Water management of canola under tile drainage in the Canadian Prairies

By

Emeka Leonard Ndulue

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Department of Biosystems Engineering
Price Faculty of Engineering
University of Manitoba
Winnipeg

Abstract

An effective water management system is necessary to address global food shortages, water scarcity, and increasing climate extremes. Southern Manitoba is a major crop production area with highly productive soils, flat topography, and seasonally high water table. The objectives of this research were to (i) determine the impacts of controlled drainage (CD), free drainage (FD), and no drainage (ND) on canola yield and quality, (ii) simulate water table depth (WTD) under canola production using the DRAINMOD model, (iii) evaluate the potential impacts of climate change on the hydrology and canola yield using the DRAINMOD model and (iv) assess the performance of the standard ET model under limiting conditions and fourteen empirical ET models in the region. The result shows large differences in yield between the years, suggesting that canola yield is significantly influenced by weather variables. In 2019 with normal average temperature and rainfall close to the long-term average, CD plots consistently yielded higher yields than FD and ND, with a significant difference with FD. As rainfall decreased and temperature increased in the following years, the impact of drainage, especially CD, becomes diminished, with no significant differences between the treatments. Also, the prevailing weather may have masked the oil quality parameters and nutrient dynamics across the soil profile, as there were no significant differences between the treatments. The WTD collected from the PESAI (Prairies East Sustainable Agriculture Initiative) site in Arborg was used to test the ability of the DRAINMOD model to predict WTD using the 2019 and 2020 canola growing seasons. Statistical analysis and graphical plots showed close agreement between the measured and simulated WTD. Economic analysis using the simulation results suggests that the 10 m drain spacing maximized the return on investment. The parameterized DRAINMOD model was thereafter run with downscaled climate model projections from CANESM2 for historical (1981-2010), midcentury (2041-2070), and late-century (2071-2100) periods under three representative concentration pathways (RCP2.6, RCP4.5, and RCP 8.5). Results showed an overall decrease in average relative canola yield under FD and CD in the future. The ET (evapotranspiration) is an essential input to hydrologic models. However, the weather variables required to compute the recommended ET model (FAO PM) equation are not readily available. The results showed that the FAO-PM model decreased with increased missing data, yielding average to poor results. The best performing models were Valiantzas-1, Valiantzas-3, Irmak, Valiantzas-2, and Priestly-Taylor models. New empirical coefficients were also developed to improve selected empirical ET models. Overall, this research is important for developing optimal drainage design variables for increased crop yield.

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Dedication

To my family and parents.

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Chapter One

Introduction

1.1 Background of the research

Water is perceived as the most important natural resource because human life and other living things depend on it for survival. While it is the most common and abundant substance on earth, its distribution is limited in time and space (Cosgrove and Loucks 2015). The earth's surface is occupied by more than 70% of water. Canada is home to about 7% of the world's freshwater resources, with an average annual water yield of 3,478 Km^3 (Statistics Canada, 2017). Canada has about 11.7% (1,169,561 Km^2) of the land area covered with water (Statistics Canada, 2017). It has the world's most extensive coastline of 243,042 km, as it is bounded by three oceans (Atlantic, Pacific, and Arctic) (Statistics Canada, 2017). From the above statistics, one can conclude that Canada is excessively rich in water resources. However, these are aggregate values and could be misleading. Water distribution in Canada is uneven temporally and spatially. Most of the water resources drain to the north. Only about 40% of the freshwater is found in the south, which has about 85% of the country's population (ECCC 2013). Some regions in the Canadian prairies receive significantly low annual rainfall (McGinn, 2010). The Canadian prairies in western Canada consist of three provinces, Saskatchewan, Alberta, and Manitoba; Canada's food basket is known for growing grains, oilseeds, and animal products.

The Canadian prairies play a crucial role in the total food production in Canada, contributing more than 50% of Canada's grain (Bueckert and Clarke 2013). The region has more than 42% of Canada's farms and more than 80% of Canada's farmland (AAFC, 2000). It is also the largest producer of canola, an important source of edible oil. Saskatchewan boasts about 53.7% of the total production in Canada, followed by Alberta (28.86%), Manitoba (16.31%) and British Columbia (0.6%) (CCC 2021). Manitoba produced more than 3.3 million tons in 2018. Canola is suited to the Canadian prairies, although crop yield and oil quality are susceptible to environmental stresses frequently experienced in the prairies. In Manitoba, excess water, drought, and heat account for a combined crop loss of 71% (MASC, 2020). Projected future climate scenarios for the region predict wetter springs and dryer summers (Sauchyn and Kulshreshtha, 2008). The winter snow and early spring rainfall could have severe consequences for soil workability, trafficability, timeliness of farm operation, and, consequently, total crop yield. According to Manitoba Agricultural Services Corporation

(MASC, 2015), a delay in planting up to the first week of June could led to a 20 - 30% reduction in yield depending on crop type. These challenges have necessitated Canadian producers, especially canola farmers, to seek sustainable water management strategies.

Agricultural drainage is an important water management technique that provides a conducive growing environment for proper crop development and growth by lowering the water table and removing excess water from the soil profile. The benefits of agricultural drainage are well documented in several textbooks and journals, some of which are increased crop yield and income, timely farm operations, early planting, improved soil health, soil properties etc. (Madramootoo et al. 1993, Fraser and Fleming 2001, Hudson and Roberts 1982, Huffman et al. 2011. Van Zandvoort et al. 2017). On the contrary, drainage has led to the loss of wetlands, mainly in North America, Europe, and Asia (Davidson 2014) and increased nutrient loadings leading to eutrophication and anoxic conditions (King et al. 2015).

It is essential to evaluate different water management systems for agronomic, economic, and environmental benefits. This is because the performance of water management systems varies from one location to another due to a variety of factors that are not fully understood (Allerhand et al. 2013). Field experiments and modelling are complementary tools that assist water managers, producers, and decision-makers in effective water management. Technological advancements in data collection and computing abilities have made hydrologic models attractive for many researchers. Models have been used to provide an understanding of the agro-hydrological process and guide decision-making processes such as water management, irrigation timing and scheduling, drainage design and management, nutrients transport, and climate change assessments (Phogat et al. 2014, Karandish and Šimůnek 2016, Gunn et al. 2018, Mante et al. 2018, Pease et al. 2017). It should be noted that model results are affected by uncertainties originating from model inputs, model assumptions, structure, and parameter uncertainty (Seiller & Anctil 2016). ET (evapotranspiration) is one of the most critical inputs to hydrologic models. In most hydrologic models, the reference evapotranspiration (ET_o) quantifies the atmospheric water demand under ideal conditions (Allen et al. 1998). The FAO Penman-Monteith (FAO PM) equation has been identified as the standard model for determining ET_o (Allen et al. 1998). However, the weather variables required to compute the FAO PM equation are not readily available. Hence, researchers have developed simple empirical ET equations that require fewer weather inputs but such methods are location specific. Thus, it is recommended to evaluate the suitability of an empirical ET_o model before use in new environments (Tabari et al. 2013).

1.2 Objectives of the research

The overall objective of this research was to determine the impact of different water management techniques, namely, controlled Drainage (CD), free drainage (FD), and no Drainage (ND) on yield and oil quality of Canola grown in southern Manitoba. Specific objectives include to:

(i) assess the effects of different water management systems on canola yield and canola oil quality parameters (oil content, protein content, glucosinolates, and fatty acid composition)

(ii) apply the DRAINMOD model to simulate water table depth under canola production and validate the model for the field.

(iii) assess how climate change may affect the hydrology and canola yield of an agricultural field and

(iv) assess the performance of the FAO PM equation and fourteen empirical ET models in southern Manitoba.

1.3 Justification of the research

Since the last century, canola and oilseed production and areas under cultivation have been rising in Canada and other countries. There has been an exponential growth in exports, trade between countries on Canola and its products. Production in Canada has been projected to reach 25 million tonnes by 2025 (Morrison et al. 2016).

Although studies have shown that water management affects canola yield and quality, the response may vary considerably among production areas that differ in growing conditions, soil properties, varieties, drainage design, and other management practices. These variations justify the need for water management strategies that are location specific. Even though subsurface drainage has been practiced for centuries, especially in humid and semi-arid regions, it is relatively new in southern Manitoba. In recent times, producers in the area have begun embracing the agricultural tile drainage installation. Despite being the highest economic crop in the province, no study has quantitatively described the impact of water management on canola production in Manitoba. This research is a follow-up to previous studies on water management in potatoes (Satchithanantham 2013) and corn (Cordeiro 2014). The findings from this study are essential for canola growers regarding the best water management strategy that will increase yield with minimal environmental impacts, especially in the face of an uncertain and changing climate. It is also important to build the local database for efficient and effective water resources management for growing Canola and decision making. The development of alternative ET models using weather data from the region would address the challenge of incomplete historical data needed for long-term modelling studies.

1.4 Scope of the research

The research evaluates one of the major problems limiting maximum production in the Canadian prairies and how water management can affect canola yield and quality in southern Manitoba. At the start of the growing season, excess water due to snowmelt may delay planting and field operations. Rainfall is uneven during the growing season, resulting in prolonged soil water deficit. The study attempts to contribute to knowledge by evaluating agronomic impacts of drainage on canola yield and quality in southern Manitoba, understanding water table dynamics through experimental and modelling exercises, predicting climate change impacts on crop yield under conventional and controlled drainage, and developing empirical constants for ET models.

This thesis contains seven chapters. Chapter one gives the general introduction, including the background of the study, objectives of the study, justification of the study, and scope of the research. Chapter two gives the literature review on the canola plant, growth and development, water management strategies, and hydrologic modelling. Chapter three evaluates three different water managements on canola yield and oil quality. Chapter four presents DRAINMOD simulations of the water table, including determining the optimum drain spacing and economic analysis. Chapter five assesses climate change impacts on crop yield under two water management systems (conventional and controlled drainage) using the parameterized model. Chapter six determined an assessment of the FAO PM equation under limiting conditions and calibration of empirical ET constant for southern Manitoba. Chapter seven presents the conclusion of this thesis, including the main findings and contribution to knowledge and recommendations for future studies.

Chapter Two

Literature Review

2.1 Canola

Canola was developed by breeding a type of rapeseed to lower the erucic acid content by plant breeders at the University of Manitoba. The name canola was coined from **Can**adian **o**il, **l**ow **a**cid. It is a dicotyledonous plant characterized by its yellow petals arranged in a cross-like pattern producing round seeds in small pods. Canola plants belongs to the genus *Brassica,* in the family of Brassicaceae, which is comprised of about 338 genera and 3700 species (Bailey et al., 2006). In Europe, Asia, and other regions, canola is also referred to as oil seed rape. For rapeseed to be called canola, it must meet the specifications set by the Canola Council of Canada (CCC). As defined by CCC (2021), Canola is '*seeds of the genus Brassica (Brassica napus, Brassica rapa or Brassica juncea) from which the oil shall contain less than 2% erucic acid in its fatty acid profile, and the solid component shall contain less than 30 micromoles of alone, or any mixture of, 3-butenyl glucosinolate, 4-pentenyl glucosinolate, 2-hydroxy-3 butenyl glucosinolate, and 2-hydroxy- 4-pentenyl glucosinolate per gram of air-dry, oil-free solid'*.

2.1.1 History – Origin, Statistics, Production, Uses

Historically, rapeseed leaves and seeds, were used as potherbs, vegetables, spices, and condiments because of their hot flavour (Daun, 2011). It was also consumed as vegetable oil and lighting oil in Asia and Europe for almost 4000 years (Barthet, 2016). Rapeseed was first grown in Canada during the Second World War to augment supplies used to service steam and marine engines. After the war, a large quantity of rapeseeds continued to be grown and produced in Canada. Meanwhile, other oil plants such as soybean and sunflower did not perform agronomically well compared to rapeseed. The climatic condition in the prairies favoured rapeseed production since it required fewer heat units to grow compared to soybean and sunflower (Barthet, 2016). However, rapeseed had erucic acid and glucosinolate contents in significant quantities, which caused heart lesions in animals (Daun, 2011). In a research effort to eliminate these unwanted compounds and improve their taste and quality, canola was born. The development of rapeseed into canola is arguably the most important in rapeseed development. Through rigorous traditional plant breeding and field trials, the *B. napus* cultivar "Tower" was registered by Dr. Baldur Stefansson in 1974. It became the first rapeseed variety low in erucic acid and glucosinolate. In 1977, Dr. Downey and his research group registered the “Candle” cultivar as the first *B. campestris* low in erucic acid and total glucosinolate. In 1978, the name canola was coined by the Rapeseed Association of Canada.

Global canola production and harvested areas have increased beginning in the last century. Production increased from about 1000 metric tons in 1943 to 2 million tons in 1977 (Barthet, 2016), then from 29.7 million tons in 1994 to 68.8 million tons in 2016. In the same vein, the cultivated area has increased from 22.72 million Ha in 1994 to 33.7 million Ha in 2016 (FAO 2018). This increase has been attributed to a number of factors, some of which are the use of herbicide-tolerant varieties, development of hybrids with better agronomic qualities, high economic returns, biodiesel potentials, and government support for green energy (Morrison et al. 2013, Harker et al. 2012). Canola is the second largest oil crop after soybeans, with a global production of 69.6 million metric tonnes in 2020 (USDA, 2022).

Canada is the largest producer of canola globally, with an annual production of 22.9 million metric tons in 2017 grown on 23.0 million acres (CCC, 2021). Canada produced about 24% of the world’s Canola and is also the largest exporter, accounting for 64% of export trade (Cliff Jamieson 2021). The Canadian prairies account for more than 98% of the total canola production in Canada, while British Columbia, Ontario and Quebec account for the remainder. According to Statistics Canada (CCC 2021), in 2018, the Canadian prairies produced about 22,302,300 metric tons. Manitoba contributed about 14.9% (3,379,100 million tons) of the total Canadian amount and is the third-largest producer behind Alberta (6,679,200 million tons) and Saskatchewan (12,244,000 million tons). Canola is Canada’s most valuable crop contributing about $29.9 billion annually to the economy, creating more than 207,000 jobs and paying $12 billion in wages (LMC International 2020). It is estimated that about 43,000 Canadian farmers grow Canola (CCC 2021). Canola oil is regarded as one of the world’s healthiest oils due to its low saturated fat and high unsaturated fat contents, even though there are conflicting, inconsistent and inconclusive results on the health benefits (Lauretti and Pratico 2017, Lin et al. 2013).

Canola is mainly cultivated for its oil. Proximate analysis of canola oil indicates 48.4% oil and 22.5% protein (Barthet, 2016). After the oil has been extracted from Canola, the by-product, canola meal, is an excellent food supplement. Industrially, canola oil can be used to produce lubricants, oils, fuel, soaps, paints, bioplastics, cosmetics or inks (CCC, 2021). Studies have shown that Canola is a stockpile of bioenergy (Fore et al. 2011). When mixed with wheat, it can be used to produce ethanol. The canola seed can also be used to produce biodiesel. Canola also has the potential for environmental reclamation and heavy metal decontamination (Ali et al. 2017).

2.1.2 Lifecycle

Canola completes its lifecycle (planting to maturity) between 80 to 120 days depending on various factors, including cultivar, environmental variables, nutrients, management etc. According to CCC (2021), Canola has eight distinct growth stages, identified using the decimal classification (BBCH) method (Lancashire et al. 1991). They include the germination (growth stage 0), leaf development (growth stage 1), stem elongation (growth stage 3), inflorescence or budding (growth stage 5), flowering (growth stage 6), seeds and pod development (growth stage 7), ripening (growth stage 8), and senescence (growth stage 9).

2.1.3 Canola planting and management

Canola is planted by seeding. Under favourable growing conditions, germination occurs after 2-4 days of planting. Canola grows across a wide range of climates, soils, and environments in North America, Asia, Europe, Australia and Africa. Canola performs well on drained soils, with pH between 5.5-8.3, and moderately tolerant to salinity (Francois 1994, CCC, 2021). A shallow planting depth of 1 cm with good soil moisture was recommended by Harker et al. (2012). The benefit includes a shortened length of time to emergence, flowering and maturity. Canola has also shown to be an excellent rotation crop with small grain crops or tuber crops such as potatoes, or soybeans (CCC, 2021). The introduction of hybrid cultivars that are herbicide and disease tolerant provides an additional benefit of weeds, insects, and diseases control (Cathcart et al. 2006, Morrison et al. 2016)**.**

Management practices, including planting date, planting density, tillage, and water conservation practices, have been reported to significantly affect canola performance (Kirkland et al. 2000, Angadi et al. 2004, Clayton et al. 2004, Hang et al. 2009, McKenzie et al. 2011, Abdullah 2014, Barthet 2016). In cold regions, planting is hindered by excess soil water due to snowmelt and low soil temperature. In Manitoba, Excess Moisture Insurance (EMI) protects against excessively wet conditions for producers who cannot plant before June 20. According to MASC (2020), $623,106,473 was paid to farmers as claims due to excess soil water in the 2019/2020 growing season. Planting date is an important management decision producers could use to maximize environmental variables (temperature and moisture) and reduce heat and water stress during sensitive growth stages. Even though early planting has been recommended (between middle to late April) (McKenzie et al. 2011, Clayton et al. 2004, Kirkland and Johnson 2000, Angadi et al. 2004), the optimal date is driven by historical frost risk, which varies with location. Benefits of early planting include efficient use of soil moisture, ensuring early flowering, avoiding heat and water stress, reducing the risk of frost damage in the fall and higher yield and oil quality (Angadi et al. 2004, Kirkland and Johnson 2000). In Australia, Kirkegaard et al. (2016) also observed that the traditional recommended planting date (usually mid to late May) decreased water use efficiency (WUE), increased frost risks, and reduced yield. Faraji et al. (2009) showed that early planting resulted in higher yield, more flowering days, longer days to maturity, higher above-ground dry matter, higher WUE and high harvest index. Their results showed that late planting decreased yield from 3780 to 582 kg/ha in 2005/2006 and 3543 to 162 kg/ha in 2006/2007. However, in Brazil, Confortin et al. (2019) reported that planting in mid-autumn (May 20) produced the highest seed and oil yield. Higher planting densities are hypothesized to increase yield and oil yield (Yousaf et al. 2002, Zhang et al. 2012, French et al. 2016). In a comparative study of different planting densities by Zhang et al. (2012), seed and oil yield increased by 10-20% and 12-18%, respectively. Likewise, in a 16-site study across western Canada, from 2010 to 2012, Gan et al. (2016) reported that, depending on the environment, higher planting density and more extended post-flowering period increased yield. In the same way, O'Donovan (1994) found out that a high planting density of 200 m^2/plant suppresses weeds. In Iran, Koocheki et al. (2014) observed that increasing plant density not only increased yield but also reduced nitrogen loss. Another important management factor is row spacing, as it affects access to nutrients and water, competition with weeds, and use of sunlight and energy. Ismail (2016) studied the optimum combination of irrigation, row spacing and intra-row spacing for growing canola. Full irrigation with a row spacing of 20 cm and an inter-row spacing of 10 cm optimized canola oil and seed production. This agrees with the report of Hu et al. (2015). They observed that 30 cm row spacing increased soil water content, canola yield and WUE in Saskatchewan. However, Potter et al. (2007) found no significant effect of row spacing on oil yield in Australia.

2.1.4 Nutrients Requirements

The major nutrients for crop growth and development are macro elements which include Nitrogen, Phosphorus, Magnesium, Sulphur, and Calcium. Fertilizer application rates depend on the available nutrients in the soil, as excessive loss of fertilizers is the major cause of water pollution, eutrophication, and algal bloom (Rabalais et al. 2007). Generally, canola plants require more N fertilizer than other oilseed plants (Singh et al. 2006). According to

Assefa et al. (2018), the nutrient requirement for canola is given as 62–12–45– 28 kg of plant N–P–K–S Mg/yield. Gan et al. (2007) reported that the nitrogen requirement for maximum yield varies between 106 to 162 kg N/ha depending on the cultivar. The effect of increased N rates on canola yield depends on weather, soil, moisture and variety (Ozer, 2003). Results from different studies suggest that high nNitrogen rates have resulted in increased canola yield by increasing the number of branches and flowers per plant, increasing leaf area index, extending the life duration of leaves, and increasing total crop absorption (Ozer 2003, CCC 2021, Wright et al. 1988). Ebrahimian et al. (2017) found out that N and Zn can be used to offset the negative effects of salinity on Canola. A mild application rate of 15 kg/ha of Sulphur and a high application rate of 120 kg/ ha of Nitrogen increased the WUE of Canola (Ngezimana and Agenbag 2015). Other microelements for the successful growth of Canola include boron, molybdenum, copper, zinc, and manganese (CCC, 2021).

2.1.5 Factors affecting Canola Yield

A lot of factors affect canola yield. While some researchers have studied only one factor (Ozer, 2003, Naghavi et al. 2015, BirunAra et al. 2011, Pavlista et al. 2016, Herget et al. 2016), others have investigated two or more factors (Younes, et al. 2011, Ismail, 2016, Kamkar et al. 2011, Koocheki et al. 2014). After reviewing more than 100 scientific publications on factors affecting canola yield, Assefa et al. (2018) ranked weather (environment) as the most important, followed by management, genetic and crop agronomic performance.

Environmental stresses, mainly temperature (heat) and water stress, significantly affect canola yield and oil quality. There is a general consensus in the literature that heat and drought stress have a very strong negative effect on canola emergence, growth, yield, and oil quality (Dreccer et al. 2018, Gan et al. 2004, Vigil et al. 1997, Elferjani and Soolanayakanahally 2018, Meng et al. 2017). Laboratory experiments and field studies have been used to evaluate the individual and combined effects of both stressors. The extent of their impacts is also dependent on the stage of development. The reproductive stage (flowering and pod development) is the most sensitive stage (Gan et al. 2004). A study by Tesfamariam et al. (2010) showed that water stress during the flowering stage reduced seed yield, oil yield and water use by 64.5, 14.6 and 53.2%, respectively, compared to the no-stress situation. Aksouh et al. (2006) demonstrated in a field experiment in Australia that exposing Canola to a short period of high temperature during the flowering stage reduced crop yield by 52% more than mild temperature stress over an extended period. This also agrees with the result of Faraji et al. (2009) in Iran. A study by

Hammic et al. (2017) showed that temperature and water stress had a more significant impact on canola yield than the nutrient condition of the soil. Of the two stresses, heat stress has the more significant detrimental effect on crop yield since Canola is a cool-season crop; therefore, it is highly susceptible to high temperatures (Angadi et al. 2000, Gan et al. 2004, Elferjani and Soolanayakanahally 2018). Elferjani and Soolanayakanahally, (2018) reported an 89% reduction in yield due to the combined impacts of drought and heat stress, while drought and heat stress alone resulted in 83 and 31% reductions, respectively. Gan et al. (2004) reported that high temperature decreased main stem pods, seeds per pod and seed weight by 75, 25 and 25%, respectively.

Canola plants under stress resulted in high protein content and low canola oil qualities such as increased concentration of glucosinolates, reduced growth, yield, and oil quality (Tesfamariam et al. 2010, Tohidi-Moghadam et al. 2011, Hammac et al. 2017, Rashid et al. 2018, Pokharel et al. 2020, Lohani et al. 2021). In a study by Champolivier and Merrien (1996), they observed a 48% reduction in yield because of water stress during the flowering stage. They further reported that oil yield decreased between 6 and 14% when subjected to water stress at different stages except for the vegetative stage, although protein content increased up to 14%. Tohidi-Moghadam et al. (2011) observed a 15% increase in glucosinolate content under water stress.

2.1.6 Water requirement of Canola

The water requirement of Canola depends on several factors, including cultivar, climate, soil type, target yield, and management practices. Under full irrigation, canola water use was 702 mm in South Africa (Tesfamariam et al. 2010). It ranged from 449 to 462 mm in Turkey (Dogan et al. 2011), 582 mm in Nebraska (Herget et al. 2016), and 400 to 480 mm in Alberta (Alberta Agriculture and Rural Development 2011). Canola is usually grown under rain-fed conditions in southern Manitoba and many other regions, although canola yield increases with water availability. Faraji et al. (2009) reported that irrigation could cushion the effects of temperature stress, especially during the flowering stage, without yield loss.

Irrigation is reported to have increased canola yield, phenology, and yield components, including the number of leaves, branches, flowers and pods, crop height, stem length, stem diameter, canopy growth, 1000-seed weights, oil yield, and biomass (Dogan et al. 2011, Bilibio et al. 2011, Ghobadi et al. 2006, Faraji et al. 2009). With irrigation amounts of 10, 20, and 30 cm in semi-arid Nebraska, canola yield increased by 519 kg/ha, 1224 kg/ha, and 1686 kg/ha, respectively, compared with the rain-fed system (Herget et al. 2016). Faraji et al. (2009)

compared supplemental irrigation and rain-fed irrigation and reported that canola yield increased by 22.5 and 12.4% in the 2005 and 2006 growing seasons. Herget et al. (2016) reported that canola yield was five to 6 times under full irrigation relative to no irrigation. For areas with limited water supply, especially in an arid and semi-arid climate, deficit irrigation could minimize yield loss (BirunAra et al. 2011, Naghavi et al. 2015, Pavlista et al. 2016, Herget et al. 2016). Mousavi et al. (2010) implemented a different form of deficit irrigation called partial root zone (PRD). They reported no significant difference in yield, pod length, number of pods, branches and seed, 1000-seed weight and plant dry matter between PRD at 50% and full irrigation.

On the other hand, too much water in the soil is detrimental to plants with low tolerance to saturated conditions such as canola. The impacts of waterlogging on crops are well known and documented in literatures (Drew 1997, Jackson 2004, and Greenway and Gibbs 2003). Under saturated conditions, soil pores are saturated with water. Consequently, the exchange of gases is stalled, oxygen gas is depleted, CO_2 concentration increases, and photosynthesis (food production) is stopped because stomata cells are closed (Jackson 2004, Bedard-Haughn, 2009, Huang 2000). Waterlogging causes hypoxia, reducing root respiration and growth and reducing nutrient uptake (Barrett-Lennard 2003, CCC, 2021). It also leads to altered soil chemistry (Evans and Fausey 1999; Jackson and Drew 1984), exposure to soil-borne pathogens (Stolzy and Sojka 1984), and if not attended to, the crop dies. Waterlogging also affects soil structure, increases the risk of salinization, increases water table and saline seepage, limits proper root development, leads to roots clustering around a certain depth, increases the emission of greenhouse gases, and slows down nitrogen fixation (Bedard-Haughn, 2009). The extent of damage is also dependent on temperature, length of ponding and stage of development (Franklin et al. 2005, Ploschuk et al. 2018, Zhou and Lin 1995). However, canola cultivars respond differently under waterlogged situations (Ashraf & Mehmood 1990, Zou et al. 2014). Waterlogging hinders canola growth and development, which ultimately leads to decreased yield (Ploschuk et al. 2018, Zou et al. 2014). Zhou and Lin (1995) reported that water logging during the seedling and bud appearance stage led to a 21.3% decline in pods per plant and a 12.5% fall in seeds per pod. They further reported that flooding at pod formation and flowering stage did not significantly impact yield. A lysimetric study of waterlogging effects on Canola by Cannell and Belford (1980) showed that plant height, seed yield, oil yield and straw declined by 17, 14, 17 and 23%, respectively. Wollmer et al. (2018) conducted a greenhouse experiment to investigate waterlogging effects on yield and oil. Results showed that waterlogging during the vegetative development stage has more impact on yield and yield components than at the flowering stage. Specifically, they reported that waterlogged conditions decreased yield by 25 and 15% during the vegetative and flowering stages, respectively but had no effect on oil quality. Zhou et al. (1997) observed that applying nutrients and growth regulators can offset the impacts of waterlogging on Canola.

2.2 Water management - Drainage

Waterlogging occurs because of too much water in the soil. The Canadian climate is prone to such, especially at the beginning of the growing season, because of the snowfall in winter. In the Canadian prairies, a summer storm of high intensity and short duration (Dumanski et al. 2015) could cause the water table to rise quickly within the root zone. Factors aiding this condition include poor internal drainage, low hydraulic conductivity, compaction, the soil type predominant in the region, and a shallow impermeable layer restricting infiltration (Madramootoo et al. 2007 Bedard-Haughn, 2009). The practical solution to this challenge is drainage. Drainage is an old technology used by ancient civilizations to remove excess water during times of flooding. It is estimated that 33% of the total agricultural land globally is under drainage (Smedema and Ochs 1997). It was introduced into North America by early settlers from Europe (Madramootoo et al. 2007) and can be found in almost every part of the world with drainage-related issues. Drainage systems and practices have evolved from open field ditches and canals (surface) to buried drainpipes (subsurface). It has also evolved from heavy clay and concrete tiles to corrugated plastic tubing installed with drainage machinery. The development of corrugated plastic tubing in the 1970s and the laser control drain plow, first developed in Canada, revolutionized the drainage industry (Irwin 1989, Madramootoo et al. 2007). Although drainage is usually practiced in regions with a humid climate, it is also advantageous for the semi-arid Canadian Prairies climate (Ayars et al. 2006, Mante et al. 2018, Dou et al. 2021).

Drainage removes excess water from the plants' root zone to provide a conducive environment necessary for root development and crop growth. Sources of excess water include rainfall, snowmelt, high water table and over-irrigation. Like most regions with poorly drained soils, drainage is essentially needed before a growing season so that the field is trafficable, and crops are planted at the right time. Studies by Satchithanantham (2014) and Cordeiro (2013) have shown that the water table can get as high as 0.4 m in southern Manitoba. This portends severe consequences for the timeliness of farm operations, crop production and total yield.

According to Manitoba agricultural services corporation (MASC, 2015), a delay in planting up to the first week of June could lead to a 20 to 30% reduction in yield depending on crop type.

There are many advantages of agricultural land drainage. Benefits accruing from drainage installation on a wide variety of soils, crops, and climates abound in many publications and textbooks (Fraser and Fleming 2001, Hudson and Roberts 1982, Van Zandvoort et al. 2017, Madramootoo et al. 1993). Drainage ensures that agricultural land can be accessed in the shortest possible time, especially after heavy rainfall, without structural damage or compaction on the soil (Mante et al. 2018). Since the heat capacity of water is far greater than the heat capacity of the soil, drainage provides conducive warm soil temperature necessary for plant germination in the early spring. Soil temperature directly impacts seed germination, and growing degree days (GDD), an index used to predict the developmental stages of crops. Most crops, including canola, require an ideal growing soil temperature of ≥ 10 ^{o}C for germination (CCC, 2012).

2.3 Types of Drainage

There are two main methods of land drainage: surface and subsurface drainage. As the name suggests, surface drainage removes excess water that collects on the surface. Ponded water on the soil surface could be removed by surface drains, open ditches, land forming, land levelling, or combinations of the above. Surface drainage is usually practiced in areas with high rainfall intensities and soils with low infiltration capacity (Huffman et al. 2011). Surface drainage reduces crop loss and controls surface runoff and soil erosion (Brown and Ward, 1997). Although it does not remove water within the soil profile (NRCS 2001), it is simple, common (Skaggs et al. 1994) and a cost-effective drainage method (Manik et al. 2019) with a high benefit-cost ratio and high net returns (Colwell 1978). A comparative study of surface, subsurface and controlled drainage subirrigation (CDSI) by Grigg et al. (2002) in a sugarcane farm in Louisiana showed that surface drainage performed better than subsurface and CDSI by reducing nitrate losses and increased crop yield. Wanchuk and Apedaile's (1988) study showed that surface drainage is more profitable than subsurface drainage. However, Madramootoo et al. (2001) argued that surface drainage performs poorly compared to subsurface methods in terms of water removal as they also restrict the use of farm machinery. Also, there is evidence in the literature that surface drainage has led to increased nutrient enrichment of water bodies because of increased runoff and peak outflow relative to subsurface drainage (Schindler et al., 2012, Rabalais et al., 2007, Blann et al. 2009, Smith et al. 2015, King et al. 2015, Stamm et al. 1998, Sharpley & Menzel, 1987).

On the other hand, subsurface drainage removes excess water below the soil profile. It is also used for salinity control and salt balance within the profile (NRCS, 2001). It uses drainage ditches and buried perforated pipes to lower the water table to the desired depth. It is applicable in areas with a high naturally occurring water table, poor internal drainage, and water-logged soils (Madramootoo et al. 2001, Huffman et al. 2011). Subsurface drainage increased agricultural activities in North America and other regions of the world (Gramlich et al. 2018) as artificially drained lands are reported to be the most productive (Skaggs et al. 1994). As the water table rises due to heavy rainfall or over-irrigation, gravitational water is drained out, and the table is kept within or below the tile drains. Through this process, the water table is quickly lowered to a depth conducive to root development and crop development, and so, field operation is unhindered or can be started.

2.4 Water table management techniques

The practice of manipulating the water table depth to remove excess water and salts from the soil profile is called Water table management (WTM). The advantages of WTM have been highlighted by many researchers (Sunohara et al. 2014, Schott et al. 2017, Jafari-Talukolaee et al. 2016, Jafari-Talukolaee et al. 2018, Vanderleest et al. 2016). WTM is implemented in three forms: free drainage (FD), controlled drainage (CD) and controlled drainage- sub-irrigation (CD-SI).

