Impact of soil and water management practices on soil strength for field operations in southern Manitoba

by

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Abstract

The main objective of this study was to assess the impact of soil and water management practices on soil strength for field operations in southern Manitoba. The specific objectives were to 1) evaluate the performance of HYDRUS (2D/3D) model in simulating soil water flow through subsurface-drained sandy loam soil under potato cultivation in southern Manitoba, 2) evaluate subsurface drainage in promoting soil strength for field operations on sandy loam soil in southern Manitoba, 3) assess the risk of subsoil compaction under different drain spacings and weather conditions in southern Manitoba, and 4) assess the impact of loose and moderately compact soil on soil water content under average weather conditions in southern Manitoba. Field studies, laboratory studies, and HYDRUS (2D/3D) simulation exercise were used to obtain data to achieve these objectives. The performance of the HYDRUS (2D/3D) model in simulating soil water flow was assessed by comparing field measured soil water content data and the simulated soil water content data as well as the ability of the model to account for actual crop evapotranspiration (ET_a). From graphical and quantitative analysis, it was established that the HYDRUS (2D/3D) model satisfactorily simulated water flow through the soil at the study site. The performance of subsurface drainage in promoting soil strength for field operations was assessed by comparing the soil strength of subsurface drained fields and undrained fields using field observed soil water content data. The HYDRUS (2D/3D) model was used to extend the study by simulating soil water content changes due to different drain spacings under different weather conditions. The results showed that subsurface drainage impact was more significant within the 0.3 m to 0.5 m depth of the soil profile at the study site. Under the different weather conditions, drain spacings less or equal to 12 m promoted soil strength in the top 0.5 m depth of the soil profile to allow field operations without any significant impact on the number of field workable days. The subsoil was found to be very vulnerable to compaction based on its high level of intrinsic susceptibility (weak in resisting compaction) and the wetness condition. The wetness condition of the subsoil was found to be either “moist” or “wet” for all the drain spacings throughout the years considered. However, having drain spacing less or equal to 12 m promoted sufficient soil strength for the top 0.5 m depth of the soil profile, which provided protection for the subsoil. The impact of loose and moderately compact soil on soil water content was assessed by studying the effect of changes in bulk density on soil water content. The ROSETTA program in the HYDRUS (2D/3D) model was used to determine the soil hydraulic parameters with respect to changes in bulk density. The results showed that loose soil had relatively high soil water content due to increased pore space. Increasing the bulk density showed a decline in the water content within the range of the loose soil (1.0 Mgm^{-3} to 1.3 Mgm^{-3}). The trend reversed as the bulk density increased in the range of moderately compact soil (1.3 Mgm^{-3} to 1.5 Mgm^{-3}). This effect was more predominant during the spring field operation period.

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Dedication

To my family.

Table of Contents

List of Tables

List of Figures

List of Copyrighted Material

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Nomenclature

$\alpha(h)$	Water stress response function
α	Reciprocal of the air-entry value
τ_f	Shear stress at failure
σ_n	Normal stress to failure plane
θ	Volumetric soil water content
θ_r	Residual soil water content
θ_s	Saturated soil water content
CI	Consistency index
h	Soil water pressure head
l	Pore connectivity
LAI	Leaf area index
LPL	Lower plastic limit
K_c	Crop coefficient
K_s	Saturated hydraulic conductivity
n	Pore size distribution index
S_e	Effective water content
$S(h)$	Actual root water uptake
S_p	Potential root water uptake rate
SWC	Soil water content
UPL	Upper plastic limit
x	Horizontal coordinate
z	Vertical coordinate

Chapter 1

General Introduction

1.1 Motivation for the research

The need for hunger reduction and improved nutrition calls for global sustainable agricultural practices to ensure high yields without compromising the quality of the environment. Agriculture has been sustaining lives since the hunter-gathering regime till now. Modern agriculture is faced with the challenge of meeting the food demand of the growing global population. As of year 2013, the global population was estimated as 7.2 billion, and it was projected to reach 9.6 billion by 2050 (UN report 2017). This food demand would imply large-scale crop production with increased reliance on heavy machinery among other measures to increase the output per farmer (Müller et al. 2011). A significant amount of research has demonstrated that use of heavy machinery on the field may result in soil structural damage leading to crop losses (Knight and Freitag 1961; Kornecki and Fouss 2001; Müller et al. 2011). Previous studies have shown that the ability of the soil to withstand structural damage is influenced by factors such as soil type, land use type, climatic condition, weather conditions, management practices, and soil water content. Soil water content is the most influential parameter among the others because it directly affects the soil strength (Porśinsky et al. 2006). Excess soil water content decreases the shear strength of the soil, which affects the bearing and traction capacity of the soil.

For agricultural soils, surface and subsurface drainage systems are used to improve excess soil water content for timely field operations (Madramootoo et al. 2007; Müller et al. 2011). Apart from drainage systems improving the soil water content, drainage extends the growing season, and improves soil condition for crop production (Smedema et al. 2004; Cordeiro 2014). Between surface drainage and subsurface drainage systems, the subsurface drainage system is proven to better improve soil water content to allow timely field operations (Paul and DeVries 1979; Müller et al. 1990; Kornecki and Fouss 2001). It should however be noted that the effectiveness of the subsurface drainage to remove the excess soil water content depends on the ability of the soil profile to allow excess water movement to the drain tiles at reasonable rates, the spacing of drain tiles, and depth of watertable to maintain (Müller et al. 1990; Kornecki and Fouss 2001; Smedema et al. 2004).

1.2 Background of the research

In southern Manitoba, farmers experience excess soil water content at the beginning of the growing season due to spring snowmelt and rainfall. The excess soil water content inhibits timely field operations. The Soil Management Guide of Manitoba recommends installation depths between 0.9 m to 1.05 m and spacing between 8 m and 15 m for high value crops, where the general drainage installation parameters adopted in the region is 0.9-m depth and 15-m spacing (MAFRI 2016). These recommendations were based on similar projects outside the region and information from the literature.

1.3 Problem addressed in the research

Previous studies (Satchithanantham 2013; Cordeiro 2014) have assessed the impact of the subsurface drainage installation parameters on crop yield in southern Manitoba. In their studies, they observed a significant yield increase of 20 – 30% for potato (Satchithanantham 2013) and 10 – 15% for corn (Cordeiro 2014). However, the impact of the installation parameters on promoting soil strength for field operations was not part of those studies. A recent study by Kaja (2017) used the HYDRUS (2D/3D) model to study the impact of subsurface drainage on soil strength for trafficability in the region. In his study, it was demonstrated that subsurface drainage with narrower drain spacing improved the number of trafficable days based on 30-year rainfall data. However, in his study, there was no information on the soil strength during the early part of the growing season when field operations are intense. Also, the simulations done for the 30 years did not factor in variation in evapotranspiration over the years and how that impacts soil water content and the drainage design criteria in the region.

1.4 Objectives of the research

The main objective of the present study was to assess the impact of soil and water management practices on soil strength for field operations on sandy loam soil in southern Manitoba. The specific objectives were to:

- Evaluate the performance of HYDRUS (2D/3D) model in simulating soil water flow through subsurface-drained sandy loam soil under potato cultivation in southern Manitoba.
- Evaluate subsurface drainage in promoting soil strength for field operations on sandy loam soil in southern Manitoba.
- Assess the risk of subsoil compaction under different drain spacings and weather conditions in southern Manitoba.
- Assess the impact of loose and moderately compact soil on soil water content under average weather conditions in southern Manitoba.

1.5 Scope of the research

This research evaluated the impact of soil and water management practices on soil strength for field operations on sandy loam soil in southern Manitoba. The study focused on subsurface drainage and its ability to improve soil water content in the upper layer (top 0.5 m depth) of the soil profile for field operations and minimize the risk of subsoil compaction. Also, the impact of loose and moderately compact soil on soil water flow was assessed. The economic analysis of the impact of subsurface drainage design and loose and moderately compact soil for improved field operations is out of the scope of this research. This was because data were not readily available for economic analysis.

There are seven chapters in this report. Chapter one presents a general introduction to the research, which comprises the motivation for the research, the background of the research, the problem addressed in the research, the objectives for the research, and the scope of the research. Chapter two presents a review on factors that affect soil and water management practices and its impact on field operations. The review focuses on the factors that affect soil shear strength, impact of soil strength on soil trafficability and workability, methods for assessing soil strength for trafficability and workability, impact of soil compaction on soil functions, methods for determining soil compaction, application of soil water in crop production, methods for measuring soil water content, application of drainage systems in crop production, factors that affect field drainage system performance, challenges associated with drainage systems, and simulation of hydrological processes. In Chapter three, the performance of HYDRUS (2D/3D) model for simulating soil water flow through a subsurface-drained sandy loam soil under potato cultivation in southern Manitoba was assessed. The HYDRUS (2D/3D) is an extensively used Windows-based computer program that simulates water flow through two- and three-dimensional variably saturated porous media by solving the Richards equation. The two-dimensional option was used in this study. The study was carried out to establish how a more advanced modeling tool such as the HYDRUS (2D/3D) could satisfactorily simulate soil water flow through a sandy loam soil under potato cultivation. A modeling tool capable of simulating soil water flow is vital for improving the design of field drainage systems under different conditions. In Chapter four, the performance of subsurface drainage in promoting soil strength for field operations on sandy loam soil under potato cultivation in southern Manitoba was evaluated. This was done by comparing the soil strength of subsurface drained fields and undrained fields. The HYDRUS (2D/3D) model was used to extend the study by simulating soil water content changes due to different drain spacings under different weather conditions. Chapter five presents the risk assessment of subsoil compaction under different drain spacings and weather conditions in southern Manitoba. To assess the risk of subsoil compaction, the intrinsic susceptibility and the vulnerability of the subsoil to compaction were determined using soil properties (textural percentages, bulk density and lower plastic limit) and soil water content. In Chapter six, changes in bulk density of a sandy loam soil was used to discuss the impact of loose and moderately compact soil on soil water content under seventeen-year-average weather conditions in southern Manitoba. Due to lack of field data showing impact of bulk density on soil water content, ROSETTA program (in HYDRUS (2D/3D) model) was used to estimate soil hydraulic parameters based on different bulk densities without any calibration and validation of the results. Chapter seven presents the main conclusions from this research, recommendations for future studies, and the significance of the research to stakeholders.

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Chapter 2

Soil and water management practices and their impact on field operations: A review

2.1 Introduction

This section discusses pertinent literature on soil and water management practices. It focuses on the factors that affect soil shear strength, impact of soil strength on soil trafficability and workability, methods for assessing soil strength for trafficability and workability, impact of soil compaction on soil functions, methods for determining soil compaction. The application of soil water in crop production, methods for measuring soil water content, application of drainage systems in crop production, factors that affect field drainage system performance, challenges associated with drainage systems, and simulation of hydrological processes are also presented.

2.2 Application of soil shear strength in crop production

2.2.1 Factors that affect soil shear strength

Soil shear strength (also referred to as soil strength) is a mechanical property of the soil that determines the ability of a soil to withstand external forces. Soil strength plays a key role in many aspects of crop production such as commencement of field operations, trafficability and workability, soil water movement, plant growth and performance, and effectiveness of field drainage systems.

The soil strength is a function of soil cohesion and internal friction angle. These parameters are obtained from the Mohr-Coulomb's criterion, which is expressed by the following equation: $\tau_f = c + \sigma_n \tan \varphi$ where τ_f is the shear stress at failure, c is the cohesion, σ_n is the normal stress to the failure plane, and φ is the internal friction angle (Mouazen et al. 2002). These parameters are affected by factors such as the soil type, bulk density, water content, organic matter content, the shearing apparatus, and the shear rate (Mouazen et al. 2002). Among these factors, soil water content and bulk density are the most influential factors.

The ability of soil particles to form aggregates (cohesion) results in a good soil structure with large pore size and high resistance to deformation. A well-structured soil enhances air and water movement and serves as a medium for root development. The amount of clay present in the soil influences the cohesiveness of the soil. The higher the clay content, the more cohesive the soil is and the less risk to deformation (Kemper and Rosenau 1984). However, increasing soil water content beyond a certain critical point decreases the cohesion of the soil particles, and hence decreases the stability of the aggregates (Kemper and Rosenau 1984; Komandi 1992; Mouazen et al. 2002). Jia et al. (1998) indicated that the maximum water content at which cohesion was maximum was equivalent to the lower plastic limit of the soil. Cohesion decreases with increasing water content because the increase in water content results in a decrease in the solid fraction of the soil (Mouazen et al. 2002). This results in decreasing interlocking and long-range forces among small particles, thereby decreasing the stability of aggregates. The decreased stability of the aggregates results in the disintegration of the aggregates into micro-aggregates and primary particles, which leads to the settlement of the particles into a more dense-packed soil (Kemper and Rosenau 1984). This occurrence may have a negative impact on crop growth and performance due to decreased pore size resulting in restricted root development, air and water movement. It may also increase the draught force and energy requirement during tillage operations (Mouazen et al. 2002).

The dependence of the internal angle of friction on soil water content is not well established. One school of thought claims there is no dependence on soil water content whereas the other claims it decreases with soil water content. Mouazen et al. (2002) demonstrated that the internal angle of friction for sandy loam soil is independent of soil water content and bulk density. Contrary to their finding, Komandi (1992) found that internal friction angle for five different types of soil including clay loam, clay, loam, sandy loam, and sand decreased with increasing soil water content. Jia et al. (1999) also demonstrated that the internal angle of friction decreased with increasing soil water content for different horizons of planosol solum soil, which has silt as the frame structure and clay filling the pore spaces.

Irrespective of the differences in the findings of the shear strength parameters dependence on soil water content, previous studies have demonstrated that either one or two of the parameters depend on soil water content. This shows that the shear strength of soil depends on soil water content.

2.2.2 Impact of soil strength on soil trafficability and workability

In crop production, the ability of the soil to withstand mechanical loading during traffic (trafficability) and implement use (workability) is vital for successful field operations and obtaining maximum yield. Soil trafficability is the ability of the soil to support traction and weight of machinery without significant settlement or displacement of the soil, whereas soil workability is the ability of the soil to be worked in a desired manner without significantly damaging the soil structure and the ecosystem (Müller et al. 2011).

Soil trafficability studies were initiated by the military in 1943 to acquire knowledge on soil-vehicle interaction to improve the mobility of their vehicles especially in natural terrain (Knight and Freitag 1961). Agricultural Engineers adopted the knowledge from military vehicular trafficability to select suitable farm machinery for agronomic operations (Knight and Freitag 1961). In the quest for ensuring food security for the growing population, farm mechanization continues to use heavier machinery to increase the output per farmer (Müller et al. 2011). Considering the advancement in farm mechanization in modern agriculture, the ability of the soil to allow trafficability and workability, and the impact of using heavy machinery for agronomic operations must be well understood to conserve the soil structure for sustainable crop production (Kornecki and Fouss 2001).

From previous studies, trafficability and workability of agricultural soils are usually considered as inseparable terms (Earl 1997; Kornecki and Fouss 2001). Müller et al. (2011) indicated that the two terms might be inseparable in the agricultural sense when the soil has sufficient moisture. Mueller et al. (2003) demonstrated that when the soil is in the medium hard consistency state (where the soil is dry, fissuring, crumbling, forms weak stable clod, and not rollable to 3-mm-diameter thread (Müller et al. 2011)) both terms are inseparable. However, in extremely wet or dry periods, the two terms do not coincide. Müller et al. (2011) indicated that in extremely dry periods, trafficability is possible but the soil cannot be worked in a desired way, and in extremely wet periods, although the soil may be manipulated, it cannot bear the weight of the machinery and/or allow traffic.

In recent years, farm machinery has been increasing in size in order to increase the output per farmer. This has a negative impact on the soil structure when machinery is used under wet soil conditions. Excess soil water content has been the main problem leading to soil structural damage and its subsequent effect of crop losses (Håkansson et al. 1987; Whalley 1995; Radford et al. 2007). Damaged soil structure also results in increased operating costs through increased tillage energy consumption, decreased drawbar pull, and increased time required to carry out an operation (Earl 1997).

2.2.3 Methods for assessing soil strength for trafficability and workability

Several methods are available to assess the soil strength for trafficability and workability. Some of the methods provide information on soil strength based on physical behavior of the soil, whereas some are related to soil engineering properties and the soil water retention characteristics curve. Some of the measurements based on physical behavior include visual inspection of depth of footprint made in the soil, the wetness of the soil surface, and stickiness of the soil on an instrument (Ciulová and Sobotková 2006). These methods give a quick judgment about the suitability of the soil to withstand mechanical loading but they are also subjective, which make them unreliable.

More reliable methods may include measurement of the shear resistance of the soil. The common ones include direct shear test and triaxial test. These are laboratory methods. Detailed descriptions of these tests can be found in Fredlund et al. (2012). These tests relate the shear strength of the soil to the stress state of the soil. From that relationship, the cohesion and internal angle of friction of the soil can be derived.

Penetrometer resistance of the soil measured by cone penetrometer (Müller et al. 2011) is a quick and reliable method used in the field. Cone penetrometers are used in field studies because they are relatively easy to handle and are reliable in detecting heterogeneities in soil strength (Alakukku et al. 2003; Müller et al. 2011). The applied force required to press the cone penetrometer into soil is an index of the shear resistance of the soil, which is known as the cone index (Ayers and Perumpral 1982). A "cone index curve", which is a plot of penetration force versus depth of penetration, is developed to provide quantitative information on soil strength (Müller et al. 2011). The penetration resistance of the soil is influenced by the soil moisture, bulk density, and soil type (Ayers and Perumpral 1982; Müller et al. 2011). These factors should be considered during the interpretation of the results from a penetrometer test.

Soil engineering properties related to soil strength are Atterberg's lower and upper plastic limits, consistency index, and proctor compaction. Atterberg's lower plastic limit (LPL), or a fraction of it, is one of the quantitative methods, which has been widely adopted as a criterion for assessing the soil strength for trafficability and workability. It determines the optimum soil water content at which the shear strength of soils can support field operations without significant soil structural damage (Dexter and Bird 2001). The LPL is related to the capillary pressure at which the water phase of the soil ceases to act as a continuum and serves as the threshold for the onset of brittleness (Mueller et al. 2003). Mueller et al. (2003) demonstrated that water content corresponding to 0.9 × LPL is suitable for sandy loam soils to allow field operations without causing significant damage to the soil structure. The LPL approach is not applicable to undisturbed soil since it is a property of a molded soil (Dexter and Bird 2001).

Consistency index is obtained from the Atterberg’s limits method. It is defined as the resistance of a material to deformation or rupture and also as the degree of cohesion or adhesion of soil mass (Poršinsky et al. 2006). The consistency index criterion considers the plasticity of the soil (Müller et al. 1990). Its application is limited if the soil is non-cohesive and has low LPL (Mueller et al. 1990). The consistency index has corresponding field characteristics as presented in Table 2.1. These field characteristics make it possible to reliably evaluate the soil conditions in the field (Mueller et al. 2003). The consistency index (CI) of the soil is determined by equation (2.1).

$$CI = \frac{\theta_{UPL} - \theta}{\theta_{UPL} - \theta_{LPL}} \tag{2.1}$$

Where, θ_{UPL} is the upper plastic limit of the soil; θ_{LPL} is the lower plastic limit of the soil; θ is the actual soil water content.

Depending on the value of the CI, the consistency states with the respective field characteristics presented in Table 2.1 are classified.

The proctor compaction test has also been used in the assessment of soil strength for trafficability and workability. The test characterizes alterations in soil density with soil water content using a standardized energy input and compaction procedure. The soil water content indicates the moisture status for maximum compaction at a defined energy impact (Müller et al. 2011). Mueller et al. (2003) demonstrated that the soil water content obtained at maximum compaction in the

Table 2.1: Consistency states of soil and the corresponding field characteristics (Müller et al. 2011)

Consistency index	Consistency state	Field characteristics
≥ 1.3	Hard (H)	Very dry, light, hard, brittle, no clods formable
1.0 – 1.3	Medium hard (MH)	Dry, not rollable to 3-mm-diameter thread, fissuring, and crumbling, weakly stable clod can be formed
0.75 – 1.0	Stiff plastic (STP)	Moist, rollable into 3-mm-diameter thread without crumbling, nonsticky
0.5 – 0.75	Soft plastic (SP)	Wet, easily deformable, rollable into 3mm diameter thread without crumbling, sticky
0 – 0.5	Very soft (VS)	Very wet and sticky, not rollable
< 0	Liquid (L)	Extremely wet, muddy, sliding out of the hand

proctor compaction test was within the range for soil workability but was closer to the wetter limit.

For modeling purposes, soil water retention characteristics curve provides suitable soil conditions for soil strength for trafficability and workability (Müller et al. 2011). The soil water retention characteristics curve describes the relationship between soil matric potential and soil water content. The threshold for soil strength for trafficability and workability on the curve is soil water content at field capacity (FC) or at a defined equivalent of FC usually at suctions between 5 kPa and 30 kPa and the water content at the inflection point (Dexter and Bird 2001). The threshold provides information for the acceptable field conditions to perform field operations but they do not consider strains in the soil and possible compaction profiles, which may result from traffic and implement use (Müller et al. 2011). The moisture content at field capacity is related to the LPL such that ratio of FC to LPL less than one is an indication that the soil will drain to soil water content at which there will be minimum soil structural damage during field operations (Dexter and Bird 2001).

Another method for assessing suitability of soil strength to allow trafficability and workability is using depth of wheel ruts. Wheel ruts of 5 cm and deeper show exceedance of trafficability limits. Also, if water stays in the ruts for a number of days, it shows the soil was not suitable for trafficability (Müller et al. 2011). Although depth of wheel ruts is a criterion to assess soil strength for trafficability and workability, it may be argued that the harm to the soil may have occurred before the assessment, and this is detrimental to the ecosystem. Moreover, farmers do not assess soil strength for trafficability and/or workability of the field using machinery, hence the criteria for assessment should represent the practical situation (Earl 1997).

2.3 Soil compaction and its impact on crop production

2.3.1 Impact of soil compaction on soil function

Soil compaction is a physical evidence of processes that cause reduction in the pore space of the soil. Soil compaction due to agricultural traffic is increasingly becoming a concern due to increased machinery size to maximize the output per farmer. The occurrence and intensity of soil compaction is dependent on the shear strength of the soil, which is influenced by the soil type, organic carbon content, soil water content, the status of pre-compaction, machinery characteristics, and soil-wheel interaction (Soane and van Ouwerkerk 1995).

Soil compaction can persist from the upper soil layer to the subsoil. Soil compaction in the upper soil layer is mainly due to tillage operations; and that of the subsoil is as a result of the weight transfer from the machinery (Håkansson et al. 1987; Whalley 1995; Radford et al. 2007).

A compacted soil has a negative impact on the function of the soil in promoting a conducive environment for crop growth and performance. A compacted soil limits the soil water movement in the soil profile and availability for crop water uptake, gaseous exchange for aerobic activities and nutrient availability and uptake by the crops, which eventually affect plant growth and performance (Taylor and Brar 1991). Whalley et al. (1995) demonstrated that a compacted soil profile hinders root development, which results in a short-term effect of yield losses and a long-term effect of poor structural generation and regeneration due to limited wetting and drying cycles in the soil profile. Poor structural generation and regeneration result in the inability of the soil to absorb high intensity rainfall and then tend to be anaerobic leading to leaching and accumulation of toxic substances, which are harmful to plant growth and performance (Whalley et al. 1995).

A compacted soil inhibits the performance of subsurface drainage systems. In compacted soil, the infiltration capacity of the soil decreases due to pore space reduction. For an optimum performance of subsurface drainage system, excess water in the soil must be able to move through the unsaturated zone and then move as interflow to the subsurface drainage tiles (Smedema et al. 2004). A poor performance of the subsurface drainage system leads to waterlogging of the soil and further soil structural damage.

In previous studies, it was demonstrated that soil compaction in the upper soil layer can be improved through tillage and natural processes such as freezing/thawing, drying/wetting and biological activity, whereas in the subsoil, natural processes may reverse the impact (Radford et al. 2007). A thorough review by Håkansson et al. (1987) revealed that freeze-thaw processes in ameliorating subsoil compaction are overestimated; and that in clayey soils, which have swell-shrink potential, under freeze-thaw conditions, subsoil compaction persists for decades. Hence, the effect may be more prominent in coarse-textured soil or regions without freeze-thaw conditions. Radford et al. (2007) demonstrated that enhancing wetting/drying cycles might improve soil compaction. However, they suggested this for clayey soil due to its swell-shrink potential. Taylor and Brar (1991) showed that worm population could be increased to create more wormholes in the soil to improve subsoil compaction. Whalley et al. (1995) indicated that although worms are important in improving the soil structure and fertility because of their ability to move, it is not universally true; and that their ability to reverse damaged soil structure depends on the worm type, climate, and soil type.

Subsoiling is done to improve compacted soil. Subsoiling is the loosening of subsoil to improve the low hydraulic conductivity of the compacted soil. Tined shanks are used for subsoiling, where the soil is lifted, shattered and loosened (Smedema et al. 2004). Müller (1988) demonstrated that performing subsoiling on soils with plasticity index more than 25% will last for more than two years. However, factors such as the strength of the top 0.15 m, the strength of the soil layer subsoiled, the watertable depth during and immediately after subsoiling, the effective depth of soil profile subsoiled, agronomic operations, soil type, and climatic factors, influence how long the enhanced soil permeability will last (Müller 1988). Although subsoiling can improve compaction, subsurface drainage capable of removing excess water to avoid waterlogging conditions in the soil profile can ensure durability of the increased soil permeability (Müller 1988; Smedema et al. 2004).

2.3.2 Methods for determining soil compaction

Due to both short and long-term effects of soil compaction on crop production and the environment, extensive studies have been done to better understand the compaction processes, avoiding, and reversing the impact. In previous studies, several approaches have been used to measure the state of soil compaction. Bulk density and total porosity are common soil parameters for measuring the state of soil compaction (Filipovic et al. 2006; Ahmad et al. 2009; Beylich et al. 2010). Alaoui et al. (2011) argued that bulk density and total porosity are non-sensitive parameters to use to assess soil compaction because at a given bulk density for the same soil, the pore geometry and continuity can differ due to differences in soil management practices. A particular bulk density may indicate an extremely compact state in one soil with reference to its natural uncompacted state, but a very loose state in another one due to differences in texture and organic matter content (Alaoui et al. 2011). Consequently, actual bulk density should be expressed as a percentage of the reference-compaction state of a given soil known as degree of compactness or relative compactness (Alaoui et al. 2011). Pore space should be quantified as void ratio as the volume of the pores per unit volume of solid. This allows the void ratio of different types of pores to be compared due to constant denominator even in soil where pore space may vary with shrinkage and swelling processes or under compaction and shearing (Alaoui et al. 2011).

Another approach to measure soil compaction is the use of water volume ratio, which is expressed as the volume of water per unit volume of solid phase of the soil. This method is independent of bulk density and is more appropriate for soils with swelling potential (Alaoui et al. 2011). The level of soil compaction can also be assessed using root elongation rate (Håkansson et al. 1987; Whalley et al. 1995). For example, Håkansson et al. (1987) observed in their study that subsoil compaction in sandy soils decreased the rooting depth of corn from 1.2 m to less than 0.5 m. Worm population data has also been used to assess soil compaction. Reduction or absence of worms in the upper layer of the soil gives an indication that the soil structure and physical fertility are damaged by soil compaction (Whalley et al. 1995). This results in increased bulk density and decreased initial infiltration rates. Soil penetration resistance is also another approach for measuring soil compaction. The penetration resistance is influenced mostly by soil water content. Other factors that may affect penetration resistance are bulk density, soil compressibility, soil strength and structure (Müller et al. 2011). Alaoui et al. (2011) proposed the use of structural pores to assess soil compaction. Damage to the macro pores creates smaller intermediate pores with increased matric potential, which leads to slower water transport. Reduction of macro pores causes a shift in the water retention curve towards lower water content. Alaoui et al. (2011) demonstrated that backscattered electron scanning images and mercury porosimetry showed the change in the structural pores compared to bulk density and total porosity measurement as criteria for assessing soil compaction. Alaoui et al. (2011) also demonstrated that in other cases, the matrix flow might be limited in preference to flow through macro pores. This is because vertically oriented macro pores are resistant to vertical compression. Consequently, they transport water downward and provide rapid flow, characterized by a drastic draining of macro pores during drainage (Alaoui et al. 2011). This effect can be assessed using saturated water conductivity, pore volume distribution analyses, dye tracer experiments and water flow dynamics during irrigation experiments to describe the effects of pore structure deterioration (Alaoui et al. 2011).

2.4 Soil water

2.4.1 Soil water in crop production

Previous studies have established that scarcity or excess soil moisture at the various stages of plant growth can affect soil processes such as root respiration, plant water, and nutrient uptake, which could lead to lower crop yield (Osborne et al. 2003; Cordeiro 2014), and also affect planning and implementation of field operations (Müller et al. 2011). Soil water is replenished from many sources such as precipitation in the form of rainfall and snowmelt, shallow groundwater up flux, and irrigation.

