ASSESSMENT OF THE SECOND-GENERATION PRAIRIE AGROMETEOROLOGICAL MODEL'S PERFORMANCE FOR SPRING WHEAT ON THE CANADIAN PRAIRIES

BY

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ABSTRACT

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To assess the accuracy of the second-generation Prairie Agrometeorological Model (PAM2nd) as an agrometeorological model for spring wheat on the Canadian Prairies, a study was conducted to validate the model using field measurements. Two locations in Manitoba and three locations in Saskatchewan were used to encompass the various soil and climatic conditions present throughout the Prairies. Soil moisture and meteorological conditions were monitored at Winnipeg and Carman, Manitoba and at Melfort, Regina and Swift Current, Saskatchewan during the 2003-2006 growing seasons. Each study site consisted of a weather station adjacent to spring wheat research plots. Soil water content was measured on a weekly basis in Manitoba and a biweekly basis in Saskatchewan using a neutron probe to a depth of 120 cm below the surface. To account for spatial variation in soil water content a network of access tubes were installed at each site within several different plots of wheat. Soil characteristics such as texture and water holding capacity were determined at several intervals of the 120 cm profile.

Result from model validation indicated soil moisture was being overestimated at most sites during the second half of the growing season, while soil moisture was underestimated during periods that experienced consecutive days of rainfall. Model overestimation was attributed to the canopy resistance increasing prematurely as the soil water decreased below field capacity. As a result, crop evapotranspiration was being restricted prior to when wheat would actually experience water stress. Model underestimation during consecutive rainfall events was attributed to infiltration being

stopped when the top-zone reached saturation. Allowing infiltration to continue during these periods reduced this error. Assessment of the original version of PAM2nd produced an overall RMSE of 62 mm of soil water (12% of field capacity). Implementation of both modifications improved the models accuracy, resulting in a RMSE of 53 mm (10% of field capacity).

In most situations, soil water holding parameters are not determined at each modeling location. Therefore, the model's accuracy was analysed using soil water holding characteristics obtained from the Soil Landscapes of Canada soil survey database. The use of soil parameters from the soil survey database decreased the accuracy of the modeled soil water, which emphasizes the need for accurate soil water holding parameters in order to obtain accurate modeled values.

Modeled evapotranspiration from the modified version of PAM2nd was compared to the FAO56 Penman-Monteith and simplified water balance methods. Evapotranspiration estimates of the modified version of PAM2nd were more responsive to day to day changes in weather compared to the FAO56 Penman-Monteith estimates. In addition, PAM2nd produced more accurate estimates when compared to the simplified water balance. However, both models produced estimates that fell within the range of water balance ET measurement error. The similarity in performance of both models to estimate ET compared to the water balance ET means the adoption of either model could be justified. However, for modeling ET over the Prairies, PAM2nd would be more appropriate because it requires fewer, more commonly measured, surface weather parameters. This approach increases the possible locations at which the model could be implemented and as a result, increases the spatial resolution of the estimates.

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LIST OF ABBREVIATIONS

ET	Evapotranspiration
ET_a	Actual evapotranspiration
$ET_{a\ adj}$	Soil water adjusted evapotranspiration
ET_c	Crop water demand
ET_p	Potential evapotranspiration
ET_0	Reference evapotranspiration
FAO56	Food and Agriculture Organization of the United Nations
K_c	Crop coefficient
K_s	Water stress coefficient
L_A	Fractional leaf area
P-M	Penman-Monteith
$PAM2^{nd}$	Second-generation Prairie Agrometeorological Model
$PAM2^{nd}_0$	Original version of $PAM2^{nd}$
$PAM2^{nd}_1$	Canopy resistance modified $PAM2^{nd}$
$PAM2^{nd}_2$	Infiltration modified $PAM2^{nd}$
$PAM2^{nd}_{1+2}$	Canopy resistance and infiltration modified $PAM2^{nd}$
PAW	Plant available water
PBL	Planetary boundary layer
RAW	Readily available water
r_a	Aerodynamic resistance
r_c	Canopy resistance
r_g	Soil resistance
TAW	Total available water
WB	Water balance

1. INTRODUCTION

The Canadian Prairies are located at the northern extent of the Great Plains of North America in the southern region of Alberta, Saskatchewan and Manitoba. Where there was once a short, mixed and tall grass prairie, now supports approximately 82% of Canada's cropland (Statistics Canada, 2006). Wheat is the dominant crop grown on the Prairies followed by canola and barley. This anthropogenic shift in land cover from perennial grassland to a cultivated, annual crop dominated landscape, has likely had an impact on the Prairie climate. Raddatz (1998) suggested the shift to annual crops changed the growing season evapotranspiration pattern resulting in an increase in convective activity during mid-season. Prior to crop emergence in the spring and after harvest, the rates of evapotranspiration are lower than they would be under grassland. As a result, there is reduced convective activity during these periods. Alternatively, during the period of rapid crop growth, evapotranspiration rates are higher than they would be compared to grasslands. This has likely decreased the frequency of early and late season thunderstorms while increasing mid-season thunderstorms (Raddatz, 1998).

On the Prairies, about two-thirds of annual precipitation falls during the growing season with the highest monthly rainfall in June through August (Ash et al., 1992). Yet, crop water demand often exceeds moisture availability during the growing season, resulting in a moisture deficit. For most agricultural regions within the Prairies there is a 70% probability that wheat will experience water stress (Nadler, 2007). This probability increases in western Saskatchewan and southern Alberta to 90% (Nadler, 2007). The lack of rainfall and soil water reserves from winter snowmelt is often considered the limiting factor for crop growth on the Prairies (Raddatz et al., 1994). Moisture for summer precipitation originates from water vapour that is advected into the region from the Pacific Ocean and the Gulf of Mexico and from moisture recycling within the Prairies via evapotranspiration within the region (Raddatz, 2005; Liu et al., 2004). Air masses originating from the Pacific Ocean are forced over the Rocky Mountains. Orographic lifting causes much of the moisture to fall as precipitation on the windward side of the mountain range, creating a rain shadow on the leeward side. As a result, the western part of the Prairies is generally much drier than the eastern side. Further removed from the rain shadow, Manitoba generally receives more precipitation with the wettest conditions in the south east corner of the province.

The Canadian Prairies are prone to extreme meteorological events such as droughts and floods. Within a span of less than a decade the Prairies experienced one of the worst droughts (1999 through 2005) and floods (1997) on record. In April and May of 1997, the Red River Valley in Manitoba experienced the greatest flood since 1826 when the Red River overflowed from spring snowmelt from within the province and from North Dakota and Minnesota. A few years later, the Prairies experienced one of the worst droughts on record. The first signs of drought were observed in 1999 and continued until 2004/2005. From September 2000 through August 2002, precipitation was below normal for 8 consecutive seasons (Bonsal and Regier, 2007). The provinces of Alberta and Saskatchewan were hardest hit by the drought.

Generally, drought is defined to be a prolonged period of abnormally dry weather that leads to a lack of water resources (AES, 1986). However, drought can be defined based on the user and geographical region in question (Bonsal and Regier, 2007). Bonsal and Regier (2007) describe four categories of drought; meteorological, agricultural, hydrological and socio-economic. A meteorological drought occurs when precipitation is significantly below normal for an extended period of time. An agricultural drought occurs during periods in which soil water content is not sufficient to support crops, while a hydrological drought occurs as a result of below normal surface run-off and shallow groundwater levels. A socio-economic drought occurs when a water shortage impacts society and the economy. These definitions can also describe the progression of drought. A meteorological drought can cause agricultural and hydrological droughts. This leads to a socio-economic drought due to the inability to grow crops, access groundwater for drinking and irrigation and the production of hydro-electricity. Droughts in Canada are not unique to the Prairies however they tend to have a greater impact due to the dependence of the region on the agricultural sector and its location within an already moisture limiting climate (Bonsal and Regier, 2007). It is estimated the Gross Domestic Product of Canada decreased by approximately 5.8 billion dollars during the drought years of 2001/2002 (DRI, 2008).

Despite the frequency and numerous studies on droughts, little is known about what initiates, maintains and terminates a drought (Liu et al. 2004). In 2005 the Drought Research Initiative (DRI) network was established. Focusing on the drought that started in 1999 and ended in 2004/05, the network's goal is to gain knowledge on the physical characteristics and processes that initiate and terminate droughts. Through better understanding of the mechanism of drought, steps can be made for better prediction and adaptation. Current projections by all Global Climate Models indicate increased temperature in the interior continent resulting in an increased risk of drought (Wheaton et al., 2007). Without an increase in precipitation to balance vegetative and atmospheric water demand, the frequency and/or length of drought on the Prairies is likely to increase.

The first step in understanding droughts is to understand and quantify the hydrological cycle of the Prairies. Due to the various networks of weather stations on the Prairies, precipitation can be quantified. However, once rain or snow has reached the earth's surface we are no longer able to fully track its movement. Very little rainfall runs off into the surface drainage network; the bulk of precipitation infiltrates into soil where it remains until it either drains into below ground aquifers or is transported back into the atmosphere via evapotranspiration. In order to monitor soil water content directly, a network of soil water sensors would have to be established on the Prairies. Due to the labour and infrastructure required it is an unlikely scenario. As a result, soil water content is not monitored on a systematic on-going basis on the Canadian Prairies. Soil moisture content can change rapidly and this lack of knowledge about current levels is concerning since it leaves a considerable knowledge gap in the state of hydrological cycle. Alternatively, models can be used to simulate components of the water cycle in order to derive estimates of soil water content and evapotranspiration. One such model is the second generation Prairie Agrometeorological model (PAM2nd). PAM2nd was selected for this study becasue it was developed as an operational model for the Canadian

Prairies. PAM2nd was developed to model the water cycle for an agricultural surface using minimal surface weather parameters (minimum/maximum air temperature and rainfall) in order to maximize the number of available weather stations. The use of these surface weather parameters is important since the major meteorological networks in Canada measure only these parameters.

At the time of development, PAM2nd was validated under limited conditions. The first objective of this study was to validate, and if necessary modify, the soil water and crop components of PAM2nd using measurements of various soil and climatic conditions in Manitoba and Saskatchewan that are representative of the Canadian Prairies. Model validation was conducted using an extensive meteorological database collected over the growing seasons of 2003-2006 in Melfort, Swift Current and Regina, Saskatchewan and Carman and Winnipeg, Manitoba. The second objective of this study was to compare the modeled estimates of evapotranspiration to two other commonly used methods; the FAO56 Penman-Monteith and simplified water balance method.

Soil water and evapotranspiration monitoring is not only important in understanding droughts but also in weather forecasting and agronomic risk assessment in the various environmental conditions that are present on the Canadian Prairies. Soil moisture and evapotranspiration have a direct effect on the energy balance which in turn affects surface temperatures and moisture cycling. Daily and seasonal changes in the energy balance affect both the weather and climate of a region. Since moisture is a limiting factor in crop production, a soil moisture monitoring system would help optimize crop selection in regions that are not conducive to a certain crop due to excess or lack of moisture. Another agronomic benefit would be in pest and disease management. The moisture status has a direct effect on the development and severity of weeds, insects and fungal diseases. As a result, pest models often need soil moisture as an input parameter. Results from this study will provide us with an indication of how accurately we can simulate these components of the hydrological cycle using PAM2nd.

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2. Improvements to the Accuracy of the Modeled Soil Water Content from the 2nd Generation Prairie Agrometeorological Model

2.1 Abstract

The direct measurement of soil moisture on a regional basis is often not practical due to the large instrumental and labour requirements. Alternatively, soil moisture estimates can be derived using models. The 2nd Generation Prairie Agrometeorological Model (PAM2nd) models soil water, crop development and evapotranspiration in order to derive an estimate of crop water demand and use for agricultural crops. Modeling soil moisture on a regional basis has many applications for drought monitoring, agronomic risk assessment, crop yield estimates and weather forecasting.

