HYDRUS Modelling to Predict Field Trafficability under Different Drainage Design and Weather Conditions in Southern Manitoba

by

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Abstract

Advancements in computation and development of physically based hydrologic models to simulate complex vadose zone scenarios helped the research community to evaluate different scenarios easily compared to long-term field experiments. However, some field data collection is necessary to obtain input data such as soil properties, water usage and land management practices to validate the model performance specific to the site. Data obtained from field experiments conducted in 2011 at Hespler farms, Winkler, MB was used in this research for model calibration and validation. The hydrologic model, HYDRUS (2D/3D) was evaluated using parameters such as visual and statistical analysis. Model evaluation during the calibration and validation stage gave RMSE values of 0.019 and 0.015 cm^3 cm^{-3}; PBIAS values of -1.01 and -0.14, respectively, suggesting that the model was efficient in simulating soil water content similar to the field observed data. The validated models were then used to simulate outcomes for different scenarios such as 30-year rainfall data (1986 – 2015), different soil physical properties, and drainage system design parameters. Models simulating free drainage predicted lower soil water content compared to controlled drainage leading to 6 – 60 more trafficable days for 8 m spacing and 0.9 drain base depth. Free drainage predicted 8 – 110 additional trafficable days compared to controlled drainage for 15 m spacing and 1.1 drain depth. Heavier than normal rainfall events caused high water contents leading to a few years with a very low to no trafficable days under controlled drainage conditions. The comparisons are presented based on models using free drain conditions. Models with 8-m drain spacing predicted a 1 to 10-day increase in the number of trafficable days compared to the 15-m drain spacing. Drains placed at a base depth of 1.1 m below the soil surface predicted 4 - 40 more trafficable days compared to those installed at a base depth of 0.9 m.

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for always being with me.

Love you

Lasya Siri – Mourya Tej

Thanks

Amma – Nanagaru

Siri – Bavagaru

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Acronyms

BD	Soil Bulk Density
ET	Evapotranspiration
FE	Finite Element
LAI	Leaf Area Index
LPL	Lower Plastic Limit
NSE	Nash- Sutcliffe Efficiency
PBIAS	Percent Bias
r	Pearson's correlation coefficient
R2	Regression coefficient
RMSE	Root Mean Square Error
RSR	Ratio of RMSE to Standard deviation
TDR	Time Domain Reflectometry

1 General Introduction

1.1 Overview

In Manitoba, winter weather conditions cause the freezing of the top layers of the soil depending on the soil water status and snow cover. This situation continues until the spring snowmelt. High soil water content compromises the length of the cropping season during the spring snowmelt. Excess water content during crop growing season limits the soil aeration within the root zone. However, subsurface drainage can be used to drain excess water. Controlled drainage regulates the drain outflow and maintains the water table at a shallower level using drainage control structures. Past research studies proved the impact of controlled drainage on lowering nutrient loss from agriculture fields (Ballantine and Tanner 2013; Drury et al. 2009). Maintaining the water table just below the crop root zone facilitates upward water flux, otherwise known as subirrigation. The effects of different water management practices on potato (Satchithanantham et al. 2012) and corn yield (Cordeiro and Sri Ranjan 2012) were assessed by multi-year field experiments conducted in Southern Manitoba.

Most of the previous studies compared the impact of different water management practices on yield and field nutrient losses. However, research on the impact of water management practices on trafficability in Manitoba is very limited. Most of the research reported in the literature quantifies the relation between soil strength and vehicular load (Chamen et al. 1992; Soane et al. 1980). Trafficability is the capacity of the soil to support vehicular passage without significant effect on soil structure. It depends on the strength of the soil to support the load. The relation between soil water content and soil physical properties such as strength and particle cohesion can be used to predict field trafficability.

Volumetric soil water content is difficult to measure and can be expensive to implement in multiple locations. Non-destructive methods such as Time domain reflectometry (TDR) miniprobes can be used to obtain temporal data. However, the TDR miniprobes have a small radius of influence making it costly to collect soil water content data.

Soil water dynamics is a non-linear process and depends on many factors such as soil type and water flux. Hydrologic models help understand the soil water dynamics. Initial calibration and validation are necessary to assess the performance of the model. Validated hydrologic models help simulate soil water content under different rainfall patterns and water management practices. Validated hydrologic models can be used to simulate soil water content data on both a temporal and a spatial basis.

1.2 Scope

Satchithanantham (2013) and Cordeiro (2014) investigated the effect of various water management practices on crop yield, nutrient loss and water use efficiency in agricultural fields in Winkler, Manitoba. However, studies on the relation between field trafficability and soil water content in this region are not known. This study focuses on the use of hydrologic modelling to investigate the soil water dynamics in the soil profile to predict field trafficability for the Winkler site. Use of computer models to simulate field observed hydrological processes under Canadian Prairie weather conditions are few and limited to water management practices. Thirty years of historical precipitation data between years 1986 and 2015 was obtained from nearby weather stations to be used in this research. The HYDRUS (2D/3D), a two- and three- dimensional hydrologic model, was used to simulate water flow using data collected from the field site. The validated HYDRUS (2D/3D) model was used to simulate various modelling scenarios representing different rainfall patterns, drainage design parameters, and soil physical properties to predict the number of trafficable days.

1.3 Objectives

The main objective of this research was to use HYDRUS (2D/3D) to investigate the parameters most favourable for increasing the number of trafficable days at the study site. The specific objectives were to:

1. Create and validate a HYDRUS – 2D model to simulate soil water dynamics at the field site under controlled drainage;
2. Use the validated models to determine the impact of drainage design and soil bulk density on Field trafficability.

1.4 Outline of thesis

This thesis consists of six chapters which include two manuscript-styled chapters covering the two objectives above. Chapter 1 is the introduction of this thesis. Chapter 2 consists of a literature review on Assessing Field trafficability by modelling soil physical properties and soil water status. Chapter 3 and 4 cover the two objectives, written in the format acceptable for submission to a scientific journal. Chapter 3 gives the details of the field data, model parameters, model simulation and model evaluation. Chapter 4 presents the use of modelling scenarios to predict the trafficability of the study site under different rainfall patterns, soil physical and drain design parameters. Chapter 5 summarises and concludes the research outcomes. Chapter 6 presents recommendations for future research.

2 Literature Review - Assessing field trafficability by modelling soil moisture dynamics under different drain design, soil, and weather conditions

2.1 Introduction

The increasing size of farms has necessitated the use of agricultural machinery to complete field operations on time. During farm operations, soil compaction could occur when the machinery load on a unit area of soil exceeds the bearing capacity of the soil (Laura and Paavo 1994). Soil compaction limits infiltration, soil air and root growth during germination. So, it is important to check the ability of the soil to support the vehicular movement, which is known as field trafficability. Field trafficability is determined by the strength of the soil to resist the failure of soil structure due to induced load (Müller et al. 1997). Soil strength varies with soil type, which causes the change of soil behaviour under various soil water contents and bulk densities (Raghavan et al. 1977).

2.2 Soil properties

Soil texture is the qualitative property of the soil based on the fraction of sand, silt and clay. Soil texture affects the behaviour of soil in many ways such as structural strength (Jones et al. 2003), soil – water interactions (National Resources Conservation Service 2016) and plasticity of the soil. The soil texture can be determined using the USDA-NRCS soil textural triangle (Moroizumi and Horino 2004) with known fractions of sand, silt and clay.

2.2.1 Soil – Water Interactions

When soil texture is identical, soil – water interaction depends on the porosity of the soil which further depends on soil bulk density (Archer and Smith 1972). Soil water present in the vadose zone is in the form of gravitational water, capillary water and hygroscopic water depending on the pressure needed to remove water from the soil (Aubertin et al. 2003). Gravitational water is the free moving water that infiltrates towards the groundwater table under gravity. Soil micropores hold the capillary water against gravity, a portion of which is available to plants for its needs. Water attached to the soil by a thin film due to adhesive forces is known as hygroscopic water. Residual water content, field capacity and saturated water content are the terminologies, which explain the extent of soil water storage. Field capacity is the capacity of a unit volume of soil to hold water in its pores, which cannot be drained by gravity. The state of soil pores entirely filled with water is known as saturated water content.

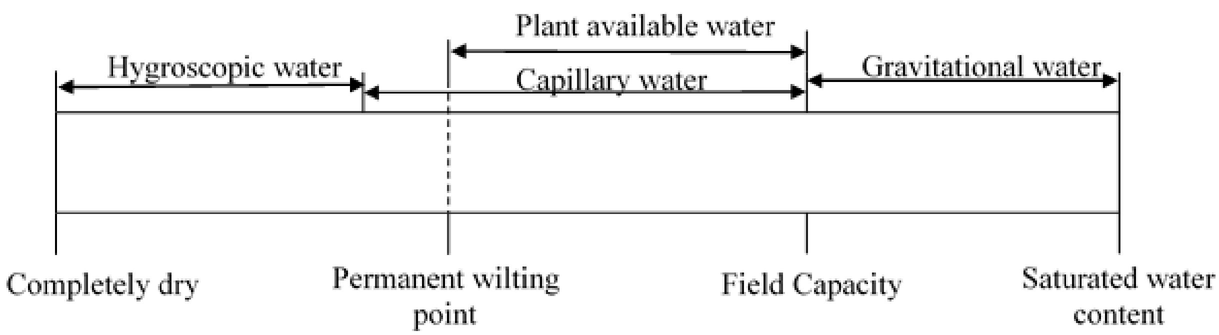

Figure 2.1 Terminology related to the soil water in the vadose zone

A soil water retention curve details the amount of water held by the soil at a given soil water potential. Soil water retention curves contain information on soil type classification, soil porosity, the relation between soil physical characteristics and soil water tension, soil structure (Too et al. 2014). Soil water retention curves can be illustrated using several models such as the Gardner model, Kosugi model, Campbell model, van Genuchten model, Brooks-Corey model, and Ruso model. Too et al. (2014) investigated the performance of ten different soil water retention models including the ones mentioned above over a range of water contents between saturation and oven drying; they concluded that five – parameter models performed well compared to four - and three - parameter models. Among the five- parameter models, the Biexponential model (Omuto 2009) performed well followed by the van Genuchten model (van Genuchten 1980). Four- parameter models such as Brooks- Corey model and Kosugi model were among the others tested by Too et al. (2014).

The behaviour of soil changes with soil water content and the change differs for each soil type depending on the proportions of soil components such as sand, silt, and clay. The presence of organic content improves the water retaining capacity. Fredlund (2002) explored the relationship of soil water retention curve, with unsaturated soil properties such as effective angle of internal friction, the coefficient of permeability, shear strength.

2.2.2 Soil strength and plasticity

Soil strength is the capacity of the soil to resist force to limit its deformation under a load. The strength of a soil type depends on the proportion of soil components (Sand-Silt –Clay) and soil water content. When the load induced on soil surpasses the bearing capacity of the soil, it starts to compact, increasing the bulk density. The degree of compaction differs and depends on the same factors i.e. soil properties and water content. Soil compaction is one of the major factors, which affects the yield of crops by limiting soil air, resistance to infiltration and root growth during germination. It is always important to avoid soil compaction for sustainable agriculture.

Soil plasticity is the ability of soil to return to its original state without cracking even after deformation. In general, plasticity index of soil is defined as the difference between the liquid limit and the lower plastic limit of soil. The lower plastic limit is defined as the water content below which the deformed soil cannot revert to its original state. The liquid limit is defined as the soil water content above which the soil begins to flow like a liquid.

Many researchers showed the effect of soil water content on soil properties such as soil strength (Arvidsson et al. 2001) and plasticity (Mueller et al. 2003). This relation between soil water content and soil physical properties can be used to quantify field trafficability.

2.3 Trafficability

Trafficability is the phenomenon, which explains the capacity of the soil to support vehicular passage without significantly deteriorating the soil structure due to compaction. In other words, it depends on the plastic nature of soil at various soil water contents. In agricultural fields, operating machinery on non-trafficable soils causes compaction, which is a major hindrance to infiltration, particularly in Canadian Prairie weather conditions can include extreme rainfall events during crop growing season. Field trafficability depends on the soil strength, which is a function of soil water content (Muller et al. 2011; Earl 1996). In early cropping season, the presence of excess soil water content in Manitoban agricultural field limits the field work days. It is important to confirm the fitness of soil profile to resist compaction and be trafficable for farm vehicles.

Removing excess water from the soil profile improves the condition of soil for vehicular movement. Subsurface drainage is commonly used in North America to drain water from the top layers of soil near the root zone. However, drainage outflow from the fields depends primarily on soil water content, drainage design parameters and rainfall events. Soil water dynamics in the soil profile affected by the physical properties of soil including soil bulk density, porosity and in addition to the presence of organic matter and heterogeneity of soil itself, which makes it difficult to predict the soil water content over the whole soil profile. Monitoring soil water content is important to avoid over draining of the soil leading to crop water stress.

2.4 Modelling soil water dynamics

2.4.1 Hydrologic modelling

Hydrologic modelling is the process of defining the naturally occurring hydrologic process in a mathematical form. The advancement of hydrologic models introduced several systems such as unit hydrograph, conceptual models, rainfall-runoff model, time series stochastic models, physically based models, and macro-scale models. In recent decades, researchers developed hydrologic models capable of simulating the solute transport and heat flow, simultaneously. Presently, one-, two-, and three-dimensional hydrologic models are highly efficient in simulating results with a resolution finer than 50 mm.

Numerical models are the base of the present-day hydrologic models. Much research into hydrologic processes helped develop numerical models incorporating equations such as Richard's equation, van Genuchten-Maulem water retention model, Per Moldrup's tortuosity model, evaporation models, adsorption models, parameter optimisation, Fickian- based convection-dispersion model.

2.4.2 Evapotranspiration

Evapotranspiration (ET) is the depth of water lost from plants or the surrounding soil surface during a given period. From the definition, evapotranspiration is a combination of both evaporation and transpiration (Allen et al. 1998). The ET is the aggregate of evaporation from the top layer of soil and transpiration through the canopy via roots.

The loss of water from a reference surface with ample amount of water supply is known as reference evapotranspiration. Reference evapotranspiration can also be defined as the evaporative power of the atmosphere (Allen et al. 1998). Reference evapotranspiration can be calculated with the Penman-Monteith equation using meteorological data such as solar radiation, the speed of the wind, air temperature and humidity (Allen et al. 1998). Actual evapotranspiration is the loss of water from the soil and/or canopy and can be limited by the amount of water in the soil (Karlsson and Pomade 2014).

2.4.4 ET Partitioning

Evapotranspiration in a barren field is mostly evaporation from the soil, whereas in a study site with vegetation, crop transpiration in addition to evaporation should be considered (Allen et al. 1998). Partitioning of ET is useful as proportions of evaporation and transpiration in ET changes with crop growth, vegetative cover and weather (Agam et al. 2012). So, partitioning of evaporation and transpiration is considered essential for water management practices (Kool et al. 2014) and also for developing water flow models (Evett and Tolk 2009).

2.4.5 Effective precipitation

During the crop-growing season, the canopy intercepts precipitation reaching the soil surface. Rainfall reaching the soil surface is the effective precipitation, which infiltrates into the soil profile. It is important to consider the rainfall intercepted by a canopy as it varies with the growth stage of the crop (Kozak et al. 2007).

Leaf Area Index is the ratio between one-sided leaf area and the projected ground area (Chen and Black 1992). Leaf area index is critical (Chen et al. 2014) non-dimensional parameter which affects numerical modelling in different ways such as rainfall interception, transpiration and evaporation from leaves, decrease in evaporation from soil surface due to the shade of the crop canopy (Bréda 2003). Therefore the LAI was used by many researchers (van Genuchten et al. 2014; Šraj et al. 2008; Teruel et al. 1997; Kustas et al. 1996) in the past for computer modelling. There are different ways to determine leaf area index; one is by direct measurement which is a destructive process or by indirect methods using Gap fraction analysis (Wilhelm et al. 2000). The

LAI should be adjusted by taking crop phenological activities into account for (Teruel et al. 1997) better computer modelling. King and Stark (1997) presented LAI of potato for the crop-growing season, which was used in this research.

2.4.6 Model Evaluation

In the model evaluation stage, the simulated output is compared with the measured data from the field or the laboratory experiment to assess the performance of the model to simulate the variations found in the observed data. Once the model is calibrated to simulate field observed data, the calibrated model is used to simulate a different data set to validate the model. Several researchers (Saraswat et al. 2015; Harmel et al. 2014; Bennett et al. 2013) asserted the need for defining model evaluation criteria before validating a hydrologic model. They also proposed an evaluation method visual and statistical analysis to assess the model efficiency. Visual evaluation with time series graphs plotted with simulated and observed data is a primary test, to check trends of simulated and observed values. However, observing a similar trend is not enough to validate the efficiency of model performance. The evaluation criteria should include commonly accepted parameters to assess the model performance, such as statistical analysis comparing observed and simulated data (ASCE 1993). Moriasi et al. (2012) stated the different statistical parameters available for evaluation of hydrologic models. Those model evaluation parameters included the coefficient of determination (R^2), Nash-Sutcliff efficiency, Pearson’s correlation coefficient, PBIAS and Root mean square error (RMSE), explained in detail in Chapter 3.2.6.

2.5 HYDRUS – 2D/3D

The HYDRUS (2D/3D) is a Windows-based two- and three- dimensional hydrologic model to simulate water flow, solute transport and heat flow in variably saturated porous media. It uses the Finite Element (FE) method to solve Richard's equation for water flow simulations numerically. Domain geometry is discretized using FE-mesh by altering mesh element size. The FE-mesh stretching option in HYDRUS (2D/3D) helps to model soil profile heterogeneity. Initial and boundary conditions are provided to the model using domain geometry. Initial conditions such as soil water content or pressure head have an impact on the model run. The type of boundary conditions to be used depends on the model objectives and selection of the model representing the study area in addition to the available data for input. Atmospheric boundary condition represents atmospheric fluxes such as infiltration, evaporation. Seepage face boundary condition for drains and other boundary conditions include free drainage, deep drainage, constant water content, variable head, variable flux, constant flux, no flux. Soil hydraulic properties are the basic input for any model which defines the soil water dynamics in both saturated and unsaturated zones of the model domain. The ROSETTA Lite v. 1.1 is a neural network prediction program integrated into HYDRUS (2D/3D), that can be used to predict initial soil hydraulic properties. Researchers used HYDRUS (2D/3D) to successfully simulate water flow in the subsurface (Mguidiche et al. 2015; El-Nesr et al. 2014), under tile drainage conditions (Filipović et al. 2014; Carlier et al. 2007). Table 2.1 shows the summary of selected research studies on hydrologic modelling using the HYDRUS (2D/3D).

Figure 2.2 shows the methodology followed to generate a HYDRUS model and validate it with the field observed soil water content data. Figure 2.3 presents the flowchart representing the procedure used in this research to simulate the possible number of trafficable days for different modelling scenarios consisting of drainage design parameters, soil physical properties, and 30-year rainfall patterns.