Shallow groundwater is a vital water resource for meeting crop water demand provided up flux does not contribute to salinization or acidification nor limit crop growth through waterlogging (Hurst et al. 2004). In view of the potential hazard of shallow groundwater up flux, it is vital to assess the groundwater quality, salinity threshold of crop, and the overall salt balance (Hurst et al. 2004). When the shallow groundwater is a useful resource, the quantity of irrigation water can be significantly reduced without compromising crop yield since the shallow groundwater has the potential for meeting up to 50% of the crop water requirement (Ayars et al. 2009). Not only will shallow groundwater resource conserve water but may also decrease the risk of waterlogging resulting from irrigation, decrease nutrient losses below the root zone, and decrease drainage outflows (Hutmacher et al. 1996; Hurst et al. 2004). One of the factors that influences groundwater up flux is the hydraulic conductivity of the soil, which is a function of the soil type (Ayars et al. 2009). The type of crop cultivated is another factor to consider. The crop type defines the extent of the effective root zone. The closer the root zone is to the watertable, the higher the potential for crop water use. This is because the flux is maintained at a higher rate over a shorter distance (Ayars et al. 2009). Notwithstanding the soil type and extent of the root zone, the needed upward gradient should be created for effective up flux to occur. The root zone should be sufficiently dry to create an upward gradient otherwise the potential use for shallow groundwater will be limited (Ayars et al. 2009).

Irrigation is the application of water to the crop root zone to supplement naturally available soil water from precipitation or groundwater to meet crop water requirement. Several irrigation methods are available for irrigation application and they include surface, sprinkler, subsurface or trickle. Irrigation farming supplies approximately 40% of the world food production on less than 18% of arable land and has a significant future role in meeting the projected world food demand (Ayars et al. 2009).

Although irrigation has been useful in meeting crop water requirement and ensuring food security, there have been recognized failures due to poor water quality resulting in salt accumulation in the soil, overexploitation of fresh water resources (approximately 80% of developed water supply worldwide), water logging, and contamination of fresh water resources as a result of discharge of silt and nutrients from the fields (van Schilfgaarde 1994; Ayars et al. 2009; Wichelns and Oster2006). Large-scale irrigation schemes that are well known for their challenges may include Mesopotamia, the Nile delta and the Indo-Gangetic plain, China, and the United States (Wichelns and Oster 2006). The challenges associated with the application of irrigation to meet crop water demand requires that caution needs to be taken with respect to water quality and use, and farm management practices. Overlooking the effect and only concentrating on the short-term developmental goals of providing income and ensuring food security will be detrimental to the soil productivity and quality and quantity of water resources (Wichelns and Oster 2006). Hence, water management practices on the field should be well understood and water resources must be managed in an integrated manner (Wichelns and Oster 2006).

2.4.2 Methods for measuring soil water content

Several methods are available for soil water content measurement in the field. These methods are categorized into classical methods (i.e. neutron scattering (NS), electrical conductivity, and gravimetric methods) and modern sensor methods (i.e. time domain reflectometry (TDR), frequency domain reflectometry and capacitance methods) (Evett 2003). Gravimetric method involves weighing a core soil sample, removing the water from the soil by oven drying, and reweighing the sample to determine the amount of water removed. The soil water content is then obtained by dividing the difference between wet and dry masses by the mass of the dry sample to obtain the ratio of the mass of water to the mass of dry soil. The gravimetric method is destructive and time consuming but it is the most important because it is used to calibrate other methods of soil water content measurements.

A neutron moisture meter uses radioactive source, which emits neutrons that are attenuated by the hydrogen nuclei of water molecules where the fast neutrons are slowed down. These low energy neutrons are detected and counted by a meter. The number of neutrons attenuated is proportional to the hydrogen nuclei and, hence, the volumetric water content in the soil system (Laryea et al. 1996). The neutron moisture meter is one of the most accurate techniques for soil moisture measurement. However, they can be hazardous due to emission of radiation, and therefore requires special training of personnel on radiation hazard and safe handling procedures (Evett 2003).

Time domain reflectometry uses the capacitance technique. The TDR measures free soil water and provides instantaneous volumetric soil water content quickly and easily by measuring the dielectric properties of a soil-water-air mixture

(Laryea et al. 1996). Probes are inserted into the soil to the required measurement depth and the measurement can either be displayed on a meter or can be recorded using a datalogger (Laryea et al. 1996).

Another technique for soil water content measurement is the use of gypsum block sensors. Gypsum block sensors measure soil conductivity and are generally used for measuring changes in soil matric potential. The soil water retention characteristic curve should be known to convert the soil matric potential to volumetric soil water content.

A tensiometer is a robust instrument used to indirectly determine soil water available to plants instead of the actual percentage of water in the soil, and it is independent of soil type (Laryea et al. 1996). A tensiometer is filled with water and sealed before installing into the soil. The water flows through a porous ceramic tip in either direction. When the ceramic is in contact with a dry soil, water flows out of the tensiometer leaving a vacuum behind. The vacuum becomes equal to the soil suction, which is directly measured using an electronic pressure transducer. As the soil dries out and rewetted by irrigation or rainfall, the tensiometer will follow and continue to read the soil suction directly. Low readings nearer zero mean wetter soil while higher suction readings mean drier soil (Laryea et al. 1996).

2.5 Improving excess soil water content with drainage systems

2.5.1 Drainage systems in crop production

Wet soil conditions in the field require intensive measures such as drainage to remove the excess water to allow timely field operations (Madramootoo et al. 2007; Müller et al. 2011). Drainage systems help reduce the time that excess water remains on a field before it reaches the receiving system, which however results in higher outflow rates than from undeveloped sites (Evans et al. 1996). Apart from the drainage system improving soil water for field operations, drainage extends the growing season especially in fields under freeze-thaw condition; it promotes aeration for plants and bacteria and leaches accumulated salts in the root zone for improved crop production; it controls erosion by controlling surface runoff; it controls flooding; it helps to protect public health by preventing the spread of water-borne diseases; and it prevents damage to roads and buildings (Cordeiro 2014).

A drainage system in crop production is comprised of field drains, collector drains and an outlet. The field drains gather the excess water from the field by means of field drainage network. The main types of field drainage system are surface and subsurface drainage systems. The surface drainage systems remove excess water from the land by lateral flow due to impeded infiltration and percolation at shallow depth by poorly permeable layers (Smedema et al. 2004). This implies excess water ponded on the soil surface will be drained by lateral overland flow, whereas soil water infiltration impeded at a shallow depth in the rootzone will be drained by interflow (Smedema et al. 2004). Subsurface drainage systems are useful when soil water is able to percolate through the soil to recharge the groundwater. The subsurface drainage removes gravitational water by means of buried perforated corrugated pipes to lower the watertable below the effective root zone (Guitjens et al. 1997; Cordeiro 2014).

Between surface drainage and subsurface drainage systems, the subsurface drainage system is proven to better enhance soil water condition timely field operations (Paul and DeVries 1979; Müller et al. 1990; Evans et al. 1996; Müller et al. 2011). The suitable watertable depth to maintain is dependent on climate, weather, soil characteristics, crop type, and management factors (Smedema et al. 2004; Müller et al. 2011). Paul and DeVries (1979) demonstrated that the critical watertable depths to ensure sufficient soil strength for trafficability for grassland and cultivated silty clay loamy soil were 0.45 m and 0.6 m from the soil surface, respectively. Evans et al. (1996) also indicated that farmers did not experience trafficability issues in North Carolina when the watertable was maintained at 0.9 m from the soil surface; and in some cases, watertable at 0.6 m from the soil surface did not affect trafficability. Müller et al. (1990) found that lowering the watertable to a depth of about 0.9 m to 1.1 m below the soil surface on heavy alluvial soils ensured trafficability and workability for an average of 26 days during the spring field operations.

2.5.2 Factors that affect field drainage system performance

The optimal design of drainage systems is influenced by several factors such as the design criteria, economic factors, climate, weather, soil condition, availability of field data on hydraulic and hydrological processes, installation practices, cropping system, tillage practices, and experience. The design criteria define how much excess water is to be controlled in/on the soil and the allowable interference of the excess water with farming.

For surface drainage, the basic design criterion establishes the length of time allowed to remove overland flow and interflow resulting from rainfall, snowmelt and irrigation (Smedema et al. 2004). The basic design criterion for subsurface drainage is to control the watertable depth due to recharge events (Smedema et al. 2004). The watertable control in subsurface drainage may be determined using steady state or non-steady state conditions (Smedema et al. 2004). The steady state condition assumes the recharge is equal to the drainage discharge, and thus the watertable depth remains constant (Smedema et al. 2004). The non-steady state condition allows fluctuation in the watertable and determines the rate at which the watertable should fall after rising to unacceptable depth (Smedema et al. 2004). The simplicity of the steady state conditions makes it more attractive in design of subsurface drainage systems than the non-steady state condition (Cordeiro 2014).

There is a high level of investment involved in improving field drainage; and that can influence the basic design criteria, which define the extent of land forming and the design of drain tile installation. The benefits of improved drainage such as good soil trafficability and workability, extended growing season, improved quality yield, among others, must be weighed against the cost of installation. It should however be taken into consideration that drainage is only a fraction of the soil and water management practices that ensures a successful crop production (Smedema et al. 2004). Another economic factor to consider is the damage to the soil structure and crop by excess soil water. This factor influences the design of the drainage system and the excess soil water the drainage system has to remove. The amount of excess water the system should be capable of handling is based on the design recharge rate. The design recharge rate should be chosen to ensure that the damage caused by uncontrolled excess water does not significantly outweigh the benefits of the drainage system. The higher the design recharge rate used in the design of the drainage system the lower the risk of crop failure. Systems capable of handling higher design recharge rate cost more, which has to be balanced against the financial loss due to crop failure (Smedema et al. 2004). In general, surface drainage systems should be able to cope with the highest precipitation amount over a two-year return period, whereas subsurface drainage systems should be able to cope with the highest precipitation amount over a five-year return period (Smedema et al. 2004). In regions where snowmelt and irrigation affect major field operations, the design has to factor in the effect to avoid significant damage to the soil structure (Smedema et al. 2004).

Usually due to lack of data on soil hydraulic and hydrological processes, new drainage systems are designed based on experience from similar design in the area or from elsewhere with similar conditions (Smedema et al. 2004). Difference in local soil conditions, management practices, and lack of historical data for the area will influence the performance of the design of the new system. Hence the new system needs to be monitored to ensure the performance of the system, and revise design criteria where necessary to meet the actual drainage requirements (Smedema et al. 2004).

2.5.3 Challenges associated with drainage systems

In recent years, the call for sustainable agriculture has resulted in the need to move from conventional drainage systems and adopt measures that can effectively enhance field operations without compromising the quality of the environment (Evans et al. 1996). Conventional drainage systems enhance the discharge of excess drainage outflow loaded with nutrients into receiving water bodies. When these nutrients exceed the assimilation capacity of the receiving water bodies, it results in enhancement of eutrophication processes, and high level of investment in reversing the effects to meet standards (Borah et al. 2006; Kresic 2007; Taylor et al. 2010).

Water resource pollution by nutrients removed from the field through drainage discharge is due to the increased use of agrochemicals to improve soil fertility for plant growth and performance. Excess nutrients, which are not used by plants, are lost to ground and surface water and consequently affect the water quality. The transport of the excess nutrients into the environment is enhanced by drainage systems.

Nitrates are soluble at concentrations found in soil and they do not adsorb on the soil particles. Hence, their mobility is mostly dependent on soil solution movement and mechanisms determining water transport. Subsurface drainage systems intercept flow through the soil and facilitate the mobilization of nitrates more compared to surface drainage.

Phosphorus transport from the field occurs through sediment-bound and dissolved forms. Sediment-bound phosphorus transport is about 80% of the total loss (Cordeiro 2014). Due to the means of phosphorus transport, its availability in the environment is largely associated with surface runoff events (Eastman et al. 2010). Notwithstanding phosphorus transport through overland flow, research has shown that subsurface drainage systems discharge significant amounts of phosphorus to the environment (Heckrath et al. 1995; McDowell and Sharpley 2001; Eastman et al. 2010). Phosphorus transport through subsurface drainage system occurs when the concentration of phosphorus in the soil cannot be retained by the soil. Beyond that critical concentration, phosphorus can leach through the soil profile. Although, interception of the interflow by subsurface drainage will minimize nutrient transport to groundwater, it will increase discharge into the receiving surface water bodies.

Over the years, water resource pollution from point sources has been considerably dealt with through pollution control standards, regulatory enforcement, and capital investment and management in industry and municipal infrastructure. Hence, point source pollution from the field through the drainage systems can also be minimized through appropriate legislation and working standards (Smedema et al. 2004). Non-point sources, such as uncontrolled surface run off from farmlands, remain a challenge for ensuring water resource quality (Daniel et al. 1998). This challenge persists because it is challenging to quantify the nutrient loads from non-point sources (Duda 1982). Duda (1982) conducted a study on point and non-point source of eutrophication in the Chowan River in Eastern North Carolina. He demonstrated that agricultural watersheds contribute about five to forty times more nitrogen and phosphorus levels to the river than forested watersheds.

To significantly minimize nutrient impact on water resources, the management strategy used should be able to retain nutrients on site and prevent them from reaching receiving waters (Evans et al. 1996). Effective management strategies should be able to reduce nitrogen and phosphorus by 30% to 40% at the point of discharge to significantly minimize its impact on water quality (Evans et al. 1996). It should however be noted that implementing effective management practices on farms may not immediately yield visible improvement, but it will begin to reverse the damage through self-cleansing of the water bodies (Evans et al. 1996).

Controlled drainage has been identified as the best approach to minimize nutrient rich drainage discharge to the environment. While ensuring environmental quality, direct crop production benefit to the farmer is not compromised (Evans et al. 1996). The controlled drainage system employs an overflow device to raise the water level on the upstream side of the drainage outlet to maintain the watertable in the soil profile to a desired level (Cordeiro and Sri Ranjan 2012). Previous studies have shown the effectiveness of controlled drainage on crop performance and nutrient export control. For instance, Kalita and Kanwar (1992) demonstrated that increasing watertable depth within 0.3 m to 0.9 m increases corn yield. Ng et al. (2001) compared the performance of conventional drainage to controlled drainage and observed 64% increase in corn yield under controlled drainage. Evans et al. (1996) indicated that controlled drainage reduces total drainage outflow by 30%, which results in 45% and 35% reduction of nitrate-nitrogen and total phosphorus, respectively.

Notwithstanding the benefits of controlled drainage in minimizing nutrient transport to the environment, weather conditions and soil drainage conditions may not permit its use in that regard during periods of maximum drainage outflow. For instance, in southern Manitoba, the controlled drainage is operated in the free drainage mode in the early growing season to lower the watertable to improve soil trafficability and workability, which coincides with maximum drainage outflow with high nutrient load (Cordeiro 2014). The watertable in the area can rise up to the surface, thereby delaying field operations and affecting yield (Cordeiro 2014).

2.6 Simulation of hydrological processes

Simulating agricultural systems in conjunction with field research is vital for improving agriculture. To a considerable extent, field studies are limited to discrete measurement, they are expensive and time consuming over a wider coverage area. Agricultural system models eliminate this drawback of field studies.

Several models are available to study the impact of different hydrological processes on soil water flow dynamics. Some of the common models include DRAINMOD (Singh et al 2006; Cordeiro 2014), RZWQM (Singh et al. 1996; Shrestha and Datta 2015) and HYDRUS 1D (Tafteh and Sepaskhah 2012). These models are one-dimensional, which simplifies the flow dynamics in the soil profile.

HYDRUS (2D/3D) is a popular model, which simulates water flow through two and three- dimensional variably saturated porous media (Šimůnek et al. 2012). HYDRUS (2D/3D) can be used to simulate water flow dynamics in the soil profile based on processes such as precipitation, irrigation, infiltration, evaporation, root water uptake (transpiration), soil water storage, capillary rise, deep drainage, groundwater recharge, and surface runoff (Šimůnek et al. 2012). HYDRUS (2D/3D) can reduce evaporation and transpiration from their potential to actual values based on the prevailing soil water condition in the soil profile and specific properties of the vegetation (Šimůnek et al. 2012). Also, HYDRUS (2D/3D) is a physically based model and may require little or no calibration when all input parameters are carefully determined experimentally (Šimůnek et al. 2012). However, in situations where there are missing parameters, HYDRUS (2D/3D) presents options to determine the missing parameters. These options include the use a catalogue of average parameters for 12 textural classes of the USDA textural triangle or pedotransfer functions using their Rosetta program (Šimůnek et al. 2012).

Rosetta is a widely used computer program for estimating soil hydraulic parameters from soil textural properties using hierarchical pedotransfer functions (Scott et al. 2000). Inverse modeling is also an option to determine missing hydraulic parameters during the calibration process. The inverse modeling is a widely used tool for determining unknown variables based on observation of their effects, as opposed to modeling of direct problems whose solution involves finding effects on the basis of a description of their causes (Hopmans et al. 2002). This approach has been widely adopted for characterizing flow through porous media (Hopmans et al. 2002).

Model evaluation is vital for assessing the performance of a modeling tool. This requires both visual and statistical analysis. Visual evaluation comparing simulated and observed results is the initial test to study whether the trends observed in the simulated results correspond to the observed results. It should however be noted that observing trends is not sufficient to assess the efficiency of the model (ASCE 1993). Therefore, statistical analysis is used to compare the simulated and observed results (ASCE 1993). Statistical parameters available for evaluating hydrological models may include the coefficient of determination (R^2) between simulated and observed data, slope and intercept of a regression line, the Nash–Sutcliffe modeling efficiency coefficient (NSE), percent bias (PBIAS), and the ratio of root mean square error to observation standard deviation (RSR). The NSE, PBIAS, and RSR values are estimated using equations 2.2, 2.3, and 2.4, respectively (Moriasi et al. 2007).

$$\mathrm{NSE} = 1 - \left[\frac{\sum_{i=1}^{n}\left(y_i^{obs} - y_i^{sim}\right)^2}{\sum_{i=1}^{n}\left(y_i^{obs} - y^{mean}\right)^2}\right] \tag{2.2}$$

$$\mathrm{PBIAS} = \left[\frac{\sum_{i=1}^{n}(y_i^{obs} - y_i^{sim}) \times 100}{\sum_{i=1}^{n}(y_i^{obs})}\right] \tag{2.3}$$

$$\mathrm{RSR} = \frac{\mathrm{RMSE}}{\text{Standard deviation}} = \frac{\left[\sqrt{\sum_{i=1}^{n}\left(y_i^{obs} - y_i^{sim}\right)^2}\right]}{\left[\sqrt{\sum_{i=1}^{n}\left(y_i^{obs} - y^{mean}\right)^2}\right]} \tag{2.4}$$

Where y_i^{obs} is the ith observation for the constituent being evaluated, y_i^{sim} is the ith simulated value for the constituent being evaluated, y^{mean} is the mean of the observation data for the constituent being evaluated and n is the total number of observations.

The R^2 determines the fraction of the variation in the observed data accounted for by the model. Values of R^2 range from 0.0 to 1.0 with values greater than 0.5 indicating acceptable model performance (Moriasi et al. 2007). The slope and y-intercept of the best fit determine how well the simulated data match the observed data. A value of slope close to one and y-intercept close to zero indicate a strong relationship between simulated and observed values. The Nash–Sutcliffe modeling efficiency coefficient (NSE) compares the variance in the simulated data to the variance in the observed data (Moriasi et al. 2007). The NSE value ranges from $-\infty$ and 1.0, with NSE equal to 1.0 being the optimal value. Acceptable model performance should have NSE values between 0.0 and 1.0 (Moriasi et al. 2007). NSE values less than 0.0 indicate that the observed mean value is a better predictor than the simulated mean value, which makes the performance of a model unacceptable (Gupta et al. 1999). Percent bias (PBIAS) shows whether the simulated results were underestimated or overestimated by the model (Gupta et al. 1999). The optimal value of PBIAS is 0.0, with low-magnitude values indicating accurate model simulation. Positive values of PBIAS indicate model underestimation bias, and negative values indicate model overestimation bias (Gupta et al. 1999). The acceptable value for model performance is ± 10%. The RSR is obtained by standardizing the Root mean square error (RMSE) with the observation data standard deviation. The RSR shows the difference between the observed values and the simulated values (Moriasi et al.

2007). The RSR value ranges from zero to a large positive value (Moriasi et al. 2007). An RSR value of zero indicates that RMSE or residual variation is zero, which implies the model simulates perfectly. A lower RSR value implies a lower RMSE value and a better model performance. RSR value less than 0.5 is considered very good (Moriasi et al. 2007). Values of 0.6 and 0.7 are considered good and satisfactory, respectively (Moriasi et al. 2007).

2.7 Summary of review

In this chapter, a review on several factors that affect soil and water management practices for improved field operations was presented. The review indicates that extensive research has been conducted to better understand soil and water management practices. From the review, it was apparent that soil and water management practices are influenced by several factors. These factors may include climate, weather, soil type, soil health, crop type, data availability, and management choices. Therefore, field specific data are needed to better design soil and water management systems to obtain expected outcomes. However, information from other studies can also be used for preliminary design and be monitored to revise design criteria to suit local conditions.

In the present study the impact of soil and water management practices on soil strength for field operations on sandy loam soil in southern Manitoba was evaluated. The study focused on subsurface drainage and its ability to improve soil water content in the top 0.5 m depth of the soil profile to provide sufficient strength for field operations and minimize the risk of subsoil compaction. Also, the impact of loose and moderately compact soil on soil water flow was assessed. This study was conducted under local conditions to better understand the drainage requirement for addressing excess soil water content during the growing season. Farmers in this region experience excess soil water especially at the beginning of the growing season when the fields need to be prepared for seeding. Although, there have been recent studies on using subsurface drainage systems to improve the soil water content in southern Manitoba (Satchithanantham 2013; Cordeiro 2014), their focus was on improving crop yield without considering the impact of the drainage design on improving the soil strength to allow field operations. A recent study conducted by Kaja (2017) addressed the impact of drainage design on soil strength but did not focus on the early part of the growing season when field operations are intense and may have significant impact on the soil structure. Also, his study did not account for evapotranspiration impact on soil water flow dynamics. Based on the reviewed literature, it was clear that a better understanding of drainage requirements under local conditions would help minimize excess soil water content to conserve the soil structure. This would ensure long-term soil health for sustainable crop production in this region.

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Chapter 3

HYDRUS (2D/3D) simulation of water flow through sandy loam soil under potato cultivation in southern Manitoba

Abstract

The objective of this study was to assess the performance of the HYDRUS (2D/3D) modeling tool for simulating water flow through subsurface-drained sandy loam soil under potato (*Solanum tuberosum*) cultivation in southern Manitoba. The model was used to simulate water flow through a two-dimensional cross section of 15-m width × 2.5-m depth. The performance of the HYDRUS (2D/3D) model for simulating soil water flow was assessed by comparing field measured soil water content data and the simulated soil water content data as well as the ability of the model to account for actual crop evapotranspiration. The measured soil water content data were obtained from the field during the growing season (i.e. from June 3 to September 24) of year 2011 at the Hespler Farms, Winkler, Manitoba. Weather data were obtained onsite and from a nearby weather station (Canada-Manitoba Crop Diversification Centre, Winkler) to estimate the reference crop evapotranspiration (ET_o). Based on the crop coefficient and the ET_o, the actual crop evapotranspiration (ET_a) was estimated and compared to the simulated ET_a data, which was based on the ET_o and the soil water pressure head. The results showed that the model was able to account for 50% to 78% of the variation in the estimated ET_a. With respect to water flow through the soil, the observed soil water content and the simulated soil water content were compared using the coefficient of determination (R^2), the Nash–Sutcliffe modeling efficiency coefficient (NSE), Percent bias (PBIAS), and ratio of root mean square error to observations standard deviation (RSR). The R^2 showed that the model accounted for 68% to 89% variation in the observed data. The intercept of the regression line varied from 0.01 to 0.08 and the slope, 0.75 to 0.99. The NSE varied from 0.62 to 0.89, PBIAS varied from -1.99% to 1.16%. The RSR varied from 0.33 to 0.61. The values for the evaluation parameters show that the model was able to simulate the water flow through the soil profile reasonably well.

Keywords: evapotranspiration, HYDRUS (2D/3D), potato (*Solanum tuberosum*), sandy loam soil, soil water content, subsurface drainage.

3.1 Introduction

Soil water content plays a key role in planning and carrying out field operations. For instance, soil water content determines the suitability of the soil to allow field operations without damaging the soil structure. Scarcity or excess soil water content at the various stages of a plant growth can affect physiological processes such as root respiration and plant water and nutrient uptake, which will lead to lower crop yield.

Obtaining field information on soil water content to design and improve soil water management systems can take a long period. Several measurement techniques for soil water content measurement in the field are available. These techniques are categorized into classical methods such as neutron scattering and gravimetric methods, and modern sensor methods such as time domain reflectometry, frequency domain reflectometry, and capacitance methods (Evett 2003; Radcliffe and Šimůnek 2010). These techniques are limited spatially and temporally, making it difficult and expensive for wider coverage measurement.

Modeling field hydrological processes in conjunction with field research is vital for improving soil water dynamics for field operations. Modeling can extend the field studies to a wider area. Several models are available for simulating the dynamics of soil water flow to predict the soil water content. Some of the common models include DRAINMOD (Singh et al 2006; Cordeiro 2014), RZWQM (Singh et al. 1996; Shrestha and Datta 2015) and HYDRUS 1D (Tafteh and Sepaskhah 2012). These models are one-dimensional, which simplifies the flow dynamics in the soil profile.

The objective of the present study was to evaluate the performance of the HYDRUS (2D/3D) model for predicting soil water content by simulating water flow through a subsurface-drained sandy loam soil under potato (*Solanum tuberosum*) cultivation in southern Manitoba. HYDRUS (2D/3D) is a Windows-based computer program that simulates water flow through two- and three-dimensional variably saturated porous media by solving the Richards equation. Detailed description of the model is available in Šimůnek et al. (2012a).

3.2 Materials and Methods

3.2.1 Field study

3.2.1.1 Field characteristics

Soil water content, groundwater depth, and weather data used in the present study were obtained from a potato farm commercially operated by the Hespler Farms during the growing season (i.e. from June 3 to September 4) of 2011 (Satchithanantham 2013). The site is located south of Winkler (49^o 10`N Lat., -97$^o$ 56`W Long., 272-m elevation) in the Rural Municipality of Stanley.

The climate of the study area is cool sub-humid continental, which makes it suitable for cultivating a wide range of agricultural crops (Smith and Michalyna

1973). During the growing season, May is the coldest month with a daily average temperature of 12.9°C and July is the warmest month with a daily average temperature of 20.1°C (Environment Canada 2016). The study area receives an annual average precipitation of 533.3 mm of which the growing season receives 341.5 mm precipitation in the form of rainfall (Environment Canada 2016).

The study site has a “nearly level” topography with the slope of the field ranging from 0.5% – 2%. The major soil type in the study area is the Reinland series, which is made up of “imperfectly drained” Gleyed Carbonated Rego Black soils (Smith and Michalyna 1973). The soil textural class at the site is sandy loam with average textural fractions of 70% sand, 19% silt, and 11% clay. This classification was based on soil samples obtained up to 1.2 m depth of the soil profile. There is an impermeable layer of clay located at 6 m below the soil surface (Cordeiro 2014).

The entire field was 5.16 ha with dimensions 300 m × 172 m. The field was divided into two subsections by a 4-m wide alleyway running in the north-south direction. Each subsection of the field with dimensions of 300 m × 84 m had 12 sub plots. The dimensions of the sub plots were either 50 m × 44 m or 50 m × 40 m. The two sides were switched during subsequent seasons to allow for crop rotation between potato and corn. In 2011, potato was cultivated on the western side and corn (*Zea mays*) on the eastern side. In the present study, soil characteristics for the plots under potato cultivation were used.

There were four watertable management systems practiced on the farm. That is free subsurface drainage with overhead irrigation (linear move irrigation system (O3000 Orbitor, Nelson Irrigation Corporation, Walla Walla, WA) (FDIR), controlled drainage with sub-irrigation (CDSI), no drainage with overhead irrigation

(NDIR), and no drainage with no irrigation (NDNI). Each water management was applied to three plots on each half of the field. Based on the sequence of numbering of the plots in the field, the simulation exercise was done for two plots, that is plot 16 and plot 18 under the FDIR plots on the western side of the alleyway. The data used for the simulation was from June 3 - August 26, 2011 for calibration and August 27- September 24, 2011 for validation.

3.2.1.2 Field data collection

Field data including groundwater level, soil water content and weather parameters were collected and used as input data in the simulation exercise. A detailed description of the field data collection is available in Satchithanantham (2013). However, a summary of the data collection procedure is presented in this section. Groundwater level was monitored at three-hour intervals with water level sensors (Solinst Leveloggers Junior 3001, Solinst Canada, Ltd., Georgetown, Ontario, Canada) hung inside of piezometers of 41.3 mm internal diameter and 2.51 m length schedule 40 steel pipe (Satchithanantham 2013). The piezometers were installed in manually augered holes to a depth of 2.2 m from the soil surface at the center of each plot. The top 0.3 m of the piezometer was above the soil surface to prevent runoff entry. The three-hour data obtained were averaged for daily groundwater level and used as input in the simulation exercise.