At the time of development, PAM2nd was validated for spring wheat using data collected from Kenaston, Outlook and Saskatoon, Saskatchewan. The objective of this study was to validate, and if deemed necessary modify, the soil water component of PAM2nd for spring wheat. Model validation was conducted using detailed surface weather and soil water measurements collected from spring wheat test plots at Melfort, Swift Current, Regina, Winnipeg and Carman during the 2003 to 2006 growing seasons to test the model under various soil and climatic conditions.

Comparison of measured and modeled soil water from the original version of PAM2nd yielded a RMSE of 62 mm (12% of field capacity). The original version of PAM2nd overestimated total soil water for the second half of the growing season for most site years. It was determined that modeled canopy resistance increased prematurely, before the crop would normally experience water stress. The canopy resistance function

was modified so canopy resistance would not start to increase until the soil water content was below 50% of plant available water. Overall this modification improved the RMSE to 56 mm (11% of field capacity). The greatest improvement to modeled soil water was observed in Melfort 2003 and Carman 2004, with improvements of 24 mm and 23 mm, respectively.

In addition, modeled soil water was underestimated during periods that experienced consecutive days of precipitation. This underestimation was a result of infiltration being stopped when the top-zone reached saturation. The model was modified to allow infiltration of water to continue independent of the top-zone's water content. This modification improved modeled soil water during periods of consecutive precipitation events. With the addition of this modification RMSE over all sites was further improved to 53 mm (10% of field capacity). The RMSE of soil water at Regina 2004 and Carman 2005 was improved by 15 mm and 22 mm, respectively.

Overall both modifications reduced the RMSE of modeled soil water by 9 mm or 2% of field capacity. The validation conducted in this study gives an indication of the accuracy of modeled soil water by the original version of PAM2nd and the modified version, PAM2$^{nd}_{1+2}$. Improving the soil water balance increases our confidence in the simulation of the evapotranspiration component of the model.

To simulate a scenario where soil characteristics were not measured at each site, PAM2$^{nd}_{1+2}$ was initialised using saturation, field capacity and permanent wilting point values obtained from soil survey data from the Soil Landscapes of Canada database. With these generalised input parameters, the RMSE increased from 53 mm to 63 or 80 mm of soil water, depending on which Carman soil was used. The model is very sensitive to the soil water holding capacity parameters and as a result accuracy of the model will be compromised if unrepresentative values are used.

2.2 Introduction

The monitoring of soil moisture in the agricultural region of the Canadian Prairies has many applications to farmers, hydrologists and meteorologists. Growing conditions on the Prairies are often under a moisture deficit and soil moisture is considered the main limiting factor for crop growth on the Prairies (Raddatz et al., 1994, DeJong and Bootsma, 1996). Crops vary in their water requirements, as such, crop water demand and moisture availability must be considered during crop selection. Detailed regionally specific soil moisture monitoring programs would provide economically beneficial information to producers.

A further limitation to crop production is the occurrence of droughts. The drought of 2001-2002 on the Canadian Prairies was one of the most severe on record (Bonsal and Regier, 2007). Due to the drought several provinces posted a negative or zero net farm income (DRI, 2008). It is estimated the Gross Domestic Product of Canada decreased by approximately 5.8 billion dollars during the drought years of 2001/2002 (DRI, 2008). Although droughts are common on the Prairies little is known about what initiates, maintains (Liu et al. 2004) and terminates these extreme events. High resolution soil moisture monitoring would provide significant insight in drought development, progression and termination.

Soil water content can be measured using several different techniques. Direct measurement of soil water is commonly conducted using the gravimetric technique. This technique is labour intensive, especially at depth, and is not practical in order to monitor large areas of land. Direct methods such as time domain reflectometry are less labour intensive; however a vast network would be required in order to obtain regional measurements. As a result, soil water content is not monitored on a systematic on-going basis on the Canadian Prairies. Soil moisture content can change rapidly and this lack of knowledge about current levels is concerning since this leaves a considerable knowledge gap in the state of the hydrological cycle at any given point in time.

To fill this knowledge gap, models such as the 2^{nd} Generation Prairie Agrometeorological model ($PAM2^{nd}$) (Raddatz, 1993) can be used to estimate soil water. $PAM2^{nd}$ estimates soil water content using a simplified water balance approach. To maximize spatial resolution of the estimates, the model was designed to use minimal surface meteorological inputs in order to maximize the number of weather stations that could be used (Hochheim et al., 2002). Due to the scarcity of meteorological stations on the Canadian Prairies and their limited instrumentation, this approach is essential in order to obtain soil water measurements from sufficient locations to be representative of the variation across the Prairies. At the time of development, the model was validated for spring wheat using data collected from Kenaston, Outlook and Saskatoon, Saskatchewan. However a more rigorous validation that encompasses the various soil and climatic conditions present throughout the Prairies would be very useful to verify the general applicability of the model in this region.

PAM2nd may be viewed as a modified version of the first-generation Prairie Agrometeorological Model (Raddatz, 1989). Major modifications of the first-generation model include the modeling of the atmospheric boundary layer and a vapour density deficit/resistance approach to estimating evapotranspiration (Raddatz, 1993). The first-generation model estimated evapotranspiration using the empirical Baier and Roberston method (Raddatz, 1989; Baier and Robertson, 1965). A comparison between the first and second generation PAM has been previously made for simulating water-use by potatoes (Raddatz et al., 1996).

The first objective of this study was to validate the soil water component of PAM2nd for spring wheat using detailed soil water and meteorological measurements obtained from five different locations in Manitoba and Saskatchewan. The second objective was to modify the model to improve the simulation of the water balance, if deemed necessary. This study was unique because the modeled soil water content of PAM2nd has never been tested under various environmental conditions over several consecutive growing seasons. Once successfully calibrated, PAM2nd could be implemented to monitor soil water conditions on the Canadian Prairies. Improved accuracy of modeled soil water will also increase the confidence in the accuracy of modeled evapotranspiration.

2.3 Methods

2.3.1 Site Description

Field sites were established in Melfort (SK), Swift Current (SK), Regina (SK) and Winnipeg (MB) in 2003 to 2006. A site in Carman (MB) was added in 2004 and continued until 2006. The Saskatchewan sites were located at Agriculture and Agri-Food Canada research facilities while the Manitoba sites were located at the University of Manitoba's agricultural research facilities. These sites span the various soil and climatic conditions on the Canadian Prairies. Since environmental conditions varied between sites and years, this provided 19 different environmental conditions for model validation.

Melfort is located in the transition between the Black and Grey soil zones and receives an average annual precipitation of 412.5 mm (Environment Canada, 2008). Swift Current is located in the Brown soil zone and is generally much drier, receiving an annual average precipitation of 349.1 mm (Environment Canada, 2008). Regina is part of the Dark Brown soil zone and receives an annual average precipitation of 388.1 mm (Environment Canada, 2008). Winnipeg is located in the Black soil zone and receives an annual average precipitation of 513.7 mm. Carman is also located in the Black soil zone and generally is the wettest climate of all the study sites, receiving an annual average precipitation of 542.3 mm (based on the Elm Creek weather station) (Environment Canada, 2008).

The plots were originally established for the purpose of testing the effects of weather on spring wheat yield and quality response. Each location consisted of a randomized complete block design with three replicates of six different varieties of spring wheat.

2.3.2 Soil Water Model Description

The soil profile of PAM2nd is divided into three sections; the top-zone, the root-zone and the sub-zone with a total depth of 120 cm. The top-zone is a fixed 10 cm depth contained within the root-zone. The top-zone soil water balance is determined using Equation 2.1 on a daily basis; where JD is Julian day. C_1 is the parameter used to determine the proportion of evapotranspiration attributed to the top-zone. The evaporation term is based solely on the top-zone's water content. Since the top-zone is also part of the root-zone, transpiration also depletes the top-zone's water content. The top-zone is recharged through precipitation (P) and through vapour flux from the root-zone when the volumetric soil moisture of the top-zone (θv_{tz}) is drier then the root-zone (θv_{rz}). The vapour flux into the top-zone occurs during the night as a result of the change from warmer to cooler soil temperatures. τ is the portion of night-time hours in each day. C_2 is a coefficient that characterizes the rate of which the top-zone and root-zone are restored to equilibrium (Raddatz, 1993). The upper limit of water content (wc) is saturation and the lower limit is 10% of the permanent wilting point.

$$wc_{tz} = wc_{tz(JD-1)} - (C_1ET-P) - \tau C_2(\theta v_{tz} - \theta v_{rz}) \qquad (2.1)$$

The root-zone's water balance is determined via Equation 2.2, where P_i is the infiltrated precipitation. The root-zone's water balance is adjusted on a daily basis to include any growth of the root zone (rz). Root-zone growth is simulated daily using a biometeorological growth function (Robertson 1968) from a modified version of the approach used by Rasmussen and Hanks (1978). The root zone is assumed to be 5 cm deep at seeding. The upper limit of the root-zone's water holding capacity is field capacity and permanent wilting point as the lower limit.

$$wc_{rz} = wc_{rz(JD\text{-}1)} - (ET\text{-}P_i) + \theta v_{sz}\,(rz_{(JD)} - rz_{(JD\text{-}1)}) \qquad (2.2)$$

Equation 2.3 describes the sub-zone's water balance. The depth of the sub-zone decreases as the depth of the root-zone increases through the growing season. Infiltration (Inf) into the sub-zone occurs when the root-zone water content exceeds field capacity. Deep drainage (DD) occurs when the sub-zone's water content exceeds field capacity.

$$wc_{sz} = wc_{sz(JD\text{-}1)} + Inf - DD \qquad (2.3)$$

Infiltration of rain into the root-zone is a function of the water holding capacity and the top-zone's water content. The amount of infiltration that occurs from a given rainfall event is limited by the available space below field capacity within the root-zone. In addition, infiltration is stopped when the top-zone reaches saturation. Any additional precipitation is assumed to run off. To simulate run-off during large rainfall events, infiltration is reduced when rainfall exceeds 25.4 mm.

Water uptake is controlled by three resistance terms. The evaporation flux is restricted by a soil resistance term (r_g) which restricts the movement of water from the top-zone to the soil's surface. The transpiration flux is restricted by a bulk canopy resistance term (r_c) which reflects the physiological resistance of the entire crop. Canopy resistance is calculated as a function of fractional leaf area (L_A) and the fraction of soil water that is plant available (PAW) (Equation 2.4).

$$r_c = \frac{r_{c\min}}{(L_A)(PAW)} \qquad (2.4)$$

Where r_{cmin} is the minimum canopy resistance for a given crop that has no water stress (PAW = 1) and a full canopy (L_A = 1). In this study r_{cmin} was assigned a value of 0.8 s cm^{-1}, which is within the range of published values for spring wheat (Kelliher et al., 1995 and Shen et al., 2002)

A stability adjusted aerodynamic resistance term (r_a) which reflects the atmospheres ability to transport water vapor is used to restrict both the evaporation and transpiration flux. PAM2nd calculates r_a by simulating the vertical profile of the planetary boundary layer. A more detailed description of PAM2nd can be found in the publication by Raddatz (1993).

2.3.3 Meteorological Data

An automated weather station was set-up adjacent to every field site. The weather stations measured air temperature, wind speed, relative humidity, solar radiation and soil temperature as hourly averages. Rainfall was measured using two tipping bucket rain gauges and averaged for a daily total. Any gaps in weather data were filled using observations from the nearest Environment Canada meteorological station. Surface meteorological measurements used for operation of PAM2nd were daily minimum and maximum temperatures and total daily precipitation.

Upper atmospheric elements were interpolated from the regional Global Environmental Multiscale (GEM) model gridded output. Upper atmospheric data included air temperature, wind speed, dew point depression and geopotential height for the standard levels of 1000 mb, 850 mb, 700 mb and 500 mb. Site specific upper atmospheric data was obtained for Melfort, Swift Current and Carman. The Regina airport was used for the Regina site and Glenlea was used for the Winnipeg, University of Manitoba research site.

Roughness length for the wheat plots was approximated as 10% of crop height (Oke, 1987). Since crop height was not monitored, a maximum height of 1.2 m was assumed. Roughness length was constant for the entire growing season since PAM2nd does not account for changes in roughness length as the crop grows. Terrain drag coefficients (drag due to terrain relief) were obtained at each station by interpolating values from a 381 km grid (Cressman, 1960) down to a 47.6 km grid (Raddatz and Khandekar, 1977).