Table 2.1 Summary of previous research studies on hydrologic modelling using HYDRUS (2D/3D) and their findings

Author and Year	Study area	Objectives	Model parameters	Results
Antonov et al. (2013)	Nuclear power plant, Kozloduy, Bulgaria	• To investigate the performance of inverse modelling of HYDRUS (2D/3D) to predict soil hydraulic properties of 4 different heterogeneous soil profile to a depth of 3.5 m below the soil surface.	• Water flow • Inverse Solution	Good performances in all layers of soil with values 0f R^2 above 0.99
El-Nesr et al. (2014)		• To understand water content distribution and solute distribution from a subsurface drip irrigation under various modelling scenarios using HYDRUS (2D/3D)	• Water flow • Root water uptake • Solute transport	Study helped the team to evaluate the impact of dual drip system and physical barrier on water and solute distribution in root zone
Deb et al. (2016)	PRSC – New Mexico State University	• To simulate the spatial and temporal distribution of water contents and NO_3-N concentration using field data.	• Water flow • Root water uptake • Solute transport	Water flow: At 20 cm depth, RMSE is 0.022 cm^3cm^{-3} At 50 cm depth, index of agreement is 0.96
Filipović et al. (2014)	Eastern Croatia (45°09' N, 18°42' E).	• Using HYDRUS (2D/3D) to simulate scenarios for comparing the impact of tile drainage, tile drainage with gravel trenches and mole drainage on drainage rate before field trials	• Water flow • Drainage boundary condition	Team found the efficiency of mole drain to drain water faster than tile drain with or without gravel trenches
Ghazouani et al. (2015)	Sousse, Tunisia	• To use HYDRUS (2D/3D) for simulating water content distribution of soil profile equipped with surface and subsurface drip line. • Using validated model to assess optimal dripline depth for improved water use efficiency	• Water flow • Root water uptake	RMSE values 0.037% and 0.038% comparing measured and simulated soil water contents at 0 and 0.2 m depths suggests the ability of HYDRUS (2D/3D) to simulate the field observed situations

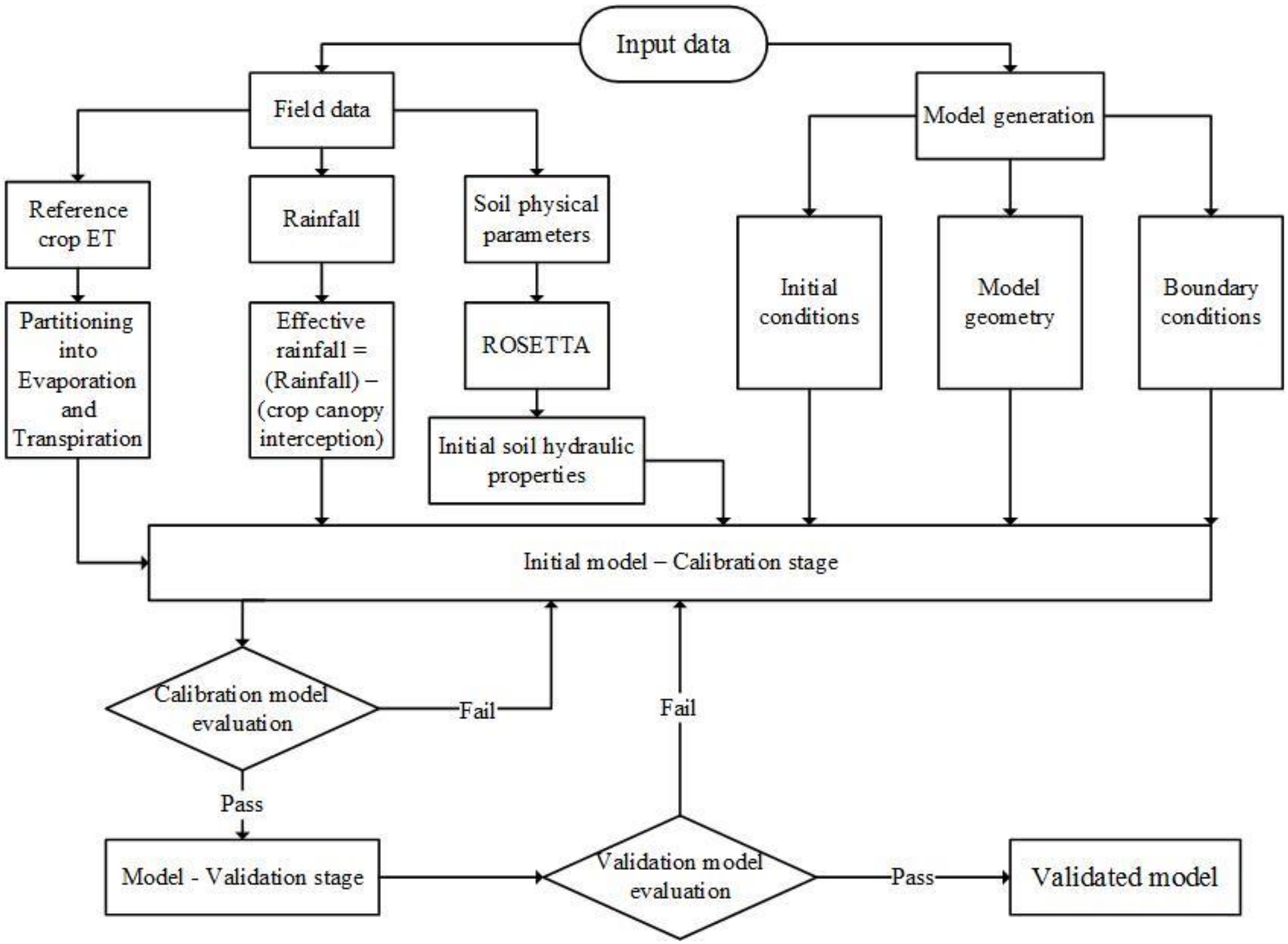

Figure 2.2 Flow chart showing the methodology used for generating a Validated HYDRUS (2D/3D) model

(See Chapter 3 for detailed explanation.)

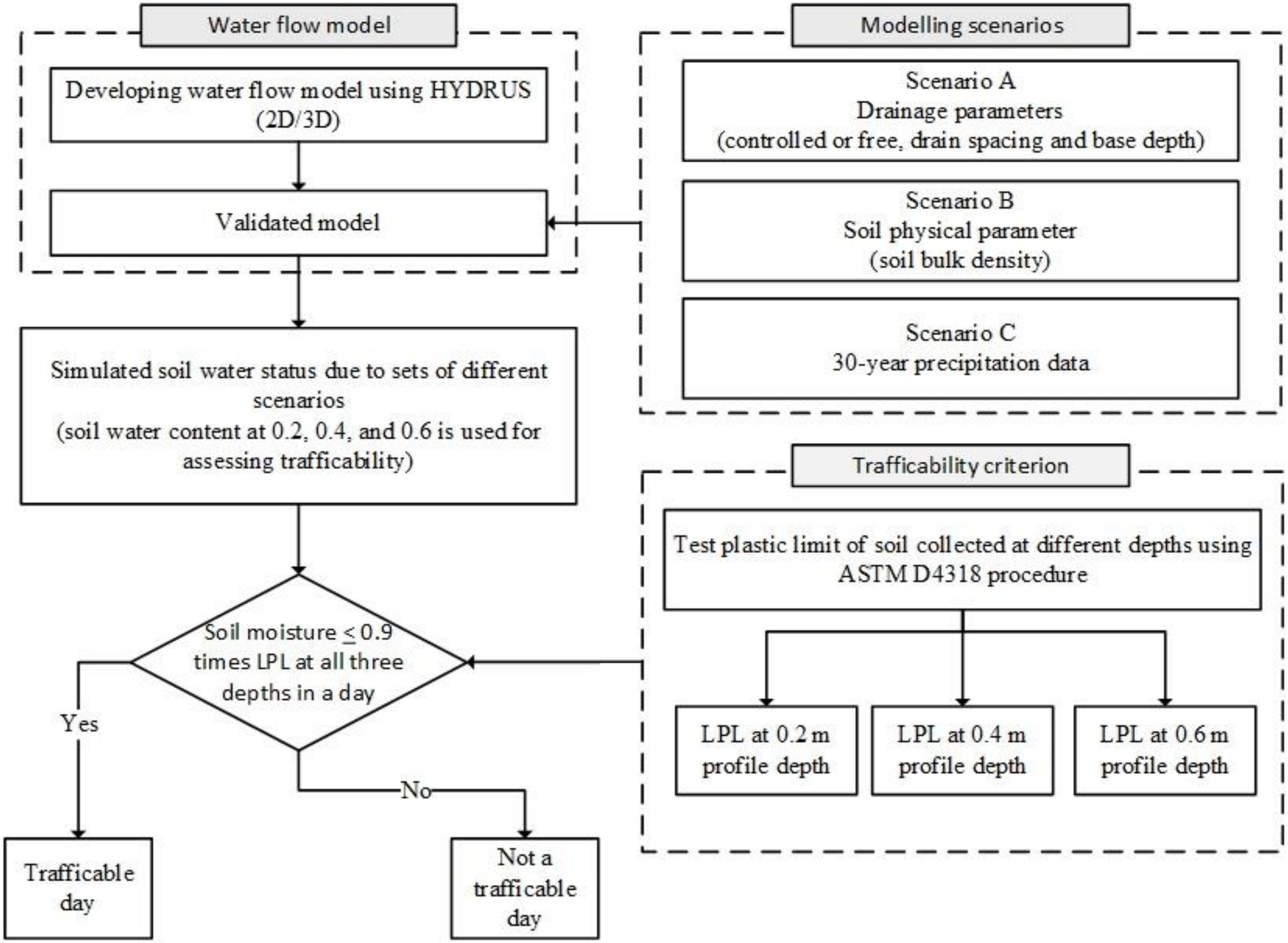

Figure 2.3 Flow chart showing the methodology used to simulate different scenarios and interpret the results (See Chapter 4 for detailed explanation.)

Chapter 3

Simulation of soil water content with HYDRUS (2D/3D) in fields under controlled drainage in Southern Manitoba

3 Simulation of soil water content with HYDRUS (2D/3D) in fields under controlled drainage in Southern Manitoba

Abstract

To conserve and manage water effectively, in recent decades farmers around the world are adopting water management practices. Manitoba, a province located in the eastern part of the Canadian Prairies, receives snowfall in the winter and heavy rainfall during the summer leaving the upper layers of the soil with excess soil water content. The main obstacle faced by farmers is to retain desired soil water content in the soil profile conducive for crop growth during the season. However, measuring the soil water content is costly and has its limitations. Numerical modelling is used as a tool to understand soil moisture dynamics at the study site located at the Hespler Farms in Winkler, Manitoba. The HYDRUS (2D/3D) was used to simulate soil water content using soil physical properties and meteorological data in a field under controlled drainage. The field data was collected during the 2011-cropping season. The model run period was divided into calibration and validation stages to model the field conditions for a better simulation. Model evaluation was used to assess the performance of the HYDRUS (2D/3D) model. Pearson correlation coefficients, 0.81 for calibration and 0.80 for validation, show the predictive power of HYDRUS (2D/3D). Visual comparison of simulated and observed data trend and statistical analysis suggests that HYDRUS (2D/3D) was able to simulate soil water content under weather conditions of Southern Manitoba.

Keywords: Soil water content, Hydrological modelling, HYDRUS (2D/3D), Model evaluation

3.1 Introduction

Soil water content plays a key role in crop production. For instance, scarcity or excess soil water content will lead to crop water stress, which affects crop growth and performance; and also delays farm operations, which in turn result in yield and financial losses (Manitoba Water Commission 1977). Soil water content can be measured using direct or indirect methods. The gravimetric method is the direct way of measuring soil water content. Acquiring moisture data on a temporal and spatial scale with this approach is time-consuming. It also compromises the structure of soil, as the sample has to be physically removed from the field. Indirect methods use properties of the soil to measure soil water content. Time domain reflectometry, neutron moisture meter, electric resistance blocks, tensiometers, and remote sensing are common types of indirect methods of measuring soil water content. These methods are limited to spatial dimensions depending on their radii of influence. Physical soil water content measurements give the past soil water status only. Therefore, predictive methods are needed to manage field operations.

Hydrologic models can be used as a predictive method to forecast soil moisture dynamics under different plant growth stage, soil, and weather conditions. A hydrologic model is a mathematical representation which models the complex relationships between the water source, sink, storage, and flow within a specified boundary (Alley et al. 1999). In recent years, water flow and solute transport numerical models played a major role in creating best water management practices in the field (Mays 2012). Modelling is cost-effective, time-saving and provides a logical explanation of factors (Qiao 2014). Hence, complimenting field studies with modelling provides a better platform in explaining hydrologic processes.

The HYDRUS (2D/3D) is a two- and three- dimensional modelling tool for variably saturated porous media used to simulate water, thermal, and solute transport. Recently, a lot of research has been done using HYDRUS (2D/3D) to simulate water flow. Most of these studies were focused on simulating soil water content in fields under conventional drainage (Filipović et al. 2014; Boivin et al. 2006) and drip irrigation (Mguidiche et al. 2015; Wang et al. 2013). However, the call for sustainable crop production requires control of drainage outflow to maintain desirable soil water content and nutrient retention in the soil profile.

Consequently, this study focuses on simulating soil water content in a field under controlled drainage located in Southern Manitoba. In Southern Manitoba, drainage outflow is normally at a maximum in the early growing season due to snowmelt infiltration and high rainfall. Over the past decade, controlled drainage has been employed to regulate drainage outflow to minimise loss of nutrient-rich soil water to the environment (Satchithanantham et al. 2012; Cordeiro and Sri Ranjan 2015). Simulating soil water content under controlled drainage will help better understand the dynamics of water flow through the soil profile for better design and performance of controlled drainage systems for crop production.

3.2 Materials and Methods

3.2.1 Study site

A study site in southern Manitoba was chosen, and field experiments were carried out for the cropping season in 2011. Detailed information on field layout, data collection, drain specifications was published earlier (Satchithanantham et al. 2014), only brief details of the experimental design will be discussed in this paper. The field study was done at Hespler Farms in Winkler, Manitoba. The climate of the study area is humid continental; with dry during both cold winters and hot summers. The average summer temperature typically ranges between 12 and 22 °C, while mean temperature range for winter is -15 to -25 °C. The average yearly precipitation at the study site is 533 mm. The soil in the field was sandy loam (Satchithanantham et al. 2014) with sand, silt and clay fractions of 67.7%, 20.8% and 11.5%, respectively, and belongs to the Reinland Series, which is classified as imperfectly drained soil. The average field capacity (FC) and permanent wilting point (PWP) of this soil are 32% and 11.6%, respectively on a volumetric basis (Cordeiro 2014). The study site was divided into two sections as shown in Figure 3.1 with dimensions, 300m in length and 84m in width. There were four water management treatments with three replicates on each section laid out as part of another larger study. The treatments were 1) no drainage with no irrigation (NDNI), 2) no drainage with irrigation (NDIR), 3) controlled drainage with sub irrigation (CDSI) and 4) free drainage with irrigation (FDIR). Potato-Corn crop rotation was done in the field. In 2011, Potato (Solanum tuberosum L.) was grown in the eastern section.

This study is focussed only on plots installed with controlled drainage with subirrigation (CDSI plots). Dimensions of plots equipped with controlled drainage were 50m length × 40m width. Each CDSI plot has four drains installed at a spacing of 8 m at a depth of 0.9m and 0.05% grade. The design drainage coefficient of the drains was 6 mm d^{-1}. A field experiment was designed to collect soil water content and piezometer data near one drain in each plot. Drainage control structures were used to maintain the water table and/or provide subirrigation, when necessary. Sub-irrigated plots were hydrologically isolated from three adjacent plots with the help of interceptor drains to arrest lateral flow from the plots.

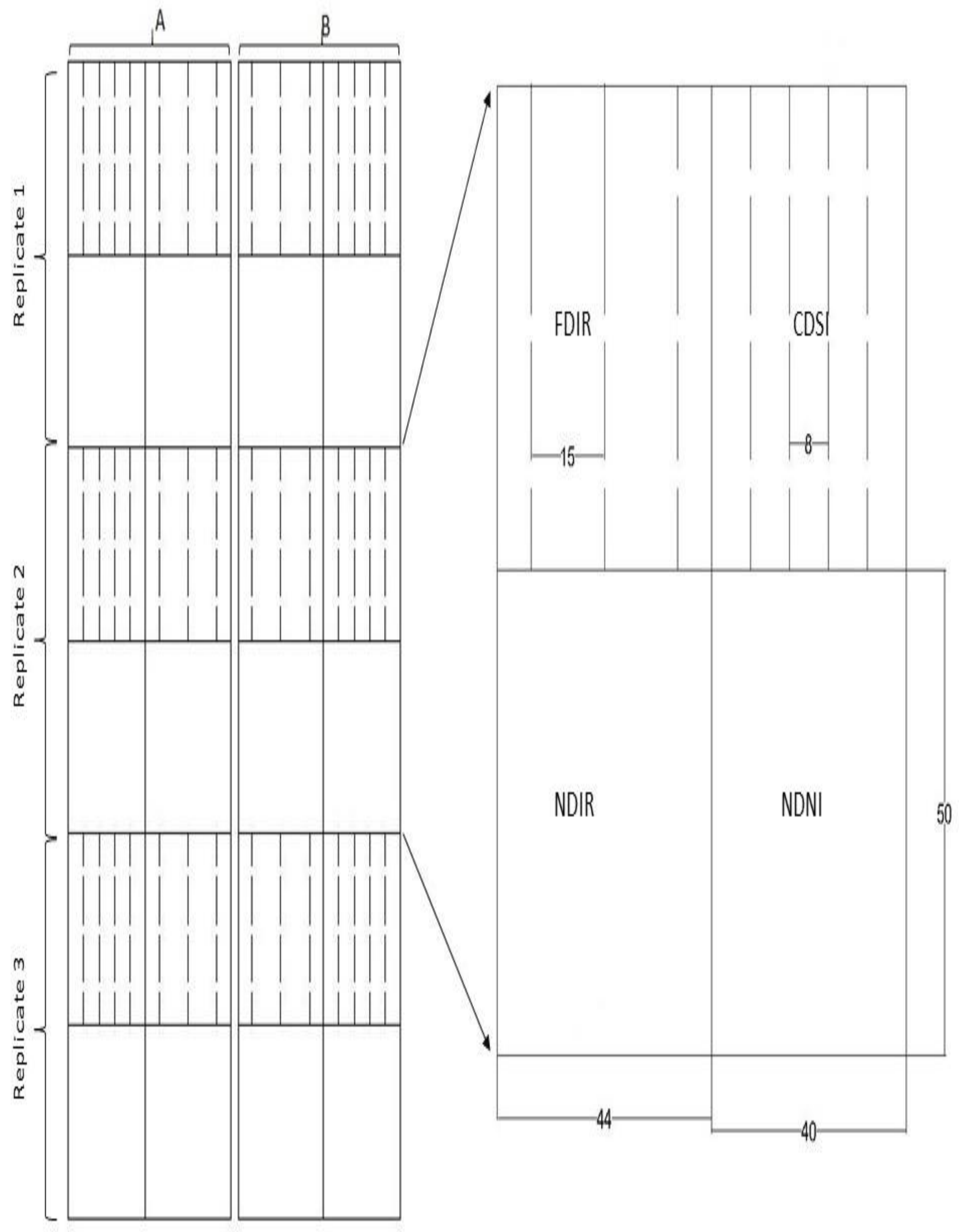

Figure 3.1 Diagram representing the design of experimental plots with three replicates of four water management practices on each section A and B with an alleyway in between. Dashed lines in FDIR plot and CDSI plot represent the position of lateral drains. NDIR – No Drainage with Irrigation, NDNI – No Drainage No Irrigation, FDIR – Free Drainage with Irrigation, and CDSI – Controlled Drainage with Sub-irrigation

3.2.2 Data monitoring and collection

An onsite weather station was used to collect precipitation, temperature, wind speed, relative humidity, and solar radiation data during the study period. Water level sensors (Solinst Levelogger Junior 3001, Solinst Canada Ltd.) hung inside piezometers were programmed to monitor groundwater levels at 3-hour intervals. Time Domain Reflectometry (TDR) mini probes were used to measure the soil water content at 0.2, 0.4, 0.6, 0.8, and 1.0 m depths below the soil surface in each plot.