Volumetric soil water content was measured at three-hour interval in the field. The volumetric soil water content was measured using EC-5 probes (Decagon Devices, Inc., Pullman, Wash). These probes were installed at five different depths (0.2 m, 0.4 m, 0.6 m, 0.8 m, and 1.0 m) on each plot (Satchithanantham 2013). The three-hour data obtained were averaged for daily volumetric soil water content and used as input in the simulation exercise.

Weather data were collected using a Watchdog Weather Station (WatchDog 2900ET, Spectrum Technologies, Inc., Plainfield, IL, USA) located onsite. The onsite weather station data were supplemented by weather data obtained from a weather station located about 2-km east at the Canada-Manitoba Crop Diversification Centre, Winkler. The weather data collected were precipitation, temperature, wind speed, relative humidity and solar radiation. The weather data collected were used to estimate reference crop evapotranspiration (ET_o) using the Penman-Monteith equation (Allen 1998).

3.2.1.3 Partitioning of reference crop evapotranspiration

In the simulation exercise, the reference crop evapotranspiration was partitioned into reference evaporation and reference transpiration values. These values were entered as separate model input in the HYDRUS (2D/3D) model. The average leaf area index (LAI) of a reference grass of assumed height (h) 0.12 m (FAO 2016) was used as the coefficient to divide the reference crop evapotranspiration into reference transpiration and reference evaporation. The LAI of the reference grass was estimated as 2.88 from equation (3.1).

$$\text{LAI} = 24\text{ h} \tag{3.1}$$

Equations (3.2a) and (3.2b) were used to estimate the reference evaporation and reference transpiration, respectively (Qiao 2014).

$$\text{Reference crop evaporation} = ET_o \times e^{-k\times \text{LAI}} \tag{3.2a}$$

$$\text{Reference crop transpiration} = ET_o \times \left\lfloor 1 - e^{(-k\times \text{LAI})} \right\rfloor \tag{3.2b}$$

Where k is the coefficient governing radiation extinction by the canopy of the reference grass, usually ranging from 0.5 to 0.75 (Šimůnek et al. 2009). In the present study k = 0.5 was used to indicate that only half of the grass actively contributed to the surface heat and vapour transfer (Allen 1998).

3.2.1.4 Estimation of actual crop evapotranspiration

Actual crop ET (ET_a) was estimated based on the crop coefficient (K_c) of the potato crop and the reference crop evapotranspiration (ET_o) as shown in equation (3.3). The crop coefficient values for potato during the different growth stages were calculated based on the growing degree days using a method proposed by Ojeda-Bustamante et al. (2004).

$$\mathrm{ET_a} = \mathrm{K_c} \times \mathrm{ET_o} \tag{3.3}$$

In the HYDRUS (2D/3D) model, root water uptake is determined based on soil water pressure head and potential root water uptake Šimůnek et al. (2012 (a)). This eliminates the use of crop coefficient to determine the actual crop evapotranspiration in the model. The HYDRUS (2D/3D) simulates actual root water uptake using water stress response function proposed by Feddes et al. (1978) (in Šimůnek et al. 2012 (a)) or the S-shape function by van Genuchten (1985) (in Šimůnek et al. 2012 (a)). In the present study, the water stress response function by Feddes et al. (1978) was used to determine the actual root water uptake S(h), which is determined in the model by equation 3.4 (Šimůnek et al. 2012 (a)).

$$S(h) = \alpha(h)\, S_p \tag{3.4}$$

Where S_p is the potential root water uptake rate, which is the potential volume of water that can be removed from a unit volume of soil per unit time (Soylu et al.

2011). The S_p is equivalent to the reference crop evapotranspiration when integrated over the rooting depth of the actual crop based on the assumption that the soil surface is fully vegetated (Soylu et al. 2011). The water stress response function α(h), is a dimensionless function, which accounts for soil water limitation in the root water uptake process as a function of pressure head (Soylu et al. 2011; Šimůnek et al. 2012 (a)). It ranges from zero to one (Šimůnek et al. 2012 (a)). The water stress response function used by the Feddes model is presented in Figure 3.1. In the Feddes model (as demonstrated in Figure 3.1), water uptake is assumed to be zero when the pressure head is less or equal to pressure head at permanent wilting point (h_4 = - 160 m) and also near saturation (h_1 = - 0.1 m) (Feddes et al. 2001). This is because at or below permanent wilting point plants cannot extract water from the soil whereas at saturation there is limited root respiration, which hinders root water uptake (Feddes 2001; Smedema et al. 2004). When the term α(h) is one (for pressure head from h_2 (-0.25 m) to h_3 ($h_{3\ low}$ = - 3.1; $h_{3\ high}$ = - 6.2 m), root water uptake is not constrained by soil water, which allows for maximum root water uptake (Feddes et al. 2001; Soylu et al. 2011).

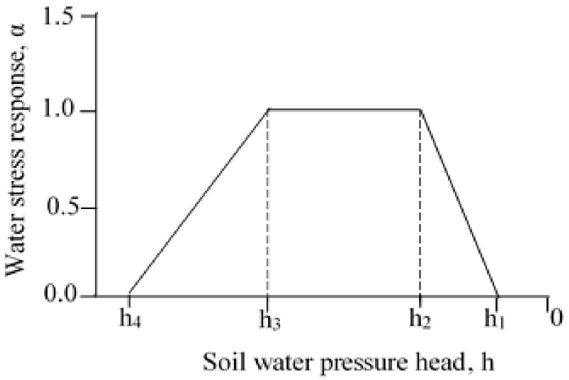

Figure 3.1:Water stress response function used by the Feddes model (Adapted from Šimůnek et al. 2012 (a))

3.2.1.5 Effective precipitation

The precipitation amount during the experimental period was reduced to account for rain interception by the crop canopy. The precipitation interception by the crop canopy was estimated using equation (3.5a) (Qiao 2014), where LAI reported in the literature for the various growth stages of potato crop was considered and the maximum interception rate was assumed to be 20%. The intercepted fraction of the precipitation was assumed to not reach the soil profile. Hence, the remaining precipitation was used as the precipitation input for the model. The effective precipitation was estimated by using equation (3.5b) (Qiao 2014).

$$\text{Interception rate} = \text{maximum interception rate} \times \frac{\text{LAI}}{\text{maximum LAI}} \tag{3.5a}$$

$$\text{Effective precipitation} = \text{measured precipitation} \times (1 - \text{interception rate}) \tag{3.5b}$$

3.2.2 Simulation of water flow through the soil

3.2.2.1 Soil Profile and drain tile representation

The HYDRUS (2D/3D) model allows two- and three- dimensional modeling of water flow through the soil profile. In this study, the two-dimensional mode was used to simulate the water flow in the vertical profile. Also, consideration of the computer memory and simulation run times made the two-dimensional mode more appropriate.

The model was used to simulate water flow through a two-dimensional cross-section of 15-m width × 2.5-m depth. This cross-section corresponded to the position of the drain tile with reference to the no flow boundaries in the dynamics of flow to the drain tile (Smedema et al. 2004), and depth below the seasonal watertable fluctuations. The soil profile was divided into four layers known as “surfaces” in the model. The first layer was from the soil surface to 0.4-m depth and the second layer was from 0.4 m to 0.6 m depth. These two layers helped to simulate the flow dynamics in the layer usually disturbed by field operations and flow dynamics in the layer where root water uptake is maximum. The third layer was from 0.6-m to 1-m depth, which helped to simulate the flow dynamics within the vicinity of the drain tile. The fourth layer was from 1-m to 2.5-m depth, which helped to account for the flow dynamics beneath the drain tile.

Based on the created soil profile, a triangular finite element (FE) mesh was created to serve as a basis for calculations for each layer. The stretching factor in the vertical direction for the FE mesh was 0.98 for the first three layers, and 0.63 for layer four. Stretching factor less than one was used so that the nodes in the vertical direction were denser than in the horizontal direction. The model domain had 31257 nodes. The mesh refinement was 0.05 m. As part of the triangular FE mesh, the drain tile was represented in the model domain as a hollow hole centered at a depth of 0.9 m. The drain tiles in the field were standard corrugated pipes having a diameter of 0.10 m. This diameter was represented with an effective diameter of 0.01 m with full permeability through the pipe walls to overcome the partial permeability of the standard corrugated pipes (Fipps et al. 1986; Qiao 2014).

3.2.2.2 Initial condition

The HYDRUS (2D/3D) model provided an option of setting the initial condition in terms of soil water pressure head or soil water content. In the present study, the volumetric soil water content determined at the various depths at the beginning of the field experimental period was used as the initial condition for the layers in the model domain. The summary of the initial condition for the layers is presented in Table 3.1.

Table 3.1: Initial soil water content for layers in the model domain

Layer (m)	Initial soil water content (m^3m^{-3})	
	Plot 16	Plot 18
0.0 - 0.4	0.29	0.15
0.4 - 0.6	0.32	0.14
0.6 - 1.0	0.38	0.25
1.0 - 2.5	0.34	0.34

3.2.2.3 Boundary conditions

The two-dimensional soil profile created had four external boundaries, which were the soil surface, the left side, the right side, and the bottom. There was also an internal boundary due to the hollow circular opening of the drain tile. The schematic of flow to a typical drain tile and the created model domain with the boundary conditions are presented in Figure 3.2(a) and Figure 3.2(b), respectively. The soil surface was assigned an atmospheric boundary, which processed daily atmospheric inputs of precipitation, evaporation, and transpiration. The left and right sides of the domain had no- flux boundary condition. The drain tile was located between two adjacent drain tiles; hence it was assumed that water did not flow horizontally across the left and right boundaries (Smedema et al. 2004). The boundary condition at the

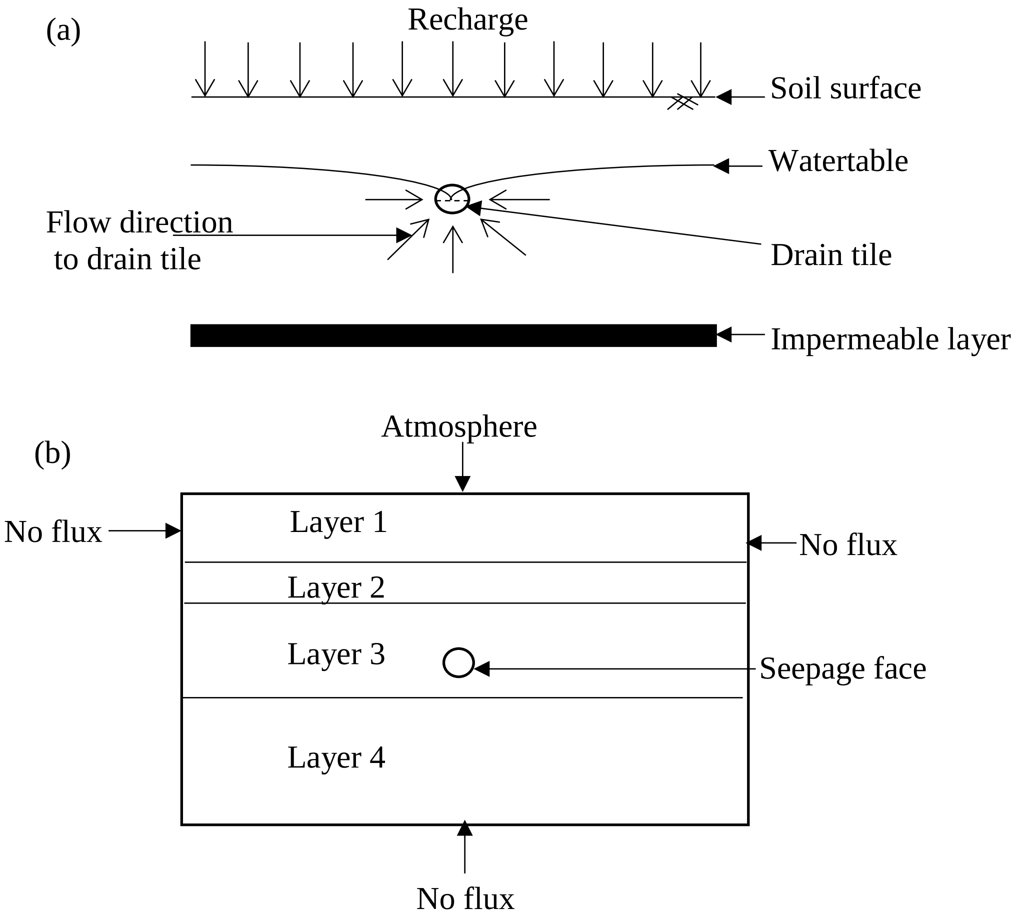

Figure 3.2: Schematic of (a) typical flow to drain tile (b) boundary conditions used in the created model domain (not drawn to scale)

bottom of the model domain was set to no-flux condition. This is because the groundwater level in the study area during the simulation period was within the model domain. Also, there is non-existence of groundwater regional flow in the study area. A seepage face was specified as the boundary condition for the drain tile.

3.2.2.4 Soil hydraulic parameter estimation

In the HYDRUS (2D/3D) model, the two-dimensional form of the Richards equation for simulating water flow through variably saturated porous media is as shown in equation (3.6) (Šimůnek et al. 2012 (b)).

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x_i}\left[K\left(\left(K_{ij}^{A}\right)\frac{\partial h}{\partial x_j} + K_{iz}^{A}\right)\right] - S \tag{3.6}$$

Where θ is the volumetric soil water content, h is the pressure head, S is the sink term, which represents the volume of water removed per unit time from a unit volume of soil due to plant water uptake, x_i (i= 1, 2) is a spatial coordinate, t is time, K^{A}_{ij} are components of a dimensionless anisotropy tensor and K is the unsaturated hydraulic conductivity function, subscripts i and j represent two directions, x shows the horizontal coordinate, and z for the vertical coordinate.

The model used the soil hydraulic functions proposed by van Genuchten (1980) and Mualem (1976) to describe the soil water retention curve, θ(h), as shown in equation (3.7), and the unsaturated hydraulic conductivity function, K(h), as shown in equation (3.8).

$$\theta(h) = \begin{cases} \theta_r \frac{\theta_s - \theta_r}{[1+|\alpha h|^n]^m}, & h < 0 \\ \theta_s, & h \geq 0 \end{cases} \tag{3.7}$$

$$K(h) = K_s S_e^{l}\left[1 - (1 - S_e^{1/m})^m\right]^2 \tag{3.8}$$

Where $m = 1 - \frac{1}{n}$, $n > 1$; $S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r}$; θ_r [-] and θ_s [-] denote the residual and saturated water content, respectively; α [L^{-1}] is the reciprocal of the air-entry value; K_s [$L\ T^{-1}$] is the saturated hydraulic conductivity, n [-] is the pore-size distribution index, S_e [-] is the effective water content; and *l* [-] is the pore-connectivity parameter with an estimated value of 0.5, resulting from averaging conditions in a range of soils (Mualem 1976).

As depicted by equation (3.7) and (3.8), to accurately describe the hydrological processes in the soil profile, the soil water retention curve and hydraulic conductivity data must be acquired. However, these data were not determined experimentally for the study site in the present study. Hence, the inverse modeling option was used to determine the soil hydraulic parameters for the calibration process. The hydraulic parameters determined include the residual soil water content (θ_r), saturated soil water content (θ_s), parameters α and n, and saturated hydraulic conductivity (K_s). The inverse modeling is a widely used tool for determining unknown causes on the basis of observation of their effects as opposed to modeling of direct problems whose solution involves finding effects on the basis of a description of their causes (Hopmans et al. 2002). This approach has been widely adopted for characterizing flow through porous media (Hopmans et al. 2002). A detailed description of the inverse modeling procedure in determining the hydraulic parameters is available in Radcliffe and Šimůnek (2010) and Šimůnek et al. (2012 (b)). The input data for the inverse modeling in the present study include measured soil water content, effective precipitation, and reference crop evapotranspiration partitioned and entered into the model separately as reference evaporation and reference transpiration. Optimization of the hydraulic parameters was done to obtain acceptable predicted estimates based on statistical and graphical comparison of the measured soil water content data and the predicted soil water content data based on the model estimated hydraulic parameters. The values for θ_r, θ_s, α, n, and K_s estimated from the inverse modeling for the soil layers are shown in Table 3.2 and Table 3.3 for plots 16 and 18, respectively. The volumetric soil water content predicted with these estimated hydraulic parameters were compared with the field-measured data, and the results are presented in section 3.3 (Results and Discussion).

Table 3.2: Soil hydraulic parameters estimated from inverse modeling for Plot 16

Depth (m)	θ_r (m^3m^{-3})	θ_s (m^3m^{-3})	α	n	K_s (m day^{-1})
0 - 0.4	0.06	0.40	0.078	1.293	1.66
0.4 - 0.6	0.04	0.42	0.019	1.576	1.21
0.6 - 1	0.04	0.42	0.019	1.576	1.21
1 - 2.5	0.04	0.43	0.048	1.173	3.50

Table 3.3: Soil hydraulic parameters estimated from inverse modeling for Plot 18

Depth (m)	θ_r (m^3m^{-3})	θ_s (m^3m^{-3})	α	n	K_s (m day^{-1})
0-0.4	0.04	0.41	0.423	1.368	3.70
0.4-0.6	0.04	0.41	0.016	1.487	1.41
0.6-1	0.04	0.41	0.016	1.487	1.41
1-2.5	0.04	0.41	0.024	1.239	3.50

3.2.2.5 Evaluation of model performance

The performance of the model to accurately simulate water flow through the soil profile was assessed by using graphical comparison of both simulated and observed soil water content data at five different observation depths (0.2 m, 0.4 m, 0.6 m, 0.8 m, and 1.0 m), the coefficient of determination (R^2) between simulated and observed data, slope, and intercept of regression line, the Nash–Sutcliffe modeling efficiency coefficient (NSE), percent bias (PBIAS), and the ratio of the root mean square error to observations standard deviation (RSR). The NSE, PBIAS, and RSR values were estimated using equations 2.2, 2.3, and 2.4, respectively (Chapter 2, section 2.6).

3.3 Results and Discussion

3.3.1 Sources of water in the soil profile

Figure 3.3 shows the variation in groundwater level in relation to precipitation and irrigation over the experimental period. The experimental period covered the four growth stages of potatoes, which are vegetative, tuber initiation, tuber bulking, and maturation. Precipitation and irrigation amount over the experimental period was

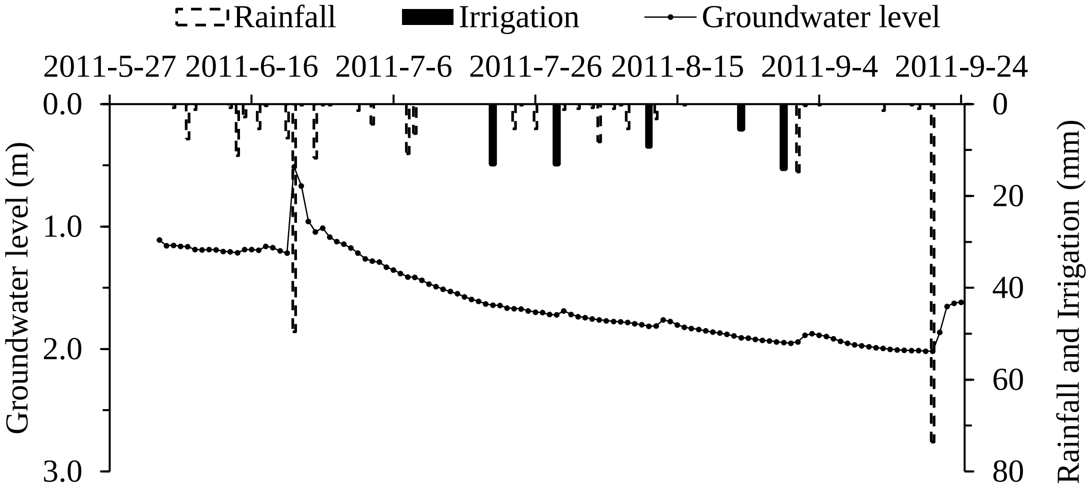

Figure 3.3: Variation in groundwater level in relation to rainfall and irrigation

242 mm and 54.6 mm, respectively. At the beginning of the experimental period, soil water content was replenished by rainfall, which recharged the groundwater. The groundwater level rose to about 0.5 m from the soil surface after a rainfall event of 49 mm on June 22. Subsequently, the groundwater level declined continuously below the drainage base of 0.9 m irrespective of subsequent recharge events. Dry period from July 20 to August 30 coincided with the tuber initiation stage through tuber bulking stage of the potato crop. Rainfall amounts of 32.2 mm occurred during that period. Moisture availability during the tuber initiation and bulking stages are critical for optimum yield (Rowe 1993). Hence, irrigation was done to meet the crop water demand. The irrigation events were monitored with tensiometers installed up to 1 m depth of the soil profile at 0.2 m intervals. An irrigation event occurred whenever the installed tensiometer at any of the top 0.6 m depth readings exceeded -25 kPa. During the experimental period, irrigation was applied through five irrigation events to replenish the losses from evapotranspiration. No supplemental irrigation was applied during the maturation stage since potatoes do not need as much water during the maturation stage (Rowe 1993). The total amount of irrigation water applied was about 50% less than the average annual moisture deficit of 90 mm due to significant moisture contribution from groundwater and rainfall. In the present study, groundwater contribution to soil water content was not evaluated. In previous studies (Abbas and Sri Ranjan 2015; Cordeiro et al. 2015), it was demonstrated that groundwater contributes to soil water to meet crop water demands at the study site.

3.3.2 Simulation of crop evapotranspiration

Soil water loss to ET_a causes significant changes in the soil water dynamics especially in the top 1.0 m depth of the soil profile (Smedema et al. 2004).

Consequently, a modeling tool capable of simulating the ET_a is vital for accurate prediction of soil water content. In the present study, the water stress response function by Feddes et al. (1978) (in Šimůnek et al 2012 (a)) was used to determine the ET_a in the model. Simulated ET_a results were compared to the estimated field ET_a results. The visual comparison between the estimated and simulated ET_a for plots 16 and 18 are presented in Figure 3.4(a) and Figure 3.4(b), respectively. Included in the figures is the volumetric soil water content (SWC) averaged over 0.6 m depth of the soil profile. The averaging was done over 0.6 m depth based on the assumption that maximum water uptake for potato crop occurs in the top 0.6 m of the rooting depth. As mentioned earlier, in the HYDRUS (2D/3D) model, root water uptake is a function of the ET_o and the soil water pressure head, which is related to the soil water content. The trend observed in the simulated ET_a values in Figure 3.4(a) and Figure 3.4(b) shows that during periods of relatively high-soil water content, the ET_a was high and vice-versa. That is increasing water content increased the ET_a and vice-versa. Also depicted in Figure 3.4, the model overestimated the ET_a in the early vegetative growth stage, underestimated during tuber initiation and the early part of tuber bulking stage. This observation was attributed to the absence of the crop coefficient in estimating the ET_a in the model. At the early growth stage, the potato crops have shallow roots, which implies low ET_a (as depicted by the trend in the estimated ET_a). During the tuber initiation and tuber bulking stage, through to the early period of maturation stage, there is an increased root development and groundcover for an increased ET_a (as depicted in the trend for the estimated ET_a). The opposite of this observation was seen in the trend for the simulated ET_a. The

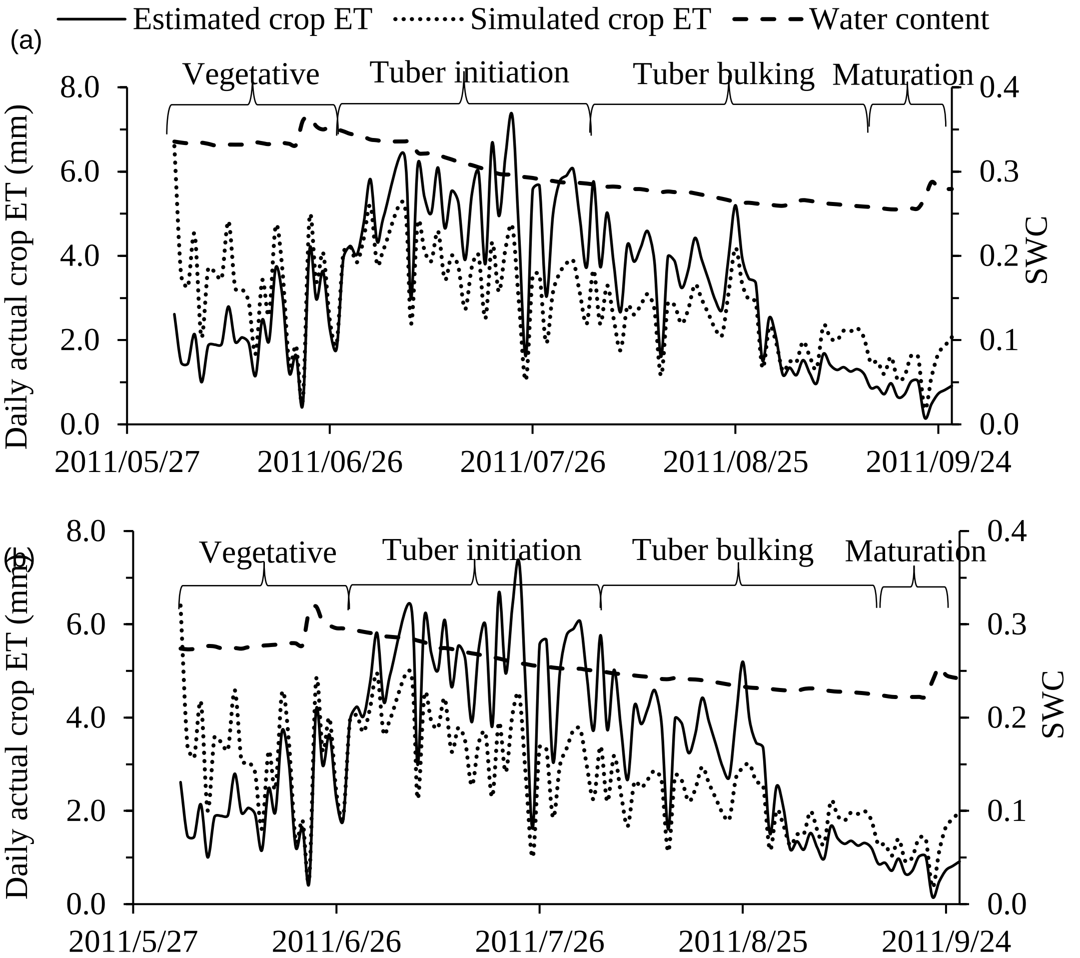

Figure 3.4: Visual comparison between estimated and simulated ET_a (a) Plot 16 (b) Plot 18

simulated ET_a was overestimated whenever there was an increase in the soil water content and vice-versa.