2.3.4 Soil Moisture Measurements

Soil water was measured using a Troxler Model 4302 neutron probe. In order to obtain a representative measure at each site, neutron probe access tubes were installed in the plots for all three replicates of two of the wheat varieties as well as one in the buffer plot adjacent to the weather station for a total of seven measurements at each site. The access tubes were placed at least 1 m from the edge of the plots. Soil water content was measured at 22.5 cm, 37.5 cm, 52.5 cm, 75 cm and 105 cm depths to represent water contents for the 15-30 cm, 30-45 cm, 45-60 cm, 60-90 cm and 90-120 cm horizons respectively. Due to the limitations of using a neutron probe for surface measurements, the water content for the top 15 cm was determined gravimetrically. Total soil water content for the entire 120 cm was calculated as a sum of these depths. An average of the seven soil water measurements were used to characterize the soil water content at each study site. Soil water measurements were taken weekly and bi-weekly in Manitoba and Saskatchewan, respectively.

Calibration of the neutron probe was conducted by correlating the neutron count ratio to an independent gravimetric measure of soil water content (Evett, 2003). Gravimetric water contents were obtained from each location for the entire 120 cm profile several times throughout the growing seasons to obtain measurements during both wet and dry conditions. Since neutron probe calibration is sensitive to clay content (Evett, 2003), separate calibration curves were created for each soil texture present at the study sites. Using the corresponding neutron probe calibration equation, moisture content was determined for all five depths.

PAM2nd requires an initial spring moisture measurement for the entire 120 cm profile as well as the top 10 cm. These measurements were taken gravimetrically during the installation of the neutron probe access tubes shortly after seeding. Initial top zone (top 10 cm) water content was approximated as 2/3 of the 0-15 cm measurement.

2.3.5 Measured Soil Water Holding Parameters

Field capacity was measured in the first year of study at each site (Appendix A). Field capacity was determined by setting up a 1 m by 1 m wooden frame close to the wheat plots, saturating the soil with approximately 20 cm of water and then covering the area with a plastic tarp to prevent evaporation. The soil was assumed to have attained field capacity after 3 days. Soil water content was determined gravimetrically using a soil auger to a depth of 120 cm.

Permanent wilting point was determined from composite samples of each of the six depths using a pressure membrane apparatus. Permanent wilting point was assumed to be 1.5 MPa. After the samples equilibrated the soil water content was determined gravimetrically.

Percent soil saturation was determined to equal the total porosity of the soil at each location (Equation 2.5).

$$\text{Saturation (\%)} = 1\text{-}\left(\frac{BulkDensity}{ParticleDensity}\right) \qquad (2.5)$$

where bulk density was determined at each location and particle density was assumed to be 2.65 g cm^{-3}. This approximation of saturation was problematic for Regina as percent saturation was calculated to be less than field capacity. As a result, percent saturation was set equal to field capacity in Regina.

2.3.6 Soil Survey Soil Water Holding Parameters

In order to simulate a more realistic scenario, another model run was conducted where soil water content was simulated using PAM2nd without site specific measurements of field capacity and permanent wilting point (Appendix B). Sensitivity to these parameters was assessed by comparing modeled soil water to the original model run that used measured values. Field capacity and permanent wilting point values for each location were obtained from the Soil Landscapes of Canada (SLC) database compiled by Agriculture and Agri-Food Canada (Soil Landscapes of Canada Working Group, 2007).

The Soil Landscapes of Canada database generalises the soils on the Prairies using soil polygons. Each soil polygon contains detailed information on the various soil types, with each soil type reported as a percentage of the soil polygon. The data is mapped on a 1:1 million scale and as a result the soil polygons can be hundreds of thousands of hectares. For this scenario, water holding parameters from the dominant soil were selected (Appendix B). In the soil polygon where the Carman site is located there were two equally dominant soil types, both representing 20% of the soil polygon and both significantly different soil types. Without further information on the location of these soils within the polygon, it is not possible to select one soil over the other. As a result, soil water was simulated using both soil types represented as Carman 1 and Carman 2.

For the SLC polygons used for this study, soil properties were reported for various depths and increments from the surface to 100 cm. Since PAM2nd requires the water holding capacity for a depth of 0-120 cm, the properties of the 100 cm depth were assumed to represent the 100-120 cm depth as well. To obtain a single saturation, field capacity and permanent wilting point value for the 120 cm profile, a weighted average of the various measured depths were used.

As reported in the SLC database, saturation, field capacity and permanent wilting point was determined to be the water retained at 0 kilopascals, 33 kilopascals, and 1500 kilopascals respectively. An alternate definition of field capacity is the water retained at

10 kilopascals which is also reported in the SLC database but was unavailable for the Saskatchewan sites. As a result the 33 kilopascal definition of field capacity was selected.

2.3.7 Soil Characteristics

Soil texture was determined via the hydrometer method for the 0-15 cm, 15-30 cm, 30-45 cm, 45-60 cm, 60-90 cm and 60-120 cm depths (Appendix A). Bulk density was measured in situ using an 11.5 cm diameter soil auger. Bulk density was determined at each site several times throughout each year for the same depths that soil texture was determined. Bulk density was determined to be the average of these measurements.

The model accepts only one soil texture per location, therefore the top 15 cm texture was used to obtain the C_2(ref) (Noilhan and Planton, 1989), b and si parameters (Cosby et al., 1984). Soil texture of the top 15 cm was used because the texture dependent values of C_2(ref), b and si are utilized only to calculate the top-zone water balance (Appendix C).

2.3.8 Statistical Procedure

To evaluate the performance of the soil moisture component of the model, modeled soil moisture was compared to the weekly/bi-weekly measurements of soil moisture. A RMSE (root mean square error) analysis of this data was conducted. RMSE was calculated by Equation 2.6.

$$\mathrm{RMSE} = \left(\frac{\sum (\mathrm{mod.} - obs.)^2}{n} \right)^{0.5} \quad (2.6)$$

where *mod.* is the modeled soil water by PAM2$^{\mathrm{nd}}$, *obs.* is the observed soil moisture at the field sites and n is the number of field observations. Observed soil water measurements were compared to modeled soil water estimates for the corresponding days.

The mean bias error (MBE), Equation 2.7, was calculated to determine whether the PAM2nd over or underestimates soil water compared to measured values. Negative values of MBE represent underestimation, while positive values represent overestimation. A MBE of zero represents equal distribution of positive and negative differences.

$$MBE = \frac{1}{n}\left[\sum_{i=1}^{N} (M_i - O_i)\right] \quad (2.7)$$

where M is the modeled soil water on day i and O is the observed soil moisture for that day. The observed soil water contents are an average of the seven sampling sites at each location. To express the spatial variability in soil water content at each site, the standard deviation of observed soil water content was determined.

2.4 Results and Discussion

2.4.1 Growing Season Weather Summary

The 2003-2006 growing seasons in Saskatchewan and Manitoba experienced a range of weather conditions (Table 2.1). In 2003, much of Saskatchewan and Manitoba were experiencing a drought which started in 1999. The sites that were the hardest hit by the drought in 2003 were Swift Current and Regina, receiving only 81 mm and 72 mm for the entire growing season, respectively. In 2004, the Prairies started to recover from the drought but experienced much cooler mean growing season air temperature. Melfort and Swift Current experienced a mean growing season air temperature of only 14.4 °C. Regina, Winnipeg and Carman all received snow in mid May resulting in delayed seeding and harvest dates. In 2005, Melfort and Winnipeg experienced very wet growing conditions, receiving 341 mm and 424 mm of precipitation. In 2006, most sites experienced warmer mean air temperature compared to the previous 2 years. For Winnipeg and Carman, the lowest amount of rainfall accumulated in 2006, only 134 mm and 116 mm, respectively. However moisture stress was limited due to the high spring volumetric content.

Table 2.1 Summary of spring volumetric water content, growing season precipitation and mean air temperature.

Year	Site	Spring Volumetric Water Content (%)	Growing Season* Precipitation (mm)	Mean Growing Season* Air Temperature (°C)
2003	Melfort	44.3	129	17.2
	Swift Current	24.0	81	18.1
	Regina	51.0	72	19.3
	Winnipeg	44.7	200	23.4
2004	Melfort	45.7	235	14.4
	Swift Current	22.4	192	14.4
	Regina	43.7	241	15.3
	Winnipeg	45.5	268	16.4
	Carman	39.8	153	16.1
2005	Melfort	39.9	341	15.2
	Swift Current	24.9	163	15.5
	Regina	45.7	192	16.6
	Winnipeg	45.7	424	18.9
	Carman	30.0	274	19.2
2006	Melfort	33.5	198	17.1
	Swift Current	37.2	174	17.6
	Regina	45.1	118	18.1
	Winnipeg	46.5	134	18.6
	Carman	37.6	116	20.0

* from crop emergence until maturity

2.4.2 Original PAM2nd Model Assessment of Soil Water Content

Model performance varied with the range of soil and weather conditions throughout the 2003 to 2006 growing seasons. Accuracy of modeled soil water was conducted for the entire soil profile (0-120 cm), referred to in this text as “total soil moisture or water”. The original version of PAM2nd (PAM2$^{nd}_{0}$) produced an overall average RMSE of 62 mm of soil water and a r^2 of 0.77 over the growing seasons of 2003 to 2006 (Table 2.2). PAM2$^{nd}_{0}$ performed most poorly in Melfort 2006. Although not indicated by the growing season precipitation, Melfort 2006 was wet with a high water table, a remnant from a very wet season the previous year. PAM2$^{nd}_{0}$ does not take into account any upward movement of water from the water table into the root zone. During field measurements, it was clear that the water table was less than 1 m from the soil surface. As a result, the measured soil water content was considerably higher compared to the modeled values. Daily measurements of the level of the water table are not readily available; therefore, no attempt was made to rectify this issue.

