that RMSE is better with measured soil input than Rosetta soil input in the model. Also, the yearly and daily model prediction of drainage flow were better than prediction of runoff while monthly runoff prediction was better than drainage (Table 2.7).

Percent deviation statistics in our study varies from 6.7% with measured soil input to 66.65% in Rosetta input. Yearly drainage deviation is 6.7% in measured soil input to 16.4% Rosetta input, while runoff deviation is 9.5% in measured soil input to 58.8% Rosetta soil input. Monthly deviation in drainage is form 9.65% measured soil input to 22.9% Rosetta soil input. Daily drainage deviation in drainage with measured soil input is 14.06% while with Rosetta soil input is 27.04%. This variation in daily runoff with measures soil input is 16.10% while with Rosetta soil input is 66.56%. The variation was more in runoff and daily as expected. This high variation in daily is because there number of days of zero rainfall events, and high variation in runoff is there is no runoff until rainfall intensity exceeds infiltrations rate. This statistic was also better in M_o than R_o in this study.

Mean absolute error measures the closeness of predicted and observed values of hydrological output and varied from 0.15 cm to 0.37 cm in yearly drainage, 0.07 cm to 0.43 cm in yearly runoff. The mean absolute error varied from 0.02 cm to 0.04 cm in monthly drainage, and 0.01 cm to 0.03 cm in monthly runoff. There is little or no variation in daily MAE drainage and runoff.

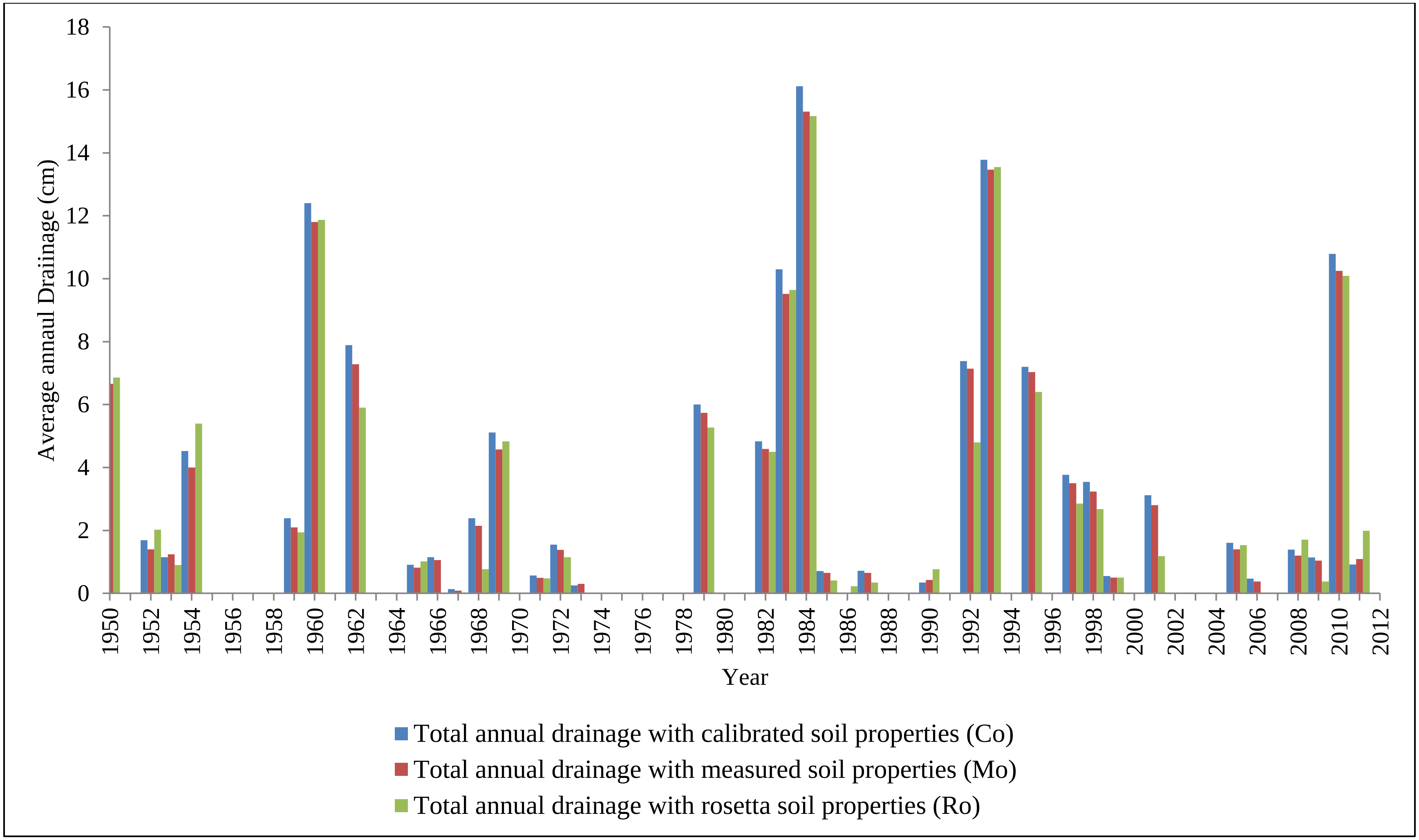

Figure 2.4 Comparison of total annual drainage in cm for long term simulation period (1950-2012)

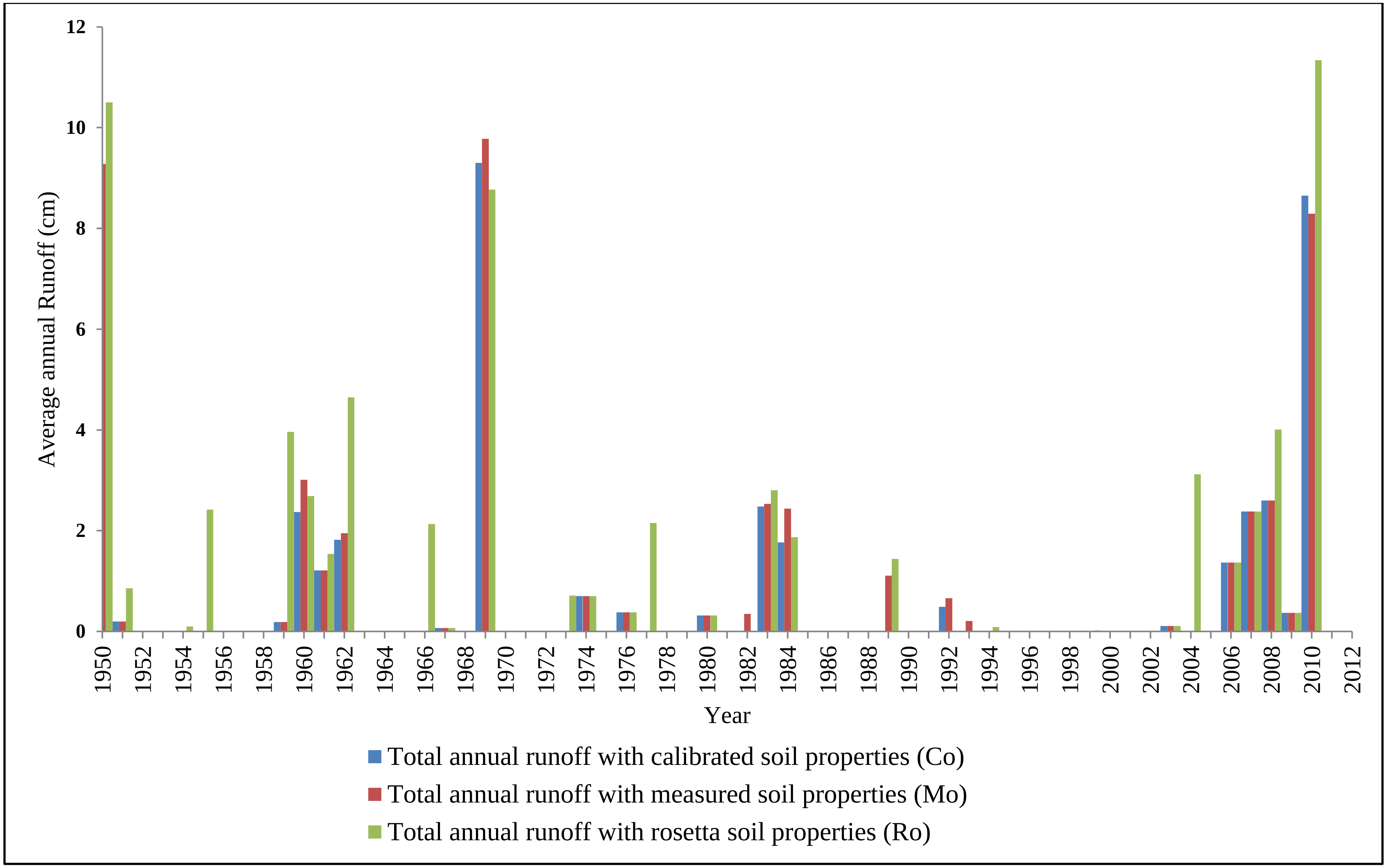

Figure 2.5 Comparison of total annual runoff in cm for long term simulation period (1950-1012)

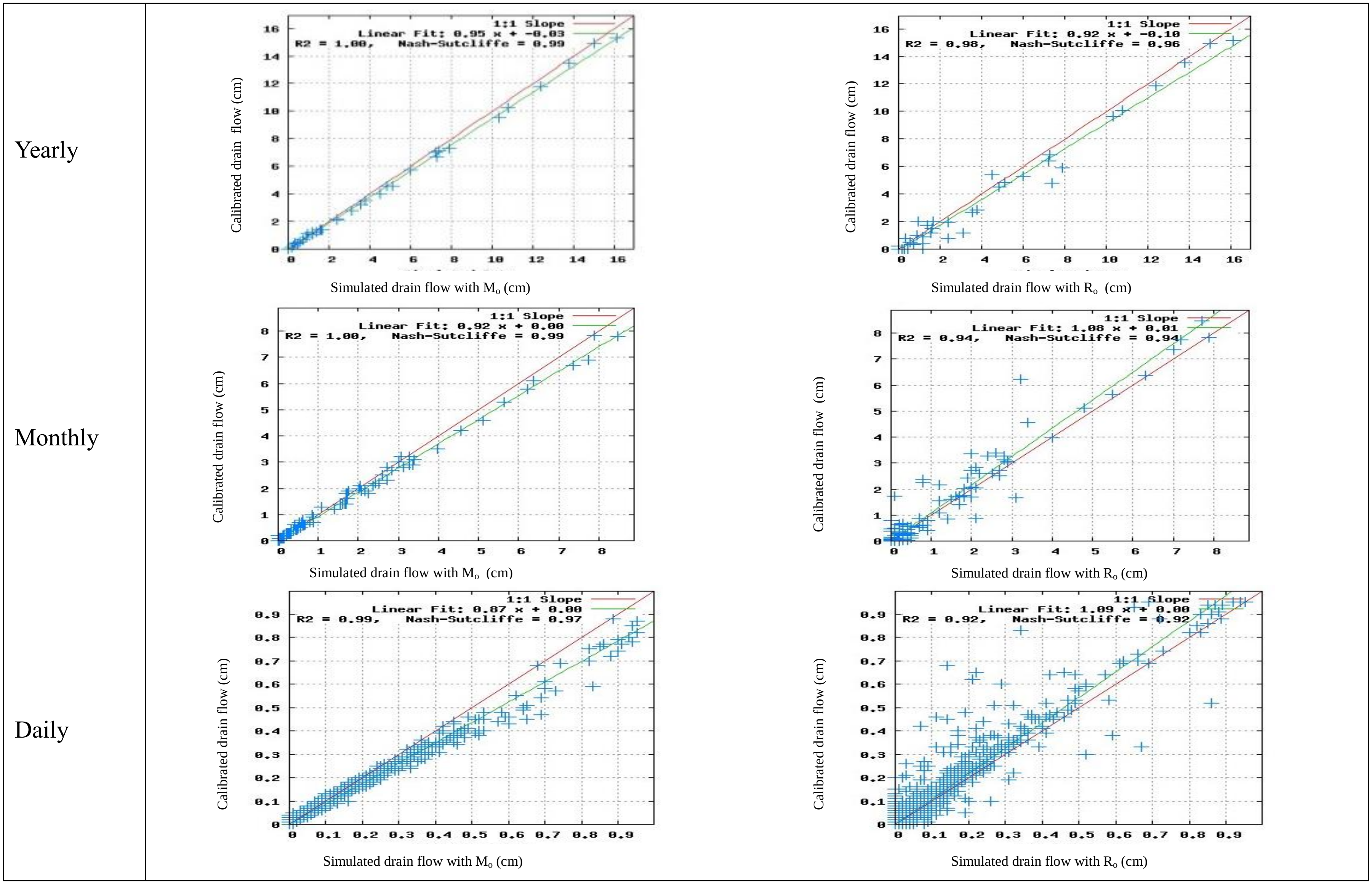

Figure 2.6 Comparison of calibrated with simulated drainage flow with rosetta soil input in model (Nash-Sutcliffe value & coefficient of determination, R^2)

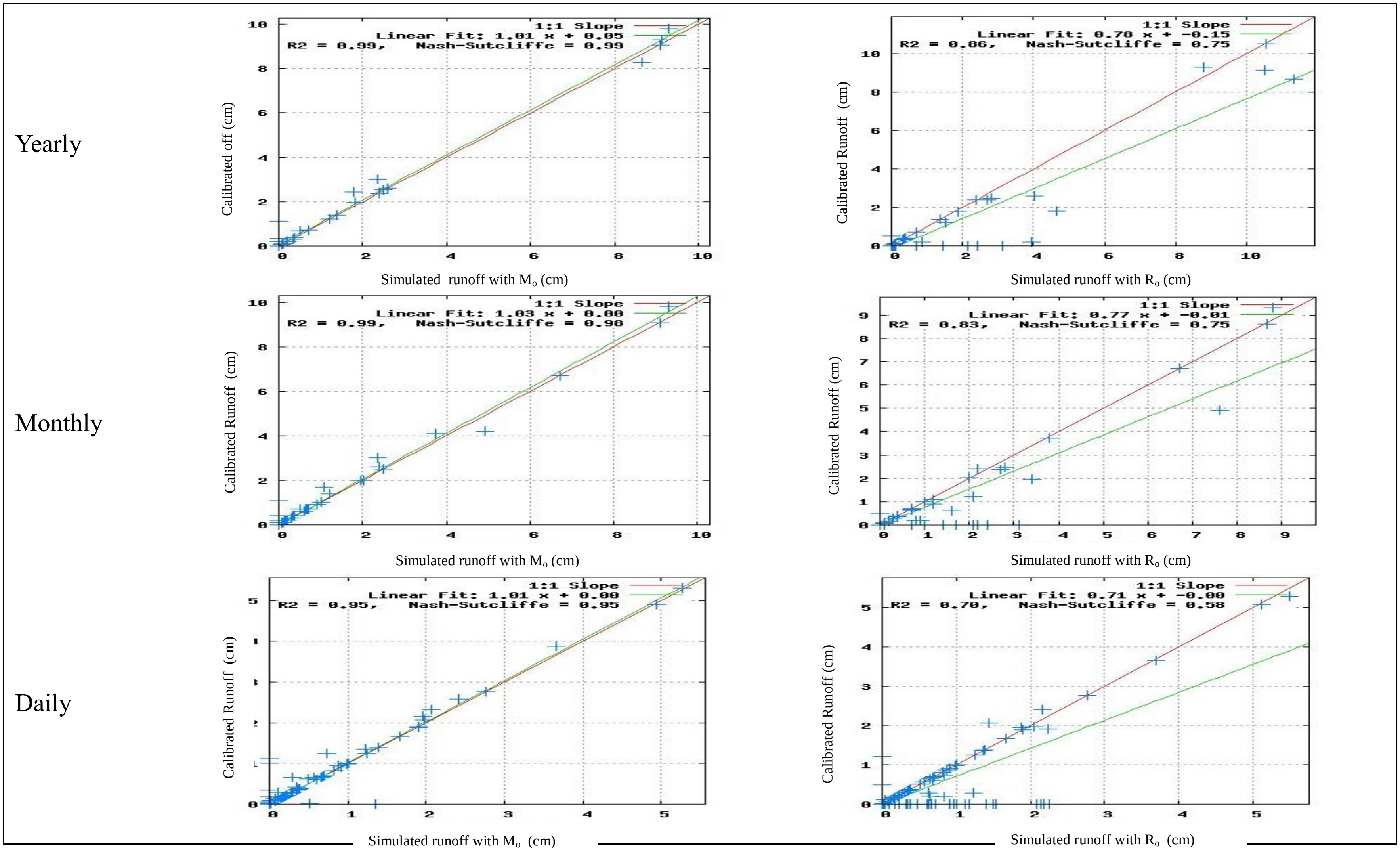

Figure 2.7 Comparison of calibrated with simulated runoff flow with rosetta soil input in model (Nash-Sutcliffe value & coefficient of determination, R^2)

Table 2.7 Statistical comparison between M_o and R_o for drainage and runoff

Soil Input	Yearly							
	Drainage				Runoff			
	E	RMSE (cm)	D_v (%)	MAE (cm)	E	RMSE (cm)	D_v (%)	MAE (cm)
R_o	0.96	0.65	16.4	0.37	0.75	0.98	8.8	0.43
M_o	0.99	0.26	6.70	0.15	0.98	0.20	0.50	0.07
Soil Input	Monthly							
	Drainage				Runoff			
	E	RMSE (cm)	D_v (%)	MAE (cm)		RMSE (cm)	D_v (%)	MAE (cm)
R_o	0.94	0.94	22.9	0.04	0.75	0.25	60.0	0.03
M_o	0.99	0.08	9.65	0.02	0.98	0.06	11.2	0.01
Soil Input	Daily							
	Drainage				Runoff			
	E	RMSE (cm)	D_v (%)	MAE (cm)	E	RMSE (cm)	D_v (%)	MAE (cm)
R_o	0.92	0.01	27.04	0.001	0.58	0.04	66.56	0.001
M_o	0.97	0.007	14.06	0.001	0.94	0.01	16.10	0.003

E=Nash-Sutcliffe efficiency

RMSE=Root Mean Squared Error

D_v=Average Percent Deviation

MAE=Mean Absolute Error

2.2.3 Sensitivity Analysis

A sensitivity analysis of growing season drainage predicted by the model to variation in soil properties (K_{sat} and SWC) was performed by changing the measured soil properties by set percentages and evaluating the change in drainage amount. The percentage changes in growing season drainage (cm) with the changes in soil properties (K_{sat}, SWC) are shown in Figure 2.8 and Figure 2.9. The results showed that a -90% change of K_{sat} value resulted in a 64% decrease in drainage amount. A 200% change of K_{sat} increased the growing season drainage by 26% . Also, a change of SWC of -50% increased the drainage amount by 70%. Finally, a change of SWC by 50% decreased the drainage amount by 20%. These results indicated the growing season drainage is more sensitive to under predicted K_{sat} and SWC, which is similar to the results of Skaggs (1980) and Workman and Skaggs (1994).