The correlation between the simulated and estimated ET_a for the various growth stages for plots 16 and 18 are presented in Figure 3.5 and Figure 3.6, respectively. The correlation between the simulated and estimated ET_a confirms the trend observed in Figure 3.4. The model performance improved with increasing root development and ground cover (from tuber initiation to tuber bulking stage) and then declined as the ground cover decreased (during the maturation stage). However,

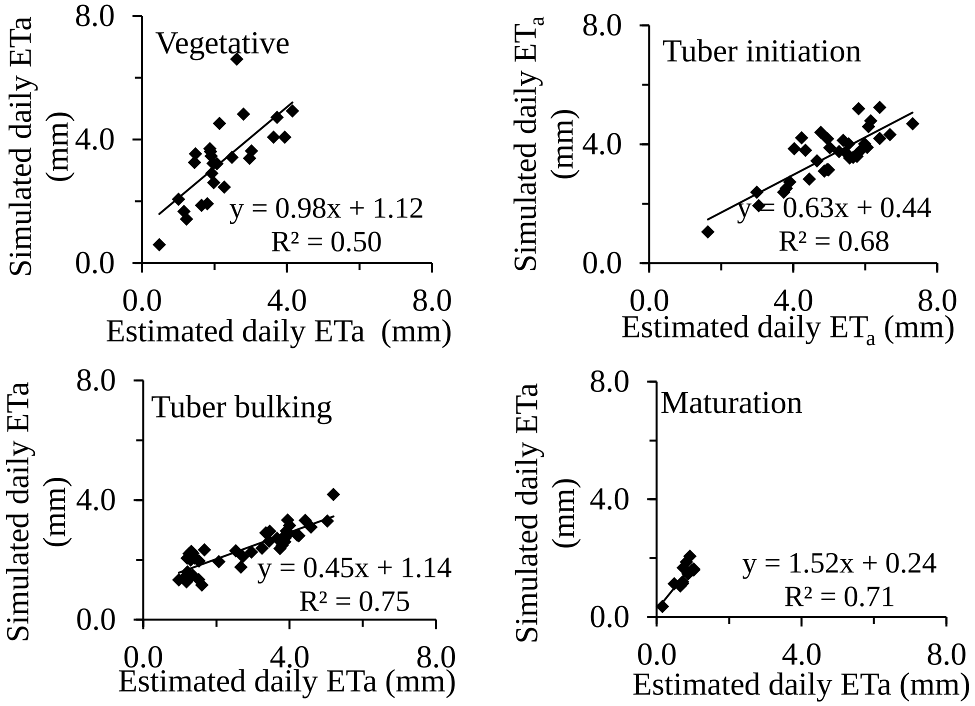

Figure 3.5: Plot 16 - Correlation between simulated and estimated daily ET_a for the various growth stages of the potato crop

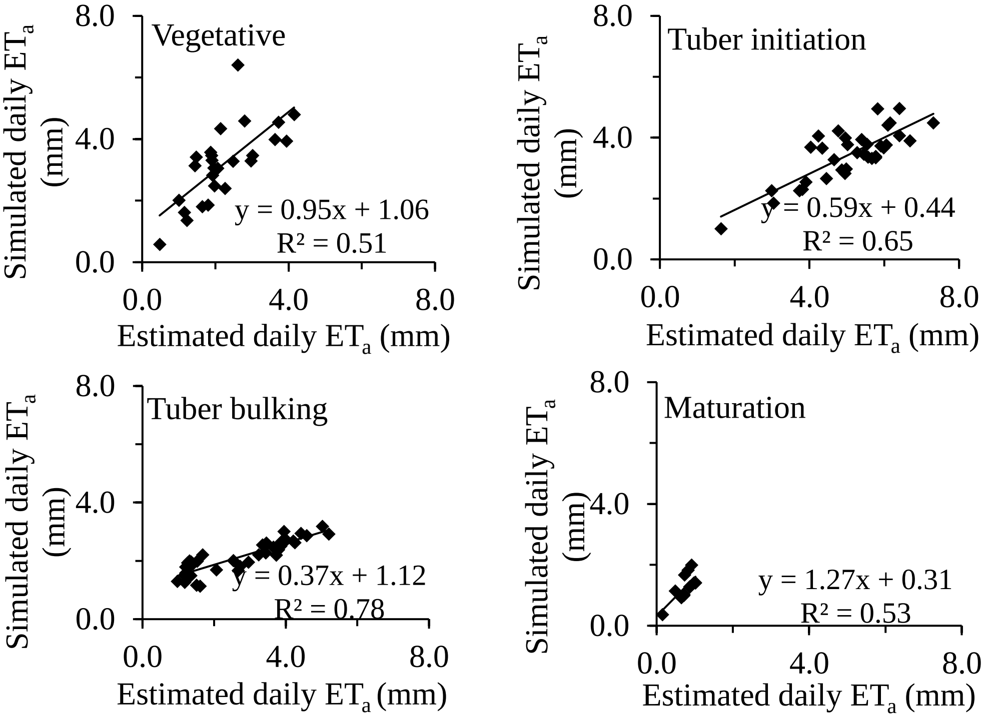

Figure 3.6: Plot 18 - Correlation between simulated and estimated daily ET_a for the various growth stages of the potato crop

values of R^2 greater than 0.5 indicate an acceptable model performance (Moriasi et al. 2007). The model accounted for 50% to 78% of the variation in the estimated data for the ET_a. Hence, simulation of the ET_a by the model was acceptable.

3.3.3 Simulation of soil water content

Figure 3.7 and Figure 3.8 show the graphical presentation of the simulated and observed soil water content for plots 16 and 18, respectively. The distribution of soil water content at five observation depths, that is 0.2 m, 0.4 m, 0.6 m, 0.8 m, and 1.0 m are shown in the figures. Soil water content up to 1.0 m depth was of interest in this study since water content changes in the top 1.0 m depth of the soil profile are significant (Smedema et al. 2004). As shown in Figure 3.7 and Figure 3.8, the simulated results for both the calibration period and validation period reasonably followed the trend depicted in the observed results for both plots.

In addition to the visual presentation, statistical analysis of the model performance was done to ascertain the effectiveness of the HYDRUS (2D/3D) model to predict the soil water content at the study site. The statistical parameters used were the coefficient of determination (R^2) between simulated and observed data, slope and intercept of best fit, the Nash–Sutcliffe modeling efficiency coefficient (NSE), Percent bias (PBIAS), and ratio of root mean square error to observations standard deviation (RSR). In general, the statistical analysis for the model performance for the calibration period was better than the validation period. This was attributed to larger sample size for the calibration than the validation. Also, since the soil hydraulic parameter values were optimized during the calibration but not during validation, the performance of the model for the calibration period was expected to be better than the validation period. The correlation (R^2) between the simulated and observed soil

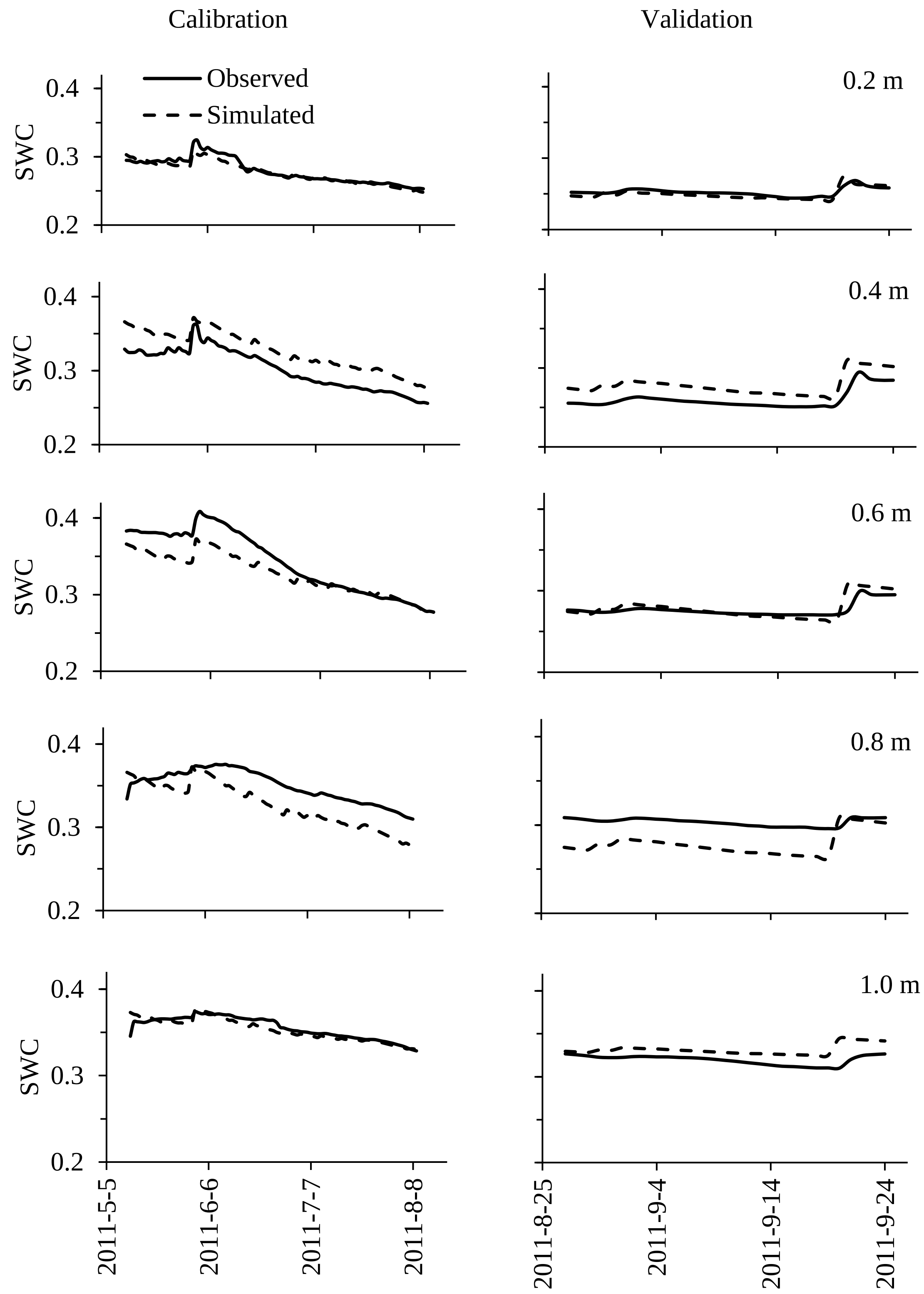

Figure 3.7: Visual comparison between observed and simulated soil water content for Plot 16

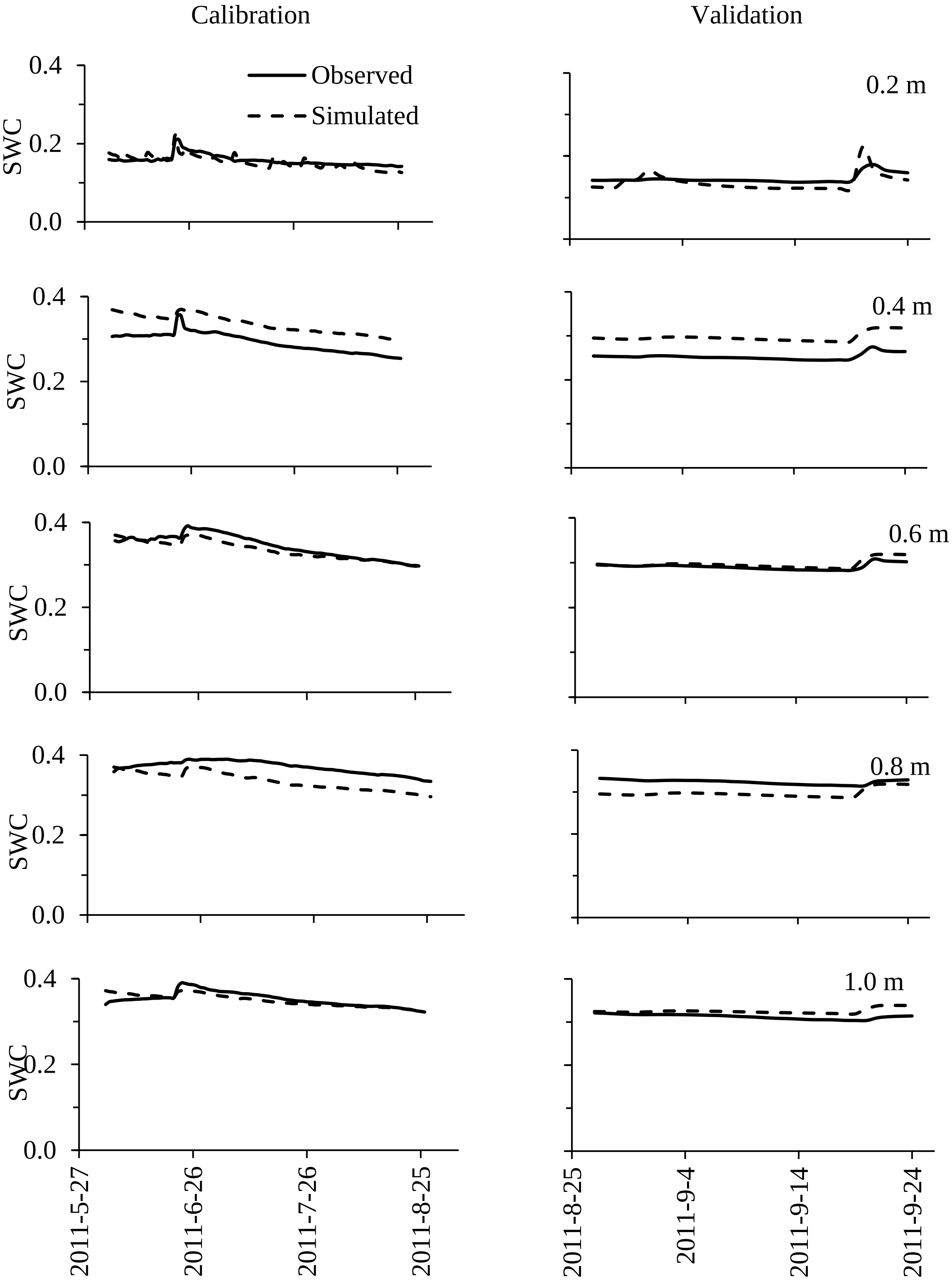

Figure 3.8: Visual comparison between observed and simulated soil water content for Plot 18

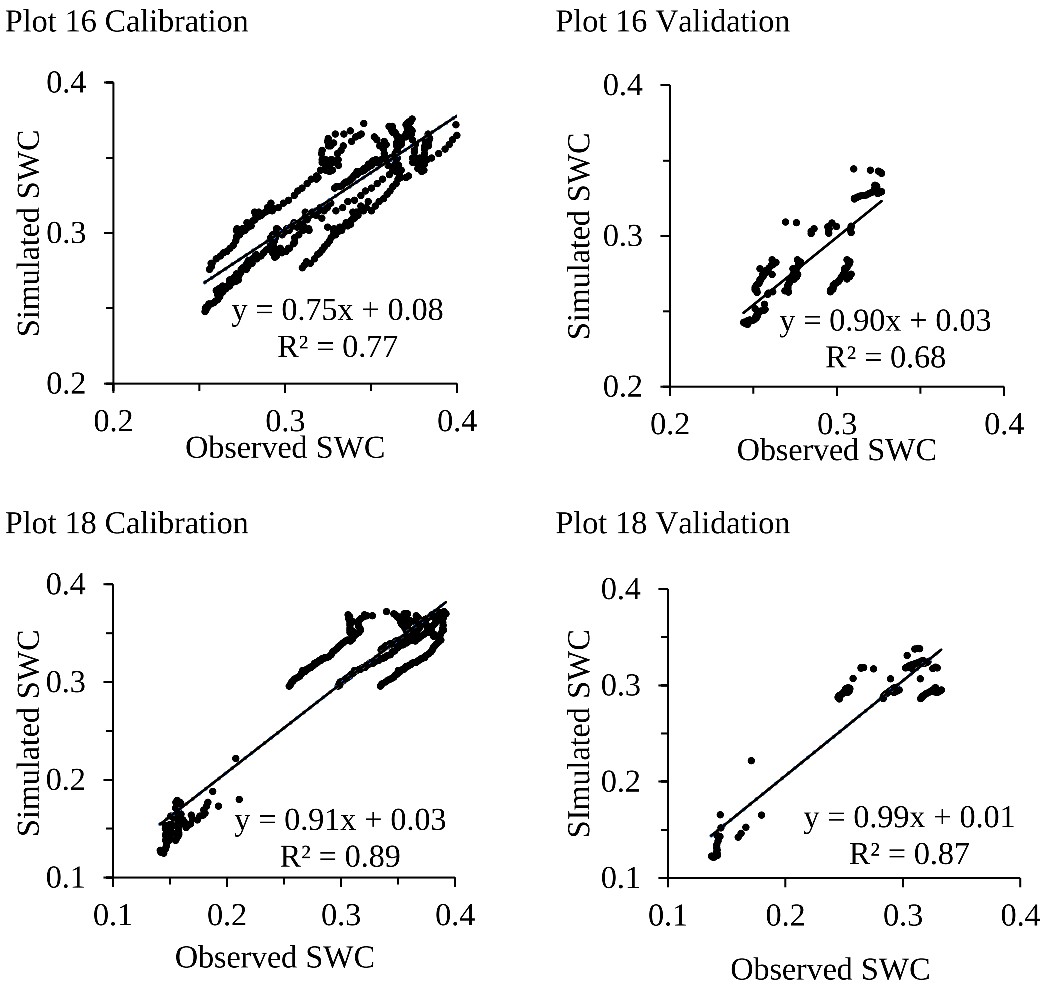

Figure 3.9: Correlation between observed and simulated soil water content

water content data is presented in Figure 3.9. Values of R^2 range from 0.0 to 1.0 with values greater than 0.5 indicating acceptable model performance (Moriasi et al. 2007). The correlation between the simulated and observed results was strong for both plots for both calibration and validation. The model accounted for 68% to 89% of the variation in the observed data, which is an acceptable performance of the model (Moriasi et al. 2007). The slope and y-intercept of the best-fit was used to determine how well the observed results matched the simulated results for the model domain. The slope of best fit for both plots were close to1.0 and the y-intercept for both plots were close to 0.0 for both calibration and validation. Slope of the best fit being closer to 1.0 indicated a strong relationship between simulated and observed values. A y-intercept close to 0.0 was an indication that the simulated and observed results were reasonably aligned (Moriasi et al. 2007).

The estimated values for the NSE, PBIAS, and RSR for both plots for the calibration and validation periods are presented in Table 3.4. Also included in the table are the corresponding values for acceptable model performance. The NSE was used to compare the variance in the simulated data to the variance in the observed data (Moriasi et al. 2007). Its value ranges from $-\infty$ and 1.0, with NSE equal to 1.0 being the optimal value. A model is considered to have an acceptable performance with NSE values between 0.0 and 1.0 (Moriasi et al. 2007). Values less than 0.0 indicates that the mean observed value is a better predictor than the simulated value, which makes the performance of a model unacceptable (Gupta et al. 1999). As shown in Table 3.4, the NSE value was acceptable and close to 1.0 for calibration and validation for both plots. The NSE values for the calibration periods were higher than the validation period for both plots due to the larger sample size used for the calibration. The model performance was satisfactory since the NSE values for calibration and validation periods were greater than 0.5. Percent bias (PBIAS) analysis was done to study how much the simulated data over- or under- estimated the observed data (Gupta et al. 1999). The optimal value of PBIAS is 0.0, with low-magnitude values indicating accurate model simulation. Positive values of PBIAS indicate model underestimation bias, and negative values indicate model overestimation bias (Gupta et al. 1999). As presented in Table 3.4, the PBIAS values for both calibration and validation for both plots were within ±10%, which indicated a very good model performance (Moriasi et al. 2007). The residual error in the data

Table 3.4:Summary of estimated values for evaluation parameters

Parameter	Plot 16		Plot 18		Acceptable values
	Calibrated	Validated	Calibrated	Validated	
NSE	0.76	0.62	0.89	0.84	0.0-1.0
PBIAS	1.16%	-0.34%	0.61%	-1.99%	±10%
RSR	0.49	0.61	0.33	0.39	< 0.7

was assessed using standardized root mean square error (RMSE) known as the RMSE-observations standard deviation ratio (RSR) proposed by Moriasi et al. (2007). The RSR value ranges from zero to a large positive value (Moriasi et al. 2007). The RSR value of zero indicates that RMSE or residual variation is zero. This implies the model simulates perfectly. A lower RSR value implies a lower RMSE value and a better model performance. RSR value less than 0.5 is considered very good. Values at 0.6 and 0.7 are considered good and satisfactory, respectively. As presented in Table 3.4, the RSR values for the calibration period for both plots were lower than that for the validation period, which was attributed to the large sample size for the calibration period and parameter optimization limited to only the calibration. The RSR values for Plot 16 were 0.49 and 0.61 for the calibration and validation, respectively; and that for Plot 18 were 0.33 and 0.39 for the calibration and validation, respectively. These RSR values indicated that the model performance varies from satisfactory to very good.

3.4 Conclusion

HYDRUS (2D/3D) model was used to simulate water flow through a subsurface-drained sandy loam soil under potato cultivation in southern Manitoba. Graphical comparison and quantitative statistics including R^2, slope and intercept of best fit, NSE, PBIAS, and RSR were used to assess the performance of the model. The ability of the model to account for root water uptake was also used to assess the model performance. The graphical comparison showed that the simulated soil water content results followed the trend in the observed results reasonably well. The correlation (R^2) between the simulated and observed soil water content data varied from 68% to 89%, which was greater than 50% as the threshold for good performance of a model. The intercept of the best fit varied from 0.01 to 0.08, which were close to 0.0. The slope of the best fit varied from 0.75 to 0.99, which were close to 1.0. The NSE varied from 0.62 to 0.89, which made the performance of the model satisfactory. PBIAS values varied from -1.99% to 1.16%, which were within the acceptable range of ±10%. The RSR values varied from 0.33 to 0.61, which were also in the acceptable range for model performance. The model was able to account for 50% to 78% of the variation in the estimated actual crop ET, which indicated a satisfactory model performance. From the graphical and quantitative analysis, the HYDRUS (2D/3D) model was able to simulate water flow through the subsurface drained sandy loam soil under potato cultivation located in southern Manitoba reasonably well.

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Chapter 4

Subsurface drainage for promoting soil strength for field operations in southern Manitoba

Abstract

The objective of the present study was to evaluate the performance of subsurface drainage in promoting soil strength for field operations in southern Manitoba. This study was conducted to address excess soil water that farmers experience in the region during the growing season. The performance of subsurface drainage in promoting soil strength sufficient for field operations was assessed using field data and modeling. Field data including soil water content, lower plastic limit, and watertable depth were collected in a potato field operated by the Hespler Farms, Winkler, Manitoba during the 2011 growing season. Seventeen-year weather data were obtained from Environment Canada for this location in addition to data acquired onsite and from a nearby weather station (Canada-Manitoba Crop Diversification Centre, Winkler) to estimate reference crop evapotranspiration. The soil strength of drained and undrained sandy-loam fields at the study site was compared to evaluate subsurface drainage in promoting soil strength for field operations. The subsurface drain tile was installed at 0.9-m depth and at 15-m spacing. A validated HYDRUS (2D/3D) model was used to extend the study by simulating soil water content changes due to different drain spacings (8 m, 10 m, 12 m, 15 m, 20 m, and 30 m) for different years and weather conditions. The soil strength to allow field operations was assessed based on soil water content corresponding to 90% of the lower plastic limit (LPL) in the top 0.3-m depth of the soil, and soil water content corresponding to the LPL in the soil layer between 0.3-m to 0.5-m depth of the soil profile. The soil strength was sufficient to allow field operations when the two criteria were met. The results showed that in the top 0.3-m depth, the soil strength was sufficient to allow field operations for all the years with or without drainage. Drainage impact was found to be more significant within the 0.3-m to 0.5-m depth of the soil profile throughout the years. Drain spacing less or equal to 12 m promoted soil strength to allow field operations without any significant impact on the number of field workable days during the season. Drain spacing wider than 12 m led to a loss of more than eighteen field workable days, especially during wet years, when rainfall exceeded evapotranspiration.

Keywords: sandy loam soil, soil water content, watertable depth, evapotranspiration, subsurface drainage, soil strength, lower plastic limit, workability, HYDRUS (2D/3D)

4.1 Introduction

Soil strength plays a key role in planning field operations for optimum crop yield. During field operations, the soil should have the ability to provide traction and support agricultural traffic and be maneuvered in a desirable manner without degrading the soil and the ecosystem (Earl 1997). Field operations performed on wet soil result in compaction (Müller et al. 2011). Compacted soil profile hinders root development which can lead to yield losses in the short term and poor soil structural generation and regeneration in the long term (Whalley et al. 1995; Alakukku 2003). Poor soil structural generation and regeneration result in the inability of the soil to absorb high intensity rainfall leading to anaerobic conditions that promote the leaching and accumulation of toxic substances (Whalley et al. 1995).

Drainage systems have been useful in removing excess soil water from fields with “poor” natural drainage to allow timely field operations (Madramootoo et al. 2007; Müller et al. 2011). The drainage system helps to reduce the time that excess water remains on a field before it reaches a receiving system (Evans et al. 1996). The drainage system in crop production comprises field drains, collector drains, and outlet. The field drains gather the excess water from the field by means of a field drainage network. The main types of field drainage systems are surface and subsurface drainage systems. The surface drainage systems remove excess water from the land by lateral flow due to impeded infiltration and percolation at shallow depth by poorly permeable layers (Smedema et al. 2004). This implies excess water ponded on the soil surface will be drained by lateral overland flow, whereas soil water infiltration impeded at a shallow depth in the rootzone will be drained by interflow (Smedema et al. 2004). Subsurface drainage systems are useful when soil water is able to percolate through the soil to recharge the groundwater. The subsurface drainage removes gravitational water in the soil profile by means of buried perforated corrugated pipes to lower the watertable below the effective root zone (Guitjens et al. 1997; Cordiero 2014). Between surface drainage and subsurface drainage systems, the subsurface drainage systems have been proven to enhance soil water conditions better to allow timely field operations (Paul and DeVries 1979; Müller et al. 1990; Evans et al. 1996; Müller et al. 2011).

In the present study the performance of subsurface drainage in promoting soil strength for field operations in southern Manitoba was evaluated. This study was conducted to address excess soil water that farmers experience in the region, especially at the beginning of the growing season following snowmelt and occasionally with heavy rainfall at mid-season or at the time of harvest due to the “imperfect” to “poor” drainage characteristics of many agricultural soils in the region (Eilers et al. 2002). Delays in seeding, mid-season input application or harvest lead to yield losses and/or crop quality deterioration (Angadi et al. 2004; McKenzie et al. 2011), and thus have a significant economic impact to the agriculture industry. Surface drainage has been used for several years to improve the drainage characteristics of the fields in this region. Subsurface drainage, on the other hand, became popular in this region only during the past decade (Dietz 2010). The Soil Management Guide of Manitoba (MAFRI 2016) recommends subsurface drainage installation depths between 0.9 m to 1.05 m and spacing between 8 m and 15 m for high value crops. The general drainage installation parameters adopted in the region is 0.9-m depth and 15-m spacing.

In previous studies, subsurface drainage in this region was demonstrated to improve corn yield by 10 – 15% (Cordeiro 2014) and potato yield by 20 – 30% (Satchithanantham 2013). Cordeiro (2014) recommended that drain spacing in the region can be as wide as 40 m for sandy loam soils without significant impact on crop yield. Although, the yield impact of subsurface drainage has been researched, the effectiveness of subsurface drainage in promoting soil strength sufficient to allow field operations is not understood well.

Hence, the objective of the present study was to assess the performance of subsurface drainage in promoting soil strength sufficient to allow field operations without significant damage to the soil structure. This was done by comparing the soil strength of subsurface drained and undrained sandy loam fields using soil water content, watertable depth, and lower plastic limit of the soil data obtained from a potato field operated by the Hespler Farms, Winkler, Manitoba during the growing season of 2011. HYDRUS (2D/3D) model was used to extend the study by simulating soil water content changes due to different drain spacings (8 m, 10 m, 12 m, 15 m, 20 m, and 30 m) for different years and weather conditions to determine the optimum drain spacing that promotes soil strength for field operations at the study site.

4.2 Materials and methods

4.2.1 Field characteristics

Field study was carried out in a potato field operated by the Hespler Farms during the growing season (i.e. from June 3 to September 4) of 2011 (Satchithanantham 2013). The farm is south of Winkler (49^{o} 10`N Lat., $-97^{o}$ 56`W Long., 272-m elevation) in the Rural Municipality of Stanley, Manitoba; and it is within the fertile western section of the Red River Valley (Eilers et al. 2002). The topography of the study site is “nearly level” with a slope ranging from 0.5 – 2%. The soil at the study site is classified as Reinland series with “imperfect” internal drainage (Smith and Michalyna, 1973). The Reinland series is made up of Gleyed Carbonated Rego Black soils (Smith and Michalyna 1973). The soil textural classification at the study site was sandy loam with average textural percentages of 70% sand, 19% silt, and 11% clay. These average textural percentages were based on soil samples obtained up to 1.2 m depth of the soil profile. An impermeable layer of clay was located at 6 m below the soil surface (Cordeiro 2014).

The field had dimensions of 300 m × 84 m with 12 subplots. The dimensions of the subplots were either 50 m × 44 m or 50 m × 40 m. There were four watertable management systems tested in this farm. They were subsurface free drainage with overhead irrigation (linear move irrigation system (O3000 Orbitor, Nelson Irrigation Corporation, Walla Walla, WA) (FDIR), subsurface controlled drainage with sub-irrigation (CDSI), no drainage with overhead irrigation (NDIR) and no drainage with no irrigation (NDNI). Each water management system was applied to three plots. Details of the field layout showing the different water management systems are given in Satchithanantham (2013). In the present study, the field data from FDIR and NDNI replicated plots were used to assess subsurface drainage impact on soil strength.

4.2.2 Data collection

For each plot, soil water content and watertable depth were monitored from June 3 to September 24, 2011. The watertable depth was monitored at three-hour intervals over the experimental period with water level sensors (Solinst Leveloggers Junior 3001, Solinst Canada Ltd., Georgetown, ON, Canada) hung inside piezometers. The piezometers (41.3 mm internal diameter and 2.51 m length schedule 40 steel pipe) were installed to a depth of 2.2 m from the soil surface at the center of each plot. The screen depth of the piezometers was 1.6 m from the tip at the bottom. The sensors had a calibrated range of 0 to 5 m with an accuracy of 0.1% full scale or ± 0.006 m (Solinst Canada Ltd., 2011). The three-hour-interval data obtained were averaged for daily watertable depth.

The volumetric soil water content (θ) was measured at three-hour intervals with dedicated EC-5 (Decagon Devices, Inc., Pullman, WA, USA) probes. The EC-5 probe determined the volumetric soil water content using the frequency domain technique operating at a frequency of 70 MHz (Decagon Devices, Inc., 2016). The

EC-5 probes were telemetrically connected to the Weather Innovations Network to provide real time soil water content data through their website. The soil water content was monitored at 0.2 m interval up to 1.0-m depth of the soil profile on each plot (Satchithanantham 2013). The three-hour-interval data obtained were averaged for daily volumetric soil water content.