The precipitation reaching the soil surface is intercepted by the crop canopy, which decreases the amount of rainfall reaching the soil. The intercepted rainfall and actual rainfall reaching soil surface are calculated by equations 3.1 and 3.2 (Qiao, 2014)

$$\text{Actual Interception} = \text{Maximum interception} \times \left(\frac{\text{LAI}}{\text{Max LAI}}\right) \qquad (3.1)$$

$$\text{PRSS} = \text{Measured rainfall} \times [1 - \text{Actual interception}] \qquad (3.2)$$

where the maximum interception is the maximum amount a crop canopy can intercept in its crop life, PRSS is the precipitation reaching soil surface; LAI is the leaf area index. In this study, the maximum interception was assumed to be 20% for the purpose of quantifying potato (Russet Burbank variety) crop canopy interception of irrigation and rainfall (Saffigna et al. 1976). Leaf area index is the ratio of the one-sided area of the leaves to the ground area (Bréda 2003). It is a critical non-dimensional parameter (Chen et al. 2014) which affects hydrologic modelling processes mainly in subsurface hydrology (van Genuchten et al. 2014). Leaf area index of potato in a cropping season based on the phenological stages used in HYDRUS (2D/3D) modelling exercise was adapted from a graph developed by King and Stark (1997). Leaf area index values changed with crop growth stage, with initial values remaining zero until 30 days after planting, after which LAI values increased until the bulking period, and decreased afterwards.

Reference evapotranspiration (ET) was estimated using the Penman–Monteith equation. HYDRUS (2D/3D) requires potential evaporation and potential transpiration data to estimate actual evaporation and actual transpiration depending on soil water status. Beer's law was used to partition potential evapotranspiration to potential evaporation and reference transpiration as shown in equations 3.3 and 3.4

$$Potential\ transpiration\ = Evapotranspiration\ (1 - \exp(-k\ .\ LAI)) \tag{3.3}$$

$$Potential\ evaporation\ = Evapotrasnpiration\ (\exp(-k\ .\ LAI)) \tag{3.4}$$

Where k is the radiation extinction coefficient. In the modelling exercise, the k was set to 0.5 with the assumption that around half of radiation is scattered or absorbed by reference crop (Haverkort et al. 1991; Simunek et al. 2009).

3.2.3 Soil moisture simulation

Water flow in potato fields equipped with controlled drainage was simulated with HYDRUS-(2D/3D) version 2.04.0580. HYDRUS (2D/3D) simulates water flow in variably saturated porous media by solving Richard's equation (3.5) as shown,

$$\frac{\partial \mathrm{\theta}}{\partial \mathrm{t}} = \frac{\partial}{\partial \mathrm{x}}\left(\mathrm{K}\frac{\partial \mathrm{h}}{\partial \mathrm{x}}\right) + \frac{\partial}{\partial \mathrm{z}}\left(\mathrm{K}\frac{\partial \mathrm{h}}{\partial \mathrm{z}}\right) - \frac{\partial \mathrm{k}}{\partial \mathrm{z}} - \mathrm{WU}\ (\mathrm{h}, \mathrm{x}, \mathrm{z}) \tag{3.5}$$

where θ is the volumetric soil water content ($L^3\ L^{-3}$), K is the unsaturated hydraulic conductivity (LT^{-1}), h is the capillary pressure head (L), x is the horizontal coordinate, z is the vertical coordinate (negative upward), t represents time (T), and WU (h, x, z) is a sink term, root water uptake (T^{-1}) in the present scenario. Both K and WU are functions of θ and/or h (Min et al.

2013). The x and z terms can be used to represent the anisotropy of soil to simulate water flow. A detailed description of the HYDRUS model is available in Sejna et al. (2014) and Šimůnek et al. (2011). The model run period was chosen by analysing the availability of all required data for model simulation. The HYDRUS program provides an option to select from four different soil hydraulic models, namely, van Genuchten-Mualem model, Modified van Genuchten model, Brooks-Corey model and Kosugi (log-normal) model. Modified van Genuchten model uses more number of parameters to proper representation of hydraulic properties near saturation, which is not of particular importance to this study. Also, optimizing more number of parameters during model calibration stage is time-consuming. As mentioned in Chapter 2.2.1, van Genuchten model performed better than Brook's-Corey and Kosugi water retention models. The van Genuchten–Mualem single porosity model in HYDRUS (2D/3D) was used to mimic soil hydraulic parameters on the domain to simulate water flow. The Feddes' model (Feddes et al. 1978) was used to represent the root water uptake parameters, which compensates overestimation of potential root water uptake to estimate actual root water uptake if any (Šimůnek et al. 2011). HYDRUS also provides a database of critical pressure head values for various crops as suggested by Wesseling et al. (1991)

3.2.4 Model domain

A model domain closely matching the field conditions was defined using a depth of 2.5 m and a width of 8 m to denote a field soil profile as shown in Figure 3.2. The Finite Element (FE) mesh was generated using MeshGen 2D. The size of the finite elements was adjusted to 5 cm discretization, and FE mesh stretching was adjusted manually for each layer during calibration stage for a better model run. Drain in the domain was represented using an opening in the FE mesh at a depth of 0.9 m as observed in the study site. The domain was divided into four layers.

Five observation nodes were placed on the domain to mimic the location of the TDR mini probes in the study site (i.e. 0.2, 0.4, 0.6, 0.8 and 1 m below the soil surface).

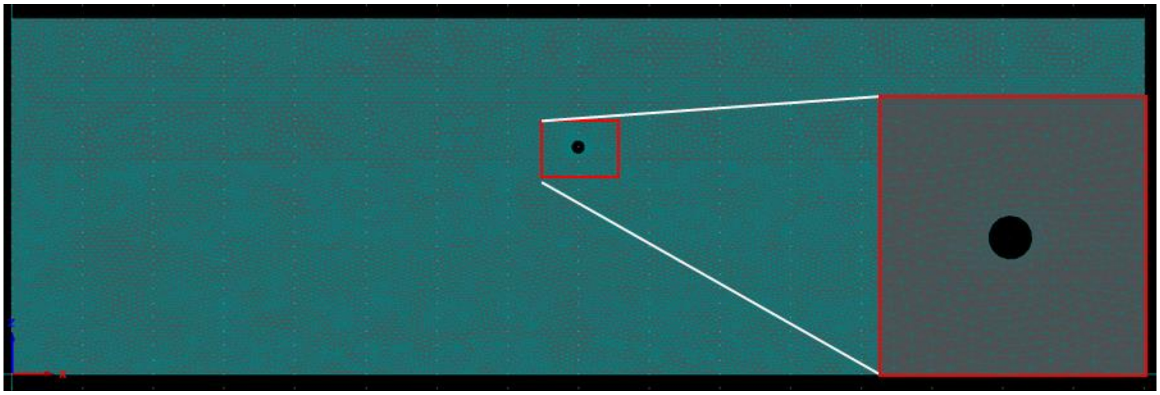

Figure 3.2. Two-dimensional model domain of HYDRUS (2D/3D) of 2.5 m depth and 8 m width with FE-mesh representing a portion of CDSI plot. The drain was represented using an opening in FE-mesh (shown in red outlined inset box) and observation nodes are the red coloured points at the top -left of the domain

The initial condition in the model domain was set using observed water content data obtained at the beginning of the experimental period in the field. The upper boundary condition was set to the atmospheric boundary to allow atmospheric fluxes. Domain sides were located at a midway distance between two drains, and the domain bottom was always below the water table during the simulation run. So, no-flux boundary condition was set on both sides of the domain as per dynamics of water flow towards the drain tiles. The domain bottom was also assigned a no-flux boundary condition as the water table is always inside the domain and also due to the non-existence of regional flow (Rutulis 1982) at the study site. As HYDRUS-2D/3D cannot simulate both controlled drainage and sub-irrigation from the same boundary in a single model run, a seepage face boundary condition was chosen to be used to represent controlled drainage because subirrigation was reported in a previous study (Satchithanantham et al. 2012) as ineffective to provide water flux to the region of interest in this study.

3.2.5 Model calibration and validation

In practice, there might be some discrepancies in hydrologic models due to the relationship between different input parameters which sometimes cannot be measured (Gupta et al. 2008) or directly modelled due to the complexity of data (Stadnyk et al. 2013). Model calibration is a process of estimating best fit input parameters for the hydrologic model used to simulate values, which are in good agreement with field observed values (Simunek et al. 2012). Estimated parameters must be in an acceptable range for that particular type of soil. Model validation is the use of calibrated parameters to run the model to check the performance of the model for its ability to accurately simulate the trend of the observed data (Moriasi et al. 2007). The calibration and validation periods are as shown in Table 3.1.

Table 3.1 Table showing model run time and actual dates of field observation for calibration and validation stages

Simulation	Period	Number of days
Calibration	22 June 2011 – 14 Sept’ 2011	85 Days
Validation	03 June 2011 – 21 June 2011	19 days

During the cropping season, the water table remained below the drains except during two periods during which the controlled drainage was operating due to high precipitation. Therefore, the cropping season was divided into the calibration and validation stages ensuring that the controlled drainage was included in each of the stages. The model calibration run was for 85 days, which had both wet and dry patterns including controlled drainage. This allowed the model to fit different hydrologic conditions during the cropping season. The Rosetta Lite v1.1 was used to obtain water flow parameters (i.e. soil hydraulic parameters) to test the initial model convergence (Sejna et al. 2014). Soil hydraulic parameters include residual soil water content

(θ_r), saturated soil water content (θ_s), saturated hydraulic conductivity (K_s) and empirical coefficients (α and n). Though the model run was successful without convergence errors, Van-Genuchten parameter obtained from Rosetta model had to be optimized to simulate field observed soil water contents. Soil hydraulic parameters were optimized manually for a few model runs. Consequently, the inverse solution module of HYDRUS 2D/3D was used to find out a better set of Van-Genuchten parameters for all the three layers in the model domain, which improved the simulation of field observed variations. The inverse solution in the HYDRUS (2D/3D) uses the Levenberg-Marquardt algorithm. During inverse solution, the saturated hydraulic conductivity of the study site observed in previous studies and soil water content data observed at different depths were used for better stability during the inverse run (Nakhaei and Šimůnek 2014).

3.2.6 Model Evaluation

Model evaluation was used to quantify the performance of the HYDRUS (2D/3D) model in predicting the trend and the variances of the observed field data. The evaluation was done using time series graphs of observed and simulated data for visual interpretation and statistical parameters. The statistical parameters used include Pearson correlation coefficient (r), regression parameter coefficient of determination (R^2), Nash-Sutcliff efficiency, PBIAS, and Root mean square error (RMSE). The regression parameter coefficient of determination (R^2), was used to find out the model efficiency to simulate variability found in field observed data. It ranges from 0 to 1, with 1 being a perfect model which can simulate all the variance same as the observed data. Pearson correlation coefficient (r) in Equation 3.6 explains the correlation between two variables, which ranges between -1 and 1, with values greater than 0.70 suggesting good hydrologic model efficiency.

$$r = \frac{\sum_{i=1}^{n}(x_i - x^{mean})(y_i - y^{mean})}{\sqrt{\sum_{i=1}^{n}(x_i - x^{mean})^2}\sqrt{\sum_{i=1}^{n}(y_i - y^{mean})^2}} \tag{3.6}$$

Nash-Sutcliff efficiency (Equation 3.7) is a dimensionless statistic which is used to determine goodness-of-fit for simulated and observed values. The NSE ranges from -∞ and 1, but the acceptable range of a model is from 0 to 1, with values ≥ 0.5 representing a satisfactory model and values 0.75 < NSE ≤ 1.0 representing a very good model.

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n}(x_i - y_i)^2}{\sum_{i=1}^{n}(x_i - x^{mean})^2}\right] \tag{3.7}$$

The PBIAS (Equation 3.8) and Root Mean Square Error (RMSE) are error indices, which give the error or deviation of simulated values from the observed values of interest. The PBIAS expresses data deviation in percentage, with 0 being the perfect model, whereas underestimation is represented by positive values and overestimation by negative values.

$$PBIAS = \frac{\sum_{i=1}^{n}(x_i - y_i) \times 100}{\sum_{i=1}^{n}(x_i)} \tag{3.8}$$

The RMSE (Equation 3.9) is a measure of deviation between simulated and observed values, which is sensitive to small variations and it is in the same units as the observed data. A perfect model has an RMSE value of 0 and any model with RMSE nearer to 0 is a good model. RMSE should be half or less than half of standard deviation for it to be considered a low enough value for a good model (Singh et al. 2008).

$$RMSE = \left[\sqrt{\frac{\sum_{i=1}^{n}(x_i - y_i)^2}{n}}\right] \tag{3.9}$$

The RSR (Equation 3.10) is the ratio between root mean square error and standard deviation. RSR value zero indicates the value of RMSE as zero, which represents the perfect model. Values of RSR between 0 and 0.6 represents that RMSE is low enough to interpret the model performance as good.

$$RSR = \frac{\sqrt{(\sum_{i=1}^{n}(x_i - y_i)^2)/n}}{\sqrt{(\sum_{i=1}^{n}(x_i - x^{mean})^2)/n}} \tag{3.10}$$

where x_i is the observed water content, x^{mean} is the mean of observed water content, y_i is the simulated water content, y^{mean} is the mean of observed water content, and n is the number of data points in a set (days in simulation).

3.3 Results and Discussion

The flow of water in the soil profile influences moisture dynamics within the soil profile (Kim and Mohanty 2015), and it depends on soil packing and properties of the underlying soil layer (Plant and Soil Sciences eLibrary 2015). Therefore, fine-tuning of soil properties in addition to other factors like FE mesh was done to find out soil properties, which could enhance the performance of the model during the calibration stage. The final hydraulic parameters of the soil used for the simulation and validation stages are presented in Table 3.2. The values θ_s of 0.4125 m^3/m^3, θ_r ranged from 0.04 to 0.05 m^3/m^3, Ks between 1.6232 m/day and 2.8268 m/day for different layers of the model domain. These values are in the range suggested by National Resources Conservation Service (2016) which represents the soil hydraulic parameters of sandy loam soil.

As mentioned earlier, the model performance was improved using the inverse solution module of the HYDRUS (2D/3D) model during the calibration stage. During the validation stage

Table 3.2 Final soil hydraulic parameters obtained from calibration stage

Soil layer (m)	θ_r (m^3/m^3)	θ_s (m^3/m^3)	K_s (m/day)
0 – 0.4	0.041	0.4125	2.83
0.4 – 1.0	0.043	0.4125	1.62
1.0 – 2.5	0.049	0.4125	2.12

relevant meteorological data was used to assess the accuracy of the HYDRUS (2D/3D) model to simulate the water content as observed in the study site with similar conditions. The visual representation of observed and simulated water content values at 0.2, 0.4, 0.6, 0.8 and 1.0 m depth from the soil surface is presented in Figure 3.3. As shown in Figure 3.3, the simulated values followed the trend of the observed field data. The correlation graphs for calibration and validation stage data are presented in Figure 3.4 for the whole model run. Correlation graphs were plotted between observed and simulated water contents for the whole domain, R^2 values and distribution of scattered points shows good agreement between simulated and observed water content.

This assessment indicated that HYDRUS 2D/3D was able to simulate most of the variances in the observed data during the calibration period. Statistical analysis of the simulated and observed water content for the calibration and validation stages are given in Table 3.3.

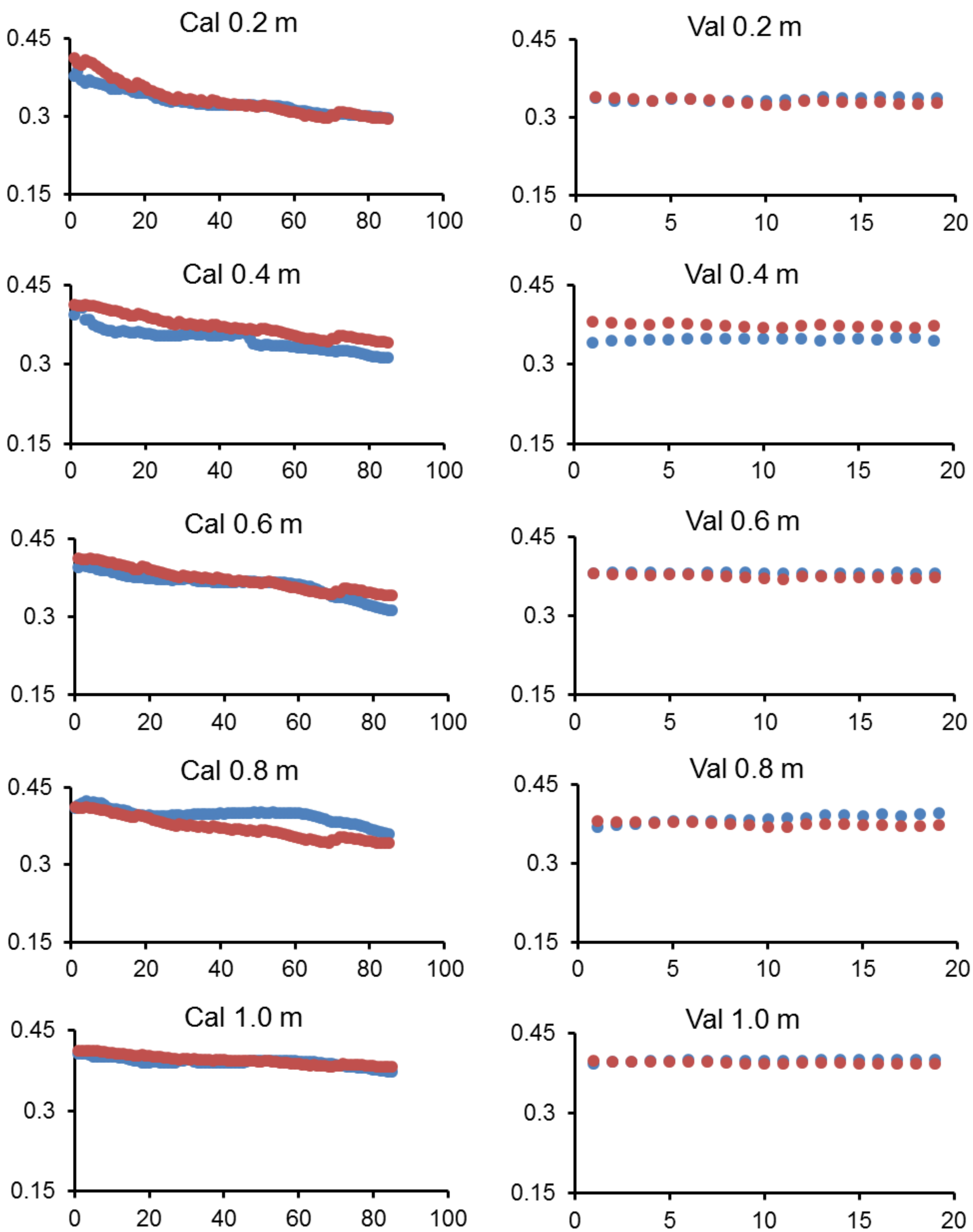

Figure 3.3 Time series graphs with volumetric water content (vertical axis) vs. Time in days (horizontal axis) representing observed (blue) and simulated (maroon) water contents at different depths during calibration (Cal) and validation (Val) stage

Table 3.3 Statistical parameters for model performance evaluation during calibration and validation stages of 2011 and 2012 model run periods

Statistical Parameters	Calibration	Validation	Values for Goodness-of-fit
R^2	0.66	0.64	0.5 - 1.0
NSE	0.63	0.64	0.5 - 1.0
r	0.81	0.80	0.5 - 1.0
PBIAS	-1.01 %	-0.14 %	±10 %
RMSE	0.019	0.015	Nearer to zero
RSR	0.6	0.6	0.5 – 0.6

Visual and statistical analysis of simulated water contents compared to the field observed water contents prove the efficiency of HYDRUS (2D/3D) to model the field soil profile under controlled drainage. This modelling procedure could be used to model the agricultural fields under Canadian Prairie climatic conditions using different rainfall patterns.