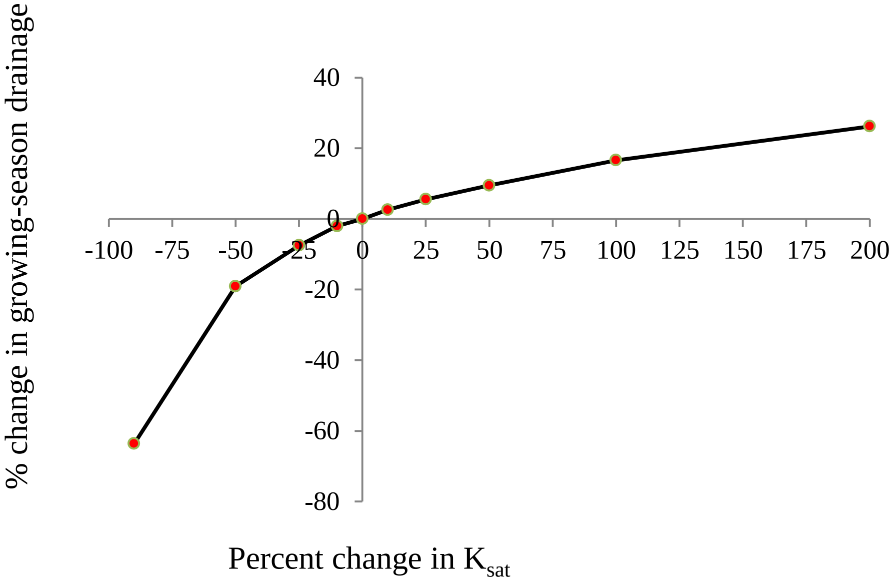

Figure 2.8 Sensitivity analysis of drainage with change in hydraulic conductivity (K_{sat})

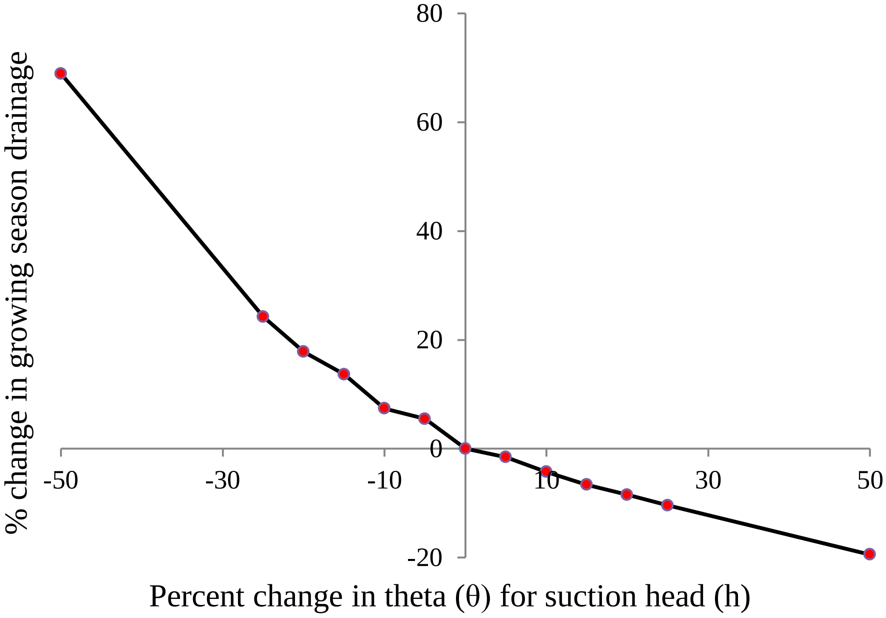

Figure 2.9 Sensitivity analysis of drainage with change in SWC Curve

2.3 Summary and Conclusions:

The purpose of this study was to determine the feasibility of running DRAINMOD simulations with Rosetta-estimated soil properties (SWC and K_{sat}) for predicting the subsurface drainage and runoff in place of measured soil properties for typical eastern South Dakota conditions. The model was run with three different sets of soil inputs as measured (M_o), rosetta derived (R_o), and calibrated (C_o). Predicted values of drainage and runoff by the model with two soil inputs, measured and rosetta derived, were compared with the calibrated values using statistical measures and graphical measures. The results showed that the SSURGO soil information and rosetta-derived soil properties could be used in the DRAINMOD for long-term hydrological simulation. As expected, the results also showed that hydrological prediction (yearly, monthly, and daily) was better using measured soil properties than using Rosetta-derived soil properties. The yearly and monthly predictions were better than for daily prediction. A sensitivity analysis was also performed for growing season drainage outputs predicted by the model to variation in soil properties. The results showed that the model was more sensitive to under-predicted soil hydraulic properties (K_{sat} and SWCC) as oppose to over-predicted values. The high values of K_{sat} and SWCC obtained from rosetta-derived soil properties also indicated that the rosetta derived soil properties are better to be used in long-term yearly simulations as over predicted soil hydraulic properties are less sensitive.

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Chapter 3:

Estimating Drainage Design Rate for South-Eastern South Dakota

3.1 Abstract.

Subsurface drainage (tile) has expanded dramatically in eastern South Dakota in the last several years, driven by increases in precipitation, and land and commodity prices. Estimating optimum drain depth and drain spacing of subsurface drainage system requires use of a simulation model and extensive data input. A relatively approach to estimating drain depth of spacing using the steady state Hooghoudt equation has been used for many years. However, success of estimation of spacing and drain depth by the Hooghoudt equation depends on a good estimate of the drainage design rate (DDR). Existing drainage design criteria for drainage intensity have been primarily developed for humid regions. It is unclear how well these criteria apply to regions such as eastern South Dakota, which lies in a transition zone from subhumid to semi-arid conditions. Better information on design criteria for these regions is needed to balance production and environmental goals for optimum drainage design. This study was designed to estimate drainage design criteria for Eastern South Dakota and to compare to existing design criteria developed for the eastern U.S.A. The DRAINMOD model was calibrated to simulate drainage conditions for the selected study area of South Dakota. The model simulations were then used to determine optimum drainage intensities that maximize economic return for continuous corn production. A steady state Hooughoudt's equation was used to estimate DDR for the optimum spacing at selected locations and soil type of eastern South Dakota. The DDR values for the study area vary from 0.43 cm/day to 0.72

cm/day for 91cm drain depth, 0.3 to 0.66 cm/day for 108 cm drain depth, and 0.26 to 0.62 cm/day for 122 cm drain depth. The result showed similar behavior as found for the eastern US, (i.e. varied with growing season precipitation, soil properties and drain depth). However the DDR in this study was less than the DDR values found in eastern the eastern US.

3.2 Introduction:

Subsurface (tile) drainage installation has increased in eastern South Dakota in recent years because of increased precipitation, changes in cropping systems, and high commodity prices (Hay and Todey, 2011). Research over the past several decades has shown that subsurface drainage has a positive impact on crop yield and is viewed positively for agricultural production. Historically, the only primary objective of subsurface drainage was to increase crop yield (Skaggs et al., 2006). Objectives of more recent drainage design systems have been supplemented by other environmental factors to consider, including downstream environmental effects as a negative environmental impact of surface and subsurface on downstream hydrology (Kalita et al., 2007). In some cases, environmental considerations are more important than increasing crop yield. Optimum design to meet both objectives includes proper combination of drainage depth and spacing, and called drainage design rate (DDR) of any particular soil and weather conditions. Closely spaced and/or deeper drain has greater drainage intensity and has increased potential of nitrate-nitrogen loss (Skaggs et al., 2005), while wider spacing and shallow drain might not be able to drain excess water.

DRAINMOD is a process based field scale hydrological model developed by Skaggs (1978) in North Carolina State University. It has been used to simulate the hydrology and crop response in poorly drained soils all over the world (Skaggs et al., 2012). DRAINMOD uses the water balance equation for a column of soil that has a unit surface area which extends from the ground surface to a subsurface impermeable layer and is located at the midway between two subsurface drains. The model has incorporated the effect of freezing, thawing and snowmelt in 2000 (Luo et al., 2000). The model can be used to simulate nitrogen and carbon cycles in soils. Soils input to DRAINMOD are some of the major inputs and play major roles in the simulated water balance. Soils inputs consist of four key components, including the soil water characteristic curve (SWCC), drainage volume, upward flux, and Green-Ampt infiltration parameters. Other inputs for the model are weather, drainage design configuration, and crop parameters.

The drainage intensity (DI) associated with the optimum drain depth and spacing for maximum crop yield is called drainage design rate (DDR). A very simple approach for determining DDR was used for eastern North Carolina using DRAINMOD simulation with economic analysis (Skaggs, 2007; Skaggs and Tabrizi, 1987). The Hooghoudt equation was used to calculate DDR as the steady state drainage rate associated with a midpoint water table that is coincident with the soil surface (Skaggs et al., 2006). The results indicated that this approach could be used to make reasonable estimates of the drain depths and spacing to maximize profits for given inputs. The same approach was used as an expansion study using 50-year DRAINMOD simulations to determine DDR for ten locations in the eastern USA with four different soils (Skaggs, 2007). This study suggested that average DDR required to maximize profits is dependent on climatic factors as affected by location and soil properties. The study also showed that the DDR was related to growing season precipitation (P) and soil properties. The study results were used to develop regression equations for predicting DDR in terms of growing season rainfall, drain depth, soil profile transmissivity, and drainable porosity (Skaggs, 2007). The study cautioned that further research was needed for validating the equation to estimate DDR for different climatic scenarios. The validity of the DDR equation is unclear for a location such as eastern South Dakota that is in a transitional climate from dry subhumid to semiarid conditions. Therefore, the objective of this study was to estimate the DDR for three drain depths, two South Dakota locations, two soil types at each location, and current economic conditions.

3.3 Methods:

3.3.1 Study Area

The study areas were located in Moody and McCook Counties in Eastern South Dakota. Locations and a summary of key climatic data are shown in Figure 3.1, and Table 3.1. Average annual precipitation (1950-2012) values for the study areas were 620 mm and 580 mm, while average annual (1950-2012) daily temperature values were 7ºC and 9ºC, respectively. Growing season precipitation and crop potential evapotranspiration (ET_c) as calculated using Hargreaves- Samani method (Hargreaves and Samani, 1985) were found to be 734 mm at Flandreau, and 759 mm at Montrose (Table 3.1). Grass reference potential evapotranspiration was calculated using REF –ET (Allen, 2000) and crop potential evapotranspiration was calculated using the crop coefficient from High Plains Regional Climate Center (HPRCC) data and crop coefficients for corn. As found in Soil Survey Geographic Database (SSURGO), typical soils from Moody county were Houdek clay loam (*HoB, Fine loamy, mesic, Typic Argiustolls*), which is also the state soil of South Dakota, and Moody-Nora silty clay loam (*MnB*, *Fine-silty, mixed, mesic*

Udic Haplustolls). Soils from McCook County were Clamo silty clay loam (*Cb, Fine, montmorillonitic, mesic Cumulic Vertic Endoaquolls*) and Wentworth silty clay loam (*WbB, Fine-silty, mixed, mesic Udic Haplustolls*).

Table 3.1 Climate parameters for study locations of South Dakota

Location	Latitude	Longitude	Average Annual precipitation (mm)	Average Annual Ref ET (mm)	Growing season Precipitation (mm)	Growing season Ref ET (mm)	Average Temperature (Degree C)
Flandreau, Moody , SD	44º 03' 06"	96 º 35’34”	620	734	514	594	7
Montrose, McCook , SD	43º 46' 12"	97º14’58”	580	759	488	607	9

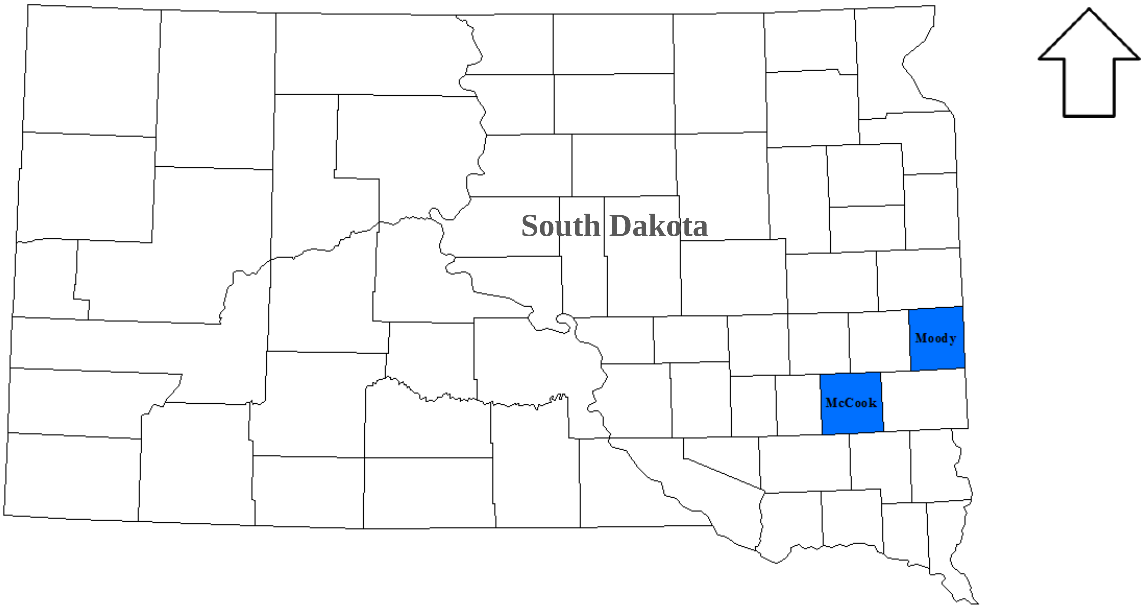

Figure 3.1 Location of study area

3.3.2 DRAINMOD

DRAINMOD is a field-scale process based, distributed simulation model originally developed as a means of quantifying, on a continuous basis, the performance of multi-component drainage and related water management systems (Skaggs et al., 2012). DRAINMOD has gone through several modifications since it was originally developed in 1978. The input parameters for DRAINMOD are weather (temperature, precipitation, and evapotranspiration), soil properties, site characteristics, drainage system designs, and crop inputs.

The model is based on water balance for a section of soil of unit area located midway between two parallel drains. The water balance for a time increment (hourly or daily) is expressed as:

$$\Delta V = D + ET + DLS - F \tag{1}$$

where,

ΔV is change in water free pore space, D is drainage, ET is evapotranspiration, DLS is deep and lateral seepage, and F is infiltration in cm. The water balance at the soil surface in each time increment is

$$\mathrm{P} = \mathrm{F} + S + RO \tag{2}$$

where,

P is precipitation, F is infiltration, S is change in volume of water stored on the surface, and RO is runoff. DRAINMOD uses time a increment based on the precipitation time step and infiltration rate from 0.05-h. to 24-h. The latest DRAINMOD version (6.0) is capable of incorporating the effects of freezing, thawing and snowmelt (Luo et al., 2000), simulating the nitrogen and carbon cycles, and simulating drainage water management practices on nitrogen losses in draining water.

DRAINMOD uses the steady state Hooughoudt equation to quantify subsurface drainage, when the water table is between the drain depth and soil surface, and is based on Dupuit-Forcheimer (D-F) assumptions (lateral flow in the saturated zone only) and an elliptical water table. The model uses the Green-Ampt equation to calculate the infiltration rate. At times when the rainfall rate is less than the infiltration rate, DRAINMOD assumes that the infiltration rate is equal to the rainfall rate. Evapotranspiration (ET) in the model can be estimated either by the Thornthwaite method within the model or can be given as user defined input as an input file. The Hargreaves-Samani method (Hargreaves and Samani, 1985) was used in this study. Reference evapotranspiration(Allen et al., 1998) estimated using in the REF-ET (Allen, 2000) model was multiplied using High Plains Regional Climate Center (HPRCC) crop coefficients for corn, which is based on growing degree days (GDD), and provided into the model as crop potential evapotranspiration for long term simulation. Actual ET is computed in the model from potential crop evapotranspiration provided in the model as limited by soil water availability.