2.4.1 Free Drainage (FD)

FD, also called conventional drainage, functions by lowering the water table by gravity flow towards the drains by using shallow drains. This represents the earliest form of subsurface drainage, where the primary objective was to remove excess water from the root zone and increase crop yield. Schott et al. (2017) compared no drainage, shallow drainage, conventional drainage, and controlled drainage in Iowa for 5 years. Results showed that shallow drainage performed best by reducing flow and nitrate loss by 60 and 61%, respectively. In Nova Scotia, Smith et al. (2019) reported that shallow drainage reduced nitrate loading better than controlled drainage and conventional drainage by decreasing nitrate load by 54.9-73.1%. However, allowing free flow of drainage water to water bodies has led to severe environmental challenges ranging from nutrient enrichment, water pollution, eutrophication, and algal bloom (Gentry et al. 2007, Rabalais et al. 2007, Randall and Goss 2008). Discharging drainage water to water bodies bypasses the natural denitrification and mineralization processes in soil. This contributes to increased nutrients, sediment, and pesticide loadings in water bodies. Notable cases include the Gulf of Mexico, China Sea, Lake Winnipeg, and the Great Lakes (Rabalais et al., 2007, Hawley et al., 2006, Schindler et al., 2012, Chen et al., 2007). However, depending on age and drain type, existing free drainage systems can be retrofitted with control structures (Strock et al. 2010)

2.4.2 Controlled Drainage

Controlled drainage, CD, also known as drainage water management (DWM), is the practice of placing control structures on subsurface drains at the outlet to regulate drainage water into water bodies. CD is regarded as one of the best management practices (BMPs). Numerous studies have reported the effectiveness of CD under different climates, soil types, and crops to include an increase in yield and income, reduction of drainage flow volume, decrease in nitrate and phosphorus concentration, disease control, salinity management, and improved soil structure (Evans et. al. 1989, Evans et al. 1995, Tan et al. 1999, Fausey 2005, Drury et al. 2009, Darzi et al. 2007, Mood et al. 2009, Crabbé et al. 2012, Fayrap and Koc 2012, Awale et al. 2015, Gunn et al. 2015, Mehring et al. 2015, Youssef et al. 2018, Smith et al. 2019). The reduction of nitrates is attributed to the denitrification process and enhanced mineralization that removes nitrates before reaching the ground or surface water (Elmi et al. 2000, Poole et al. 2013, Gramlich et al. 2018).

Management practices like tillage also affects the performance of CD. In a comparative study of Controlled Drainage-No Tillage and free drainage in a clay loam soil in Ontario, Tan et al. (1999) reported that nitrate loss decreased from 27.3 kg N/ha to 19.8 kg N ha while drainage volume decreased by 22%. A review of the literature showed that the performance of CD varies with soil, prevailing weather conditions, crops, and management. While it is successful in one location, it is insignificant or sometimes detrimental in another. In relation to other water table management, it is expensive and requires expert management to avoid crop failure and shallow root development (Huffman et al. 2011, Madramootoo et al. 2001). Despite its economic, agronomic, and environmental benefits, the CD has witnessed low patronage and adoption by farmers. An economic analysis by Chette et al. (2012) showed that CD has a payback of 3-4 years, yet farmers are still very uncertain (Madramatoo et al. 2007). Other factors contributing to low adoption include lack of extension services, increased labour, and cost (Dring et al. 2016, Huffman et al. 2011). Tan et al. (1998) conducted a 2-year field study on clay loam in Ontario. Their results showed that CD did not increase soybean. In addition, the CD has the potential for increased overland flow, salinization, and greenhouse gas (GHG) emissions. Hornbuckle et al. (2005) reported that CD has the potential for increased salinization. CD also provides an alternative route to nitrogen losses either through gaseous or groundwater seepage (Sunohara et al. 2014) and has the potential to increase GHG emissions (Nangia et al. 2013). Kumar et al. (2014) observed GHG releases like CO_2, N_2O, and CH_4 in a poorly drained soil in Ohio, although at low concentration. Hydrologic models have been coupled with GCMs to assess future impacts of controlled drainage with climate change. Hanke (2018), via modelling, reported worse performance of CD under climate change. SWAT simulation results showed increased surface runoff leading to increased nutrient losses in Ontario. However, Van Zandvoort et al. (2017) reported no significant difference in GHG flux in CD and FD. Their results agree with Nangia et al. (2013) except for CO_2 emissions.

2.4.3 Controlled Drainage-Subirrigation (CDSI)

The principle of operation of controlled drainage allows irrigation to be practiced alongside it through capillary action. This is called Controlled Drainage - SubIrrigation (CDSI). It is a system that enables dual functions of irrigation and drainage. Under excess water conditions, the drainage mode is activated, and the subirrigation mode is used during water deficit. It effectively enhances crop growth and nutrient uptake, increases yield, and reduces nutrient loss in the field (Drury et al. 2009). Experiments have shown that CDSI improves crop yield and water quality, conserves water, and significantly reduces nitrate and phosphorus loss (Ng et al. 2001, Tan et al. 1998, Bonaiti and Borin 2010, Tan and Zhang, 2011, Drury et al. 2009). Tan et al. (1999) showed that CDSI effectively increases crop yield and agricultural water quality. In a field study in Ontario, the tomato was grown on sandy loam soil under two water table management: CDSI and Free drainage (FD). The experimental results showed that nitrate concentration and nitrate loss decreased by 38 and 37%, respectively, while tomato and corn yield increased by 64% and 11%.

Similarly, CDSI reduced drainage volume, nitrate concentration and Nitrate by 45, 6.3 and 50% relative to free drainage (Tan et al. 1998). Also, tomato yield was increased by 11%. Bonaito and Borin (2010) studied the combined effect of irrigation and drainage under four treatments from 1997 to 2003 in Italy. Results showed that treatments under CDSI conserved more water, had the lowest nitrate loss, and reduced drainage volume. Similarly, Tolomio and Borin (2018) combined open and subsurface drains with free and controlled drainage. Their results indicated that comparing CD with FD, discharge, nitrogen and phosphorus loss decreased by 81, 92 and 65%, respectively. CDSI is also an effective method for reducing and controlling phosphorus loss in the field (Tan and Zhang et al. 2011). They conducted a 5-year study to study the efficiency of CDSI and FD in mitigating P loss. They reported that CDSI lowered Total Phosphorus and Particulate Phosphorus by 12 and 15%. Drury et al. (2009) compared three water management strategies in a corn-soybean field in Ontario with clay loam soil and two fertilization rates. Results showed that nitrate concentration and loss were less than the conventional drainage at both nitrogen fertilization rates, but the yield was also larger. The performance of subirrigation is weather dependent. Under very wet conditions, it has recorded poor performance. A 2-year field study in southwestern Québec by Madramootoo et al. (2001) recorded a 25% loss in corn yield in the first year. They recommended high management effort for subirrigated fields. In a four-year study in Ohio, Fausey (2005) found no significant difference in corn yield due to water table management. Satchithanantham (2013) found no significant impact on potato yield due to CDSI in southern Manitoba.

2.5 Requirements of Water Table Management (WTM)

For a successful implementation of WTM according to NRCS, (2001) the proposed site must meet the following conditions: flat topography, naturally occurring high water table, a shallow impermeable layer, negligible deep seepage loss, a suitable outlet, and an adequate water supply with good water quality. Past studies in southern Manitoba have reported that an impermeable layer mainly of clay lies below the water table at 6m below the soil surface (Cordeiro 2014, Satchithanantham, 2013). Design considerations include soil, topography, drainage intensity, water availability and water quality. The rate at which the drainage system removes excess water by lowering the water table height is dependent on drainage intensity (DI). It is defined as the drainage rate (cm/day) at the water table being lowered at some depth below the soil surface (Skaggs et al. 2006). DI is strongly affected by two main design factors: drain spacing and drain depth. Drain depth and spacing dictate the amount of flow from a subsurface drainage system. This directly affects crop yield, water table depth, soil moisture content, and most especially, water quality. There is a consensus in the literature, supported by field studies and modelling, that drains installed at a deeper depth and closer spacing increase drainage rate.

In contrast, shallow and or widely spaced drains result in lesser drainage rate (Skaggs et al. 2005, Skaggs et al. 2006, Cooke et al. 2002, Schott et al. 2017). Skaggs et al. (2005) plotted published findings of nitrate losses with drainage rates in Indiana and North Carolina. It was evident that a strong positive relationship exists between drainage rate and nitrate losses, although the magnitude varies. This variation was attributed to site conditions such as management, soil type and climate. By running a 50-year simulation in DRAINMOD, Skaggs et al. (2005) reported that for soils with low hydraulic conductivity (K) values, drains need to be closely spaced to avoid excess water stress. Simulation results showed that relative yield starts decreasing at spacing more significant than 15 m, while for soils with higher K values, an 80% relative yield was obtained at a spacing of 35 m. Of the two design variables, drain spacing seems to have a lesser impact on drainage flow and nutrient transport (Skaggs et al. 2005, Tan and Zhang 2014, Madani and Brenton, 1995, Gremling et al. 2018). Tan and Zhang (2014) found that drain depth played a more significant role in P transport than spacing. They concluded by recommending that drain depth could be an effective method of minimizing P loss.

2.6 Integrated Water Management

A holistic approach is important for effective water management (UNESCO 1987, Kunz and Moran, 2016). It is a method that integrates parts into a whole system. The hydrologic cycle is made of different components, including precipitation, evaporation, runoff etc. Addressing the challenges or constraints of effective water management requires a fundamental understanding of the hydrologic cycle. Hydrologic models integrate these different components into a system to better understand the dynamics and complexities involved in natural systems. Agriculture is mainly dependent on factors that are variable and uncertain. Therefore, decision-making and management have necessitated the use of agricultural system modelling.

Agricultural system modelling allows simulations of the impacts of different management practices without actually implementing them. Modelling has become a powerful tool to provide researchers and scientists with both qualitative and quantitative answers. Models are effective tools used for investigating the impacts of agricultural practices and evaluating multi objectives such as agronomic, economic and environmental (Masasi et al. 2020). In recent times, the use of models in agricultural management has gained popularity. This has been attributed to technological advancements in computer and computer speed and developments in electronics and sensors for data collection (Beven 2012. There are numerous models developed within the last three decades, and some of them have minimal differences and similarities. Models vary in structure, processes and complexities (Ranatunga et al. 2008). Models have been broadly classified into empirical, mechanistic, deterministic, stochastic or distributed models (Ranatunga et al. 2008, Chow et al. 1998).

Different models are used to demonstrate other processes in agriculture and thus are used for various purposes. Numerous models exist and have been used in simulating crop growth and yield (AQUACROP), irrigation management and scheduling (SIMDUAL Kc), water management (DRAINMOD), surface water hydrology (SWAT), groundwater hydrology (MODFLOW), soil water dynamics and nutrient transport (HYDRUS), salinity (SALTMED), soil-water-plant continuum (SWAP) and water quality (RZWQM2). These are standard models used in agricultural water management, and most studies have found them reliable and accurate. Thus, they can be used as a management tool and assist in making decisions.

2.7 Model Assessment

Model performances are assessed using a qualitative and statistical test. Qualitative assessment involves a graphical plot of observed versus simulated on a 1:1 scale with zero intercepts. Standard statistical tests used in hydrologic model assessment include the coefficient of determination (R^2), NSE (Nash Sutcliffe Efficiency), root mean square error (RMSE), mean percent error (MPE) and mean absolute error (MAE). Details of the statistical indices are contained in subsequent chapters. Generally, NSE and R^2 values close to 1 and error indices (RMSE, MAE, MBE) close to 0 indicate a perfect model (Moriasi et al. 2015, Jackson et al. 2019).

Chapter Three

Canola yield and quality under tile drainage in the Canadian Prairies

Abstract

For areas with seasonally shallow water tables and poorly drained soils, subsurface drainage systems are ideal for removing excess water from the root zone and improving soil workability, trafficability, and timeliness of field operations. With increased interest in tile drainage in southern Manitoba, the objective of this study was to evaluate the impacts of drainage on canola yield and canola oil qualities over three growing seasons (2019-2021) in Winkler, Manitoba. The study was carried out on replicated field plots with three different drainage treatments: controlled drainage (CD), free drainage (FD), and no drainage (ND). Subsurface drain tiles were installed at 8 m spacing for CD and 15 m spacing for FD, at a depth of 0.9 m. Compared to FD plots, the CD plots had significantly higher yields in 2019 with good rainfall. With deficient rainfall in the following years (2020 and 2021), the impact of drainage, especially CD, diminished, with no significant differences between the treatments. This could be related to the narrower drain spacing, rapidly removing water during short periods of high-intensity rainfall. The results showed no significant difference between the treatments but significant differences in canola oil quality parameters between the years, suggesting that environmental variables (mainly temperature and precipitation) may have masked drainage impacts.

Keywords: Subsurface drainage, Water management, canola, Southern Manitoba.

3.1 Introduction

Canada, ranked fifth as a global exporter of many agricultural products, is a key player in global agricultural production (FCC, 2020). Agricultural production is concentrated in the Canadian Prairies (Saskatchewan, Alberta, and Manitoba). Canada is the largest producer and exporter of canola, accounting for 24 and 64% of the total global production and export trade, respectively (Cliff Jamieson 2021). The Canadian Prairies accounts for a significant amount of the total canola production in Canada. Canola is a type of rapeseed with significantly lower erucic acid and glucosinolates contents, making it fit for human consumption and animal feed. Canola is ranked as the second most-produced oilseed after soybean, with 69.6 million metric tonnes in 2020 (USDA, 2022). Canola production in Canada has increased steadily over the past two decades. The total production in 2018 (20.7 million tonnes) is more than 1.6 times the production in 2008 (12.6 million tonnes) (CCC 2022). This tremendous increase is due to an increase in cultivated area, improved hybrid cultivars, biofuel potentials, management methods, and high economic returns (Morrison et al. 2016). In Manitoba, canola generated the highest economic return, contributing $1.6 billion in 2021 (Manitoba Agriculture, 2022).

Hydrologic extremes, including waterlogging, drought, and high temperature, are the major threats to canola production in the Canadian Prairies. In Manitoba, this accounts for a combined historical crop loss of 71% (MASC, 2020). Projected future climate scenarios for the region predict wetter springs and dryer summers (Sauchyn and Kulshreshtha, 2008). The accumulated snow in the winter and early rainfall in the spring could have severe consequences on soil workability, trafficability, timeliness of farm operations, and consequently total crop yield. According to Manitoba Agriculture, a delay of planting up to the first week of June could lead to a 20 - 30% reduction in yield depending on crop type. These challenges have necessitated Canadian producers, especially canola farmers, to introduce sustainable water management practices.

Agricultural drainage is an important water management technique that provides a conducive growing environment necessary for root development and crop growth by lowering the water table and removing excess water within the root zone. Although drainage is mainly practiced in humid climates, it is also of great importance in semi-arid climates such as the Canadian Prairies in controlling salinization (Dou et al. 2021). The benefits of agricultural drainage are well documented in the literature, two of which are an increase in crop yield and a decrease in nutrient and drainage outflows (Fraser and Fleming 2001, NRCS 2001, Huffman et al. 2011). On the other hand, drainage has led to the loss of wetlands, mainly in North America, Europe, and Asia (Davidson 2014). Subsurface drainage has also led to increased nutrient loadings and eutrophication of most water bodies (King et al. 2015). Notable cases include the Gulf of Mexico, China Sea, Lake Winnipeg, and the Great Lakes (Hawley et al., 2006, Rabalais et al., 2007, Schindler et al., 2012, Chen et al., 2013). To reduce nutrient loadings, controlled drainage (CD), was developed, which is the practice of placing control structures on subsurface drains at the outlet. Early studies on CD can be traced to the United States in the 1970s. Due to its enormous benefits, it has been recommended and adopted in various countries, including Canada, Italy, Sweden, Australia, China, and Iran (Wesström et al. 2014, Sunohara et al. 2016, Tolomio and Borin 2018, Jouni et al. 2018, Dou et al. 2021).

Numerous studies have reported varying results on the agronomic and environmental impacts of different water management systems. Using CD, for example, which is regarded as one of the best management practices (BMPs), a number of studies have reported positive benefits, including increased yield and income, decrease in drainage flow, drop in nitrate and phosphorus export, disease control, salinity control, and improved soil structure (Tan et al. 1999, Fausey 2005, Darzi et al. 2007, Drury et al. 2009, Skaggs et al. 2012, Cordeiro et al. 2014, Satchithanantham et al. 2014, Awale et al. 2015, Gunn et al. 2015, Mehring et al. 2015, Sunohara et al. 2016, Smith et al. 2019, Wang et al. 2020, Mourtzinis et al. 2021, Dou et al. 2021, Helmers et al. 2022). On the contrary, negative results have also been reported for CD, including lower yield, increase in surface runoff, alternative routes to nutrients losses, increased potential for salinization and increased GHG emissions (Tan et al. 1998, Hornbuckle et al. 2005, Nangia et al. 2013, Kumar et al. 2014, Hanke 2018).

The above literature suggests that the performance of a water management system may be location-specific, which can be linked to a variety of factors that are not fully understood (Allerhand et al. 2013). Therefore, an understanding of the underlying factors affecting drainage systems is critical. It is also important to continuously evaluate different drainage systems, especially with global changes in climate variables, climate variability, and uncertainty, even as the Canadian Prairies are vulnerable to climate change impacts (Qian et al. 2012). This study was also necessitated by the increasing number of agricultural drainage system installations in the region. Therefore, there is the need to develop local datasets of crops commonly grown for long-term simulation modelling studies and develop alternative management scenarios. The main objective of the study is to evaluate the impacts of three water management practices, including free drainage (FD), controlled drainage (CD), and no drainage (ND-control), on canola yield and canola oil quality, including oil content, protein content, glucosinolate content and fatty acid composition, in Winkler, southern Manitoba. The prevalence of flat topography and seasonal shallow water tables in southern Manitoba provides an opportunity to implement the three different water table management treatments.

3.2 Materials and method

3.2.1 Study Area

Field data were collected on research plots at Hespler Farms, located on latitude 49.12°N; longitude 97.93°W, in southern Manitoba (Fig. 3.1). The region has a semi-arid climate, with average annual precipitation of 563.3 mm. Historical weather analysis obtained from the closest weather station (Schanzenfeld), located 10 km from the study site, revealed that rainfall and snowfall account for 80 and 20% of the precipitation. Also, the historical analysis showed that rain and snowfall have peak values in June (100.1 mm) and December (22.9 mm), respectively. The area has an average annual temperature of 4.0 ^{o}C, with the lowest monthly temperature of -14.6 ^{o}C in January and the highest temperature of 20.0 ^{o}C in July (Environment Canada, 2019). The soil in the study area belongs to the Gleyed carbonated Rego black sub-group of the Reinland soil found in Morden-Winkler (Smith et al.1973). The soil is classified as imperfect to moderately well-drained (Smith et al.1973). The soil belongs to the sandy loam textural class with 69% sand, 20% silt, and 11% clay. The average bulk density, field capacity, porosity, and drainable porosity are 1.38 g/cm^3, 0.31 m^3/m^3, 47.8%, and 14.1%, respectively (Cordeiro, 2014). These average values were obtained over the 1.2 m profile (Cordeiro, 2014). It also has a distinct soil colour change from black soil in the top 30 cm to light-coloured (brown) soil at depths > 60 cm.

3.2.2 Experimental Layout

The whole field is approximately 5.2 ha, with canola and soybean in a 3-year rotation (2019-2021). Canola was planted in the eastern section in 2019 and 2021 and the western section in 2020. A buffer strip of about 4 m separated both crops. Each section measuring 84 m * 300 m is divided into three, with each representing a replicate (Figure 3.1). Each replicate contained the three treatments: Controlled drainage (CD), Free drainage (FD), and No drainage (ND) as the control. The ND has an area of 0.2 ha (40 m* 50 m), CD 0.2 ha (40 m* 50 m), and FD 0.23 ha (44 m* 50 m). For drained plots, (FD and CD) drain tiles were installed 90 cm below the soil surface, parallel to the planting row in the North-South direction. The drain tiles are corrugated plastic pipes with 0.1 m diameter and 50 m long connected to the submain, about 0.4 m in diameter. On CD plots, drain tiles were spaced 8 m apart. Drainage control structures (Agridrain Corp, Adair Iowa), with adjustable stop logs, were placed at the outlet of the submain to conserve water and limit drainage flow. On FD plots, drain tiles were spaced at 15 m, connected to the submain, which discharged to the outlet separately. All the plots received equal amounts of water as canola is usually cultivated as a rainfed crop.

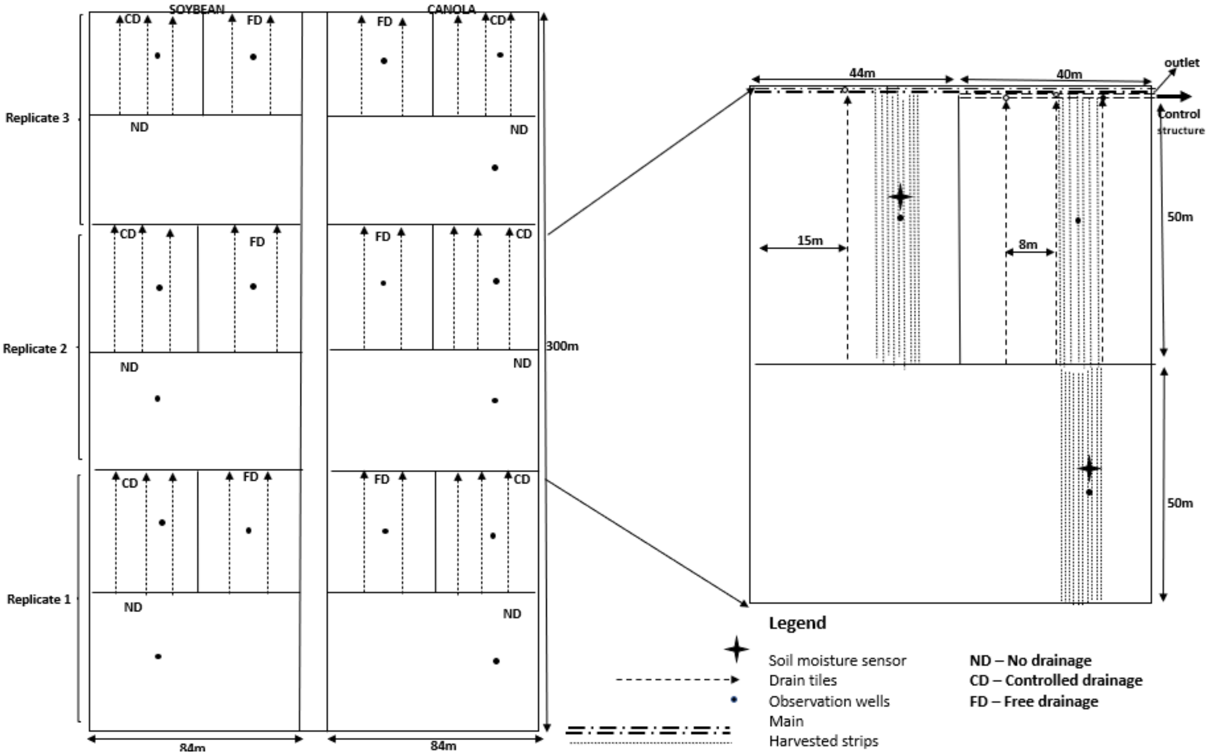


Figure 3.1: Field layout and assignment of treatments

3.2.3 Agronomic practices - Tillage, planting, chemigation, and harvesting

Table 3.1 shows the agronomic practices, including tillage equipment, planting, harvest, fertilizer application, and chemigation during the study period. Plant rows were arranged parallel to the drains (North-South direction). Canola (c.v. 'Invigor') was seeded at 5cm depth, at a 5 lb/ha rate, on an inter-row spacing of 25 cm and planting spacing of 10-12 cm. Fertilizers were applied based on soil tests, usually done after harvest in the preceding year. The 2019 fertilizer application was done based on a soil test in September 2018. All treatment plots received the same fertilizer amount each year.

Harvesting was done on 533.4 m^2 area (Fig. 2, that is, the length of the combine swath (10.7 m) and width of the plot (50 m)) on each plot using a combine harvester (John Deer s680). The combine passed through centred on the location of the piezometers for measuring the water table elevation. The yield per plot (Mg/ha) was calculated as the quantity of seed weighed on the combine as it moved down the strip of the plots.

Table 3.1: Agronomic practices during the study period

Year	Tillage	Planting date	Harvest date	N	P	S	K	Chemical (product)	Application rate (L/ac)	Application date
2019	John Deere 730-disc drill	May 2nd	Sep-15	115	20	10	0	Herbicides (liberty)	1.5	Jun-06
									1.5	June 14
								Fungicide (Proline)	1.126	Jun-26
								Desiccant (glyphosate)	1.0	Aug-14
2020	Heavy Harrow	May-18	Sep-09	147	0	4	31	Herbicide (liberty)	1.5	June 11
								Herbicide (RT540)		Aug-20
								Fungicide (Rovral)	0.84	July 2
								Fungicide (Rovral)	0.42	July 9
2021	No-tillage. The seed was planted on stubble	May-04	Sept. 2	127	31	15	29	herbicides-liberty No fungicide was applied because of the extreme dry weather	1.2	June 4
									1.5	Jun-15

3.2.4 Instrumentation and Data Collection

3.2.4.1 Weather

An on-site weather station located about 150 m from the study area collected daily maximum and minimum temperature, precipitation, and evapotranspiration. Additional weather data, including relative humidity, wind speed and solar radiation, were collected on an hourly time step from the Winkler weather station, managed by Environment Canada, located about 12.53 km from the study area. The data from both sources provides complete weather information of the study area.

3.2.4.2 Water table depth

Within each replicate, three wells were installed to measure groundwater depth. A total of nine wells were installed on the canola field. Watertable depth was measured using water level sensors (Solinst Levelogger Junior 3001, Solinst, Canada, Ltd., Georgetown, Ontario, Canada) suspended inside a piezometric well. Also, a barometric pressure sensor (Solinst Barologger) was used to correct the readings of the levelogger for atmospheric pressure. A 0.1 m diameter hole was dug to about 2 m using the hand auger. The piezometers are made of schedule 40 steel pipe, with an internal diameter of 0.0413 m and pointed edges. A Kevlar rope was used to suspend the sensor, tied to a ring (0.038 m diameter) hung on a bolt located 0.038 m from the top edge of the piezometer. The sides have slits covered with a geomembrane to allow easy movement of water and prevent soil and clay particles from entering the piezometer. The piezometers were inserted in the auger holes, and an offset of about 0.3 m was left above the soil surface. Bentonite sand mixture was packed into the annular space after installation to prevent preferential flow along the length of the piezometer. The piezometers had caps on the top to prevent rainwater entering from the top. Sensors were installed and set on a 3-hr logging interval. On drained plots, the wells were located mid-spacing between two drain tiles.

3.2.4.3 Soil nutrient

Soil samples were collected and analyzed on all the treatment plots for soil nitrate-N and soil test phosphorus-P (STP). A soil auger was used to collect the soil samples at 30 cm, 60 cm, and 90 cm depth during different developmental stages. The samples were sent to the Agvise laboratory for analysis. The soil nitrate-N and phosphate-P were extracted using the cadmium reduction nitrate method and the Olsen phosphorus method, respectively (Gelderman and Beegle 2015).

3.2.5 Canola Quality Analysis

Oil, protein, and glucosinolate content were analyzed using Near-Infrared Spectroscopy (NIRS), which works on the principle of reflectance. The NIR spectroscopic analysis was done using a NIR scanning monochromator (XDS Rapid content ™ Analyzer). About 5 – 7 g (n = 30) of canola seeds free of debris, were collected in the standard ring cup (diameter = 0.014 m, height = 0.01 m). Spectra data were recorded as the logarithm of reciprocal reflectance in the wavelength range of 400 – 2500 nm at 0.5 intervals. The scanning process per sample is approximately 1 min. The data was analyzed using the WinISI II software.

The fatty acid composition was determined by gas chromatography (GC) of fatty acid methyl esters. Three subsamples from each plot were used for this analysis. The GC procedure is given below. First, about 300 mg of canola seeds were crushed in a test cylinder and placed in a 13 × 100 mm test tube, 3 ml of heptane was added and allowed to stand overnight to extract oil, after which supernatant was decanted into a 13×100 mm test tube the next day. This was followed by adding 500 ul of 0.5 N sodium methoxide reagent. The mixture was shaken for 30 minutes. This separates the fatty acid from the mixture. After this, 100 ul of acidified water (0.3% acetic acid) was added, mixed gently and was allowed to clear by putting it in the fridge for 102 hours. About 500 ul of the mixture was put into a 2 ml autosampler vial for analysis. GC was performed on a 3900 Varian model fitted with CP-8400 autosampler and flame ionization detector. Six major fatty acids (Palmitic (C16:0), Stearic (C18:0), Oleic (C18:1), Linoleic (C18:2), Linolenic(C18:3), and Erucic (C22:1)) were analyzed and expressed as percentages of the total fatty acids. Peak areas were measured using the Varian star workstation software system. Canola quality tests were done at the Plant Science Department, Oil Quality Lab, University of Manitoba.

3.2.6 Statistical analysis

Field data, including canola yield and nutrients (nitrates and phosphates), were analyzed separately for each year and the 3-year average by conducting an ANOVA test using the JMP software (Version 16, SAS Institute, Inc, Cary, N.C). ANOVA was used to check the differences in treatment means for each measured field data. Soil nitrates and phosphates tests were analyzed for each sampling date. The mean values of the field data were separated using the using Tukey's test at a 5% ($p<0.05$) significance level.

3.3 Results and discussions

3.3.1 Weather variables

The observed growing season rainfall (May to September) during the study period (2019-2021) was compared with the 30-year (1981-2010) monthly average. Figure 2 summarizes the average monthly weather during the study period and the long-term periods. Apart from the 2019 growing season with a total rainfall of 374.2 mm, close to the long-term average (376.5 mm), the 2020 and 2021 growing seasons were 35.6 and 38.9% lesser than the long-term average. The total growing season rainfall impact may have been masked by the monthly variation observed within the season. Monthly analysis showed that the study periods deviated significantly from the monthly historical data. For example, in September 2019, the site received more than three times (151 mm) the long-term value (42.2 mm). Apart from July 2020, with rainfall 14.9% greater than the long-term average, all the other months were substantially lower than the long-term values. In 2021, May, June, July, and September received 49.6, 55.6, 70.3, and 47.9% less than the long-term values. The average temperature for the 2019 growing season (16.4 ^{o}C) is almost the same as the long-term average (16.6 ^{o}C), slightly higher (17.1 ^{o}C) in the 2020 season and significantly warmer in 2021 with an average temperature of 18.0 ^{o}C. The monthly temperatures during the study periods were greater than the long-term average, except in May. The figure also showed an increasing temperature trend across all the months except in September, where 2019 was slightly higher than 2020. Also, peak average temperature values were recorded in July, corresponding to periods of highest water use and least values in May.

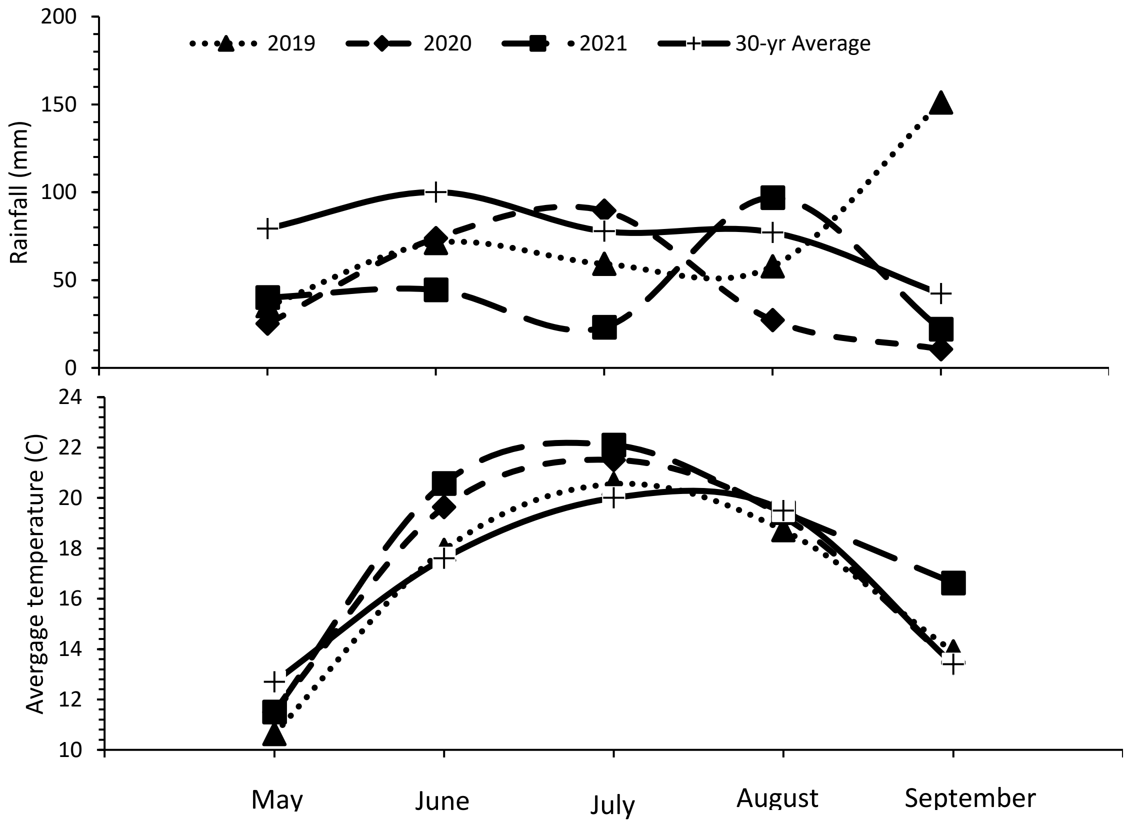


Figure 3.2: Comparison of monthly rainfall and average temperature during the study period and 30-year average.