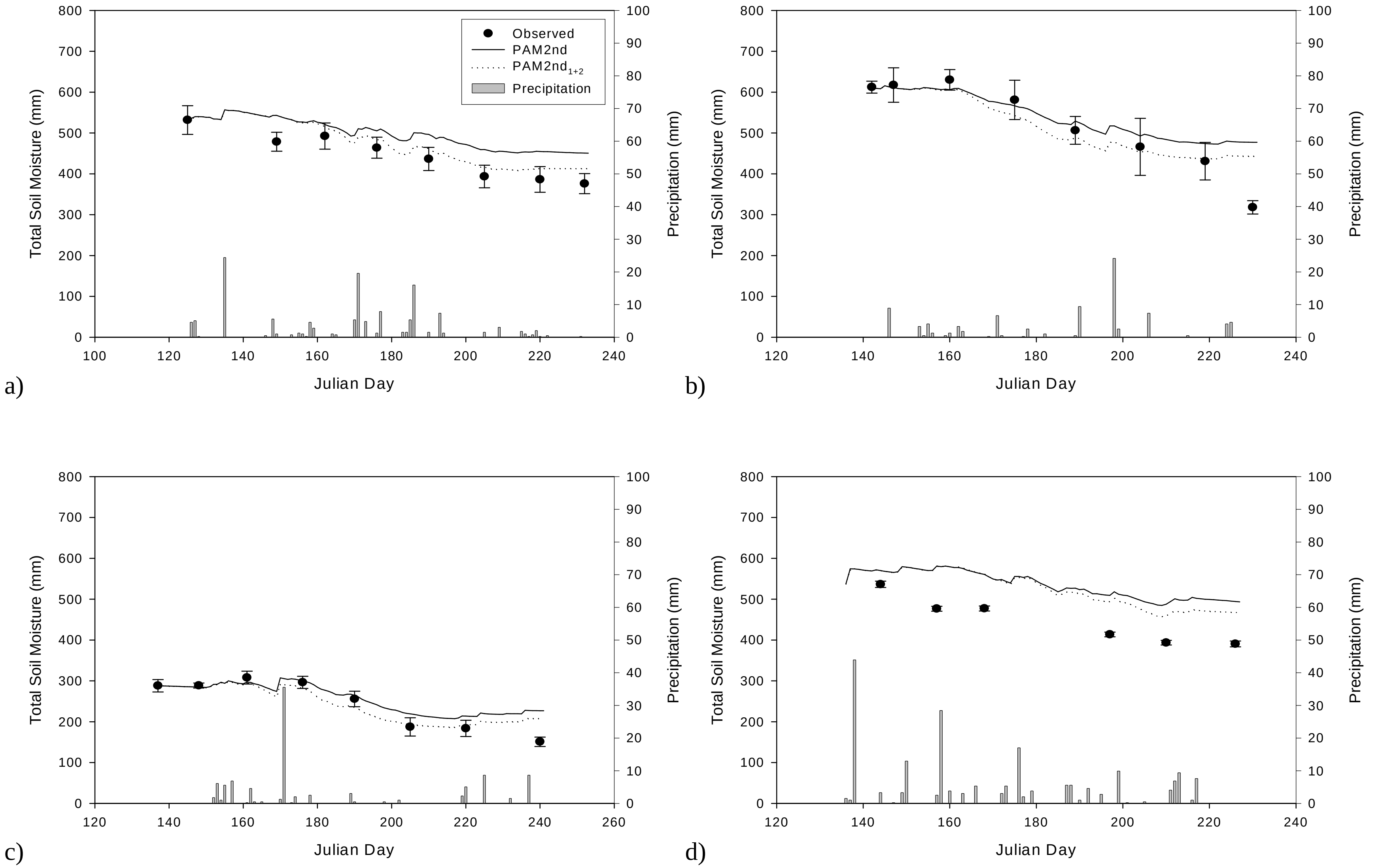
As indicated in Table 2.2 the majority of the site years contain measured soil water measurements above the measured field capacity values. Since the upper limit of the water holding capacity of the root-zone and sub-zone is field capacity, PAM2nd must discount any moisture above field capacity as deep drainage. Since only six site years do not have measured soil water values above field capacity, much of the error in modeled soil water may be a result of this restriction. The model is limited by field capacity since it is assumed that on a daily time step the soil profile would not remain at saturation for the entire day, but instead drain to field capacity. This error may be due to this assumption or in the measurement of field capacity.

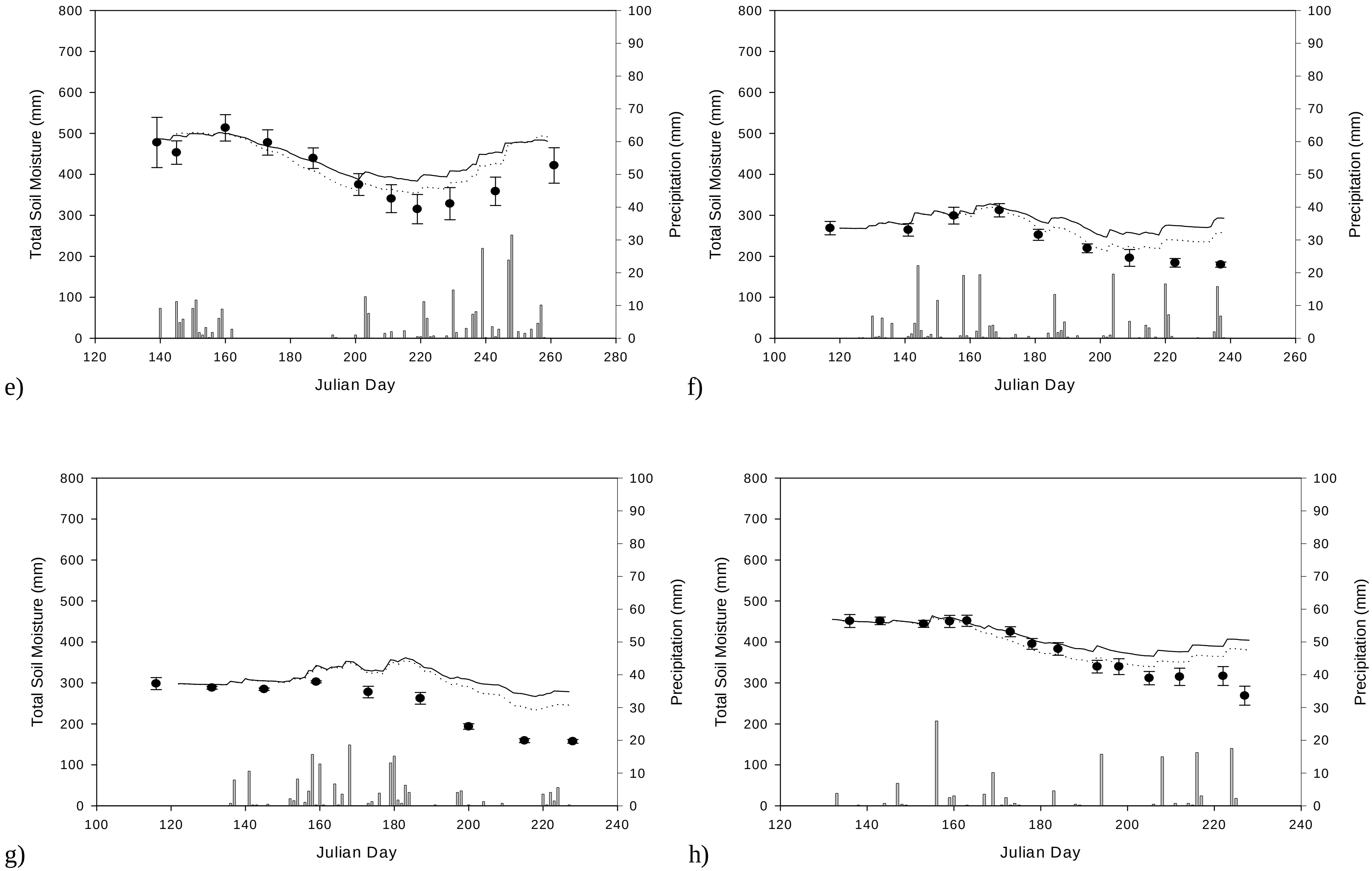
A general trend in many of the site years was the overestimation of modeled soil water, particularly for the second half of the growing season (Figure 2.1a-i). Often total soil water was modeled fairly well for the first half of the season but about the time of anthesis, modeled soil water would stay relatively constant or increase while observed soil water decreased. Another error in modeled soil water estimates was underestimation of soil water. This generally occurred in wetter years during periods that experienced several consecutive days of precipitation (Figure 2.2a-e). To reflect these general tendencies in modeling errors, model performance was characterized based site years that fell into one of three categories; overestimation of soil water (Figure 2.1), underestimation of soil water (Figure 2.2) and a third category which included site years that did not fall into the previous two categories (Figure 2.3). The “other” category included some site years that experienced both over and underestimation errors at different times throughout the growing season. Except for Swift Current, all locations are represented in each category, thus, model performance did not exhibit a non site-specific effect. Swift Current is categorized in the “overestimation” category for each year of the study.

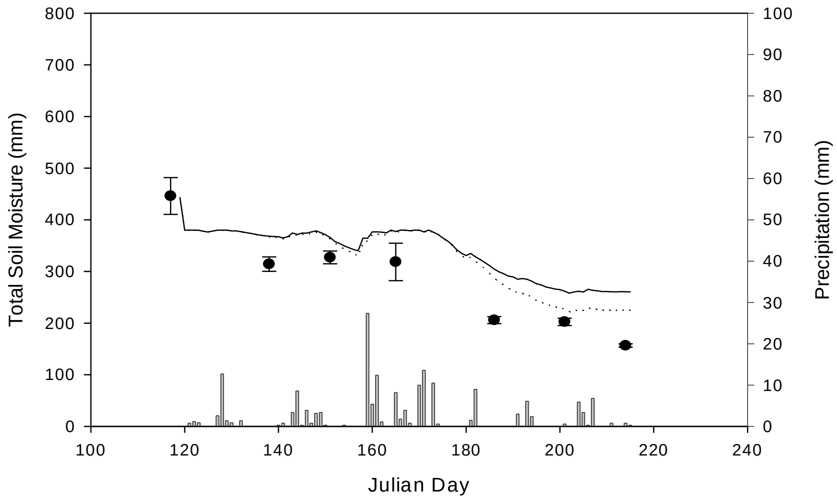
Table 2.2 Root mean square error (RMSE) of modeled versus observed soil water content (mm) of the $PAM2^{nd}_{0}$, $PAM2^{nd}_{1}$, $PAM2^{nd}_{2}$, $PAM2^{nd}_{1+2}$ versions of the model.

			RMSE (mm)			
Category	**Site**	**Year**	**$PAM2^{nd}_{0}$**	**$PAM2^{nd}_{1}$**	**$PAM2^{nd}_{2}$**	**$PAM2^{nd}_{1+2}$¶**
Overestimation						
	Melfort	2003	56	32	57	32 (6)
	Regina*	2003	60	48	61	48 (8)
	S.C.	2003	31	25	23	23 (6)
	Winnipeg	2003	89	76	90	77 (13)
	S.C.	2004	60	37	60	37 (10)
	Carman*	2004	50	36	51	36 (7)
	S.C.	2005	74	61	74	61 (16)
	S.C.*	2006	73	56	73	57 (15)
	Carman	2006	50	36	50	37 (7)
Mean			60	45	60	45 (10)
Underestimation						
	Regina*	2004	71	77	56	56 (9)
	Winnipeg*	2005	60	61	60	60 (10)
	Carman*	2005	72	80	50	51 (10)
	Melfort*	2006	102	109	100	107 (19)
	Regina*	2006	73	72	62	64 (10)
Mean			76	80	66	68 (12)
Other						
	Melfort*	2004	58	60	59	60 (11)
	Winnipeg*	2004	19	38	18	34 (6)
	Melfort*	2005	66	63	62	57 (10)
	Regina*	2005	80	64	85	72 (12)
	Winnipeg*	2006	30	36	31	36 (6)
Mean			50	52	51	52 (9)
Overall			**62**	**56**	**59**	**53 (10)**

* contains measured soil water above measured values of field capacity
¶ Values in parenthesis are reported as percent of field capacity

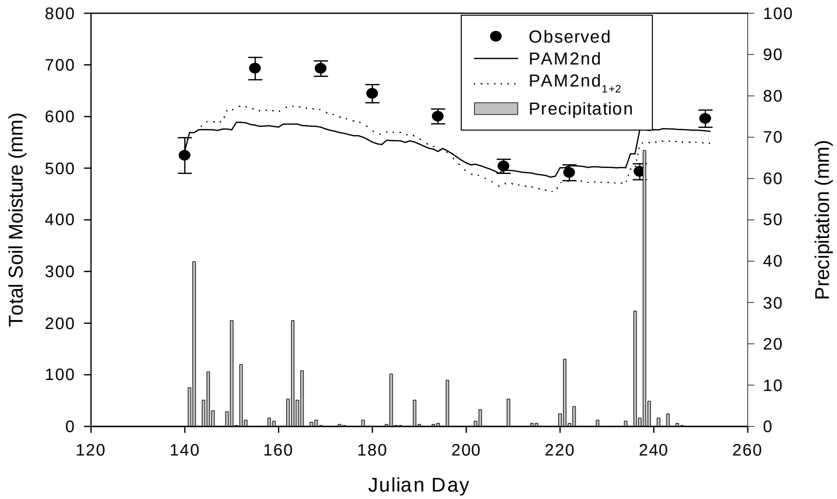

Observed
PAM2nd
PAM2nd1+2
Precipitation
Total Soil Moisture (mm)
Precipitation (mm)
Julian Day
a)
b)
c)
d)


Total Soil Moisture (mm)
Precipitation (mm)
Julian Day
e)
f)
g)
h)