3.3.3 Model Simulations

First of all, DRAINMOD (version 6.0) simulation was performed for 2013-2014, and was calibrated against observed water table by changing lateral hydraulic conductivity. Then, long-term DRAINMOD simulation was run to predict hydrology and crop yield for continuous corn considering the effects of freezing, thawing, and snowmelt within the model (Luo et al., 2000) at the study areas in South Dakota. Simulations were conducted for representative soils in the study area, two from Moody County and two from McCook County. Soil properties for these selected soils were taken from the SSURGO (USDA) data set and Rosetta (Schaap et al., 2001) was used to derive the soil hydraulic properties in DRAINMOD input format. DRAINMOD simulations were run for these selected soils for 62 years (1950-2011) of climatological data. The simulations included drain depths of 91cm (3 ft.), 108cm (3ft. 6 inch), 122cm (4 ft.), and spacing varying from 5 m (16 ft.) to 100 m (328 ft.). A brief summary of DRAINMOD input for this study is shown in Table 3.2. DRAINMOD simulations were performed for the same periods of 62 years to find relative yields (RY) as a function of drain spacing for selected drain depths. An economic analysis was conducted to determine optimum drain spacing, which is defined as the drain spacing corresponding to the maximum annual returns. Relative yield (RY) was converted to annual average yield by multiplying relative yield by potential yield. Potential yield of 16319 kg/ha (260 bu/ac) and average assumed corn price or $0.16/kg ($4/bushel) was based on National Agricultural Statistics Services (NASS) data (USDA, 2013a), and (USDA, 2013b). Annual cost of corn production was assumed to be $1502/ha ($608/acre) (Davis, 2014). Drainage system costs were assumed at $3.95/m ($1.2 per ft.) based on data from Iowa (William and Ann, 2014). This cost assumes that surface drainage is in good condition and no extra surface drainage is required. Drainage system costs were calculated by amortizing the initial cost of the system over an assumed life of 30 years at an interest rate of 6%. Annual maintenance cost was assumed to be 25% of initial cost. Average annual net return was plotted against drain spacing for three different depths at two locations with two different soils at each location.

Table 3.2 DRAINMOD input parameters

Description of Parameters	Value
Drain depth (cm)	91
Drain spacing (m)	5 m to 100 m
Effective radius (cm)	0.51
Depth of impermeable layer from surface (m)	2.0
Drainage coefficients (cm/day)	2.5
Initial depth to water table (m)	1.65
Maximum surface storage (cm)	1
Crop input Parameters	
Parameter description	Value
Lower limit of water content in the root zone	0.14 cm^3/cm^3
limiting water table depth for no crop damage	30
Desired planting date (Day of years)	125 (5 May)
Length of growing days for corn	180
Last day of Planting without yield loss	130
Parameters for freezing, thawing and snowmelt	
Parameters description	Value
Computational depth function	
a	2.5 cm
b	1.21
Thermal conductivity function	
a	0.39
b	1.33
Diurnal Phase lag of air temp	8 hrs.
Base temperature as boundary (ºC)	7.2
Rain/snow dividing temp (ºC)	0
Snow melt base temperature (ºC)	2
Degree day coefficient (mm/day)	5
Critical ice content (cm^3/cm^3)	0.18

Daily weather data (maximum and minimum temperature, and precipitation) required for the model were taken from national climatic data center (NCDC), Climatic Data Online (CDO), (NOAA, 2014) for Flandreau in Moody County and Montrose in McCook County. Data for the entire period of 1950-2011 were not available at Montrose, so data from the nearest station Bridgewater, which is 20 miles southwest from the site, were used to fill gaps. The gaps are missing precipitation and temperature data for some days in the period of study. Daily precipitation data were uniformly distributed to the four-hour period starting at 17:00 as per a subroutine provided in DRAINMOD for derivation of hourly precipitation and simulation. Potential evapotranspiration (PET) was calculated using the Hargreaves-Samani method (Hargreaves and Samani, 1985) and supplied as an input to DRAINMOD after applying crop coefficients using High Plains Regional Climate Center (HPRCC) data and crop coefficients for corn, which is based on growing degree days (GDD). A summary of soil properties input for DRANMOD is shown in Table 3.3.

Table 3.3 Summary of soil properties and drainage parameter used in DRAINMOD

Soil properties	Houdek CL		Moody-Nora SiCl		Clamo SiCL		Wentworth SiCL	
Depth to restrictive layer > (cm)	200		200		200		200	
Depth wise saturated Hydraulic conductivity (K_s) (cm/hr.)	Depths (cm)	Ksat	Depths (cm)	Ksat	Depths (cm)	Ksat	Depths (cm)	Ksat
	(0-20)	3.24	(0-25)	2.77	(0-28)	0.33	(0-20)	3.24
	(20-43)	3.24	(25-89)	3.24	(28-56)	0.33	(20-51)	3.24
	(43-109)	3.24	(89-122)	3.24	(56-76)	0.33	(51-152)	3.24
	(109-152)	0.97	(122-152)	3.24	(76-152)	3.24		
Average K_s (cm/hr.)	2.6		3.16		1.77		3.24	
Transmissivity cm^2/hr.	394.96		480.73		271.32		492.48	
Average saturated water content (cm^3/cm^3)	0.43		0.46		0.49		0.39	
Water content at lower limit (cm^3/cm^3)	0.14		0.15		0.18		0.16	

3.4 Results and Discussion:

The predicted 62-year average relative corn yield and net annual profit for two location and four soils are plotted as function of drain spacing for three different depths as shown in Figure 3.2 through Figure 3.4, and is shown in Appendix (Table 3.6 and Table 3.7). Relative yield, which is the ratio of actual yield to potential yield, varies from 60 percent to 81 percent depending on the spacing, depth and soil type. Potential yield is the average yield that would have be obtained if there is no dry or wet stress, and planted on time, whereas the actual yield was affected by stress factors depending on the moisture conditions. The result showed less relative yield at very narrow or very large drain spacing for all drain depths and soil types. The reason was that narrow spacing increased dry stress, while larger spacing increased wet stress, causing reductions in relative yield in the model. The plots of relative yield and net annual return for all soils and locations were all similar in shape. The relative yield at Montrose for Clamo silty clay loam and Wentworth silty clay loam soils tended to be more flat at wider spacing, and net annual return was less compared to Flandreau. The difference related to crop drought stress during most of the year, which lead to lower relative yields. On average, about 20%-40% of relative yield was lost due to stress caused by soil moisture deficits in both studied fields. However, the stress and relative yield varied from year to year. Also, close spacing and deep drain depths reduced the relative yield. Drain spacing corresponding to maximum annual return, which was considered the optimum spacing, for all four soils and three different depths in both locations was calculated in shown in Table 3.4. The magnitude in net annual return was dependent on assumed annual corn price, production cost, and potential yield and assumed to that it doesn’t affect the optimum spacing (Skaggs et al., 2006). The optimum drain spacing was found to be proportional to hydraulic transmissivity at Montrose for Clamo SiCL and Wentworth SiCL soil, while it did not follow the same pattern at Flandreau (Houdek CL and Moody SiCL soils). This is because the Moody soil has relatively higher saturated hydraulic conductivity as compared to the Houdek soil resulting wider optimum spacing which ultimately reduces the drainage cost.

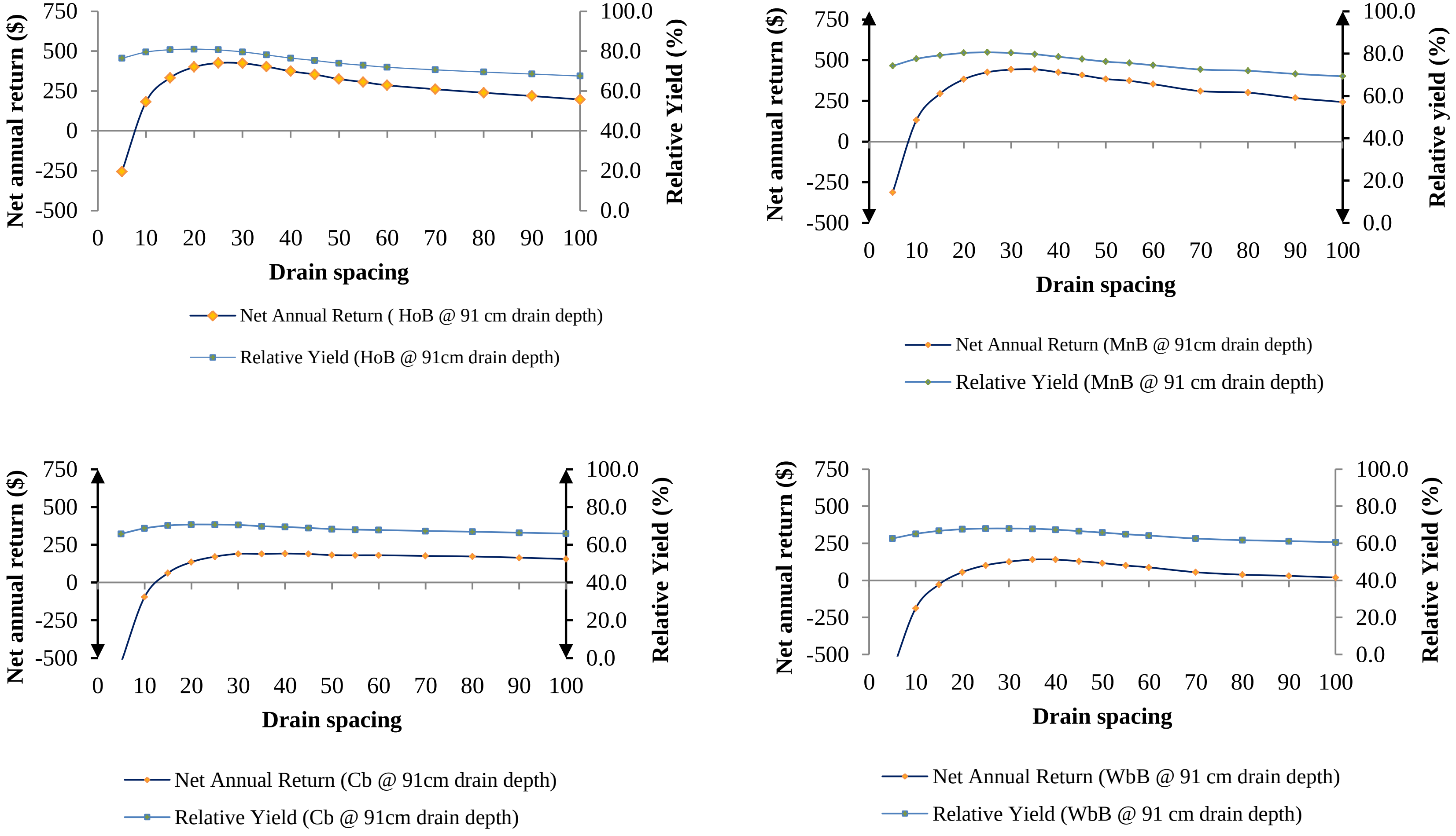

Figure 3.2 Effect of drain spacing @ 91cm drain depth on long-term average yield and annual return for different soil type

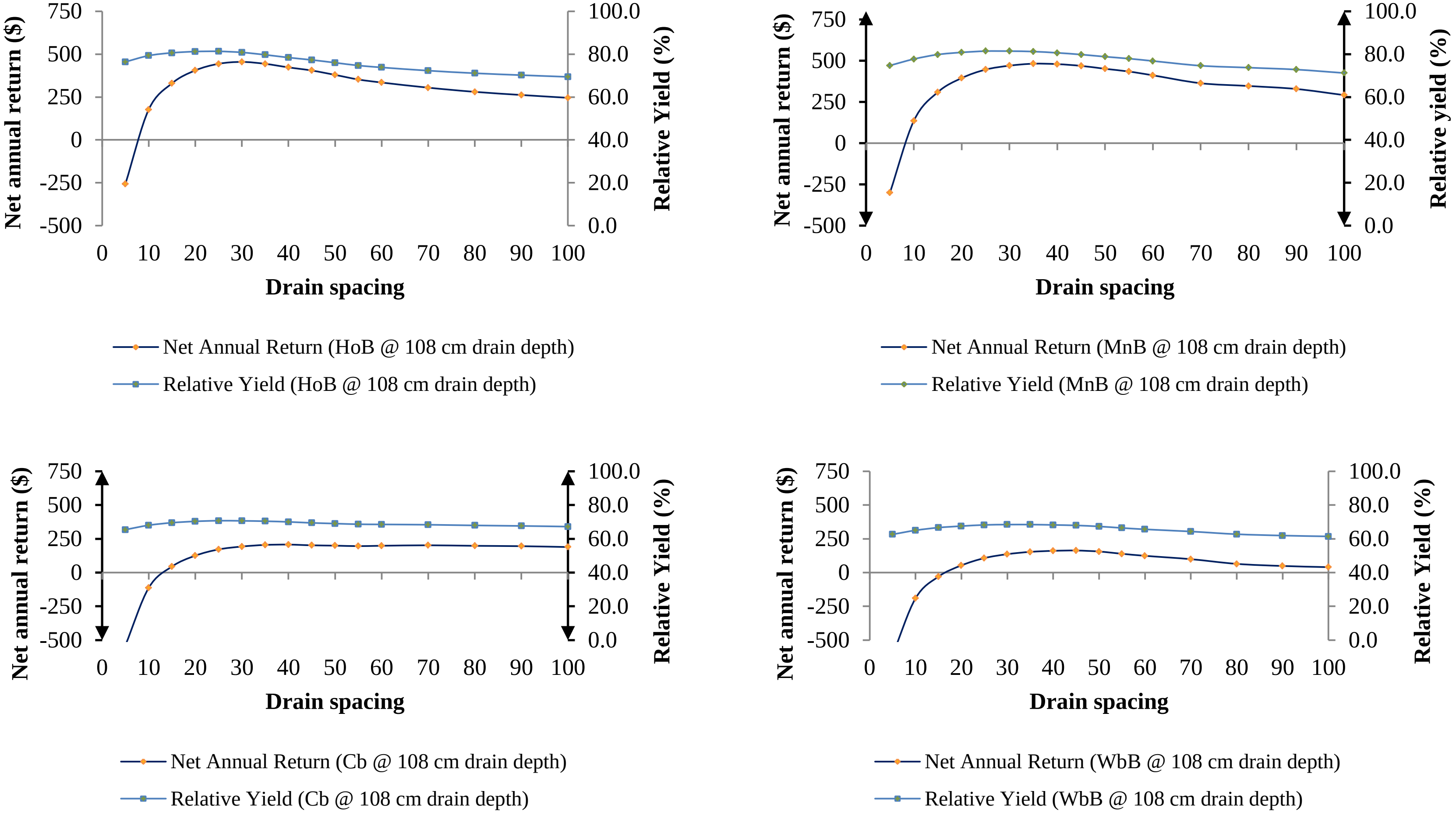

Figure 3.3 1 Effect of drain spacing @ 108 cm drain depth on long-term average yield and annual return for different soil type

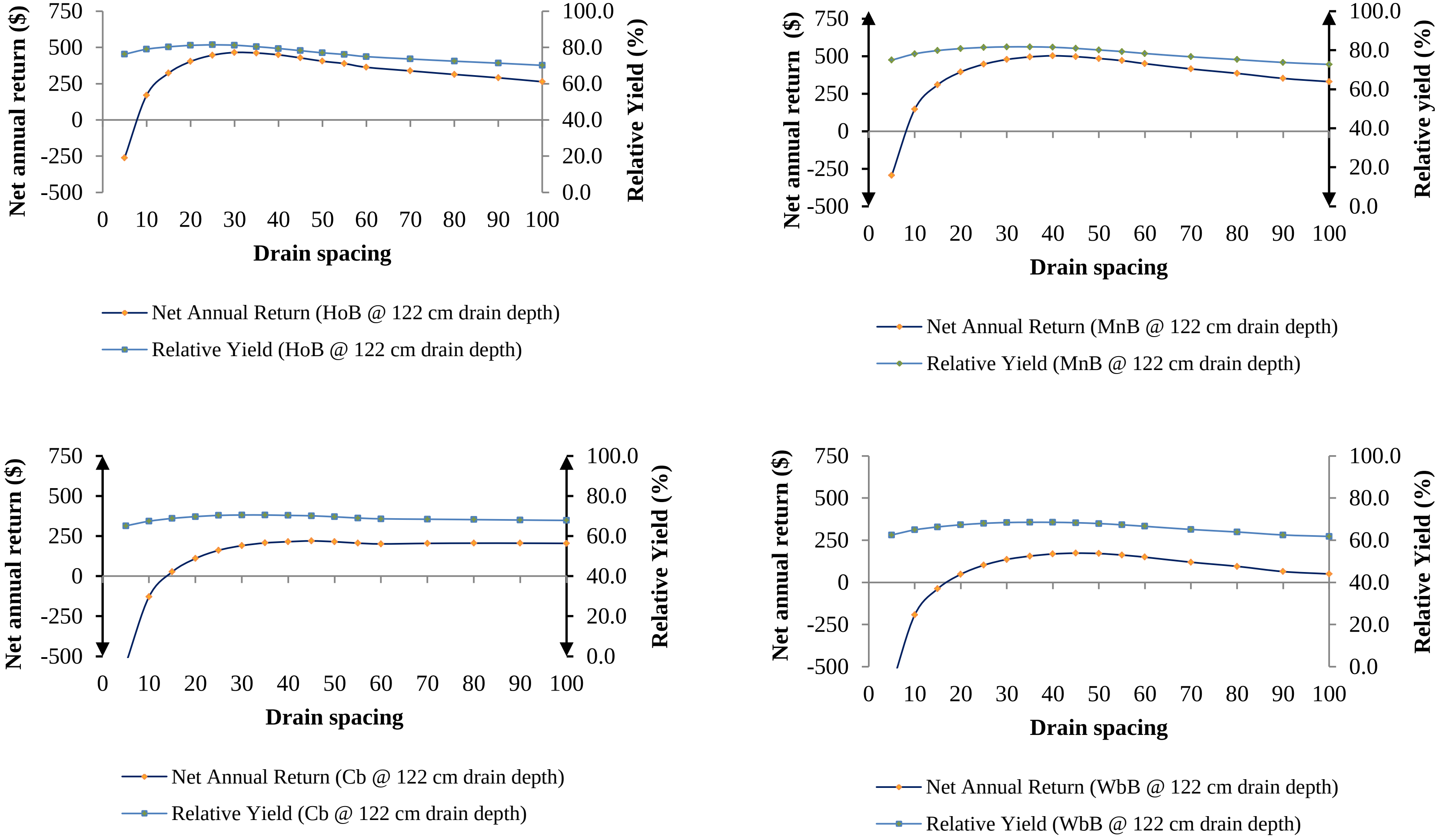

Figure 3.4 Effect of drain spacing @ 122 cm drain depth on long-term average yield and annual return for different soil type

The optimum DDR values for the Houdek CL and Moody SiCL in Moody County were found to be 0.71 cm/day and 0.67 cm/day, respectively. The optimum DDR values for the Clamo SiCL and Wentworth SiCL soils in McCook County were 0.42 and 0.59 cm/day, respectively, for the 91 cm drain depth. The optimum DDR values found in this study are less than those found by Skaggs (2007). For example, the DDR value found at the location nearest to South Dakota at Waseca in eastern Minnesota in the Skaggs (2007) study for four different soils varied from 0.78 cm/day to 1.1 cm/day for 100 cm drain depth with growing season precipitation of 520 mm, which are greater than those found for the Moody county soils. The optimum DDR in Montrose, where the growing season precipitation was 492 mm, was even less (0.59 and 0.42 cm/day).