3.3.2 Canola yield

Figure 3.3 shows the average annual yield per treatment. The result shows large differences in crop yield between the years, suggesting that yield may have been influenced by weather variables. The average yields during the study period were 3.2 Mg/ha in 2019, 2.9 Mg/ha in 2020, and 1.3 Mg/ha in 2021. Relative to the 2019 growing season, there was a consistent decrease in yield across the treatments and years. This could be linked to unfavorable weather variables and drainage design (drain spacing).

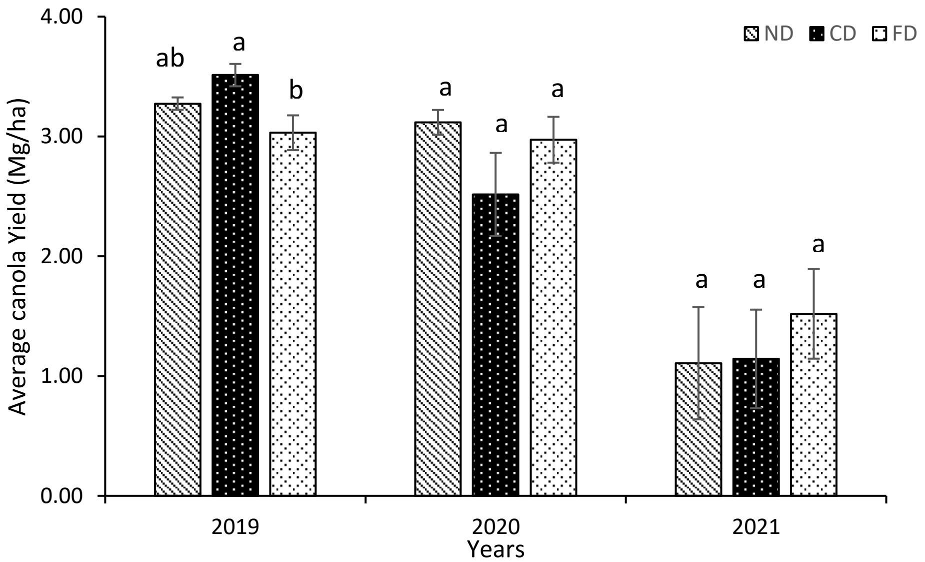


Figure 3.3: Average yield per treatment throughout the study period (2019-2021)

Means followed by different letters are significantly different based on Tukey's means separation at 5% significance level.

In 2019, the yield per plot differed among treatments ($p = 0.0143$). The average yields per treatment were 3.27, 3.51, and 3.02 Mg/ha for ND, CD, and FD, respectively. For each replicate, CD plots were consistently higher than other treatments. Statistical analyses revealed that there was a significant difference between CD and FD. Although there was no significant difference between CD and ND, CD was higher. The drain spacing may explain the significant difference in yield between CD and FD. The excess soil water generated as a result of high intense rainfall was quickly removed through the drain tiles since the CD plots are closely spaced, thereby providing a quicker return to good growing conditions for the crop. Another reason is the cumulative benefits of CD. Studies have shown that CD has long-term benefits that may be hidden in short study periods (Thorp et al. 2008, Cooke and Verma, 2012).

In 2020, the average yields per treatment were 3.12, 2.52, and 2.97 Mg/ha for ND, CD, and FD, respectively. There was no significant difference among the treatments ($p>0.05$). CD had the lowest yield because of high variability within the replicates. Another reason for low average yields in CD could be linked to the drain spacing. Since the 2020 and 2021 growing seasons were dry, the closely spaced drains in CD plots could have intercepted and removed the infiltrating rainwater, making it unavailable to the plant roots. Also, controlled drainage plots may have removed the excess rainfall received late in the 2019 growing season resulting in less soil water for the 2020 growing season. This together with significantly low rainfall in spring could have adversely affected yield. Closely spaced drains tend to draw water rapidly from the profile. Unlike the ND plots, where the groundwater table is recharged by the rainwater, and through capillary action, plants roots can meet their water requirements. Moreover, since the soil has "imperfect" internal drainage (Smith et al. 1973) with heterogeneous texture and structure, a capillary barrier could easily form the layers. This creates a dry layer in the soil profile despite the presence of groundwater. The dry layer is formed due to the mismatch between high ET demand and upward flux from groundwater. Kross et al. (2015) noted that the inherent and intrinsic soil properties are crucial to understanding how crop yields are affected by water management practices.

In 2021, the average yields per treatment were 1.14, 1.52, and 1.07 Mg/ha for CD, FD, and ND, respectively, with no significant difference between the treatments due to high variability within the replicates. The results showed a further decrease in average yield by 61.6 and 56.2% relative to the 2019 and 2020 growing seasons, respectively. The inconsistency of the combine harvester under low yields could have led to the underestimation (personal communication with the farmer), even though canola production in Canada fell by 35.4 % (12.6 million tonnes), the lowest level since 2007 (Statistics Canada, 2022). This was due to the extreme drought and heat stress in the Canadian Prairies. The 2021 growing season started with deficit soil moisture content due to the low snow accumulation in the preceding winter, low spring runoff, and spring rainfall. The drought and heat continued into the developmental and reproductive growth stages (budding, flowering, and pod development). In June and July, the rainfall was 55.5% and 70.4% lower when compared with the long-term monthly average. Also, in 2021, there were 20 days with $T_{max} > 30\,^oC$ in June, seven days with $T_{max} > 30\,^oC$ in July, and one day with $T_{max} > 30\,^oC$ in August, respectively. Also, there were two days each with $T_{max} > 35\,^oC$ in June, July, and August. Using 29.5 ^oC as the threshold temperature, the heat stress index, which is defined as the summation of the difference between the maximum temperature and the threshold temperature (Morrison and Stewart 2002), the total heat stress index calculated from June to September in 2021 (126.9) was almost thrice (45.3) and twice (63.8) the 2019 and 2020 growing seasons, respectively.

In the field, both high temperatures and drought coexist. They reduce crop yield by altering the biochemical, molecular, and physiological processes responsible for growth and development, such as photosynthesis, respiration, flowering, pollination, seed filling (Prasad and Staggenborg 2008). While water stress would reduce the ability to obtain the nutrients needed for the development of reproductive organs, photosynthesis, and carbon assimilation, heat stress disrupts reproductive processes such as embryo sac differentiation, pollen gametogenesis, and embryo development, ovule fertilization, endosperm development, etc. resulting in the reduction of the number of flowers, number of pods, seeds per pods, and number of pods per plant which ultimately results in low yield. (Morrison et al. 2002, Gan et al. 2004, Hammac et al. 2017, Elferjani and Soolanayakanahally, 2018).

Generally, the prevailing weather conditions could affect the impacts of drainage on the crop. In this study, the beneficial effects of drainage, especially CD, appeared to decrease with increasing drought conditions when the control structures are not set correctly to hold back the water. This agrees with other studies that state that the effects of CD are minimal, hidden, or insignificant under drought conditions due to the inability to store soil water within the profile (Kross et al. 2015). Skaggs et al. (2012) explained that CD benefits crop yield by retaining water that would have been lost via drainage and making that water available to the plant at later times. The yield results in this study agree with previous studies in the same area (Cordeiro 2014, Satchithanantham 2013 and other related studies (Helmers et al. 2012, Schott et al. 2017, Acharya et al. 2019). In 2012 with low rainfall, Cordeiro et al. (2012) and Satchithanantham et al. (2012) found no significant difference between the treatments. Acharya et al. (2019) studied the impacts of drainage and other management practices (tillage and crop rotation) on corn and soybean yield from 2014-2017 in North Dakota. Drainage treatments studied included ND, FD, and CD. They reported that rainfall throughout their study period was less than the 30 – year average, varying between 17 to 46%. Their results showed no significant difference in soybean yield between the treatments implying that drainage had an insignificant impact on soybean yield.

Conversely, corn yield was not affected by drainage for years with significantly low rainfall (2016 and 2017). In a 5-year (2011-2015) study in Iowa, Schott et al. (2017) reported no significant difference between the drainage treatments during 2011, 2012, and 2013 growing seasons. Also, Helmers et al. (2012) reported no significant difference in corn yields between the treatments during 2007, 2008, and 2010 growing seasons and no significant difference in soybean yields during the 2007 and 2008 growing seasons. These studies have demonstrated that drainage impacts on crop yield are dependent on the prevailing weather (rainfall). On the other hand, Poole et al. (2013) reported an average increase of 11 and 10% for corn and soybean yields, respectively, when compared with the conventional drainage but no significant impact on wheat yield.

Overall, the results suggest that the impacts of drainage diminished with increasing dry conditions. In 2019 with good growing season rainfall, CD plots were significantly different from FD and consistently had higher yields than FD and ND. As drying persisted in the following years, the benefits of CD were not apparent, even though there were no significant differences between the treatments. Given that the growing season has been predicted to be dry in the summer and that drying will persist in the future, under rainfed conditions, the results in this study suggests that CD should be operated in a way to limit the outflows from drain tile during periods of rainfall to improve soil storage. During the springtime and heavy rainfall periods, the drain outflow could be pumped into water storage structures that could be reused during prolonged dry periods. This would provide both environmental and agronomic benefits. Careful management of the drainage control structures to conserve water is needed.

3.3.3 Nutrient analysis

3.3.3.1 Soil Nitrate-N content

Figures 3.4 show the soil nitrate-N content within the root zone for each treatment at different growth stages during the 2020 and 2021 growing seasons. The ND plots had higher nitrate concentrations relative to drained plots (FD and ND) for all the different growth stages. Even though ND was higher, the differences were not statistically significant ($p>0.05$). This may be due to the high variability of the data (see standard error value in Figure 3.4).

In this study, soil Nitrate-N content seems to vary with rainfall events. Samples collected after rainfall events had lower concentrations when compared with those collected after prolonged dry periods. Results also showed that the averaged nitrate content was higher than those reported in previous studies (Abbas 2015). This indicates low nitrate release and uses due to low soil moisture, resulting in low yields. Favourable temperature and sufficient soil moisture are needed for nutrient release (Abbas 2015). Given that nitrogen fertilizer has poor efficiency because less than half of applied N-fertilizer is absorbed by the plants (Wiesler 1998), under drought conditions, canola produces less yield leaving more residual N in the soil, which accumulates via soil mineralization and nitrogen fertilization (Randall et al. 2005, Maaz et al. 2016).

Depth analysis showed increasing nitrate-N content as depth increases. The statistical test showed that the 90 cm nitrate-N content was significantly higher than other depths, especially during the vegetative and flowering growth stages. This may be because of the plant's root depth. Another factor is the nutrient-rich groundwater found in the study area. A previous study measured nitrate content in the groundwater and reported high values varying from 55 to 90 ppm (Haider 2005). Where no significant difference exists (maturity and after harvest), nitrate-N at the 90 cm depth was still greater.

The 2021 soil nitrate-N analysis was like the preceding year (Fig. 3.4). This may be because both years were dry. The results also showed no significant differences between the treatments even though ND plots had higher nitrate content than drained plots. However, depth analysis showed that soil nitrate was concentrated on the topmost layer and decreased with depth during vegetative and flowering growth stages. This corresponded to June and July, with significantly low rainfall. The third and fourth sampling periods saw a reversal of nitrate concentration between the 90 and 30 cm depths, with an increasing trend. This corresponded to August and September, which received significant rainfall amounts. This may be due to the following factors: rainfall washing down the nitrate-N content, capillary flux, or crop use at the later stages.

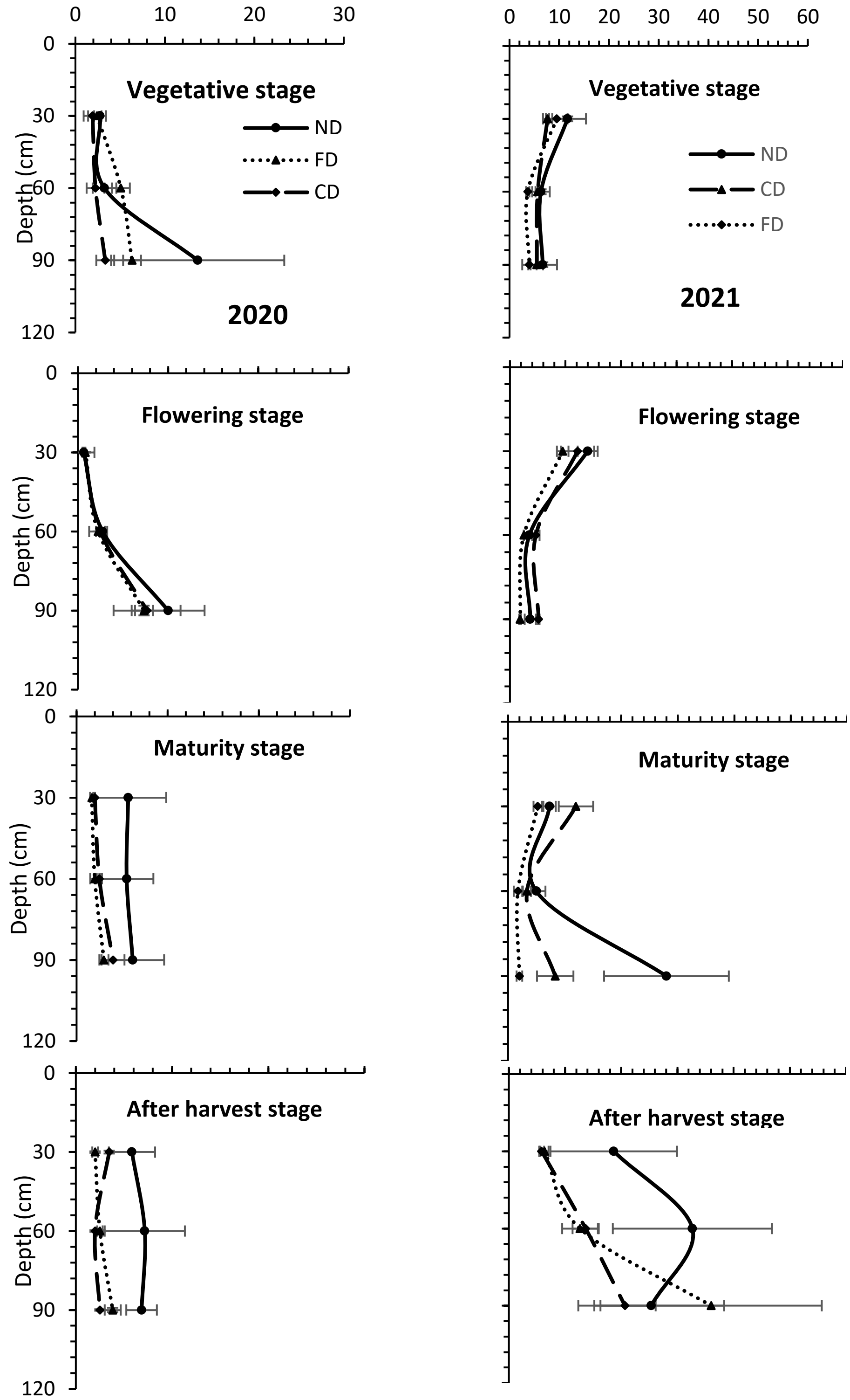


Figure 3.4: Soil Nitrate-N content within the rootzone during 2020 and 2021 growing

3.3.3.2 Soil Test Phosphate (STP)

Figure 3.5 shows the STP content within the root zone for each treatment at different growth stages during the 2020 and 2021 growing seasons. In 2020, only the 30 cm depth was analyzed. Results show no consistent STP trends and no statistical differences between the treatments due to the high variability in the sample. However, STP was highly concentrated at the top layer throughout the study period. Phosphate (P) is not as mobile as other nutrients as it is adsorbed to soil particles. This agrees with other studies (Vadas et al. 2005, King et al. 2015, Gramlich et al. 2018, Pease et al. 2018, Liu et al. 2021). Wilson et al. (2016) observed that STP at the top depth (0-15 cm) was significantly higher than 15-60 cm depth under different fertilizer inputs, management, and histories in eight fields in southwestern Manitoba. They reported a mean average of 10.8 and 2.8 mg/kg for 0-15 cm and 15-60 cm.

Meanwhile, too much fertilizer application can cause the downward transport of P in the soil profile and P export in drainage water. As shown in Fig. 3.5, STP decreased with increasing depth. Due to low rainfall and high temperature, low soil moisture might also have limited dissolved P, limited P release, and reduced nutrient uptake, resulting in reduced yield. Pease et al. (2018) reported that weather conditions influence nutrient dynamics.

The STP is an indicator of dissolved P in snowmelt runoff and export from drain tiles (Vadas et al. 2005, King et al. 2015, Gramlich et al. 2018, Grenon et al. 2021). Several studies have reported a strong positive correlation between STP and dissolved P in drain tiles (Pease et al. 2018) and runoff (Wilson et al. 2019, Liu et al. 2021). According to the Manitoba soil fertility guide (2007), the level of STP in the study area is classified as very high STP (>15 ppm), medium STP (8-11 pm) and low STP (<3 ppm) for the top, mid-profile, and deep profile, respectively. The high concentration of STP at the study site poses an increased risk of P enrichment and water pollution as research has shown that sites with STP higher than the recommended values would have high soluble P concentrations in drainage water and runoff (Pease et al. 2018).

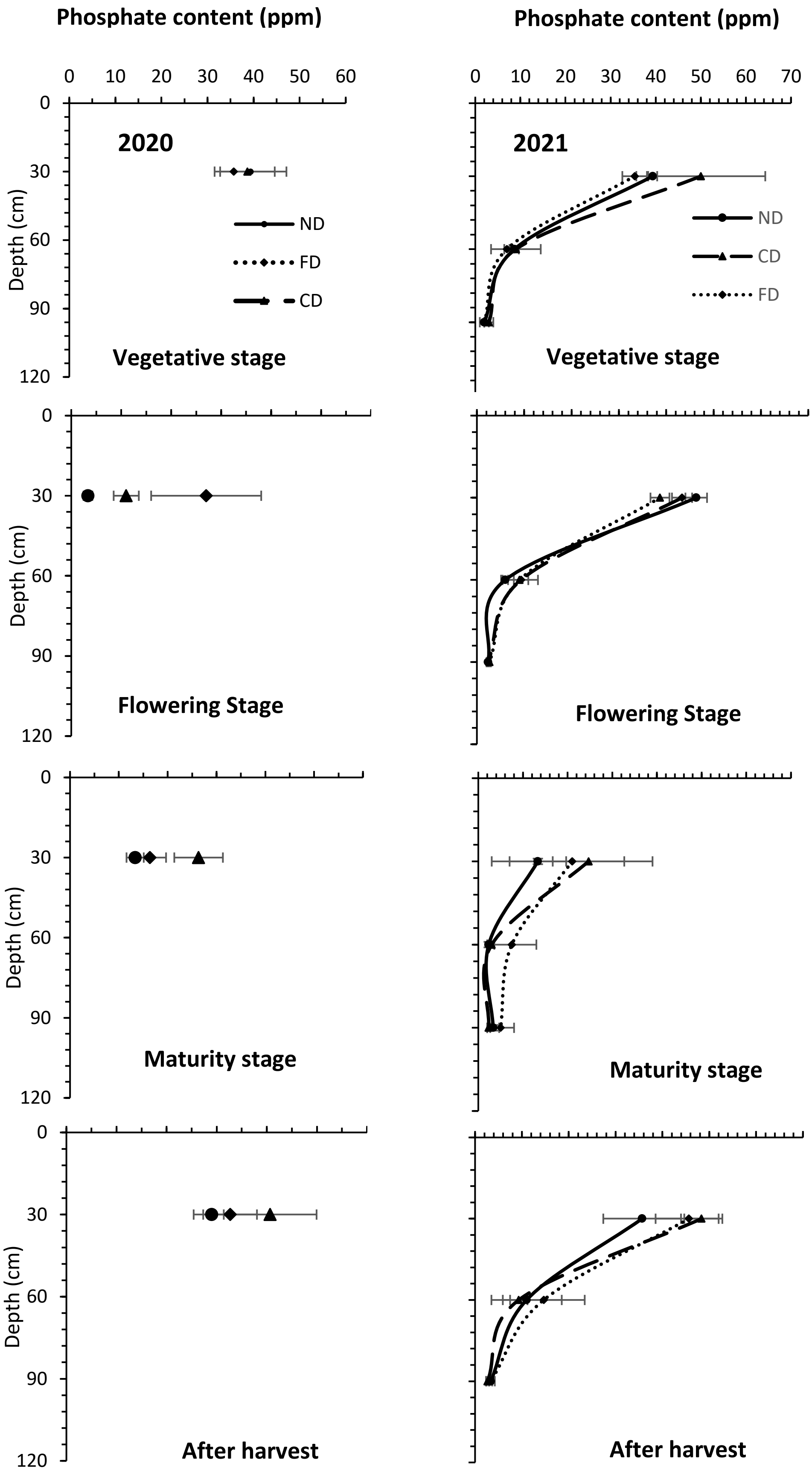


Figure 3.5: Soil Test Phosphate within the rootzone during 2020 and 2021 growing seasons

3.3.4 Canola quality assessments

3.3.4.1 Oil content, Protein content, and Glucosinolate contents

Canola quality assessments, including oil, protein, and glucosinolate contents, are presented in Figure 3.6. The figure shows the average annual values across the treatments. Statistical results showed no significant statistical differences between ND, CD, and FD. Also, there were no clear observable trends between the treatments during the study periods. However, there was a statistical difference between the years for some of the parameters. This suggests that environmental variables may have masked drainage impacts. This is in line with studies that reported that the environment has the most significant influence on canola quality (Omidi et al. 2010, Hammac et al. 2017).

Oil content is positively correlated to yield (Khalatbari et al. 2021) since it constitutes about 40-45% of the dry weight (Barthet, 2020). Across the treatments, average oil content was 45.9% in 2019, 46.0% in 2020, and 43.3% in 2021. The average protein content was 24.6, 24.2, and 27.8% in 2019, 2020 and 2021. Also, the average glucosinolate was 5.7, 19.6, and 13.9 μmol/g in 2019, 2020 and 2021, respectively. Despite the unusual weather observed in 2021, the glucosinolate content did not exceed the threshold set by the Canada Council of Canola. The values in this study were consistently higher than western Canada's 5-year average for oil, protein and glucosinolate content (Barthet, 2020).

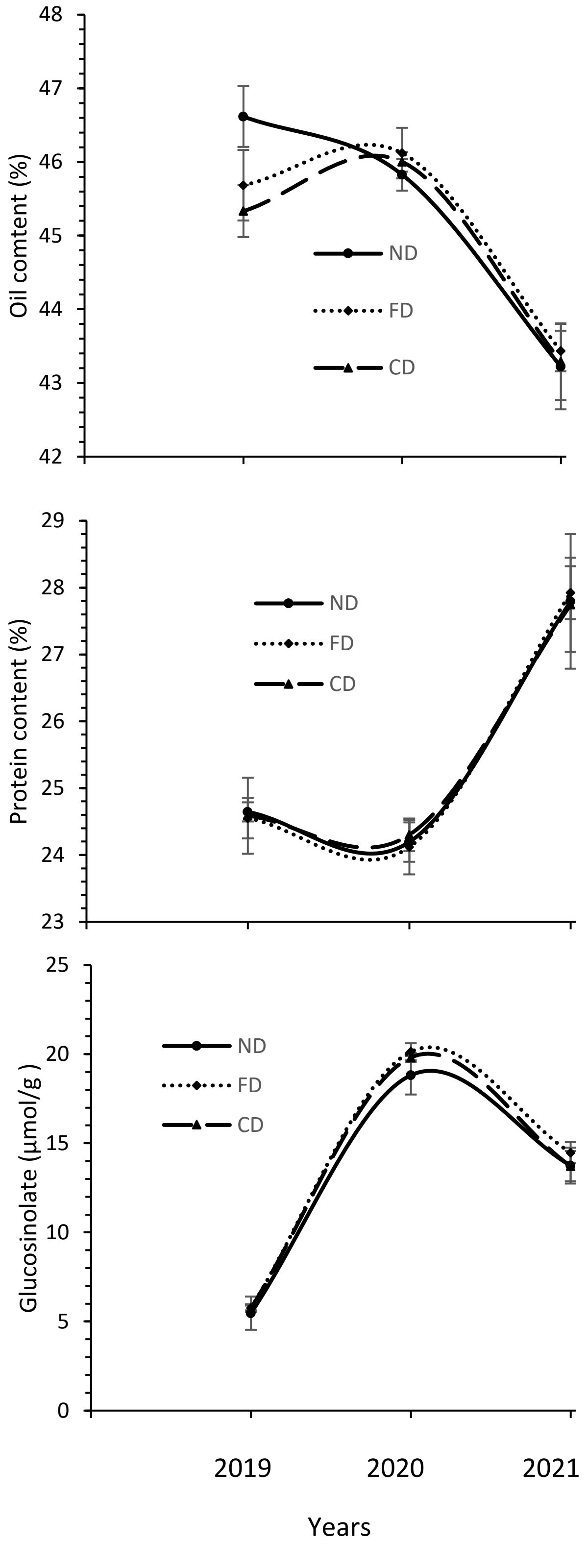


Figure 3.6: Average annual oil, protein, and glucosinolate contents per treatment during the study period (2019-2021)

The results showed there was a significant decrease in oil content and increased protein content in 2021 relative to 2019 and 2020. The 2021 growing season was characterized by heat and drought stress. This agrees with other research that reported oil and protein content are inversely related (Rathke et al. 2005, Aksouh-Harradj et al. 2006, Hossain et al. 2019). Heat stress decreases oil content by downgrading the expression of genes associated with photosynthesis and lipid metabolism. In contrast, protein content is increased because of upgrading the expression of genes related to protein biosynthesis (Zhou et al. 2018). Also, the increase in protein content under heat stress could be related to the competition for carbon during the biosynthesis process (Rathke et al. 2005) and increased nitrogen bioavailability, resulting in more amino acid assimilation (Singer et al. 2016). However, the oil content recorded in this study was higher when compared with similar studies (Pavlista et al. 2016, Elferjani and Soolanayakanahally 2018, Khalatbari et al. 2021, Chaganti et al. 2021), despite the weather conditions. This may be due to cultivar differences and other local factors such as soil and nutrients.

3.3.4.2 Fatty Acid (FA) constituents

Figure 3.7 shows the annual average of the FA components per treatment. As expected, of the total fatty acid profile, the oleic acid (C18:1) was highest, comprising 63.8% of the total fatty acid content, followed by Linoleic acid (C18:2), 19.1%, linolenic acid (C18:3), 8.8%, Palmitic (C16:0), 3.7%, Stearic acid (C18:0), 3.7%, and erucic acid (C22:1), 0.1%. Statistical results showed no clear observable trends for all the FA components and no significant differences between the treatments. However, there was a significant decreasing trend for Stearic and Oleic acid over the study period while Linoleic and Erucic acid increased. Also, there was a higher proportion of Linoleic, Erucic acids in 2021; Linolenic and Palmitic acids and 2020; while Stearic and Oleic acids had higher contents in 2019. This could be related to the weather of the growing periods, which was classified as normal, hot-dry, and extremely hot and dry for 2019, 2020, and 2021 respectively. The results of this study agree with numerous studies that state that the FA composition is mainly affected by heat and drought stress. The trend observed in Oleic, Linoleic, Linolenic acid agrees with Zhou et al. (2018), while the trend in Stearic acid agrees with Moghadam et al. (2011) and that of Palmitic agree with Pokharel et al. (2020).

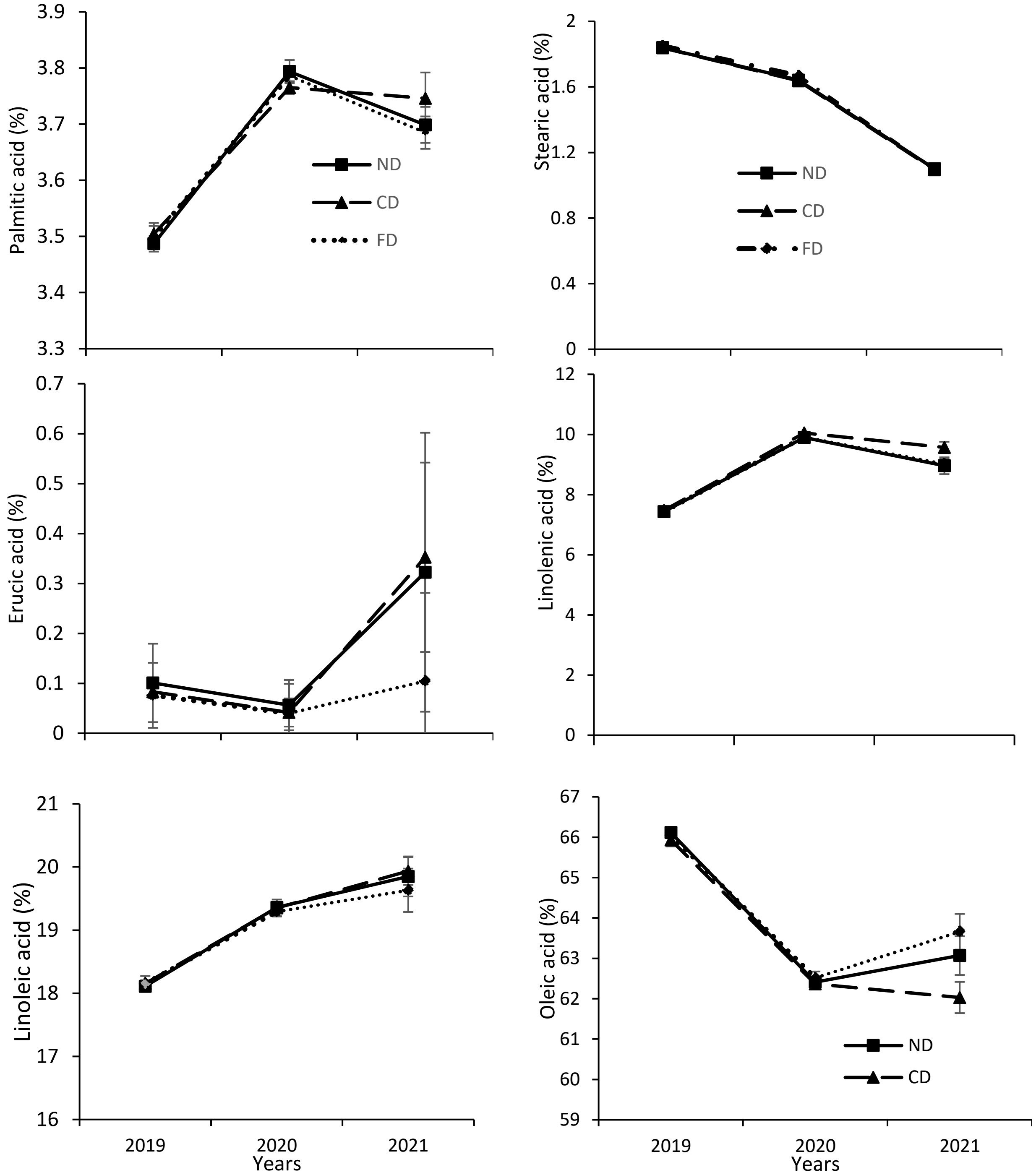


Figure 3.7: Average annual proportions of fatty acids (Palmitic acid (C16:0), Stearic acid (C18:0), erucic acid (C22:1), Linolenic acid (C18:3), Linoleic acid (C18:2), Oleic acid (C18:1) per treatment during the study period (2019-2021)

There are inconsistent trends of canola fatty acid profile in the literature due to environmental stresses. This is because of the strong interaction between cultivar and environment (Hammac et al. 2017, Pokharel et al. 2020). However, a lot of studies report that heat and drought stress increased relative proportions of saturated fatty acids (palmitic and stearic acid), oleic acid (monosaturated fatty acid) and decreased polyunsaturated fatty acids (linoleic and linolenic) (Pritchard et al. 2000, Pavlista et al. 2011, Aksouh et al. 2006, Pokharel et al. 2020). On the contrary, while some studies reported decreased and increased proportions of oleic and linoleic acid, respectively (Elferjani and Soolanayakanahally 2018, Zhou et al. 2018), Pavlista et al. (2016) reported a slight impact on fatty acid composition, with no significant effect on Oleic and linoleic acid.

3.4 Conclusion

The impacts of water management on canola yield and qualities were evaluated under three different treatments: controlled drainage (CD), free drainage (FD), and no drainage (ND) for three growing seasons (2019-2021). Canola yield, oil quality tests (oil, protein, and glucosinolate contents), fatty acid profile tests, nitrate and phosphate contents were also measured for each treatment. The result showed that weather variables likely influenced drainage impacts on yield. In 2019 with relatively reasonable rainfall amount and average normal temperature, results showed that CD plots consistently had the highest yield with a significant statistical difference compared to FD. However, as the growing season rainfall decreased in the following years, the impact of drainage, especially CD, diminished, resulting in no significant differences between the treatments. Soil nutrient analysis showed that ND had higher soil nitrate content across the treatments, even though it was not significantly different compared to CD and FD, respectively.

Canola oil quality results, including oil, protein, glucosinolate, and fatty acid profile, indicated that environmental variables might have masked drainage impacts. There were no significant differences between the treatments but varied significantly over the years. With the predicted rise in temperature and prolonged water deficits in the future in the Canadian Prairies, the results in this study suggest re-examination of the field drainage design and precise water management strategies. A significant amount of water from snowmelt is lost during springtime, which could otherwise be captured, stored, and re-used during sensitive growth periods.