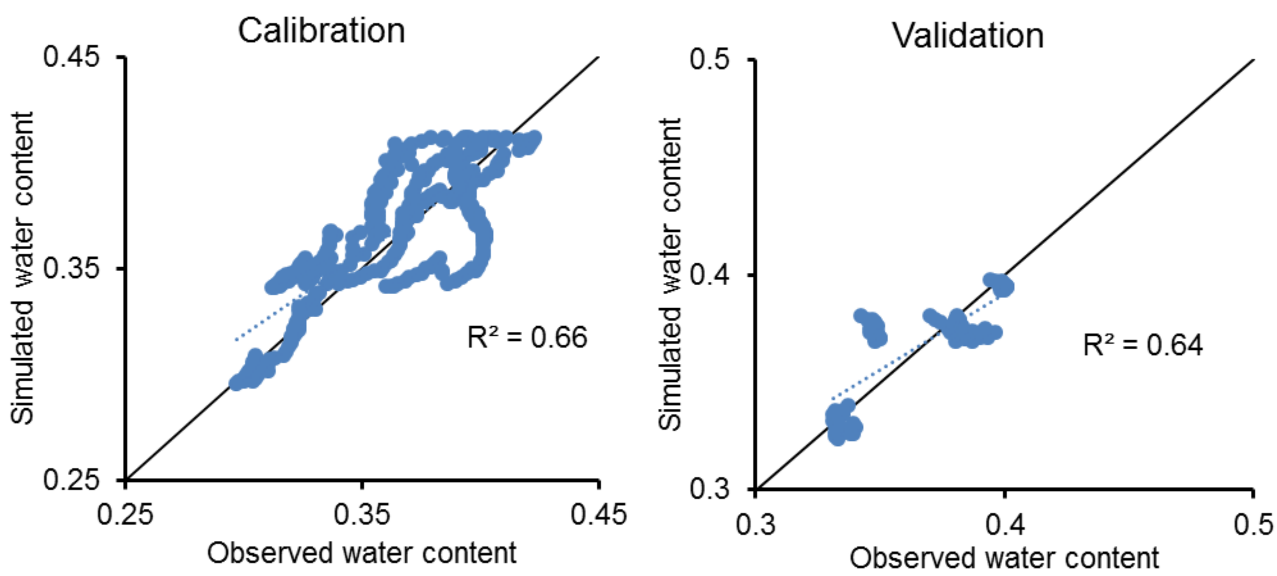

Figure 3.4 Correlation graphs between observed and simulated soil water content (m^3m^{-3}) for calibration and validation stages

3.4 Conclusion

The present study used HYDRUS (2D/3D) to simulate soil water content of a field under controlled drainage in the Canadian Prairies. In the year 2011, the calibration period was from June 22 to September 14, whereas the validation period was between June 03 and June 21. The performance of the model to simulate soil water content was evaluated using statistical analysis with Nash-Sutcliff efficiency (NSE), percent bias (PBIAS) and Root Mean Square Error (RMSE). In a visual comparison, simulated and observed soil water content followed the similar trend during most of the model run period. The strong positive Pearson correlation values of 0.81 and 0.80, regression coefficient (R^2) values 0.66 and 0.64, and NSE values 0.63 and 0.64 for calibration and validation respectively, show goodness-of-fit of simulated over observed soil water content. The PBIAS between -10 and 10 and RMSE values nearer to zero and less than half of standard deviation of observed soil water content values represent a low error index for the model simulation. From the graphical representation and the statistical analysis, it can be inferred that HYDRUS (2D/3D) model can be used to simulate soil water content of a field under controlled drainage under climatic conditions in the Canadian Prairies. This paper presented a method that can be used to simulate field conditions under different water management practices to predict their outcomes.

Chapter 4

Predicting trafficability under different drainage design and weather conditions using a validated HYDRUS (2D/3D) model

4 Predicting trafficability under different drainage design and weather conditions using a validated HYDRUS (2D/3D) model

Abstract

In the Canadian prairies, agricultural fields experience high soil water content, which limits field trafficability leading to a loss of field work days. Subsurface drains are installed to rapidly drain excess water from the fields causing a reduction in water content. Drain design parameters such as spacing and installation depth need to be tailored to the long-term weather conditions and soil properties of the agricultural fields under consideration. Different combinations of drain spacing and installation depths impact the drainage outflow differently. Field-scale testing of different conditions is expensive and time-consuming. Hydrologic modelling software (HYDRUS (2D/3D)) can be used to model agricultural fields under drainage and understand the subsurface soil water dynamics. In this research, field-validated HYDRUS (2D/3D) model runs were used to simulate soil water content and predict field trafficability under different scenarios consisting of a combination of 30-year rainfall data, two drain spacings (8 m, 15 m) and two drainage base depths (0.9 m and 1.1 m) and three soil bulk densities (1.3, 1.4, 1.53 Mg/m^3). Controlled drainage models with similar drainage design parameters simulated significantly higher mean soil water content and fewer (6 – 110) trafficable days compared to free drained models. The following comparisons were made only for those years with trafficable days in models with free drainage. Drainage base depth of 1.1 m had a significant effect ($P \leq 0.05$) on lowering soil water content and predicted 4 - 40 additional trafficable days during the growing season, compared to drains placed at a base depth of 0.9 m. Decreasing the drain spacing from 15 m to 8 m led to an additional 1 - 7 trafficable days.

Keywords: HYDRUS (2D/3D), Modelling scenarios

4.1 Introduction

In Manitoba, agricultural fields experience high volumetric water content and high water table at the beginning of the growing season. Spring snowmelt and extreme rainfall events are the main causes for the high water table, among others. The presence of high volumetric water content hinders farm operations, causing potential loss of growing season in the Canadian Prairies (Western Potato Council 2003). The high volumetric water content in the top layers of the soil limits the strength of the soil to facilitate trafficability (Hamza and Anderson 2005). The soil type will determine the limiting water content for trafficability. Excess soil water can be removed using field drainage systems (Pavelis 1987). Field drainage can be classified as surface or subsurface drainage based on the removal of water from the soil surface or below the crop root zone, respectively. For crop production, surface drainage alone is not enough to make the field productive due to the presence of water in layers within the root zone (FAO 1997). Hence, draining the water from within the root zone is necessary.

Subsurface drainage is an extensively used water management practice in North America (Pavelis 1987). The drainage outflow is not the same for all cropping seasons and periods within the cropping season (Ballantine and Tanner 2013). Controlled drainage is used to maintain the desired volumetric water content in the profile. At the end of the cropping season, these fields under controlled drainage are operated as free drainage to facilitate vehicular movement. However, freely-drained fields still have volumetric water content higher than the optimum level in the top layers of soil. It is important to investigate the impact of controlled drains on field trafficability in the study area. Much research has been done in the past to quantify the effect of drainage parameters such as drain spacing (Madani and Brenton 1995) and drain installation depth or different combinations of both (Jafari-Talukolaee et al. 2016) on volumetric water content within the soil profile. The recommended drain spacing in Manitoba is 12-15 m, but the proper drain spacing for a field depends on the permeability of soil (Manitoba Agriculture, Food and Rural Initiatives 2008). The drain spacing for fields with controlled drainage should be narrower compared to conventional drainage to maintain uniform water table depth (Dobb 2013). The installation depth of subsurface drains affects the drain outflow volumes with shallower drains draining less water compared to deeper drains (Sands et al. 2008). Subsurface drainage does depend on the soil properties present in the study area, with soil hydraulic conductivity being one of the most important factors (Oosterbaan and Nijland 1994). Hydraulic conductivity of soil varies mainly with soil texture but also with soil bulk density. The drainage parameters suitable for agricultural fields depend on the type of soil as well as weather conditions and depth to the impermeable layer from the soil surface (Skaggs and Chescheir III 2003).

Hydrologic modelling is an inexpensive way to assess the impact of drainage design parameters unique to a given area. Moroizumi and Horino (2004) used HYDRUS software to simulate drainage discharge from both tilled and untilled soils successfully. Field data collected from the study site was used to develop a two-dimensional model using HYDRUS (2D/3D) software, to simulate volumetric water content trends as observed in the field.

In the present study, a validated HYDRUS (2D/3D) model was used to simulate volumetric water content for different drainage design scenarios and soil management practices under Canadian Prairie climatic conditions. The simulated data was used to understand the influence of different drainage design scenarios on trafficability of the study site. The capacity of the soil to support vehicular movement without significant effect on soil structure is defined as trafficability. It varies with soil type, physical and chemical properties of soil. Soil-water interaction plays a major role in controlling the strength of the soil, which was used in this research study to quantify trafficability. The volumetric water content was used as a tool to assess the field trafficability. The criterion, soil water content less than or equal to 0.9 times lower plastic limit of the soil is used to estimate field trafficability. A trafficable day is when the top three soil depths (0.2, 0.4, and 0.6 m) are all trafficable in a day.

4.2 Materials and Methods

4.2.1 Study site

A commercially operated Hespler Farm located at Winkler, Manitoba was chosen as the study site, to carry out research on water management practices focussed on farm drainage. The soil at this site belongs to the Rhineland series which is classified as Gleyed Rego Black Soil, and it is considered as imperfectly drained sandy loam with sand, silt, and clay fractions of 67.7%, 20.8%, and 11.5%, respectively (Satchithanantham et al. 2014).

Meteorological data consisting of precipitation, temperature, wind speed, relative humidity, and solar radiation was collected throughout the year using a weather station located at the study site for the year 2011. Historical rainfall data over a 30-year period was obtained from near the study site, or nearby weather stations for further study as illustrated in Fig. 4.1. Table 4.1 presents the fractions of sand, silt, and clay for each layer of soil as reported by Cordeiro (2014). For modelling purposes, the sand, silt, and clay percentages of the 0-0.4 m and 0.4-1.0 m soil layers were the averaged values of the top 0-0.3 m and 0.6-0.9 m soil layers, respectively.

Evapotranspiration (ET) is the sum of soil surface evaporation and plant transpiration, calculated by the Penman–Monteith equation using meteorological data. Precipitation intercepted by the crop canopy, which eventually evaporates from the leaf surface, is considered as a loss to

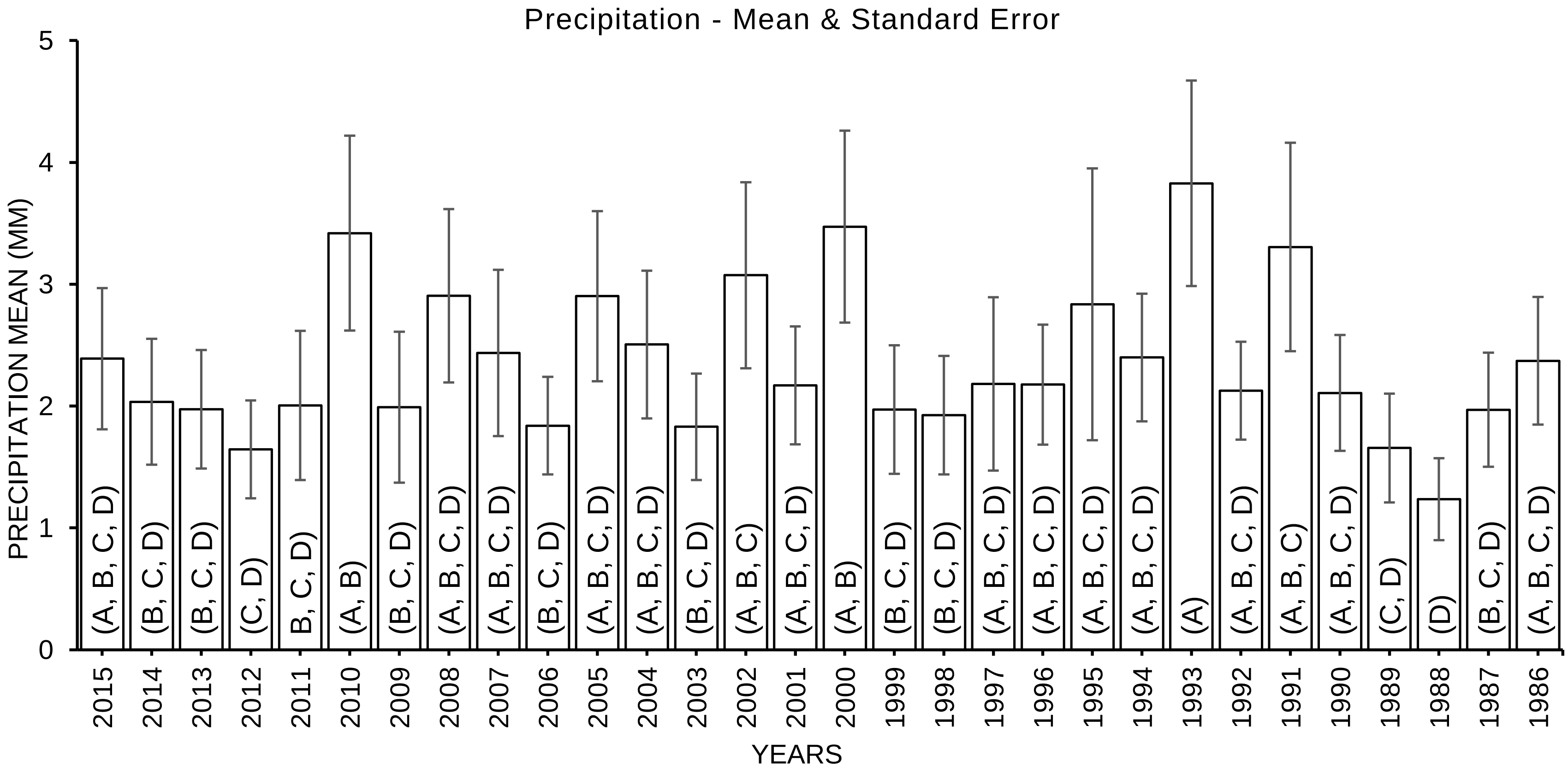

Figure 4.1 Graph representing precipitation average for the period (June 3 – September 24) used in the model run for each year

Footnote: Graph bars with same letters are not significantly different the system. Precipitation reaching the soil surface otherwise called effective precipitation has to be considered for better simulation (Kozak et. al. 2010). Leaf area index (LAI) is the ratio of the one-sided area of leaves per unit canopy projected ground area. Leaf area index of potato used in this study is adapted from a graph presented by King and Stark (1997), which was used to calculate effective precipitation (Sumner and Jacobs 2005; Chen et al. 2014). Groundwater levels were monitored using Water level sensors (Solinst Levelogger Junior 3001, Solinst Canada Ltd., Georgetown, Ontario, Canada) at a three-hour interval. Time domain reflectometry (TDR) probes were used to measure the volumetric water content using the concept of dielectric constant. The TDR probes were installed at 0.2, 0.4, 0.6, 0.8 and 1.0 m below the soil surface.

Table 4.1 Sand, Silt, and Clay percentages averaged over each layer from the values reported by Cordeiro (2014)

Profile depth	Sand (%)	Silt (%)	Clay (%)
0 - 0.4 m	70	20	10
0.4 - 1.0 m	70	18.5	11.5
1.0 - 2.5 m	62	26	12

4.2.2 Trafficability

Trafficability of soil is defined as the capacity of the soil to support vehicular movement and farm operations, both of which depend on soil strength. Soil strength is the resistance to penetration or deformation due to external forces. The strength of soil depends on soil type, mainly the clay content that is a source of cohesion between soil particles. The strength of the soil to support vehicular movement can be determined either using the cone penetrometer tests or the soil consistency values obtained using Atterberg's index indicators (Porsinsky et al. 2006).

Soil plasticity index is the difference in volumetric water content at the Upper Plastic Limit or Liquid Limit (LL) and Lower Plastic Limit, at which soil behaves like plastic. Soil consistency is a measure of the soil resistance to external forces such as load or mechanical stress at particular volumetric water content. In this study, threshold of 90% of volumetric soil water content at the lower plastic limit or below (Mueller et al. 2003) was used as a criterion for field trafficability. Soil samples were collected from the different locations of the study site using zig-zag sampling patterns. In each site, multiple soil samples were collected at different depths (0.2, 0.4, 0.6, 0.8, and 1.0 m) below soil surface. Each soil sample was analysed individually in the laboratory to measure soil plastic properties.

4.2.3 Liquid Limit and Plastic Limit

Liquid limit is the volumetric water content at which soil turns from the plastic state to liquid state with the addition of water. In the present work, the liquid limit of the soil sample was measured using the Casagrande apparatus. The lower plastic limit (LPL) is defined as the water content below which soil is non-plastic and crumbles upon deformation. The LPL was obtained by measuring the volumetric water content at which a moist soil sample can be uniformly kneaded to threads that are 3.2 mm diameter using the hand. Both methods followed the standard ASTM - D 4318 procedure and the values are shown in Table 4.2 for the depths of 0.2, 0.4, and

Table 4.2 Plastic Limit and Liquid Limit Values for different depths below soil surface

Profile depth (m)	0.2 m	0.4 m	0.6 m
Liquid Limit (m3/m3)	0.44	0.44	0.44
Plastic Limit (m^3/m^3)	0.38	0.39	0.37
0.9 * LPL (m^3/m^3)	0.35	0.35	0.33

0.6 m from the soil surface. The Atterberg's limits measured on volumetric basis for the sandy loam soil collected at the study site, were in the range of the values suggested by Mapfumo & Chanasyk (1998) for similar soil textural class.

Many researchers reported compaction of the soil to a depth of 50 cm below the soil surface induced by vehicular traffic (Arvidsson 2001; Arvidsson et al. 2001). The relation between soil water status and the plastic limit is used to assess the trafficability of soils. In this study, simulated volumetric water content equal to or less than 0.9 times the plastic limit (or 0.9LPL) to a depth of 0.6 m below the soil surface was considered as trafficable for that particular water content state on a given day. Understanding the behaviour of soil under various water contents and soil water movement due to different rainfall patterns helps estimate the necessary steps to be taken for improving the trafficability of the fields. For the same purpose, 30 years (1986 – 2015) of rainfall data was used to understand the soil water dynamics in the top-60-cm soil layer.