Optimum spacing for three drainage depth for four soils at two location is shown in Table 3.4. The result shows that spacing increases with increase in depth and change and related to hydraulic conductivity. DDR value for less conductive soil is lower than high conductive soil. DDR value for the Montrose is comparatively less than Moody. Comparative annual return predicted from DDR with this study for 91 cm drain depth and DDR from regression equation Skaggs (2007) is shown in Table 3.5. The DDR value estimated from regression equation is higher than found from optimum net return in this study. The resulting higher DDR shows reduction in net annual return. The reduction is attributed to reduction in long-term average relative yield as a result of crop in stress condition. The predicted annual return using DDR at drainage depth of 91 cm for both locations and all four soils were plotted as function of drainage intensity (DI) and are shown in Figure 3.5 and found some close to predicted by Skaggs's regression. A regression equation as a function of growing season precipitation (mm), combining DDR (cm/day) for eastern US and this study is shown in Figure 3.6 for comparison of DDR with eastern US only. The DDR for Montrose are less than the DDR in eastern U.S.A as shown in red dot in Figure 3.6. The equation is shifted from (0.0041P-1.1) for eastern US only to (0.0042-1.2) including South Dakota study while R^2 value was reduced from 0.63 to 0.56.

Table 3.4 Optimum spacing and DDR for study area for three specific drain depths

Location	Soil type	Drain depth (cm)			Drain depth (cm)		
		91	108	122	91	108	122
		Optimum spacing (m) for different depths			DDR (cm/day) for different depths		
Flandreau	Houdek CL	28	32	35	0.71	0.66	0.62
Flandreau	Moody-Nora SiCL	32	36	40	0.67	0.64	0.59
Montrose	Clamo SiCL	30	40	45	0.42	0.30	0.26
Montrose	Wentworth SiCL	35	43	46	0.59	0.48	0.46

Table 3.5 Optimum DDR for 91 cm drain depth and average annual return based on this study and on Skaggs (Skaggs, 2006)

Location	Soil type	DDR Value (cm/day)		Annual Return ($/ha)	
		This study	Skaggs et al, (2006)	This study	Skaggs et al, (2006)
Flandreau	Houdek CL	0.71	0.956	428	400
Flandreau	Moody-Nora SiCL	0.67	0.956	446	413
Montrose	Clamo SiCL	0.42	0.850	190	135
Montrose	Wentworth SiCL	0.59	0.85	140	112

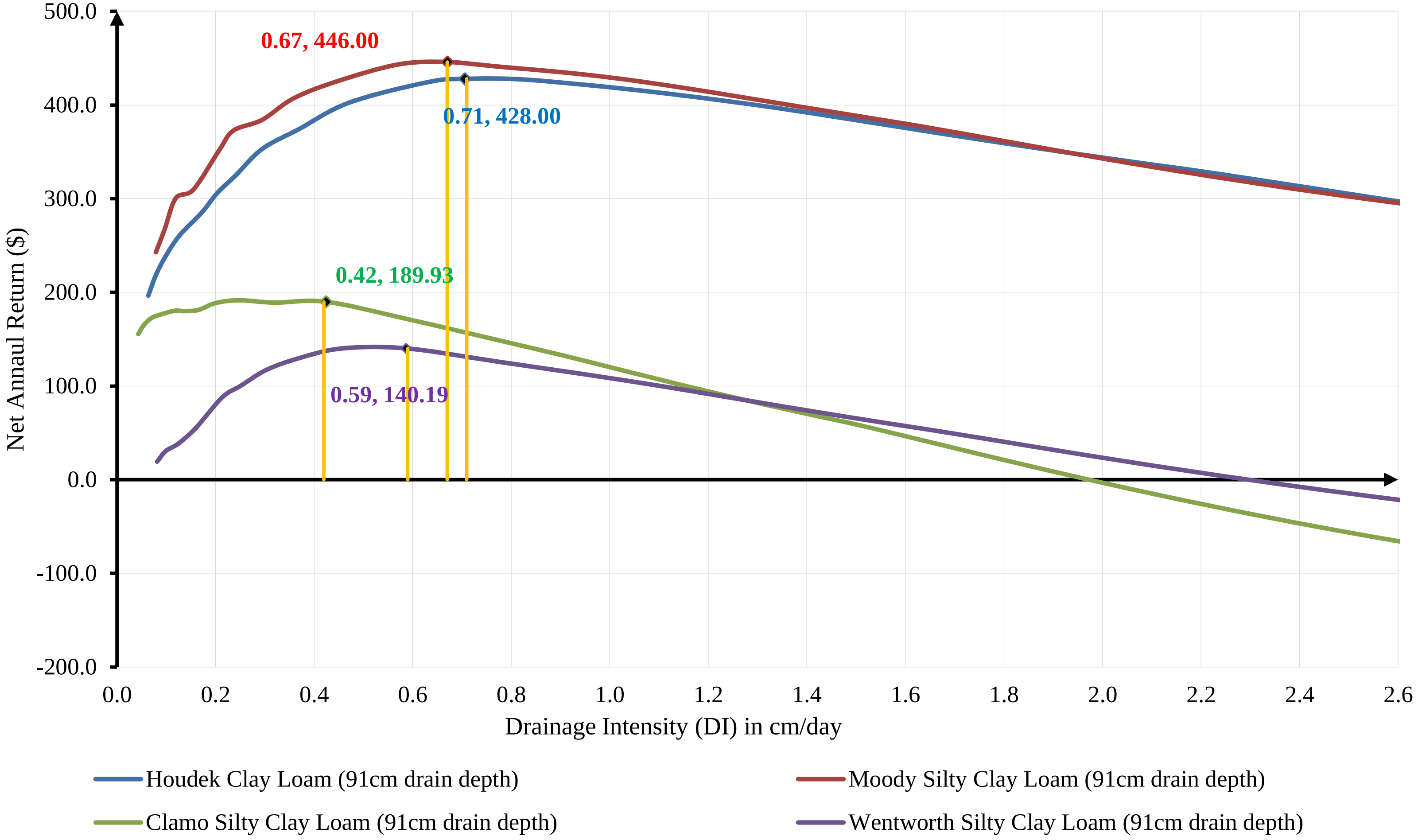

Figure 3.5 Predicted effect of DDR on net annual return for continuous corn yield in SD

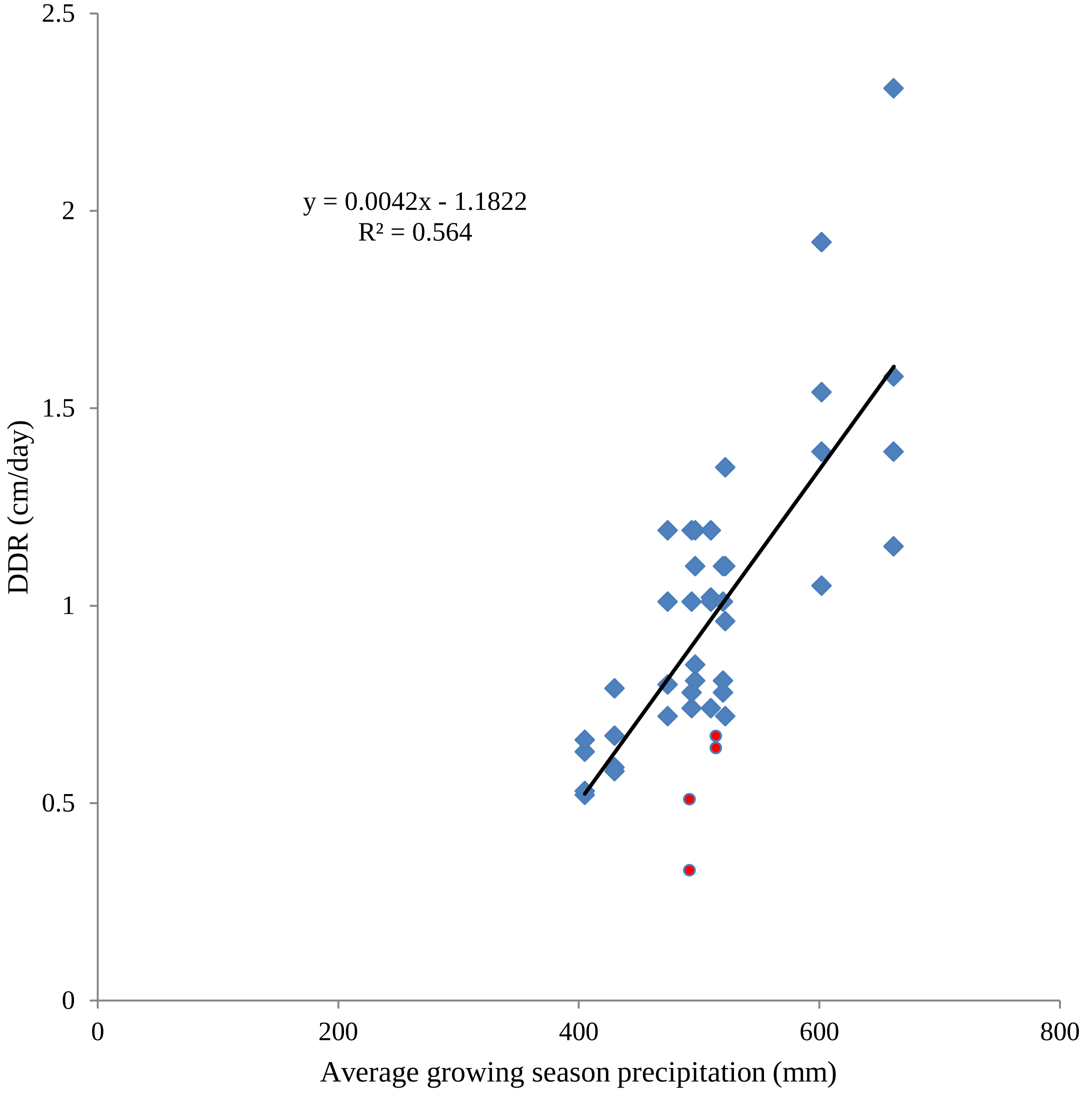

Figure 3.6 Regression equation for eastern US and including eastern South Dakota

● In Figure indicates the data points from this study

3.5 Summary and Conclusions:

The purpose of this study was to estimate optimal drainage intensity using DRAINMOD simulation for four typical soil of two location of eastern South Dakota in continuous corn production, and compare it with the optimal drainage intensity found for the eastern USA. Long term average relative yield obtained from DRAINMOD simulation were used for economic analysis to find maximum drain spacing that maximize net return. Results indicated that optimum DI to maximize profit is dependent on weather and soil properties as found in eastern USA. The results were also compared to the result obtained for the eastern USA. The results followed the same overall behavior as found in in eastern USA; i.e., DDR is a function of growing season precipitation and soil hydraulic properties. However, the optimal DDR values found in this study were between 0.62 - 0.71 cm/day for Houdek CL, lower than found in eastern USA. Drain spacing to achieve these DDR values were 28 to 35 m . The optimum DDR values for Moody Nora SiCL soils at Flandreau were also found lower than easten USA, and found to be 0.59 to 0.67 cm/day. Drain spacing to achieve the DDR values for the Moody-Nora SiCL were 32 to 40 m. For the Montrose location the DDR values were even lower than eastern USA. The optimum DDR values were 0.26 to 0.42 cm/day for the Clamo SiCL soil and 0.46 to 0.59 cm/day for the Wentworth SiCL soil. The associated drain spacings were 30 to 46 m. A regression equation (Skaggs, 2007) for the eastern USA was found to be DDR = 0.004P-1.1 ($R^2 = 0.63$) while this equation was changed to DDR = 0.0042P-1.2 ($R^2 = 0.56$) if included DDR values for 91 cm drain depth. This equation could be used to estimate DDR for eastern South Dakota. However, it should be noted that this regression equation is based on the study of two location of four soils and limited to a three drain depths. Additionally the model used here used Rosetta derived soil input for the study. Further study in multiple locations of South Dakota with measured soil properties, weather data, and controlled drainage could lead to improved estimates of DDR for transitional regions like South Dakota.

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Appendix

Table 3.6 Relative yield for varying soil type and drainage depth for study area

Soil Type	Drain spacing (m)	Drain Depth (91 cm)		Drain Depth (108 cm)		Drain Depth (122 cm)	
		Relative Yield (%)	Annual Return/ha ($)	Relative Yield (%)	Annual Return/ha ($)	Relative Yield (%)	Annual Return/ha ($)
HoB	5	76.4	-256.3	76.4	-256.3	76.2	-261.4
	10	79.5	182.1	79.3	176.9	79.0	169.2
	15	80.7	332.5	80.6	329.9	80.3	322.2
	20	81.0	400.0	81.2	405.1	81.1	402.6
	25	80.6	425.6	81.3	443.6	81.4	446.1
	30	79.6	423.8	80.8	454.6	81.2	464.9
	35	78.1	402.3	79.7	443.4	80.4	461.4
	40	76.5	374.0	78.4	422.8	79.4	448.5
	45	75.3	353.1	77.3	404.5	78.2	427.7
	50	73.9	325.1	76	379.1	77.0	404.8
	55	72.9	306.0	74.7	352.2	76.1	388.2
	60	71.9	285.7	73.8	334.5	74.9	362.8
	70	70.6	260.8	72.3	304.5	73.6	337.9
	80	69.5	239.0	71.1	280.1	72.4	313.5
	90	68.5	218.2	70.2	261.9	71.3	290.2
	100	67.5	196.5	69.4	245.4	70.1	263.3
MnB	5	74.2	-312.8	74.7	-300.0	74.9	-294.8
	10	77.5	130.7	77.7	135.8	78.1	146.1
	15	79.2	293.9	79.8	309.4	79.8	309.4
	20	80.3	382.0	80.8	394.8	80.8	394.8
	25	80.6	425.6	81.4	446.1	81.4	446.1
	30	80.3	441.8	81.4	470.0	81.7	477.8
	35	79.7	443.4	81.2	482.0	81.7	494.8
	40	78.5	425.4	80.6	479.4	81.5	502.5
	45	77.4	407.1	79.8	468.8	80.9	497.1
	50	76.2	384.2	78.8	451.1	80.1	484.5
	55	75.5	372.8	77.9	434.5	79.3	470.4
	60	74.5	352.5	76.8	411.6	78.3	450.2
	70	72.5	309.7	74.6	363.6	76.6	415.0
	80	71.9	300.6	73.7	346.9	75.2	385.4
	90	70.4	267.1	72.8	328.8	73.7	351.9
	100	69.3	242.8	71.2	291.6	72.7	330.2

Table 3.7 Relative yield for varying soil type and drainage depth for study area

Soil Type	Drain spacing (m)	Drain Depth (91 cm)		Drain Depth (108 cm)		Drain Depth (122 cm)	
		Relative Yield (%)	Annual Return/ha ($)	Relative Yield (%)	Annual Return/ha ($)	Relative Yield (%)	Annual Return/ha ($)
Cb	5	65.8	-528.7	65.4	-539.0	65.1	-546.7
	10	68.7	-95.5	68.0	-113.5	67.4	-128.9
	15	70.2	62.7	69.5	44.7	68.8	26.7
	20	70.7	135.3	70.3	125.0	69.7	109.6
	25	70.7	171.2	70.7	171.2	70.3	160.9
	30	70.5	189.9	70.6	192.5	70.5	189.9
	35	69.8	189.0	70.4	204.4	70.5	207.0
	40	69.4	191.6	70.0	207.0	70.3	214.7
	45	68.9	188.7	69.4	201.5	70.1	219.5
	50	68.3	181.2	69.0	199.2	69.6	214.6
	55	68.0	180.0	68.6	195.5	69.0	205.7
	60	67.8	180.3	68.5	198.3	68.6	200.9
	70	67.3	176.0	68.3	201.7	68.4	204.3
	80	66.9	172.1	67.9	197.8	68.2	205.6
	90	66.4	164.3	67.6	195.1	68.0	205.4
	100	65.9	155.4	67.2	188.8	67.8	204.2
WbB	5	62.6	-610.9	62.6	-610.9	62.5	-613.5
	10	65.1	-188.0	65.0	-190.5	64.9	-193.1
	15	66.7	-27.3	66.6	-29.9	66.3	-37.6
	20	67.6	55.6	67.5	53.1	67.3	47.9
	25	68.0	101.8	68.2	106.9	68.0	101.8
	30	68.0	125.7	68.4	136.0	68.4	136.0
	35	67.9	140.2	68.4	153.0	68.5	155.6
	40	67.4	140.2	68.2	160.7	68.5	168.4
	45	66.6	129.6	67.9	163.0	68.3	173.2
	50	65.8	117.0	67.3	155.5	67.9	170.9
	55	64.9	100.4	66.4	138.9	67.3	162.0
	60	64.2	87.8	65.6	123.8	66.6	149.5
	70	62.6	55.2	64.3	98.9	65.1	119.5
	80	61.7	38.5	62.7	64.2	63.9	95.0
	90	61.2	30.6	61.9	48.6	62.5	64.1
	100	60.6	19.2	61.4	39.8	61.8	50.0