Chapter Four

DRAINMOD simulation of drain spacing impact on canola yield in heavy clay soils in the Canadian Prairies

Abstract

Excess moisture within the root zone due to the shallow water table is a leading cause of crop loss in Manitoba. In this study, the ability of the DRAINMOD model to predict water table depth (WTD) in clayey soil was evaluated using measured field data from the 2019 and 2020 canola growing seasons in Arborg, Manitoba, Canada. Statistical analysis and graphical plots showed close agreement between the measured and simulated WTD with an overall coefficient of determination (R^2), root mean square error (RMSE), mean average error (MAE), and mean bias error (MBE) of 0.93, 9.84 cm, 7.06 cm, and -0.13 cm, respectively. Since the model simulation was deemed satisfactory, the model was run with 30-year historical climate data to assess the impacts of different drain spacings on canola yield. Simulation results showed that the average surface runoff increased while average drainage and relative canola yield decreased as the drain spacing increased. The simulation results suggest that the long-term average yield would be maximized by close drain spacing ≤ 15 m. Economic analysis showed that 10 m drain spacing would maximize the return on investment. The need for long-term simulations to develop appropriate site-specific water management strategies is demonstrated.

Keywords: DRAINMOD, model, drain spacing, canola yield, Canadian Prairies

4.1 Introduction

The water table (WT) is an important component of the agro-hydrologic cycle, especially in an area with a shallow water table, such as in southern Manitoba. The WT directly or indirectly affects other hydrologic variables such as drainage, runoff, flood, and droughts (Amatya et al. 2019). It affects biochemical processes such as nutrient cycling, organic matter mineralization, and nitrification (Amatya et al. 2019). Under dry conditions, WT can satisfy crop water demands through capillary action. It also affects field operations such as tillage, planting, and harvesting, etc. A high-water table could result in saturated soil conditions. Excess soil water is the leading cause of crop loss in Manitoba (MASC, 2020). Therefore, understanding water table dynamics is key to sustainable water management in the region, especially in the face of increased climate variabilities and extremes.

However, water table dynamics are complex and often difficult to predict because they depend on soil, crop, climate, topography, and management practices. Because of this, hydrologic models have been developed to address the present and future needs of producers while ensuring environmental sustainability (Masasi et al. 2020). To address the challenges of limited field data and uncertainties in measured data, models are first parameterized in other to gain confidence in the model's output. Models can accommodate climatic variability using historical weather data. Models run with long-term weather data have been used to evaluate drainage design (Cordeiro and Sri Ranjan 2015; Sands et al. 2015), operation strategies of water table management systems (Ale et al. 2009), fertilizer rates and fertilizer application (Hashemi et al. 2020; Wilson et al. 2020) in order to suggest better alternatives. With increased climatic variability and uncertainty, there is a need to identify a cost-effective drainage system that maximizes crop yield and reduces nutrient loss.

Drainage design variables, e.g., drain depth and spacing, are the most critical factors that can be used to control water table depth and assess the performance of a drainage system (Kladivko et al. 2004). When installing a drainage system in a new area, most drainage contractors develop their own rules or adopt what is practiced elsewhere (Sands et al. 2015). Modelling and field studies have shown that drainage design variables are location-specific due to differences in soil, weather, and management practices. For example, Singh et al. (2006) recommended drain depth and spacing of 1.05 m and 25 m, respectively, to reduce subsurface drainage and maximize crop yield in Iowa with silty clay loam. In southern Minnesota with the same soil texture, Sands et al. (2015) reported an optimal drain depth and spacing of 1.35 and 46 m, respectively. For environmental benefits, Hashemi et al. (2020) recommended a drain depth and spacing of 0.4 m and 50 m, respectively, for silty clay soil in Iran.

There are numerous hydrologic models, but only a few include processes that can simulate the hydrology of cold regions. Model simulation in a cold environment is challenging, limiting the use of models in such areas (Dayyani et al. 2010; Morrison et al. 2014). In cold climates, snowmelt and soil freeze-thaw are important processes that affect the hydrologic cycle as it controls infiltration, groundwater recharge, crop water uptake, and available plant water (Baulch et al. 2019).

DRAINMOD is one of the standard hydrologic models used for water management in poorly drained soils (Skaggs 1978, Skaggs et al. 2012). The DRAINMOD model has been applied globally under different climates, water management systems, soil, and crop types (Singh et al.

2006; Wang et al. 2006; Yang 2008; Luo et al. 2010; Sands et al. 2015; Malota and Senzanje 2015; Mohammadighavam and Klove 2016; Gaj and Madramootoo 2017; Yousseff et al. 2018; Askar et al. 2020; Saadat et al. 2020). In Canada, DRAINMOD has mainly been applied in humid and Atlantic regions (Shukla et al. 1994; Singh et al. 1994; Yang et al. 2007; Dayyani et al. 2010; Morrison et al. 2014; Golmohammadi et al. 2016) with limited application in the Canadian prairies with a semiarid climate, even though the region contributes significantly to the Canadian agriculture. The model was first evaluated in southern Manitoba with sandy loam soil under corn and potato production (Cordeiro and Sri Ranjan, 2015; Satchithanantham and Sri Ranjan 2015). It should be noted that even under a similar climate, model performance varies with location (Orth et al. 2015). Most DRAINMOD applications under canola production were carried out in Iran (Hassanpour et al. 2011, Davoodi et al. 2019, Hashemi et al. 2020). There has not been any study of DRAINMOD model application under canola production in the Canadian Prairies. This study fills the knowledge gap. Canola is an important crop with significant economic value, contributing an average of $29.9 billion per year to the Canadian economy since 2016 (LMC International 2020). Canada is the world's largest producer of canola, exporting about 20 million tonnes annually (Statistics Canada, 2018). The Canadian prairies (Saskatchewan, Alberta, and Manitoba) account for more than 98% of Canadian production. Manitoba produced more than 3.3 million tons in 2018 (Statistics Canada, 2018).

Extensive model testing and evaluation under different climate, soil, crop, and management practices are still needed, especially in cold environments (Yang et al. 2007; Saadat et al. 2020). Therefore, the overall objective of this study is to evaluate the DRAINMOD model. The specific objectives are (i) to calibrate and parameterize the DRAINMOD model, (ii) to simulate water table depth under canola production in the Interlake region of Manitoba, Arborg (iii) to determine the water balance components of the agricultural field using a 30-year historical climate data (1986-2015), (iv) to evaluate the impact of different drain spacings (8, 15, 30, 50, 70 and 90 m) on canola yield, drainage, and runoff, and (v) to determine the drain spacing that would maximize the return on investment. This study emphasizes the need for long-term studies under different water management strategies to maximize yield, increase profitability, and ensure environmental sustainability.

4.2 Materials and methods

4.2.1 Study Area

A field drainage experiment was designed to evaluate drainage impacts on crop yield at the PESAI (Prairies East Sustainable Agriculture Initiative) site (Arborg, Manitoba, Canada, to assess drainage impacts on crop yield. The PESAI site (latitude 50.904, longitude -97.273, elevation 229 m) is an agricultural research farm in the rural municipality of Bifrost-Riverton, near Arborg, MB. The region has a semiarid climate, with cold-dry winters and warm summers (Bueckert et al. 2013). The experimental area was divided into four sections (Fig. 4.1).

The first three sections measure 600 m by 60 m and contain the drainage treatment replicated three times. Each of the plots is separated by a 5 m buffer zone and is of equal size with an area of 1.2 ha. Nine out of the twelve plots have drain tiles installed at a design drainage depth of 0.9 m with three different spacing (4.57, 9.14, and 13.72 m). This site serves as a demonstration site for showcasing tile drainage's impact on crop performance. Therefore, three different spacings were used with three other crops in rotation. However, this study used the data from the plots with the 13.72 m spaced drain tiles planted with canola. The remaining three plots are the control treatments (no drain).

The laterals are installed at an average slope of 0.15%, varying from 0.9 m to 1.1 m, in the North-South direction, and connected to 200 mm headers which discharge into the outlets at the south edge of the field. The drain tiles are made up of corrugated pipes, 200 m long and 100 mm diameter. The area has a nearly flat topography with a slope of 0.01%. The soil belongs to the Fyala series, which consists of poorly drained Rego Humic Gleyol soil that develops weakly to moderately calcareous, lacustrine clay deposits (Podolsky, 1982). The soil is predominantly heavy clay with low permeability, deep water table depth and peat content. The soil is prone to shrinkage and swelling due to its high clay content. Thus, soil cracks are common in the field.

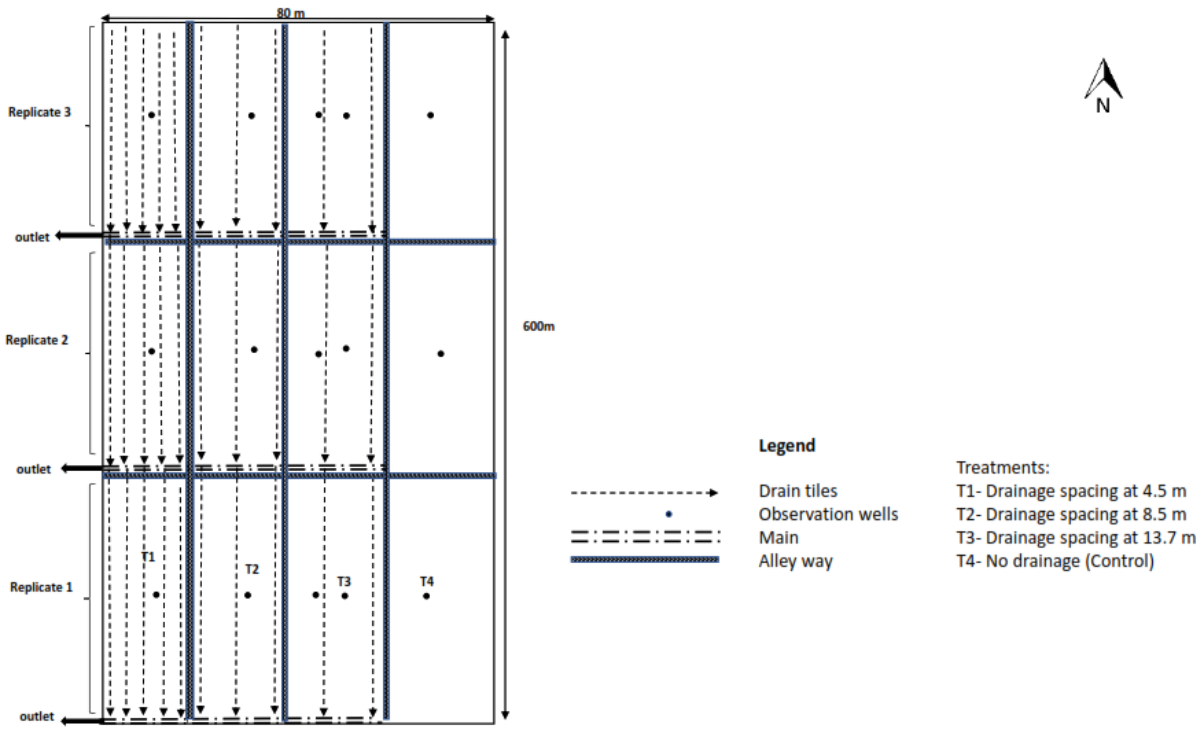


Figure 4.1: Layout of the study area (Not to scale)

During the study period, tillage was done after harvest in the fall. Canola (*Brassica napus* cultivar 'Invigor' L233P) was seeded using a 3.7 m wide Salford air seeder at a rate of 7.85 Kg/ha on May 29th and 21st in 2019 and 2020, respectively. The inter-row and plant spacings are 0.19 m and 0.10 m, respectively. Fertilizer application was based on the residual soil nutrient status. Soil tests for Nitrogen and Phosphorus were done annually in September, preceding the growing season at the Farm Edge laboratory using standard procedures. In 2019, 89.7-123.3 kg/ha of Nitrogen and 44.8 kg/ha of Phosphorus were applied. In 2020, while all the plots received 20 kg/ha of Phosphorus, the tile-drained and undrained plots received 112.1 and 56 kg/ha of Nitrogen, respectively. Weeds were controlled by spraying Liberty at 3.34 L/ha. Similarly, Decis was sprayed on June 25 at a rate of 0.124 L/ha to control insects, while Reglone, a desiccant, was sprayed at 2.06 L/ha on Aug 25. For both years, canola attained full maturity between 16-17th August and was harvested on September 9th and 2nd in 2019 and 2020, respectively. Crop yield was determined after each year's harvest by weighing using the Wintersteiger plot combine. Canola yield was calculated based on the weight of seeds from two approximately 20 m long strips and 1.25 m wide, from each replicate.

4.2.2 Field instrumentation and data collection

Water table depth was measured using water level sensors (Solinst Levelogger Junior 3001, Solinst Canada, Ltd., Georgetown, Ontario, Canada) suspended inside the piezometric wells.

The sensor has inbuilt data logging capabilities, set on a 3-hour logging interval. A barometric pressure sensor (Solinst Barologger) was also installed at the outlet of replicate 1 to correct the readings of the levelogger for atmospheric pressure. The wells are made of schedule 40 steel pipe, with an internal diameter of 0.0413 m. A Kevlar rope was used to suspend the sensor, tied to a ring (0.038 mm diameter) hung on a bolt made very close (0.038 m) from the top. The wells have slits on the sides and are covered with socks to allow easy movement of water and prevent soil and clay particles from clogging. The pipes were inserted in the auger holes. Bentonite was used to avoid preferential flow, and wells also had a cap at the top to prevent direct entry of rainwater. The average mid-spacing water table depth for the tiles installed at 13.72 m spacing was used for model simulation in this study. As read from the contractor design, the drain tile closest to the observation well was approximately 1.06 m, despite having a design depth of 0.9 m. In 2019, the levelogger sensor was installed on the 12th of July due to late delivery and installation of the water level sensor, but in 2020, monitoring started on May 25th. The monitoring period in 2019 was shorter than the 2020 growing season. In order to accommodate more data points, the monitoring period was extended to the end of September.

4.2.3 DRAINMOD MODEL

DRAINMOD is a process-based, field-scale, hydrologic model developed to evaluate the impacts of different water management systems in poorly drained agricultural fields (Skaggs 1978). DRAINMOD performs water balance on a soil profile, midway between two tile drains from the soil surface to an impermeable layer (Skaggs 1978). It also calculates the water balance at the soil surface. The model predicts surface runoff, sub-surface drainage, evaporation, infiltration, crop yield, and water table depth on a daily, monthly, and yearly time scale. A detailed description of the model is reported by Skaggs (1978). Since its inception in the 1970s, more processes have been added to simulate hydrologic processes accurately. Examples include the inclusion of soil nitrogen and salinity (Kandil et al. 1995; Brevé et al. 1997), freeze-thaw processes (Luo et al., 2000), C-N dynamics (Youssef et al. 2005), coupling with crop growth models (Negm et al. 2014), and phosphorus fate and transport (Askar et al. 2020). The DRAINMOD model computes the relative yield of crops using the stress-day method (Evans and Skaggs, 1991), which considers yield reduction due to excess water, drought, planting delay, and salinity stress. In this study, salinity was not considered because the measured soil electrical conductivity (ECe) ranged between 0 - 4 dS/m (https://agrimaps.gov.mb.ca/agrimaps/), is less than the threshold (5-10 dS/m) that causes yield reduction in canola (Francois 1994, CCC, 2021).

Therefore, the relative yield is computed as the product of YR_w, YR_d, and YR_p.

$$Y_R = YR_w \times YR_d \times YR_p \tag{4.1}$$

where Y_R is the overall relative yield, YR_w is the relative yield due to water stress only, YR_d relative yield due to drought only, YR_p and relative yield due to planting delay only. The linear functions showing yield reduction arising from wet stress, drought, and planting delay are given by Evans and Skaggs (1991).

4.2.3.1 Model inputs

The inputs required to run the DRAINMOD model are classified into the soil, drainage design, crop, temperature, and trafficability properties. One of the advantages of the DRAINMOD model is that it requires few measured data (Jin and Sands 2003). It has in-built subroutines for determining complex model inputs that are usually time-consuming and difficult to obtain.

4.2.3.1.1 Weather data

An on-site weather station, located about 100 m from the study plots, and managed by Manitoba Agriculture, provided the data used in this study. Weather data is used to determine the potential evapotranspiration (ET). The model offers the option for users to input already computed ET or use Thornmwaite's (1948) ET equation. In this study, the latter was used. Hourly precipitation, maximum and minimum temperature, and geographic location are the required inputs to determine ET.

4.2.3.1.2 Soil

The required soil inputs include soil-water characteristics, drainage volume, WTD, upward flux relationship, and infiltration parameters. The soil information for the study area was obtained from Manitoba Agrimap and fed into the ROSETTA software to derive the initial soil hydraulic properties of the study area. As read from the digitized Manitoba Agrimap and Podolsky (1982), average saturation, field capacity, permanent wilting point, clay, silt, and sand fractions are 45.4%, 37.6%, 21.6%, 90%, 9%, and 1 %, respectively with pH of 7.0-7.5. The average bulk density for heavy clay is 1.07 g/cm^3 (Manitoba Agriculture, 2021). The ROSETTA software uses a pedotransfer function to determine the soil water retention and hydraulic properties from soil texture and bulk density (Schaap et al. 2001). ROSETTA-derived soil hydraulic parameters are as good as experimentally derived soil parameters (Salazor et al. 2008). Based on field excavation, the soil profile was divided into two layers (0-40 cm) and (40-250 cm) to represent the top and deep layers, respectively. Table 4.1 shows the final calibrated soil hydraulic parameters.

Table 4.1: Soil hydraulic parameters of the study area

Layer (cm)	θ_r (m^3/m^3)	θ_s (m^3/m^3)	α^* (cm^{-1})	L	n (-) *	K_{sat}(cm/day) *	K_o (cm/d)
0-40	0.01094	0.516	0.021	-0.6831	1.13	24	20
40-250	0.01942	0.540	0.019	-0.8319	1.12	23.5	20

θ_r - residual water content, θ_s- saturated water content, α^* curve parameter, n curve shape parameter, K_{sat} is saturated hydraulic conductivity, K_o matching point at saturation

* Calibrated parameter

4.2.3.1.3 Drainage design

The drainage system inputs were obtained directly from the field, as shown in Table 4.2. Drain spacing was 13.72 m, drain depth was 1.06 m, the effective radius was 0.51 cm (actual radius was 5 cm), and the depth to the impervious layer was assumed 6 m following Cordeiro and Sri Ranjan (2015) and Satchithanantham and Sri Ranjan (2015). DRAINMOD has an internal subroutine that determines the equivalent depth from the drain to the impermeable layer and Kirkham's coefficient based on drain spacing, effective radius, and distance between the drain and the impervious layer.

Table 4.2: Model inputs in DRAINMOD

Model inputs	Value
Drainage system	
Drain spacing (m)	13.72
Drain depth (m)	1.06
Effective drain radius (cm)	0.51
Drainage coefficient (cm/day)	1
Distance from surface to impermeable layer (m)	6
Maximum surface storage (m)	0.5
Kirkham's depth for flow to drains	0.25

Crop parameters		
Desired planting date (day)	138	
Last day of the year to plant without yield loss (day)	140	
Length of the growing season (day)	90	
Days required to prepare seedbed and plant (day)	2	
Root zone lower water content	0.1*	
Limiting water table depth (cm)	30	
Period to count wet and dry days	May 1 - August 31	
Yield reduction parameters		
Linear relationship relating excess water stress to relative yields	Intercept 100% Slope: -0.3*	
Linear relationship relating drought stress to relative yields	Intercept 100% Slope: -1.22*	
Crop susceptibility factors (DAP)	0(0-6), 0.3 (7-44), 0.15(45-59), 0.1 (60-89), 90 (0) *	
Trafficability	Period I	Period II
Start counting work days (day)	April 1	September 15
End counting work days	June 30	November 15
Minimum air volume required to work the land (cm)	1.5	
Minimum rain to stop delay work (cm)	1	
Minimum time after rainfall before work can restart (day)	2	
Soil temperature		
Soil thermal conductivity (W/m/ ^{o}C)	a = 0.5, b = 1.5	
Average air temperature which precipitation is snow (^{o}C)	0	
Average air temperature above which snow starts to melt (^{o}C)	2	
Snowmelt coefficient (mm/day/^{o}C)	3*	
Critical ice content above which infiltration stops (cm^3/cm^3)	0.2	
Diurnal phase lag of air temperature (^{o}C)	8	

* Calibrated

4.2.3.1.4 Crop data

The crop input data include desired planting date, harvest date, effective rooting depth, and stress crop parameters. The optimum planting date was set as May 25, according to Manitoba Agriculture. Recent canola species have a shorter growing period as they are due for harvest between 90-100 days after planting (DAP). Although the maximum rooting depth for the canola crop can reach 1 m (Cutforth et al. 2013), the effective rooting depth is where more than 70% of water uptake occurs (Hashemi et al. 2020). Therefore, the effective rooting depth ranged from 3 to 30 cm, as shown in Table 4.3. The model uses this depth to define the zone from which water can be removed in response to ET under soil limiting conditions. As contained in Table 4.2, the crop susceptibility factors were obtained from Hassanpour et al. (2011) and interpolated between the dates.

Table 4.3: Effective root depth of canola used in the simulation

Month	Day	Depth (cm)
1	1	3
4	25	3
5	14	30
5	27	30
6	1	30
6	20	30
7	24	30
8	20	30
9	24	3
10	25	3
12	31	3

4.2.3.1.5 Trafficability

The trafficability input parameter was set for spring and fall conditions to check for trafficable conditions necessary for planting and harvest. In DRAINMOD, planting is delayed when all the conditions set by the user are not met: the minimum required air volume to work the land, the minimum rain to restart work, and the delay after rain to continue work. The values for these conditions are listed in Table 4.2.

4.2.4 Model performance

The performance of the DRAINMOD model was assessed using both graphical and statistical indices. A visual plot showing a close match between simulated and measured water tables is deemed acceptable. Also, statistical indices commonly used in hydrologic model performance were used. They include R^2, RMSE, MBE, and MAE.

Coefficient of determination (R^2)

The coefficient of determination (R^2) is used to show a correlation between measured and predicted values. It ranges from 0, indicating no correlation, to 1, meaning perfect agreement between observed and predicted. It is calculated as:

$$R^2 = \left(\frac{\sum_{i=1}^{n}(O_i-\overline{O})(P_i-\overline{P})}{\sqrt{\sum_{i=1}^{n}(O_i-\overline{O})^2}\sqrt{\sum_{i=1}^{n}(P_i-\overline{P})^2}}\right)^2 \tag{4.2}$$

Root Mean Square Error (RMSE)

RMSE is used to quantify the mean differences between observed and predicted values. It is given as:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(O_i-P_i)^2}{n}} \tag{4.3}$$

Mean Bias Error (MBE)

MBE is used to quantify model over or underestimation. Positive and negative values indicate overestimation and underestimation, respectively.

$$MBE = \frac{\sum_{i}^{n}(P_i-O_i)}{n} \tag{4.4}$$

Mean Absolute Error (MAE)

MAE is a measure of error variability. The average error is better measured using the MAE than the RMSE (Willmot and Matsuura 2005).

$$MAE = \frac{\sum_{i}^{n}|(P_i-O_i)|}{n} \tag{4.5}$$

where, O_i is measured values, P_i is the predicted values, $\overline{O_i}$ is the mean of observed values, and n is the total number of observed data points. An optimal model is obtained when R^2 is equal to 1, and RMSE, MAE and MBE are equal to 0 (Mkhabela and Bullock 2012, Hashemi et al. 2020).

4.2.5 Assessment of drain spacing on predicted relative canola yield

After model calibration, the model can be extrapolated over various scenarios, management practices and weather conditions (Boumann et al. 1996). In this study, historical weather data (1986-2015), including maximum and minimum temperature, and precipitation were obtained from the archives of Environment Canada for the Arborg weather station and used to run DRAINMOD. Daily precipitation was uniformly distributed over 4 hours, using the inbuilt weather utility in DRAINMOD. Missing temperature and rainfall data were gap-filled using the closest station (Gimli).

According to Cordeiro and Sri Ranjan (2015), drainage contractors in Manitoba have generally adopted a tile drain installation depth of 1.06 m and a spacing of 15 m. They attributed this choice to reduced energy requirements during installation. In this study, drain depth was kept constant while the drain spacing was changed during the simulation. Six drain spacings were selected (8, 15, 30, 50, 70, and 90 m). The DRAINMOD model was first run with long-term climate data to determine the water balance components. This was followed by running the model on different drain spacing to evaluate the impacts on water balance variables and relative canola yield. A 2-year warm-up period (1984 and 1985) was used to initiate and stabilize the model.

4.2.5.1 Economic analysis

The rate of return on investment under different spacing was determined by subtracting the average production cost ($/ha) and drainage cost ($/ha) from the production income ($/ha). The average annual canola production income was calculated as the product of the relative yield, potential canola yield, and unit canola price. In this study, the potential canola yield, unit canola price, and annual canola production cost (excluding land cost) were assumed as 2796.4 kg/ha (45 bu/ac), $0.45/kg ($11.25/bu), and $862.64/ha ($349/ac) according to MARD (2021). The equation for annual drainage cost was obtained from Ghane et al. (2021). The initial cost of the drainage system was $3.76/m, assuming that it cost $2469.1/ha ($1000/ac) for 15.2 m (50 ft) drain spacing in Manitoba. The interest rate on investment per year, depreciation per year based on a 50-year expected lifetime, and maintenance rate per year were assumed as 6%, 2%, and 0.25%, respectively, according to Crabbé et al. (2012).

4.3 Results and Discussions

4.3.1 Weather variables

During the 2019 and 2020 growing seasons, the total precipitation received was 326 and 237 mm, respectively, 26.6 and 42.6% lower than the 30-year average of 499 mm. Monthly rainfall analysis showed that the site exhibited wide variation from the long-term average values (Figure 4.2). For example, the long-term average was significantly higher than the 2019 and 2020 values in May and August. The 2020 rainfall was higher than the 2019 and long-term rainfall in June, while in September 2019, 2019 was more than twice and four times the 30-year average and 2019 values, respectively. Compared to the long-term average, both years are considered dry, with 2019 being the drier since the September rain had occurred around the harvest period.

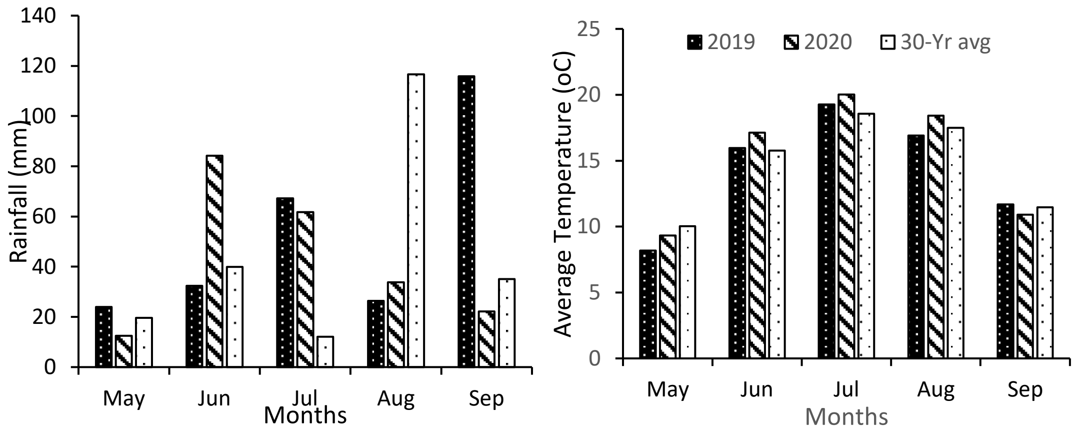


Figure 4.2: Comparison of monthly rainfall and average temperature during the study period and 30-year average

The average temperature during the study period was very close to the long-term average values. The highest average temperature was recorded in July, corresponding to the period of highest crop water use. The average temperatures for 2019, 2020, and long-term are 0.86, 2.29, and 1.56 ^{o}C, respectively.

4.3.2 Model parameterization

The model was calibrated by manually changing parameters affecting the hydrology of agricultural fields following Singh et al. (2006). The initial values were obtained from the literature (Cordeiro and Sri Ranjan 2015 and Satchithananantham and Sri Ranjan 2015) and adjusted through trial and error until predicted matched measured values. The calibration parameters include soil hydraulic parameters, ET correction factors, and snow coefficient (Table 4.1 and 4.2). Given the high variability of soil properties, Ksat was used as a calibration parameter. After several trial-and-error attempts, the final calibration values were 0.9 and 0.1 cm/hr for layers 1 and 2, respectively, which are close to the reported values in the region (Podolsky, 1982). Another soil hydraulic parameter is the alpha, which modifies the relationship between water table depth vs volume drained, and water table depth vs upward flux was also calibrated. The calibrated monthly ET correction factors are 1.0, 1.2, 1.2, 1,2, 0.5, 0.9, 1.0, 1.1, 1.2, 1.2, 1.2, and 1.2 for January through December. To account for freeze-thaw and snowmelt, the soil temperature input data is required. The initial temperature parameters were obtained from the literature with similar weather characteristics (Cordeiro and Sri Ranjan 2015 and Satchithanantham and Sri Ranjan 2015) and later adjusted during calibration. The calibrated snowmelt coefficients and critical ice content above which infiltration stops were set to 3 mm/day/ºC and 0.2 cm^3/cm^3

4.3.3 Water table dynamics

Figure 4.3 shows the measured and simulated water table depth (WTD) in 2019 and 2020. Water table fluctuation was mainly in response to rainfall, ET, and drainage. The graphical comparison between measured and simulated WTD shows that the model followed the same trend as the measured, even though they differed in magnitude. The dry weather of the 2019 growing season caused the water table to be around 2m at the start of the monitoring period, as the model overpredicted WTD by 15%. We observed that the 37 mm of rainfall on July 12th only caused a slight rise in simulated and observed water tables due to the extremely dry soil profile. As presented in Figure 4.2, the total rainfall in May, June, July, and August were 56.6, 60.0, 4.4, and 6.2%, respectively, lower than the 30-year long-term values. Extreme dry and drought conditions were also reported in North Dakota, which is also part of the great plains of North America (Acharya et al. 2019). However, as the simulation progressed, we observed a closer match between simulated and measured and WTD rise in response to rainfall in September. The average simulated and measured WTD are 196.17 cm and 189.68 cm, respectively. The statistical result showed acceptable model performance with R^2, RMSE, MBE, and MAE of 0.553, 8.745 cm, -6.625 cm, and 7.301 cm, respectively. The negative MBE is an indication that the model underpredicted WTD.

Similarly, in 2020, the plot also shows that DRAINMOD could capture the WTD changes during the monitoring period. With minor observable differences, the model followed the rise and fall of the measured water table. For example, the 32 mm rainfall on June 25th caused the water table to rise to 63.5 cm, although the model lagged by one day and under predicted by 15% (53.6 cm). The trend of the WTD was in close agreement till the end of the growing season in September. At the start of the simulation, observed and simulated followed the same trend even though DRAINMOD was slightly higher than the measured WTD. Towards the end of the growing season, there was little, or no response of both simulated and observed WTD to the late rainfall received in August. This lack of response may be due to the prolonged dryness between the rainfall events. Given the low hydraulic conductivity of clay soil, the rain may have only wet the soil profile or used by the crop through ET. The graphical plot (Fig. 3 & 4) showed that the model satisfactorily simulated WTD throughout the growing season. The average simulated and measured WTD are 135.67 and 139.36 cm, respectively. As indicated in Table 4, statistical results showed satisfactory model performance with R^2, RMSE, MBE, and MAE of 0.896, 9.712 cm, 3.698 cm, and 6.259 cm, respectively. The positive MBE is an indication that the model overpredicted WTD

The model performance in 2020 was better than the 2019 growing season. This may be due to the larger datasets used in 2020. The rise and fall of the water table in heavy textured soil may be affected by the presence of an impermeable layer that causes water to flow horizontally from mid-way in the drains (Wahba and Christen 2006). Also, the ET estimation method may affect the difference between simulated and observed WTD since ET is a significant pathway for water loss during the growing season. Overall, the model performance during the monitoring periods was excellent.