4.2.3 Advantages of computer modelling

Soil water movement in a soil profile is a non-linear process, which is affected by many factors such as antecedent volumetric water content, soil physical properties, the elevation of the groundwater table and flux, weather conditions. The most common methods for determining volumetric water content are either destructive or expensive and can deliver only *in-situ* data for a single instance in time and space. Estimating volumetric water content by varying even one of the factors mentioned above is nearly impossible without field trials. Field experiments on various water management practices over an extended period are expensive.

Many researchers used computer modelling to simulate volumetric water content data on both spatial and temporal scales (Shouse et al. 2011; Provenzano 2007) which can save time. Validated computer simulations can be used for policy making (Moriasi et al. 2007). From recent developments in hydrologic modelling, the main advantage is the ease of defining the model representing different hydrological conditions as seen in the field.

This study used HYDRUS 2D/3D to create a two-dimensional model, which can simulate volumetric water contents similar to the field. The HYDRUS 2D/3D uses Richard's equation to calculate water flow in saturated-unsaturated porous media by discretizing the domain and using the finite element method to solve the flow equation.

4.2.4 Model Description

A two-dimensional domain with 2.5 m depth and 8 m width was created to represent a part of the field to minimise calculation time based on computer capacity. Only the section of the field with field data was selected for the simulation to avoid errors and oversimplification of the model. An opening was created in the model domain at a depth of 0.9m from the soil surface to represent a field drain in the study site. The model simulation periods was chosen based on available data obtained from the study site. Calibration was used to estimate soil hydraulic parameters, which are the best fit for the particular study area. The calibration stage used the data from the 85-day period of 22 June 2011 – 14 Sept' 2011, and the validation stage used the 19-day period of 03 June 2011 – 21 June 2011.

Volumetric water content was input to the model as initial conditions for the simulation. No flux boundary condition was specified on the sides and bottom of the domain. An atmospheric boundary condition was specified on the top boundary of the model to allow precipitation and ET. A brief discussion on the boundary conditions is presented in Chapter 3.2.4. Final simulation output from the observation nodes, placed in the HYDRUS (2D/3D) model domain, corresponding to the field measured volumetric water content locations was compared with data obtained from the TDR probes to assess the performance of HYDRUS 2D/3D model, in the model evaluation phase. During this phase the efficiency of the model to simulate water flow was evaluated by time series graphs along with statistical parameters. Statistical parameters include Nash-Sutcliffe efficiency (Equation 4.1), Root Mean Square Error (Equation 4.2) and the ratio of the root mean square error to the standard deviation of measured data (Equation 4.3), explained in chapter 3.2.6.

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n}(x_i - y_i)^2}{\sum_{i=1}^{n}(x_i - x^{mean})^2}\right] \tag{4.1}$$

$$RMSE = \left[\sqrt{\frac{\sum_{i=1}^{n}(x_i - y_i)^2}{n}}\right] \tag{4.2}$$

$$RSR = \frac{\left[\sqrt{\frac{\sum_{i=1}^{n}(x_i - y_i)^2}{n}}\right]}{\left[\sqrt{\frac{\sum_{i=1}^{n}(x_i - x^{mean})^2}{n}}\right]} \tag{4.3}$$

The calibrated soil hydraulic parameters and model settings were used during the validation stage for further evaluation. Model evaluation was used to assess the efficiency of HYDRUS (2D/3D) to simulate the variation of volumetric water content as observed in the measured data obtained at different depths below the soil surface.

4.2.5 Modelling scenario

Risk assessment is the process of analysing potential real-world outcomes under different but representative conditions. In hydrological modelling, modelling scenario is used to evaluate the changes in hydrological process under different drainage parameters (Maalim and Melesse 2013), climate (Dietrich et al. 2007), land use (Kepner et al. 2012) or a combination (Wijesekara 2013) with the help of validated models. Developing a modelling scenario (MS) is crucial to the outcome, which can be used for future decision-making. Kepner et al. (2012) suggested classifying the whole MS into scenario definition, construction, analysis, assessment, and risk management.

In this study, MS was utilised to understand the hydrologic processes in the study area under different drain parameter and soil physical properties to improve the trafficability of the soil. Table 4.3 presents the steps of modelling scenarios defined for this research work based on the steps suggested by Kepner et al. (2012).

Table 4.3 Steps of modelling scenario as suggested by Kepner et al. (2012)

Stages of modelling scenarios	Description
Scenario definition	Soil water dynamics is affected by subsurface drain parameters (Sands et al. 2008) (Madani and Brenton 1995) and soil bulk density (Lipiec et al. 2003)
Scenario construction	Three sets of drain spacing and installation depth, and three different soil bulk densities (modelling parameters) were modelled using 30 years of precipitation data.
Scenario analysis	Soil water contents simulated with 2011 precipitation data in various modelling parameters were compared to those of water contents measured at the study site in 2011. Remaining models were compared among the same sets of drain parameters and soil bulk densities to find a better set of parameters for improving field trafficability.
Scenario assessment	Presented in Results and Discussion
Risk management	Use the results of field application to design drainage systems that maintain acceptable levels of trafficability.

A validated two-dimensional HYDRUS (2D/3D) model was used to investigate the changes in soil water dynamics under different scenarios consisting of various drain parameters and bulk densities. Though, the soil temperature impacts root growth, plant development, LAI and atmospheric water, the relation between precipitation and soil temperature was not considered in this study. Model geometry, drain, FE-mesh, input parameters, initial, and boundary conditions were kept the same except for precipitation for the different years. The volumetric water content is dependent on various soil parameters such as soil texture, porosity, and soil bulk density. Therefore, a change in soil bulk density akin to soil compaction and/or organic matter content impacts the pore space, which affects available soil water.

In each modelling scenario, thirty individual models were simulated, by altering precipitation input for each model, using 30-year (1986-2015) historical precipitation data obtained from the internet archives of Environment Canada for a nearby meteorological station. Each model run simulated the same 114 day period and used the same soil hydraulic input parameters, finite element mesh parameters and the same boundary conditions as the validated HYDRUS (2D/3D) model.

4.2.6 Soil bulk density

Soil bulk density is a major factor which affects the penetration resistance, and hence the strength and trafficability of soil (Mapfumo and Chanasyk 1998). Changes in soil bulk density alter the hydraulic parameters of the soil, which further affects the soil water dynamics. This part of the study was used to simulate soil water status for different soil bulk densities and use them to predict trafficable days for each condition. Whetter and Saurette (2008) reported the bulk densities of the soil found at three different locations of the study site at Hespler Farms, Winkler, MB. The bulk densities at four different depths (0-0.15, 0.15-0.30, 0.30-0.60, and 0.60-0.90 m)

Table 4.4 Modelling scenarios used to simulate soil water dynamics under different conditions

Drainage design parameter	Bulk density	Drain spacing – Installation depth	Modelling scenario
0.6 m (Controlled drain)	1.54 Mg/m^{-3}	8 m – 0.9 m	B3NSC
		15 m – 1.1 m	B3WDC
	1.40 Mg/m^{-3}	8 m – 0.9 m	B2NSC
		15 m – 1.1 m	B2WDC
	1.30 Mg/m^{-3}	8 m – 0.9 m	B1NSC
		15 m – 1.1 m	B1WDC
Drain level (free drain)	1.54 Mg/m^{-3}	8 m – 0.9 m	B3NSF
		15 m – 1.1 m	B3WDF
		8 m – 1.1 m	B3NDF
		15 m – 0.9 m	B3WSF
	1.40 Mg/m^{-3}	8 m – 0.9 m	B2NSF
		15 m – 1.1 m	B2WDF
		8 m – 1.1 m	B2NDF
		15 m – 0.9 m	B2WSF
	1.30 Mg/m^{-3}	8 m – 0.9 m	B1NSF
		15 m – 1.1 m	B1WDF
		8 m – 1.1 m	B1NDF
		15 m – 0.9 m	B1WSF

below the soil surface is presented in the report by Whetter and Saurette (2008). The mean bulk density in the top 0-0.15 m soil layer is 1.01 Mg/m-3, whereas it was found to be between 1.45

and 1.54 Mg/m-3 in the 0.30 – 0.90 soil layers, which were comparable to the values reported by Cordeiro (2014).

The optimum bulk density range for plant yield is 1.3-1.45 Mg/m^3, as specified by Negi et al. (1981) for the corn crop in sandy loam type soil found at St. Amble, Quebec, Canada. Archer and Smith (1972) suggested that the bulk density of sandy loam soils should be around 1.50 Mg/m^3 for agronomic purposes, which might vary with different soil texture. The relation between bulk density and soil water flow is complex and non-linear. Till the cut-off bulk density of 1.50 Mg/m^3, the volumetric water content increases with an increase in compaction in sandy loam soils, and the cut-off bulk density varies for other soil types (Archer and Smith 1972).

The impact of bulk density on volumetric water content was investigated by simulating eighteen modelling scenarios consisting of 12 scenarios for free drainage (3 soil bulk densities x 2 drainage depths x 2 drain spacing) along with six scenarios for controlled drainage (3 soil bulk densities x 2 drainage depth-drain spacing combinations). During controlled drainage modelling, the target water table was set at 0.6 m below the soil surface by applying pressure head at the drain (0.3 m for 0.9 m drain depth and 0.5 m for 1.1 m drain depth) in the model domain. No pressure head was applied to drains for the free drainage scenario.

These modelling scenarios given in Table 4.4 were coded as follows. Three Bulk densities shown as B1, B2, and B3 represent 1.30, 1.40, and 1.53 Mg/m^3, respectively. Drain spacing of 8 m and 15 m apart are denoted by N (narrow) and W (wide), respectively. Drain depths 0.9 and 1.1 m below the soil surface are represented by S (shallow) and D (deep). The controlled drainage condition was modelled to maintain the water table at 0.6 m below the soil surface, and represented by C (controlled drainage) whereas the free drain condition is represented by F.

Each modelling scenario has thirty rainfall models, with different rainfall patterns using historical precipitation data between 1986 and 2015. In these modelling scenarios, soil hydraulic parameters for the top three layers (0 – 1.0 m below soil surface) of the model domain are estimated using ROSETTA v 1.1 module of the HYDRUS (2D/3D) software. The ROSETTA program, a reliable pedotransfer function integrated into HYDRUS, was used to find soil hydraulic parameters with Sand-Silt-Clay percentage of the each layer and bulk density, to be used for simulation of modelling scenarios with 1.30 and 1.40 Mg/m^3 bulk densities. The output values of volumetric water content at different depths of the model domain were collected. The volumetric water content data for the top three depths (0.2, 0.4, and 0.6 m) below the soil surface were compared with the optimum trafficable volumetric water content to determine the number of trafficable days, for a given bulk density, drain parameter, and precipitation pattern.

4.3 Results and Discussion

4.3.1 HYDRUS (2D/3D) model

HYDRUS 2D/3D was formulated to simulate the soil water dynamics under controlled drainage conditions in the study site. Input parameters such as physical properties of the soil and weather data and drainage design parameters obtained from the field were used to generate a model domain, initial and boundary conditions. The output data was compared with field observed data to assess the performance of the model.

Visual representation of a comparison between observed and simulate values is shown in Figure 4.2. Overall, NSE values were 0.63 and 0.64 for calibration and validation respectively in 2011. Low RMSE values of 0.02 and a RSR value of approximately 0.6 for both calibration and validation suggest the ability of HYDRUS 2D/3D to simulate (Moriasi et al. 2007) volumetric water content as explained in detail in Chapter 3.

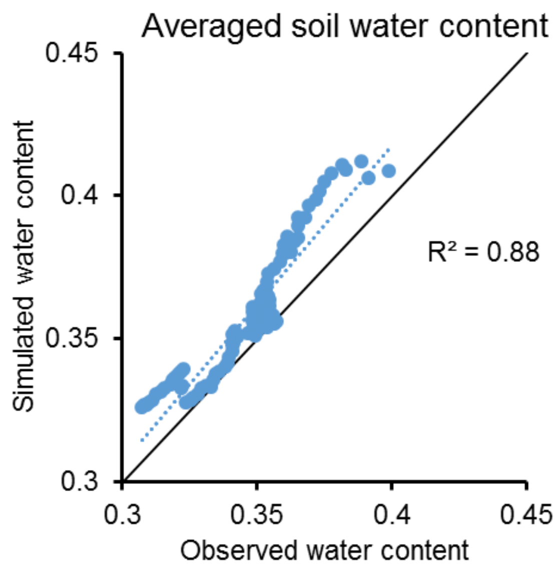

Figure 4.2 Field observed (OBS) and simulated (SIM) soil water content averaged over the top 60 cm soil layer June 3, 2011 –September 14, 2011

4.3.2 Modelling scenarios

The validated HYDRUS model, representing a field with similar hydrologic conditions was used to simulate soil water contents with respect to different drainage design, soil physical parameters, and 30-year historical precipitation data.

Output from different modelling scenarios were analysed for a better understanding of the soil water dynamics of free drainage and controlled drainage. Comparing soil water content simulated with 8 m drain spacing, controlled drainage simulated soil water content significantly ($P \leq 0.05$) higher than soil water content simulated using free drainage for all 30 years of precipitation data. Similar behaviour was observed in models with 15 m drain spacing, where a significant difference was found in mean simulated water content under controlled and free drainage. In controlled drainage models, water contents simulated with two different sets of drainage design parameters (8 m spacing with 0.9 m base depth and 15 m spacing with 1.1 m base depth) were compared for all three bulk densities.

Under free drainage conditions, modelling scenarios simulated using 8-m drain spacing showed significantly ($P < 0.05$) lower water content for the 1.1 m drainage depth compared to the 0.9 m drainage depth for all three simulated bulk densities (1.30, 1.40, and 1.53 Mg/m3). Similarly, the 15-m drain spacing showed a significant influence ($P < 0.05$) of deeper drainage depth on lowering soil water content.

The 0.9 times lower plastic limit values for different profile depths and their respective simulated volumetric water content output for all the modelling scenarios were used to calculate trafficability index values and presented as time series graphs in Fig. 4.3 – 4.14. Those graphs, facilitate visual comparison of trafficability index values for model run with 30-years historical precipitation data simulating 30 cropping seasons. Trafficability index on the left axis of the graphs represents the difference between simulated volumetric water content and 0.9* lower plastic limit, with negative values representing trafficable conditions at respective depths (0.2, 0.4, and 0.6 m) below the soil surface.

For the same bulk density and drain spacing, when simulated volumetric water contents are compared between different target water table depths (0.6 m below the soil surface and drain level), the trafficable number of days were found to be greater when the fields were under free drainage compared to controlled drainage. The condition was due to the presence of higher water content at 0.6 m below the soil surface in controlled drainage at the start of the model run. The water table lowered during the model run period which simulated soil water contents lower than optimum water content for trafficability at each depth. A closer analysis of the number of trafficable days based on volumetric water content at different depths for different bulk densities helps understand soil water dynamics.

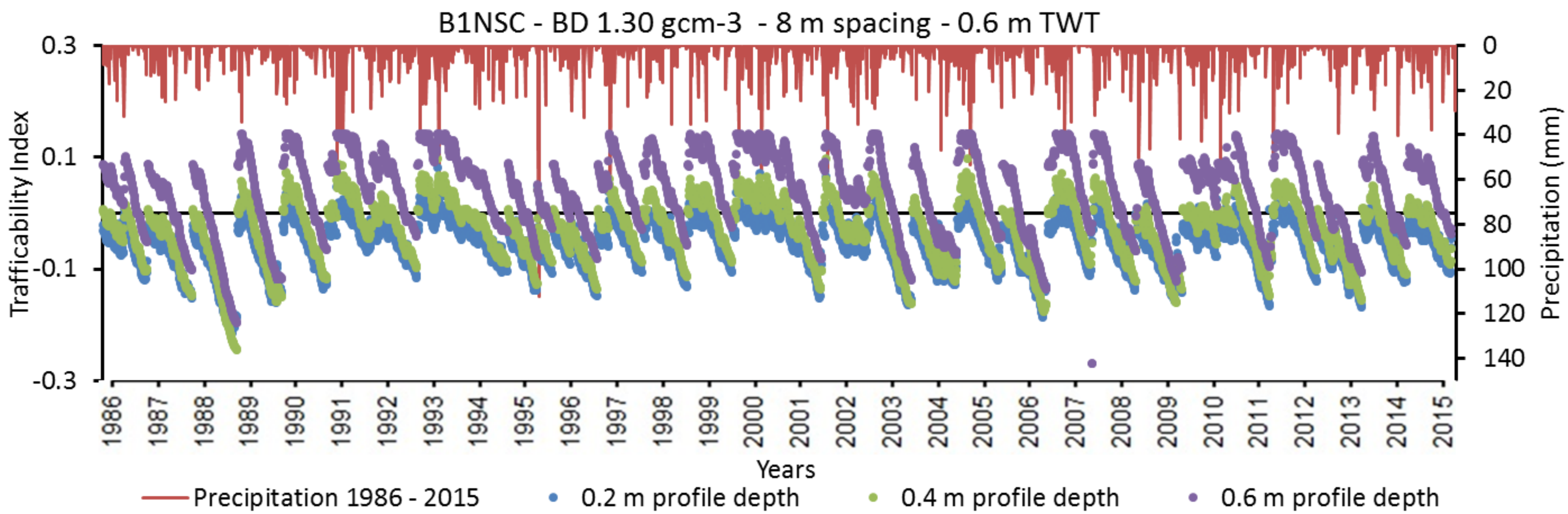

Figure 4.3 Trafficability index at three different depths simulated for the modelling scenario B1NSC

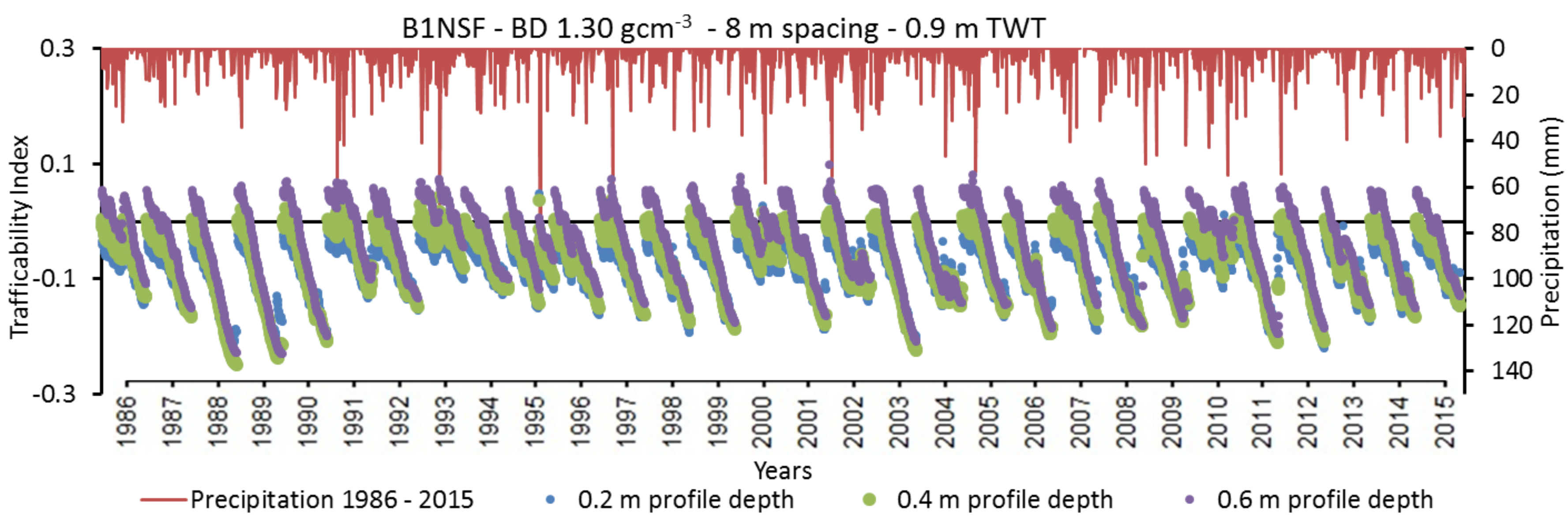

Figure 4.4 Trafficability index at three different depths simulated for the modelling scenario B1NSF