Chapter 4:

Impact of subsurface drainage on field-scale water yield in eastern South Dakota

4.1 Abstract:

Subsurface drainage in agricultural land changes the field water balance by providing an alternate pathway for subsurface water. Determining the effects of subsurface drainage on downstream hydrology requires quantifying the components of the water balance. A number of studies have looked at the hydrological impacts of subsurface drainage. However, the effects are complex and difficult to generalize. The complex interaction involves the interrelation among variables such as soil type and properties, climate (rainfall and evapotranspiration), and drainage design configuration (drainage intensity and drainage coefficient), which all are local in nature. Additionally, most studies have been conducted in humid climates, whereas eastern South Dakota is located in a transitional dry subhumid climate. The objective of this study was to determine the impact of subsurface drainage on water yield (runoff plus drain flow) at the field scale in eastern South Dakota in terms of soil type, weather, and drainage design (drain depth and spacing). Long-term simulations were performed in DRAINMOD, a field scale deterministic process based hydrological model, to quantify each component involved in the water balance. The hydrologic outputs (daily, monthly, and yearly) of DRAINMOD were used to determine the impact of subsurface drainage for various scenarios of selected soil type, climatic condition, and drainage design that are typical for the study area. The results of the impacts of tile drainage on water yield at the *field scale were presented as functions of soil, climate, and drainage design. The results showed the water yield increased with increased drainage intensity (DI) for all selected soils. The subsurface drainage amounts also increased with increased DI. The results also showed that runoff decreased with increased in DI within the same soil type. Also, the proportion of drainage to water yield increased with increased DI. Water yield decreased as saturated hydraulic conductivity increased. Improved understanding of impacts at the field scale is an important first step towards understanding the impacts of subsurface drainage on stream flow.*

4.2 Introduction:

Subsurface (tile) drainage installation has increased in eastern South Dakota in recent years because of increased precipitation, changes in cropping systems, and high commodity prices (Hay and Todey, 2011) Subsurface drainage has agronomic and economic benefits for crop production by providing improved growing conditions and trafficability and increased crop yield. However, adverse environmental effects are also associated with increased subsurface drainage as it modifies flow paths and timing (Irwin and Whiteley, 1983) (Kladivko et al., 2004), and (Kalita et al., 2007). Agricultural subsurface drainage is considered to be a primary source of nitrogen loss, causing significant water quality problems in downstream surface water and is directly related to the drainage intensity (Skaggs et al., 2005). Aquatic ecosystem have been substantially modified and impacted by the land use, hydrologic, and water quality changes associated with extensive development of agricultural surface and subsurface drainage (Blann et al., 2009).

The impacts of tile drainage on water yield (drainage amount plus runoff amount) have been the growing concern and topic of research. There have several studies addressing water yield. The first comprehensive study was performed in 1990 by Robinson (Robinson, 1990). Studies are continued all over the world in evaluating the effect on downstream hydrology. Generally, the study of hydrological effects can be categorized in to three main categories as a function of: soil type (including macro-pore and surface storage), weather (rainfall and evapotranspiration), and drainage design intensity (Skaggs et al., 2005), while methods of studies can be categorized into two types: field studies, and modelling studies (Robinson, 1990). Many past field and modelling studies on change in downstream water yield showed that the effects are site specific, local in nature, and are functions of soil type, weather, and drainage intensity and complex interactions among them.

The field study by Robinson (1990) in the United Kingdom (UK) at six different field sites showed that subsurface drainage decreased peak flow in clayey soils under drained conditions, while it increased in sandy soils (Robinson, 1990). The same trend was followed in the study by Harms (Harms, 1986), however there were exceptions in some fields in both studies. The decreased peak flows in clayey soils for the drained condition was attributed to increased effective permeability of the soil because of improved drainage thus increasing the proportion of the total drain flow that is routed through the subsurface pathway. These soils would otherwise have been in frequent waterlogged conditions leading to significant surface runoff. Conversely, in sandy soils, which have high natural permeability, further increases in permeability of the subsurface from improved drainage increased in peak flows. Exceptions were found in two fields studied by Robinson (1990) where existence of macro pores in clay soils have played a counter effect, i.e. increased peak flow in dry summers and decreased flow during other seasons. This effect was attributed to creation of macro pores in clay soils due to dry, cracking soils in summer. Similar results were found in a study by Schwab (Schwab et al., 1985). Depressional storage also resulted in reduced surface runoff and increased infiltration leading to increased drainage flow.

The effect of weather is complex in influencing the effect of subsurface drainage on hydrology because of complexities of rainfall pattern and evapotranspiration (Skaggs et al., 1994a). It is even more complex because actual evapotranspiration is also related to available soil moisture condition and precipitation (Franz et al., 2015). Studies have found that increased precipitation caused a large amount of surface runoff in undrained scenario, which increased peak flows (Robinson and Rycroft, 1999) and (Franz et al., 2015). The model study in Iowa (Franz et al., 2015) suggested that high-magnitude intense storms overwhelm the soil infiltration capacity quickly, such that drainage does not affect peak flows. However, results of those models also suggested that peak flow increased in tile-drained soils experiencing consecutive storms. Higher frequency, low to moderate magnitude precipitation events are more likely to produce increased peak flows due to tile drainage. It has been noticed the effect of surface storage and pre-drainage water condition on both study.

Drainage intensity (drain spacing and depth) and drainage capacity (drainage coefficient) were found to other modifying factors for hydrologic response (Skaggs et al., 2012). A DRAINMOD simulation study in the UK for poorly drained soil found that decreasing drain spacing initially decreases peak flow to some point, and then started increasing (Robinson, 1990). The study in Iowa (Franz et al., 2015) also conclude the same result with DRAINMOD and SWAP model simulation. This behavior was first found by Wiskow (Wiskow and van der Ploeg, 2003) who developed a semi-analytical procedure in order to determine an optimal drain-spacing that would allow for the greatest soil water retention during extreme rainfall events, thereby attenuating daily peak flows (Wiskow and van der Ploeg, 2003).

In the context of the trend of increased subsurface drainage in South Dakota, the objective of this study was to determine the impact of subsurface drainage on water yield (runoff plus drain flow) at the field scale in eastern South Dakota using long term DRAINMOD simulation for selected scenarios of soil type, climatic condition, and drainage design. The result was presented as a function of soil, climate, and drainage design.

4.3 Methods:

4.3.1 Study Area

This DRAINMOD modeling study was performed using model input parameters primarily from the Southeast Research Farm (SERF) near Beresford in Clay County of southeastern South Dakota (Figure 4.1). The land parcel is divided into six (6) plots, three drained and three maintained as undrained with a control structure at each outlet and a monitoring well installed midway between drains in each plot. The parcel consist of 5.75ha (14.25 acre) with each plot in average of 0.96 ha (2.375) acres in size. The plots were drained separately, and drain outflow from each plot was measured with a pressure transducer that measured flow depth in each control structure. The flow rate was calculated from the flow depth using a local calibration (Partheeban et al., 2014). The observed data from the monitoring wells were used for calibration purposes. Pressure sensors were installed to observe the data in the well at 1.372 m below ground level to measure the water table depth below the soil surface. Water table depths were continuously measured with data logger and were recorded since June 2014.

The soils in the study area were Egan-Trent silty clay loam, (EhA, mixed, pachic haplustolls). The climate in the area is classified as dry subhumid, with average annual (1950-2012) precipitation of 642 mm, and average annual (1950-2012) daily maximum and minimum temperatures of 14.7 ºC and 1.8 ºC, respectively.

The study area has insufficient of long-term weather data therefore gaps were filled conducted using nearby weather at Centerville, located nineteen (19) kilometers northwest from SERF. Soils input for model simulations were taken from the USDA NRCS SSURGO data base (SSURGO). Soils were converted into DRAINMOD input format using Rosetta-PTF (Schaap et al., 2001). Reference evapotranspiration (Allen et al., 1998) estimated using in the REF-ET (Allen, 2000) and High Plains Regional Climate Center (HPRCC) crop coefficients for corn were used to obtain potential crop potential evapotranspiration (ET_c).

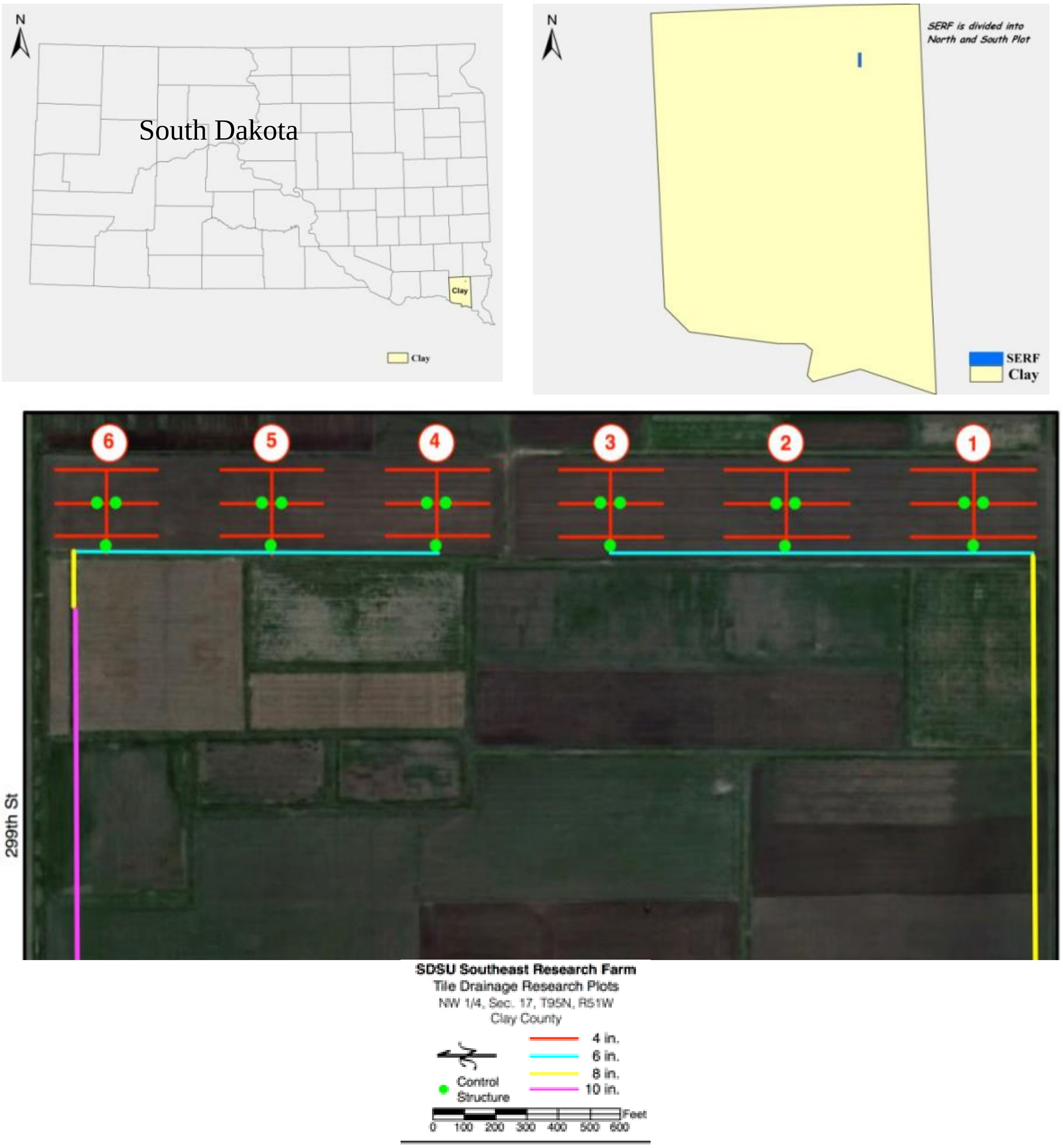

Figure 4.1 Study area

4.3.2 DRAINMOD

DRAINMOD is a field scale, process based, distributed simulation model (Skaggs et al., 2012). It was developed by Dr. Wayne Skaggs in the Biological and Agricultural Engineering Department at North Carolina State University, and has been extensively used to evaluate hydrology in poorly drained soils for over 30 years. It calculates surface and subsurface water balances using equations (equation *1* and equation *2*), on an hourly or daily basis for a thin column of soil that has a unit surface area which extends from the ground surface to the subsurface impermeable layer and is located midway between two tile drains (Figure 4.2, Skaggs, 1978).

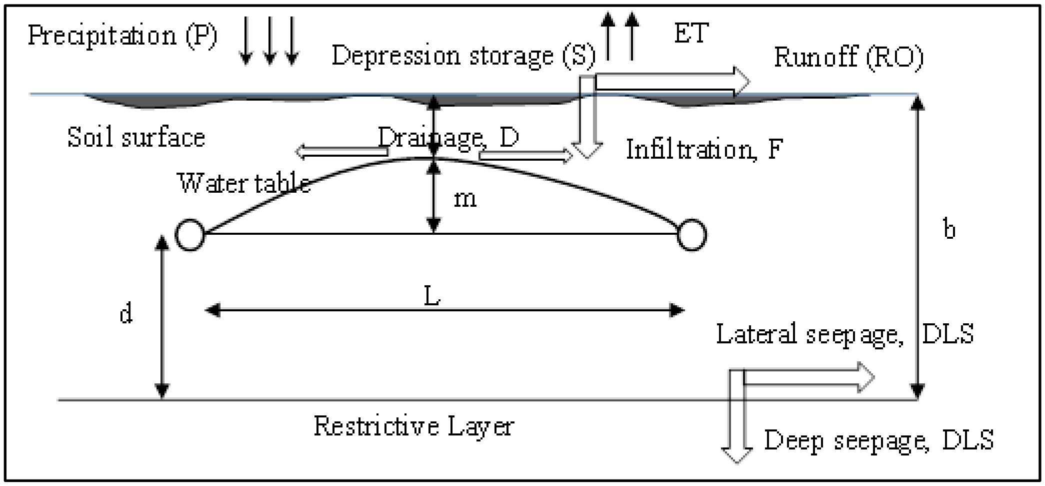

Figure 4.2 Schematic diagram of water management system with subsurface drains used in DRAINMOD adapted from Skaggs (1978)

$$\Delta V = D + ET + DLS - F \qquad (1)$$

$$P = F + S + RO \qquad (2)$$

where,

ΔV is change in water free pore space, D is drainage, ET is evapotranspiration, DLS is deep and lateral seepage, F is infiltration, P is precipitation, S is change in volume of water stored on the surface, and RO is surface. DRAINMOD (Version 5.0 and higher) is capable of incorporating the effects of freezing, thawing and snowmelt (Luo et al., 2000), which requires additional parameters in the model input, and makes the model more adapted for use in cold climates like South Dakota. These versions (5.0 and higher) are also capable of simulating the nitrogen and carbon cycles in shallow water table soils and effects of drainage, and drainage water management practices on nitrogen losses in draining water (Skaggs et al.,2012). The model inputs for DRAINMOD are soil properties, weather, drainage systems, and crop-related parameters.

4.3.2.1 Subsurface Drainage

DRAINMOD uses the steady state Hooughoudt equation (3) when the water table is between the drain depth and the soil surface. The Hooghoudt equation includes Dupuit-Forcheimer (D-F) assumptions (lateral flow in the saturated zone only) and assumes an elliptical water table.

$$q = \frac{4\mathrm{k}_e m\ (2d_e + m)}{L^2} \qquad (3)$$

Where,

q is drainage flux (cm/hr.), d_e is the equivalent drainage depth of the impermeable layer below the drain (cm), m is midpoint water table height above the drain (cm), K_e is effective lateral hydraulic conductivity (cm/hr.), and L is the lateral spacing between the drain (cm).

4.3.2.2 Infiltration

Infiltration is calculated using the Green-Ampt equation (equation 4) (Skaggs, 1980)

$$\begin{cases} f = K_v + \dfrac{K_v M S_{av}}{F} \\ \quad = B + \dfrac{A}{F} \end{cases} \qquad (4)$$

where,

K_v is saturated vertical hydraulic conductivity, M is the fillable porosity (water content at saturation minus water content at desired water table depth), S_{av} is suction at the wetting front, *F* is the cumulative infiltration, and *A* and *B* are constants. Additionally, at times, when rainfall rate is less than the infiltration rate, DRAINMOD assumes that the infiltration rate is equal to the rainfall rate.

4.3.2.3 Evapotranspiration

ET can be estimated either by the Thornthwaite method within the model or can be given as a user defined input in an input file. However, the Hargreaves-Samani method (Hargreaves and Samani, 1985) was used in this study as it was found to compare well with the Food and Agricultural Organization Penman-Monteith equation when using a time-step of five days or longer (Allen et al., 1998; Hargreaves and Allen, 2003). Reference evapotranspiration(Allen et al., 1998) estimated using in the REF-ET (Allen, 2000) model was multiplied using High Plains Regional Climate Center (HPRCC) crop coefficients for corn, which is based on growing degree days (GDD), and provided into the model as crop potential evapotranspiration for long term simulation. Actual ET was computed in the DRAINMOD from crop potential evapotranspiration provided in model after correction with crop coefficient as limited by soil water availability.