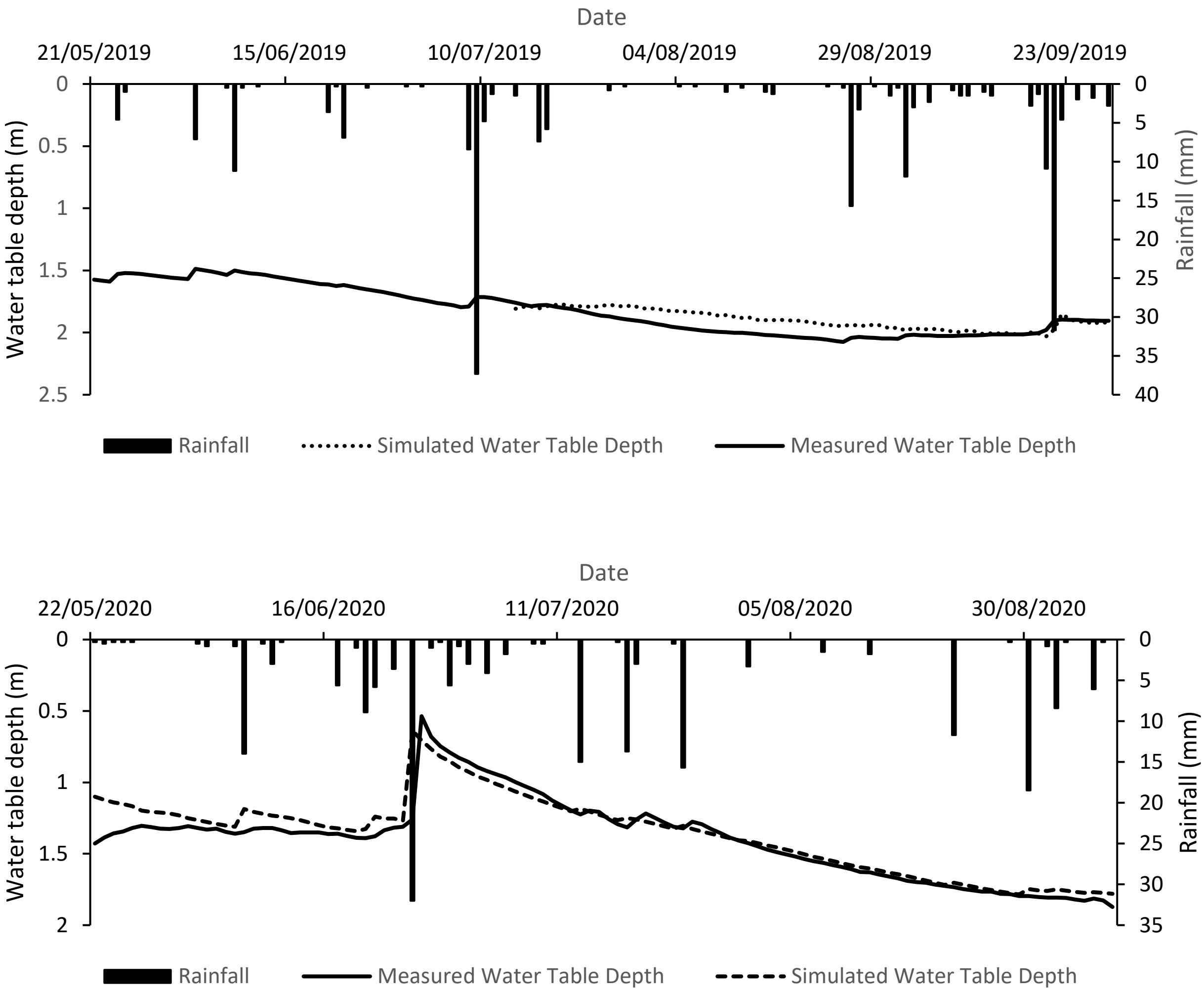


Figure 4.3: Comparison of measured and predicted WTD in response to rainfall during the 2019 and 2020 growing season

Table 4.4: Summary of statistics indices on DRAINMOD performance for simulating WTD

	R^2	RMSE (cm)	MBE (cm)	MAE (cm)
2019	0.553	8.772	-6.625	7.301
2020	0.896	9.712	3.698	-6.259
Overall	0.927	9.838	0.135	7.056

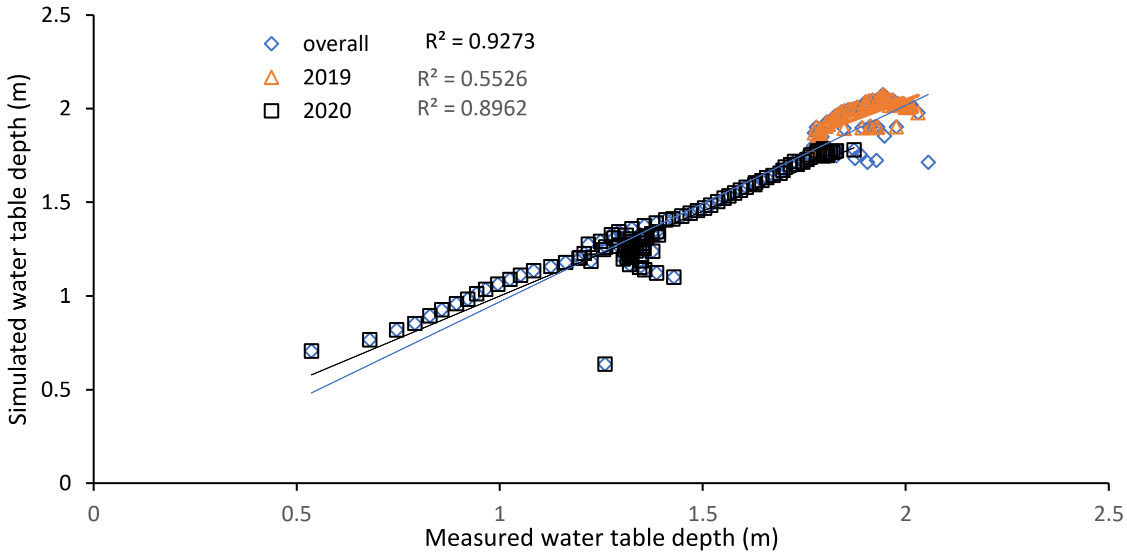


Figure 4.4: Regression of measured and simulated WTD over the study period

4.3.4 DRAINMOD Hydrologic long-term assessment

The main outputs of the DRAINMOD model include ET, sub-surface drainage, surface runoff, water loss (sub-surface drainage + surface runoff), and water table depth. The average total ET was 297 mm on the annual scale, with the highest ET of 355.2 mm in 2015 and the lowest value of 220.6 mm in 1992. Similarly, the average water loss was 222.7 mm, with a maximum value of 399.6 mm in 2008 and a minimum value of 51.9 mm in 2003. Average water table depth was shallowest in 1993 (64.53 cm), deepest in 1989 (213 cm), with an average value of 102.1 cm.

Water balance analysis (Table 4.5) shows that ET, water loss (drainage + runoff) accounted for 57.2 and 42.9% of the total precipitation. About 94.1% of ET occurs during the growing season (May - September), and 56.62% is water loss, where drainage and runoff account for 34.1 and 22.4%, respectively. Similarly, in the non-growing season (October - April), drainage and runoff represent 19.97 and 23.4%, respectively, of the water loss. Runoff peaked in April, which corresponds to the period of high snowmelt in the region. However, runoff constitutes about 48.9% in the growing season. Similarly, peak subsurface drainage occurred in May, and drainage represents approximately 63.06% in the growing season.

Table 4.5: Summary of annual average water balance

Hydrologic Variables	Annual Average	Growing Season (GS)	Non-growing season NGS)
Rainfall (mm)	519.4	356.1	163.3
Infiltration (mm)	417.5	307.2	110.2
Evapotranspiration (mm)	297.0	279.6	17.4
Runoff (mm)	101.9	49.9	52.1
Drainage (mm)	120.5	75.9	44.5
Water loss (mm)	222.8	126.1	96.6

Similar results were also observed under different drain spacing. Also, under increasing drain spacing, across the months, drainage rates decreased while surface runoff increased. We also observed that drainage and runoff were highest at the beginning of the growing season (April and May) and gradually decreased into the winter. Results also showed no runoff from December through February and minimal drain discharges from December to March. This corresponds to the winter period with frozen ground. This study agrees with similar long-term simulation studies with similar climates (Jin and Sands 2003, Satchithanantham and Sri Ranjan 2015). Also, the results agree and disagree to some extent with the field study conducted by Kokulan et al. (2019) in the same province. They reported that tile drainage constituted about 10-25% of the annual runoff. The difference may be due to the prevailing weather of the study periods.

The long-term water balance analysis allows us to manage water by altering the variables controlling hydrology. ET is the largest source of water loss during the growing season, followed by drainage and runoff from the above analysis. Therefore, water management strategies such as controlled drainage would conserve water and potentially reduce nutrient losses from drainage tiles.

Figure 4.6 presents the simulated average monthly water balance components for the different spacing. As drain spacing increases, the predicted average annual runoff increases with a marginal increase in ET, while infiltration and subsurface decrease. This has a practical implication on the predicted relative yield because as drain spacing increases, less water is removed from the profile, trafficable conditions are not met, planting is delayed, which would result in reduced yield.

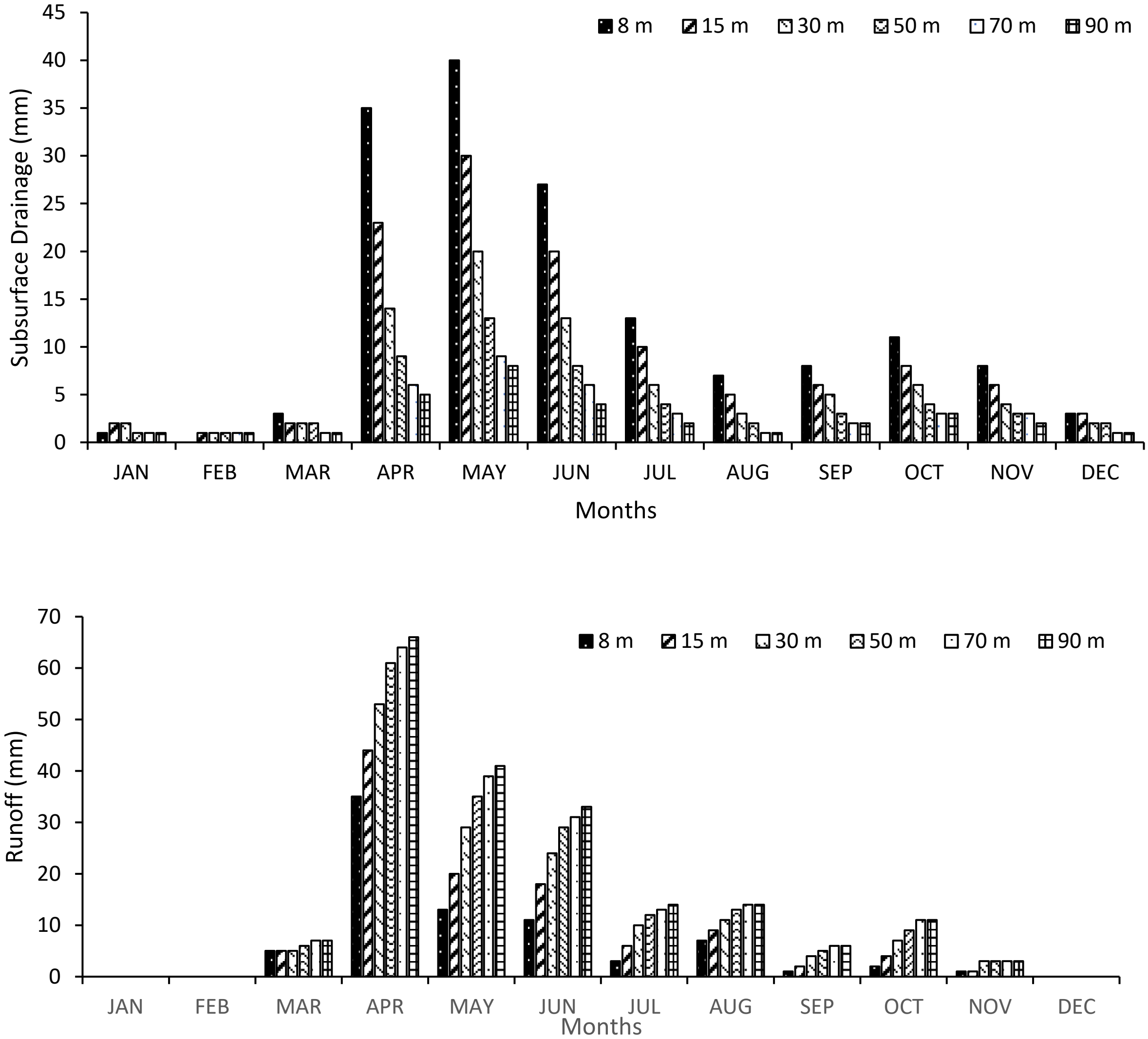


Figure 4.5: Monthly average drainage and runoff under different drain spacing

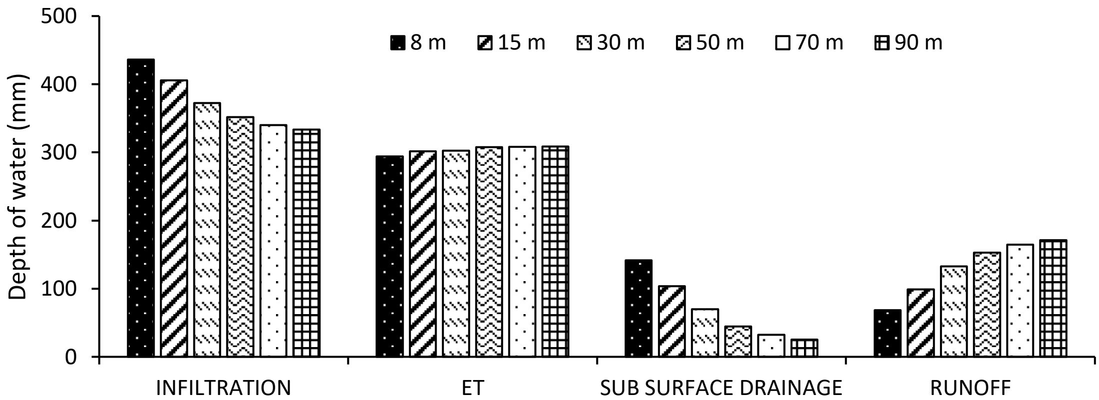


Figure 4.6: Impact of drain spacing on the average annual water balance components

4.3.5 Impact of drain spacing on canola yield

Figure 4.8 presents the average predicted relative canola yield under different drain spacings. Only years with yield results across all six spacings are given. The years 1993, 2000, 2005, 2007, and 2008 were excluded because zero yields were obtained at drain spacings > 50 m. Out of the 25 years, 16 experienced yield reduction due to excess water, six due to combined effects of excess water and planting delay, while the remaining were due to all the stressors. Wet stress caused the highest yield reduction followed by planting delay and drought stress, as shown in Fig. 8.

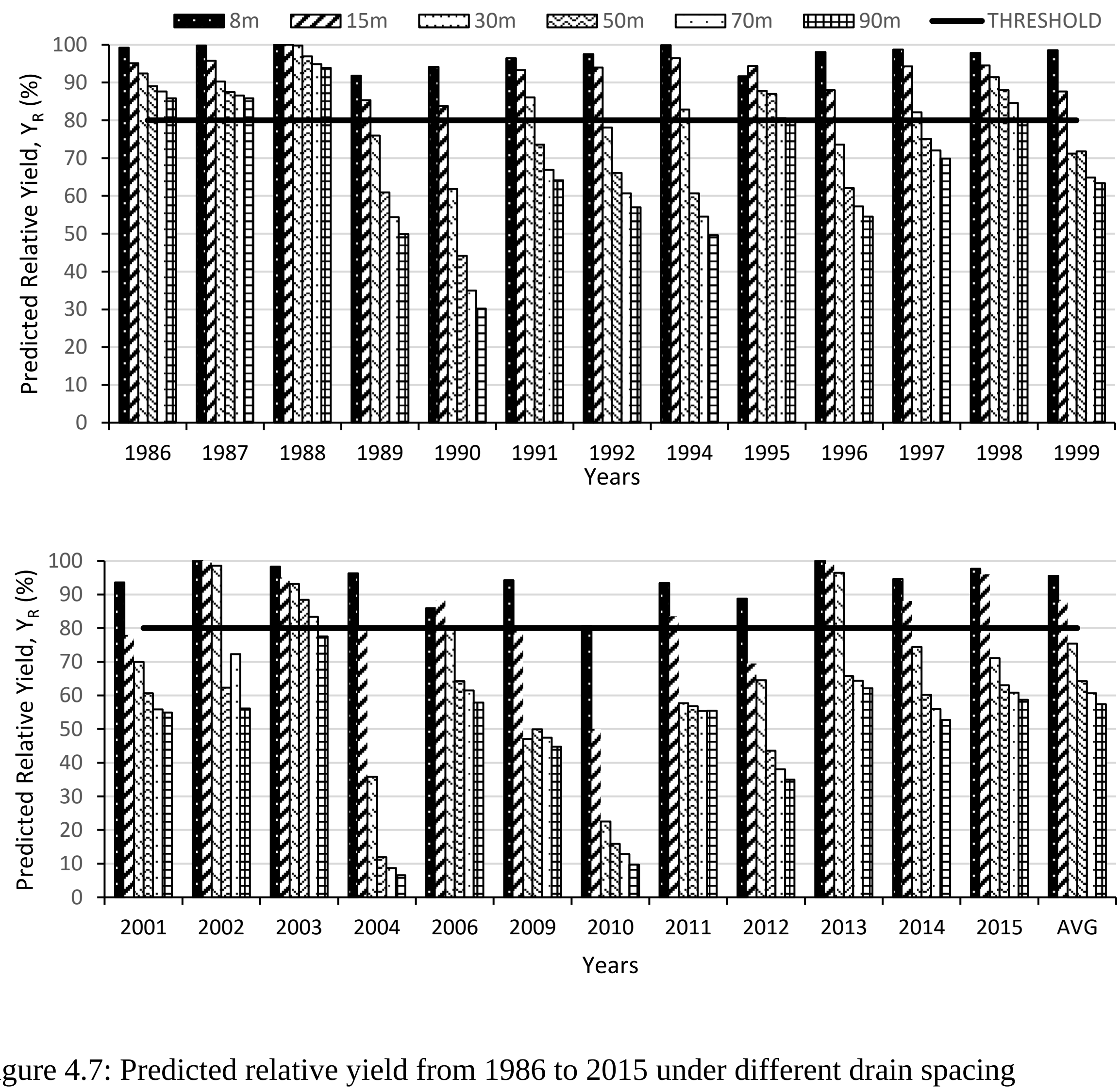


Figure 4.7: Predicted relative yield from 1986 to 2015 under different drain spacing

Simulation results showed varying weather-yield results, indicating underlying factors influencing yield. Simulation results suggest that years with precipitation greater than the long-term average had relative yield reduction due to excess water. Examples include 2010 (749 mm; 48.2% above average), 2012 (656 mm; 29.8% above average), 1996 (558.4 mm, 10.5% above average) etc. However, it should be noted that high precipitation amount does not directly translate to yield reduction due to wet stress. The timing of the rainfall is a significant determining factor. We observed that the highest reduction was associated with years with high rainfall amounts in May and June. This corresponds to the period with the highest susceptibility factor (0.28), as canola yield is most susceptible during the vegetative stage (Hassanpour et al., 2011). Wet stress was also observed in years with precipitation less than the average long-term average. These years have the highest predicted relative yield because they experienced no wet stress at the early developmental stage. Examples include 1987 (348.8 mm; 31.6% below average), 1988 (368 mm; 27% below average), 2002 (19.2% below average) etc. The simulation results also showed that the predicted relative yield was affected by factors such as the precipitation amount received during the late part of the previous year and rainfall duration. The antecedent water table depth and snowmelt and early spring rain in the incoming year would likely affect yield through wet stress and planting delay stress. We observed that years with total precipitation amounts > 50 mm in April had yield reduction. Therefore, with low drainage amounts for widely spaced drains, yield reduction is likely to happen mainly because of excess water, a shift in planting date, and non-workable conditions.

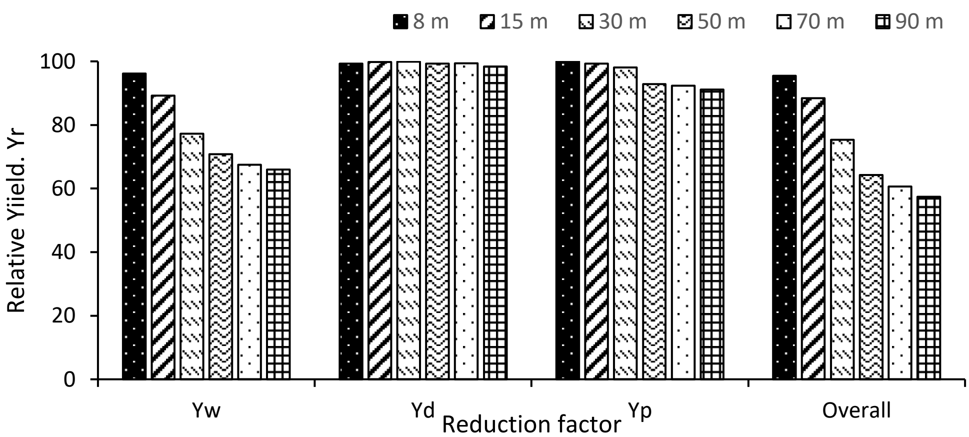


Figure 4.8: Yield reduction factors caused by wet stress (Yw), dry dress (Yd), and planting delay (Yd) under different spacing.

Overall, as drain spacing increased, SEW-30 (sum of excess water within the 30 cm rootzone) and planting delay increased while the predicted relative yield and workdays decreased (Table

4.6). The average predicted relative canola yields were 95.5, 88.4, 75.4, 64.2, 60.6, and 57.4% for 8, 15, 30, 50, 70, and 90 m drain spacing.

Table 4.6: Relationship between predicted relative yield and objective functions under different spacing

Drain spacing (m)	SEW-30 cm-days	Workdays	Planting delay (years)*	Predicted relative Yield
8	60.2	101.5	1 (1)	95.5
15	174.3	89.3	2 (11)	88.4
30	356.9	73.1	4 (15)	75.4
50	450.3	64.6	9 (23.9)	64.2
70	503.6	61.3	9 (25.6)	60.6
90	529.8	60.7	10 (26.3)	57.4

* Planting delay in years is the number of years out of the 25 simulated years with planting delay, while the value in bracket represents average planting delay (days)

Based on figure 4.9, to achieve at least 80% of its potential yield regardless of the precipitation amount, drains should be closely spaced, at most 15 m apart for the heavy clay soil in Arborg, Manitoba. The results of this study agree with some field and simulation studies (Acharya et al. 2019, Hashemi et al. 2020, Singh and Nelson 2021). Scherer et al. (2015) recommended close spacing for finer soils such as clay. In a field study in North Dakota, Acharya et al. (2019) reported that narrow spacing resulted in the highest crop yield and residual soil nitrate in silty clay loam soil. Hashemi et al. (2020) reported that drain spacing greater than 40 m with heavy clay soil resulted in reduced drainage, increased surface runoff, and potential for runoff. However, close drain spacing has economic and environmental concerns (Cordeiro and Sri Ranjan 2015, Asker et al. 2020).

Close drain spacings would result in increased costs arising from installation, labour, and materials. To this end, an economic analysis was conducted. From Figure 4.9, the 10 m drain spacing is the optimal spacing that would maximize the return on investment

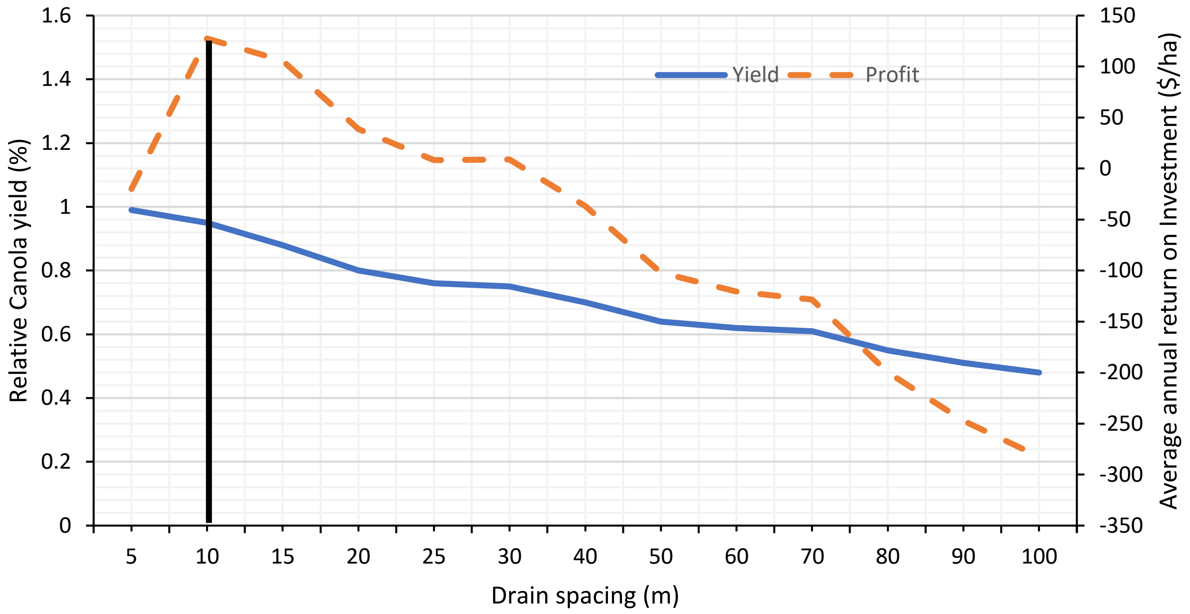


Figure 4.9: Effect of drain spacing on relative canola yield and average annual return on investment.

4.4 Conclusion

Subsurface drainage is essential for agricultural production, especially in poorly drained soils. In Manitoba, excess water from early spring and snowmelt is the leading cause of crop loss. Thus, producers in the area have embraced subsurface drainage, leading to a rapid increase of agricultural fields with drainage. However, drainage design parameters are location-specific because of the unique soil, climate, and management practices. Most drainage contractors install these drainage systems by adopting what is practiced somewhere else without considering these unique characteristics. To assess the performance of these systems using field studies is insufficient to evaluate the drainage systems under varying climate and management conditions. This has necessitated the use of hydrologic models together with field data to run the hydrologic model. In this study, the DRAINMOD model was first parameterized by simulating water table depth over two growing seasons under canola production. Both statistical and graphical results showed that the predicted water table depth was in close agreement with measured values. Thereafter, a 30-year simulation was conducted to determine the hydrology and evaluate the impacts of drainage spacing on canola yield. Water balance results showed that ET, Runoff, and Drainage peaked in July, April, and May, respectively. This provides a basis for water management for the region. The simulation results showed that drain spacing affects the predicted relative canola yield. Also, results show that maximum yields were achieved under closed spacing. Even though close spacings could increase cost, the economic analysis showed that the 10 m drain spacing would maximize the return on investment. This study underscores the need for site-specific drainage design variables to maximize yield, increase profitability and ensure environmental sustainability.

Chapter Five

Assessment of the potential impacts of climate change on the hydrology and canola yield using the DRAINMOD model

Abstract

Climate change is a major concern for agricultural production regions like the Canadian Prairies. The Canadian Prairies accounts for most of Canada's grain and oil crop. Therefore, understanding the hydrologic and crop yield response to climate change is important for adaptation and mitigation. Downscaled climate model projections from CANESM2 for historical (1981-2010), midcentury (2041-2070), and late-century (2071-2100) periods under three representative concentration pathways (RCP2.6, RCP4.5, and RCP 8.5) were used as climate inputs to drive a parameterized DRAINMOD model. The model was parameterized using measured water table depth from two canola growing seasons (2019 and 2020) in Arborg, Manitoba, Canada. The projected changes in the climatic variables showed that even though the mean annual precipitation is projected to increase, rainfall is expected to decrease, and temperature increase during the growing season. DRAINMOD simulation results suggest that during the midcentury, subsurface drainage outflow is expected to decrease by 11, 17, and 15% for RCP2.6, RCP4.5, and RCP8.5, respectively. During the late century, similar flow reductions were observed under the same climate scenarios. On the other hand, ET and surface runoff are expected to increase under all climate scenarios except for runoff during the late century under RCP 8.5. Furthermore, results showed that the relative canola yield would decrease due to drought stress caused by temperature rise and reduced rainfall during the growing season. Simulation results showed that yield reduction due to excess water would be lower in the future while it would be higher due to drought stress. Even though controlled drainage can decrease the drainage outflow from subsurface drainage in the future, comparable canola yield did not improve due to drought stress during the growing season. The presence of heavy clay with low hydraulic conductivity could limit water movement, thereby minimizing the impact of CD on crop yield. Tile drainage could be used to drain the water, to facilitate field operations before planting, and this water could be stored for subsequent use to overcome the anticipated drought stress during the growing season. The results presented in this study represent a wide range of options for water managers and producers to develop strategies that would mitigate projected heat and drought stress in the future.

Keywords: DRAINMOD modelling, canola yield, climate change, subsurface drainage

5.1 Introduction

Climate change is arguably the most significant environmental challenge in the twenty-first century, as it affects almost all the facets of life, including health, agriculture, infrastructure, social, economic etc. (Rosenzweig and Parry 1994, Lal 2005, Kang et al. 2009, Romero-Lankao et al. 2014, IPCC 2013). Observations worldwide provide undeniable evidence that the global climate has changed and will continue to change (Romero-Lankao et al. 2014, Qian et al. 2016, Qiu et al. 2020). In recent times, extreme hydrologic events (droughts, flooding, wildfires etc.) have increased, and new temperature records are set for many locations, including Canada. Changes in climatic variables are a significant threat to food security, livestock management and production and water resources (Rosenzweig and Parry 1994, Lal 2005). Greenhouse gases (GHG) are the leading cause of climate change (IPCC 2013). Studies have shown that increasing GHG concentration will further lead to increased warming and long-term changes in climatic variables (IPCC 2013, Almazroul et al. 2021). Temperature and precipitation are the major indices used in climate change studies (Almazroul et al. 2021). Changes in these climatic variables can alter the water cycle (Hanke 2018, Jalota et al. 2018, Modi et al. 2021).

Water resources and climate are closely interlinked. Therefore, projected changes in climate variables such as temperature, precipitation, and CO_2 concentration have far-reaching consequences on crop growth, productivity, and the hydrologic variables. Even though climate change is global, the impacts and severity vary by location (Abd-Elaty et al., 2019). The location of Canada in the northern hemisphere has predisposed it to more serious negative impacts even though there are also potential benefits (Qian et al. 2019). The Canadian Prairies are vulnerable to climate change events such as droughts, prolonged dryness, and intense soil moisture deficits (Bonsal et al. 2019). This may be because crop production, especially canola, depends solely on rainfall (Qian et al. 2019). Canada is the world's largest producer and exporter of canola (CCC, 2021). The Canadian prairies account for more than 98% of the total production (CCC, 2021). A recent economic report shows that canola contributes $29.9 billion annually to the economy, 207,000 jobs and $12 billion in wages (LMC International 2020). Excess water from snowmelt or prolonged dryness hinders optimum crop production in the Canadian Prairies. Understanding the projected changes in climatic variables, mainly temperature and precipitation, is vital for developing effective water management strategies and sustained crop production.

Field experimentation and hydrologic modelling are complementary tools that provide guidelines and effective water management strategies to cope with predicted climate change impacts (Qian et al. 2019, Kurki-Fox et al. 2019, Qiu et al. 2020, Sojka et al. 2020, Adhikari et al. 2020). Future climate data are usually obtained from global circulation models (GCMs), advanced tools for reliable future climate data. However, GCMs cannot be directly run with hydrologic models because of their coarse resolution (>250km). Scientists have developed different downscaling or bias correction methods to overcome this challenge (Wilby and Wigley 1997), after which they are used as inputs in a hydrologic model. Commonly used models for climate change assessment include DRAINMOD (Awad et al. 2021), SWAT (Wagena and Easton 2018), RZWQM2 (Jiang et al. 2020), HYDRUS (Haghnazari et al. 2020), etc.

There are numerous studies on future climate change impacts on water resources (Barnett et al. 2004, Schilling et al. 2020). In Canada, a lot of these impact studies have focused on crop yield, biomass, greenhouse gases emissions, and permafrost degradation (Zhang et al. 2008, Wang et al. 2012, Smith et al. 2013, He et al. 2018, Qian et al. 2018, Qian et al. 2019, Jiang et al. 2020). The predicted impacts vary from one location to another due to the uncertainties associated with the GCMs, models, and other local factors such as soil types, climate, crop, and management (Qian et al. 2016). For example, Qian et al. (2019) reported that canola yield would increase in the future using three different crop models even as temperature increases. On the other hand, Qian et al. (2018) reported a 21-42% decrease in yield in the Canadian Prairies using the CSM-CROPGRO-Canola model. This justifies the need to assess climate change impacts using robust agricultural models. Smith et al. (2013) applied the DNDC model to simulate wheat yield and nitrous oxide emissions in western Canada. They reported that climate change would increase crop yield and GHG emissions. In Iowa and Quebec, Wang et al. (2015) and Jiang et al. (2020) simulation results using the RZWQM2 model indicated that climate change would increase drainage outflow, nitrate loss and soybean yield, while corn yield would decrease. Using the integrated farm system model, Cordeiro et al. (2019) reported increased forage and biomass production due to climate change in Newfoundland. Using the SWAT model under projected climate change scenarios, Wagena and Easton (2018) reported that tile drainage would be environmentally beneficial by decreasing surface runoff, sediment export and dissolved and total phosphorus. Climate change studies do not precisely predict climate change impacts. Instead, they provide possible potential impacts from which decisions, management, adaptation, and mitigation can be developed (Gunn et al. 2018, Qiu et al. 2020, Pease et al. 2017, Wagena and Easton 2018, Sojka et al. 2020, Adhikari et al. 2020).

The DRAINMOD model is a comprehensive water management system with successful applications in simulating water table depth, drainage flow, nitrates concentration, runoff, and crop yield (Cordeiro and Sri Ranjan 2015, Satchithanantham and Sri Ranjan 2015, Ndulue and Sri Ranjan 2022). Most climate change studies using the DRAINMOD model were conducted in the U.S. (Singh et al. 2009, Pease et al. 2017, Kurki-Fox et al. 2019, Vepraskas et al. 2020, Adhikari et al. 2020), humid regions in Canada (Dayyani et al. 2012, Golmohammadi et al. 2016, Golmohammadi 2021), China (Awad et al. 2021), Poland (Sojka et al. 2020). Although some studies have examined climate change impacts on crop yield and nitrous emission in the Canadian Prairies (Wang et al. 2012, Smith et al. 2013, Qian et al. 2018, Qian et al. 2019), there are limited studies focused on climate change impacts on water management using DRAINMOD.

Understanding projected climate change impacts in the Canadian Prairies and assessing different water management strategies cannot be overemphasized. Therefore, the overall objective of this study is to use a parameterized DRAINMOD model to determine how climate change may affect the hydrology of an agricultural field and how that impacts canola yield. The specific objectives are to (i) characterize future climate in an agricultural field in Arborg, Manitoba, in the twenty-first century under different climate scenarios (ii). determine the potential impact of climate change on the hydrologic variables (subsurface drainage, surface runoff, evapotranspiration, water table depth), and crop yield (iii) suggest management practices to adapt to and mitigate climate change.