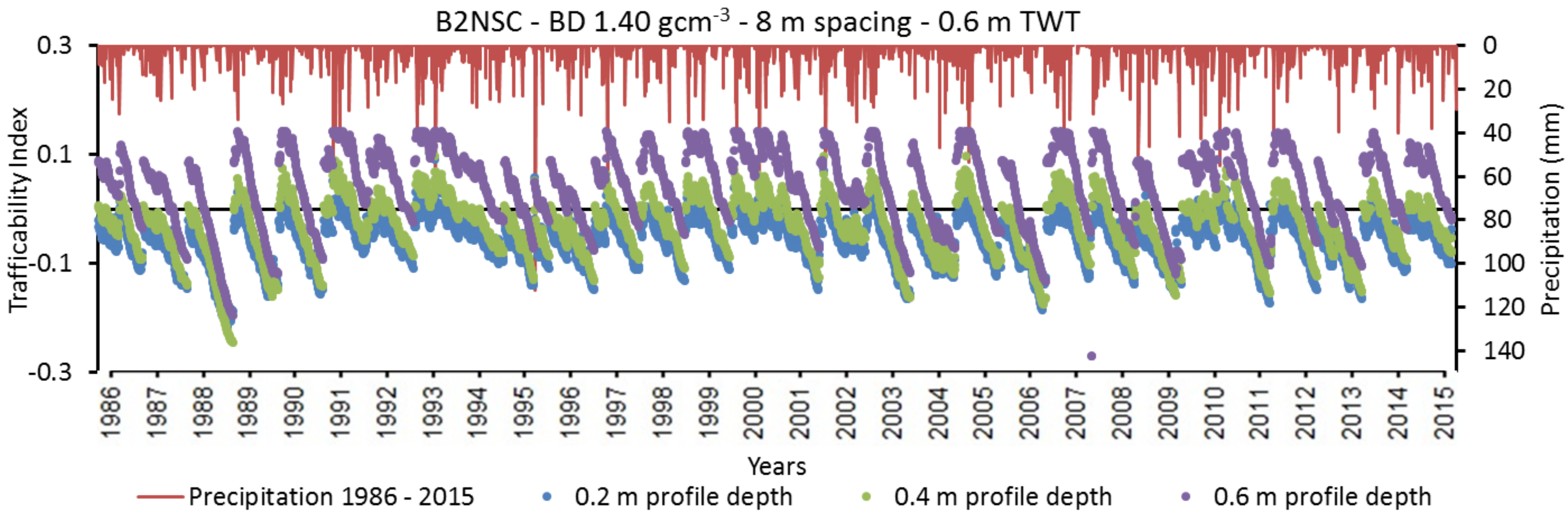

Figure 4.5 Trafficability index at three different depths simulated for the modelling scenario B2NSC

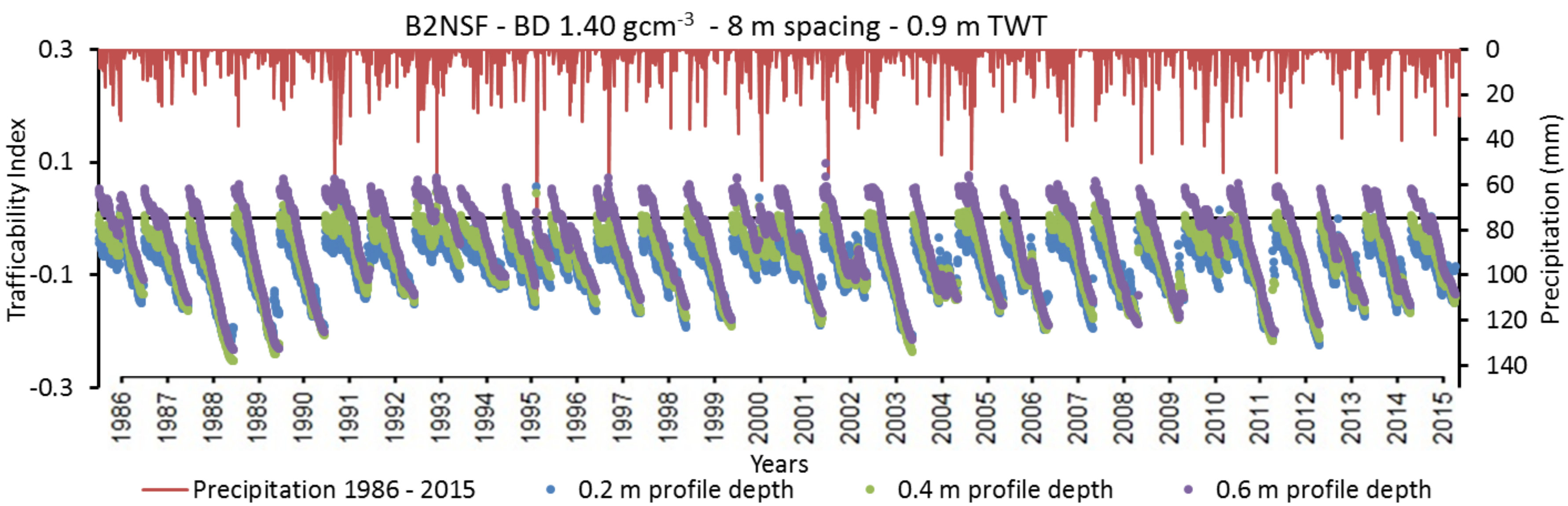

Figure 4.6 Trafficability index at three different depths simulated for the modelling scenario B2NSF

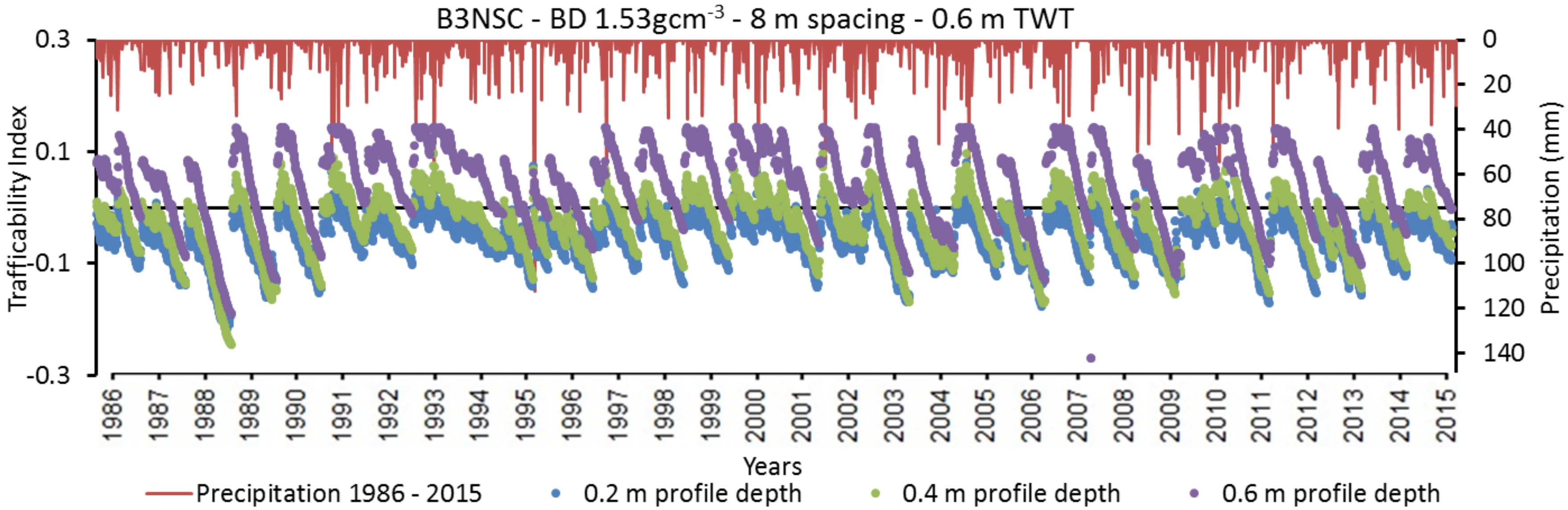

Figure 4.7 Trafficability index at three different depths simulated for the modelling scenario B3NSC

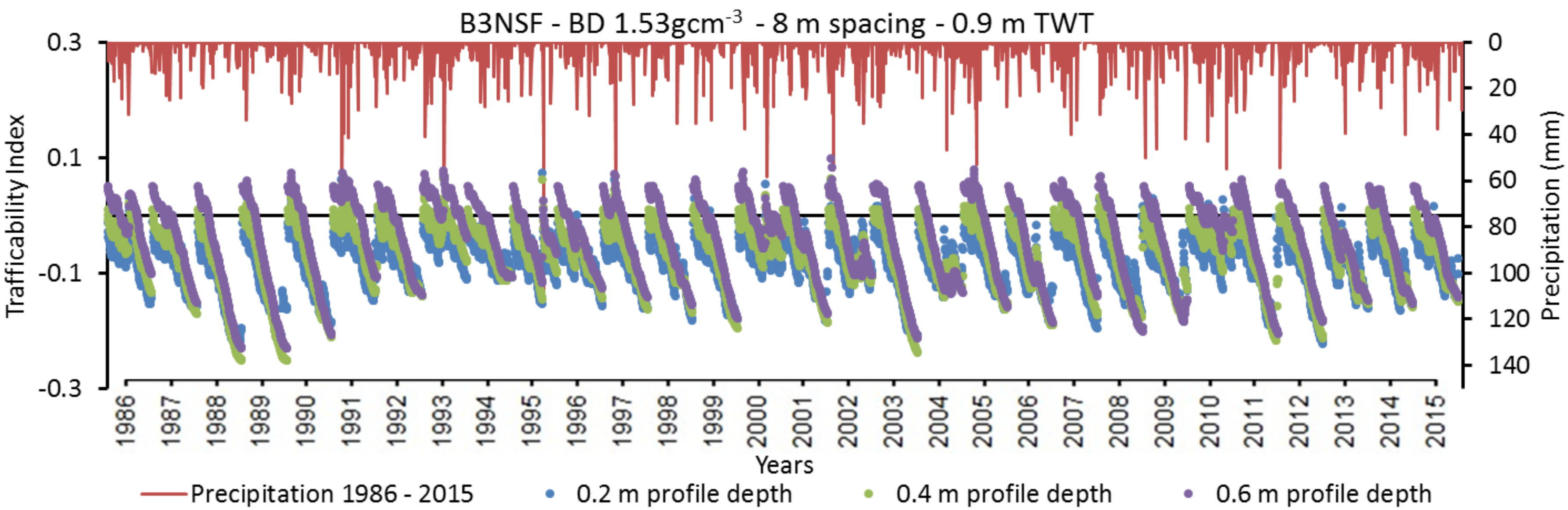

Figure 4.8 Trafficability index at three different depths simulated for the modelling scenario B3NSF

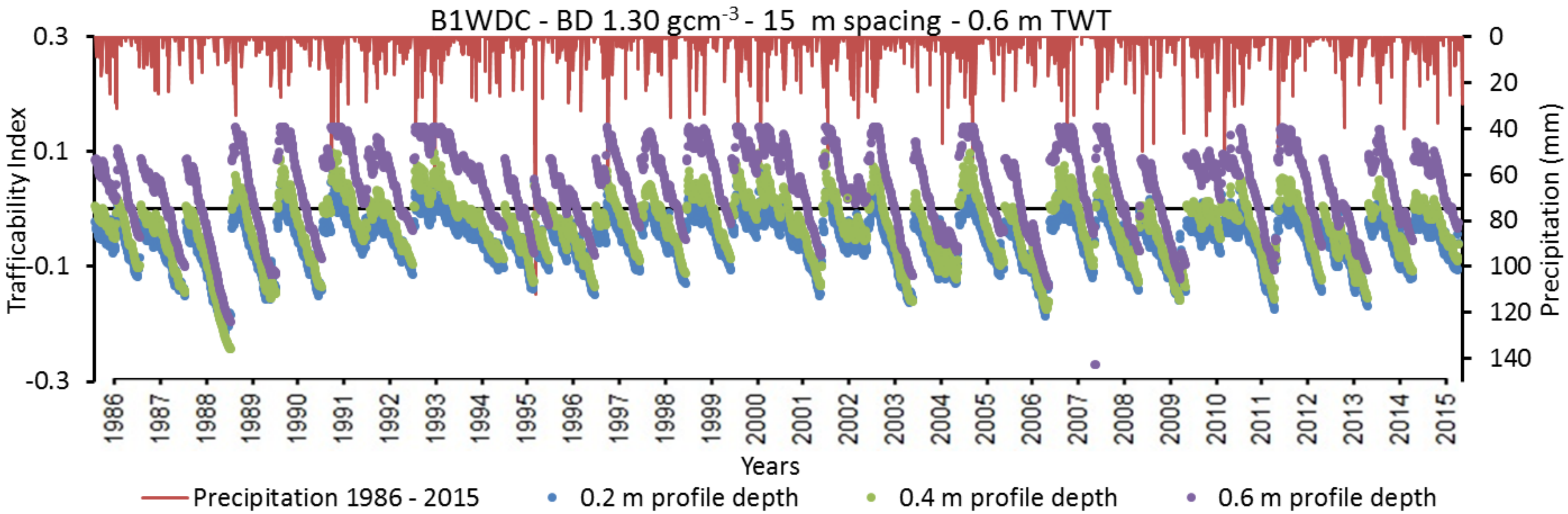

Figure 4.9 Trafficability index at three different depths simulated for the modelling scenario B1WDC

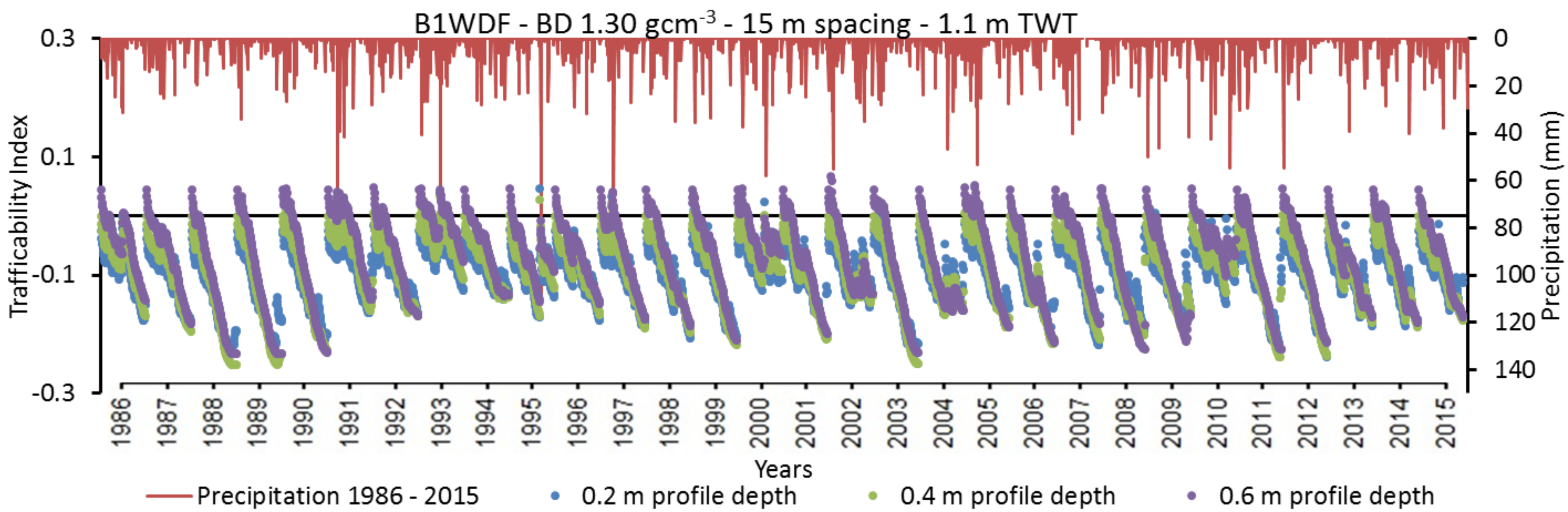

Figure 4.10 Trafficability index at three different depths simulated for the modelling scenario B1WDF

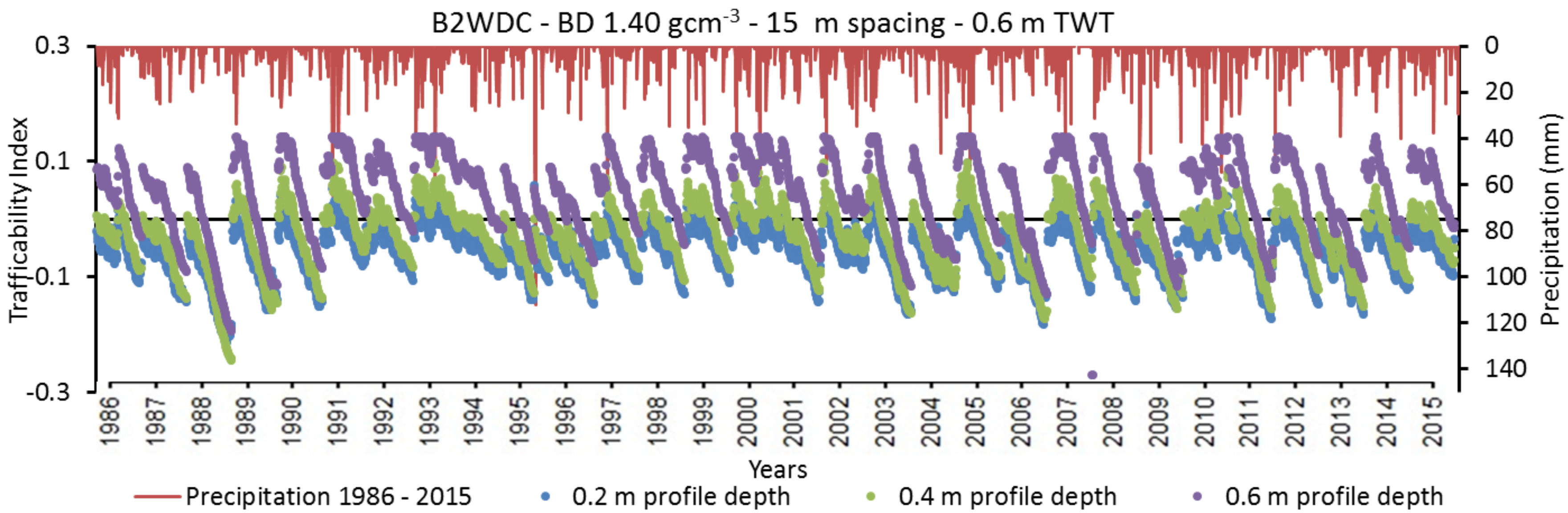

Figure 4.11 Trafficability index at three different depths simulated for the modelling scenario B2WDC