4.3.3 Rosetta

Rosetta (Schaap et al., 2001) is a set of pedotransfer functions that use five hierarchies of surrogate soil data (soil textural classes, bulk density, and moisture content at field capacity and permanent wilting point) to estimate vertical saturated hydraulic conductivity. Prediction of saturated hydraulic conductivity using Mualem (1976) pore size model is given by

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{[1 + (\alpha h)^n]^{1-\frac{1}{n}}} \qquad (5)$$

where,

θ(h) represents the water retention curve defining the water content, θ as a function of the soil water pressure head h (cm) θ_r and θ_s are residual and saturated water contents respectively, and α and n are curve shape parameters. Equation (5) can be rewritten to yield the relative saturation (S_e) as:

$$Se = \frac{\theta(h) - \theta_r}{\theta_s - \theta_r} = [1 + (\alpha h)^n]^{1-\frac{1}{n}} \qquad (6)$$

Equation (6) is used in conjunction with the pore-size distribution model of (Mualem, 1976) to yield the Van Genuchten-Mualem model(Van Genuchten, 1980):

$$K(S_e) = K_0 S_e^L \left\{1 - \left[1 - S_e^{\,n/(n-1)}\right]^{1-1/n}\right\}^2 \qquad (7)$$

where,

K is the unsaturated hydraulic conductivity, K_0 is the matching point at saturation and similar, but not necessarily equal to the saturated hydraulic conductivity, K_{sat}. The parameter *L* is an empirical pore tortuosity/connectivity parameter that is normally assumed to be 0.5 (Mualem, 1976). Rosetta predicts *L* which will be negative in most cases, which although this leads to some theoretical complication, gives better results (Kosugi, 1999; Schaap and Leij, 2000).

In DRAINMOD, a routine is available to convert the Rosetta output into a DRAINMOD readable format and requires the following inputs: θ_r, θ_s, α, n, L, K_0 and K_s.

4.3.4 Soil Hydraulic Properties

Four typical agricultural soils in eastern South Dakota were identified and selected from SSURGO data, as shown in Figure 4.4. The four selected soils were Egan

Trent (Silty Clay Loam, EhA), Albaton (Silty Clay, Ac), Bon (Clay Loam, Bm), Ticonic (Loamy Fine Sand, Tr). The four soils are shown in Figure 4.3. Physical soil properties from SSURGO data were input into Rosetta (Schaap et al., 2001) to derive soil hydraulic properties required for DRAINMOD simulation. Textural class, Rosetta output for DRAINMOD, other physical properties, and derived soil water characteristics curve of the selected soils for the study are shown in Figure 4.3, Table 4.1, Table 4.2, and Figure 4.4.

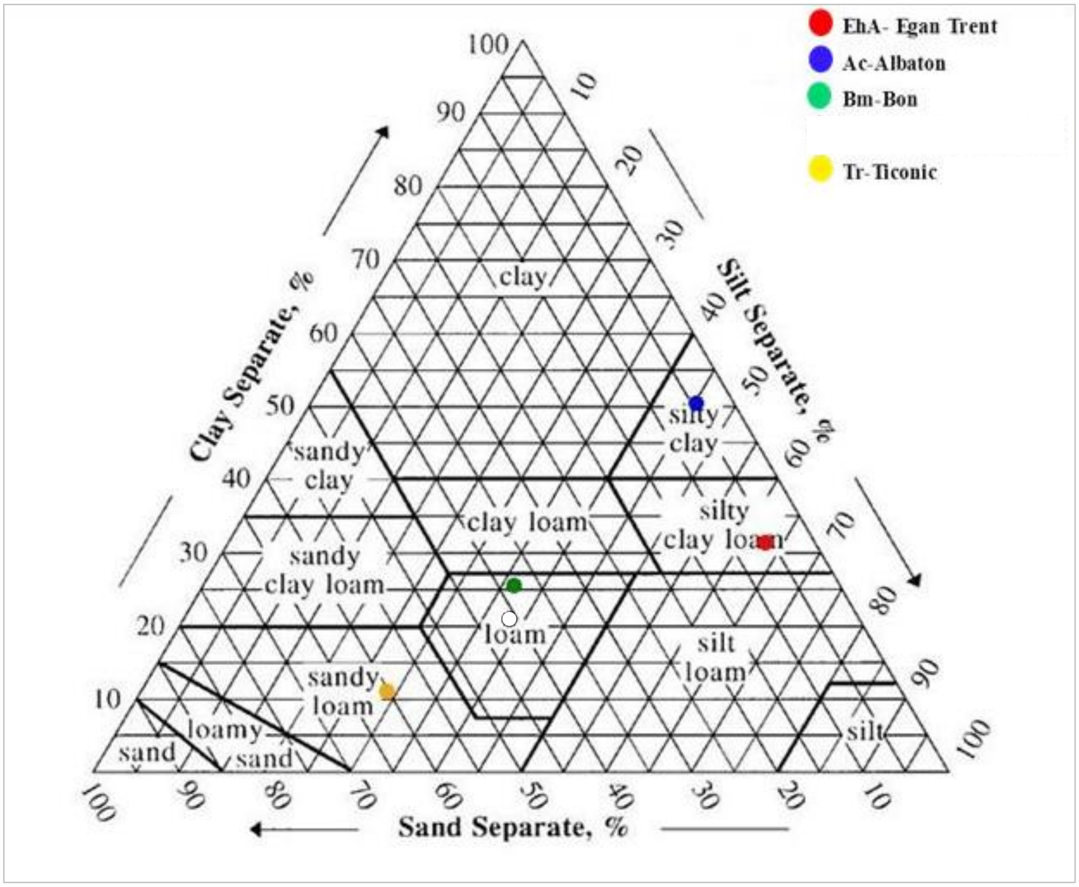

Figure 4.3 Textural classification of soil at study area

Table 4.1 Rosetta output for DRAINMOD of selected soils for the modeling study

Soil Type	Depths (cm)	(θ_r)	(θ_s)	(α)	(n)	(K_s)	(K_o)	(L)
		cm^3/cm^3	cm^3/cm^3	log(1/cm)	Log_{10}	(cm/day)	(cm/day)	
Egan SiCL	0-20	0.084	0.490	0.019	1.307	34.143	6.812	-1.19
Egan SiCL	20-66	0.069	0.459	0.014	1.343	23.096	5.179	-0.66
Egan SiCL	66-86	0.065	0.455	0.013	1.357	21.95	5.072	-0.54
Egan SiCL	86-137	0.063	0.389	0.016	1.248	4.342	4.591	-1.54
Egan SiCL	137-152	0.062	0.388	0.015	1.253	4.443	4.535	-1.47
Albaton SiCL	0-23	0.178	0.467	0.062	1.275	12.262	7.178	-3.27
Albaton SiCL	23-152	0.180	0.465	0.063	1.271	11.96	6.972	-3.34
Ticonic FineSM	0-23	0.021	0.416	0.049	1.370	181.671	43.98	-1.24
Ticonic FineSM	23-66	0.017	0.411	0.059	1.420	237.767	60.53	-1.17
Ticonic FineSM	66-127	0.037	0.388	0.010	1.405	19.437	4.902	-0.18
Ticonic FineSM	127-203	0.033	0.371	0.008	1.433	18.010	3.922	-0.01
Bon Clay Loam	0-109	0.064	0.463	0.016	1.324	31.984	6.481	-0.75
Bon Clay Loam	109-142	0.085	0.435	0.042	1.357	31.393	17.25	-1.76
Bon Clay Loam	142-152	0.055	0.421	0.037	1.363	34.597	20.56	-1.38

Note: **EhA**: Egan Trent (Silty Clay Loam), **Ac** :Albaton (Silty Clay), **Bm**: Bon (Clay Loam), **Tr**: Ticonic (Loamy Fine Sand)

$\boldsymbol{\theta_r}$: Residual water content, $\boldsymbol{\theta_s}$: Saturated water content, $\mathbf{K_s}$: Saturated hydraulic conductivity, $\mathbf{K_o}$: Matching point hydraulic conductivity, **α** and **n**: Shape parameters, **L**: Empirical tortuosity/connectivity parameters.

Table 4.2 Soil properties of selected soil for modeling study

Soil properties	Ac-Albaton (Silty-Clay)		EhA-Egan(Silty-Clay-Loam)		Tr-Taconic (Loamy-Fine-Sand)		Bm-Bon(Clay loam)	
Depth to restrictive layer > (cm)	200		200		200		200	
Depth wise saturated Hydraulic conductivity (K_s) (cm/hr.)	Depths (cm)	K_s (cm/day)	Depths (cm)	K_s (cm/day)	Depths (cm)	K_s (cm/day)	Depths (cm)	Ks (cm/day)
	0-23	3.28	0-20	1.74	0-23	7.75	0-109	3.24
			20-43	3.24	23-66	9.9	109-142	3.24
	23-152	0.86	43-109	3.24	66-127	3.24	142-152	8.28
			109-152	1.74	127-152	1		
% sand	5		7		62		40	
% silt	45		62		28		38	
% clay	50		31		10		22	
Bulk density (cm^3/cm^3)	1.39		1.38		1.4		1.3	
θ at -33 kPa (%)	0.35		0.31		0.18		0.26	
θ at -1500 kPa (%)	0.29		0.18		0.065		0.15	

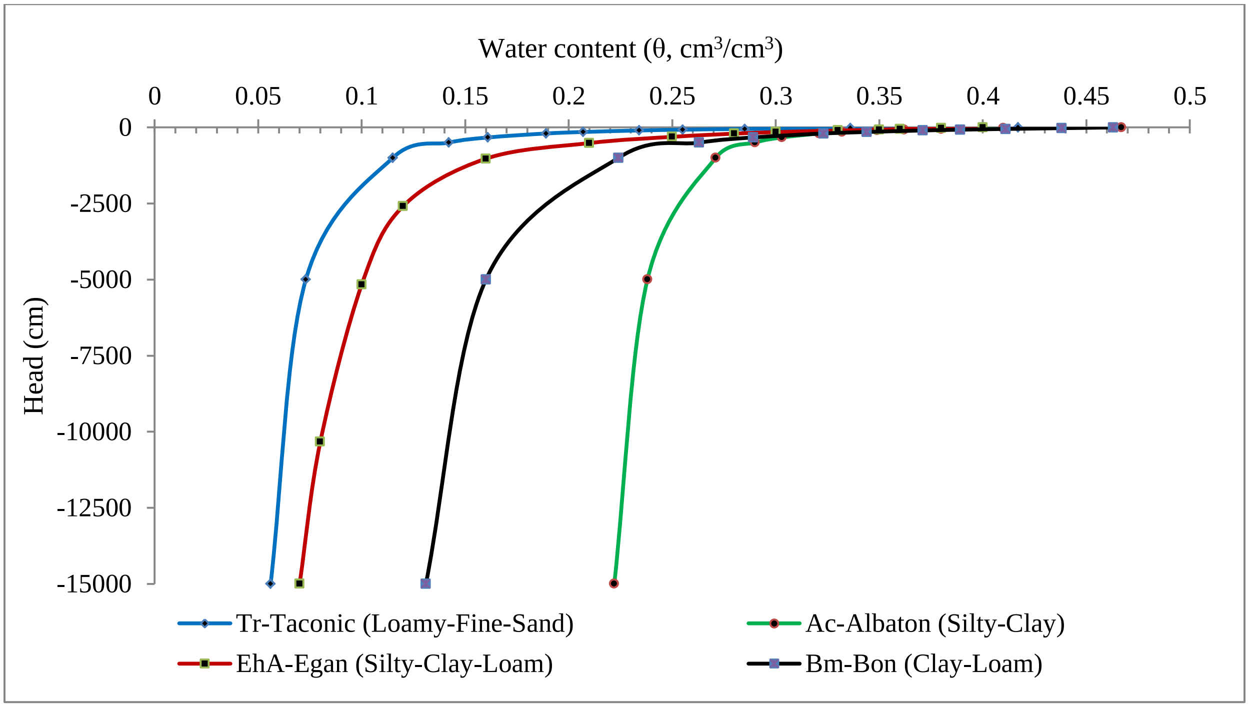

Figure 4.4 Soil water characteristic curves for soils used for the modeling study

4.3.5 Model Simulations

DRAINMOD (version 6.0) with calibrated input parameters was used to simulate hydrology for continuous corn considering the effects of freezing, thawing, and snowmelt within the model (Luo et al., 2000) using four selected soils and Rosetta derived soil hydraulic properties. The saturated water content, θ_s (cm^3/cm^3), residual water content, θ_r (cm^3/cm^3), curve shape parameters α (1/cm) and n, and K_{sat} (cm/day) (Table 4.1) were used in the Van Genuchten model via Rosetta to obtain values for the tortuosity parameter, L, and matching point at saturation, K_o (cm/day). These hydraulic parameters were inputs into a subroutine in DRAINMOD to create soil inputs needed in the model. Derived soil water characteristic curves are shown in Figure 4.4. Horizontal conductivity was assumed to be 1.4 times the vertical saturated conductivity, depth to the impermeable depth was assumed to be below 3.0 m. The impermeable depth was assumed based on the SSURGO data base information. No vertical seepage was allowed in the model to generalize the model. Daily weather data were converted into hourly data using the subroutine provided in the model. PET was estimated using the Hargreaves Samani (Hargreaves and Samani, 1985) method in (Allen, 2000) Reference evapotranspiration(Allen et al., 1998) estimated using in the REF-ET (Allen, 2000) model was multiplied by High Plains Regional Climate Center (HPRCC) crop coefficients for corn, which is based on growing degree days (GDD), and provided into the model as crop potential evapotranspiration for long term simulation. Long-term DRAINMOD simulations were then run for these selected soils, crop inputs, drainage conditions, and climatological data. The simulations included varying drain depths and spacings in the form of four drainage intensities: 0 (undrained), and 0.32, 0.64 and 0.95

cm/day for drained conditions. Undrained conditions were simulates by using a drainage coefficient close to zero with excessively wide spacing (>1000 m). Simulations also included the selected dry year (2012), wet year (2010), and average weather year (2001) to see the effects of dry and wet years in water yield. Daily, monthly and yearly drainage and surface runoff (water yield) or hydrological output were exported as outputs of long-term simulations to a spreadsheet for further analysis of different scenarios.

4.4 Result and Discussions

4.4.1 Effect of Soil Type on Water Yield (Drainage and Runoff)

DRAINMOD simulations were performed for the period of (1950-2012) for the study area using input parameters for four selected soil types and four drainage intensities and water yield (drainage plus runoff) obtained are shown in (Table 4.3 and Figure 4.5). The results showed the drainage water and water yield increased with increased in drainage intensity for all selected soils. Runoff decreased within the same soil type as the drainage intensity increased. Also, the ratio of drainage to water yield was increased with the increased drainage intensity. The amount of water yield was decreased with the change in soil texture from fine-textured or less permeable soil (silty clay) to coarse-textured soil or permeable (sandy loam). The decrease in water yield was attributed to increased infiltration in the coarser soil thus increasing the potential for plant use leading to increased evapotranspiration (ET) component in water balance (Figure 4.6). The result also showed the drainage amount in the Egan soil (silty-clay-loam) was greater than in the Bon (loam) soil. DRAINMOD uses a soil water characteristic curve to derive drainage volume versus water table and upward flux versus water table. Infiltration, and

ET component are directly related to the soil characteristics curve shown in (Figure 4.4), in the same manner in increased infiltration in water balance as shown in (Figure 4.6).

Table 4.3 Average annual water yield (drainage plus runoff) for four soil type under undrained, and drained conditions at four drainage intensities (0 or undrained, 0.32, 0.64 and 0.95 cm/day).

Soil Type	Drainage intensity (cm/day)	Drainage (cm)	Runoff (cm)	Total	% increase over drainage
Ac Albaton (Silty-Clay)	0 (Undrained)	0.00	5.21	5.21	0.0
	0.32	0.97	4.96	5.93	16.3
	0.64	1.40	4.95	6.36	22.1
	0.95	1.71	4.93	6.64	25.7
EhA-Egan (Silty Clay loam)	0 (Undrained)	0.00	2.94	2.94	0.0
	0.32	0.77	2.83	3.61	21.5
	0.64	0.95	2.83	3.78	25.2
	0.95	1.10	2.78	3.87	28.4
Bm-Bon (Clay loam)	0 (Undrained)	0.00	0.80	0.80	0.0
	0.32	0.59	0.68	1.27	46.4
	0.64	0.85	0.69	1.54	55.3
	0.95	1.04	0.68	1.72	60.6
Tr-Ticonic (Sandy loam)	0 (Undrained)	0.00	0.37	0.37	0.0
	0.32	0.72	0.18	0.90	80.1
	0.64	1.08	0.15	1.23	88.0
	0.95	1.33	0.14	1.47	90.5

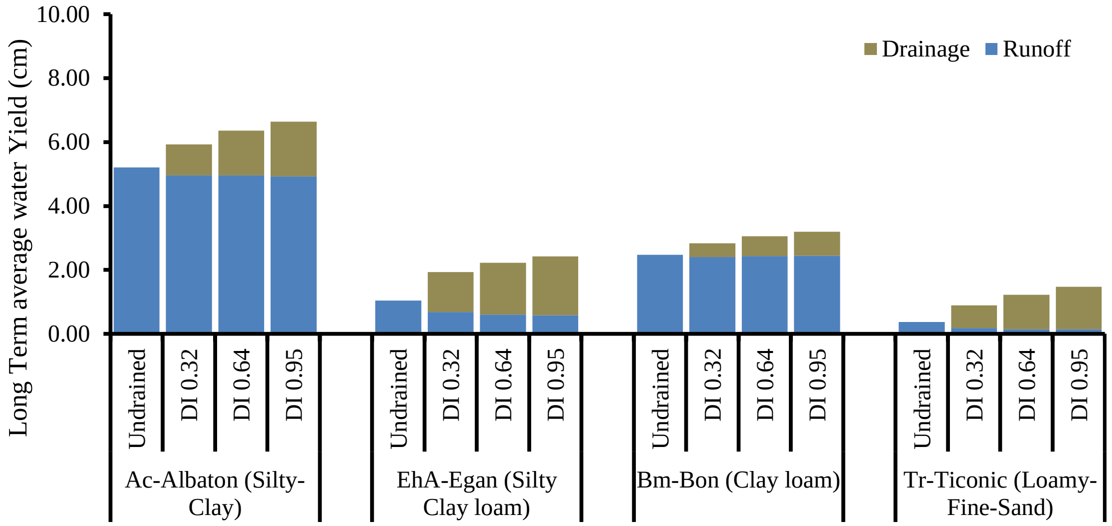

Figure 4.5 Average water yield (drainage plus runoff) for four soil type and four drainage intensities