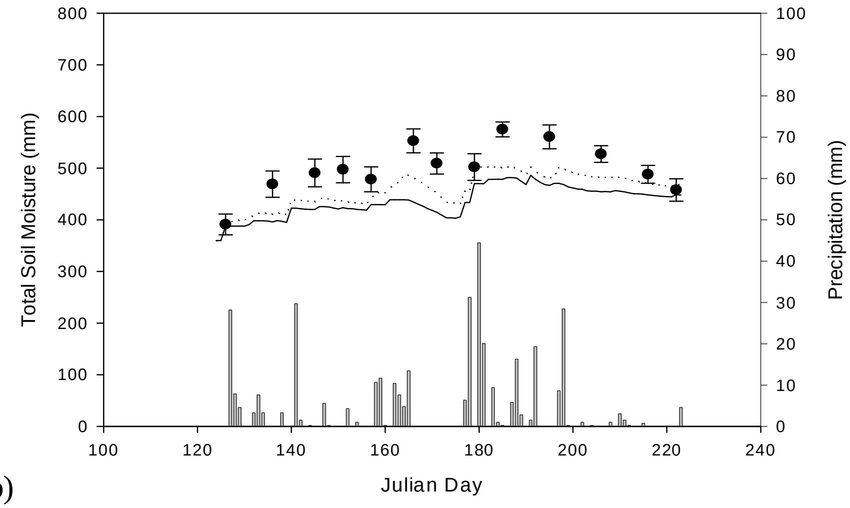


i)

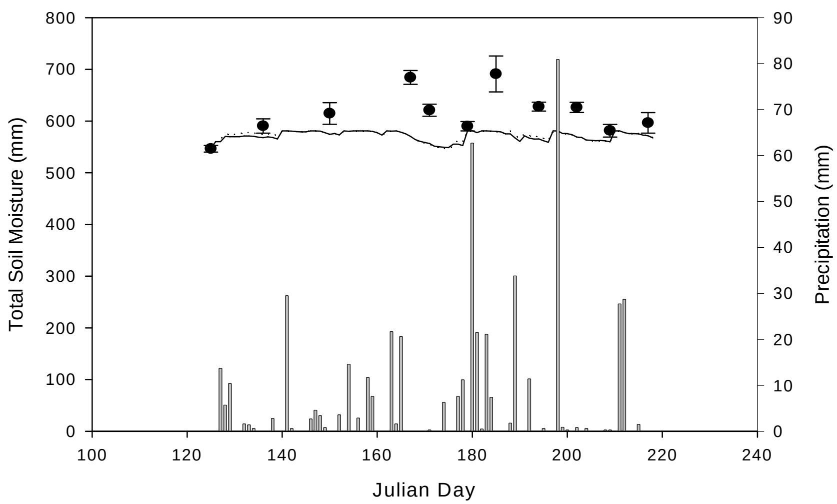
Figure 2.1 Comparison of observed soil water (120 cm profile) to modeled soil water from PAM2$^{nd}_{0}$ and PAM2$^{nd}_{1+2}$ for a) Melfort 2003 b) Regina 2003 c) Swift Current 2003 d) Winnipeg 2003 e) Carman 2004 f) Swift Current 2004 g) Swift Current 2005 h) Carman 2006 and i) Swift Current 2006. Error bars indicate one standard deviation.


Observed
PAM2nd
PAM2nd$_{1+2}$
Precipitation
Total Soil Moisture (mm)
Precipitation (mm)
Julian Day

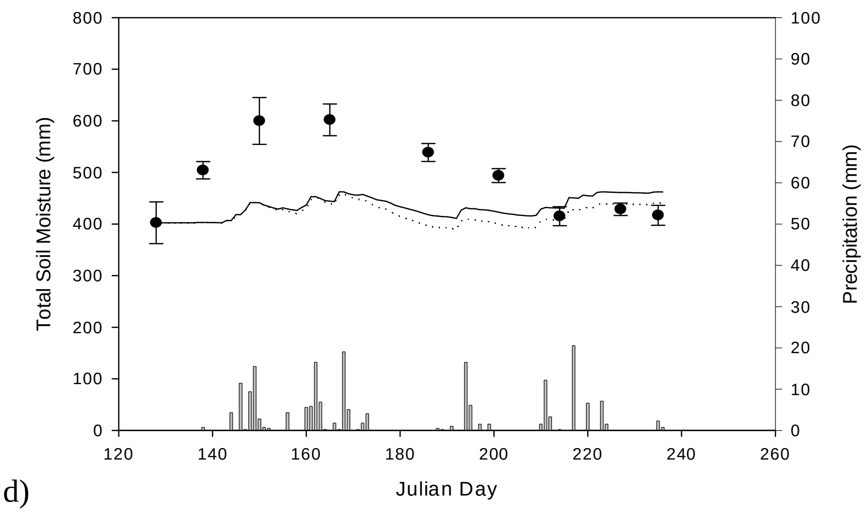
a)


Total Soil Moisture (mm)
Precipitation (mm)
Julian Day

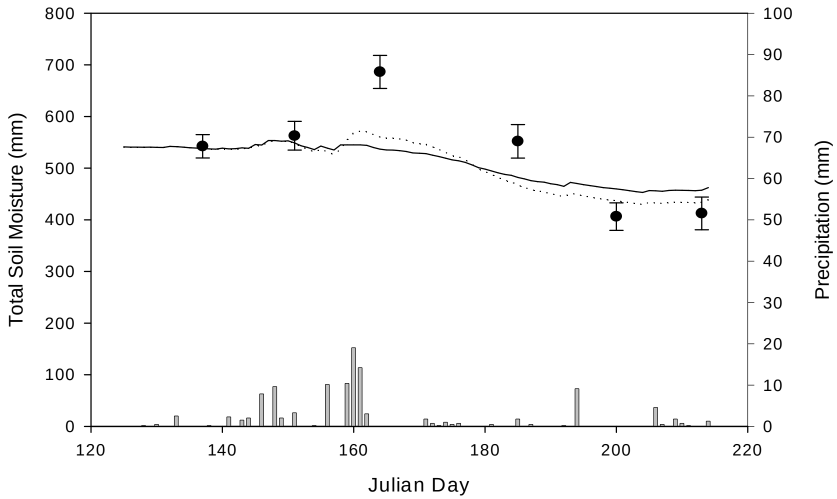
b)


Total Soil Moisture (mm)
Precipitation (mm)
Julian Day

c)

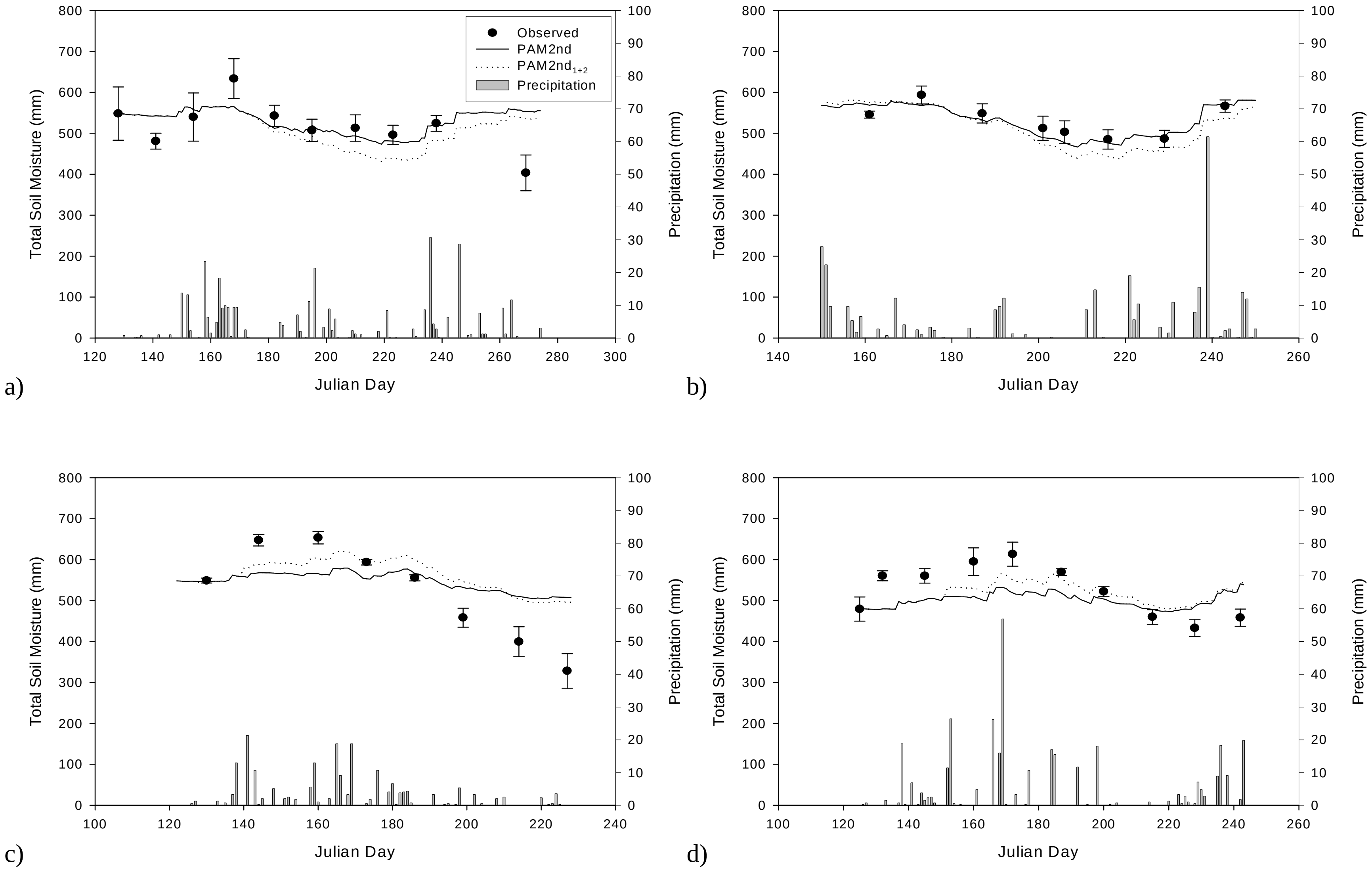

Total Soil Moisture (mm)
Precipitation (mm)
Julian Day

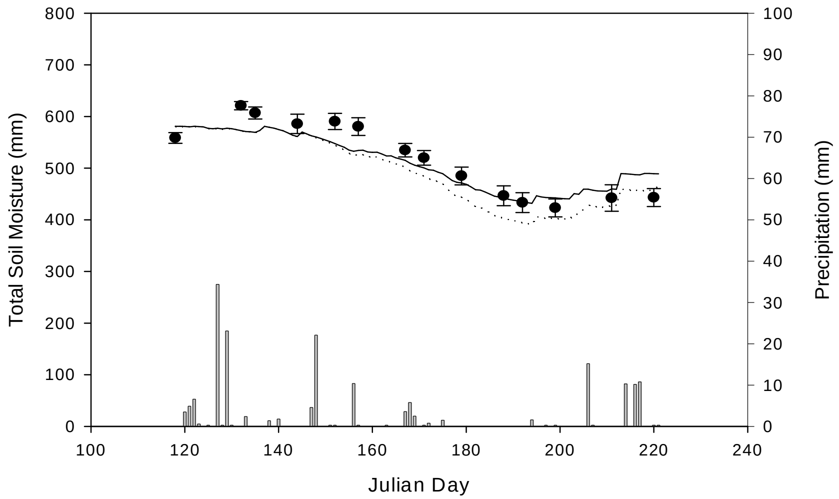
d)



e)

Figure 2.2 Comparison of observed soil water (120 cm profile) to modeled soil water from PAM2$^{nd}{}_{0}$ and PAM2$^{nd}{}_{1+2}$ for a) Regina 2004 b) Carman 2005 c) Winnipeg 2005 d) Melfort 2006 e) Regina 2006. Error bars indicate one standard deviation.


a)
b)
c)
d)
Observed
PAM2nd
PAM2nd$_{1+2}$
Precipitation
Total Soil Moisture (mm)
Precipitation (mm)
Julian Day



e)

Figure 2.3 Comparison of observed soil water (120 cm profile) to modeled soil water from $PAM2^{nd}_{0}$ and $PAM2^{nd}_{1+2}$ for a) Melfort 2004 b) Winnipeg 2004 c) Regina 2005 d) Melfort 2005 e) Winnipeg 2006. Error bars indicate one standard deviation.