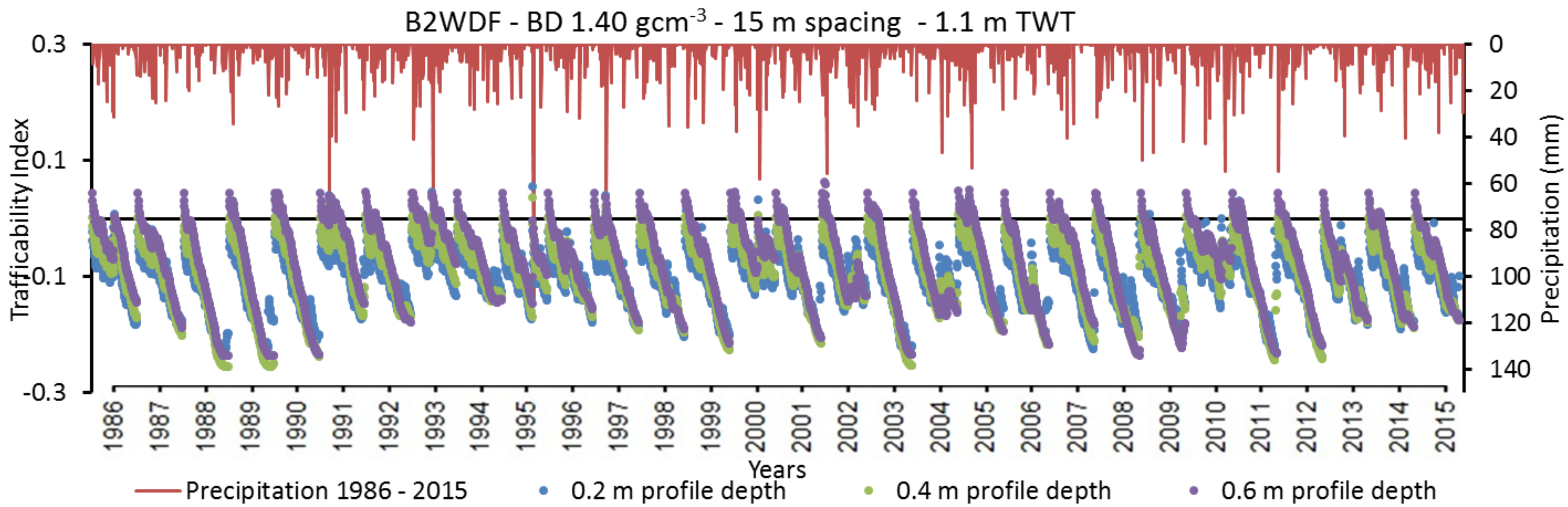

Figure 4.12 Trafficability index at three different depths simulated for the modelling scenario B2WDF

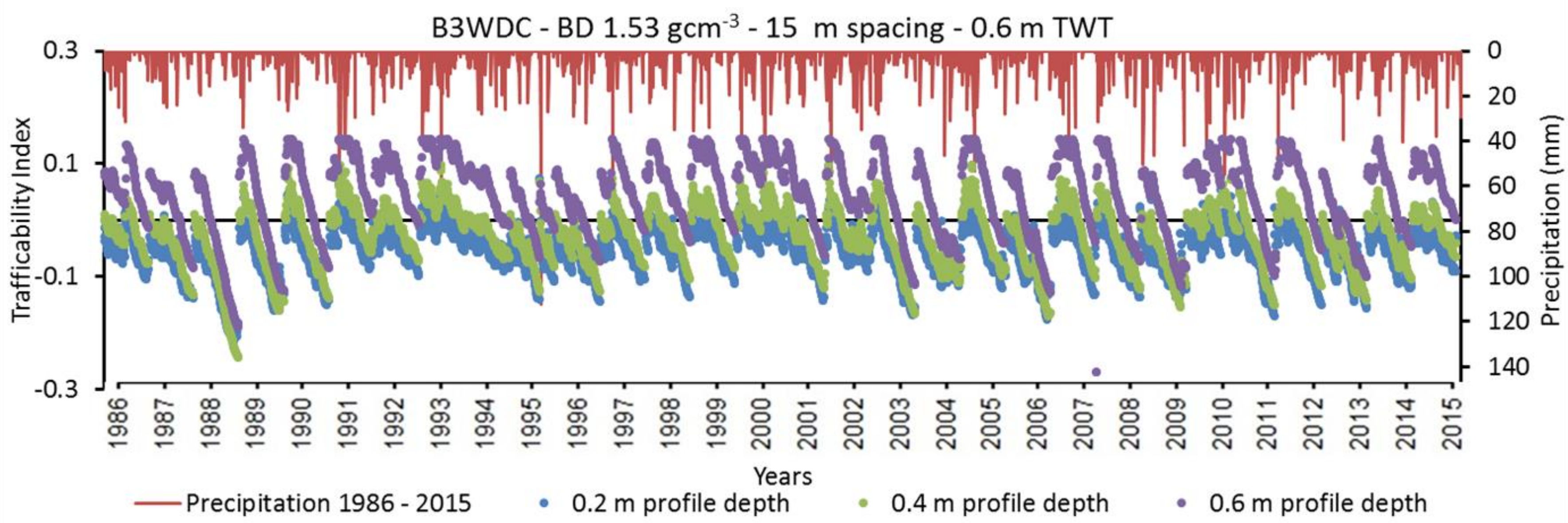

Figure 4.13 Trafficability index at three different depths simulated for the modelling scenario B3WDC

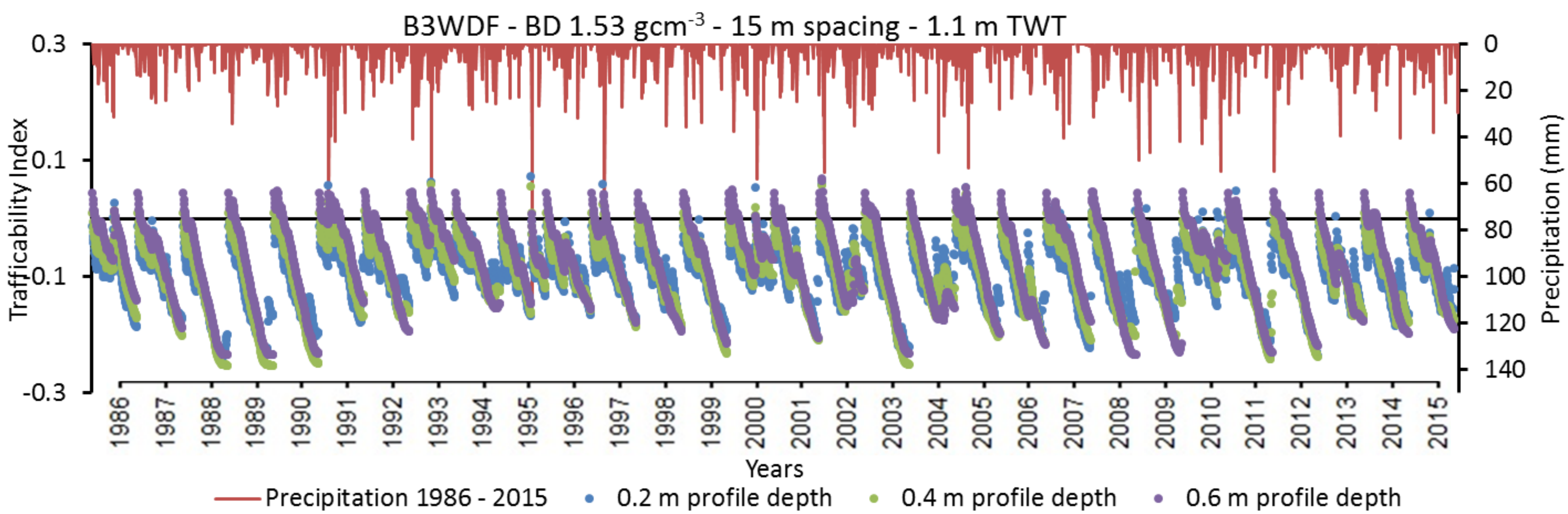

Figure 4.14 Trafficability index at three different depths simulated for the modelling scenario B3WDF

From the graphs representing trafficability index values for controlled drainage modelling scenarios (B3NSC, B3WDC, B2NSC, B2WDC, B1NSC and B1WDC), it can be observed that trafficability index values for 0.6 profile depth are higher, which influenced the number of trafficable days due to the trafficability criterion of all of the soil water contents at 0.2, 0.4, and 0.6 m being lower than 0.9 x LPL values at the corresponding depths. In years with higher precipitation (1993, 2000, and 2010) than normal, the difference between the trend of trafficability index values of 0.6 m profile depth and other two depths (0.2 and 0.4 m) can be observed for controlled drainage modelling scenarios.

In modelling scenarios under free drainage conditions with drainage base depth at 0.9 m, the simulated trafficability index values at 0.2 and 0.4 m depths are almost always negative values for most of the years simulated with their respective precipitation, suggesting the soil is trafficable at these depths throughout the model run period. However, some of the simulated trafficability index values at 0.6 m profile depth were above zero, implying the presence of days with non-trafficable conditions at that particular depth. Whereas, in models with free drainage condition at a base depth of 1.1 m, most of the days are trafficable due to the prediction of ideal water contents for field trafficability at all three soil profile depths (0.2, 0.4 and 0.6 m) below the soil surface.

Trafficability index values were used to count the number of trafficable days predicted in each of the 540 models. In the following analysis, the number of trafficable days was counted, if all three depths had water contents conducive for traffic. Figure 4.15 shows the number of trafficable days predicted for the various scenarios under controlled drainage for soils with 1.3, 1.4, and 1.53 Mg/m^3 bulk densities. The number of trafficable days predicted for the model with free drainage scenarios is presented in Fig. 4.16. The number of trafficable days per growing season differed significantly ($P \leq 0.05$) across the range of 30-year historical precipitation data. The drains at 1.1 m base depth had 4 to 40 additional trafficable days compared to the 0.9 m depth for all three bulk densities under free drainage conditions, same can be observed in Fig. 4.16. The drainage base depth has a significant effect ($P \leq 0.05$) on field trafficable days, in modelling scenarios with 1.53 Mg/m^3, 1.40 Mg/m^3, and 1.30 Mg/m^3 for both 8 and 15 m drain spacing.

In Models with 1.53 Mg/m^3 bulk density, the number of trafficable days predicted with drains placed 8-m apart is significantly ($P=0.008$) more compared to drains with 15 m spacing at the same drain base depth, though the difference in the number of trafficable days was found to be not more than a day except for a few cases. In modelling scenarios with 1.40 and 1.30 Mg/m^3 bulk densities, similarly, drains with 8-m spacing simulated 1 - 7 more trafficable days than 15 m spaced drains. The drainage base depth seems to have a greater influence than the drain spacing on the number of trafficable days. This modelling exercise shows that the drainage design parameters 15 m spacing with 1.1 m drain base depth can be used to maintain the volumetric water content optimum for trafficability in this field without any change in soil bulk density.

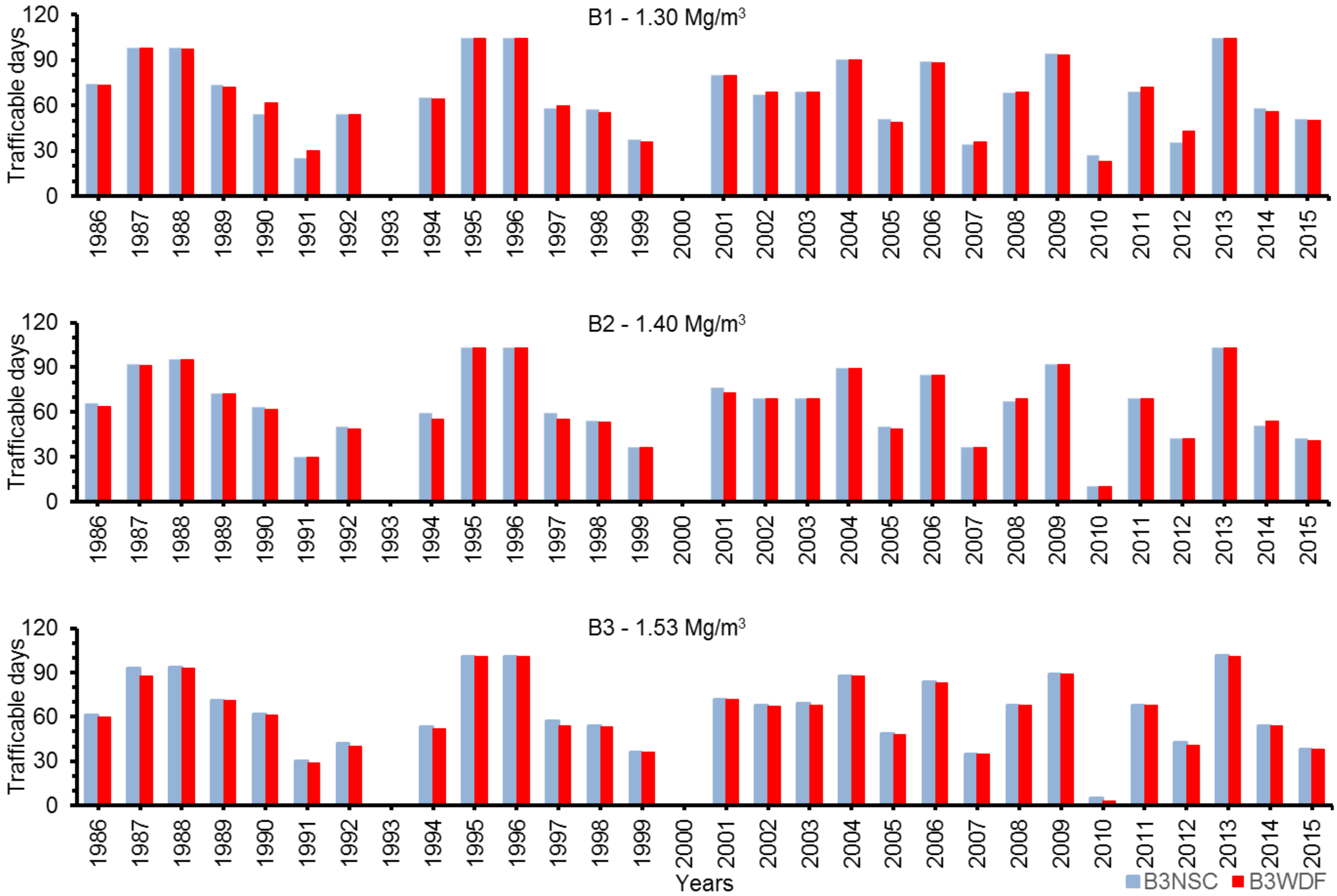

Figure 4.15 Number of trafficable days at three depths under two different modelling scenarios and at three soil bulk densities under controlled drainage

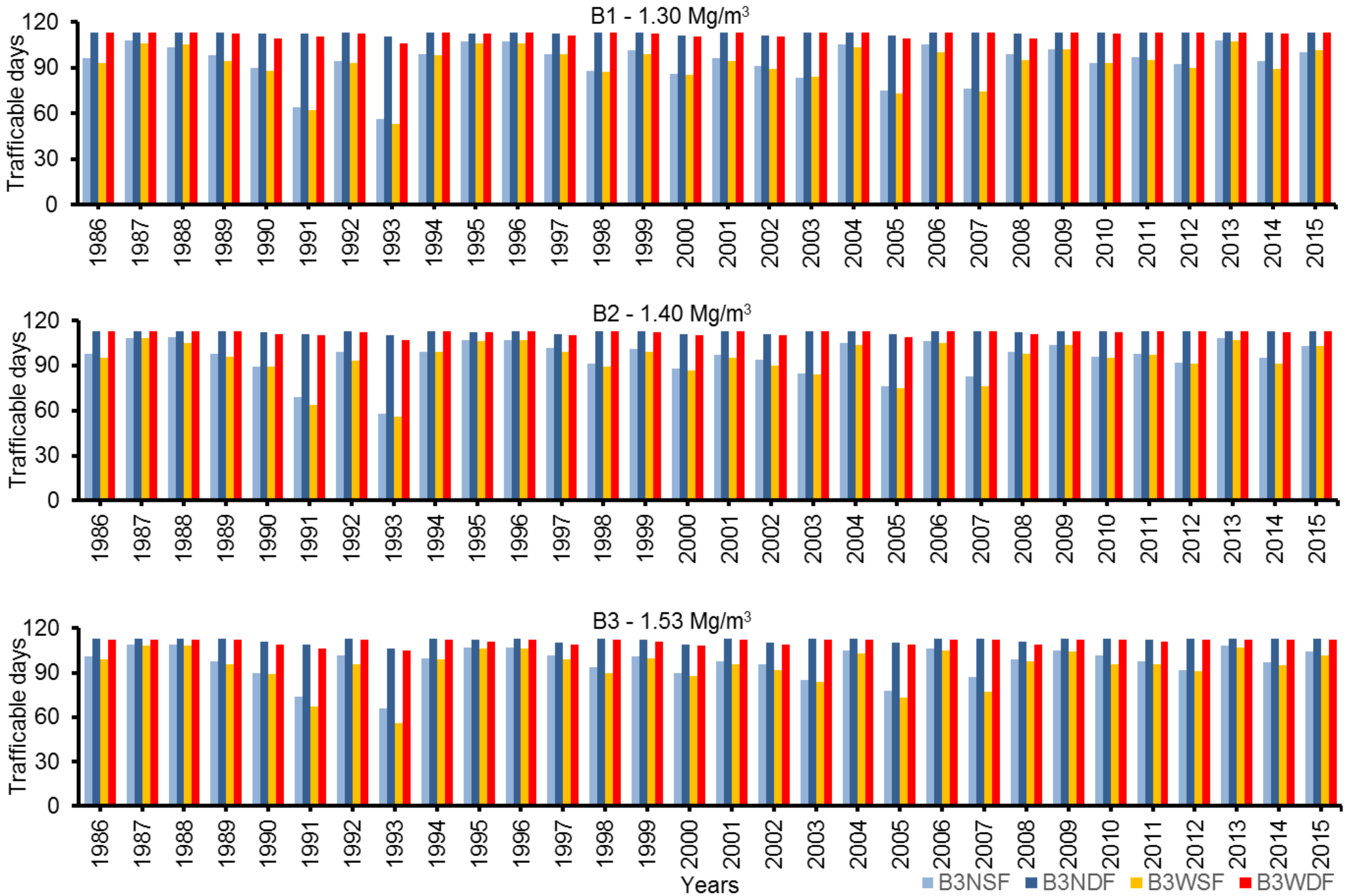

Figure 4.16 Number of trafficable days at three depths under four different modelling scenarios and at three soil bulk densities under free drainage

4.4 Conclusion

The HYDRUS (2D/3D) software was efficient in simulating volumetric water content measured at the study site. The validated hydrologic models were used to simulate various scenarios to investigate the effects of drainage design and soil physical parameters on field trafficability under different rainfall patterns over a 30-year period. Soil water content less than or equal to 0.9 x LPL at all the three depth (0.2, 0.4, and 0.6 m) was the criterion used to designate a trafficable day. The models using free drainage predicted to 6 – 97 more trafficable days for 8 m spacing and 0.9 drain base depth compared to controlled drainage. Free drainage predicted 8 – 110 additional trafficable days compared to controlled drainage with 15 m spacing and 1.1 drain depth. Under free drainage modelling scenarios, drains with 8-m drain spacing predicted 1 – 10 additional trafficable days compared to 15-m drain spacing, in models with drain base depth at 0.9 m below the soil surface. In models with drains at 1.1 m base depth, zero to three day increase in trafficable days occurred when drain spacing was lowered to 8 m from 15 m. The drains at 1.1 m base depth had simulated more trafficable days compared to the 0.9 m depth for all three bulk densities. Even in free drainage models with 0.9 m drain base depth, field trafficability was mostly affected by the water status present at 0.6 m profile depth. This study suggests the free drains installed at 1.1 m depth without altering field soil bulk density is adequate for maintaining soil water content favourable for better field trafficability. This modelling methodology could be used with soil properties and historical weather data from other fields to predict trafficability in those areas.