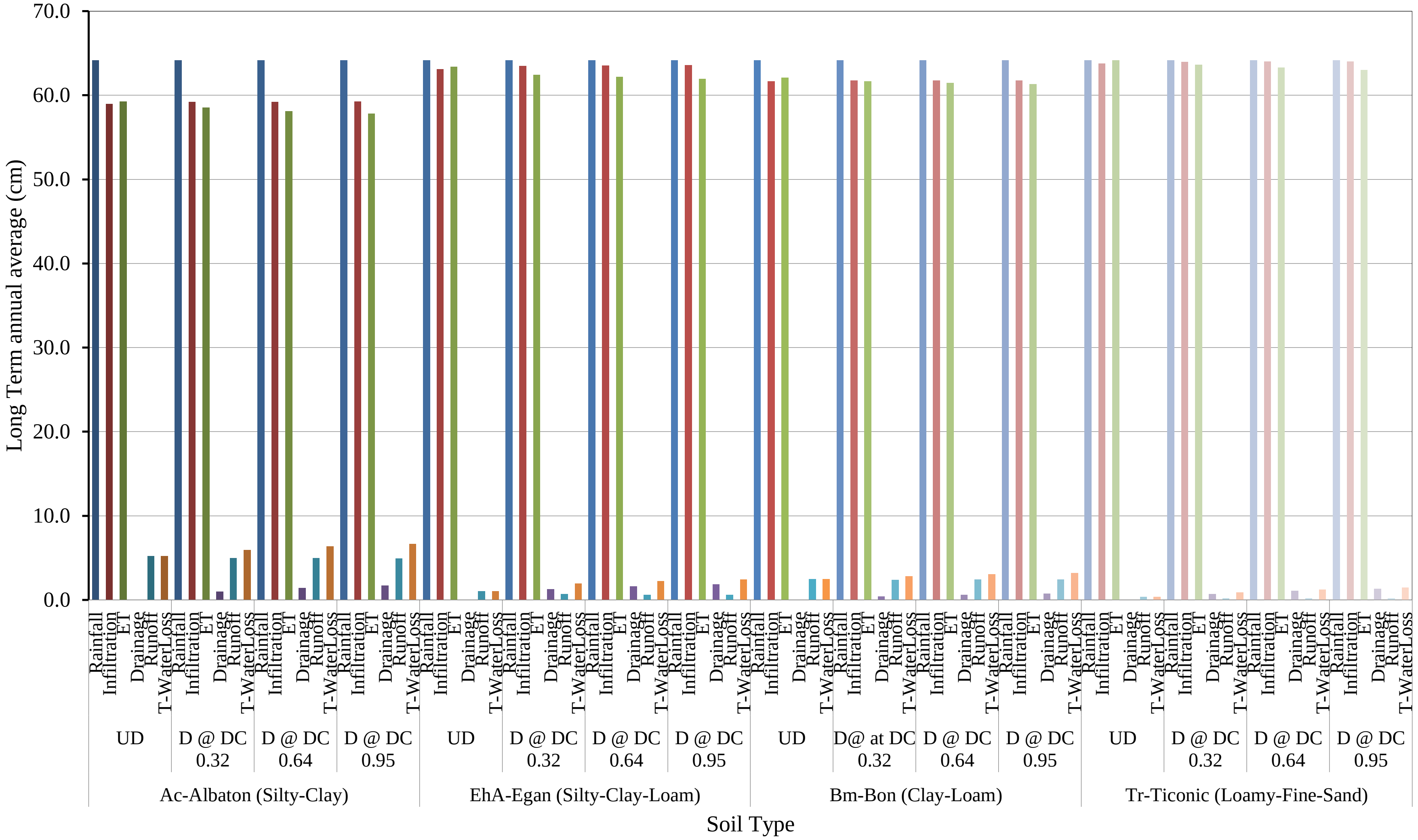

Figure 4.6 Long-term annual water balance components for four soil type and four drainage intensities (cm/day)

4.4.2 Effect of Drain Spacing on Water Yield (Drainage and Runoff):

DRAINMOD simulation results for four selected soil types and various drain spacings at the study area are shown in Figure 4.7 and Table 4.4. As expected, the results showed that the addition of drainage increased water yield. The results also showed that increasing the drain spacing reduced the water yield in all selected soils. The increased water yield in drained condition was attributed to increased infiltration and decreased ET (Figure 4.6) as infiltrated water has new pathways through subsurface drainage. ET was decreased under drained conditions and increased with increasing drain spacing. Narrower drain spacing resulted in increasing drainage for all soil types. The decrease in drainage amount with the increase in spacing was very small for the Ticonic loamy fine sand soil. In undrained soils or for large drain spacing, water yield was dominated by surface runoff. As drain spacing decreased, more flow was routed through the subsurface, increasing the drainage flow. The results indicated that water yield was affected by drain spacing in the same manner as it does in soil type; i.e. water yield was decreased with the change in soil texture from fine-textured soil (silty clay) to coarse-textured soil (sandy loam).

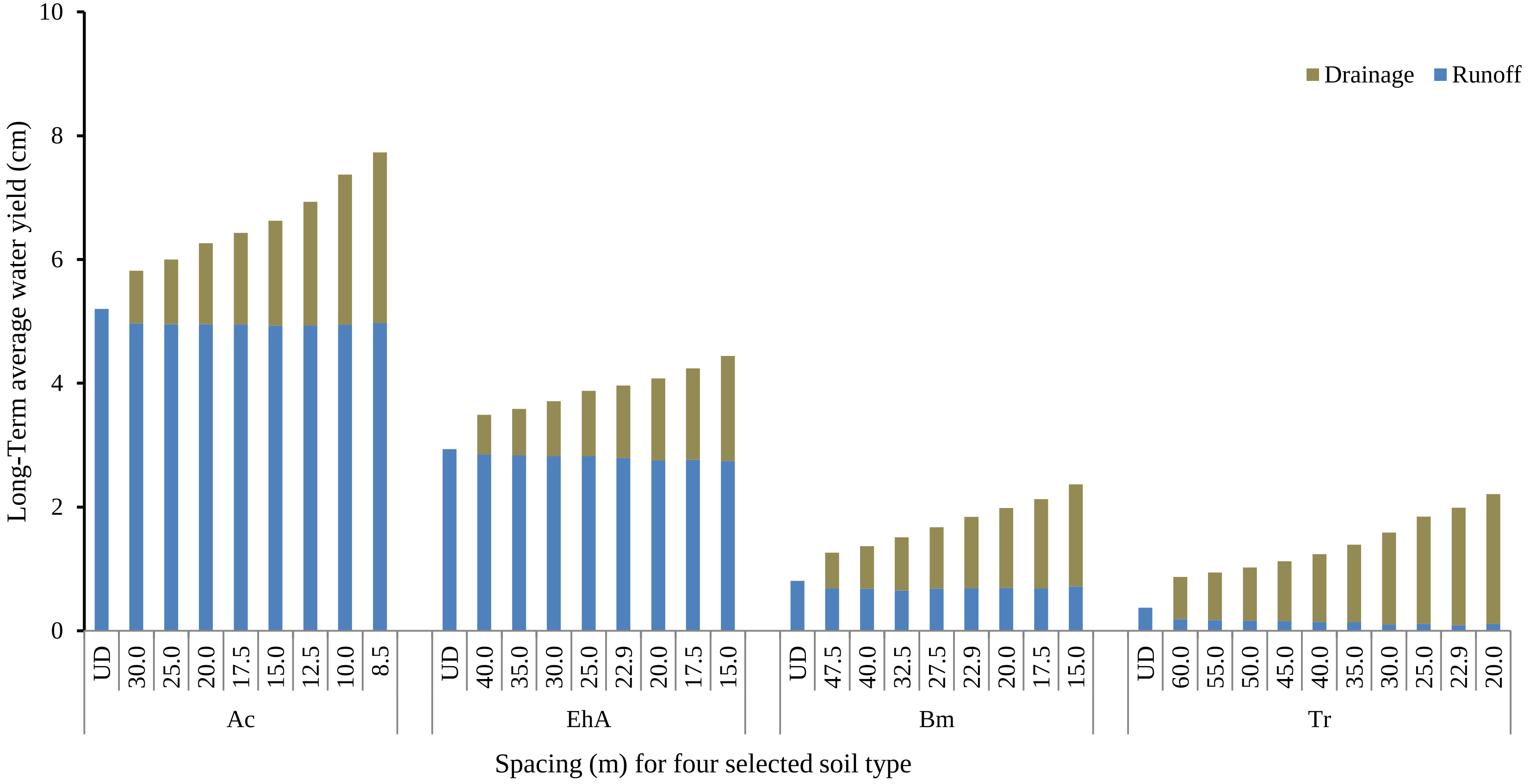

Figure 4.7 Long-term average water yield (drainage plus runoff) for four soil type at various drainage spacing

Table 4.4 Long-term average water yield (drainage plus runoff), and percentage of drainage water to the total water yield for four soil type at various drainage spacing

Soil Type	Drain spacing (m)	Drainage (cm)	Runoff (cm)	Total (cm)	% of drainage
Albaton SiCL (Ac)	0 (Undrained)	0.00	5.20	5.20	0.0
	8.5	2.76	4.97	7.73	35.7
	10.0	2.43	4.95	7.37	32.9
	12.5	2.00	4.94	6.93	28.8
	15.0	1.70	4.93	6.63	25.6
	17.5	1.48	4.95	6.43	23.0
	20.0	1.31	4.95	6.26	20.9
	25.0	1.04	4.95	6.00	17.4
	30.0	0.85	4.97	5.82	14.6
Egan SiCL loam (EhA)	(0) Undrained	0	2.94	2.94	0.0
	15.0	1.70	2.74	4.44	38.2
	17.5	1.48	2.76	4.24	34.8
	20.0	1.32	2.76	4.08	32.4
	22.9	1.17	2.79	3.96	29.6
	25.0	1.06	2.82	3.88	27.2
	30.0	0.89	2.82	3.71	23.9
	35.0	0.75	2.83	3.58	20.9
	40.0	0.64	2.85	3.49	18.4
Bon CL (Bm)	(0) Undrained	0.00	0.80	0.80	0.1
	15.0	1.65	0.71	2.36	69.8
	17.5	1.44	0.68	2.13	67.9
	20.0	1.29	0.69	1.98	65.0
	22.9	1.16	0.68	1.84	62.9
	27.5	1.00	0.68	1.68	59.5
	32.5	0.86	0.65	1.51	56.8
	40.0	0.69	0.68	1.37	50.6
	47.5	0.58	0.68	1.26	45.8
Ticonic loamy find sand (Tr)	(0) Undrained	0	0.37	0.37	0.0
	20.0	2.10	0.11	2.21	95.0
	22.9	1.90	0.09	1.99	95.4
	25.0	1.73	0.11	1.84	94.0
	30.0	1.49	0.10	1.59	93.8
	35.0	1.25	0.14	1.39	89.9
	40.0	1.09	0.14	1.24	88.4
	45.0	0.97	0.15	1.12	86.2
	50.0	0.86	0.16	1.02	84.1
	55.0	0.77	0.17	0.94	81.8
	60.0	0.69	0.18	0.87	78.9

4.4.3 Effect of Climate (Dry Year and Wet Year):

DRAINMOD simulations were performed for a selected dry year (2012), wet year (2010) and average precipitation weather year (2001), keeping all other input parameters constant. The results in all three years showed the similar pattern, i.e., drainage water and water yield increased with increased drainage intensity for all selected soils and runoff was decreased within the same soil type as drainage intensity increased (Figure 4.8, and Table 4.5). Water yield however was zero for the dry year 2012 except for a small amount of runoff for the Albaton silty clay soil. The small runoff amount in Albaton silty clay was because of very low effective lateral conductivity thus leading to runoff even in small amount of rainfall. Daily hydrographs were also plotted to see how closely storm events affected daily hydrograph and the water yield. An event of one week (25-31 May) in 1995 was chosen to represent one moderate precipitation event (Figure 4.9, and Figure 4.10). The results showed increased drainage flow and peak flow in Ticonic loamy fine sand (Tr) and Bon clay loam (Bm) soil, decreased in Egan silty-clay loam (EhA), while there was hardly any difference in Albaton silty clay (Ac) for the drainage intensity of 0.95 cm/day as compared to the undrained condition.

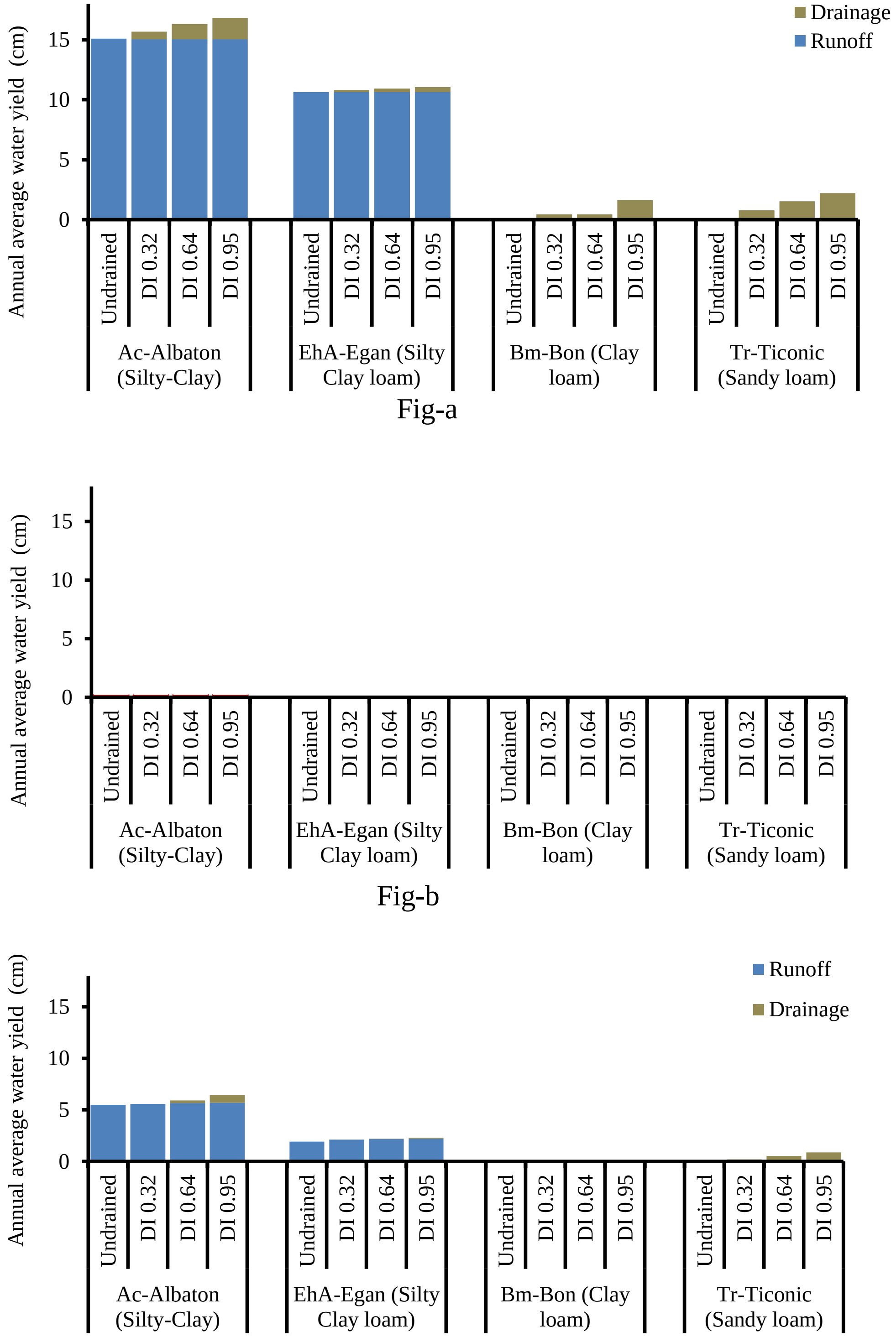

Fig-a

Fig-b

Fig-c

Figure 4.8 Annual average water yield for four soil type under undrained and drained conditions at four drainage intensities (cm/day) for selected wet, dry, and average year

Fig-a: Wet year 2010, Fig-b: Dry year 2012, and Fig-c: Average year 2001

Table 4.5 Annual average water yield for four soil type and four drainage intensities

Year	**Water Yield as a function of soil type and DI (cm per day)**			
	Soil Type	Drainage intensity (cm/day)	Drainage (cm)	Runoff (cm)
2010 (wet)	Ac	0 (Undrained)	0.00	15.09
		0.32	0.64	15.04
		0.64	1.28	15.04
		0.95	1.76	15.04
	EhA	0 (Undrained)	0.00	10.64
		0.32	0.16	10.64
		0.64	0.29	10.64
		0.95	0.41	10.64
	Bm	0 (Undrained)	0.00	0.00
		0.32	0.44	0.00
		0.64	0.44	0.00
		0.95	1.62	0.00
	Tr	0 (Undrained)	0.00	0.00
		0.32	0.77	0.00
		0.64	1.53	0.00
		0.95	2.22	0.00
2012 (Dry)	Ac	0 (Undrained)	0.00	0.19
		0.32	0.00	0.19
		0.64	0.00	0.19
		0.95	0.00	0.19
	EhA	0 (Undrained)	0.00	0.00
		0.32	0.00	0.00
		0.64	0.00	0.00
		0.95	0.00	0.00
	Bm	0 (Undrained)	0.00	0.00
		0.32	0.00	0.00
		0.64	0.00	0.00
		0.95	0.00	0.00
	Tr	0 (Undrained)	0.00	0.00
		0.32	0.00	0.00
		0.64	0.00	0.00
		0.95	0.00	0.00
2001 (Average)	Ac	0 (Undrained)	0.00	5.57
		0.32	0.05	5.62
		0.64	0.33	5.66
		0.95	0.75	5.70
	EhA	0 (Undrained)	0.00	2.01
		0.32	0.06	2.14
		0.64	0.11	2.19
		0.95	0.17	2.22
	Bm	0 (Undrained)	0.00	0.00
		0.32	0.00	0.00
		0.64	0.00	0.00
		0.95	0.00	0.00
	Tr	0 (Undrained)	0.00	0.00
		0.32	0.29	0.00
		0.64	0.63	0.00
		0.95	0.96	0.00