2.4.3 Modification of Modeled Canopy Resistance

The original version of the model, $PAM2^{nd}_0$, overestimated soil water content for 9 out of the 19 site years. With the exception of Winnipeg 2003 (Figure 2.1d), at all of these site years the overestimation occurred during the second half of the growing season (Figure 2.1). Since the overestimation was specific to the second half of the growing season this implied that it was likely linked to crop development. Initially the crop growth function was investigated to solve the problem. Validation of this function was limited due to the lack of actual fractional leaf area data. However, the maximum fractional leaf area corresponded reasonably well with the observed heading and anthesis dates, the crop stages at which fractional leaf area would be at its maximum. In addition, preliminary experimentation with the fractional leaf area function to smooth out the growth curve and prolong the period of minimum canopy resistance did not address the overestimation of late season soil moisture.

Another component of the model that is linked to crop phenology is canopy resistance (Equation 2.4). Canopy resistance for wheat increases with a decrease in green canopy and soil water content (Shen et al., 2002). During the second half of the growing season, the crop starts to senesce and the soil is typically at its driest level since crop demand often exceeds water supply on the Canadian Prairies.

In the $PAM2^{nd}_0$ simulation, canopy resistance increased as soon as soil water fell below field capacity (Figure 2.4). This implied that the crop experiences some water stress as soon as water content is below field capacity. However, a study conducted by Shen et al. (2002) demonstrated that canopy resistance for wheat does not start to increase until soil water content drops below a threshold of 50% plant available water. For plant available water less than 50% of capacity, canopy resistance is inversely proportional to soil moisture, whereas, for plant available water greater than 50% of capacity, canopy resistance is reasonably stable and is considered to be at its minimum (Shen et al., 2002). Similarly, Allen et al. (1998) stated that crops do not experience water stress until the readily available water (RAW) has been depleted (Allen et al. 1998). RAW is calculated as the fraction of total plant available water in the root zone the crop can take up before the crop starts to experiences water stress (Allen et al. 1998).

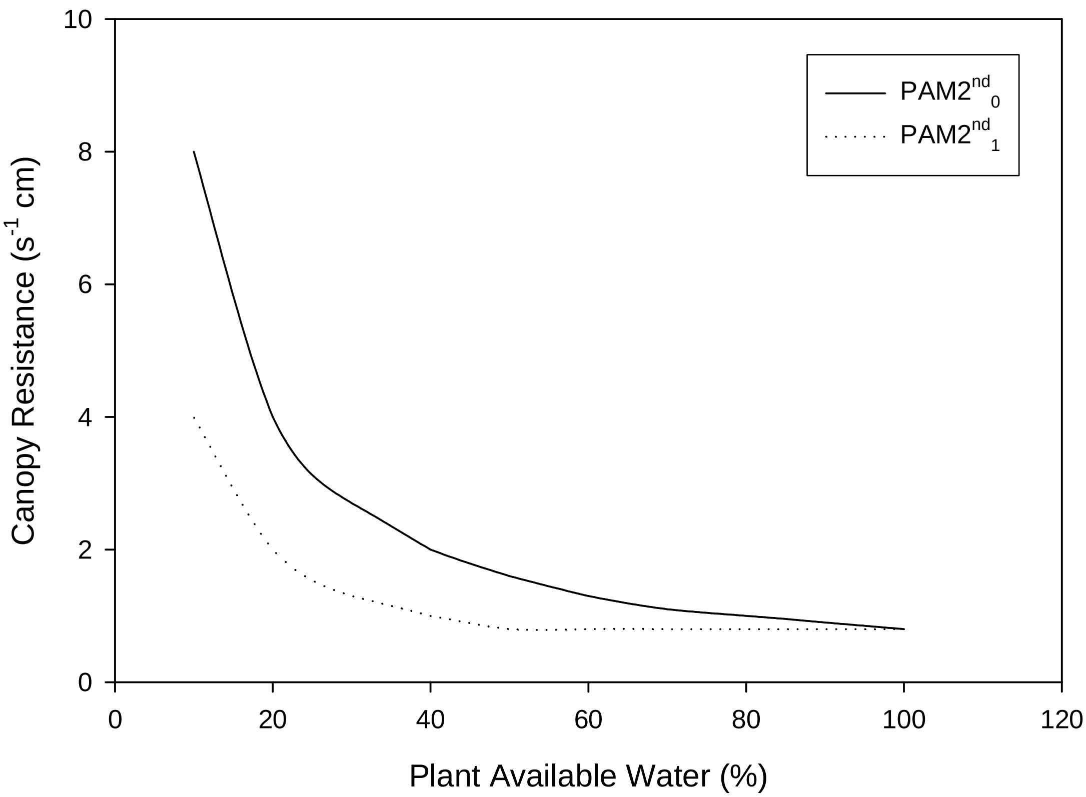


Figure 2.4 Canopy resistance curves as a function of plant available water at a fractional leaf area of 100% for $PAM2^{nd}_0$ and $PAM2^{nd}_1$.

It was determined that canopy resistance was increasing too soon and too rapidly as soil water content decreased, resulting in decreased rates of modeled evapotranspiration and overestimation of soil water. In an attempt to improve this aspect of the model, a modification was introduced and designated as $PAM2^{nd}_{1}$. In this modified version of the model, 50% of total plant available water was selected as the threshold where canopy resistance starts to increase. As a result, the simulation of canopy resistance in $PAM2^{nd}_{1}$ was modified as follows:

$$r_C = \frac{r_{C\min}}{(L_A)(PAW)}$$

$$PAW = \frac{W_A - W_{PWP}}{W_{FC} - W_{PWP}}$$

If PAW > 50% then PAW = 1, else PAW = 2*PAW

where r_{cmin} is the minimum canopy resistance, PAW is the fraction of soil water that is plant available, W_A is the actual soil water content, W_{FC} is water content at field capacity and W_{pwp} is water at the permanent wilting point of the root zone. Applying this modification limited any increase in canopy resistance due to reductions in soil moisture until soil water content was below 50% of PAW and decreased the maximum canopy resistance that occurs as PAW approaches the permanent wilting point (Figure 2.4).

The modified canopy resistance term generally lowered canopy resistance for the entire growing season (Appendix D), maintaining the characteristic U-shaped trend associated with crop growth (Shen et al., 2002). The greatest change in modeled canopy resistance occurred at the beginning and at the end of the growing season. During these periods, canopy resistance was often stable near 2.7 s cm^{-1} since fractional leaf area has a minimum of 0.3 for the canopy resistance function and the plant available water has not been depleted. In some cases the modified canopy resistance term increased canopy resistance compared to the original version (Appendix D, Figure A.1b, c, h). In all three cases, the higher values of resistance occurred during the senescence period of the crop resistance curve. This occurred because the modification allowed the soil to dry out more rapidly once it fell below 50% PAW. During mid-season, the canopy resistance also frequently attained the minimum value of 0.8 s cm^{-1}. In the $PAM2^{nd}_{0}$ version, this minimum canopy resistance value was rarely attained since soil water content was rarely at field capacity during maximum fractional leaf area and r_c was reduced whenever soil moisture levels were below field capacity.

The $PAM2^{nd}_{1}$ modification to the model lowered the overall RMSE from 62 mm to 56 mm (Table 2.2). The greatest improvement in modeled soil water was observed in the site years where it was determined overestimation of soil water was occurring. $PAM2^{nd}_{1}$ lowered the RMSE of the "overestimation" category from 60 mm to 45mm (Table 2.2). The RMSE of Melfort 2003 and Swift Current 2004 were lowered by 24 mm and 23 mm respectively (Table 2.2). This modification also lowered the MBE of the "overestimation" category from 46 mm to 29 mm indicating a reduction in model overestimation (Table 2.3). As a result, the $PAM2^{nd}_{1}$ version of the model accomplished the goal to reduce the overestimation of late season soil water content.

In the "underestimation" and "other" categories the RMSE increased by 4mm and 2mm, respectively (Table 2.2) and increased the growing season underestimation as indicated by the MBE (Table 2.3). As would be expected, a modification that potentially decreases soil water content would increase the RMSE of those site years that were underestimated initially. In this category, the modification had little effect on the RMSE of Winnipeg 2005 and Regina 2006. In the case of Winnipeg 2005, the measured soil water was above the measured field capacity of 581 mm. As a result, the modeled soil water approached field capacity for nearly the entire season. Thus the modification of canopy resistance would have likely decreased estimated soil water content. However, since there was an abundance of water, modeled values remained at field capacity. Even though this modification increased the RMSE slightly at some site years, the overall improvement and specifically the improvement in drier years justifies implementation of this modification in the model.

Table 2.3 Mean Bias Error (MBE) of modeled versus observed soil water content (mm) of the PAM2$^{nd}_{0}$, PAM2$^{nd}_{1}$, PAM2$^{nd}_{2}$, PAM2$^{nd}_{1+2}$ versions of the model.

			MBE (mm)			
Category	**Site**	**Year**	**PAM2$^{nd}_{0}$**	**PAM2$^{nd}_{1}$**	**PAM2$^{nd}_{2}$**	**PAM2$^{nd}_{1+2}$**
Overestimation						
	Melfort	2003	50	27	52	27
	Regina	2003	26	4	24	4
	Swift Current	2003	15	0	17	2
	Winnipeg	2003	86	73	87	74
	Swift Current	2004	46	25	46	26
	Carman	2004	33	15	32	15
	Swift Current	2005	62	53	62	53
	Swift Current	2006	69	53	69	53
	Carman	2006	31	14	31	14
Mean			46	29	47	30
Underestimation						
	Regina	2004	-35	-55	-15	-36
	Winnipeg	2005	-48	-48	-47	-47
	Carman	2005	-64	-71	-41	-43
	Melfort	2006	-64	-80	-62	-79
	Regina	2006	-23	-35	-11	-30
Mean			-47	-58	-35	-47
Other						
	Melfort	2004	11	-8	12	-7
	Winnipeg	2004	-8	-31	-2	-25
	Melfort	2005	-26	-40	-6	-11
	Regina	2005	15	0	39	30
	Winnipeg	2006	-11	-28	-9	-28
Mean			-4	-21	7	-8
Overall			**9**	**-7**	**15**	**0**

2.4.4 Modification of Modeled Infiltration

To decrease the underestimation of soil water content during periods of consecutive days of precipitation, the simulation of infiltration was modified. PAM2$^{nd}_{0}$

stopped all infiltration when the top-zone reached saturation, with the remainder partitioned as run-off. However, observed soil water measurements indicated that some of this water was in reality infiltrating into the soil and not discounted as run-off since observed soil water increased during these periods (Figure 2.2). A second modification was introduced to change the infiltration term. This version of the model ($PAM2^{nd}_2$) allowed infiltration to continue regardless of the water content of the top-zone. Infiltration rates are highest into dry soils and decline rapidly as the soil macropores fill with water and shrinkage cracks close. However, infiltration does not stop when the top-zone is saturated but rather reaches a steady state. Wosten and van Genuchten (1988) report hydraulic conductivity values at field capacity (0.1 bar) in the range of 500, 20 and 2 mm day^{-1} for a coarse, medium and fine textured soil, respectively. Over the period of a day the hydraulic conductivity of most soil textures would be large enough to infiltrate 25.4 mm of water, which is considered in this study the limit where infiltration is reduced and run-off occurs. For a soil profile that is dominated by heavy clay this assumption may be inaccurate over a 24 hour time period, however in reality infiltration from a 25.4 mm event could occur over a longer time period. The dense canopy of a wheat field would limit surface evaporation due to the low vapour density deficit and high aerodynamic resistance. As a result, rainfall that exceeds the soil's rate of infiltration would puddle and continue to infiltrate over a longer time period with minimal loss from surface evaporation. For this modification we are assuming soil water flux of at least 1.06 mm h^{-1} in order to infiltrate 25.4 mm of water per day which is not an unreasonable assumption even in a fine-textured soil. In the $PAM2^{nd}_2$ version of the model, the only limitation to the infiltration of rain is the available space below field capacity.