Weather data were obtained for the study area from Environment Canada in addition to data obtained onsite and from a nearby weather station (Canada-Manitoba Crop Diversification Centre, Winkler) to estimate reference crop evapotranspiration. The nearby weather station was about 2-km east from the study site. Three-year (year 2010 to 2012) weather data including precipitation, temperature, wind speed, relative humidity, and solar radiation data were collected using a Watchdog Weather Station (WatchDog 2900ET, Spectrum Technologies, Inc., Plainfield, IL, USA) located onsite and from the nearby weather station (Satchithanantham 2013). The data obtained onsite and from the nearby weather station were used to determine reference crop evapotranspiration (ET_o) using the Penman-Monteith equation (Allen 1998). For the HYDRUS (2D/3D) simulation exercise, seventeen years of weather data (2000-2016) including precipitation, minimum temperature, maximum temperature, and relative humidity were obtained from Environment Canada (Environment Canada 2017). These years were considered due to data unavailability prior to year 2000. The minimum temperature, maximum temperature, and relative humidity data were also used to determine the reference crop evapotranspiration as proposed by Maulé et al. (2006). The reference crop evapotranspiration data obtained from both methods for years 2010-2012 were compared to ascertain the efficiency of the method proposed by Maulé et al. (2006). The data from the two methods compared reasonably well (results not shown). The method proposed by Maulé et al. (2006) accounted for more than 70% of the variation in the data obtained using the Penman-Monteith equation. The reference crop ET data obtained for the seventeen years using the method proposed by Maulé et al. (2006) was used as input data in the HYDRUS (2D/3D) modeling exercise to predict the soil water content changes due to different weather conditions and drain spacings.

4.2.3 Criteria for soil strength to allow field operations

Subsurface drainage impact on soil strength was assessed within the top 0.5-m-layer of soil, which is directly influenced by field operations. To define the criteria for soil strength to allow field operations in the present study, two layers were considered. Layer one was from the soil surface to 0.3 m depth, and the second layer, was from 0.3 m to 0.5-m depth. Water content less than or equal to 90% of the lower plastic limit (0.9-LPL) of the soil was used for the top 0.3 m to ensure that the soil has sufficient strength to meet traction requirements and allow equipment to be maneuvered in a desirable way. In the second layer (0.3 m - 0.5 m), due to a higher average bulk density of 1370 kgm^{-3} compared to 1030 kgm^{-3} of layer one, soil water content corresponding to the LPL was used to assess its suitability to allow field operations. This is because at relatively high bulk density, the soil susceptibility to compaction is low (Imhoff et al. 2004). The LPL (or fraction of the LPL) is a widely accepted criterion used to ensure the shear strength of plastic soils can support field operations without significant soil structural damage (Dexter and Bird 2001). The LPL is related to the capillary pressure at which the water phase of the soil ceases to act as a continuum and serves as the threshold for the onset of brittleness (Haigh et al. 2013).

In the present study, the LPL was determined using the Casagrande plastic limit method known as the rolling method. The rolling method as described by ASTM D 4318 2010 standard was followed (ASTM D 4318-10e1. 2010). The LPL of the soil was determined at the Soil and Water Engineering Laboratory at the University of Manitoba. The rolling method for determining the LPL of the soil is subjective due to the unscientific nature, and it is considered operator specific (Haigh et al. 2013). To minimize operator variability and ensure precision, one operator conducted the test and repeated three times per sample collected from 0.2 m and 0.4-m depths of the soil profile at three different locations in the field. The summary of the LPL determined and the average textural percentages at 0.2 m and 0.4-m depths is presented in Table 4.1.

Table 4.1: Summary of LPL determined with the average textural percentages

Depth (m)	Sand	Silt	Clay	Average LPL
0.2	71.3	19.0	9.7	$0.39 \pm 4.4\times10^{-6}$
0.4	70.0	19.0	11.0	$0.37 \pm 5.7\times10^{-4}$

4.2.4 Simulation of soil water content changes due to different drain spacing

The HYDRUS (2D/3D) model was used to extend the study to assess drain spacing impact on soil water content and the subsequent effect on soil strength for field operations for the entire growing season (May – September). Extending the study helped to understand how drain spacing affects the soil strength, especially during spring operations, which is the most critical period for field operations in southern

Manitoba. Every year, the Manitoba Agricultural Services Corporation pays out millions of dollars to farmers under the Excess Moisture Insurance if they are not able to seed their fields prior to June 20 due to excessive soil water content (Manitoba Agricultural Services Corporation 2017).

The HYDRUS (2D/3D) model is a Windows-based computer program that simulates water flow through two- and three-dimensional variably saturated porous media by solving the Richards equation (Šimůnek et al. 2012 (a)). In this study, the two-dimensional option was used to simulate the water flow through the soil profile to predict the soil water content. This option was chosen due to practical consideration of computer memory and simulation run times. The two-dimensional form of the Richards equation for simulating water flow through variably saturated porous media is as shown in equation (4.1) (Šimůnek et al. 2012 (b))

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

where θ is the volumetric water content, h is the pressure head, S is the sink term, x_i is a spatial coordinate, t is time, $K^A{}_{ij}$ are components of a dimensionless anisotropy tensor and K is the unsaturated hydraulic conductivity function, subscripts i and j represent two directions, x shows the horizontal coordinate and z for the vertical coordinate.

4.2.4.1 Soil profile and drain tile representation

Six different two-dimensional scenarios were simulated. These scenarios represented water flow to drain tiles at different spacings. The following model domains were created: 8-m width × 2.5-m depth, 10-m width × 2.5-m depth, 12-m width × 2.5-m depth, 15-m width × 2.5-m depth, 20-m width × 2.5-m depth, and 30-m width × 2.5-

m depth. The width of the cross-section corresponded to the position of the drain tile with reference to the no flow boundaries on either side of the drain tile; and the depth corresponded to the depth below the seasonal watertable fluctuations. The 15-m spacing represented the drain spacing in the field. Each scenario profile was divided into four layers, which is known as “surfaces” in the model. The first layer corresponded with the top 0.4 m depth of the soil profile and the second layer was from 0.4 m to 0.6 m. The first and second layers helped to simulate the flow dynamics in the layer usually disturbed by field operations and flow dynamics in the layer where root water uptake is maximum. The third layer, 0.6 m to 1.0 m allowed for simulating water flow dynamics in the vicinity of the drain tile. The fourth layer, 1 m to 2.5 m, was included to accommodate the flow dynamics beneath the drain tiles.

Based on the defined simulation soil profile, a triangular finite element (FE) mesh was created to serve as a basis for calculations for each layer. The mesh refinement was 0.05 m. In the FE mesh, the drain tile was represented as a hollow hole centered at a depth of 0.9 m, which corresponded with the depth of the drain tile in the field. The drain tiles in the field were standard corrugated pipes with diameter of 0.10 m. The partial permeability of the corrugated pipe was accounted for by representing the diameter of the pipe with an effective diameter of 0.01m with full permeability through the pipe walls (Fipps et al. 1986; Qiao 2014).

4.2.4.2 Initial condition

Soil water content determined at the various depths at the beginning of the field experimental period (June 3, 2011) was used as the initial condition for the layers specified in the model domain. The summary of the initial soil water contents for the layers are as presented in Table 4.2

Table 4.2: Initial soil water content for the layers in the model domain

Depth (m)	Initial soil water content (m^3m^{-3})
0.0 - 0.4	0.29
0.4 - 0.6	0.32
0.6 - 1.0	0.38
1.0 - 2.5	0.40

4.2.4.3 Boundary condition

Four external boundaries were defined for the model domain. The boundaries included the soil surface, left side, right side, and the bottom. There was also an internal boundary due to the hollow circular opening of the drain tile. The boundary condition at the soil surface was specified as atmospheric, which processed daily atmospheric inputs of precipitation, evaporation, and transpiration. The left and right sides of the model domain had no flux boundary condition. This was because the drain tile was located between two adjacent drain tiles, creating a no flow boundary, which coincided with the mid-spacing with the adjacent tiles. The bottom of the model domain was set to no-flux boundary condition since the watertable depth in the study area during the simulation period was within the model domain.

4.2.4.4 Soil hydraulic parameter estimation

The hydrological processes in the soil profile are described by the soil water retention curve, the saturated hydraulic conductivity, and the unsaturated hydraulic conductivity of the soil (Radcliffe and Šimůnek 2010). The HYDRUS (2D/3D) model uses the soil-hydraulic functions proposed by van Genuchten (1980) and Mualem (1976) to describe the soil water retention characteristic curve, θ(h), as shown in equation (4.2), and the unsaturated hydraulic conductivity function, K(h), as shown in equation (4.3)

$$\theta(h) = \begin{cases} \theta_r \frac{\theta_s - \theta_r}{[1+|\alpha h|^n]^m}, & h < 0 \\ \theta_s, & h \geq 0 \end{cases} \tag{4.2}$$

$$K(h) = K_s S_e^l \left[1 - (1 - S_e^{1/m})^m\right]^2 \tag{4.3}$$

where $m = 1 - \frac{1}{n}$, $n > 1$; $S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r}$; θ_r [-] and θ_s [-] denote the residual and saturated water content, respectively; α [L^{-1}] is the reciprocal of the air-entry value; K_s [L T^{-1}] is the saturated hydraulic conductivity, n [-] is the pore-size distribution index, S_e [-] is the effective water content; and l [-] is the pore-connectivity parameter with an estimated value of 0.5, resulting from averaging conditions in a range of soils (Mualem, 1976).

The soil water retention characteristics curve and the hydraulic conductivity of the soil were not determined experimentally for the soil profile at the study site. Hence, the hydraulic parameters, that is, the residual water content (θ_r), saturated water content (θ_s), parameters α and n, and saturated hydraulic conductivity (K_s) were determined using the inverse modeling option in the HYDRUS (2D/3D) model. The inverse modeling is an alternative way of determining the optimum hydraulic parameters for water flow through the soil. In the inverse modeling, the soil-hydraulic functions are fitted to observed data to determine the optimal values for the hydraulic parameters. A detailed description of the inverse modeling procedure in determining the hydraulic parameters is available in Radcliffe and Šimůnek (2010) and Šimůnek et al. (2012 (b)). The input data for the inverse modeling included measured soil water content, effective precipitation, and reference crop evapotranspiration partitioned and entered into the model separately as reference evaporation and reference transpiration.

The effective precipitation was obtained by reducing the measured precipitation amount during the experimental period to account for interception by the crop canopy. The intercepted amount was assumed to not reach the soil profile. The interception rate by the crop canopy was estimated using equation (4.4), where LAI (Leaf area index) for the various growth stages of potato was considered. The maximum interception rate was assumed to be 20%. The effective precipitation was estimated using equation (4.5).

$$\text{Interception rate} = \text{maximum interception rate} \times \frac{\text{LAI}}{\text{maximum LAI}} \tag{4.4}$$

$$\text{Effective precipitation} = \text{measured precipitation} \times (1 - \text{interception rate}) \tag{4.5}$$

The reference crop evapotranspiration (ET$_o$) was partitioned into reference evaporation and reference transpiration by using equation (4.6) and (4.7)

$$\text{Reference crop evaporation} = \text{ET}_o \times e^{-k \times \text{LAI}} \tag{4.6}$$

$$\text{Reference crop transpiration} = \text{ET}_o \times \left\lfloor 1 - e^{(-k \times \text{LAI})} \right\rfloor \tag{4.7}$$

where k is the coefficient governing radiation extinction by the canopy of the reference grass, usually ranging from 0.5 to 0.75 (Šimůnek et al. 2009). In the present study k = 0.5 was used to indicate that only half of the grass actively contributed to the surface heat and vapour transfer (Allen 1998). The average LAI of reference grass of assumed height (h) 0.12 m (FAO 2016) was used as the coefficient to divide the reference crop evapotranspiration into reference transpiration and reference evaporation. The LAI (= 24 h) of the reference grass was estimated as 2.88. It should be noted that in the HYDRUS (2D/3D) model, the actual crop evapotranspiration (ET_a) is determined based on soil water pressure head (which is related to the soil water content) and the ET_o. This eliminates the use of crop coefficient to determine the actual crop evapotranspiration (ET_a) in the model (Radcliffe and Šimůnek 2010; Šimůnek et al. 2012). A detailed description of how HYDRUS (2D/3D) accounts for the ET_a is presented in Chapter 3.

Field data obtained for the 2011-growing season, from June 3 to August 26, 2011, were used as input data for the inverse modeling. Optimization of the hydraulic parameters was done to obtain acceptable predicted estimates based on statistical and graphical comparison of measured soil water content data and predicted soil water content data based on the model estimated hydraulic parameters. The values for θ_r, θ_s α, n, and K_s estimated during the inverse modeling for the soil layers are presented in Table 4.3. The estimated hydraulic parameters for predicting the water flow at the study site were validated with data obtained from August 25 to September 24, 2011.

Table 4.3: Soil hydraulic parameters estimated from inverse modeling

Depth (m)	θ_r (m^3m^{-3})	θ_s (m^3m^{-3})	α	n	K_s (m day^{-1})
0.0 - 0.4	0.06	0.40	0.078	1.293	1.66
0.4 - 0.6	0.04	0.42	0.019	1.576	1.21
0.6 - 1.0	0.04	0.42	0.019	1.576	1.21
1.0 - 2.5	0.04	0.43	0.048	1.173	3.50

4.2.4.5 Evaluation of model performance

The model performance to accurately simulate the observed soil water content data was evaluated by using the coefficient of determination (R^2), the Nash–Sutcliffe modeling efficiency coefficient (NSE), percent bias (PBIAS), and the ratio of root mean square error (RMSE) over the observations standard deviation (RSR). The NSE, PBIAS and RSR values were estimated using equations 2.2, 2.3, and 2.4, respectively (Chapter 2, section 2.6).

4.3 Results and Discussion

4.3.1 Watertable response to recharge events under no drainage (ND) and free drainage (FD)

Figure 4.1 shows the changes in field observed watertable depth in response to rainfall events in the drained and undrained fields. The comparisons of drained and undrained fields were based on field data acquired prior to irrigation events

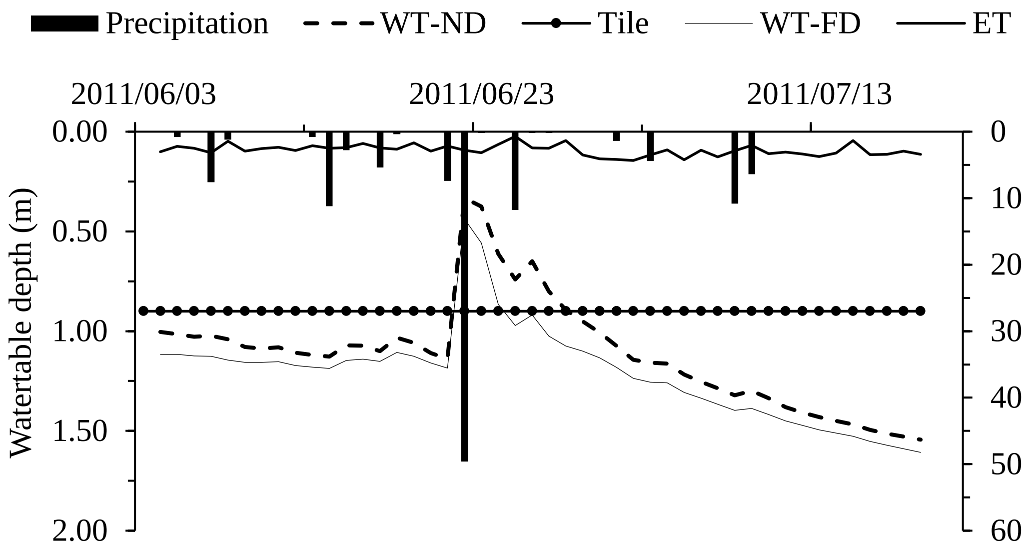

Figure 4.1: Watertable depth response to rainfall events in drained and undrained fields

(i.e. June 3 (15 Days After Planting (DAP)) -July 17 (59 DAP), 2011) for a better comparison of drainage and no drainage fields. Hence, the notation FD and ND are used to represent free drainage and no drainage, respectively in this section and here after. Data could not be obtained prior to June 3 to avoid interference with field operations by installed wells and sensors. The cumulative rainfall depth over June 3 to July 17, 2011 was 122.6 mm. The average watertable depth from the soil surface was 1.11 m and 1.21 m for the ND and FD fields, respectively. A 49-mm rainfall event occurred on June 22, which caused a sharp rise in the watertable into the root zone. The watertable rose up to 0.33 m and 0.44 m from the soil surface in the ND and FD fields, respectively. The watertable in the FD field was lowered below 0.9 m in three days compared to the watertable in the ND field, which took seven days. The lowering of the watertable in the FD field was attributed to the combined effects of subsurface drainage and soil water loss to evapotranspiration (ET). In the ND field, the lowering of the watertable was mainly attributed to soil water loss to ET. The loss of water to deep percolation was assumed to be negligible due to the presence of an impermeable layer of clay at about 6 m below the soil surface in this field.

4.3.2 Soil workability of ND and FD fields

As indicated earlier in section 4.2.3, subsurface drainage impact on soil strength for soil workability was assessed within the top 0.5-m-layer of the soil, which is directly influenced by field operations. The criteria for the soil strength assessment were based on the soil water content within the top 0.3-m depth of the soil profile being less than 0.9 × LPL, and the soil water content being less than the LPL within the 0.3 m – 0.5-m depth of the soil profile. The volumetric soil water content as a function of time, and the workability criteria for 0.2-m and 0.4-m depths of the soil profile are presented in Figure 4.2. The soil water content determined at 0.2-m and 0.4-m depths was lower for the FD fields compared to the ND fields. The average volumetric soil water content over the experimental period for the FD fields was 0.25 and 0.32 at 0.2-m and 0.4-m depths, respectively, whereas the average volumetric soil water

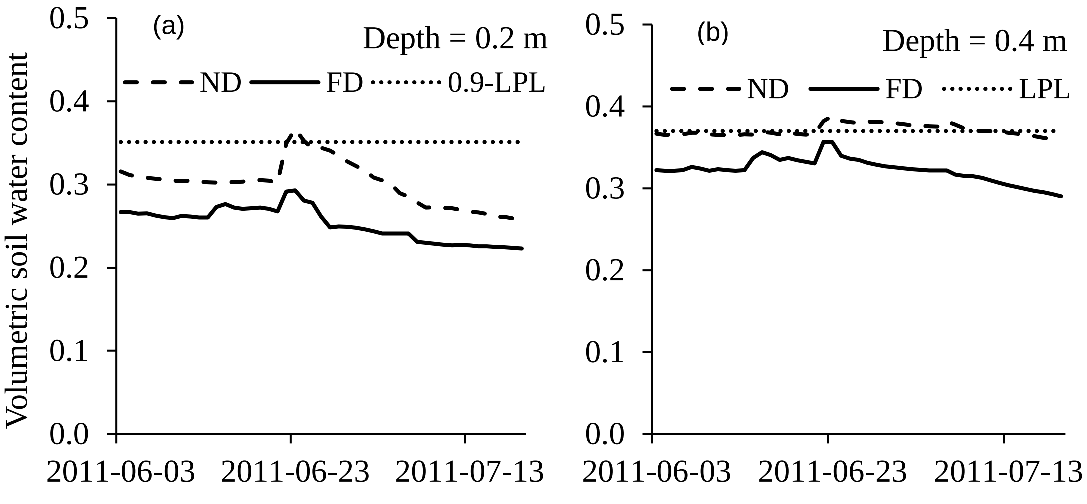

Figure 4.2: Soil water content in ND and FD fields with workability criteria for (a) 0.2-m depth and (b) 0.4-m depth

content for the ND field was 0.30 and 0.37 at 0.2-m and 0.4-m depths, respectively. Subsurface drainage decreased the soil water content by about 17% at the 0.2-m depth and 13% at the 0.4-m depth. As shown in Figure 4.2, the lower soil water content in the drained fields led to an increased number of workable days. However, the soil water content in the ND fields was in the desirable range at 0.2 m except during the occurrence of the 49-mm rainfall event, which raised the watertable to about 0.33-m depth within the root zone. As a result of the 49-mm rainfall event, the soil water content increased and the number of workable days at 0.2-m depth for the ND fields decreased by 2 days, and at 0.4-m depth, the workable days decreased by 12 days. The soil water dynamics observed in the drained and undrained fields indicate that evapotranspiration dominates the soil water content changes in the top 0.2-m depth compared to the 0.3-m to 0.5-m depth because the presence/absence of drains did not affect the soil workability. However, at 0.3-m - 0.5-m depth the presence/absence of drains had an influence on the soil workability.

4.3.3 Soil water content changes due to drain spacing for different weather conditions

From the workability analysis of field data from June 3 to July 19, it was observed that draining the field with drain tile at 0.9 m-depth and 15-m spacing in the study area resulted in more workable days than undrained fields. Considering that field operations are more critical during spring and harvesting time, it was necessary to extend the study through modeling to assess the impact of drainage on the soil strength to allow field operations during these periods. Consequently, the HYDRUS (2D/3D) model was used to predict soil water content changes due to different drain spacing scenarios to study the impact of drain spacing on soil workability under different weather conditions. The drain spacings simulated were 8 m, 10 m, 12 m, 15 m, 20 m, and 30 m. During the simulation exercise, seventeen years of rainfall data and the corresponding reference crop ET for the entire growing season (May to September) were used as input data to study the impact of different weather conditions on soil water content and the drainage requirements for the study area.

4.3.3.1 Calibration and validation

The HYDRUS (2D/3D) model was calibrated and validated with field data to assess its performance before simulating the different subsurface drainage scenarios under the different weather conditions for the entire growing season. Field data from June 3 to August 24, 2011 was used to calibrate the model, whereas data from August 25 to September 24, 2011 was used for validation of the model. The performance of the model was evaluated using the coefficient of determination (R^2), the Nash–Sutcliffe modeling efficiency coefficient (NSE), Percent bias (PBIAS), and the ratio of root mean square error to observations standard deviation (RSR). A detailed description of the application of these parameters are presented in Chapters 2 and 3. The summary of the values of the evaluation parameters is presented in Table 4.4. As shown in Table 4.4, the model accounted for 67% to 76% of the variation in the observed soil water content data. This indicates that there was a very strong correlation between the observed and simulated soil water content data (Moriasi et al. 2007). The variance in the simulated soil water content data was compared to the variance in the observed soil water content data using the NSE. The NSE values during the calibration and validation periods were 0.78 and 0.55, respectively, which made the model performance satisfactory. The tendency for the model to overestimate or underestimate the predicted data compared to the observed data

Table 4.4: Summary of values for the model evaluation parameters

Evaluation parameter	Calibration	Validation	Acceptable range
R^2	0.76	0.67	0.5 - 1.0
NSE	0.78	0.55	0.0 - 1.0
PBIAS	0.21%	1.42%	±10%
RSR	0.47	0.59	< 0.7

was assessed using the PBIAS. The PBIAS values estimated for calibration and validation periods were 0.21 % and 1.42 %, respectively, and they were within ±10%, which were considered very good for the model performance (Moriasi et al. 2007). The residual error in the data was assessed using the RSR. The RSR values estimated were 0.47 and 0.59 for the calibration and validation, respectively, which indicated an acceptable performance of the model. Based on the values obtained for the evaluation parameters, the HYDRUS (2D/3D) model simulated the water flow through the soil profile for the study site reasonably well.

4.3.3.2 Drainage requirement for workability for different year weather conditions

The validated model was used to study the impact of drainage spacing on soil workability for different years and weather conditions in the study area. Figure 4.3 and Figure 4.4 show the number of non-workable days for seventeen years (2000-

2016). A non-workable day was defined as any day in which the soil water content exceeded the soil workability criteria (i.e. for 0 to 0.3-m depth, the soil water content should be less or equal to 0.9 × LPL, and for 0.3-m to 0.5-m depth, the soil water content should be less or equal to the LPL). The variation in ET and rainfall influences the drainage requirement for field operations. As presented in the figures, soil water content is influenced by both drain spacing and the ET. During years of higher ET than rainfall, the number of non-workable days was low or zero. At a drain spacing of 8 m, there were no non-workable days, and only a limited number of non-workable days with drain spacing at 10 m and12 m (Figure 4.3 and Figure 4.5). This is because narrower drain spacings had higher drainage intensity, which increased the rate at which the excess water was removed from the root zone. Non-workable days tended to occur in the early season from May 1 to May 18, which may not significantly affect timely field operations and long-term yield. It should however be noted that increased drainage intensity will rapidly remove the gravitational water that might otherwise be available to the plants in the very short term. Although gravitational water is not considered as part of the plant available water, it still replenishes the capillary water in the short term if ET continues. Cordeiro and Sri Ranjan (2015) have shown the impact of increased drainage intensity on corn relative yield during deficit rainfall years. Their simulations showed that increased drainage intensity resulted in increased yield during wet years and decreased yield during dry years (Cordeiro and Sri Ranjan 2015). Increased drainage intensity also leads to excessive drying of the soil leading to an increase in field operations costs through increased tillage energy consumption, decreased drawbar pull, and increased time required to carry out an operation (Earl 1997). The decreased soil moisture

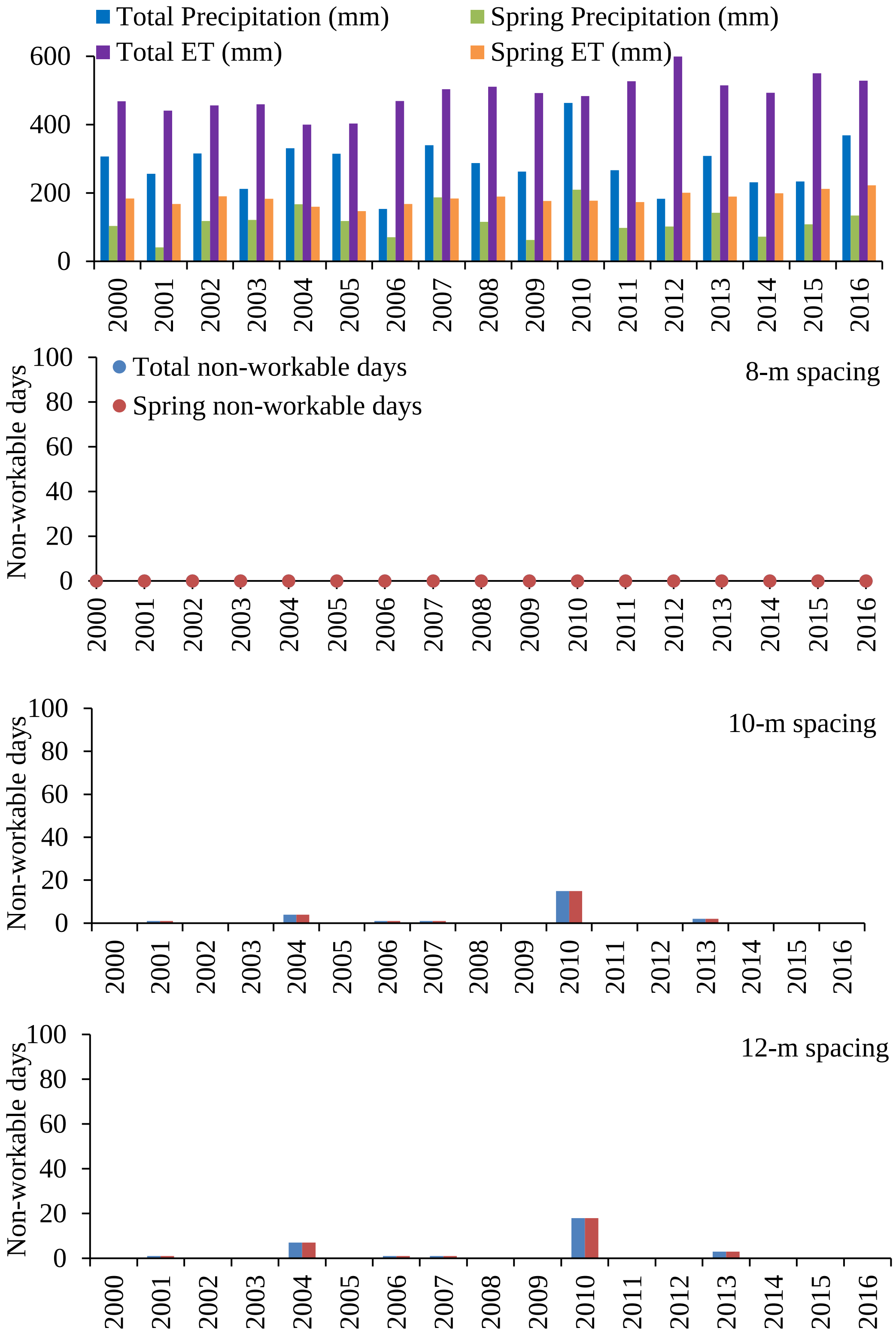

Figure 4.3: Weather condition and drain spacing (8 m, 10 m, 12 m) impact on the number of non-workable days during spring operations and entire growing season