5.2 Methodology

5.2.1 Site description

Field data was collected from the PESAI (Prairies East Sustainable Agriculture Initiative) experimental research site in Arborg, Manitoba (Latitude 50.904, Longitude -97.273, Elevation 229 m). The site is in the Interlake region of Manitoba, which is bounded on the south, east and west by Winnipeg, Lake Winnipeg, and Lake Manitoba, respectively. The region is in the Icelandic River drainage basin with a boreal plain ecozone (Kean 1998). The climate is a dry subhumid, cool continental climate. The non-growing season usually starts around October and lasts until March, with temperatures remaining below freezing point. Snowmelt and soil thawing begins in late March and early April when soil temperature rises (> 0 ^oC). The long-term mean temperature ranges from -18.3 ^oC in January to 18.6 ^oC in July (Environment Canada 2021). The long-term annual precipitation is 499.4 mm, with rainfall and snowfall accounting for about 81 and 19%, respectively (Environment Canada 2021). The long-term data show that the average monthly rainfall begins to rise in April, peaks in June, and gradually decreases in September when snowfall begins. The average snowfall is highest in the winter, reaching its highest value between November and January. During the 2019 and 2020 study periods, the observed rainfall during the growing season was 26.6 and 42.6% less than the long-term average. Still, the observed temperature was like the long-term average (Ndulue and Sri Ranjan 2022). Depending on the crop, planting usually starts in May, and the growing season extends to September. Since the dominant soil type is heavy clay, topography, and climatic condition, waterlogging and drainage are major water management issues hindering trafficability and crop production. The predominant soil type is heavy clay with low permeability, high water table depth and peat content. The soil in the area belongs to the Fyala series, which consists of poorly drained Rego Humic Gleyol soil that developed on weakly to moderately calcareous, lacustrine clay deposits (Podolsky, 1982).

5.2.2 Experimental layout

The complete detail of the experimental layout is reported in (Ndulue and Sri Ranjan 2022). A summary is presented herein. Three drainage treatments replicated thrice were applied on the experimental site: three drained plots with different drain spacings of 4.57 m (15 ft), 9.14 m (30 ft), 13.72 m (45 ft), and control plots with no drainage. All the drained plots have drain tiles installed between 0.9 and 1.1m below the soil surface, at a slope of 0.01%, in the North-South direction of the field. The tiles are connected to a collector drain that discharges to a drainage control structure at the edge of the field. Piezometers were installed on the centre of each plot to measure water table depth using water level sensors every 3 hours (Solinst Levelogger Junior 3001, Solinst, Canada, Ltd., Georgetown, Ontario, Canada).

The site is a 5-ha field comprising wheat, canola, and soybean in rotation, with land preparation and tillage usually done in the fall after harvest. Throughout the study period, planting and harvesting followed the same sequence: wheat first, followed by canola, and then soybean. Fertilizers, including N and P, were added based on the initial soil test. Herbicides, fungicides and desiccants were applied following standard management procedures for growing the crops in the area.

5.2.3 Climate projections

Daily climate model projections were downloaded from the pacific climate impact consortium (PCIC) website (https://data.pacificclimate.org/portal/downscaled_gcms/map/). The PCIC database provides statistically downscaled climate data across Canada from 1950 to 2100 via an interactive web interface. It uses the BCCAQ method for downscaling coarse GCMs from low resolution to fine-scale resolution. The BCCAQ is a hybrid method that combines two downscaling methods: BCCA and QDM. The BCCA uses a spatial aggregation from a linear combination of historical analogues for daily scale fields. In contrast, QDM uses quantile mapping to preserve relative changes in GCMs quantiles to avoid inflationary effects. The robustness and performance of BCCAQ have been verified by (Werner and Cannon 2015). The BCCAQ method performed better than other downscaling methods; thus, it was recommended for hydrologic modelling impact studies (Werner and Cannon 2015). In this study, the updated method, BCCAQV2, was used to obtain climate data for the baseline (1981-2010), midcentury (2041-2070) and late century (2071-2100) under three emission scenarios called Representative Concentration Pathways (RCP 2.6, RCP 4.5, and RCP 8.5). The RCPs represent the net radiative forcing (W/m^2) expected by the end of the twenty-first century. Therefore RCP 2.6, RCP 4.5, and RCP 8.5 represent net radiative forcing of 2.6 W/m^2, 4.5 W/m^2, and 8.6 W/m^2, respectively, are low, medium, and high baseline scenarios (Van Vuuren et al. 2011).

The downscaled GCM used in this study, CANESM2, is one of the GCMs hosted by the Coupled Model Intercomparison Project Phase (CMIP5) (Taylor et al. 2012). It has a spatial resolution $1/12^o$ and has been used for many climate change studies in North America (Cordeiro et al. 2019). It was selected based on the ordering of Giorgi and Francisco (2000) as recommended by (https://pacificclimate.org/data/statistically-downscaled-climate-scenarios). CANESM2 outputs, maximum temperature, minimum temperature, and precipitation were used as climate inputs to run the DRAINMOD model. Daily precipitation data was disaggregated on hourly time steps using the inbuilt disaggregation tool in the model.

5.2.4 DRAINMOD MODEL

DRAINMOD is a versatile, process-based, field-scale, hydrologic model developed to evaluate the impacts of different water management systems in poorly drained agricultural fields (Skaggs 1978). The model simulates hydrologic variables, including surface runoff, sub-surface drainage, evaporation, infiltration, water table depth, and crop yield on a daily, monthly, and yearly time scale. The model has undergone tremendous improvements over the years to include many processes such as soil nitrogen and salinity dynamics, freeze-thaw, Phosphorus fate and transport etc.

5.2.4.1 Model setup, inputs, and parameterization

DRAINMOD was parameterized using a 2-year water table depth measured at the study site. Soil-derived properties, including soil water characteristics curve, WTD vs upward flux etc., were derived from the soil properties using the ROSETTA model. Crop properties, including rooting depth over the growing season, were obtained from the literature. Drainage design parameters, including drain depth and spacing, were based on site design. Calibration was done by manually changing soil hydraulic parameters, E.T. correction factors, and snow coefficient. Final calibrated values are reported in (Ndulue and Sri Ranjan 2022). The model performed satisfactorily based on the graphical and statistical analysis of observed and simulated water table depth. The simulated daily water table depths closely matched the observed with an R^2 ranging from 0.55 to 0.93 (Table 5.1). Also, error indices, including MAE, and MBE, were within the recommended acceptable range (Skaggs et al. 2012).

Table 5.1: Summary of statistical indices used to assess the DRAINMOD model (Adapted from Ndulue and Sri Ranjan 2022)

	R^2	RMSE (cm)	MBE (cm)	MAE (cm)
2019	0.553	8.772	-6.625	7.301
2020	0.896	9.712	3.698	-6.259
Overall	0.927	9.838	0.135	7.056

The above table showed that the DRAINMOD model performed well in simulating the ground water hydrology of the study area. Consequently, the parameterized model was used to evaluate how climate change could affect field hydrology and canola yield under future climate scenarios. It is assumed that the parameterized model outputs are representative of the study area given the excellent model performance.

5.2.5 DRAINMOD simulations for climate change assessment

Each climate variable from the baseline and future period were compared on annual, monthly and seasonal periods to determine the relative changes in the variable. The parametrized

DRAINMOD model parameters were kept unchanged to assess climate change impacts. At the same time, it was driven by baseline and future climate scenarios under two water management scenarios: free drainage and controlled drainage. Eighteen scenarios were generated (3 RCPs, three-time periods, and two water management strategies). In DRAINMOD, the difference between free drainage and controlled drainage is the consideration of the weir settings. The controlled drainage is simulated by considering the outlet conditions (gate elevation, storage capacity in the outlet ditch, drainage flux etc.). This study sets the weir to 0.6 m during the growing season (May 15-August 30). The weir height is set to the drain depth during planting and harvest to allow trafficable conditions. After harvest and nongrowing periods, the weir is raised to 0.3 m below the ground surface to reduce drainage outflow. The result from each scenario was compared with the baseline and expressed as a percent increase or decrease.

Also, the t-test was used to analyze the mean ET, runoff, and subsurface drainage between free drainage and controlled drainage. ANOVA test with Tukey procedure at a 5% ($p<0.05$) significance level was used to assess the relative yield difference between the baseline, midcentury, and end of the century periods. All statistical analyses were done in JMP software (Version 16, SAS Institute, Inc, Cary, N.C).

5.3 Results and Discussions

5.3.1 Projected changes in climatic variables

Table 5.2 summarizes the projected changes in maximum temperature, minimum temperature, and precipitation in the 21st century (2041-2100) relative to the baseline climate (1981-2010). Figure 5.1 shows the long-term seasonal climatic changes for baseline and predicted periods. The mean annual results show a general increase in precipitation and temperature in the region under all future scenarios. Temperature is projected to be warmer in the future under all climate scenarios. During the midcentury, the average annual temperature is predicted to rise by 2.2, 3.2 and 6.9 ^{o}C under RCP 2.6, RCP 4.5, and RCP 8.5 scenarios, respectively, relative to the baseline. By the end of the century, the average mean temperature is projected to increase by 2.5, 4.2, and 6.9 ^{o}C for the same scenarios. Monthly analysis showed a significant increase in average temperature, especially during spring (March and April) and Winter (November and December). Also, the temperature rise intensified during the late century and high scenario (RCP 8.5). Generally, for each RCPs, the projected increase in temperature intensified toward the end of the 21st century.

Table 5.2: Projected changes in the annual climatic variables

Periods	T_{max}	T_{min}	T_{avg}	PCP (%)
R2.6-2041-2070	2.20	2.23	2.21	9.98
R2.6-2071-2100	2.41	2.52	2.47	8.19
R4.5-2041-2070	3.16	3.32	3.24	5.63
R4.5-2071-2100	4.08	4.23	4.16	8.89
R8.5-2041-2070	3.63	3.90	3.77	9.34
R8.5-2071-2100	6.63	7.11	6.87	9.34

*Tmax, Tmin, Tavg, PCP are maximum, minimum, and mean temperature and precipitation, respectively

Similarly, there was also a general increase in annual precipitation between the different scenarios and periods. During the midcentury, the average annual precipitation increased by 9.8, 5.63, and 9.3% relative to the baseline period under RCP2.6, RCP4.5, and RCP8.5, respectively. Yearly average precipitation would increase by the end of the century (2071-2100) by 8.2, 8.9, and 9.34% for the same scenarios, respectively. Rainfall inter-seasonal variation may have been masked using the annual values. Monthly and seasonal analysis showed that the highest increase in precipitation is expected during spring, followed by fall and winter. On the other hand, the results indicated that precipitation is predicted to decrease in the summer, ranging from 0.2 to 13.3% for all the climate scenarios except during the midcentury under RCP2.6, with a 6.3% increase. However, precipitation is projected to increase more in the nongrowing season ranging from 12.4 to 29.5% for all climate scenarios, than in the growing season, ranging from 0.54-8.7%, except during the late century under RCP 4.5 and RCP 8.5.

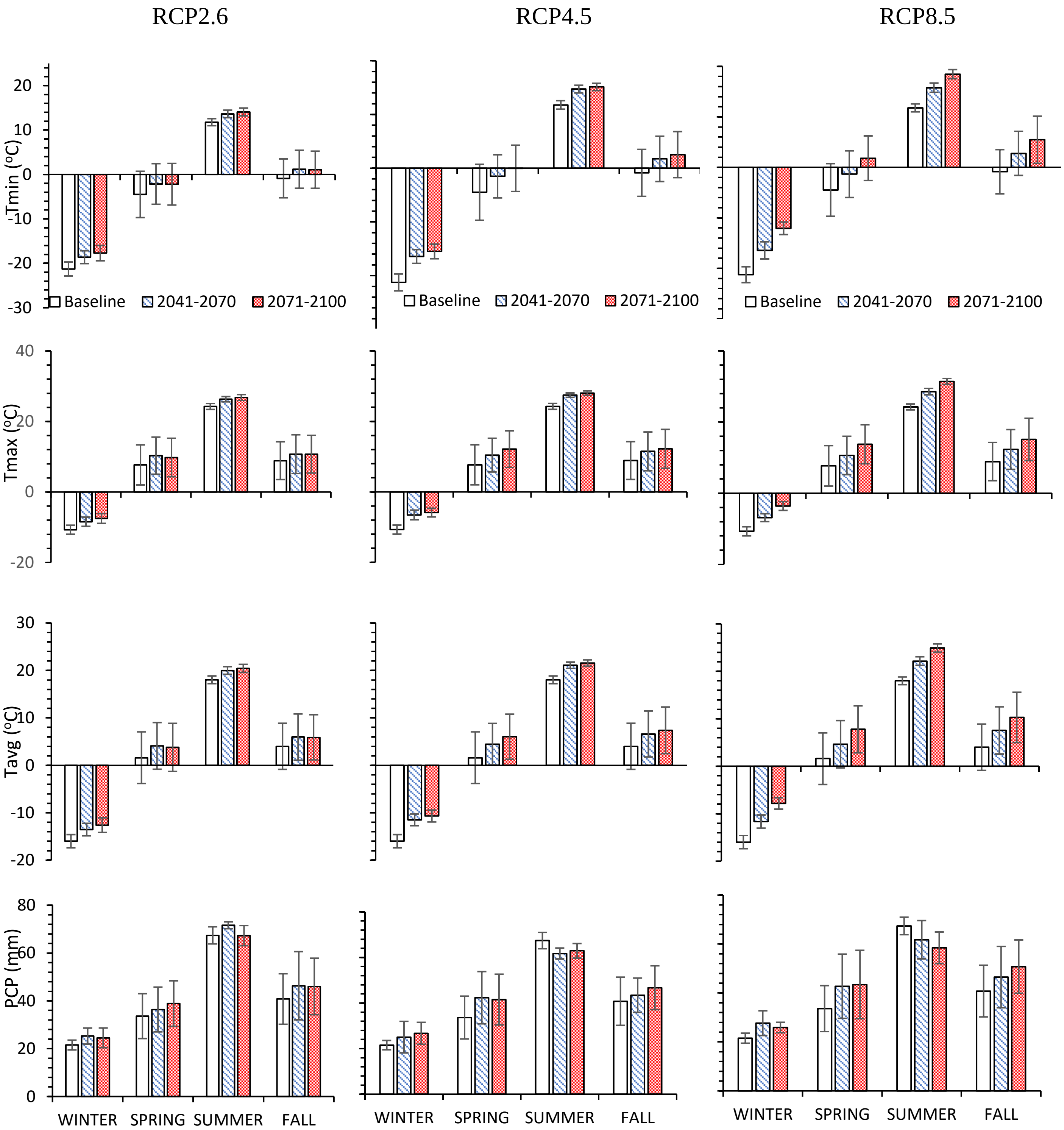


Figure 5.1: Seasonal distribution of minimum temperature (T_{min}), maximum temperature (T_{max}), average temperature (T_{avg}), and precipitation (PCP) for baseline, midcentury (2041-2070), and end of the century (2071-2100) periods under three climate scenarios (RCP 2.6, RCP 4.5, and RCP8.5). The standard error represents uncertainty in the data

Overall, the projected changes in precipitation and temperature indicate a potential warmer climate and drought conditions in the growing season. The results of this study are comparable to other research in the Canadian Prairies (Vincent et al. 2018, Bush and Lemmen 2019, Zhang et al. 2019, Chipanshi et al. 2021). For example, the annual mean temperature for the study area is projected to rise between 4-8.2 ^{o}C and precipitation 7-10% between 2021-2100 under a high scenario (http://climatedata.ca).

5.3.2 Projected changes in the hydrology under free drainage and controlled drainage

5.3.2.1 Subsurface drainage

DRAINMOD simulations (Table 5.3) showed that the average annual subsurface drainage is predicted to decrease in the future compared to the baseline period, even though the decrease is not statistically different from the free drainage system. The mean annual subsurface drainage during the midcentury is predicted to decrease by 11.1, 17.2, and 15.2% under RCP2.6, RCP4.5, and RCP8.5, respectively. Subsurface drainage will decrease by 19.2, 13.1, and 11% for the same scenarios by the end of the century.

During the baseline period, more than 51% of subsurface drainage was accounted for during the growing season, while the remainder occurred during the nongrowing season. However, the reverse was observed for all climate scenarios in the future. Seasonal analysis showed that the increase in subsurface drainage during the nongrowing seasons would come from the winter period during the late century under RCP2.6, RCP4.5, and RCP8.5, spring period midcentury for RCP4.5 and RCP 8.5 and late century RCP 4.5. Across all the future climate scenarios and baseline periods, subsurface drainage was highest during the spring and lowest during winter except during the late century under RCP8.5. This is due to temperatures falling below the freezing point during the winter. Randall and Goss (2011) reported that freezing reduces subsurface drainage during winter, especially in seasonally frozen soils. Changes and temperature rises could be the main factor driving subsurface drainage during the spring. This could lead to waterlogging and delay in planting as farm equipment will not be able to access and work in the field due to decreased soil trafficability. The results of this study agree with Pease et al. (2017) but disagree with Hanke (2018), Dayanni et al. (2012) and Singh et al. (2009). They reported that predicted temperature rise resulted in increased subsurface drainage during the winter. The results may be due to differences in climate projections and models used in the study area.

DRAINMOD simulations under controlled drainage showed a significant difference between future climate scenarios and the baseline period. Also, there were further reductions in subsurface drainage in the future compared with the free drainage systems. Results showed that subsurface drainage differed significantly from the baseline period, ranging from 21 to 29.6%. The effect of controlled drainage was more evident during May-September. The reduction in subsurface drainage during the growing season is more significant than during the nongrowing season, unlike the free drainage system. As an important water management strategy, this confers a considerable advantage over free drainage by reducing flow and nutrient loss through the drains under future climatic conditions. Cordeiro et al (2014) and Satchithanantham et al. (2014) reported a significant reduction in nutrient export from fields under controlled drainage compared to free drainage during the spring snowmelt period. However, the need for access to the field for land preparation during the spring may not be conducive to operating the drainage control structures to hold the water back in the field. One way to overcome this limitation is to pump the water out of the drainage control structures into off-farm water storage reservoirs. This stored water could subsequently be used for irrigation to alleviate the drought stress during the growing season under projected climate scenarios.

5.3.2.2 Runoff

Simulation results show that the average annual runoff is predicted to rise under free drainage for all climate scenarios except during the late century for RCP8.5 (Table 3). The increase ranged from 1.2% during the late century for RCP 4.5 to 24.1% during the late century for RCP 2.6. Runoff losses during the nongrowing season were more than the growing season for both the baseline and future periods, with the highest occurring during spring and constituting about 75-84%. Spring is the transition period between the nongrowing and growing season and is usually marked by high snowmelt and soil thawing processes. With a projected increase in rainfall, more runoff loss is expected. Pagán et al. (2016) stated that climate change is worsened in water-stressed regions where runoff is dominated by snowmelt. The increase in rainfall could result in a decrease in infiltration and an increase in runoff. Since rainfall in the region is characterized by high intensity and short duration (Satchithanantham and Sri Ranjan 2015), more runoff is expected. Also, the increase in rainfall during winter and spring alongside a rise in temperature across the seasons, especially winter and spring, would result in less snow accumulation and more runoff.

Nevertheless, surface runoff is predicted to decrease during the growing season and increase during the nongrowing season compared with the baseline period. This is due to the decreased rainfall in the summer period. Also, runoff during the winter is expected to increase due to the projected temperature rise relative to the baseline period.

As expected, runoff loss was more under controlled drainage (CD) than free drainage (FD), ranging from 8 to 24%. Generally, CD decreases subsurface drainage and increases soil water storage, leading to high water table and runoff potentials. One of the trade-offs associated with controlled drainage is the increase in surface runoff. This could be a potential pathway for nutrient loss in the subsurface drained field (King et al. 2015). According to Hanke (2018), more than ten times the total phosphorus loss would occur via surface runoff with controlled drainage in a simulated study in Ontario. They concluded that controlled drainage would result in increased water quality problems now and in the future.

Table 5.3: Summary of DRAINMOD hydrologic simulation

		Free Drainage (FD)							Controlled Drainage (CD)						
Hydrologic parameter	Periods	Annual average	GS	NGS	Winter	Spring	Summer	Fall	Annual average	GS	NGS	Winter	Spring	Summer	Fall
Drainage (mm)	Baseline (1981-2010)	99	51	48	6	58	20	15	71	34	37	3	45	5	18
	RCP2.6-2041-2070	88	41	47	5	50	18	15	56	23	33	3	35	4	14
	RCP2.6-2071-2100	80	36	44	7	48	14	11	50	22	28	3	34	2	11
	RCP4.5-2041-2070	82	39	43	5	62	11	4	55	24	31	4	47	1	3
	RCP4.5-2071-2100	86	34	52	6	61	11	8	52	18	34	4	44	2	6
	RCP8.5-2041-2070	84	39	45	6	60	11	7	52	22	30	4	45	2	5
	RCP8.5-2071-2100	88	26	62	14	56	5	13	57	17	40	9	38	1	11
Runoff (mm)	Baseline (1981-2010)	83	31	52	0	68	11	4	106	39	67	0	87	13	6
	RCP2.6-2041-2070	98	25	73	4	82	9	3	122	36	86	4	100	13	5
	RCP2.6-2071-2100	103	25	78	7	82	7	7	123	32	91	7	101	8	7
	RCP4.5-2041-2070	88	25	63	2	77	6	3	108	34	74	3	94	7	4
	RCP4.5-2071-2100	84	19	65	6	68	8	2	105	26	79	7	87	9	2
	RCP8.5-2041-2070	98	26	72	3	83	9	3	119	35	84	3	103	10	3
	RCP8.5-2071-2100	72	15	57	10	54	2	6	90	22	68	11	71	2	6
Evapotranspiration (mm)	Baseline (1981-2010)	306	287	19	0	27	240	39	310	290	20	0	27	241	42
	RCP2.6-2041-2070	348	322	26	0	39	269	40	358	332	26	0	39	273	46
	RCP2.6-2071-2100	342	318	24	0	37	268	37	354	331	23	0	37	275	42
	RCP4.5-2041-2070	345	320	25	0	38	275	32	355	330	25	0	38	279	38
	RCP4.5-2071-2100	362	327	35	0	50	272	40	375	339	36	0	50	279	46

	RCP8.5-2041-2070	351	318	33	0	43	264	44	363	331	32	0	43	271	49
	RCP8.5-2071-2100	377	328	49	1	67	272	37	388	339	49	1	68	277	42
Water table depth (cm)	Baseline (1981-2010)	107	106	107	116	76	113	122	93	94	92	100	61	103	106
	RCP2.6-2041-2070	111	120	104	112	76	124	130	100	108	94	102	62	115	120
	RCP2.6-2071-2100	117	126	110	116	80	133	138	105	115	99	105	64	124	129
	RCP4.5-2041-2070	125	130	121	130	71	138	160	118	122	116	126	62	132	154
	RCP4.5-2071-2100	120	130	113	123	69	137	150	109	119	102	113	53	129	142
	RCP8.5-2041-2070	121	132	113	118	73	143	149	111	122	104	109	59	136	142
	RCP8.5-2071-2100	118	141	103	108	68	152	146	111	133	95	102	53	146	145

FD: Free drainage, CD: Controlled drainage; GS: growing season (May-September); NGS: Nongrowing season (October-April); Winter (December-February), Spring (March-May), Summer (June-August); Fall (September-November)

5.3.2.3 Evapotranspiration (ET)

The ET is an important component and a significant driver of the energy balance and water cycle in agricultural fields. In this study, ET accounts for more than 90% of the rainfall lost to the atmosphere during the growing season. ET is highest in the summer (May-September), followed by fall and spring, with negligible amounts during the winter. Results showed that the mean annual ETs from the climate scenarios were significantly different ($p<0.0001$) from the baseline period, with increases ranging from 42.3 to 49.7%.

Similarly, water loss by ET is higher when compared with the free drainage system, even though the difference was not significant. This is expected because CD generally decreases subsurface drainage while increasing ET and surface runoff, as confirmed in simulation and field studies (Skaggs et al. 2010). The simulation results show that controlled drainage reduced subsurface drainage and outflow under the different climate scenarios by 21-29% and 3-15%, respectively, due to a 1.8-15% increase in surface runoff. The projected rise in temperature is the major cause of water loss, mainly through soil evaporation and plant transpiration under both free drainage and controlled drainage. Previous studies in the same area have shown that temperature has a strong positive correlation with ET (Martel et al. 2018, Ndulue and Sri Ranjan 2021). As temperature rises, the radiative energy required to evaporate water increases, resulting in prolonged drought conditions.

5.3.2.4 Water table depth (WTD)

The mean WTD during the baseline period is within the drain installation depth. Simulation results indicate that water depth is predicted to be slightly deeper ranging from 110 to 124.8 cm, and deeper during the growing season, from 120 to 140.6 cm during the 21st century. The springtime happens to have the shallowest WTD for all the future climate scenarios and the baseline period. This is due to snowmelt happening around this period. A rise in temperature during the springtime, as predicted, could have also contributed to shallow water depth relative to the baseline period. During the summer period, all climate scenarios had water tables deeper than the baseline in the future. The result agrees with Kurki-Fox et al. (2019), who found out that climate change will cause the water table to fall. Under CD, the mean WTD was shallower in relation to the free drainage. With the low hydraulic conductivity of the heavy clay in the study area, capillary flux may be minimal even though the water table is within the drain depth. The WTD changes under CD during the season were similar but differed in magnitude (Table 3) to that observed under free drainage.

5.3.3 Projected changes in relative yield of canola

Relative to the baseline period, the canola yield showed a decreasing trend with time for all the RCPs. The mean annual relative yields during the midcentury and late century were significantly lower than the baseline under RCP8.5 for both FD and CD (Table 5.4). The DRAINMOD model computes crop yield by considering stressors due to excess water, drought, and planting delays. Analysis of the stressors shows that relative yield due to planting delay gave mixed results under different climate scenarios and water management systems. However, relative yield due to wet stress will decrease in the future, while relative yield due to dry stress will increase. This is due to the marginal increase in average annual precipitation, reduced rainfall during the growing season (summer), and an overwhelming increase in temperature, especially during the growing season (June-August). Heat stress would lead to more water loss and drought conditions. The negative impacts of heat and drought on canola yield have been confirmed by numerous field studies (Angadi et al. 2000, Gan et al. 2004, Elferjani and Soolanayakanahally, 2018, Hammac et al. 2018, Wu et al. 2018). Angadi et al. (2000) and Gan et al. (2004) reported a maximum yield reduction of 53 and 77% under heat and drought stress conditions during the flowering stage, respectively. Elferjani and Soolanayakanahally, (2018) reported 89% reduction in seed yield due to drought and temperature stress. These studies agree with the predicted effects of high temperature and drought on canola yield using DRAINMOD.

Simulation results showed that during the midcentury under RCP 2.6, RCP 4.5 and RCP 8.5, relative yield due to wet stress was similar in magnitude under free drainage and controlled drainage. It was highest during the late century for all RCPs. Also, all climate scenarios showed that yield decrease was mainly caused by drought stress under free drainage and controlled drainage, and its impacts increased with increasing RCPs. This is confirmed in the DRY DAYS values, which indicate the number of days with deficit soil water conditions. During the late century for RCP 8.5, the number of dry days was more than ten times compared to the baseline period. Relative yield under controlled drainage was lower than free drainage for all the climate scenarios. This may be due to the number of WORKDAYS and SEW-30 (sum of excess water within the 30 cm rootzone) values (Table 5.4). The simulation results agree with other studies that reported low or no significant crop yield under water management systems that depend on capillary flow, such as controlled drainage and subirrigation. This is due to the low hydraulic conductivity of the soil, which declines rapidly as soil moisture decreases, resulting in reduced capillary flow from the water table to the plant roots (Skaggs 1978). Gunn et al. (2018) reported that the lower yield in field plots with clay was attributed to the lower soil hydraulic conductivity.

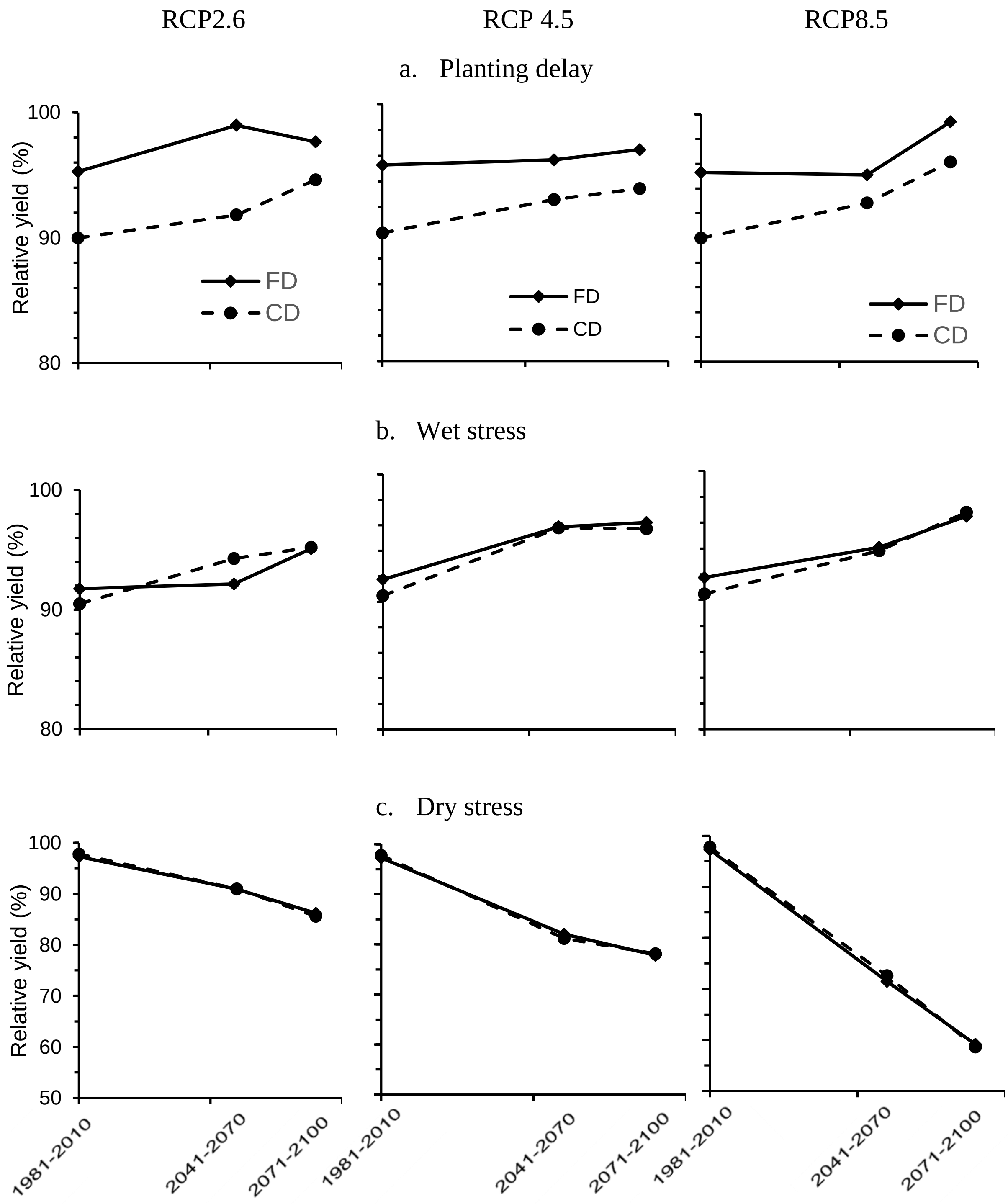


Figure 5.2: Relative yield due to different stressors (planting delay, wet stress and dry stress) as a function of time (baseline, mid-century, and late-century periods) under free drainage and controlled drainage under three climate scenarios (RCP2.6, RCP4.5, and RCP8.5)

Table 5.4: Canola yield, SEW_{30}, Dry days, and workdays under different climate scenarios and water management system

Climate scenario & Water Management	SEW-30 (cm-day)	Dry days	Workdays	Overall Relative Yield (%)*
FD-BASELINE	119.2	4.5	78.7	84.6 a
FD-RCP-2.6-2041-2070	113.4	13.0	91.4	82.6 a b
FD-RCP-2.6-2071-2100	77.9	19.1	95.6	79.7 a b
CD-BASELINE	130.7	4.6	68.3	79.2 a b
CD-RCP-2.6-2041-2070	84.8	11.8	80.1	78.1 a b
CD-RCP-2.6-2071-2100	85.3	17.3	84.7	76.8 a b c
FD-RCP-4.5-2041-2070	63.2	22.3	93.0	75.0 a b c d
FD-RCP-4.5-2071-2100	52.3	27.1	95.2	72.2 a b c d
CD-RCP-4.5-2041-2070	64.3	21.1	89.6	71.6 a b c d
CD-RCP-4.5-2071-2100	56.5	25.6	84.3	69.6 b c d e
FD-RCP-8.5-2041-2070	96.6	32.2	94.9	62.6 c d e f
CD-RCP-8.5-2041-2070	108.0	30.9	86.3	62.1 d e f
FD-RCP-8.5-2071-2100	53.6	45.1	99.7	56.7 e f
CD-RCP-8.5-2071-2100	49.2	44.1	88.1	54.5 f

*Different letters are significantly different based on Tukey's means separation at 5% significance level.