The PAM2^{nd}_{2} version of the model decreased the overall RMSE by only 3 mm; however the improvement was mainly in the "underestimation" category (Table 2.2). In this category the RMSE was reduced by 10 mm with the greatest improvement occurring in Regina 2004 and Carman 2005 with a reduction of 15 mm and 22 mm, respectively (Table 2.2). The RMSE in the "overestimation" category did not change while the RMSE in the "other" category increased by 1 mm. The modification reduced the MBE from -47 mm to -35 mm indicating a reduction of the underestimation of soil water.

2.4.5 Adoption of the Modifications to Canopy Resistance and Infiltration

A final version of the model (PAM2^{nd}_{1+2}), which included both the canopy resistance and infiltration modifications, was compared to observed soil water content in order to determine whether improvements in modeled soil water remained when both modifications were used simultaneously. Since the modifications are independent of each other (periods of overestimation versus periods of underestimation) the improvements in RMSE and r^2 remained when the modifications were combined (Table 2.4).

Table 2.4. Summary of RMSE and r^2 for each version of PAM2nd.

Category	RMSE (mm)				r^2			
	Model				Model			
	PAM2$^{nd}_{0}$	PAM2$^{nd}_{1}$	PAM2$^{nd}_{2}$	PAM2$^{nd}_{1+2}$	PAM2$^{nd}_{0}$	PAM2$^{nd}_{1}$	PAM2$^{nd}_{2}$	PAM2$^{nd}_{1+2}$
Overestimation	60	45	60	45	0.86	0.9	0.87	0.90
Underestimation	76	80	66	68	0.51	0.57	0.55	0.63
Other	50	52	51	52	0.37	0.58	0.37	0.44
Overall	62	56	59	53	0.77	0.82	0.81	0.84

Overall, the $PAM2^{nd}_{1+2}$ version of the model improved the soil moisture RMSE for 16 of 19 site years over the original version. $PAM2^{nd}_{1+2}$ obtained an overall RMSE of 53 mm, an improvement of 9 mm from the original version (Table 2.4). The overall r^2 and slope of the linear regression increased from 0.77 to 0.84 and from 0.64 to 0.73, respectively (Table 2.4; Figure 2.5: Figure 2.6). The increase in the r^2 and slope indicates a reduction in the variability and an improvement in the accuracy of soil water estimates. The three site years that were not improved were those afflicted with wet conditions and possibly water table issues, which could not be addressed in this study (Table 2.2). The MBE analysis indicated $PAM2^{nd}_{0}$ was overestimating soil water over all sites and years (Table 2.3). After the modifications to canopy resistance and infiltration, the overall MBE was reduced to 0 indicating an equal distribution of positive and negative differences. To put the error of modeled soil water in perspective, the average error (RMSE) represented 10% of field capacity with the maximum error occurring in Swift Current, 2005 (16% of field capacity) (Table 2.2).

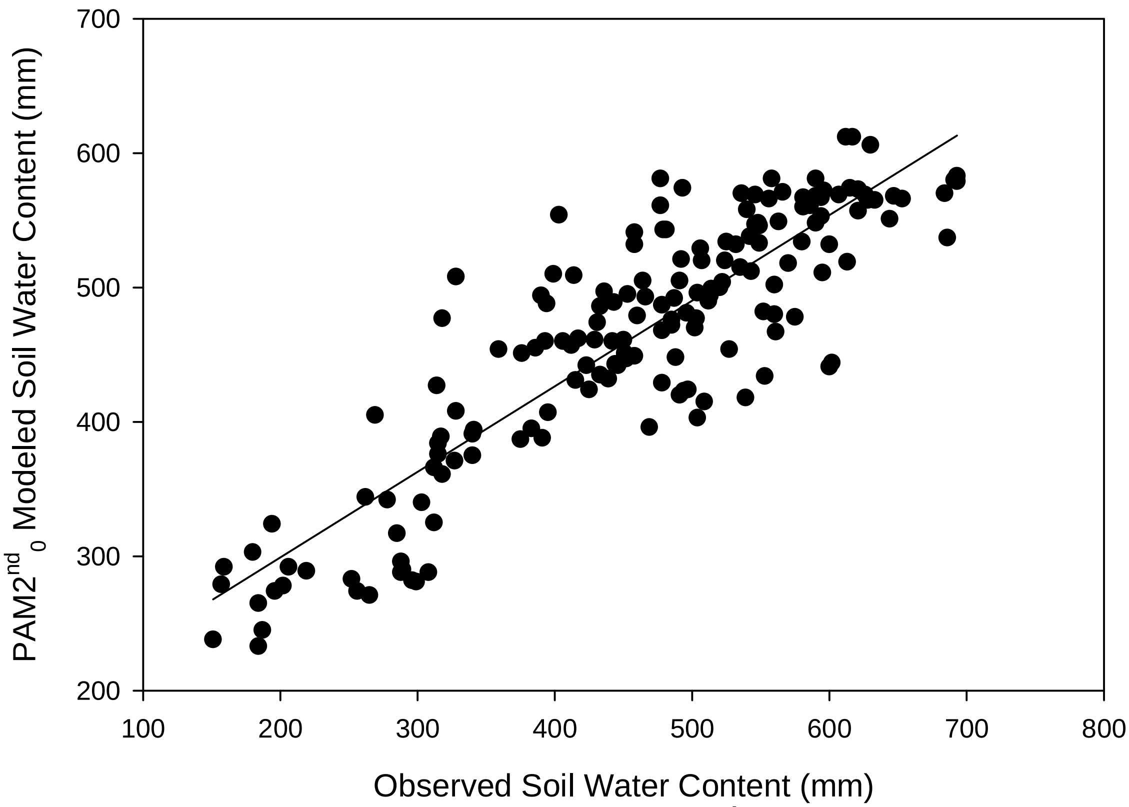


Figure 2.5 Linear regression of observed versus PAM2$^{nd}{}_{0}$ modeled soil water content. (—) linear regression

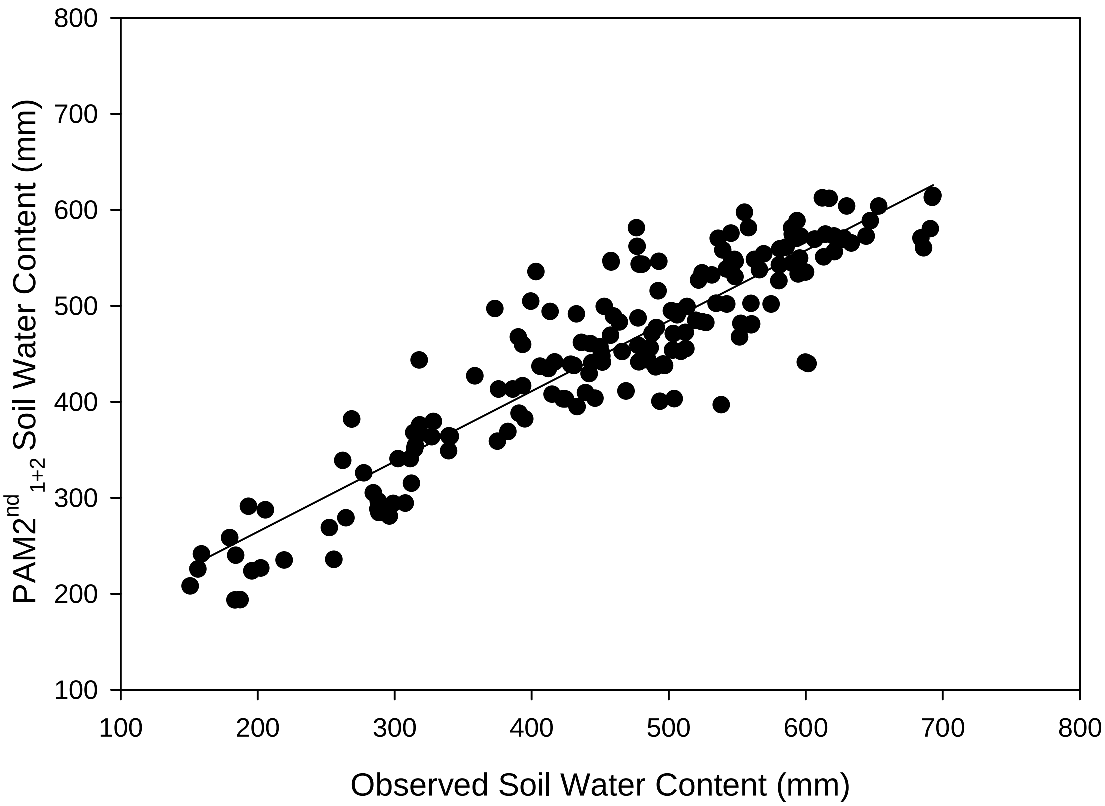


Figure 2.6 Linear regression of observed versus PAM2$^{nd}_{1+2}$ modeled soil water content. (—) linear regression

2.4.6 Sensitivity to Soil Water Holding Parameters

The lowest RMSE for each site occurred either in 2003 or 2004, which were the driest years of the study as the Prairies were recovering from a drought. In wetter growing seasons the model had greater difficulty in modeling soil moisture. This discrepancy is caused by the use of field capacity as the upper limit of the root-zone's water holding capacity. In 2005 and 2006 measured soil water content was much higher than previous years. As a result, measured soil moisture exceeded the measured field capacity value and reached saturation. Since the model is limited by field capacity, excess water drains out of the root-zone as deep drainage, resulting in underestimation of water content. In 2003 and 2004, actual soil water content did not approach field capacity. Since the model did not have to discount any excess water as deep drainage, the model was able to more accurately simulate the water balance.

This may be a limitation of using field capacity as an upper limit of plant available water or not allowing the root-zone to reach saturation. The field capacity concept can be misleading since soil water content above field capacity is still available to plants (Sykes and Loomis, 1967) and it may take more than one day for the soil to drain to field capacity after a heavy rainfall. Currently, the model does not allow the root-zone to exceed field capacity. It is assumed soil water will drain from saturation to field capacity within a daily time step. This may be an oversimplification. Measurements of soil water were never taken while it was raining and rarely after a large rainfall event and still we have near saturated measurements of the root-zone. This indicates that either our measurements of field capacity and saturation are incorrect or the assumption that the root-zone will drain to field capacity on a daily basis is not valid.

2.4.7 Soil Input Parameters

PAM2nd was developed with the goal of creating an evapotranspiration model that operates using readily available input data in order to maximize the number of locations where it can be run. It achieved this goal by using commonly measured surface weather parameters: minimum/maximum air temperature and rainfall. However, the model also requires soil input parameters that are not as accessible. For any model that simulates the soil water balance, it is necessary to quantify the water holding capacity of a given soil.

PAM2nd quantifies the maximum soil water holding capacity as field capacity and the lower limit of plant available water as permanent wilting point. These parameters are dependent on soil texture, soil structure, porosity, pore size and organic matter content. Due to the spatial variability of soil characteristics, water holding capacity of soil can vary over relatively short distances. However, measuring this variation is not feasible for all weather stations and we must rely on measurements done during soil survey operations.

The use of soil water holding parameters from the soil survey increased the overall RMSE of modeled soil water (Table 2.5). The sensitivity of the model to these parameters is highlighted at Carman. Since there were two equally dominant soils in the Carman soil polygon, the model run was conducted twice, one with each soil type. The soil type used in Carman 1 is a Deadhorse soil which is sand dominated soil texture (Appendix B). The soil type used in Carman 2 is a Rignold soil which is a clay dominated soil texture (Appendix B). As a result, both of these soils have very different water holding capacities. The Rignold soil has a field capacity of 526 mm compared to the Deadhorse soil with only 357 mm. Even though the Deadhorse soil has a lower permanent wilting point, the Rignold soil has more plant available water; 262 mm compared to 195 mm for the Rignold and Deadhorse soil, repectively. These differences in soil water holding parameters significantly affected the accuracy of modeled soil moisture. Using the Rignold soil instead of the Deadhorse soil decreased the RMSE on average across all years of Carman by 106 mm. In fact the soil survey values from the Rignold soil produced a lower RMSE compared to the measured values. Overall the RMSE of all the site years increased to either 62 or 80 mm, depending on which Carman soil was used. This stresses the need for accurate soil water holding parameters in order to obtain accurate estimates.