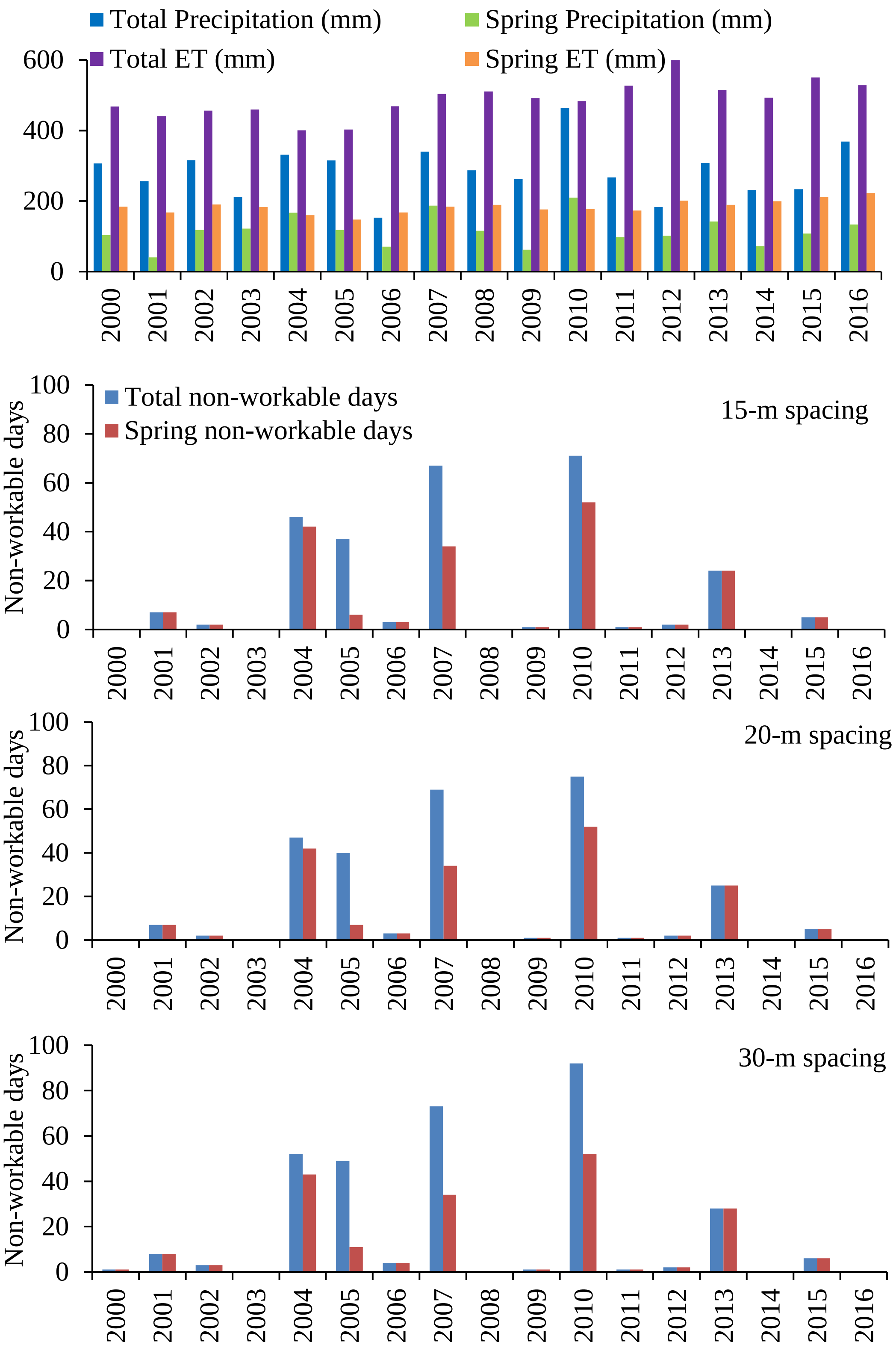

Figure 4.4: Weather condition and drain spacing (15m, 20 m, 30 m) impact on the number of non-workable days during spring operations and entire growing season

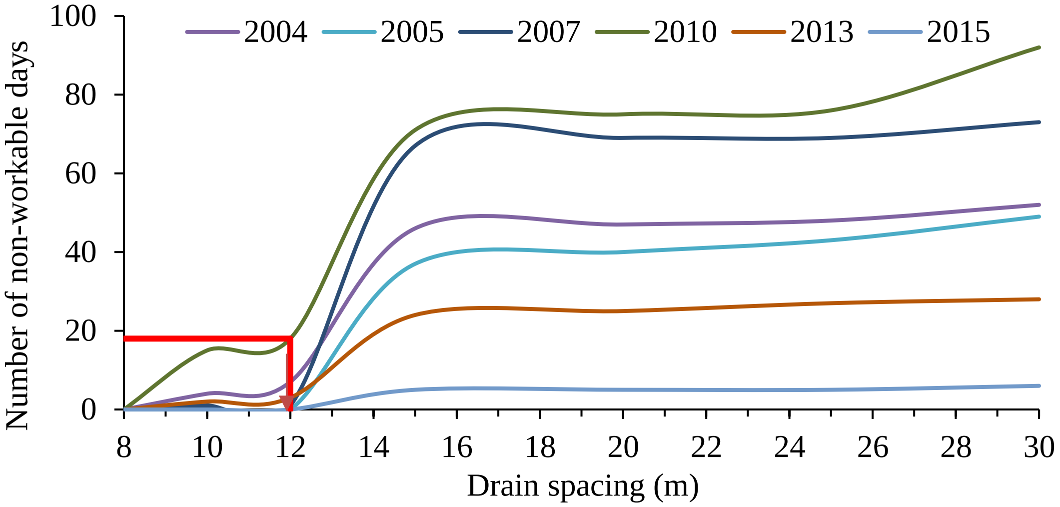

Figure 4.5: Summary of drain spacing impact for years with more than six non-workable days

storage also requires subsequent irrigation. On the other hand, as shown in Figure 4.4, the number of non-workable days increased with drain spacing ≥ 15 m. This impact was more obvious during the wet years (i.e. years 2004, 2007, 2010, and 2013), when rainfall was higher than or close to ET. The number of non-workable days within the spring operations period for the wet years ranged from 24 to 52 days, which may impact timely field operations. In that regard, the field manager must consider the benefit of installing drains at wider spacing and its impact on field operations and long-term yield.

4.4 Conclusion

In the present study, the impact of subsurface drainage on soil strength of sandy loam soil in southern Manitoba was assessed by determining the number of field workable days in drained and undrained fields. The study was extended by using HYDRUS (2D/3D) model to predict soil water content changes due to different drain spacings (8 m, 10 m, 12 m, 15 m, 20 m, and 30 m) under different weather conditions, and how that impact the number of field workable days. The field was considered workable when the following two criteria were met: 1) soil water content in the top 0.3-m depth corresponded to 90% of the lower plastic limit (LPL) of the soil, and 2) soil water content within 0.3-m to 0.5-m depth of the soil profile corresponded to the LPL of the soil. The results showed that at shallow depth of 0.2-m depth, evapotranspiration alone was more than adequate to maintain the soil water content below 90% of the LPL with or without drainage. However, at 0.4-m depth of the soil profile, the drainage spacing affected the number of workable days. For spacing wider than 15 m, the number of non-workable days increased with increasing drain spacing both during the spring operations period as well as throughout the season. From a workability standpoint, drains spaced at 12 m or less resulted in non-workable days less than 18, which was found to be acceptable for scheduling field operations.

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Chapter 5

Risk assessment of subsoil compaction under different drain spacings and weather conditions in southern Manitoba

Abstract

The objective of the present study was to assess the intrinsic susceptibility and vulnerability of sandy loam soil to subsoil compaction in southern Manitoba using soil properties (textural percentages, bulk density, and lower plastic limit) and soil water content. The soil property data were obtained from a potato field operated by the Hespler Farms, Winkler, Manitoba. A validated HYDRUS (2D/3D) model was used to simulate water flow through the soil profile to predict the soil water content changes resulting from different drain spacings (8 m, 10 m, 12 m, 15 m, 20 m, 25 m, and 30 m) and different year weather conditions (i.e. years 2000 - 2015) for the study area. Based on the texture and packing density of the subsoil at the study site, it was found that the subsoil had a high level of susceptibility to compaction. In addition, the subsoil was found to be very vulnerable to compaction throughout the years considered due to the subsoil wetness condition being either “moist” or “wet” for all the drain spacings. However, drains spacing ≤ 12 m had the upper layer (i.e. top 0.5 m of the soil profile) having volumetric soil water content less than the threshold of 0.34, which provided protection for the subsoil. Drain spacings wider than 12 m provided no protection for the soil during wet spring seasons where rainfall exceeded ET.

Keywords: compaction risk, soil texture, packing density, sandy loam, subsoil, HYDRUS (2D/3D), subsurface drainage, soil water content, rainfall and evapotranspiration.

5.1 Introduction

Soil compaction is a physical evidence of processes that cause reduction in the pore space of a soil structure. Soil compaction can persist from the upper soil layer to the subsoil. Soil compaction in the upper soil layer is mainly due to tillage operations, and that of the subsoil is as a result of weight transfer of machinery (Håkansson et al. 1987; Radford et al. 2007; Whalley 1995). The subsoil is defined as the soil layer in which tillage operations are considered undesirable and uneconomical (Alakukku et al. 2003). Soil compaction in the subsoil due to weight transfer of agricultural traffic is increasingly becoming of concern due to increase in machinery size to maximize the output per farmer (Jorajuria and Draghi 1996; Alakukku et al. 2003; Jones et al. 2003). It has been established from previous studies that the extent of subsoil compaction may depend on the load intensity, the number of vehicular passes, the wetness condition of the soil, the strength of the soil, the clay content of the soil, and time (Håkansson et al. 1987; Jorajuria and Draghi 1996). Jorajuria and Draghi (1996) showed that agricultural traffic induced significant compaction at soil layers ranging from 0.53 to 0.60 m for clayey soils. In their study, they observed that high intensity traffic (10.5 Mg km ha^{-1}) had significant impact on the soil structure at only one pass and that of light intensity traffic (5.8 Mg km ha^{-1}) had similar impact at about ten passes. Håkansson et al. (1987) conducted a study on subsoil compaction and observed that axle load greater than ten tonnes had significant impact on the soil at deeper depths greater than 0.50 m. In their study, they observed that the intensity of the subsoil compaction and its extent were influenced by increase in clay content and number of passes by the vehicle. They however observed that the response to subsoil compaction decreased with time due to increase soil strength over time, which makes the subsoil less susceptible to compaction. Alakukku et al. (2003) demonstrated that subsoil compaction might occur within the top 1 m depth of the soil profile. They observed that the stress from vehicular traffic within the soil increased with soil water content and the traffic intensity.

It has been demonstrated in previous studies that once subsoil compaction occurs, alleviating it is extremely difficult and expensive (Jones et al. 2003; Alakukku et al. 2003), and has negative influence on the function of the soil in promoting a conducive environment for crop growth and performance. Compacted soil limits the soil water movement in the soil profile and availability for crop water uptake, gaseous exchange for aerobic activities, and nutrient availability and uptake by the crops, which eventually affect plant growth and performance (Taylor and Brar 1991). Compacted soil profile hinders root development, which results in a short-term effect of yield losses and a long-term effect of poor structural generation and regeneration due to limited wetting and drying cycles in the soil profile (Whalley et al. 1995). For example, Håkansson et al. (1987) observed in their study that subsoil compaction in sandy soils decreased the rooting depth of corn from 120 cm to less than 50 cm. Poor structural generation and regeneration result in the inability of the soil to absorb high intensity rainfall and then tend to be anaerobic leading to leaching and accumulation of toxic substances, which are harmful to plant growth and performance (Whalley et al. 1995). Compacted soil inhibits the performance of subsurface drainage systems. In compacted soil, the infiltration capacity of the soil is decreased due to pore space reduction. For optimum performance of subsurface drainage systems, excess water in the soil must be able to move through the unsaturated zone to the subsurface drainage tiles (Smedema et al. 2004). Poor performance of the subsurface drainage system leads to waterlogging of the soil and further soil structural damage, which leads to yield losses.

In southern Manitoba, farmers experience excess soil water content especially during the springtime field operations. The excess soil water content results from snowmelt infiltration and high rainfall. The excess soil water content delays field operations, which leads to significant yield losses. Studies have shown that subsurface drainage improves the soil water condition to ensure soil suitability to allow field operations in the region. It should however be mentioned that the performance of the subsurface drainage system is dependent on the weather condition, soil hydraulic behaviour, and the drainage intensity.

The objective of the present study was to assess the intrinsic susceptibility and vulnerability of sandy loam soil to subsoil compaction in a potato field under different drain spacings and weather conditions in southern Manitoba. The risk assessment at the study site was done based on an approach proposed by Spoor et al. (2003). A validated HYDRUS (2D/3D) model was used to generate soil water content changes data due to different drain spacings and weather conditions for sixteen years. The HYDRUS (2D/3D) model is a Windows-based computer program that simulates water flow through two- and three-dimensional variably saturated porous media by solving the Richards equation (Šimůnek et al. 2012). A detailed description of the simulation process for this study site was presented in Chapter 4.

5.2 Materials and Methods

5.2.1 Field data acquisition

The risk of subsoil compaction at the study site was assessed based on risk assessment method proposed by Spoor et al. (2003). The assessment involves the determination of the intrinsic susceptibility, and vulnerability of the subsoil to compaction. To assess the risk of subsoil compaction, field data including soil bulk density, soil texture, lower plastic limit (LPL), and volumetric soil water content were obtained from a potato field at the Hespler Farms, Winkler, Manitoba. The field characteristics have been described in previous chapters (Chapters 3 and 4). Weather data were obtained for the study area from Environment Canada in addition to data acquired onsite and from nearby weather station (Canada-Manitoba Crop Diversification Centre, Winkler) to estimate reference crop evapotranspiration. Detailed description of obtaining the field data has been presented elsewhere. The bulk density, the soil texture, and the volumetric water content obtained at the study site are presented in Satchithanantham (2013) and summarized in previous chapters 3 and 4. The detailed procedure for obtaining the lower plastic limit of the soil has been presented in Chapter 4. Therefore, a summary of the data acquisition is presented in this Chapter.

The bulk density of the soil was for three different locations in the field at 0.15 m, 0.30 m, 0.60 m, 0.90 m, and 1.2 m depths (Satchithanantham 2013). Soil samples were also collected to determine the textural percentages of the soil at the same depths at six different locations. The percentages obtained at the various locations were averaged for each depth sampled (Satchithanantham 2013). The average bulk density and average soil textural percentages at different depths are presented in Table 5.1. It should however be noted that the bulk density and the textural percentages at 0.6 m depth of the soil profile were used to assess the risk of subsoil compaction at the study site.

Table 5.1: Bulk density and textural percentages at various depths from the soil surface at the study site (adapted from Satchithananantham 2013).

Depth (m)	Bulk density (Mgm^{-3})	Textural percentage		
		Sand	Silt	Clay
0.15	1.03	71	19	10
0.3	1.33	70	20	10
0.6	1.41	69	19	12
0.9	1.38	71	18	11
1.2	1.43	62	26	12

Volumetric soil water content in free drainage plots (three replicates) in the field was monitored at three-hour interval from June 3 - September 24, 2011. The volumetric water content was determined at 0.2 m interval up to 1.0 m depth in the soil profile for each plot (Satchithananantham 2013). The three-hour-interval data obtained were averaged for daily volumetric soil water content. The daily volumetric soil water content was used to determine the wetness condition of the soil and used as input data in the modeling exercise to determine the soil water content changes to drain spacing under different weather conditions. It should be noted that detailed simulation processes for water flow through the soil profile under different drain spacing and weather conditions for this study site have been presented in Chapter 4.

Weather parameters including precipitation, temperature, wind speed, relative humidity and solar radiation data were collected using a Watchdog Weather Station (WatchDog 2900ET, Spectrum Technologies, Inc., Plainfield, IL, USA) located onsite. Weather data obtained from the weather station located at the Canada-Manitoba Crop Diversification Centre, Winkler were used to supplement the data collected onsite. This weather station was about 2-km east from the study site. For the HYDRUS (2D/3D) simulation exercise, sixteen years of weather data (i.e. from 2000-2016) including precipitation, minimum temperature, maximum temperature and relative humidity were obtained from Environment Canada (Environment Canada 2017). These years were considered due to data unavailability prior to year 2000. The minimum temperature, maximum temperature, and relative humidity data were used to determine the reference crop evapotranspiration as proposed by Maulé et al. (2006). The reference crop ET data obtained for the sixteen years using the method proposed by Maulé et al. (2006) were used as input data in the HYDRUS (2D/3D) modeling exercise to determine the soil water content for assessing the risk of subsoil compaction at the study site.

Soil samples were obtained from the field at three different locations up to a depth of 0.6 m to determine the lower plastic limit (LPL) of the soil. The lower plastic limit of the soil was used to define the threshold for soil water content to ensure the soil had sufficient strength to allow field operations without significant damage to the soil structure through soil compaction. The soil samples were taken to the Soil and Water Engineering Laboratory at the University of Manitoba to determine the LPL of the soil. The LPL of the soil was determined using the Casagrande plastic limit method known as the rolling method. The rolling method as described by ASTM D 4318 2010 standard was followed (ASTM D 4318-10e1. 2010). The LPL for each location and depth was repeated three times to ensure consistency in the data. This was necessary since the rolling method for determining the LPL of the soil is subjective and considered operator specific (Haigh et al. 2013). The data obtained from the different locations were averaged to represent the LPL of the soil at the study site. The summary of the LPL determined is presented in Table 5.2.

Table 5.2: Average LPL values determined for the study site

Depth (m)	Average LPL
0.2	$0.39 \pm 4.4\times10^{-6}$
0.4	$0.37 \pm 5.7\times10^{-4}$
0.6	$0.36 \pm 1.5\times10^{-5}$

5.3 Results and Discussion

5.3.1 Assessment of subsoil susceptibility to compaction

The intrinsic susceptibility of the subsoil to compaction was assessed at 0.6 m depth of the soil profile. As indicated earlier in section 5.2.1, the risk of the subsoil to compaction was assessed by using the susceptibility to compaction assessment proposed by Spoor et al. (2003). The assessment was based on the FAO/UNESCO

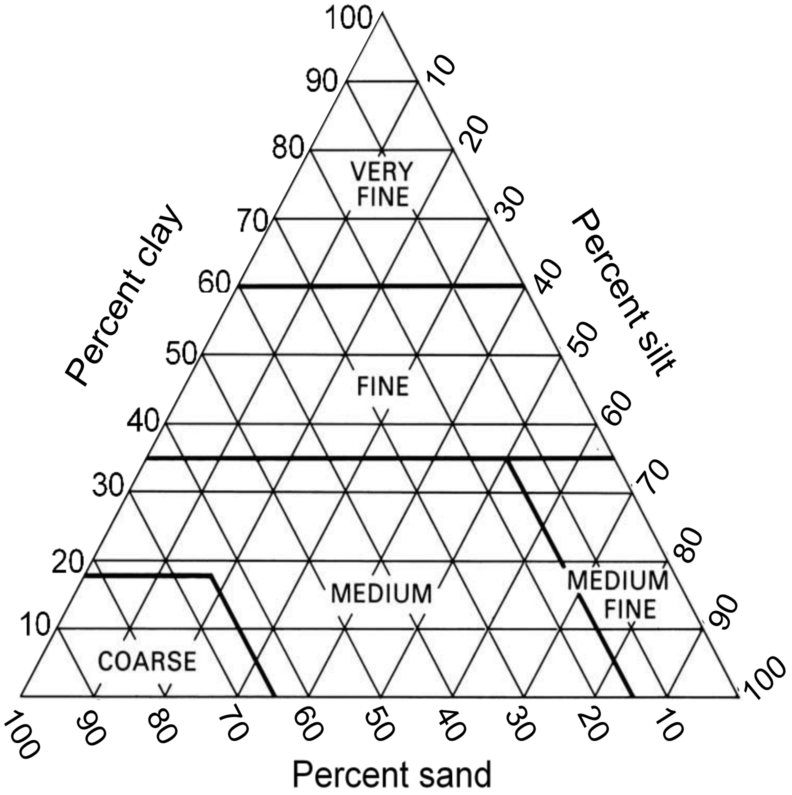

Figure 5.1: FAO/UNESCO textural class classification (from: Spoor et al. 2003)

textural class classification as shown in Figure 5.1 and the packing density of the subsoil (Spoor et al. 2003). The packing density of the subsoil was estimated using equation (5.1).

$$\rho_p = \rho_{db} + 0.009 \cdot C \qquad (5.1)$$

Where ρ_p is the packing density in Mgm^{-3}, ρ_{db} is the dry bulk density in Mgm^{-3} and C is the clay content (wt.%) (Spoor et al. 2003). As presented in Table 5.1, the average bulk density at 0.6 m depth of the field was determined to be 1.41 Mgm^{-3}. The clay content at 0.6 m depth of the field was determined as 12 %. Hence, the packing density of the soil at 0.6 m depth was estimated as 1.52 Mgm^{-3}. Based on the average

Table 5.3: Susceptibility level of subsoil to compaction based on textural class and packing density (from: Spoor et al. 2003)

Textural class	Susceptibility level Packing density Low (<1.4)	 Medium (1.4-1.75)	 High (>1.75)
Coarse	Very high	High	Moderate
Medium (< 18% clay	Very high	High	Moderate
Medium (>18% clay)	High	Moderate	Low
Medium fine (< 18% clay)	Very high	High	Moderate
Medium fine (> 18% clay)	High	Moderate	Low
Fine	Moderate	Low	Low
Very fine	Moderate	Low	Low
Organic	Very high	High	

textural percentage of the subsoil at 0.6 m (69% sand, 19 % silt, and 12 % clay) and Figure 5.1, the texture of the soil was within the coarse textural class, which is equivalent to sandy loam under the Canadian System of Soil Classification (Soi1 Classification Working Group 1998).

The estimated value for the packing density and the textural class of the soil was used to determine the level of susceptibility. The susceptibility level of the subsoil compaction in the study area was characterized based on the description provided in Table 5.3. Based on the description in Table 5.3 and the soil characteristics, the susceptibility level of the subsoil to compaction at the study site is high, which implies the subsoil has very weak potential in resisting compaction due to weight transfer from machinery.

5.3.2 Assessment of the subsoil vulnerability to compaction under different drain spacing and weather patterns

The degree of vulnerability of the subsoil to compaction under different drain spacings for different weather conditions was determined from the intrinsic susceptibility level and the degree of wetness of the soil. The subsoil may be susceptible to compaction but the degree of risk that compaction may occur is dependent on the wetness condition. Spoor et al. (2003) considered soil water content at field capacity or higher to indicate a “wet” soil condition. In the present study, soil water content greater than the lower plastic limit (LPL = 0.36 m^3m^{-3}) of the subsoil was used to define “wet” soil condition. This approach was more appropriate since the LPL was higher than the field capacity (0.32 m^3m^{-3} (in Satchithanantham 2013)) at the study site. The degree of wetness was classified as “very dry” when the volumetric soil water content was at permanent wilting point (0.09 m^3m^{-3}) or less.

When the volumetric soil water content was within the upper half range of permanent wilting point and LPL (θ_{LPL} - θ_{PWP}, 0.22 m^3m^{-3} to 0.36 m^3m^{-3}), the wetness was classified as “moist” and when it was in the lower half range (0.09 m^3m^{-3} to 0.22 m^3m^{-3}), it was classified as “dry”. The description of the degree of vulnerability of the subsoil to compaction as determined by the susceptibility level and wetness condition is presented in Table 5.4. The volumetric soil water content obtained from the simulation exercise (Chapter 4) was used to assess the wetness condition of the subsoil. Sixteen-year (2000-2015) ET and rainfall effect on soil water content were considered for seven different drain spacings (8 m, 10 m, 12 m, 15 m, 20 m, 25 m, and 30 m). The variation in rainfall, ET, and the daily volumetric soil water content for the subsoil is presented in Figure 5.2 (year 2000 - 2003), Figure 5.3 (year 2004 - 2007), Figure 5.4 (year 2008 - 2011), and Figure 5.5 (year 2012 - 2015). Included in the figures are the thresholds for “wet” (LPL), “moist” (dry to moist, D-M) and “dry” (PWP) wetness conditions. The figures showed that rainfall distribution and ET over the years varied, which had impact on the soil water content. Also in the figures, it is shown that drain spacing impacted the soil water content. The figures show that irrespective of the ET, the rainfall distribution, and drain spacing, the subsoil wetness condition was in the range of “moist” to “wet” wetness condition. The drain spacing impact on the subsoil wetness condition is summarized in Table 5.5 where “M” represents “moist” and “W” represents “wet”. As presented in the table, the narrower the drain spacing, the less the number of days the subsoil was in the “wet” wetness condition range. This is because narrower drain spacing has high drainage intensity, which lowers the soil water content faster than wider drain spacing. For example, drain spacing less than or equal to 12 m resulted in less than 10% of the growing

Table 5.4: Degree of vulnerability of subsoil to compaction based on soil susceptibility and wetness condition (Adapted from: Spoor et al. 2003)

Susceptibility class	Degree of vulnerability			
	Wetness Condition			
	Wet	Moist	Dry	Very dry
		Upper 0.5 of	Lower 0.5 of	
	$(\theta_v \geq \theta_{LPL})$	$(\theta_{LPL} - \theta_{PWP})$	$(\theta_{LPL} - \theta_{PWP})$	$(\theta_v \leq \theta_{pwp})$
Very high	Extremely vulnerable	Extremely vulnerable	Very vulnerable	Very vulnerable
High	Very vulnerable	Very vulnerable	Moderately vulnerable	Moderately vulnerable
Moderate	Very vulnerable	Moderately vulnerable	Not particularly vulnerable	Not particularly vulnerable
Low	Moderately vulnerable	Not particularly vulnerable	Not particularly vulnerable	Not particularly vulnerable

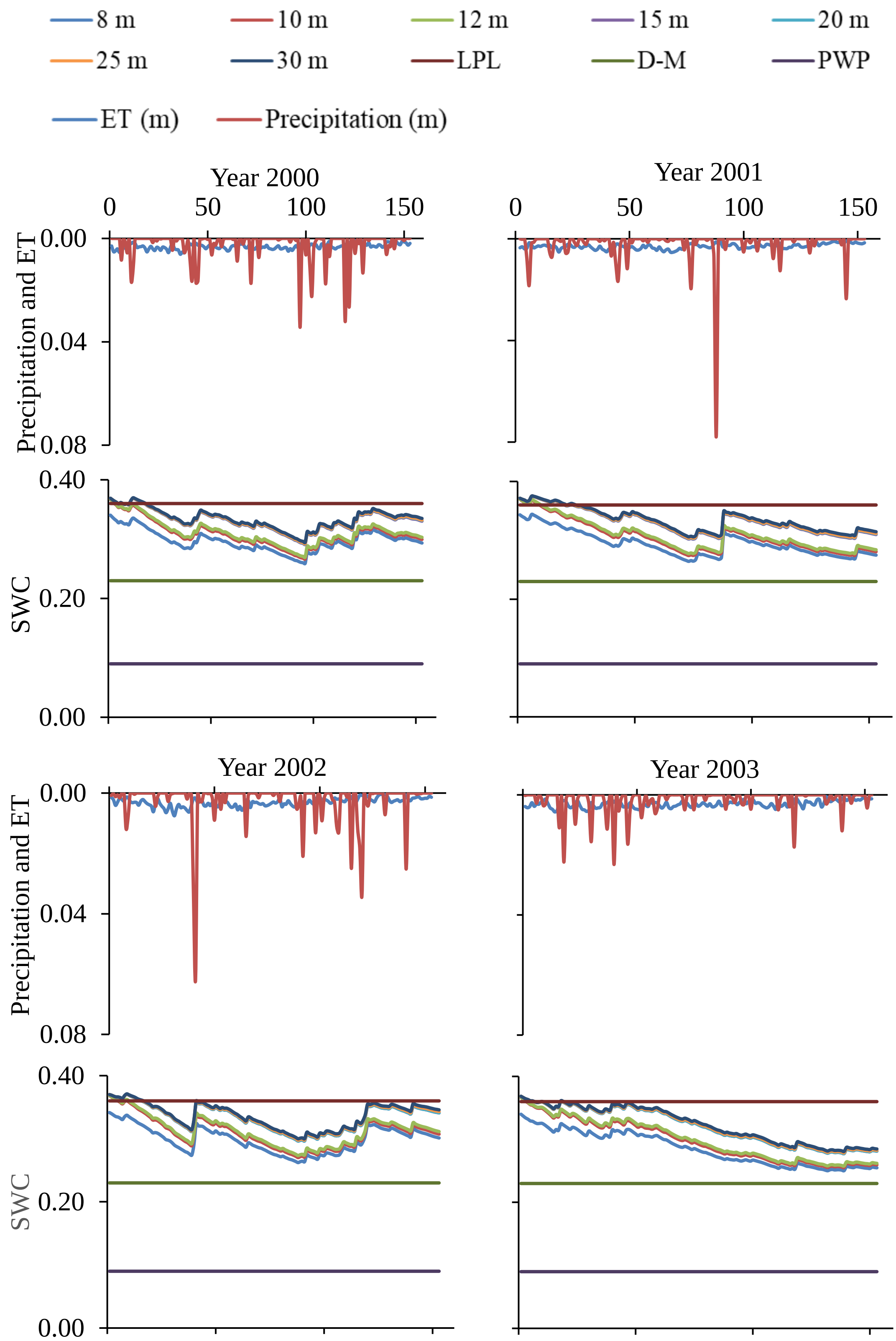

Figure 5.2: (2000 - 2003): Variation in precipitation, ET and volumetric soil water content for the subsoil for sixteen years under different drain spacing