From the above simulation results, water managers and producers can develop strategies to deal with the predicted impacts of climate change. One of such strategies is to capture, store, and reuse the large quantity of drainage water from snowmelt usually loss before planting. This could reduce vulnerability to heat and drought stress and improve canola productivity. Studies have identified irrigation as an adaptive strategy to climate change (Zou et al. 2012, Kresovic et al. 2014, Chartzoulakis and Bertaki 2015, Kashyap and Agarwal 2020, Rosa et al. 2020, Thiery et al. 2020). Water saving techniques such as deficit irrigation or alternate wetting and drying can also be practiced. This would not only save water but also reduce GHG emission (Setyanto et al. 2018). Another strategy is to engage in management practices that would not only increase ground water storage but also retain residual soil water content such as mulching, cover crop, crop residue, and zero tillage. Other adaptive and mitigation practices to heat and drought stress include modification of planting dates, use of drought-resistant cultivars, improved breeding techniques (Wu et al. 2018, Raza et al. 2019), and reduction of activities that encourage GHG release.

5.4 Conclusion

Climate change is predicted to alter the hydrologic cycle and crop yield globally. The impacts and severity may vary from location to location. Understanding how these projected changes can affect hydrology and crop yield is important for developing climate change adaptation strategies using water management, especially in the Canadian Prairies because it is Canada's food basket. The DRAINMOD model was parameterized using the 2019 and 2020 water table data measured at the PESAI research site. Bias-corrected CANESM2 GCM participating in the CMIP5 under RCP 2.6, 4.5, and 8.5 were used to drive the DRAINMOD model. The projected changes in the climatic variables indicate that even though the mean annual precipitation is projected to increase, rainfall is expected to decrease during the growing season, and the climate becomes warmer.

DRAINMOD simulation results suggest that in the future, subsurface drainage is expected to decrease due to lower growing season precipitation. In contrast, ET and surface runoff are expected to increase under all climate scenarios except under RCP 8.5 for runoff during the late century. Also, simulation results indicate that the average canola yield is predicted to decrease by 2.5-32.9% due to drought stress caused by the rise in temperature and reduced growing season rainfall. The capture and storage of off-season drainage water in reservoirs for subsequent irrigation could be one strategy to mitigate increased growing season dry stress under all climate scenarios as an adaptation method to overcome the impact of climate change, as reported in this research. Both field and modelling studies have shown that drainage water recycling (DWR) has not only increased crop yield but improved water quality (Frankenberger et al. 2017, Kaur et al. 2021, Moursi et al. 2022). Even though DWR could reduce farm size and increase cost, Frankenberger at al. (2017) argued the long-term benefit in yield would offset the cost.

Chapter Six

Performance of the FAO Penman-Monteith Equation under limiting conditions and fourteen Reference Evapotranspiration Models in Southern Manitoba

Abstract

Evapotranspiration is a key component of water and energy balance. An accurate estimate of reference evapotranspiration (ET_o) is important for determining the water demand of field crops, water management, and hydrological modelling. The FAO-PM ET_o equation is the standard equation for estimating ET_o. Its use is limited by the requirement for too many observed inputs that are not readily available in most weather stations. Empirical models requiring readily available inputs have been developed as an alternative. However, their performance is location specific. Therefore, this study assesses the performance of the FAO-PM ET_o computed with limited data and fourteen empirical ET_o models. Meteorological data (2012-2019) was analyzed under the semi-arid climate conditions in southern Manitoba. Model performance was assessed using statistical indices, including R^2, RMSE, NSE, MPE, and MAE. Results showed that ET_o estimates under missing wind speed, relative humidity, or solar radiation were acceptable, although model performance decreased with increased missing data yielding average to poor performance. Based on R^2, RMSE, and NSE values, among the 14 models compared, the best performing models are Valiantzas-1, Valiantzas-3, Irmak, Valiantzas-2, and Priestly-Taylor model. New empirical coefficients were developed, requiring one or two climatic inputs to improve empirical models. Results showed that the calibrated models performed better than the original equation. The sensitivity analysis showed that ET_o is most sensitive to maximum temperature (T_{max}) and solar radiation (R_s), followed by vapour pressure deficit (VPD), wind speed (U_2), and minimum temperature (T_{min}). Therefore, it is recommended to ensure accurate measurements of temperature and solar radiation for accurate ET_o estimates. This study provides alternative ET_o models with lesser inputs, reasonable and accurate ET_o estimates for southern Manitoba and other areas with similar climate characteristics.

Keywords: Reference evapotranspiration, ET_o Models, Prairies, southern Manitoba.

6.1 Introduction

Water resources management is a global issue exacerbated by climate change, population explosion, and poor water management (Duran-Encalada et al. 2017). Efficient and sustainable water management in agriculture accurately determines the irrigation water requirements of crops. Efficient water management implies applying water only, when necessary, at the right quantity and time (Sharma and Irmak, 2012). An accurate estimate of evapotranspiration ensures optimal water use. Evapotranspiration (ET) is a combined evaporation and transpiration term, which describes water loss through the soil surface and stomatal openings in leaves. These processes co-occur, which makes it difficult to separate them (Allen et al. 1998). It is challenging to estimate because of the complex plant-soil interactions (Singh and Xu, 1997). After precipitation, ET is the most important component of the hydrological cycle (Alexandris et al. 2008). The determination of the crop evapotranspiration (ET_c) is usually preceded by calculating reference evapotranspiration (López-Urrea et al. 2006). The term "reference evapotranspiration (ET_o), as defined by Allen et al. (1998), refers to the evapotranspiration rate from a well-watered hypothetical grass surface of 0.12 m in crop height, an albedo of 0.23 and surface resistance of 70 m/s." The ETo is essential for determining irrigation water requirement of crops (Allen et al. 1998), irrigation scheduling, planning, and management (Sentelhas et al. 2010), ecological and climate change studies (Nistor et al. 2017), and hydrological modelling (Schneider et al. 2007).

There are two methods for determining ETo: direct and indirect. Direct methods are based on the principle of water balance and water vapour transfer. They include the use of lysimeter and eddy covariance methods (Shuttleworth, 2008). These methods are accurate and give better results than any other method, but they are usually expensive, time-consuming and requires skill and experience (Allen et al. 1998). The indirect method involves using meteorological data from a weather station or pan observation. They are usually empirical and or physically based equations relating ET_o to weather parameters. The FAO Penman-Monteith equation (FAO-PM) is the recommended standard equation for estimating ET_o because it correlates strongly with lysimeter data and provides consistent ET_o values in a wide range of locations and climates (Allen et al. 1998). Thus, it is widely adopted as the benchmark for evaluating other empirical ET_o models.

Despite its accuracy, robustness and global acceptance, the use of the FAO-PM method is limited because it requires many data inputs absent in most weather stations. For most regions, including Canada, most stations measure only temperature and precipitation (Maule et al. 2006). Under data-scarce conditions, Allen et al. (1998) provided alternative methods for estimating missing solar radiation, relative humidity, and wind speed. Most studies, including Jabloun and Sahli (2008), Djaman et al. (2018), and Koudahe et al. (2018), have reported good performance of the FAO-PM equation under limiting conditions. Similar results were also reported by Sentelhas et al. (2010) and C'ordova et al. (2015) except during missing solar radiation.

Empirical ET_o models with fewer climatic inputs have been developed as an alternative to the FAO-PM model. However, their performance is location specific. In southern Greece, with a semi-arid Mediterranean climate, Xystrakis & Matzarakis (2011) evaluated thirteen ET_o models. Their results showed that the Hanson and Turc models could serve as an alternative to the FAO-PM equation. Under the Sahelian climate in Senegal, Djaman et al. (2015) showed that Valiantzas, Trabert, Romanenko, Schendel, and Mahringer equations performed well compared to the FAO-PM equation. Tabari et al. (2013) evaluated the performance of thirty-one ET_o models under a humid climate in Iran. Their results showed that two developed radiation-based equations, Blaney–Criddle, modified Hargreaves (M4), and the Snyder pan evaporation-based equation, performed well compared to the FAO-PM equation. Likewise, the Turc equation ranked first above four other ET_o equations under a humid climate (Trajkovic and Kolavic 2009). Gao et al. (2017) reported that under different regions and climates, the Priestly Taylor, Hargreaves Samani, and Makkink equations were the best for arid, semi-arid, and humid climates respectively. Under humid continental climate, Sentelhas et al. (2010) found that simple ET_o models, after calibration, could serve as an alternative to the FAO-PM equation. In the Canadian Prairies, with semi-arid and sub-humid climates, Maulé et al. (2006) developed simple ET_o and compared it with the traditional Linacre and Baier-Robertson ET_o models. They reported that the Maule models gave accurate and precise ET_o estimates. Similarly, Martel et al. (2018) compared the performance of seven ET_o models against the FAO-PM equation in the Canadian Prairies. They reported that the Maule model ranked first and performed best while the Blaney-Criddle ranked worse.

With so many empirical ET_o models, there is no rule of thumb regarding the ET_o equations under various climate because of the mixed results obtained even under the same climatic conditions (Paparrizos et al. 2014) and also, lack of objective criteria in model selection (Singh and Xu 1997). Therefore, it becomes necessary to assess the performance of empirical ET_o models before their application in a location different from that for which it was initially developed. Although considerable studies have been carried out on empirical ET_o model comparison across the globe, including Canada, the global changes in climate (Azhar and Perera 2011, USGRP 2018), the lack of long-term data, and the diverse nature of the Canadian Prairies justify the need to continuously evaluate ET_o models especially ET_o models not yet evaluated and under limiting conditions. The

Canadian Prairies is vast, supporting various grain and oil crops such as wheat and canola in large quantities. For example, the Prairies contribute about 50% of Canada's grain (Bueckert and Clarke 2013) and also is the highest producer of canola in Canada (Statistics Canada, 2018). From a detailed literature search, there is no information on the performance of recently developed models like the Valiantzas ET_o models in Canada. Thus, the objectives of this study were to (i) assess the performance of FAO-PM under missing data conditions. (ii) analyze the performance of fourteen empirical ETo models relative to the FAO-PM equation, (iii) calibrate and develop new empirical constants, and (iv) determine the most sensitive climate variables influencing ET_o in southern Manitoba.

6.2 Materials and Methods

6.2.1 Weather data

Weather data was obtained from the Winkler weather station in southern Manitoba (Fig. 6.1). The station is located at latitude 49.122°N; longitude 97.932°W, elevation 279 m, and managed by Manitoba Agriculture. The weather station is located in the midst of rural agricultural lands as shown in Fig. 1. Weather data collected included solar radiation ($MJ/m^2/day$), minimum and maximum air temperature measured at 2 m (^oC), relative humidity (%) and wind speed (m/s) at 10 m for a 7-year period (2012-2019). Routine checks and equipment maintenance are usually followed to ensure data quality and integrity (Ojo, 2020, personal communication). Manitoba has a semi-arid climate, with annual precipitation of 450 to 520 mm, an average annual temperature of 2.2 ^oC, an average minimum temperature of -16 ^oC in January and an average maximum temperature of 23 ^oC in July (Bueckert and Clarke 2013). The textural class of the area is sandy loam. Southern Manitoba is the center of agricultural activities in the province, accounting for more than 60% of its agricultural employment in 2017 (Statistics Canada, 2017).

Figure 6.1: Location of the study area form Manitoba Agriculture (https://agrimaps.gov.mb.ca/agrimaps/#)

6.2.2 The FAO-Penman-Monteith (FAO-PM) Equation

The FAO-PM is the standard equation for determining reference crop evapotranspiration, and it was used for estimating daily ET_o in this study. All other empirical ET_o models were compared to the FAO-PM equation. According to Allen et al. (1998), it is given as:

$$ETo = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273}[e_s - e_a]u_2}{\Delta + \gamma * (1 + 0.34 * u_2)} \tag{6.1}$$

where ET_0 is the reference crop evapotranspiration [mm day^{-1}]; R_n is the net radiation [MJ m^{-2} day^{-1}]; G is the soil heat flux [MJ m^{-2} day^{-1}]; T is the average daily air temperature at the height of 2 m [°C]; u_2 is the wind speed at a height of 2 m [m s^{-1}]; e_s is the saturation vapour pressure [kPa]; e_a is the actual vapour pressure [kPa]; e_s -e_a is the vapour pressure deficit [kPa]; Δ is the slope of the saturation vapour pressure-temperature curve [kPa °C^{-1}]; and γ is the psychrometric constant [kPa °C^{-1}].

6.2.3 Empirical ETo models

Based on input requirements, Tabari et al. (2013) classified empirical ET_o models into temperature-based, radiation-based, mass-transfer based, and combination-based models. As the name implies, the major requirement for temperature and radiation-based models are temperature and solar radiation data, respectively. The mass transfer-based models are based on Dalton's gas law (Tabari et al., 2013). The combination based ET_o models combine aerodynamic and energy balance components.

In this study, fourteen common, simple, and some recent empirical ET_o models (Table 6.1) were evaluated and compared with the FAO-PM equation. Temperature-based models include Hargreaves Samani, Trajkovic, Ravazzani, and Schendel model. The radiation-based model includes Irmak, Priestly-Taylor, Tabari 1, and Tabari 2 model. Mass transfer-based models include Romanenko and Penman, while combination-based models are Alexandris (Copais), Valiantzas 1, Valiantzas 2, and Valiantzas 3.

Table 6.1: ETo models and their input requirements

S/No	Model	Equation	Inputs
1	Hargreaves-Samani (1985)	$ET_o = 0.0023 * R_a * 0.408 * (T_a + 17.8)^{0.5}$	T_a
2	Trajkovic (2007)	$ET_o = 0.0023 * R_a * 0.408 * (T_a + 17.8)^{0.424}$	T_a
3	Ravazzani et al. (2012)	$ET_o = (0.817 + 0.00022z)0.0023 * R_a * 0.408 * (T + 17.8)^{0.5}$	T_a
4	Schendel (1967)	$ET_o = 16 * \left(\frac{T_a}{RH}\right)$	T_a
5	Irmak et al. (2003)	$ET_o = -0.611 + 0.149R_s + 0.079T_a$	$T_{a,}$ R_s
6	Tabari 1 et al. (2013)	$ET_o = -0.642 + 0.174R_s + 0.0353T_a$	$T_{a,}$ R_s
7	Tabari 2 et al. (2013)	$ET_o = -0.478 + 0.156R_s - 0.0112T_{max} + 0.0733T_{min}$	$T_{max,}$ $T_{min,}$ R_s
8	Priestly-Taylor (1972)	$ETo = 1.26\frac{\Delta + R_n}{2.45(\Delta + \gamma)}$	
9	Romanenko (1961)	$ET_o = (0.0018 * (T_a + 25)^2 * (100 - RH))$	$T_{a,}$ RH
10	Penman (1948)	$ETo = \left(\frac{0.000479}{U_2} + 2.625\right)(e_s - e_a)$	RH, U_2
11	Alexandris and Kerkides (2003) Copias approach	$ET_o = 0.057 + 0.227c2 + 0.643c1 + 0.0124c1 * c2$ where $c1 = 0.646 - 0.078RH + 0.372R_s - 0.00264R_sRH, c2 = -0.0033 + 0.00812T_a + 0.101R_s - 0.00584R_sT_a$	$T_{a,}$ RH, R_s
12	Valiantzas 1	$ET_o = 0.0393R_s\sqrt{T_a + 9.5} - 0.19R_s^{0.6}\varphi^{0.15} + 0.048(T_a + 20)\left(1 - \frac{RH}{100}\right)U_2^{0.7}$	$T_{a,}$ $U_{2,}$ RH, R_s
13	Valiantzas 2	$ET_o = 0.0393 * R_s\sqrt{T_a + 9.5} - 0.19R_s^{0.6}\varphi^{0.15} + 0.078(T_a + 20)\left(1 - \frac{RH}{100}\right)$	$T_{a,}$ RH, R_s
14	Valiantzas 3	$ETo = 0.0393 * R_s\sqrt{T_a + 9.5} - 0.19R_s^{0.6}\varphi^{0.15} + 0.0059(T_a + 20)(T_a - Tmin - 0.45(T_{max} + T_{min}) + 3.45)^{0.8}$	T_a,T_{min},T_{max} Rs,

Where $T_{min,}$ is minimum temperature (^oC), T_{max} is maximum temperature (^oC), T_a is average daily air temperature (^oC), Rs is Solar radiation (MJ/m-^{2} day^{-1}), RH is relative humidity (%), U_2 wind speed corrected to 2 m, Ra is extraterrestrial radiation (MJ m^{-2} day^{-1}), φ is latitude (rad)

6.2.4 ET_o estimates under limiting conditions

In the absence of complete weather variables, Allen et al. (1998) gave recommendations to estimate inputs for the FAO-PM equation. Solar radiation is usually estimated from the Hargreaves solar radiation equation; actual vapour pressure is related to relative humidity and is estimated using the assumption that dew point temperature is approximately equal to the minimum temperature, while a global average of 2 m/s or an average wind speed data from a close station can be used. In this study, a global average of 2 m/s was used for wind speed. The equation for estimating missing solar radiation and actual vapour pressure is presented in equation 2 and 3, respectively

$$R_s = K_{rs} * R_a * 0.408 * (T_{max} - T_{min})^{0.5} \tag{6.2}$$

$$e_a = 0.611\exp\left[\frac{17.27T_{min}}{T_{min}+237.3}\right] \tag{6.3}$$

where, K_{rs} is an adjustment coefficient having a value of 0.16 and 0.19 for inland and coastal locations, respectively. In this study, K_{rs} was calibrated for the study location. Empirically, K_{rs} is determined as stated by (Allen 1997)

$$K_{rs} = K_{Ra} * (\frac{P}{P_o})^{0.5} \tag{6.4}$$

where, K_{Ra} is an empirical coefficient equal to 0.17 for interior regions and 0.20 for coastal areas, P is mean atmospheric pressure at the weather station site (kPa); P_o = mean atmospheric pressure at the sea level (101.3 kPa)

6.2.5 Model calibration and validation

Two-thirds of the weather data (2012 to 2017) were used to determine new empirical constants (calibration), while the remaining one-third (2018-2019) was used for validation of the calibrated equation. Model calibration was done using the non-linear generalized reduced gradient (GRG) solving method in Microsoft excel. The solver tool determines empirical constants by minimizing the sum of squared residual. Numerous studies have adopted this optimization technique (Bogawski and Bednorz 2014, Djaman et al. 2018).

6.2.6 Sensitivity analysis

Sensitivity analysis is usually carried out to determine the most influential or sensitive variable (Irmak et al. 2006). Across the globe, weather stations are limited, expensive to establish and maintain, and measure few variables. Therefore, it is important to identify climatic variables that are most sensitive to ET_o so that efforts can be geared towards their accurate measurements. Under scarce data conditions, Jersurki et al. (2019) and Shafieiyoun et al. (2020) have argued to apply the ET_o model based on the sensitivity to ET_o to climatic variables. Sensitivity analysis is also important in understanding the variability of climatic variables and ET_o, especially under increased climate uncertainties (Nouri et al. 2017).

In this study, a simple method that involved plotting the relative change in each of the climatic variables (T_{max}, T_{min}, R_s, and VPD) against relative change in ET_o. Numerous researchers have applied this method (Irmak et al. 2006, Yin et al. 2010, Gao et al. 2016, Ndulue et al. 2020, Shafieiyoun et al. 2020). The VPD was used because RH exceeded the maximum value (100%) when increased by 15%, thereby rendering it physically meaningless (Biazar et al. 2019). The plot was drawn by determining the base FAO PM ET_o (that is, ET_o calculated from the average daily value of each climatic variable for the given study period, April to October, n = 215). New sets of ET_o were determined by increasing and decreasing each climatic variable by ±5 to ±25% while keeping other variables constant. Then, a plot showing the percent change in each variable to ET_o is developed. Variables with the steepest slope and highest average values are the most sensitive.

6.2.7 Model performance assessment

A qualitative and statistical test assessed model performance. Qualitative assessment involves a graphical plot of empirical ET_o models against the FAO-PM ET_o model on a 1:1 scale. The slope coefficient (*b*) and the coefficient of determination (R^2) indicate model accuracy and precision. R^2 ranges from 0 to 1. An R^2 =1 means a perfect agreement between observed and predicted. It is calculated as:

$$R^2 = \left(\frac{\sum_{i=1}^{n}(O_i - \overline{O})(P_i - \overline{P})}{\sqrt{\sum_{i=1}^{n}(O_i - \overline{O})^2}\sqrt{\sum_{i=1}^{n}(P_i - \overline{P})^2}} \right)^2 \tag{6.5}$$

Statistical tests commonly used for model assessment (Moriasi et al. 2015, Johnson et al. 2019) to quantify mean differences between measured and predicted values were also used, including:

Root Mean Square Error (RMSE)

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(O_i - P_i)^2}{n}} \tag{6.6}$$

Mean Percent Error (MPE)

$$MPE = \frac{\sum_{i}^{n}(P_i - O_i)}{n} \times 100 \tag{6.7}$$

MPE is used to quantify model over or underestimation. Positive and negative values indicate overestimation and underestimation, respectively.

Mean absolute error (MAE) is a measure of the magnitude of the average error.

$$MAE = \frac{\sum_{i}^{n}|O_i - P_i|}{n} \tag{6.8}$$

Nash Sutcliffe efficiency (NSE)

NSE range form -∞ to 1. A negative NSE value is an indication that the observed mean is a better predictor than the model. NSE equal to 0 implies that the model estimates are as accurate as the observed mean. In contrast, a positive NSE value means that the model is a better predictor than the observed mean (Martel et al. 2018).

$$NSE = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}\left(O_i - \overline{O}\right)^2} \tag{6.9}$$

where O_i is $ET_{O\text{-}FAO\text{-}PM}$ estimates, P_i is the $ET_{O\text{-}EMPIRICAL}$, $\overline{O_i}$ is the mean of $ET_{O\text{-}FAO\text{-}PM}$, and *n* is the total number of observed data points. A perfect model is obtained when NSE, R^2, and *b* is equal to 1, and RMSE, MPE and MAE is equal to 0 (Moriasi et al. 2015, Johnson et al. 2019).

6.3 Results and Discussions

6.3.1 Climatic conditions of the study area

Table 6.2 summarizes the study area's measured daily climate variables during the study period (April to October). The average monthly analysis showed that the highest Tmax, Tmin, and Rs were recorded in July, corresponding to the period of highest water use for most field crops such as canola (Alberta Agriculture and Rural Development, 2011). Lowest T_{max}, T_{min}, were also observed in April, whereas the lowest Rs was observed in October.

Table 6.2: Daily average climatic variables at the study site from 2012-2019[1]

	T_{max}(°C)	T_{min}(°C)	RH (%)	Rs (MJ/m^2/day)	U_2 [2] (m/s)
Minimum	3.56	-6.48	49.08	4.71	1.03
Maximum	29.22	16.05	80.52	26.21	3.76
Average	19.87±7.12	6.88±5.88	67.78±6.28	16.69±5.17	2.15±0.53
30yr-average[3] (1981-2010)	19.23±6.36	7.59±5.95	-	-	-

[1] 2016 was excluded from the analysis because of incomplete solar radiation data
[2] wind speed corrected to 2 m height.
[3] Historical data from the Environment Canada website
(https://climate.weather.gc.ca/climate_normals/results_1981_2010_e.html?stnID=3626&autofwd=1)

6.3.2 Relationship between ETo and weather variables

The relationship between the FAO-PM ETo estimates and meteorological variables (solar radiation, vapour pressure deficit, average temperature, relative humidity, and wind speed) is presented in Figure 6.2. Figure 6.2 shows that ET_o has a strong positive correlation with vapour pressure deficit, solar radiation, and temperature ($R^2 > 0.5$). In contrast, a weak correlation was observed with relative humidity and wind speed ($R^2 < 0.5$). The strength of correlation among the weather variables could also indicate factors controlling the evapotranspiration process. The results suggest that the area's evapotranspiration process is more energy-driven than the water vapour transfer process. This agrees with other studies in arid and semi-arid climates (Preeyaphorn 2011, Martel et al. 2018, Djaman et al. 2018, Koudahe et al. 2018). However, Martel et al. (2018) observed a negative relationship between ET_o and wind speed. The relationship between ET_o and weather variables indicates the accuracy of ET_o estimates under missing data conditions. Thus, it is likely that under missing solar radiation, ET_o estimates would be of lesser accuracy when compared with missing wind speed.

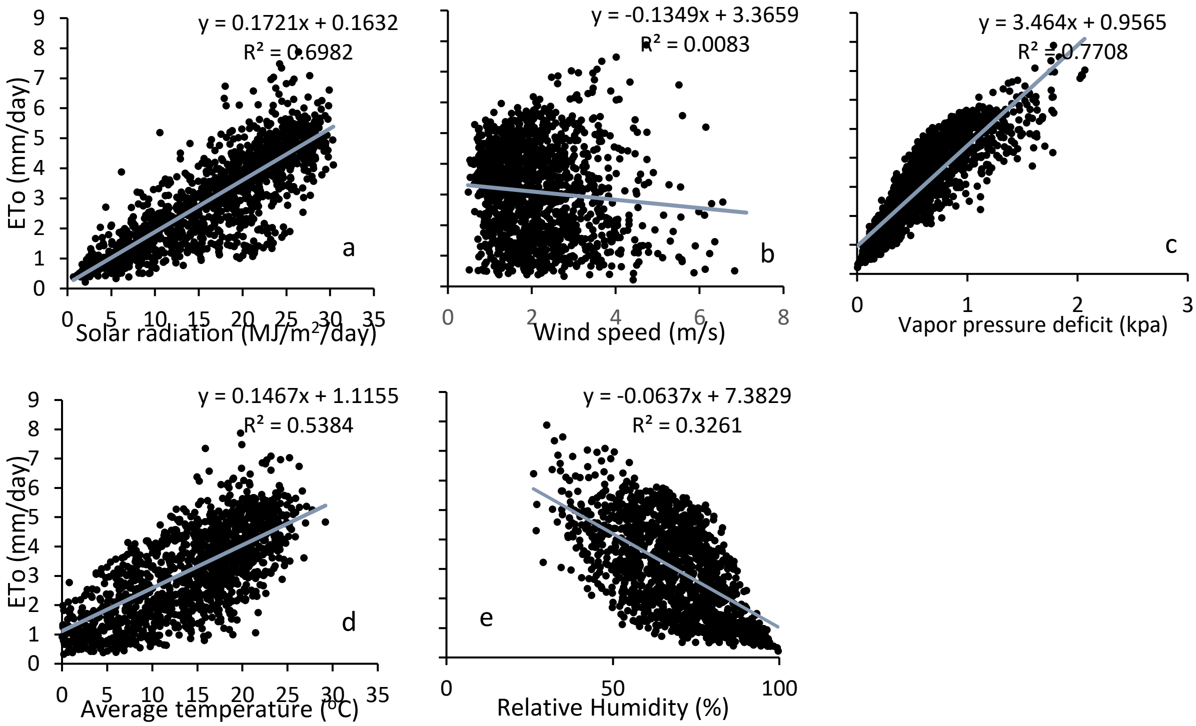


Figure 6.2: Linear regression of ETo and (a). solar radiation (b). wind speed (c). vapor pressure deficit (d). average temperature (e). relative humidity

6.3.3 ET_o assessment under missing data

As stated earlier, the recommendations of Allen et al. (1998) were followed under the missing data scenario. In this study, ET_o estimates under missing wind speed, relative humidity, solar radiation is represented as ETo-U_2, ET_o-RH and ET_o-Rs, respectively. Other combinations and statistical results are presented in Table 6.3 and shown in Figure 6.3.

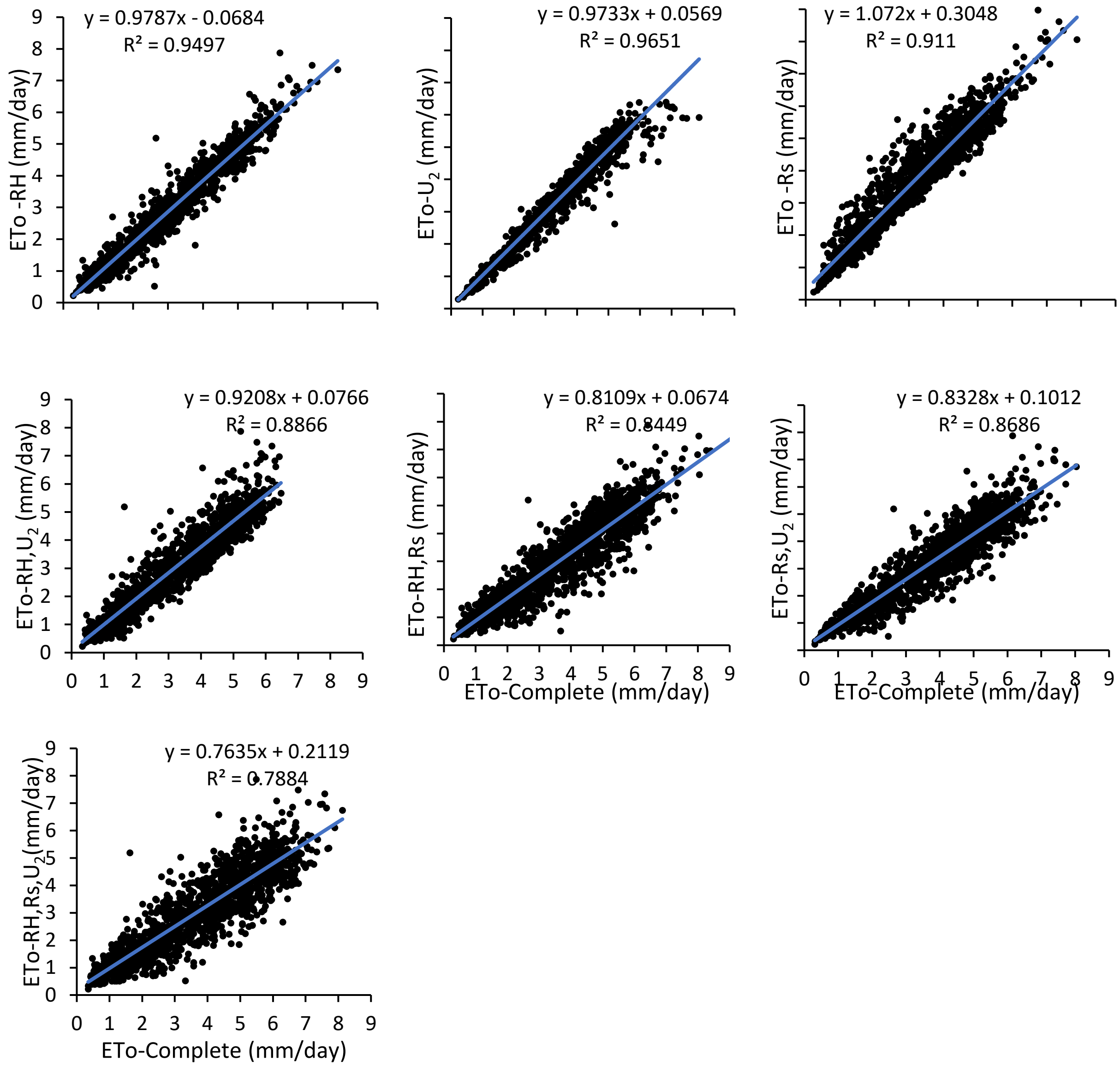


Figure 6.3: Regression of ET_o computed with complete and incomplete datasets.

Fig. 6.3 shows the linear regression of the FAO PM ET_o computed with full datasets and FAO PM ET_o computed with missing data. As expected, the accuracy of FAO PM ET_o estimates decreased as the number of missing variables increased. Statistical results showed that ET_o computed when only one variable is missing performed best with R^2 and NSE > 0.9 and RMSE < 0.35 mm/day. Under this scenario, ET_o-U_2 performed best, followed by ET_o-RH and ET_o-Rs. The above results suggest that ET_o estimate under limiting data condition is acceptable. However, a comparison of measured Rs and Rs computed using the Hargreaves equation showed that the Hargreaves equation accounted for 63% (R^2 = 0.63) of the variation in measured Rs, and an overwhelming overestimation. Calibration of the solar radiation constant, Krs, has been reported to improve Rs and ET_o estimates (Aladenola & Madramootoo 2014, Tabari and Talaee 2016). The result herein agrees with the findings of Ngogondo et al. (2013), Popova et al. (2006), Jabloun and Sahli (2008), C'ordova et al. (2015), and Djaman et al. (2018). Under the ETo-U_2 scenario, Sentelhas et al. (2010) reported precision of 96 to 99% and RMSE < 0.3 mm/day across all Ontario stations. Under semi-arid climates, Jabloun and Sahli (2008), Koudahe et al. (2018), and Djaman et al. (2018) reported a precision ranging from 87 to 91%. On the other hand, Shafieiyoun et al. (2020) found that ETo computed under data-scarce conditions were unacceptable.

When two variables are missing, the FAO PM ET_o decreased, although ET_o-Rs,U_2 and ET_o-RH, U_2 performed relatively well with NSE > 0.8 and RMSE of about 0.55 mm/day. Under this condition, ET_o-Rs, U_2 and ET_o-RH, U_2 gave similar results and performed better than ET_o-Rs, RH. This may be because RH has a stronger correlation with ET_o than U_2 (Figure 6.2). The poorest performance was obtained when all three weather variables were missing. This condition overestimated ET_o by more than 36% and RMSE > 0.82 mm/day. The results of this study agree with Djaman et al. (2018), who reported an R^2 ranging from 0.723 to 0.84, slope coefficient of 0.723 to 1.104, RMSE of 0.85 to 1.10 mm/day, and MAE 0.7 to 1.43 mm/day across five stations in New Mexico, while Sentelhas et al. (2010) reported low regression coefficient between 0.08 to 0.49 and an average RMSE of 1.194 mm/day across sites in Southern Canada.