5 Overall conclusion

Field data collected from Hespler Farms, Winkler in Manitoba was used to model different drainage design scenarios using 30-years of rainfall data. The HYDRUS (2D/3D) model was used to calibrate and validate the conditions prevailing at the site. The validated HYDRUS (2D/3D) model was used to simulate soil water content and predict the possible number of trafficable days for a set of modelling parameters. The conclusions are:

1. The HYDRUS (2D/3D) was able to accurately simulate soil water contents in comparison to field-observed data collected at the study site. This model could be used to test the impact of drainage design and soil properties on the hydrologic processes at the study site.
2. Drain design parameters had a significant effect on soil water content at different depths included in the model domain. The models using free drainage predicted to 6 – 97 more trafficable days for 8 m spacing and 0.9 drain base depth compared to controlled drainage. Free drainage predicted 8 – 110 additional trafficable days compared to controlled drainage with 15 m spacing and 1.1 drain depth. Models with drains located at 1.1 m depth significantly ($P \leq 0.05$) lowered the soil water content compared to models with drains at 0.9 m depth below the soil surface, resulting in 4 to 40 additional trafficable days during the season. Drain spacing had a significant ($P \leq 0.05$) influence on number of trafficable days. The 8-m spaced drains performed better than 15 m spacing by 1 – 10 additional trafficable days. However, the difference in trafficable days varied with drain base depth. Except for the modeling scenarios with free drainage at 1.1 m base depth, water status at the 0.6 m profile depth influenced the number of trafficable days in each model which results in only a few (0 – 1) trafficable days in years with high precipitation (1993, and 2000).

The effects of drainage design parameters and soil physical properties on the number of trafficable days were evaluated as summarized above. This research methodology can be used to model field observed conditions for different sites under Canadian Prairie conditions, to assess the other field sites with different soil properties and water management practices for field trafficability with varying rainfall patterns.

6 Recommendations for future research

1. Field data such as soil physical parameters and monitored soil water content at different depths from a different site could be used with HYDRUS (2D/3D) model to test the methodology developed in this study. Validated model with fine-tuned parameters representing field observed conditions could be used to optimize the drain design parameters for the particular site.
2. Model and validate hydrologic processes of the agricultural fields for the whole year under Canadian Prairie weather conditions including winter snow and spring thaw conditions. The validated model could then be used to simulate a continuous model to predict field trafficability conditions for the following cropping season, when winter cover crops are grown to decrease the depth of frozen soil layer in the preceding season.
3. The study methodology can be further extended to use the relation between penetration resistance of the soil and soil water content to estimate the allowable load per unit area with prevailing soil water conditions at different soil depths. Computer models such as PFC (Particle Flow Code) or ProFor can be used with HYDRUS or other hydrologic models to extract simulated soil water output, to investigate conditions such as degree and depth of compaction under various vehicular loads and effectiveness of agricultural implements.

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Appendix – A

Appendix A-1. SAS Code for multiple T test comparing rainfall data between different years

```
PROC IMPORT OUT= WORK.Krishna
        DATAFILE= "H:\Precipitation Data.csv"
        DBMS=CSV REPLACE ;
GETNAMES=YES;
MIXED=NO;
SCANTEXT=YES;
USEDATE=YES;
SCANTIME=YES;
RUN;
proc data Krishna;
      input Year Precipitation @@;
proc anova data=Krishna;
  class year;
  model precipitation = year;
means year / LSD;
run;
```

****

Precipitation data are saved in CSV file format with two columns named “Year” and “Precipitation”, so there is a “Proc Import” in the start

This code was used for multiple comparisons of 30 years of rainfall data, this code also groups set of years with no significant difference in rainfall.

Results provided below

****

Appendix A-2. Multiple T test comparing rainfall data between different years

The SAS System

The ANOVA Procedure

t Tests (LSD) for Precipitation

Note: This test controls the Type I comparison wise error rate, not the experiment wise error rate.

Alpha	0.05
Error Degrees of Freedom	3503
Error Mean Square	44.06215
Critical Value of t	1.96064
Least Significant Difference	1.7238

Means with the same letter are not significantly different.						
t Grouping				**Mean**	**N**	**Year**
		A		3.8281	114	1993
		A				
B		A		3.4719	114	2000
B		A				
B		A		3.4193	114	2010
B		A				
B		A	C	3.3053	114	1991
B		A	C			
B		A	C	3.2193	114	1985
B		A	C			
B		A	C	3.0737	114	2002
B		A	C			
B	D	A	C	2.9018	114	2005
B	D	A	C			
B	D	A	C	2.8351	114	1995
B	D	A	C			
B	D	A	C	2.8026	114	2008
B	D	A	C			
B	D	A	C	2.5053	114	2004
B	D	A	C			
B	D	A	C	2.3991	114	1994
B	D	A	C			
B	D	A	C	2.3886	114	2015

B	D	A	C			
B	D	A	C	2.3711	114	1986
B	D	A	C			
B	D	A	C	2.2439	114	2007
B	D	A	C			
B	D	A	C	2.1807	114	1997
B	D	A	C			
B	D	A	C	2.1763	114	1996
B	D	A	C			
B	D	A	C	2.1693	114	2001
B	D	A	C			
B	D	A	C	2.1263	114	1992
B	D	A	C			
B	D	A	C	2.1070	114	1990
B	D		C			
B	D		C	2.0351	114	2014
B	D		C			
B	D		C	2.0044	114	2011
B	D		C			
B	D		C	1.9912	114	2009
B	D		C			
B	D		C	1.9728	114	2013
B	D		C			
B	D		C	1.9719	114	1999
B	D		C			
B	D		C	1.9351	114	1987
B	D		C			
B	D		C	1.9246	114	1998
B	D		C			
B	D		C	1.8386	114	2006
B	D		C			
B	D		C	1.8298	114	2003
	D		C			
	D		C	1.6561	114	1989
	D		C			
	D		C	1.6447	114	2012
	D					
	D			1.2351	114	1988

Appendix – B

Table B-1 represents number of trafficable days at three depths (0.2, 0.4, and 0.6 m) below soil surface under four different modelling scenarios with 1.30 Mg/m3 soil bulk density with free drainage.

	B1NSF			*B1NDF*			*B1WSF*			*B1WDF*		
Drain spacing (m)	*8*			*8*			*15*			*15*		
Drain base depth (m)	*0.9*			*1.1*			*0.9*			*1.1*		
Profile Depth (m)	*0.2*	*0.4*	*0.6*	*0.2*	*0.4*	*0.6*	*0.2*	*0.4*	*0.6*	*0.2*	*0.4*	*0.6*
1986	114	114	96	114	114	113	114	114	93	114	114	113
1987	114	114	108	114	114	113	114	114	106	114	114	113
1988	114	114	103	114	114	113	114	114	105	114	114	113
1989	114	114	98	114	114	113	114	114	94	114	114	112
1990	114	114	90	114	114	112	114	113	88	114	114	109
1991	113	113	64	114	114	112	113	113	62	114	114	110
1992	114	114	94	114	114	113	114	114	93	114	114	112
1993	113	113	56	113	114	110	113	113	53	113	114	106
1994	114	114	99	114	114	113	114	114	98	114	114	113
1995	113	113	108	113	114	113	113	113	107	113	114	113
1996	114	114	107	114	114	113	114	114	106	114	114	113
1997	113	113	99	114	114	112	113	113	99	114	114	111
1998	114	114	88	114	114	113	114	114	87	114	114	113
1999	114	114	101	114	114	113	114	114	99	114	114	112
2000	114	114	86	114	114	111	114	113	85	114	114	110
2001	114	114	96	114	114	113	114	114	94	114	114	113
2002	113	113	91	114	114	111	113	112	89	114	113	110
2003	114	114	83	114	114	113	114	114	84	114	114	113
2004	114	114	105	114	114	113	114	114	103	114	114	113
2005	114	113	75	114	114	111	114	112	73	114	114	109
2006	114	114	105	114	114	113	114	114	100	114	114	113
2007	114	114	76	114	114	113	114	114	74	114	114	113
2008	114	114	99	114	114	112	114	114	95	114	114	109
2009	114	114	102	114	114	113	114	114	102	114	114	113
2010	114	114	93	114	114	113	114	114	93	114	114	112
2011	114	114	97	114	114	113	114	114	95	114	114	113
2012	114	114	92	114	114	113	114	114	90	114	114	113
2013	114	114	108	114	114	113	114	114	107	114	114	113
2014	114	114	94	114	114	113	114	114	89	114	114	112
2015	114	114	100	114	114	113	114	114	101	114	114	113

Table B-2 represents number of trafficable days at three depths (0.2, 0.4, and 0.6 m) below soil surface under four different modelling scenarios with 1.40 Mg/m3 soil bulk density with free drainage.

	B2NSF			*B2NDF*			*B2WSF*			*B2WDF*		
Drain spacing (m)	*8*			*8*			*15*			*15*		
Drain base depth (m)	*0.9*			*1.1*			*0.9*			*1.1*		
Profile Depth (m)	*0.2*	*0.4*	*0.6*	*0.2*	*0.4*	*0.6*	*0.2*	*0.4*	*0.6*	*0.2*	*0.4*	*0.6*
1986	114	114	98	114	114	113	114	114	95	114	114	113
1987	114	114	108	114	114	113	114	114	108	114	114	113
1988	114	114	109	114	114	113	114	114	105	114	114	113
1989	114	114	98	114	114	113	114	114	96	114	114	113
1990	114	114	89	114	114	112	114	113	89	114	114	111
1991	113	113	69	113	114	112	113	113	64	113	114	111
1992	114	114	99	114	114	113	114	114	93	114	114	112
1993	113	113	58	113	113	110	113	113	56	113	113	107
1994	114	114	99	114	114	113	114	114	99	114	114	113
1995	113	113	108	113	114	113	113	113	107	113	113	113
1996	114	114	107	114	114	113	114	114	107	114	114	113
1997	113	113	102	113	114	112	113	113	99	113	114	111
1998	114	114	91	114	114	113	114	114	89	114	114	113
1999	114	114	101	114	114	113	114	114	99	114	114	112
2000	113	114	89	114	114	111	113	113	88	114	114	110
2001	114	114	97	114	114	113	114	114	95	114	114	113
2002	113	113	94	113	113	111	113	112	90	113	113	110
2003	114	114	85	114	114	113	114	114	84	114	114	113
2004	114	114	105	114	114	113	114	114	104	114	114	113
2005	113	113	76	113	114	111	113	112	75	113	114	109
2006	114	114	106	114	114	113	114	114	105	114	114	113
2007	114	114	83	114	114	113	114	114	76	114	114	113
2008	114	114	99	114	114	112	114	114	98	114	114	111
2009	114	114	104	114	114	113	114	114	104	114	114	113
2010	114	114	96	114	114	113	114	114	95	114	114	112
2011	113	114	98	114	114	113	113	114	97	114	114	113
2012	114	114	92	114	114	113	114	114	91	114	114	113
2013	114	114	108	114	114	113	114	114	107	114	114	113
2014	114	114	95	114	114	113	114	114	91	114	114	112
2015	114	114	103	114	114	113	114	114	103	114	114	113

Table B-3 represents a number of trafficable days at three depths (0.2, 0.4, and 0.6 m) below soil surface under four different modelling scenarios with 1.53 Mg/m3 soil bulk density with free drainage.

	B3NSF			*B3NDF*			*B3WSF*			*B3WDF*		
Drain spacing (m)	*8*			*8*			*15*			*15*		
Drain base depth (m)	*0.9*			*1.1*			*0.9*			*1.1*		
Profile Depth (m)	*0.2*	*0.4*	*0.6*	*0.2*	*0.4*	*0.6*	*0.2*	*0.4*	*0.6*	*0.2*	*0.4*	*0.6*
1986	114	114	101	114	114	113	114	114	99	114	114	112
1987	114	114	109	114	114	113	114	114	108	114	114	112
1988	114	114	109	114	114	113	114	114	108	114	114	112
1989	114	114	98	114	114	113	114	114	96	114	114	112
1990	114	114	90	114	114	111	114	113	89	114	114	109
1991	112	113	74	112	114	111	112	112	67	112	114	108
1992	114	114	102	114	114	113	114	114	96	114	114	112
1993	112	113	66	112	113	107	112	110	56	112	113	106
1994	114	114	100	114	114	113	114	114	99	114	114	112
1995	113	113	108	113	113	113	113	113	107	113	113	112
1996	114	114	107	114	114	113	114	114	106	114	114	112
1997	113	113	103	113	114	111	113	112	100	113	114	110
1998	114	114	94	114	114	113	114	114	90	114	114	112
1999	114	114	101	114	114	112	114	114	100	114	114	111
2000	112	113	91	112	114	110	112	111	89	112	114	109
2001	114	114	98	114	114	113	114	114	96	114	114	112
2002	113	113	96	113	113	110	113	112	92	113	113	109
2003	114	114	85	114	114	113	114	114	84	114	114	112
2004	114	114	105	114	114	113	114	114	103	114	114	112
2005	113	113	78	113	113	110	113	112	73	113	113	109
2006	114	114	106	114	114	113	114	114	105	114	114	112
2007	114	114	87	114	114	113	114	114	77	114	114	112
2008	114	114	99	114	114	111	114	113	98	114	114	109
2009	114	114	105	114	114	113	114	114	104	114	114	112
2010	114	114	102	114	114	113	114	114	96	114	114	112
2011	113	113	98	113	114	113	113	113	96	113	114	112
2012	114	114	92	114	114	113	114	114	91	114	114	112
2013	114	114	108	114	114	113	114	114	107	114	114	112
2014	114	114	97	114	114	113	114	114	95	114	114	112
2015	114	114	104	114	114	113	114	114	102	114	114	112

Table B-4 represents number of trafficable days at three depths (0.2, 0.4, and 0.6 m) below soil surface under four different modelling scenarios with 1.30 Mg/m3 soil bulk density with controlled drain.

		B1NSC			*B1WDC*	
Drain spacing (m)		*8*			*8*	
Drain base depth (m)		*0.9*			*1.1*	
Profile Depth (m)	*0.2*	*0.4*	*0.6*	*0.2*	*0.4*	*0.6*
1986	114	114	74	114	114	73
1987	114	114	98	114	114	98
1988	114	114	98	114	114	97
1989	114	108	73	114	106	72
1990	113	87	54	112	93	62
1991	111	69	25	110	78	30
1992	114	114	54	114	114	54
1993	113	52	0	110	48	0
1994	114	114	65	114	114	64
1995	113	113	105	113	113	105
1996	114	114	104	114	114	104
1997	113	103	58	113	106	60
1998	114	102	57	114	102	55
1999	114	89	37	114	89	36
2000	112	54	0	112	77	0
2001	114	112	80	114	111	80
2002	113	95	67	113	96	69
2003	114	92	69	113	91	69
2004	114	114	90	114	114	90
2005	112	83	51	111	83	49
2006	114	114	89	114	114	88
2007	113	83	34	113	87	36
2008	114	97	68	114	96	69
2009	114	114	94	114	114	93
2010	114	114	27	114	113	23
2011	114	104	69	114	106	72
2012	114	76	35	114	92	43
2013	114	114	104	114	114	104
2014	114	109	58	114	109	56
2015	114	114	51	114	114	50

Table B-5 represents number of trafficable days at three depths (0.2, 0.4, and 0.6 m) below soil surface under four different modelling scenarios with 1.40 Mg/m3 soil bulk density with controlled drainage.

		B2NSC			*B2WDC*	
Drain spacing (m)		*8*			*8*	
Drain base depth (m)		*0.9*			*1.1*	
Profile Depth (m)	*0.2*	*0.4*	*0.6*	*0.2*	*0.4*	*0.6*
1986	114	114	66	114	114	64
1987	114	114	92	114	114	91
1988	114	114	95	114	114	95
1989	114	108	72	114	107	72
1990	113	98	63	112	95	62
1991	111	80	30	110	81	30
1992	114	113	50	114	111	49
1993	113	56	0	111	54	0
1994	114	114	59	114	114	55
1995	113	113	104	113	113	104
1996	114	114	103	114	114	103
1997	113	108	59	113	106	55
1998	114	101	54	114	101	53
1999	114	90	36	114	90	36
2000	112	81	1	112	79	0
2001	114	110	76	114	110	73
2002	113	97	69	113	97	69
2003	114	92	69	113	92	69
2004	114	114	89	114	114	89
2005	112	85	50	111	83	49
2006	114	114	85	114	114	85
2007	113	89	36	113	88	36
2008	114	97	67	114	97	69
2009	114	114	92	114	114	92
2010	112	103	10	112	98	10
2011	113	106	69	113	106	69
2012	114	90	42	114	94	42
2013	114	114	103	114	114	103
2014	114	108	51	114	109	54
2015	114	114	42	114	114	41

Table B-6 represents a number of trafficable days at three depths (0.2, 0.4, and 0.6 m) below soil surface under four different modelling scenarios with 1.53 Mg/m3 soil bulk density with controlled drainage.

	B3NSC			*B3WDC*		
Drain spacing (m)		*8*			*8*	
Drain base depth (m)		*0.9*			*1.1*	
Profile Depth (m)	*0.2*	*0.4*	*0.6*	*0.2*	*0.4*	*0.6*
1986	114	114	61	114	112	60
1987	114	114	93	114	114	88
1988	114	114	94	114	114	93
1989	113	108	71	113	108	71
1990	112	99	62	112	97	61
1991	111	82	30	110	81	29
1992	114	109	42	114	109	40
1993	111	61	0	110	59	0
1994	114	114	53	114	114	52
1995	113	113	102	113	113	102
1996	114	114	101	114	114	101
1997	113	108	57	113	108	54
1998	114	103	54	114	103	53
1999	114	95	36	114	93	36
2000	112	82	0	112	81	0
2001	114	110	72	114	110	72
2002	113	98	68	112	97	67
2003	113	93	69	113	92	68
2004	114	114	88	114	114	88
2005	112	85	49	111	85	48
2006	114	114	84	114	114	83
2007	112	93	35	112	91	35
2008	114	99	68	114	99	68
2009	113	114	90	113	114	90
2010	112	98	5	112	96	3
2011	113	107	68	113	107	68
2012	114	97	43	114	97	41
2013	114	114	102	114	114	101
2014	114	109	54	114	109	54
2015	114	114	38	114	114	38