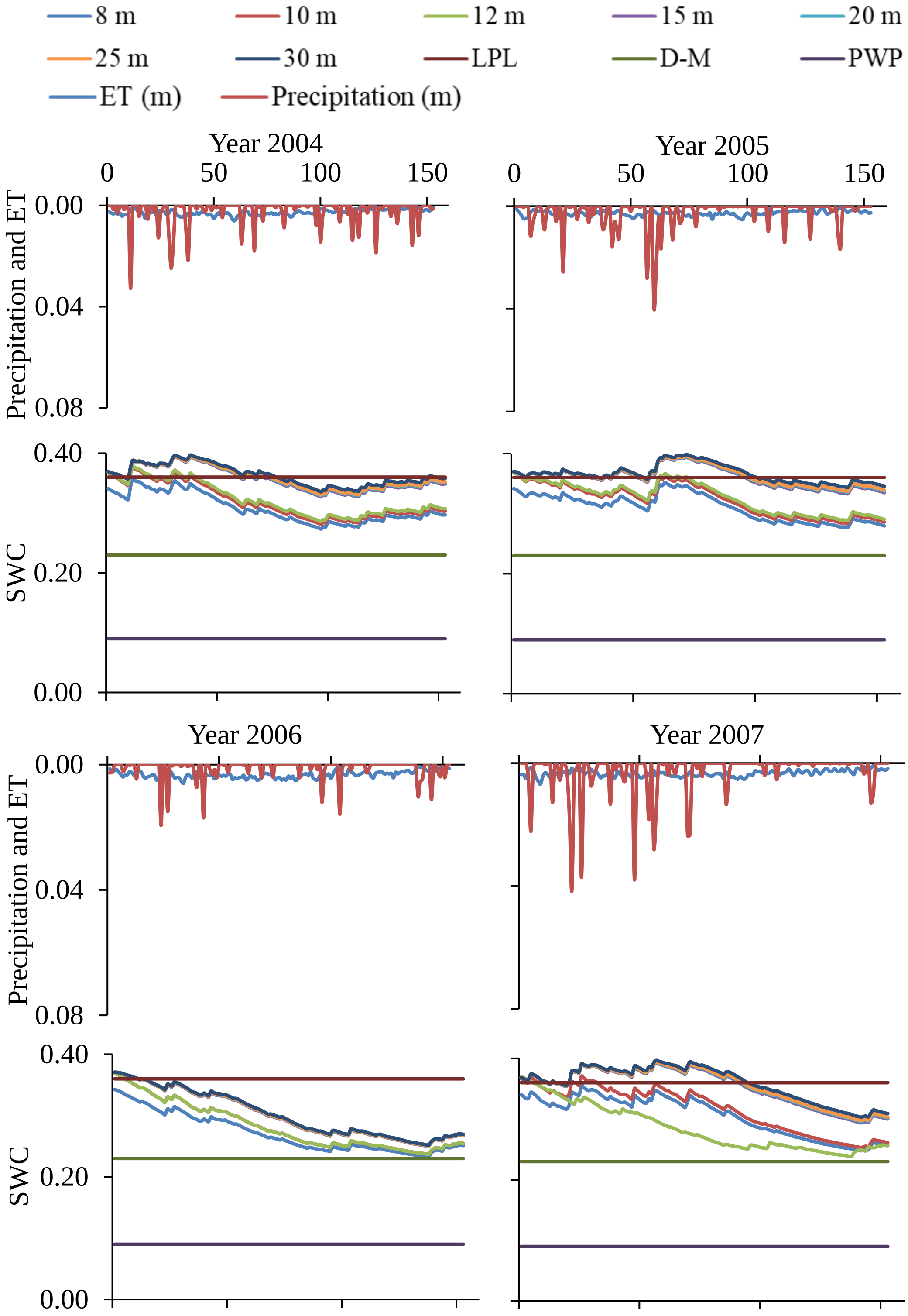

Figure 5.3: (2004 - 2007): Variation in precipitation, ET and volumetric soil water content for the subsoil for sixteen years under different drain spacing

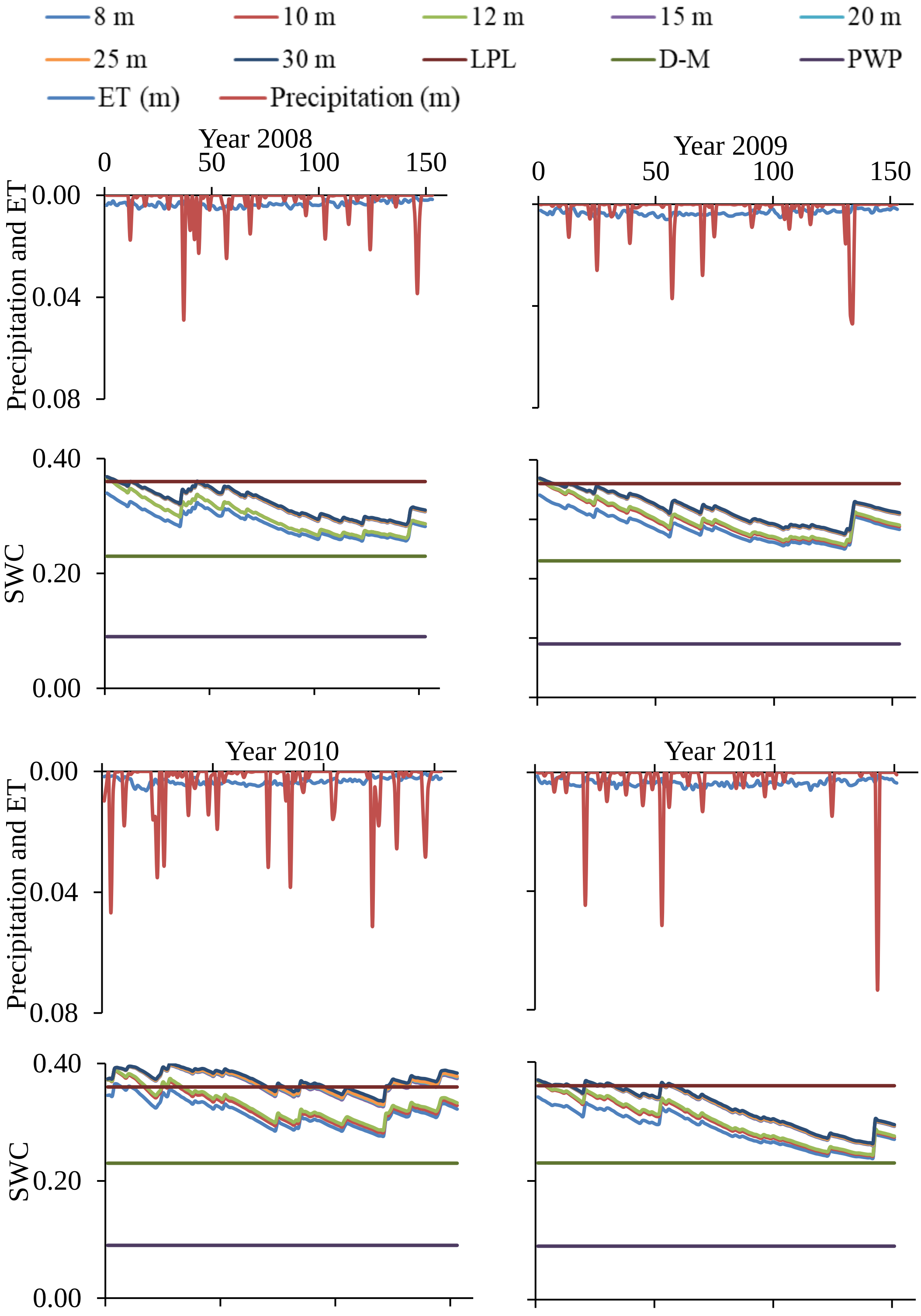

Figure 5.4: (2012 - 2015): Variation in precipitation, ET and volumetric soil water content for the subsoil for sixteen years under different drain spacing

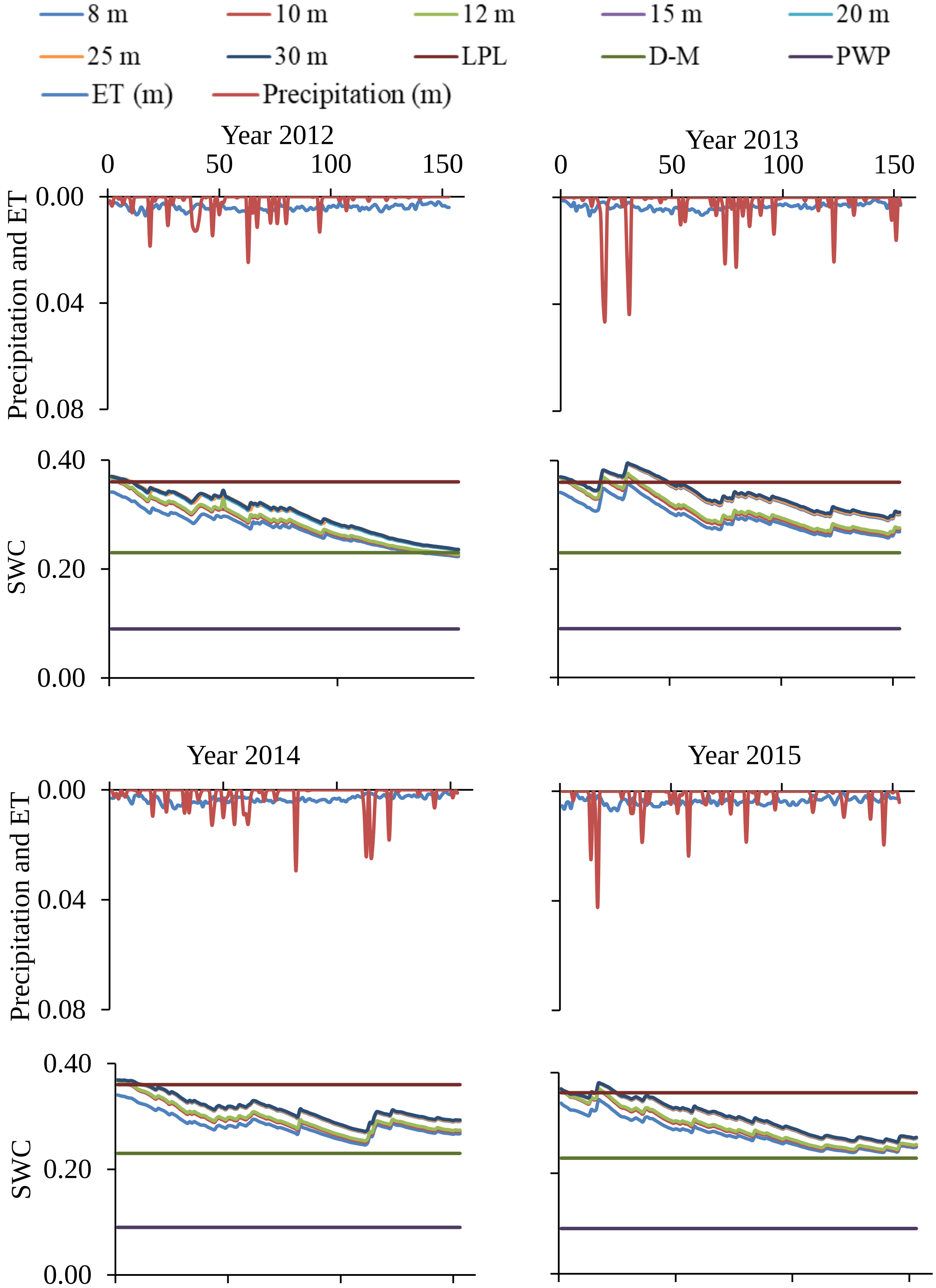

Figure 5.5: (2012-2015): Variation in precipitation, ET and volumetric soil water content for the subsoil for sixteen years under different drain spacing

Table 5.5: Number of days for subsoil wetness condition under different drain spacings for different years (2000-2015)

Year	8 m		10 m		12 m		15 m		20 m		25 m		30 m	
	M	W	M	W	M	W	M	W	M	W	M	W	M	W
2000	153	0	150	3	150	3	141	12	141	12	139	14	139	14
2001	153	0	144	9	143	10	132	21	131	22	130	23	128	25
2002	153	0	148	5	146	7	138	15	138	15	137	16	136	17
2003	153	0	150	3	150	3	146	7	146	7	146	7	144	9
2004	153	0	135	18	127	26	90	63	87	66	83	70	76	77
2005	153	0	149	4	140	13	71	82	66	87	64	89	56	97
2006	153	0	148	5	148	5	143	10	142	11	142	11	141	12
2007	153	0	150	3	150	3	141	12	141	12	141	12	139	14
2008	153	0	150	3	150	3	147	6	147	6	147	6	146	7
2009	153	0	150	3	150	3	147	6	147	6	147	6	146	7
2010	147	6	130	23	127	26	61	92	52	101	49	104	36	117
2011	153	0	149	4	149	4	130	23	129	24	124	29	120	33
2012	153	0	149	4	149	4	145	8	145	8	144	9	144	9
2013	153	0	141	12	139	14	117	36	116	37	115	38	114	39
2014	153	0	148	5	146	7	143	10	142	11	142	11	141	12
2015	153	0	148	5	148	5	139	14	139	14	139	14	139	14

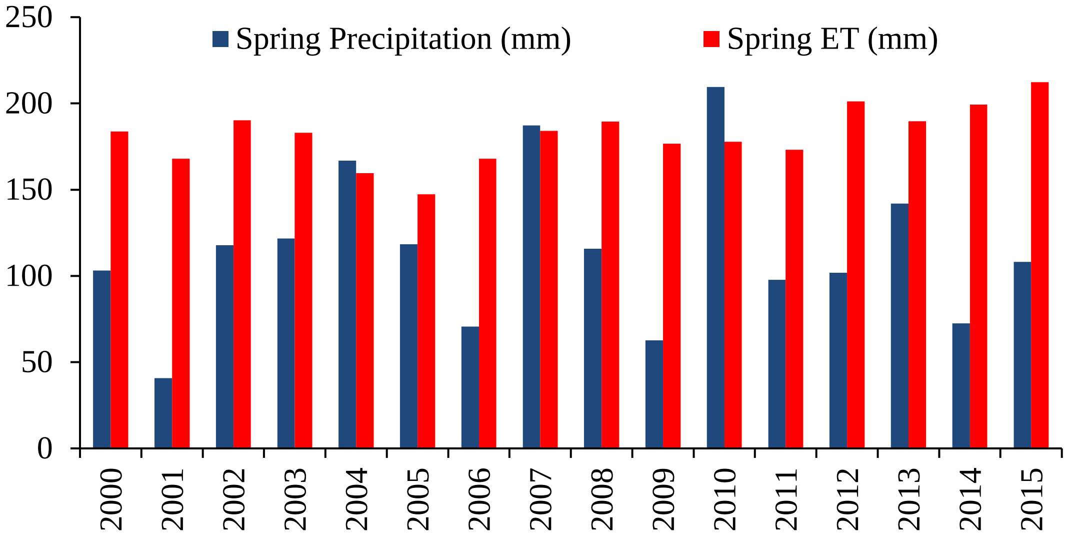

Figure 5.6: Variation in precipitation and ET for sixteen years during the spring operations period

season days for all the years in the “wet” wetness condition except for years 2004 and 2010, which had about 17% of the growing season days in the “wet” wetness condition. This observation was more dominant during the spring operations season (i.e. from May 1 to June 20). This is because the spring operations period of years 2004 and 2010 were wet seasons, when rainfall exceeded ET (as presented in Figure 5.6). During the spring operations period, the total rainfall was 166.8 mm and 209.6 m, and the total ET was 159.5 mm and 177.7 mm, for 2004 and 2010, respectively. As indicated in section 5.3.1, the subsoil in the study area has very weak potential in resisting compaction due to the high level of intrinsic susceptibility to compaction. This implies that having the soil water content within the “moist” and “wet” wetness condition makes the subsoil very vulnerable to compaction throughout the growing season for all the years considered. The soil wetness impact is more problematic during the spring operations period, where farmers need to prepare the land for seeding. As presented in Figures 5.2 to 5.5, the spring operations period generally had higher soil water content for all the years under the different drain spacings.

The subsoil may be vulnerable to compaction but depending on the strength of the upper layer of the soil, the subsoil may be considered protected (Spoor et al. 2003; Jones et al. 2003). This is because, stress transfer to deeper depths of the soil profile reduces when the upper soil layer has sufficient strength (Alakukku et al. 2003) The strength of the upper layer of the soil (i.e. top 0.5 m of the soil profile) was assessed using the criterion of soil water content corresponding to 90% of the soil water content at LPL (0.34 m^3m^{-3}). For the upper layer to provide protection for the subsoil, the volumetric water content of the upper layer should be equal or less than 0.9 × LPL. Figure 5.7 and Figure 5.8 show the average volumetric soil water content for the top 0.5 m depth of the soil layer for each year under the different drain spacings. Also on the figure is the threshold (0.9 × LPL) for ensuring the top 0.5-m depth of the soil profile had sufficient strength to provide protection for the subsoil. As per the criterion, drain spacings ≤ 12 m had soil water content below the threshold in the top 0.5-m depth of the soil layer for all the years, which provided protection for the subsoil throughout the years. For drain spacings wider than 12 m, the subsoil lost protection during the spring operations period for years 2004, 2007, and 2010. This was because the rainfall during the spring operations period for these years exceeded ET (as shown in Figure 5.6), which resulted in higher soil water content compared to the other years.

The vulnerability to subsoil compaction for the three years for drain spacing wider than 12 m could have detrimental effect on the soil structure for subsequent seasons. Freeze-thaw process, which is a characteristic of the region, could be a

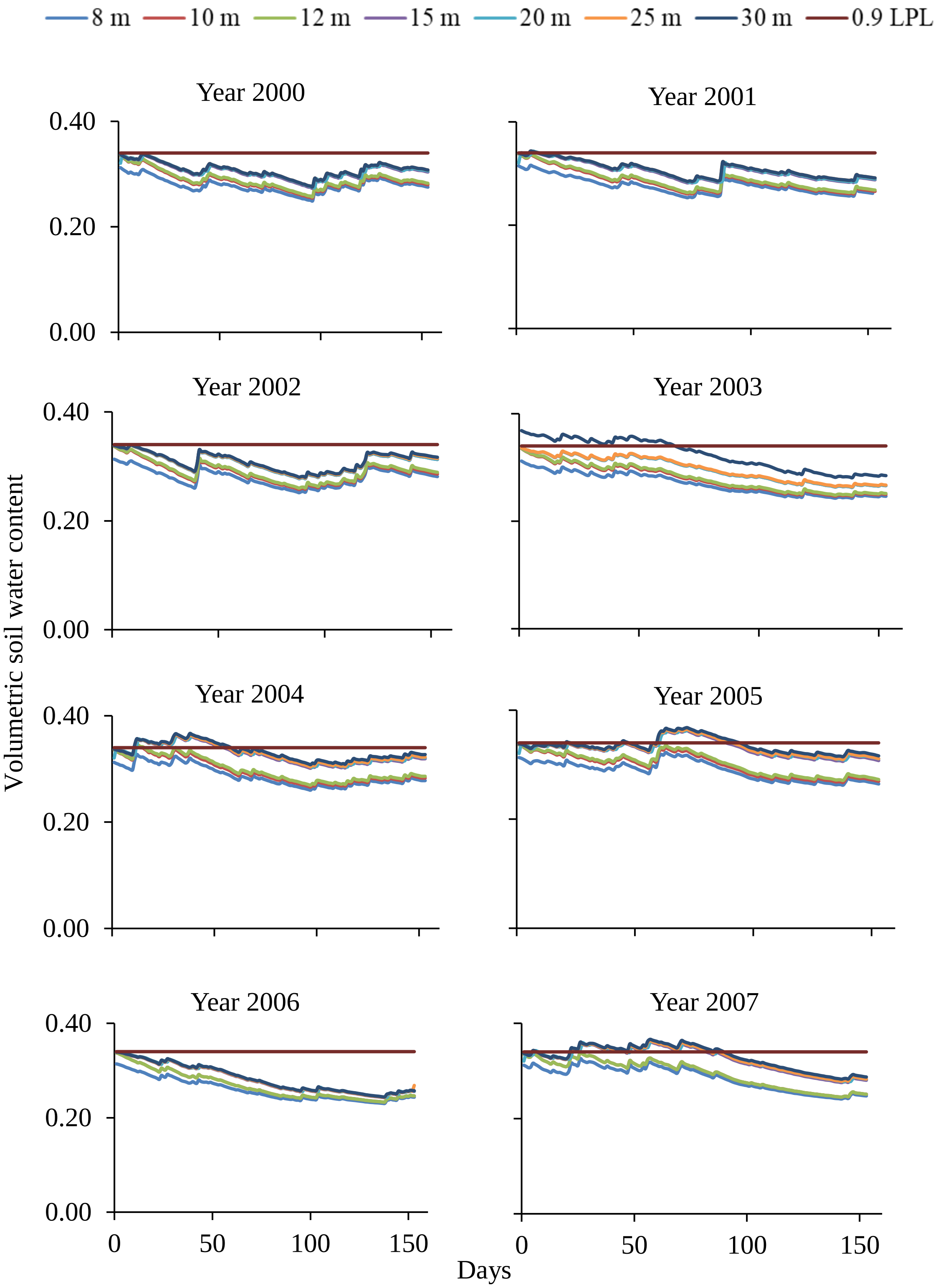

Figure 5.7: (2000-2007): Variation in average volumetric soil water content for the top 0.5 m of the soil profile with threshold for sufficient strength to provide protection for the subsoil

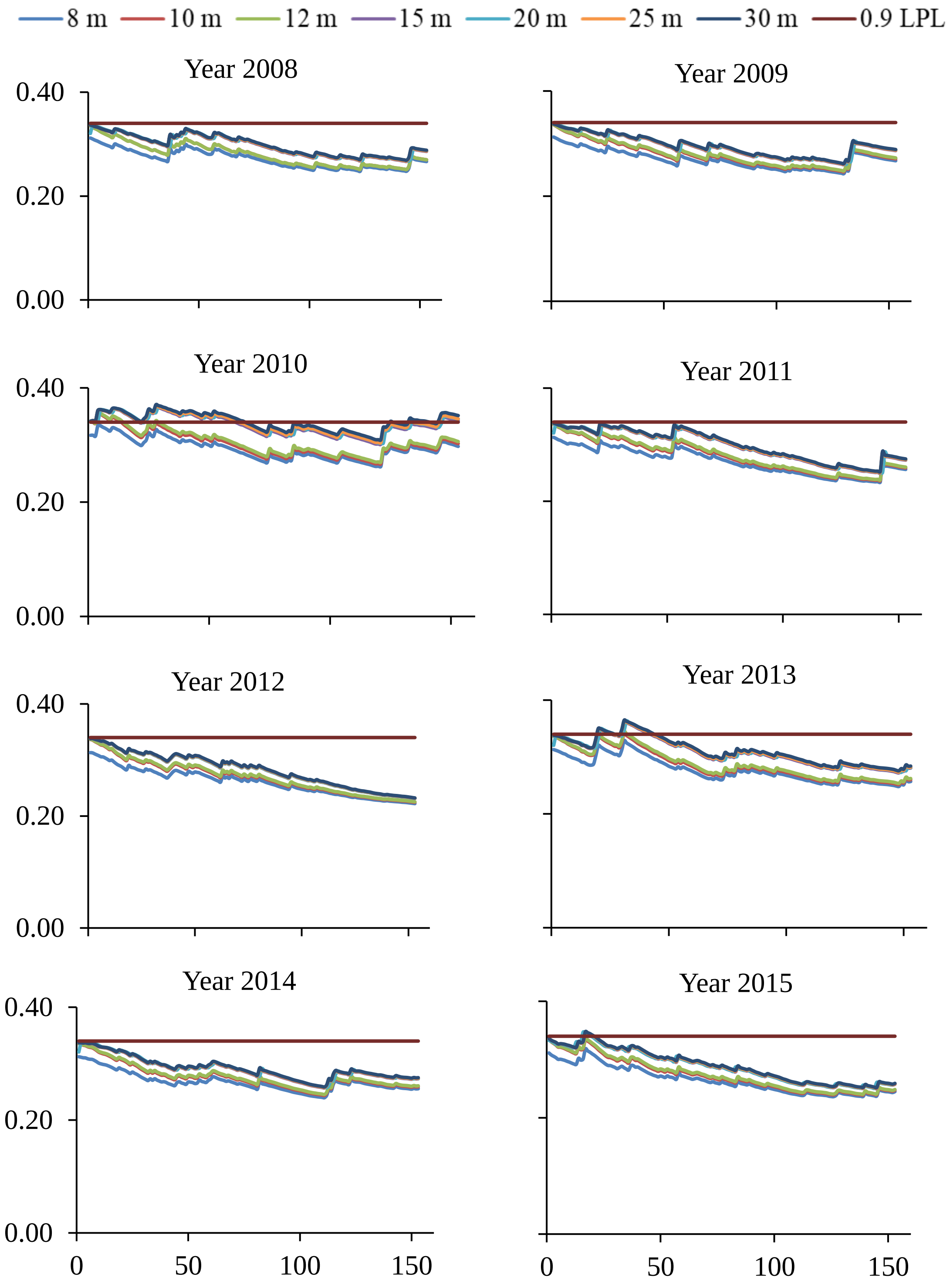

Figure 5.8: (2008-2015): Variation in average volumetric soil water content for the top 0.5 m of the soil profile with threshold for sufficient strength to provide protection for the subsoil

means of ameliorating subsoil compaction. However, a thorough review by Håkansson et al. (1987) showed that ameliorating subsoil compaction through freeze-thaw processes, are overestimated. In clayey soils, which have shrink-swell potential, under freeze-thaw conditions, subsoil compaction persists for decades, hence the effect may be more for the sandy loam soil in the study area. Also, due to lack of loosening of the subsoil, compaction at deeper depths can persist for decades (Håkansson et al. 1987). Notwithstanding, a loosened subsoil will re-compact easily (Alakukku 2003; Spoor et al. 2003). Müller (1988) demonstrated that performing subsoiling on soils with plasticity index more than 25% would last for more than two years. However, factors such as the strength of the upper layer of the soil, the strength of the soil layer sub-soiled, the watertable depth during and immediately after subsoiling, the effective depth of soil profile sub-soiled, agronomic operations, soil type, and climatic factors, influence how long the enhanced soil permeability would last (Müller 1988).

5.4 Conclusion

The objective of this study was to assess the intrinsic susceptibility and vulnerability of subsoil (0.6-m depth of the soil profile) to compaction in a potato field under different drain spacings and weather conditions (for years 2000 - 2015) in southern Manitoba. The compaction risk assessment of the subsoil at the study site was assessed based on risk assessment method proposed by Spoor et al. (2003). A validated HYDRUS (2D/3D) model was used to acquire soil water content data under different drain spacings for the sixteen years. The study showed that based on the soil textural class and the packing density of the subsoil at the study site, the subsoil was found to be highly susceptible to compaction. This implies the subsoil had very weak potential in resisting compaction due to weight transfer from machinery used in field operations. Throughout the years considered, the subsoil wetness condition under all the drain spacings (8 m, 10 m, 12 m, 15 m, 20 m, 25 m, and 30 m) was either “moist” or “wet”, which made the subsoil very vulnerable to compaction. The subsoil wetness impact was more problematic during the spring operations period (May 1 to June 20), when farmers need to prepare the land for seeding. The spring operations period generally had higher soil water content for all the years under the different drain spacings. Notwithstanding the wetness condition of the subsoil, for drain spacings ≤ 12 m, the upper soil layer (i.e. the top 0.5 m of the soil profile) had volumetric soil water content lower than the threshold of 0.34, which provided protection for the subsoil against compaction. Drain spacings wider than 12 m provided no protection for the subsoil during wet spring seasons when rainfall exceeded evapotranspiration. Lack of protection in the wet years could have detrimental effect on the soil structure for subsequent seasons.

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Chapter 6

Impact of loose and moderately compact soil on soil water content under average weather conditions in southern Manitoba

Abstract

The objective of the present study was to assess the impact of loose and moderately compact soil on soil water content under average weather conditions in southern Manitoba. The impact of loose soil and moderately compact soil on the soil water flow dynamics was studied through simulating scenarios for different bulk densities (1.0, 1.1, 1.2, 1.3, 1.4, and 1.5 Mgm^{-3}). The ROSETTA program (in HYDRUS (2D/3D) was used to estimate the soil hydraulic parameters corresponding to the bulk densities to predict the soil water content. The ROSETTA program was used due to lack of field data showing changes in soil water content as a result of changes in bulk density indicating loose and moderately compact soil. The results showed that loose soil had relatively high soil water content due to increased pore space. Increasing the bulk density within the range of loose soil (< 1.3 Mgm^{-3}) showed a decline in water content. Within the moderately compact soil range, the soil water content increased with increasing bulk density. This effect was more predominant during the spring field operations period, where the average rainfall amount was more than the average evapotranspiration amount. Increasing water content at the deeper layers presents a risk of subsoil compaction resulting from weight transfer of field machinery during field operations. It should however be noted that, although, loosening the soil (subsoiling) may improve the water movement through the soil, further field operations will cause the soil to re-compact. This therefore makes it necessary to monitor field operations on soil re-compaction processes and adapt field operations

to soil conditions to avoid further damage to the soil structure and the cost for subsoiling again.