6.3.4 Comparison of ET_o models

All the selected empirical ET_o equations were compared with the FAO-PM equation, the standard ET_o equation. Regression and statistical analyses showing their performance are presented in Figure 6.4. The empirical ET_o models exhibited varying performance in the study area. Overall, among the 14 models, the Valiantzas-1 model performed the best while the Romanenko model performed the worst.

Table 6.3: ETo computed with complete data sets Versus ETo computed with missing parameters

MODELS	RMSE (mm/day)	MPE (%)	MAE (mm/day)	NSE
ETo-U_2	0.335	17.41	0.234	0.951
ETo-RH	0.367	13.67	0.276	0.941
ETo-Rs	0.467	19.65	0.328	0.905
ETo-Rs,U_2	0.554	16.92	0.416	0.866
ETo-RH,U_2	0.555	18.14	0.429	0.866
ETo-RH,Rs	0.683	31.9	0.516	0.796
ETo-RH,Rs,U_2	0.822	36.19	0.641	0.705

6.3.4.1 Combination-based models

The statistical results showed that combination-based models performed best for estimating ET_o. Of the combination-based models evaluated, the Valiantzas-1 model performed the best based on its statistical indices. It can also be observed that almost all the scatter plots' points fall on the regression line (Figure 6.4). Although the Valiantzas-1 model has the same weather data requirement as the FAO-PM, it is simple and involves the direct substitution of variables, unlike the FAO PM model. Thus, the Valiantzas-1 model could be used in place of the FAO-PM equation, which agrees with Valiantzas (2013), who used global data sets, Djaman et al. (2018) in New Mexico, Ahooghalandari et al. (2017) in Australia, Djaman et al. (2015) in Senegal, Valipour (2014) in Iran, and Bourletsikas et al. (2017) in Greece. These studies have reported precision and accuracy greater than 98% and low RMSE values. In contrast, Peng et al. (2017) and Valle Júnior et al. (2020) reported poor performance of the Valiantzas ET_o models in China and Brazil, respectively. Of the four models, the Copias model had the lowest performance, with the lowest NSE (0.77) and the highest RMSE (0.73 mm/day). This disagrees with Valle Júnior et al. (2020), who reported that the Copias model performed better than Valiantzas-2 and Valiantzas-3 models. In Australia, Alexandris et al. (2008) reported a slope coefficient of 1.005 and an RMSE of 0.281 mm/day with the Copais equation. Bourletsikas et al. (2017) also reported similar performance. From Figure 6.4, it is also seen that Valiantzas-3 performed better than Valiantzas-2 despite requiring lesser inputs (solar radiation and temperature). However, Valipour (2014) reported that the Valiantzas-2 (Rs, T, RH) gave accurate ET_o estimates under Iran's limited data. The MPE values indicated that Valiantzas-3, Copias, and Valiantzas-1 models overestimated ET_o while Valiantzas-2 underestimated ET_o.

6.3.4.2 Radiation-based models

The radiation-based models closely follow the combination-based models with good model performance. It is seen that R^2 is greater than 0.8, slope coefficient ranged between 0.78 to 0.98, and had low RMSE values. The Irmak model performed best with an R^2 of 0.87, NSE of 0.86, RMSE of 0.55 mm/day and MAE of 0.4 mm/day, while Tabari 2 performed least with RMSE and NSE of 0.89 mm/day and 0.648, respectively. This result agrees with Irmak et al. (2003), Tabari et al. (2013), and Bourletsikas et al. (2017). Valle Júnior et al. (2020) evaluated 21 models and reported that 3 out of the 5-best selected ET_o were radiation-based models. The good performance of radiation-based models is likely related to the strong relationship between ET_o and Rs (Fig. 2) in the study area. All the models in this group underestimated $ET_{o,}$ with the Priestly-Taylor model have the least MPE. This is consistent with the report of Celestin et al. 2020, who reported an underestimation of up to 78.6%. In Iran, Tabari et al. (2013) reported an overestimation of 18.10% by the Irmak model. Tabari 1 & 2 models use minimum and maximum temperature in place of average temperature, which improved their performance (Tabari et al. 2013). A similar result was also reported by Xystrakis & Matzarakis (2011).

6.3.4.3 Temperature-based models

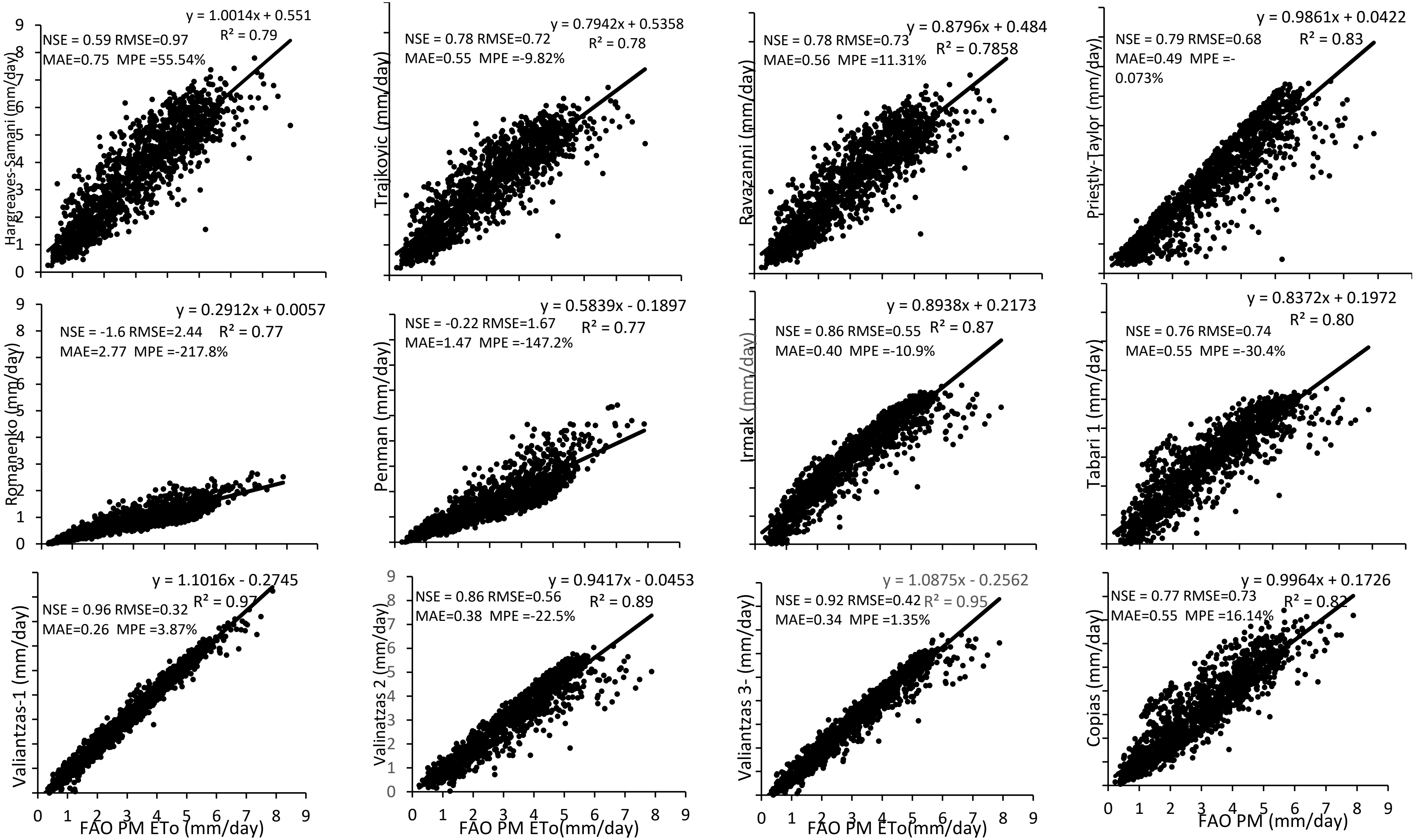
The temperature-based models showed acceptable and moderate results (R^2 >0.5), as indicated in Figure 6.4. From the RMSE and MAE values, the temperature-based models ranked third behind combination-based and radiation-based model classification. The Ravazanni model performed best in this category with NSE= 0.789, RMSE of 0.727 mm/day and MAE = 0.55 mm/day. The worst performing model in this category was the Schendel model with an NSE of 0.459 and RMSE of 1.11 mm/day. Thus, the Ravazanni model could be a promising ET_o model under limited data conditions in the study area. It should be noted that the Trajkovic and Ravazanni models are variants of the Hargreaves-Samani model, which is one of the widely used ET_o models. While numerous studies have calibrated the Hargreaves-Samani coefficients, Ravazanni et al. (2012) introduced a correction factor for elevation since ET_o is also affected by non-weather related factors such as latitude, elevation, and topography (Baizer et al. 2019). This result agrees with numerous studies including (Razzagahi and Sepaskhah 2011, Bourletsikas et al. 2017, Peng et al.

2017, Sentalhas et al. 2010, Jabloun and Sahli 2008, Martel et al. 2018) that found the performance of the temperature-based models to be acceptable; but disagrees with Pandey et al. (2016), Shafieiyoun et al. (2020), and Valle Júnior et al. (2020). The result also showed that only the Trajkovic model underestimated ET_o by 9.8%, which agrees with Celestin et al. (2020). Djaman et al. (2015) reported a percent of error estimate (PE) of 38.81%, RMSE of 2.65 mm/day for the Schendel model, a PE of 70.18% and RMSE of 4.67 mm/day for the Trajkovic model, and PE of 69.58% and RMSE of 4.66 mm/day, for Ravazzani model at Ndiaye in Senegal.

6.3.4.4 Mass transfer-based models

The mass transfer-based models also showed average performance ($R^2 > 0.5$) but inferior precision, as shown in the scatter plot in Figure 6.4. The mass transfer-based models performed worse based on model classification. Of the two-mass transfer-based model, the Penman model performed better. The Romanenko model performed worst, having the least NSE and highest RMSE of -1.603 and 2.44 mm/day, respectively. Both models overwhelmingly underestimated $ET_{o,}$ which is seen in the scatter plots of each model. The regression line is greatly deflected to the FAO-PM axis. Both models, especially the Romanenko model, underestimated ET_o when ET_o values were > 4 mm/day. The results disagree with the findings of Djaman et al. (2015), Bourletsikas et al. (2017), Tabari et al. (2013), and Celestin et al. (2020). Djaman et al. (2015) reported that the Romanenko model yielded accurate ET_o estimates in Senegal. Celestin et al. (2020) ranked the Romanenko model second and recommended its use when temperature and relative humidity are available. Although Tabari et al. (2013) reported worse performance of the mass transfer models, the Romanenko model performed well with R^2, RMSE, and PE of 0.92, 0.66 mm/day, and 11.99%, respectively, while the Penman model yielded an R^2 of 0.8, RMSE of 0.81 mm/day, MAE of 0.41 and an overestimate of 17.59%.

From the above, the combination-based model classification performed best. This is due to their robust nature and the number of required data inputs. Specifically, based on the NSE and RMSE values, the performance of the fourteen empirical ET_o models evaluated in this study is in the following descending order: Valiantzas 1, Valiantzas 3, Irmak, Valiantzas 2, Priestly-Taylor, Copais, Tabari 1, Ravazzani, Trajkovic, Tabari 2, Hargreaves-Samani, Schendel, Penman, and Romanenko model. However, for models with average to poor performance, calibration was used to improve model performance.



Hargreaves-Samani (mm/day)
y = 1.0014x + 0.551
R² = 0.79
NSE = 0.59 RMSE=0.97
MAE=0.75 MPE =55.54%
Trajkovic (mm/day)
y = 0.7942x + 0.5358
R² = 0.78
NSE = 0.78 RMSE=0.72
MAE=0.55 MPE =-9.82%
Ravazanni (mm/day)
y = 0.8796x + 0.484
R² = 0.7858
NSE = 0.78 RMSE=0.73
MAE=0.56 MPE =11.31%
Priestly-Taylor (mm/day)
y = 0.9861x + 0.0422
R² = 0.83
NSE = 0.79 RMSE=0.68
MAE=0.49 MPE =-0.073%
Romanenko (mm/day)
y = 0.2912x + 0.0057
R² = 0.77
NSE = -1.6 RMSE=2.44
MAE=2.77 MPE =-217.8%
Penman (mm/day)
y = 0.5839x - 0.1897
R² = 0.77
NSE = -0.22 RMSE=1.67
MAE=1.47 MPE =-147.2%
Irmak (mm/day)
y = 0.8938x + 0.2173
R² = 0.87
NSE = 0.86 RMSE=0.55
MAE=0.40 MPE =-10.9%
Tabari 1 (mm/day)
y = 0.8372x + 0.1972
R² = 0.80
NSE = 0.76 RMSE=0.74
MAE=0.55 MPE =-30.4%
Valiantzas-1 (mm/day)
y = 1.1016x - 0.2745
R² = 0.97
NSE = 0.96 RMSE=0.32
MAE=0.26 MPE =3.87%
Valinatzas 2 (mm/day)
y = 0.9417x - 0.0453
R² = 0.89
NSE = 0.86 RMSE=0.56
MAE=0.38 MPE =-22.5%
Valiantzas 3- (mm/day)
y = 1.0875x - 0.2562
R² = 0.95
NSE = 0.92 RMSE=0.42
MAE=0.34 MPE =1.35%
Copias (mm/day)
y = 0.9964x + 0.1726
R² = 0.82
NSE = 0.77 RMSE=0.73
MAE=0.55 MPE =16.14%
FAO PM ETo (mm/day)
FAO PM ETo(mm/day)
FAO PM ETo(mm/day)
FAO PM (mm/day)

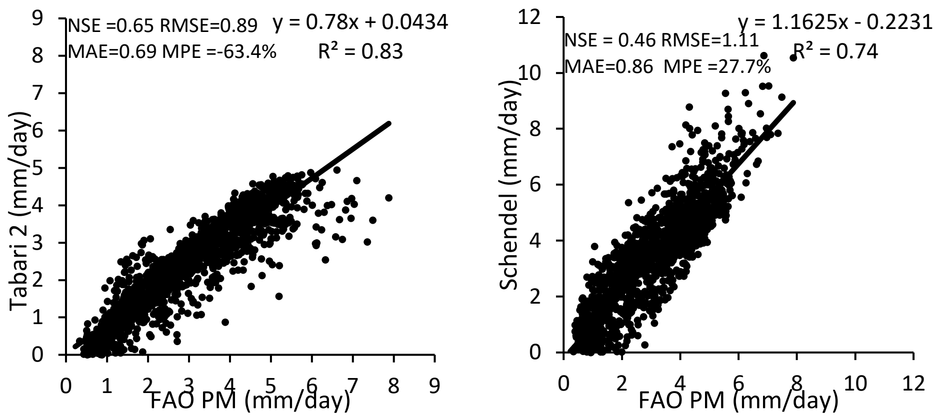


Figure 6.4: Regression analysis between empirical ET_o models versus FAO PM equation

6.3.5 Model calibration and validation

6.3.5.1 Determination of Hargreaves solar radiation adjustment coefficient, Krs

A new empirical coefficient was developed for the study area using the procedure outlined in section 6.2.4. After multiple runs, the calibrated solar radiation constant is 0.146, which is 10.4% lower than the recommended 0.16 (Allen et al. 1998). This agrees with Aladenola & Madramootoo (2014) and Tabari et al. (2016). In a related study, Aladenola & Madramootoo (2014) reported a coefficient of 0.15 for Winnipeg, which is close to the study area. In Iran, Tabari et al. (2016) obtained a coefficient of 0.14 for the semi-arid climate. Under tropical climates, Adaramola (2012) and Ndulue et al. (2019) found coefficients greater than 0.19. When comparing calibrated and original Rs with measured Rs, it is observed that the statistical indices improved (Table 4), especially the MPE values, which decreased from 256.4 to 62.06%. Similarly, Tabari et al. (2016) reported a 25% reduction in RMSE.

Table 6.4: Statistics indices using original and calibrated Krs for Rs and ETo computation

Rs estimate	R^2	RMSE (mm/day)	MPE (%)	MAE (mm/day)	NSE
Calibrated Krs=0.146	0.688	4.208	62.06	3.29	0.681
Original Krs=0.16	0.688	4.962	256.41	3.821	0.557
ETo					
Calibrated Krs	0.934	0.409	6.636	0.289	0.933
Original Krs	0.929	0.502	25.18	0.348	0.899

Furthermore, the FAO-PM ET_o equation was calculated using measured Rs, Rs computed using the calibrated coefficient, and Rs using the original Krs coefficient. Results showed a significant reduction in the magnitude of RMSE values when compared to the Rs computation. This can be attributed to the cumulative influence of other climatic variables. Overall, the calibrated Krs of 0.146 resulted in improved ETo estimates (Table 6.4). For example, NSE increased by 3.2% while MAE, MPE, and RMSE decreased by 16.9, 73.6, and 18.4%, respectively.

6.3.5.2 Determination of empirical coefficients for ETo models

Table 6.5 shows developed empirical coefficients for 7 out of the 14 evaluated ET_o models. These models were chosen because they are widely used, simple, and require fewer climate inputs. They included two temperature-based (Hargreaves Samani and Schendel), three radiation-based (Priestly-Taylor, Irmak, and Tabari), and 2 mass transfer-based models

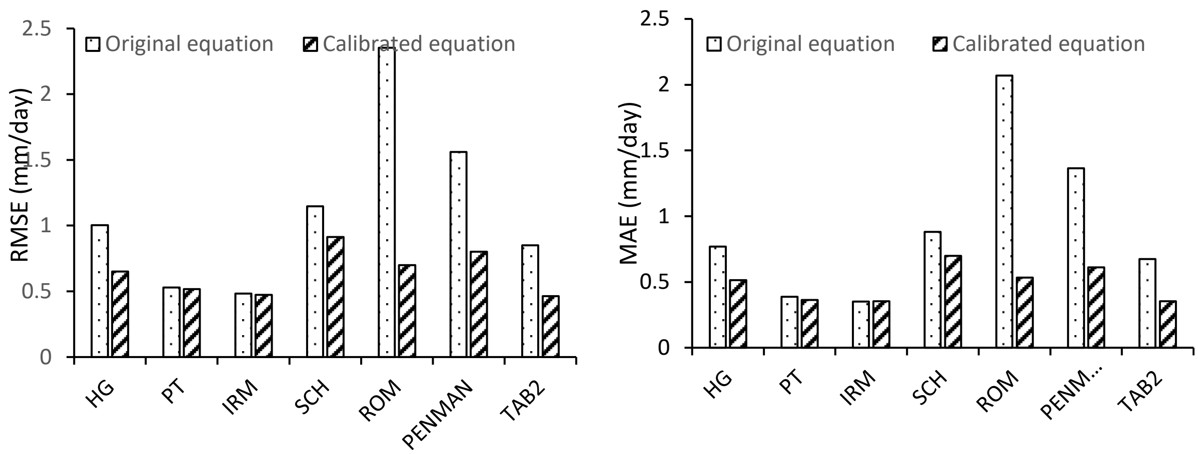
(Penman and Romanenko). It is worthy to note that the Trajvokic and Ravazzani models are variants of the Hargreaves-Samani model, while Tabari 1 and Irmak models are the same in structure and data requirements.

Table 6.5: statistical indices of calibrated empirical models

Models	Calibrated model	NSE	RMSE (mm/day)	MPE (%)	MAE (mm/day)
Hargreaves-Samani	$ETo = 0.00146(T_a + 24.76)(T_{max} - T_{min})^{0.56} \times R_a$	0.829	0.651	-12.916	0.514
Schendel	$ETo = 13.55\frac{T_a}{RH}$	0.664	0.914	19.45	0.698
Priestly-Taylor	$ETo = 1.215\frac{\Delta + R_n}{2.45(\Delta + \gamma)}$	0.893	0.516	6.639	0.362
Irmak	$ETo = -0.405 + 0.09714T_a + 0.129R_s$	0.909	0.474	0.0858	0.354
Penman	$ETo = \left(\frac{0.47543}{U_2} + 4.366\right)(e_s - e_a)$	0.74	0.803	13.401	0.611
Romanenko	$ETo = 0.00175(T_a + 30.61)^{2.247}(100 - RH)$	0.803	0.701	7.83	0.534
Tabari 2	$ETo = -0.5609 + 0.122R_s + 0.0717T_{max} + 0.0225T_{min}$	0.913	0.464	-0.0201	0.354

Table 6.5 also shows the calibrated models and their statistical performance. Using the Hargreaves Samani model, the calibrated solar radiation coefficient, temperature constant, and temperature exponent are 0.00146, 24.76, and 0.56, respectively, against the original constants of 0.0023, 17.78, and 0.5. In Texas, Awal (2020) reported constants of 0.00138, 24.49, and 0.685. Sentelhas et al. (2010) obtained coefficients ranging from 0.0017 to 0.022 for various locations in Ontario, while Djaman et al. (2018) reported coefficients ranging from 0.00202 to 0.00346 in New Mexico. Overall, the calibrated models resulted in improved model performance and better ETo estimates compared to the original coefficients (Figure 6.5). For the Hargreaves-Samani model, results showed that NSE increased from 0.7 to 0.75, RMSE decreased from 0.5 to 0.2 mm/day, MAE decreased from 0.6 to 0.3, MPE decreased from 55 to 25%. Similar results were obtained for Irmak, Schendel, Romanenko, Penman, Priestly-Taylor, and Tabari 2 models. Among the calibrated models, the greatest model improvement

was observed for Romanenko and Penman models. RMSE decreased from 2.35 to 0.7 mm/day, MPE decreased from 2.068 to 0.078, MAE decreased from 2.068 to 0.734 mm/day, and NSE increased from -1.22 to 0.803 for the Romanenko model. For the Penman model, RMSE decreased from 1.56 to 0.803 mm/day, MPE decreased from 1.363 to 0.134, MAE decreased from 1.363 to 0.611 mm/day, and NSE increased from 0.021 to 0.741.



HG-Hargreaves-Samani, PT-Priestly Taylor, IRM-Irmak, SCH-Schendel, ROM-Romanenko, TAB2-Tabari2

Figure 6.5: Statistical indices for ETo computed using original and calibrated ETo equations.

6.3.6 Changes of climatic variables to changes in ETo

Figure 6.6 shows the plot of percent changes in ET_o to percent changes in each meteorological variable (Tmax, Tmin, Rs, U2, and VPD). The figure showed that changes to ET_o to climatic variables were generally linear. The results also showed that Tmax and Rs happen to cause the most significant changes to ET_o, followed by VPD, U_2, and Tmin in the study area. A 25% increase in Tmax and Rs resulted in an 11.45 and 11.07% increase in ET_o. This translates to an average rise of ET_o by 0.37mm, varying between 0.02 to 0.74 mm. The exponential relationship between temperature and saturation vapor deficit (SVP) and the linear relationship between vapor pressure deficit (VPD) and ETo explains the dominating influence of temperature under semi-arid and arid climate (Irmak et al. 2006). Also, from the Clausius-Clapeyron relationship, temperature increases SVP by approximately 7%/K (Held and Soden, 2006), resulting in an increased VPD, which ultimately leads to an increased ETo.

The results also showed that U_2 had a higher impact than Tmin, with the former causing a ± 4.14% variation and the latter 2.16% in response to a ±25% change. A similar result was found by Darshana et al. (2013), Patle and Singh (2015), Poddar et al. 2018, Biazar et al. (2019), and Ndulue et al. (2020). In the semi-arid climate of Iran, the wind speed was reported as the most sensitive variable (Tabari and Talaee 2014, Nouri et al. 2017)

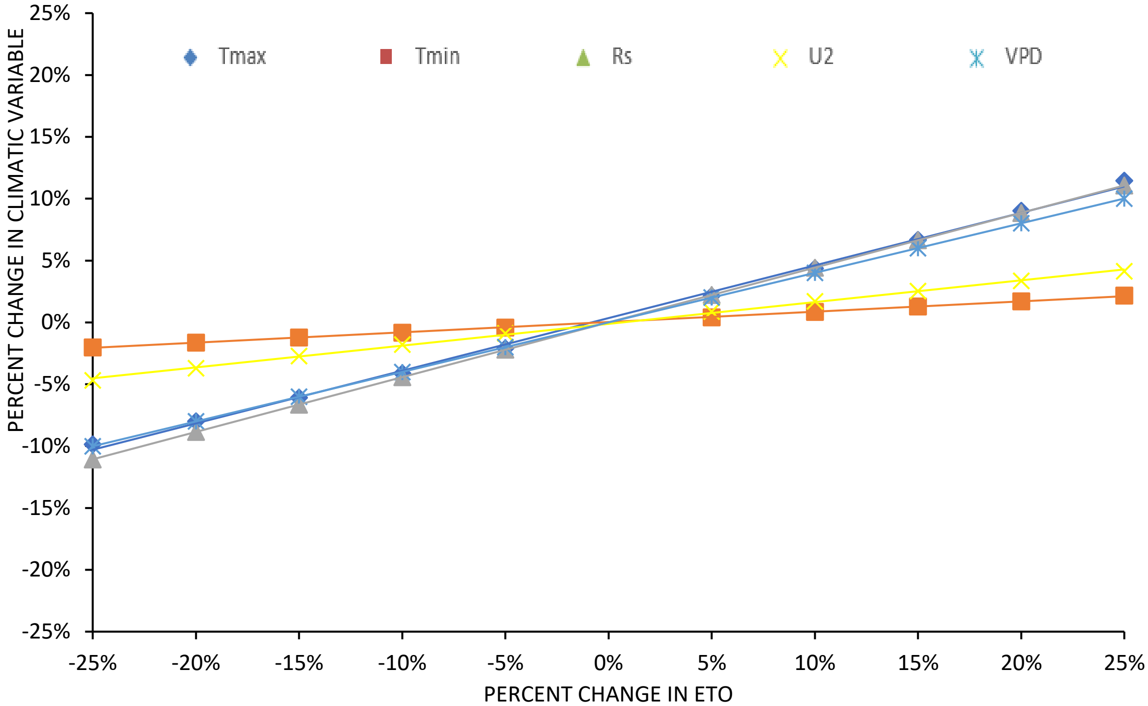


Figure 6.6: Percent change in each climatic variable to percent change in ET_o

The result also confirms the dominating influence of energy-related terms in the FAO-PM equation in the study area. Thus, a small increase in Tmax has a higher impact on ET_o than a larger increase in U_2. For example, a 25% increase in Tmin and U_2 resulted in a 2.2 and 4.1% increase in ET_o, while a 10% increase in Tmax caused ET_o to increase by 4.4%. In the arid climate of Rajasthan, India, Goyal (2004) found that a 1% increase in temperature resulted in a 15 mm increase in ET. Overall, the sensitivity of ETo to climatic variables in the study area is ranked as Tmax>Rs>VPD>U_2>Tmin. Therefore, accurate measurements of temperature and solar radiation are essential for reliable ET_o estimates.

6.4 Conclusion

An accurate estimate of ET_o is important in determining the water demand of field crops, irrigation scheduling, agricultural planning, water usage, and effective water resources management. The FAO-PM equation is the globally accepted equation for estimating ETo. Despite its accuracy, it is limited by requiring too many inputs not readily available because most weather stations hardly report ET_o. Thus, empirical ET_o equations have been developed as an alternative. In this study, ET_o derived from complete data sets was compared with missing data sets. Results showed that ET_o estimates under missing wind speed, relative humidity, or solar radiation were acceptable with RMSE < 0.9 and R^2 > 0.8. However, their performance decreased with an increasing number of missing data yielding average to poor performance. Furthermore, the performance of fourteen empirical ET_o models was compared with the FAO PM model. Based on their NSE and RMSE values, the performance of the fourteen empirical ET_o models evaluated is in the following descending order: Valiantzas 1, Valiantzas 3, Irmak, Valiantzas 2, Priestly-Taylor, Copais, Tabari 1, Ravazzani, Trajkovic, Tabari 2, Hargreaves-Samani, Schendel, Penman, and Romanenko model. New empirical coefficients (calibration) were developed for simple ETo models requiring one or two climatic inputs. Results showed that calibration resulted in improved model performance. The sensitivity analysis result showed that ETo is most sensitive to changes in Tmax and Rs, followed by VPD, U_2, and Tmin. Therefore, accurate measurements of temperature and solar radiation are important for reliable ET_o estimates in Winkler. This study provides simple and alternative ETo models with reasonable ET_o estimates for use in southern Manitoba and other areas with similar climate characteristics. Further studies can validate the calibrated ET_o models using lysimeter, water balance, or modelling.

Chapter Seven

Conclusion

7.1 Main findings

1. The impacts of three water management techniques, controlled drainage (CD), free drainage (FD), and no drainage (ND), on canola yield and oil qualities, were evaluated over three years (2019-2021). The result shows significant differences in crop yield between the years, suggesting that yield may have been influenced by weather variables (temperature and rainfall). In 2019 with relatively reasonable rainfall amounts (May to August) and normal average temperature, CD plots had consistently higher yields across all replicates. The CD yield was significantly higher compared to FD. As the drought continued in the following years, the impact of CD diminished, showing no significant differences between the three treatments.
2. The results showed that the prevailing weather may have masked the impacts of drainage on canola oil qualities and soil nutrient dynamics across the soil profile. There were no significant differences between the treatments in 2020 and 2021.
3. The DRAINMOD model was calibrated and validated by comparing simulated and observed water table depth. Based on graphical and statistical tests, the DRAINMOD model was found adequate to simulate water table depth and predict other hydrological variables. Thus, the validated DRAINMOD model of the field was used to make sound water management decisions to achieve maximum agricultural productivity and economic and environmental sustainability.
4. The model was used to assess different drainage designs and determine the optimal drain spacing that would maximize the return on investment. The simulation results suggest that the long-term average yield would be maximized by close drain spacing ≤ 15 m. Economic analysis showed that 10 m drain spacing would maximize the return on investment.
5. The validated DRAINMOD model was run using downscaled GCMs to assess climate change effects on the hydrology of an agricultural field and canola yield under two water table management systems: free and controlled drainage. DRAINMOD simulation results suggest that subsurface drainage is expected to decrease during the mid-century while ET and surface runoff are expected to increase.

6. Even though CD can decrease the drainage outflow from subsurface drainage in the future, comparable canola yield did not improve due to drought stress during the growing season. The presence of heavy clay at the study area, with low hydraulic conductivity would limit water movement, which could have minimized CD impacts on crop yield.
7. The results presented in this study represent a wide range of options for water managers and producers to develop strategies that would mitigate heat and drought stress in the future. Water could be drained to facilitate field operations before planting. This drained water could be stored for later use to overcome the anticipated drought stress.
8. The ET is an essential input for most hydrologic models. Due to limited weather variables, alternative ET models with low inputs have been developed. However, these models should be tested before use in a new environment as they could affect model results in simulations to determine adequate soil and water management strategies.

7.2 Practical applications and contributions

This research has practical applications in Manitoba and regions with similar soil and climatic characteristics. It has also contributed to existing literature and advanced the knowledge of soil and water management in southern Manitoba in the following ways

1. This research has shown that weather has a significant impact on the performance of water management systems on canola yield and quality parameters in southern Manitoba. This study showed that depending solely on rainfall would not achieve the potential or target canola yield.
2. The results presented in this study indicate that existing drainage systems should be re-examined in design and operation. During springtime, drainage water allowed to leave the field could be stored and reused for irrigating crops during prolonged water deficits. Farmers and producers should channel the drainage water into water conservation structures such as retention ponds and reuse the captured water for irrigation during acute development stages.
3. This research study has also shown that drainage contractors adopting drainage design variables from other regions without considering local factors such as soil, climate, and crop type may not be suitable to achieve maximum agronomic, economic, and

environmental gains. Long-term modelling results from this study have shown that closer draining spacing would maximize canola yield for the PESAI site with heavy clay soil.

4. Under climate change, rainfall is projected to decrease during the growing season, and temperature will increase in the future. From a water management perspective, using the DRAINMOD model, simulation results showed that canola yield losses due to excess water would be lower in the future. In comparison, yield losses due to drought stress would be higher. Stakeholders and water managers can use these results from future impacts of climate change on canola yields to adapt, mitigate, and develop other management strategies to cope with the effects predicted.
5. Limited and incomplete weather data pose a severe challenge to long-term studies needed for soil and water management in southern Manitoba. ET is one of the most critical inputs for hydrologic modelling. Researchers have used empirical ET models with fewer inputs as an alternative to the recommended FAO-PM model. Since the choice of an ET model could affect model results, the empirical ET model should first be parameterized using local data. In this study, new empirical constants applicable to southern Manitoba were developed. For example, the calibrated solar radiation constant was 0.146, rather than the recommended 0.16. Also, the calibrated empirical ET coefficients for the Hargreaves-Samani ET equations are 0.00146, 24.76 and 0.56 instead of the original coefficients: 0.0023, 17.8, and 0.5.

7.3 Recommendations for future studies

1. Future studies should improve the observed water table depth model simulation by extensive data collection, including growing and non-growing seasons. Also, for robust results, measured data for model application should include soil water content, drainage outflow, runoff, nitrate content, and phosphate
2. Future studies could evaluate soil water dynamics and crop yield under pulse irrigation. Canola is mainly grown in the Canadian prairies under a rainfed system. However, pulse irrigation using the drain tile could be used for irrigation under high temperature and drought conditions as experienced in the 2021 season. The prevalence of flat topography and seasonal shallow water tables in southern Manitoba provides an opportunity for this modified form of subirrigation. This method works by applying water in pulses to wet the

soil profile, and the crop ET is met through capillary flow. The conventional practice of raising the water table by subirrigation by pumping water back through the tile may lead to more water loss to deep percolation. Therefore, pulsing the water application can minimize this loss.

3. Long-term field studies should be conducted to clearly determine the impacts of subsurface drainage, especially CD on canola yield and quality parameters.

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