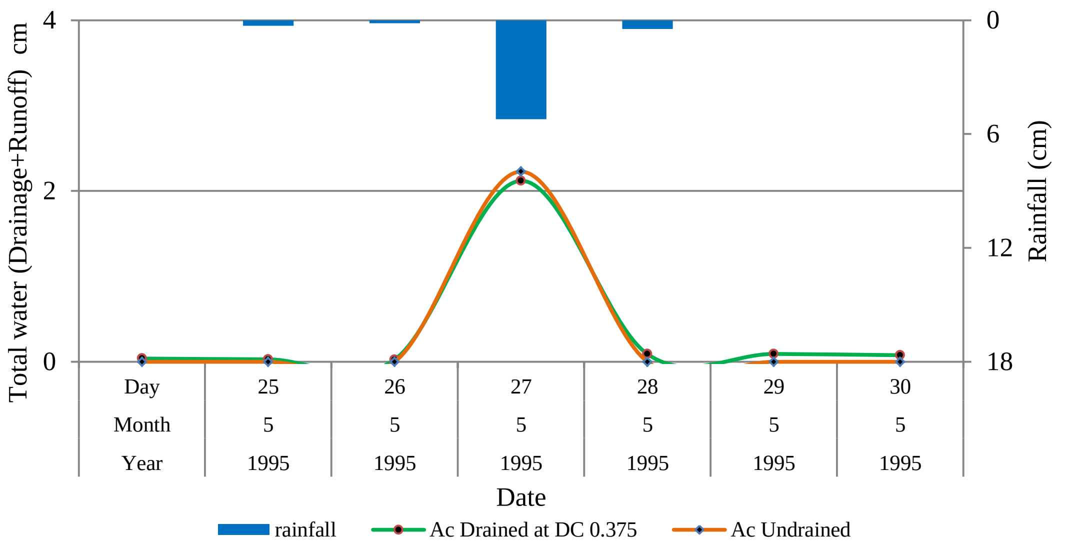

Fig-a

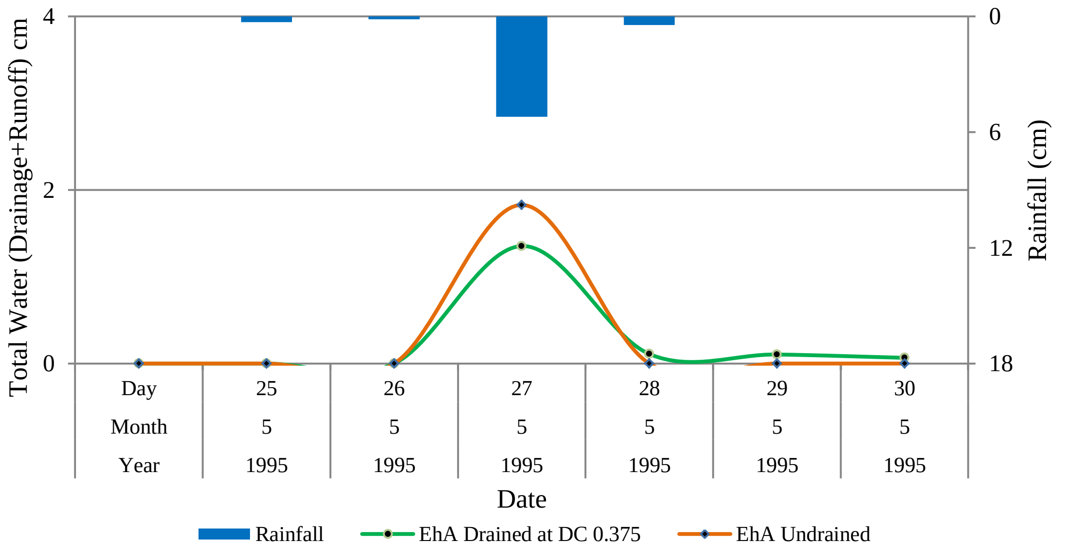

Fig-b

Figure 4.9 Daily hydrographs for four soils and selected event (May 25-31, 1995) under undrained, and drained condition at DI 0.95 cm/day (0.375 inch/day)

Fig-a Soil Type : Albaton Silty Clay (Ac)
Fig-b Soil Type : Egan Trent Silty Clay Loam (EhA)

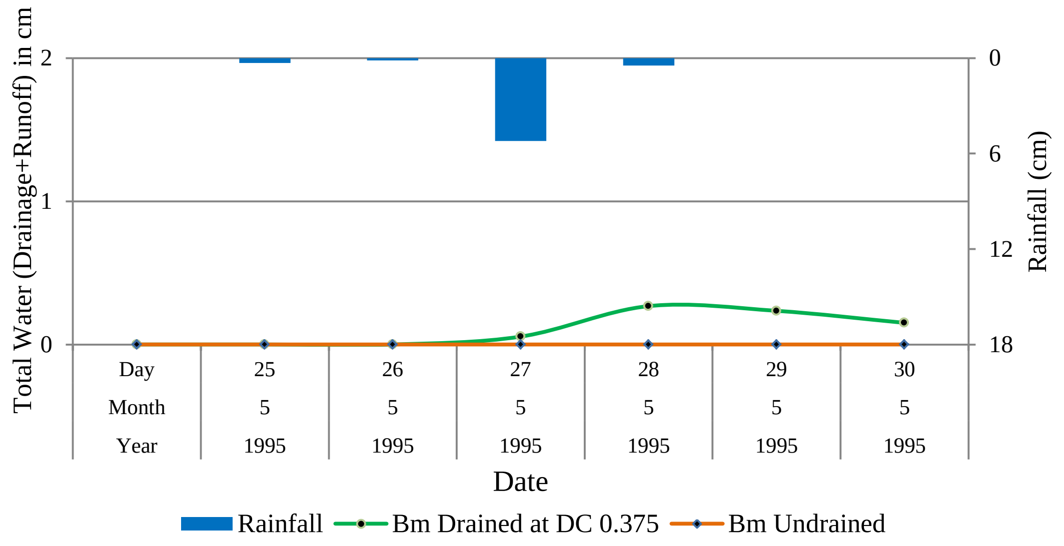

Fig-a

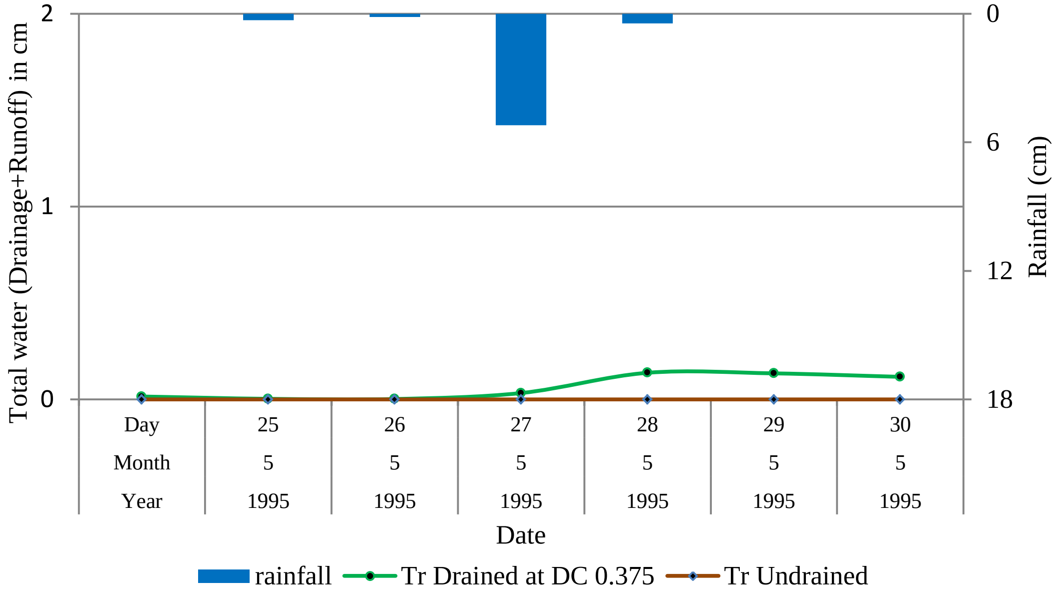

Fig-b

Figure 4.10 Daily hydrographs for selected soil and selected event (May 25-31, 1995) under drained and undrained scenario (Scale of figure 4.10 is different from in Figure 4.9)

Fig-a Soil Type: Bon Clay Loam (Bm)
Fig-b Soil Type : Ticonic Loamy Fine Sand (Tr)

4.4.4 Seasonal Variation of Water Yield:

Water yield in monthly output file (*GRM file in DRAINMOD) obtained from DRAINMOD simulations in the study area for drainage intensities of 0 and 0.95 cm/day were averaged for four seasons. The four seasons were the climatological seasons: December to February as winter, March to May as spring, June to August as summer, and September to November as fall. The results showed the water yield was the greatest during summer in all soil types, while the drainage was greatest during spring and least during summer (Table 4.6 and Figure 4.11). This was because the tile drains in cold areas tend to freeze during winter with increased drainage occurring during and shortly after snow melt and spring thaw. The increase in water yield goes on increasing from coarse soil (Tr-Ticonic) to fine soil (Ac-Albaton). Also the results showed that the drainage percentage of the total water yield during spring varied from 45 percent in Albaton clay to 80 percent in Ticonic loamy fine sand.

Table 4.6 Average seasonal water yield (drainage plus) under undrained and drained condition at DC 0.95 cm/day

Soil Type	Season	Drainage intensity (cm/day)	Drainage (cm)	Runoff (cm)	Total (cm)
Ac	Fall	0 (undrained)	0.00	0.37	0.37
		0.95	0.00	0.37	0.37
	Spring	0 (undrained)	0.00	0.46	0.46
		0.95	0.35	0.41	0.76
	Summer	0 (undrained)	0.00	0.84	0.84
		0.95	0.18	0.80	0.98
	Winter	0 (undrained)	0.00	0.06	0.06
		0.95	0.04	0.06	0.11
EhA	Fall	0 (undrained)	0.00	0.20	0.20
		0.95	0.00	0.19	0.19
	Spring	0 (undrained)	0.00	0.30	0.30
		0.95	0.22	0.28	0.50
	Summer	0 (undrained)	0.00	0.43	0.43
		0.95	0.12	0.39	0.51
	Winter	0 (undrained)	0.00	0.05	0.05
		0.95	0.03	0.06	0.09
Bm	Fall	0 (undrained)	0.00	0.00	0.00
		0.95	0.01	0.00	0.01
	Spring	0 (undrained)	0.00	0.18	0.18
		0.95	0.20	0.16	0.36
	Summer	0 (undrained)	0.00	0.04	0.04
		0.95	0.11	0.00	0.11
	Winter	0 (undrained)	0.00	0.04	0.04
		0.95	0.04	0.06	0.10
Tr	Fall	0 (undrained)	0.00	0.00	0.00
		0.95	0.01	0.00	0.01
	Spring	0 (undrained)	0.00	0.07	0.07
		0.95	0.25	0.05	0.30
	Summer	0 (undrained)	0.00	0.06	0.06
		0.95	0.14	0.00	0.14
	Winter	0 (undrained)	0.00	0.00	0.00
		0.95	0.05	0.00	0.05

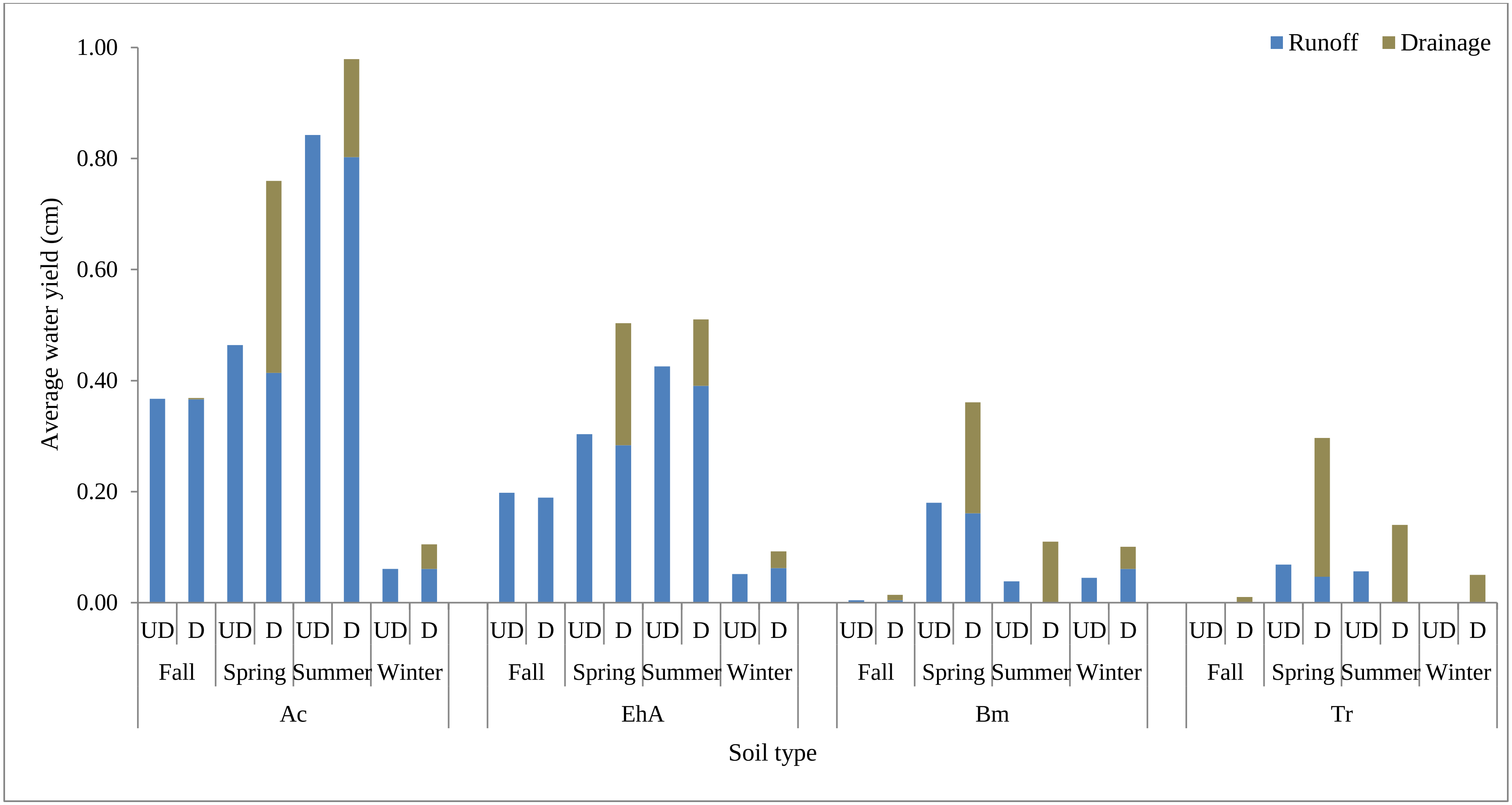

Figure 4.11 Seasonal water yield (drainage plus runoff) for selected soil type under undrained, and drained conditions at DC 0.95 cm/day

4.5 Summary and Conclusions

The purpose of this study was to find the impact of tile drainage on water yield as function of soil type, drainage intensity and climate for typical eastern South Dakota conditions and was performed by DRAINMOD modelling study.

The study showed that the amount of water yield was decreased with the change in soil texture from fine-textured or silty clay to coarse-textured soil loamy fine sand. Runoff decreased as soil texture changed from fine to coarse, so was the subsurface drainage. The model also showed that fine texture soil contributed more water yield as compared to coarse texture soil in undrained condition as water infiltrated slowly and there was more surface runoff in fine soils. Drainage percentage varied from 15 percent to 90 percent to water yield while it was upto 11 percent to total precipitation.

Spacing of tile drainage on water yield had also the similar effects in drained versus undrained condition, i,e; dominated by surface runoff. The result showed that greater drain spacing reduced the water yield in all selected soils. In undrained soils or for large drain spacing, water yield was dominated by surface runoff.

Effect of precipitation also showed that the drainage water and water yield increased with increased drainage intensity for all selected soils, and runoff decreased within the same soil type as drainage intensity increased. The model showed no drainage flow in dry precipitation year. ET component in average water balance increased when there was no drainage flow.

The result of seasonal variation showed that the water yield was the greatest during summer in all soil types, while the drainage was greatest during spring and least during summer. The result also showed that the drainage percentage of the total water yield during spring varied from 45 percent in Albaton clay to 80 percent in Ticonic loamy fine sand soil.

The study results, for the most part, agree with the conclusion with some the previous field scale studies. However, there is scope of future work that needs to be carried out to validate the findings of this study. The DRAINMOD is not capable of incorporating the effect of micropores, which might be very important during the summer months in fine soil or less permeable soils. Other model such as SWAP (Soil-Water-Atmosphere-Plant) which has the capability of incorporating effect of micropores will be helpful to support the conclusion of this study. Additionally, hourly precipitation weather input with more specific measured soil input and hourly output analysis would give more specific result of output hydrograph response. Continuance detailed studies of tile drainage on impact of hydrology with more specific detail input in field scale model will be useful to watershed scale, and can produce positive impact on engineering, economics, and ecological environment.

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