Keywords: bulk density, subsoiling, compaction, soil water content, subsurface drainage, HYDRUS (2D/3D), ROSETTA program.

6.1 Introduction

Soil compaction has both short-term and long-term effects on crop production and the environment. This has led to extensive research to better understand the compaction processes and how to avoid and reverse the impact. Subsoiling is one of the measures that is taken to improve soil compaction. Subsoiling is the process of loosening a subsoil, which has a low hydraulic conductivity. Tined shanks are used for subsoiling, where the soil is lifted, shattered and loosened (Smedema et al. 2004). Loosened soil improves the water flow through the soil. Several approaches can be used to measure the state of the soil structure for crop production. These approaches may include measuring the changes in bulk density, penetration resistance, structural pores, root elongation, air permeability, and hydraulic conductivity (Al-Adawi and Reeder 1996; Alaoui et al. 2011). Among the different approaches, bulk density is one of the common parameters used to measure the state of compaction.

The bulk density is a measure of the packing of the soil particles. Although, bulk density is widely used in soil structural status assessment, it has been argued that it is a non-sensitive parameter (Al-Adawi and Reeder 1996; Alaoui et al. 2011). This is because at a given bulk density for the same soil, the pore geometry and continuity can differ due to differences in soil management practices (Alaoui et al. 2011). Also, for soils with shrink-swell potential, the bulk density will not be a reliable parameter to determine the status of the structure (Al-Adawi and Reeder 1996). In spite of the limitation of using bulk density as a measure of soil structural status, several studies have observed significant changes in the bulk density of soils during field operations and its direct impact on the soil water content, penetration resistance of the soil, infiltration capacity of the soil, total porosity of the soil, the hydraulic conductivity, and root development (Filipovic et al. 2006; Ahmad et al. 2009; Beylich et al. 2010; Alaoui et al. 2011).

In the present study, the objective was to use changes in bulk density of a sandy loam soil through HYDRUS (2D/3D) modeling to assess soil water content response in loose and moderately compact soil under average weather conditions in southern Manitoba.

6.2 Materials and Methods

6.2.1 Simulating water flow through the soil profile

The HYDRUS (2D/3D) model was used to set up the changes in bulk density to depict loose and moderately compact sandy loam soil. Field characteristics in a potato field at the Hespler Farms, which is located south of Winkler (49^o 10`N Lat., -97$^o$ 56`W Long., 272-m elevation) in the Rural Municipality of Stanley were used in the simulation exercise. A detailed description of the study site is documented in Satchithanantham (2013). Field data including soil water content and soil texture were obtained from the study site and used as input in the model. Detailed description of the data collection is presented in Chapter 4 and Chapter 5. In Addition to the soil water content and the soil texture, seventeen-year weather data (2000-2016) including precipitation, minimum temperature, maximum temperature, and relative humidity were obtained for the study area from Environment Canada (Environment Canada 2017). The minimum temperature, maximum temperature, and relative humidity data were used to determine the reference crop evapotranspiration (ET) as proposed by Maulé et al. (2006). The reference crop ET determined for the seventeen-year average for the growing season was portioned into reference crop evaporation and reference crop transpiration. The partitioned data were used together with the corresponding average precipitation as input in the model for simulating water flow through the soil. Seventeen-year data were considered due to data unavailability prior to year 2000.

The HYDRUS (2D/3D) model is a Windows-based computer program that simulates water flow through two- and three-dimensional variably saturated porous media by solving the Richards equation (Šimůnek et al. 2012). The two-dimensional option was used in the present study due to practical consideration of computer memory and simulation run times.

Six bulk density scenarios were simulated for studying the impact of loose and moderately compact soil on soil water flow. The bulk densities were 1.0, 1.1, 1.2, 1.3, 1.4, and 1.5 Mgm^{-3}. These bulk densities were chosen based on their impact on water flow and crop growth and performance in sandy loam soils (USDA/NRCS 2017). Bulk densities ideal for crop growth in sandy loam soils should be less than 1.4 Mgm^{-3} (USDA/NRCS 2017). Based on the packing density, which is defined as $\rho_p = \rho_b + 0.009C$, where ρ_p is packing density (Mgm^{-3}), ρ_b is bulk density (Mgm^{-3}) and C is clay content (11.2 %, w/w), the bulk densities studied can be classified into states of soil compaction (Canarache 1991). The states of soil compaction based on the packing density is presented in Table 6.1. Packing density values less than

Table 6.1: State of soil compaction based on packing density

Bulk density (Mgm^{-3})	Packing density (Mgm^{-3})	State of compaction
1.0	1.1	Non-compact
1.1	1.2	Non-compact
1.2	1.3	Non-compact
1.3	1.4	Threshold
1.4	1.5	Moderately compact
1.5	1.6	Moderately compact

1.4 Mgm^{-3} are considered non-compact soil (or loose soil), whereas values greater than 1.4 Mgm^{-3} are considered moderately compact soil (Canarache 1991).

A homogeneous soil profile was assumed in the simulation exercise. Hence, the model domain was created for 15-m width × 2.5-m depth. The width of the domain corresponded to the position of a drain tile with reference to the no flow boundaries on either side of the drain tile. The depth of the domain corresponded to the depth below the seasonal watertable fluctuations. Drain tile was introduced in the model domain to avoid a waterlogging effect especially in the loose soil.

Based on the defined simulation soil profile, a triangular finite element (FE) mesh was created to serve as a basis for the calculations. The mesh refinement was 0.05 m. In the FE mesh, the drain tile was represented as a hollow hole centered at a depth of 0.9 m, which corresponded with the depth of drain tile generally adopted in southern Manitoba. The drain tiles in the field were standard corrugated pipes with diameter of 0.10 m. The partial permeability of the corrugated pipe was accounted for by representing the diameter of the pipe with an effective diameter of 0.01 m with full permeability through the pipe walls (Qiao 2014).

The model domain had four external boundaries. That is, the soil surface, the left side, right side, and bottom. There was also an internal boundary due to the hollow circular opening of the drain tile. The boundary condition at the soil surface was specified as atmospheric. The left side, right side and the bottom of the model domain had no flux boundary condition. Volumetric soil water content of 0.29 was used as the initial condition for the model domain. The volumetric water content was determined in previous field studies at the Hespler Farms during springtime operations on June 3, 2011.

In the present study, the hydraulic parameters, that is, the residual water content (θ_r), saturated water content (θ_s), parameters α and n, and saturated hydraulic conductivity (K_s), that define the soil water retention characteristics curve and the hydraulic conductivity of water flow through a soil profile (Mualem 1976; van Genuchten 1980), were determined using the ROSETTA v 1.1 program in HUDRUS. The ROSETTA program is a computer program, which is widely used for estimating soil hydraulic parameters using a neural network (Acutis and Donatelli 2003). The ROSETTA program approach to determine the hydraulic parameters was used due to unavailability of data showing impact of loose and moderately compact soil on soil water content. It is however acknowledged that soil and water management practices in the field affect the soil water flow dynamics and the soil structure. Therefore, using the ROSETTA program without further calibration and validation to reflect “real” soil conditions will affect the accuracy of the output. Hence, care must be taken in using the results (Acutis and Donatelli 2003).

In ROSETTA, five PTFs are available for the prediction of the soil hydraulic parameters depending on the input data. The hierarchical sequence of input data used in the ROSETTA program include, soil textural class; sand, silt, and clay percentages; sand, silt, and clay percentages, and bulk density; sand, silt, and clay percentages, bulk density, and a water retention point at 33 kPa; sand, silt, and clay percentages, bulk density, and water retention points at 33 kPa and 1500 kPa. The first model provides class average hydraulic parameters based on basic soil textural class according to the USDA soil classification. The other four models were

Table 6.2: Estimated hydraulic parameters from ROSETTA

Bulk density	θ_r, (m^3m^{-3})	θ_s (m^3m^{-3})	α	n	K_s (m day^{-1})	l
1.0	0.052	0.517	2.45	1.4047	2.16	0.5
1.1	0.051	0.488	2.52	1.4266	1.68	0.5
1.2	0.049	0.461	2.61	1.4492	1.26	0.5
1.3	0.048	0.430	2.75	1.4723	0.86	0.5
1.4	0.047	0.411	2.89	1.4804	0.65	0.5
1.5	0.045	0.386	3.14	1.4692	0.45	0.5

developed based on neural network analyses. Incorporating more input variables provides a more accurate prediction of the hydraulic parameters (Zhang and Schaap 2017). Data input for predicting the hydraulic parameters in the present study were the average textural percentages. The average textural percentages for the soil were 68.4% sand, 20.4% silt, and 11.2 % clay. The hydraulic parameters predicted by the ROSETTA program are presented in Table 6.2.

6.3 Results and Discussion

6.3.1 Impact of bulk density on soil hydraulic parameters

Figure 6.1 shows a non-linear relationship between bulk density and soil hydraulic parameters. The hydraulic parameters define the water flow dynamics in the soil profile. As depicted in the figure, increasing the bulk density decreases the values of

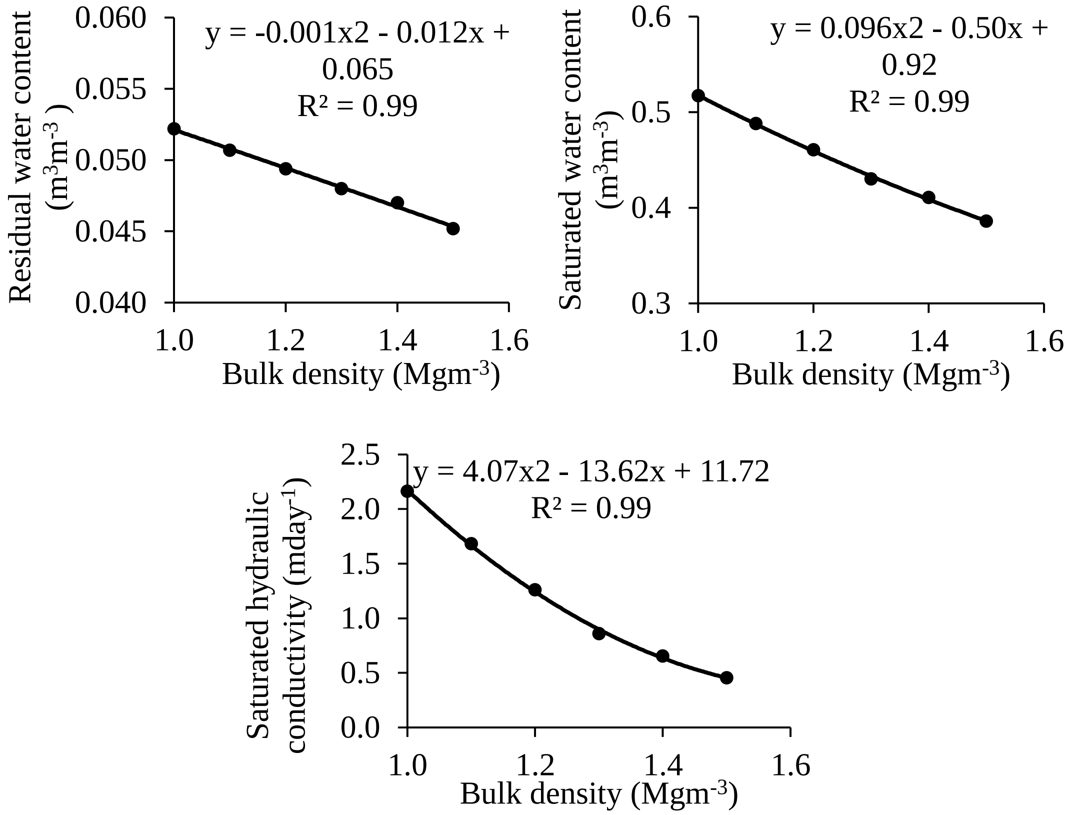

Figure 6.1: Relationship between bulk density and the soil hydraulic parameters

the soil hydraulic parameters due to decreased pore space. This observation agrees with previous studies, which indicate that reduced pore space decreases the water retention curve and the hydraulic conductivity (Mouazen et al. 2002).

6.3.2 Impact of bulk density on soil water content

Figure 6.2 shows the soil water content response to changes in bulk density within the top 0.6 m depth of the soil profile. The figure shows that increasing bulk density within the range of loose soil decreases the soil water content available in the soil. This observation can be attributed to increased solid particles per unit volume and thereby decreasing the pore space for air and water (Mouazen et al. 2002). This observation contradicts an observation made by Negi et al. (1981) in their study. They indicated that increasing the density and decreasing the pore space might increase the amount of water content and then decrease at a very high density. Archer and Smith (1972) also made similar observation as Negi et al. (1981). The contrast in the observation in previous studies and the present study may be attributed to differences in weather conditions, approach used to assess the impact of bulk density on soil water content, and soil and water management practices.

In the present study, the relationship between bulk density and soil water content shows that loose soil (< 1.3 Mgm^{-3}) has relatively higher moisture storage, which may be useful for plant growth and performance. Whereas, tight soil (>1.3 Mgm^{-3}) has lower moisture storage, which may affect the availability of water and nutrients for the crop. Decreased soil water content also decreases the rate of crop ET. Also at higher bulk densities, the soil is less susceptible to compaction (Negi et al. 1981). However, increased bulk density may affect root development and soil function.

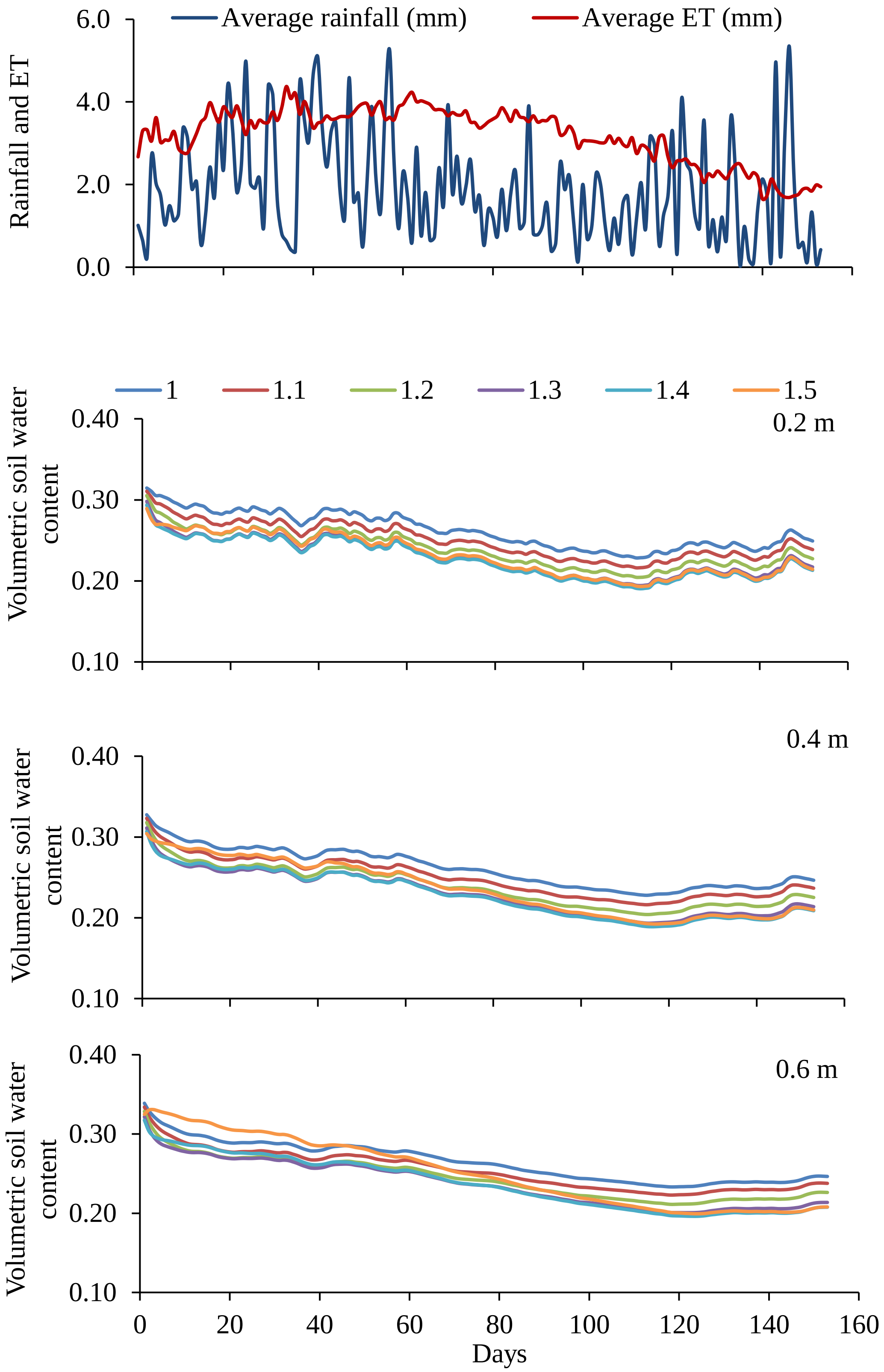

Figure 6.2: Soil water content response to changes in bulk density up to 0.6 m depth of the soil layer

Compacted soil limits the soil water movement in the soil profile and availability for crop water uptake, gaseous exchange for aerobic activities, and nutrient availability and uptake by the crops, which eventually affect plant growth and performance (Taylor and Brar 1991). Whalley et al. (1995) demonstrated that compacted soil profile hinders root development, which results in a short-term effect of yield losses and a long-term effect of poor structural generation and regeneration due to limited wetting and drying cycles in the soil profile. For fields with subsurface drainage, compacted soil inhibits the performance of drainage systems. In compacted soil, the infiltration capacity of the soil decreases due to pore space reduction. For an optimum performance of subsurface drainage systems, excess water in the soil must be able to move through the unsaturated zone to the subsurface drainage tiles (Smedema et al. 2004). Poor performance of the subsurface drainage system leads to waterlogging of the soil and further soil structural damage.

Also from Figure 6.2, it can be seen that increasing bulk density with decreasing water content trend reversed for bulk density higher than 1.3 Mgm^{-3}. This effect was more predominant at 0.4 m and 0.6 m during the spring operations period (May 1 to June 20, i.e. the first 51 days into the growing season). During that period, rainfall exceeded ET. The total rainfall amount during the spring operations period was 117 mm, which was about 41 % of the total rainfall for the growing season, whereas the total average ET was 180 mm, which was about 37% of the total ET for the growing season. This observation shows moderately compact soils restrict soil water movement with the impact being more predominant at the deeper layers. The restricted water flow through the profile led to higher soil water content, which may result in waterlogging challenges and increased susceptibility of subsoil to compaction. According to USDA/NRCS (2017) sandy loam soil with bulk density more than 1.3 Mgm^{-3} affects root development. Negi et al. (1981) found in their study that sandy loam with density above 1.5 Mgm^{-3} was excessively dense and affected plant yield. Archer and Smith (1972) demonstrated that bulk density of 1.5 Mgm^{-3} was the optimum for optimum permeability, drainage rate, trafficability, and root penetration in sandy loam soil in their study area. The bulk density at which soil is conducive for plant growth may be attributed to differences in study area characteristics and soil and water management practices.

To avoid waterlogging and subsoil compaction, subsoiling may be done to loosen the soil for improved soil water flow. It should however be noted that subsoiling may improve the soil infiltration capacity, but further field operations will cause the soil to re-compact. This challenge makes it necessary to monitor the effect of field operations on soil re-compaction and the performance of subsurface drainage with time. Understanding the re-compaction process will help adapt agronomic operations to the soil condition, which will in turn minimize soil structural damage and decrease the cost of improving the soil structure. It is also important to mention that subsoiled field should have subsurface drainage installed to remove excess water from the soil profile. As mentioned earlier, loose soil has higher soil moisture storage due to increased pore space. The subsurface drainage will be useful in controlling waterlogging challenges (Smedema et al. 2004).

This modeling study shows the impact of loose and moderately compact soil on soil moisture availability and the potential of waterlogging effect and subsoil compaction. However, a thorough field study needs to be done to assess the physical effect of subsoiling and tillage impacts on the soil structure and water flow dynamics.

6.4 Conclusion

In the present study, the impact of loose and moderately compact soil on soil water content under seventeen-year average weather condition in southern Manitoba was assessed. This was achieved by using HYDRUS (2D/3D) model to simulate scenarios for different bulk densities (1.0, 1.1, 1.2, 1.3, 1.4, and 1.5 $\mathrm{Mgm^{-3}}$) and their impact on soil water content. Bulk density less than 1.3 $\mathrm{Mgm^{-3}}$ was considered loose soil, whereas bulk density greater than 1.3 $\mathrm{Mgm^{-3}}$ was considered compact soil. The ROSETTA v. 1.1 program (in HYDRUS (2D/3D) was used to estimate the hydraulic parameters corresponding to the bulk densities to predict the soil water content. The results showed that bulk density had a non-linear relationship with the hydraulic parameters, which determine the water retention and hydraulic conductivity of the soil. Increasing the bulk density decreased the value of the hydraulic parameters. The results also showed that loose soil had relatively high soil water content due to increased pore space. Increasing the bulk density caused a decline in the water content until bulk density of 1.3 $\mathrm{Mgm^{-3}}$. The trend reversed as the bulk density increased in the range of moderately compact soil. This effect was more predominant during the spring field operations period, where the average rainfall amount was more than the average evapotranspiration amount. Increasing water content at the deeper layers during springtime presents a risk of subsoil compaction resulting from weight transfer of field machinery. It should be noted that, although, subsoiling (loosening the soil) may improve the water movement through the soil, further field operations will cause the soil to re-compact. This makes it necessary to monitor impact of field operations on soil re-compaction processes and adapt field operations to soil conditions to avoid further damage to the soil structure.

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Chapter 7

Main conclusions, contribution to knowledge and recommendation for future research

7.1 Main conclusions from research

The main conclusions from this research are presented below:

- The performance of the HYDRUS (2D/3D) model was evaluated for simulating soil water content for subsurface-drained sandy loam soil in southern Manitoba. Based on graphical and statistical evaluation, the results showed that the HYDRUS (2D/3D model simulated water flow through the subsurface-drained sandy loam soil under potato cultivation in southern Manitoba reasonably well.
- The soil strength of drained and undrained sandy-loam fields in southern Manitoba was compared to evaluate subsurface drainage in promoting soil strength for field operations. The results showed that in the top 0.3 m depth of the soil layer, the soil strength was sufficient to allow field operations under different weather conditions with or without drainage due to evapotranspiration effect. Drainage impact was found to be more significant for improving the soil water content within the 0.3-m to 0.5-m depth of the soil profile under different weather conditions. Under different weather conditions, narrower drain spacing (<15 m) promoted soil strength to allow field operations without any significant impact on the number of field workable days. Drain spacings wider than 15 m led to a significant loss of field workable days, especially in wet years.
- The intrinsic susceptibility and vulnerability of the subsoil to compaction was assessed under different drain spacings and different weather conditions. Based

on the texture and packing density of the soil, it was found that the subsoil in the study area had high level of susceptibility to compaction, which makes it very weak in resisting compaction. In addition, the subsoil was very vulnerable to compaction throughout the years considered due to the subsoil wetness condition being either moist or wet for all the drain spacings. However, drain spacings ≤ 12 m had upper soil layer with sufficient strength, which provided protection for the subsoil. Drain spacings wider than 12 m were found to be vulnerable to compaction during wet years, when rainfall exceeded ET.

- The impact of loose and moderately compact soil on soil water content under average weather conditions in southern Manitoba was assessed. The study showed that loose soil had relatively high soil water content. Increasing the bulk density in the range of loose soil caused a decline in the soil water content. In the range of the moderately compact soil, the water content increased with increasing bulk density. This effect was more predominant during the spring field operation period, when the average rainfall amount was more than the average evapotranspiration amount.

7.2 Significance of research to stakeholders

This research had four main objectives. These objectives were set to address part of the knowledge gap in soil and water management practices in southern Manitoba. Below is the significance of this research to stakeholders.

- Farmers need to perform field operations in a timely manner to obtain maximum yield. The water content of the soil influences the decision to carry out agronomic operations. Understanding the application of soil water content in crop production is vital for scheduling field operations, and meeting crop water demand throughout the growing season. Hence, making the quantification of soil water content available in the soil profile necessary. Several field techniques are available to measure soil water content. However, acquiring information and developing criteria tested locally takes a long time. Also, field studies are limited. Considering the limitations of field studies, the availability of a tested modeling tool in conjunction with field research is vital for studying soil moisture dynamics for effective agronomic operations. This study showed that the HYDRUS (2D/3D) model satisfactorily simulates soil water content under southern Manitoba weather conditions. The model incorporates several hydrological processes that affect the soil water dynamics relevant to a study area. This makes it possible to study water dynamics in different soil profiles over a wide area of coverage. Consequently, existing soil water management systems can be improved, and new systems can be better designed with a higher level of confidence.

- This study also showed the influence of subsurface drainage in removing excess soil water to promote soil strength for crop production. This is paramount to preserving the soil structure and promoting an environment conducive for plant growth and performance. This study demonstrated that under different weather conditions, narrower drain spacings (<15 m) promoted soil strength to allow field operations without any significant impact on the allowable fieldwork days. Drain spacings wider than 15 m led to a significant loss of fieldwork days, especially in wet years.
- The susceptibility of the subsoil to compaction was also assessed in this study under different drainage designs and weather conditions. This was necessary due

to weight transfer from field machinery during filed operations. Based on the texture and packing density of the soil, it was found that the subsoil in the study area had a high level of susceptibility to compaction, which makes it very weak in resisting compaction. In that regard, installing subsurface drainage may be useful in protecting the subsoil from compaction. It was however found that irrespective of the drainage design, the subsoil was very vulnerable to compaction throughout the years considered due to the subsoil wetness condition being either “moist” or “wet”. Notwithstanding, assessment of the top 0.5-m depth of the soil layer showed that drain spacing ≤ 12 m provided protection for the subsoil. Drain spacings wider than 12 m were found to be vulnerable to compaction during wet years, when rainfall exceeded ET. Understanding the drainage requirements under different weather conditions is helpful for the field manager to make informed decision on installing drain tiles at a particular spacing and depth, and the impact that it will have on field operations and yield.

- This study also showed the impact of loose and moderately compact soil on soil water content. Soil compaction has both short-term and long-term effects on crop production and the environment. This has led to conducting extensive research to better understand the compaction processes, and how to avoid and reverse the impact. Subsoiling is one of the measures that are taken to improve soil compaction. Loosened soil improves the water flow dynamics of the soil. The study showed that loose soil has relatively higher water content. Increasing the bulk density in the range of loose soil caused a decline in the water content. In the range of the moderately compact soil, the water content increased with increasing bulk density. This effect was more predominant during the spring field operation period, when the average rainfall amount was more than the average evapotranspiration amount. This becomes more problematic at deeper layers due to risk of subsoil compaction resulting from weight transfer of field machinery during field operations. In the upper layers of the soil, tillage operations may loosen the soil. For the subsoil, measures such as subsoiling may be taken to improve the infiltration capacity of the soil to avoid soil structural damage. It should be noted that, although, subsoiling may improve the water movement through the soil, further field operations may cause the soil to re-compact. Having this understanding will be useful for field managers and researchers to make informed decisions on monitoring field operations on soil compaction and adapt the field operations to soil conditions to avoid further damage of the soil structure and investment in re-subsoiling.

- This study also provides a methodology, which is vital for building the database for researchers to improve on soil and water management practices in the region. Policy makers will make informed decisions on investing into monitoring and revising soil and water management guidelines to address soil water challenges in the region, especially during spring operations period.

7.3 Recommendations for future research

Soil and water management practices are becoming popular in southern Manitoba with the overarching goal of improving the soil water content for timely field operations, which has subsequent effects on plant growth and performance. The present study was limited in terms of resources to conduct field studies to reconcile the findings made based on past data and also extend the study to cover wide variety of soil conditions in the region. It is therefore recommended that a field research should be conducted to:

- Cover a wide range of soil conditions in the region for a better understanding of controlling wet soil conditions, especially during the spring operation period. Southern Manitoba has a wide range of soil types with different internal drainage classes. This makes it necessary to assess the impact of drainage (surface and subsurface) in controlling excess water for different soil conditions. Having a generalized drainage design installation for all the soil conditions may not be useful in achieving timely field operations.
- Assess the impact of loose and compact soil on soil water flow dynamics in the field. Soil loosening is done to improve the water flow movement through the soil. However, loosened soil will re-compact due to agronomic operations. Hence, the re-compaction process should be monitored over a period of time. The information from this will be useful in modeling loading effect on soil structure, which will help to adapt field operations to the soil condition to minimize soil structural damage.