Table 2.5 RMSE (mm) of total soil moisture using measured versus soil survey water holding capacity input parameters for all site years.

	2003		2004		2005		2006	
Location	**Measured**	**Soil Survey**	**Measured**	**Soil Survey**	**Measured**	**Soil Survey**	**Measured**	**Soil Survey**
Melfort	32	22	60	65	57	56	107	115
Regina	48	65	56	100	72	66	64	71
Swift Current	23	43	37	55	61	66	57	77
Winnipeg	77	37	34	76	60	97	36	79
Carman 1	-	-	36	137	51	163	37	115
Carman 2	-	-		25		47		26

As previously mentioned, some site years had a lower RMSE when the soil survey values were used compared to when using the measured values. These changes occurred as a result of a shift in the upper and lower limits of water holding capacity as well as total available water. For example, using soil survey data decreased the field capacity of Melfort and Winnipeg (Appendix A and B), which helped decrease an overestimation of soil water in Melfort, 2003 and Winnipeg, 2003.

The accuracy of field capacity and permanent wilting point values would also significantly affect the accuracy of crop evapotranspiration. PAM2nd requires the simulation of the soil water balance in order to determine the amount of plant available water and canopy resistance. Without accurate values of field capacity, the model cannot determine how much water remains in the soil, is lost through deep drainage or is accessible to plants for transpiration.

2.5 Conclusion

The second generation Prairie Agrometeorological model was validated using weather and soil moisture data from Melfort, Regina, Swift Current, Winnipeg and Carman for the growing seasons of 2003 to 2006. At 9 of 17 site years, the model was overestimating soil moisture during the second half of the growing season. It was determined that canopy resistance was increasing prematurely resulting in lower rates of ET and overestimation of soil water. The original version of the model increased canopy resistance as soil water content decreased below field capacity. Shen et al. (2002) demonstrated that canopy resistance for wheat remains relatively constant until soil water is depleted to 50% of plant available water. To address the overestimation of late season soil moisture, the canopy resistance function was modified to incorporate the findings of Shen et al. (2002). This modification of the model decreased the RMSE of the overestimated site years by 15 mm and by 6 mm over all site years.

Model validation also indicated that soil water was underestimated during periods that experienced consecutive days of precipitation. The underestimation was attributed to the infiltration function. The original version of the model stopped infiltration when the top-zone reached saturation with the excess precipitation discounted as run-off. Rates of saturated hydraulic conductivity indicated infiltration of precipitation would continue when the top-zone was saturated. As a result, the model was modified to allow infiltration of water to continue regardless of the water content of the top-zone. This modification addressed the underestimation of soil water and reduced the RMSE of the underestimated site years by 16 mm.

Overall both modifications reduced the RMSE of modeled soil water by 9 mm and increased the r^2 from 0.77 to 0.84. The greatest reduction in RMSE occurred in Swift Current 2004 where RMSE was reduced by 6% of field capacity or 10 mm of water. Overall the error associated with modeled soil water for the entire 120 cm profile represented 10% of field capacity. It is important to note that model performance did not appear to be site-specific but rather dependent on weather conditions for a specific year. The only site-specific effect that was evident was that Swift Current was overestimated for all years, however this still likely due to the drier climate at this location. The validation and modifications conducted in this study provide an indication of the accuracy of modeled soil water by PAM2nd. Improving the soil water balance increases our confidence in the simulation of the evapotranspiration component of the model since the accuracy of the soil water balance will greatly impact the accuracy of modeled crop evapotranspiration.

In order to use $PAM2^{nd}_{1+2}$ as an operational model on the Prairies, the input parameters must be available at a high enough spatial resolution in order to produce accurate estimates over the entire region. By using limited surface weather parameters, the model can maximise the number of weather stations used. However soil water holding parameters are less available and must be estimated for any specific location. By using soil survey data to estimate soil water holding characteristics, the accuracy of modeled soil water decreased. The RMSE increased to 63 or 80 mm depending on which soil was used for the Carman location. Due to the sensitivity of the model to these parameters the accuracy of modeled soil water will greatly depend on the accuracy of these values. Further modifications could be considered to increase the accuracy of $PAM2^{nd}_{1+2}$; however inaccurate characterisation of soil water holding capacity will likely eclipse any potential improvements. Due to the spatial variability and loss of resolution with soil survey data, model accuracy will likely have to be sacrificed when scaling up to a regional estimate.

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3. Comparison of Crop Evapotranspiration Estimates

3.1 Abstract

Evapotranspiration (ET) models have become essential tools in climate modeling, weather forecasting and irrigation planning to name a few. The sheer quantity of ET models can be overwhelming, however it is important to realise ET is a dynamic process and not one model can be representative of all global conditions and applications. The modified second-generation Prairie Agrometeorology Model (PAM2^{nd}_{1+2}) models crop evapotranspiration for spring wheat with the application of estimating regional evapotranspiration on the Canadian Prairies. PAM2^{nd}_{1+2} uses minimal surface weather parameters in order to maximize the number of weather stations that can be utilised. PAM2^{nd}_{1+2} estimates crop ET using a vapour density deficit approach that is moderated by canopy, soil and aerodynamic resistance. The objective of this study was to compare estimates from PAM2^{nd}_{1+2} to other ET models that use different approaches to obtain crop ET. The FAO56 Penman-Monteith (FAO56 P-M) uses a reference surface/combination approach while the simplified water balance method estimates ET as the residual of precipitation and the change in soil water.

A direct comparison of daily ET between PAM2^{nd}_{1+2} and FAO56 P-M indicated significant differences in their estimation of crop water demand (ET_c) (RMSD = 1.88 mm/day, r^2 = 0.45) and actual ET (ET_a) (RMSD = 1.65 mm/day, r^2 = 0.45). When compared to the water balance derived ET, PAM2^{nd}_{1+2} (slope= 0.65, r^2 =0.62) produced more accurate estimates of ET_a than FAO56 P-M (slope = 0.50, r^2 = 0.61). However, both models produced overall ET estimates that fell within the range of the measurement error associated with the water balance ET method. Since PAM2^{nd}_{1+2} produced relatively accurate estimates of crop ET_a while using

minimal surface weather parameters, this model would be best suited to derive regional estimates of crop ET on the Canadian Prairies from the maximum number of weather stations available.

3.2 Introduction

Evapotranspiration (ET) is a key component of the hydrological cycle in which water is returned from the earth's surface to the atmosphere as water vapour. ET is an integral part of the global energy balance influencing micro and macro-climatic conditions via latent heat exchange and the greenhouse effect as a result of water vapour. ET is a major driving force of many meteorological phenomenon including precipitation and convective activity leading to severe weather associated with thunderstorms. Moisture for summer rainfall on the Canadian Prairies originates from horizontal advection of water vapour into the region and from regional recycling of water vapour as a result of local ET (Raddatz, 2000; Raddatz, 2005). A study conducted by Raddatz (2005) indicated that moisture recycling by ET was a factor determining whether areas within the Canadian Prairies experienced a dry, normal or a wet summer.

In the agricultural sector, the measurement of ET is important in several disciplines. Water management is necessary in agricultural regions that rely on irrigation as a source of water. Since water for irrigation is often limiting, managers must obtain a good sense of the rate of ET for their crops in order to implement water-efficient irrigation practices. Monitoring seasonal soil moisture and crop water requirements are also essential for crop selection and drought monitoring.

On the Canadian Prairies, cropland is a large component of the Prairie landscape; therefore, ET from crops has a large influence on the Prairie climate. Cropland on the Prairies represents 82% of Canada's total cropland (Statistics Canada, 2006). Of Canada's total cropland 28% was seeded to wheat in 2008, the largest proportion of any annual crop (Statistics Canada, 2008). As a result, atmospheric water vapour that originated from ET on the Canadian Prairies is principally from spring wheat. Therefore, monitoring crop water use by spring wheat provides a good indication of the moisture status for a significant area of the Prairies.

Although the importance of ET is well known, the ability to quantify it has been problematic. Due to the expense of instrumentation that measures ET directly; many empirical methods have been developed to estimate ET. Unfortunately many ET models require input data that is not readily available, and are limited to specific study sites. In order to obtain estimates of ET on a much larger scale, such as the Canadian Prairies, it is necessary to use a model that requires only readily available data from a large number of locations.

The modified second-generation Prairie Agrometeorological Model ($PAM2^{nd}_{1+2}$) estimates ET by simulating crop development, the soil water balance and evapotranspiration using minimal, commonly measured, surface weather parameters (Raddatz, 1993). $PAM2^{nd}_{1+2}$ requires daily minimum/maximum surface air temperature and daily rainfall. This maximises the number of weather stations that can be used, and as a result maximises the spatial resolution of ET estimates.

$PAM2^{nd}_{1+2}$ is a modified version of the original second-generation Prairie Agrometeorological Model ($PAM2^{nd}_{0}$) (Raddatz, 1993). As described in Chapter 2, modifications to $PAM2^{nd}_{0}$ include changes in the way canopy resistance and infiltration is modeled. These modifications were made to improve the simulation of the soil water balance and increase confidence in modeled evapotranspiration.

The first-generation Prairie Agrometeorological Model is described by Raddatz (1989). Major modifications of the first-generation model include the modeling of the atmospheric boundary layer and a vapour density deficit and resistance approach to estimating evapotranspiration (Raddatz et al., 1996). The first-generation model estimated evapotranspiration using the empirical Baier and Roberston method (Raddatz, 1989). A comparison between the first-and-second generation Prairie Agrometeorological Model has been made previously for simulating water-demand for potatoes (Raddatz et al., 1996). This study concluded that $PAM2^{nd}_{0}$ was more responsive to daily differences in weather conditions even though growing season ET totals were comparable.

One of the unique components of $PAM2^{nd}_{0}$ and $PAM2^{nd}_{1+2}$ compared to other ET models is the modeling of the vertical profile of the planetary boundary layer (PBL) in order to accurately simulate the atmospheric demand for water vapour. It is necessary to know the entire PBL profile because ET is controlled not only by the surface and surface layer but also by the vapour and temperature gradients in the PBL (Oke, 1987; McNaughton and Jarvis, 1983). The PBL is a turbulent layer of the atmosphere that can extend from the ground to several thousand meters during summer months (Raddatz, 1993). The turbulence of the PBL facilitates the transport of heat, vapour and momentum from the surface into the atmosphere (McNaughton and Jarvis, 1983). The atmosphere above the PBL is often stably stratified and therefore heat and vapour fluxes are usually confined within the PBL (McNaughton and Jarvis, 1983). During stable PBL conditions, large potential temperature and humidity gradients form. During unstable/mixed PBL conditions large gradients are only present in the lowest 10% or less of the PBL (McNaughton and Jarvis, 1983). As a result, daily rates of ET are directly affected by the stability of the PBL which exhibits a diurnal cycle. $PAM2^{nd}$ models the PBL twice a day, once at 1200Z and 0000Z in order to capture the diurnal cycle.

The objective of this chapter is to compare the estimates of spring wheat ET from $PAM2^{nd}{}_{1+2}$ to those obtained using other methods including the FAO56 Penman-Monteith method and a simplified water balance. In the context of this study, the water balance method is the closest to a direct measurement of actual ET. However since we are not solving for the complete water balance, it remains only an estimate of ET rather than an actual direct measurement.

3.3 Evapotranspiration Model Description

3.3.1 Water Balance

The complete water balance for an agricultural system is described as follows:

$$\delta S = P + I + CR - ET - D - R - SS \qquad (3.1)$$

where δS = Change in soil moisture storage, P = Precipitation, I = Irrigation (*if present*), CR = Capillary rise from groundwater, ET = Evapotranspiration, D = Deep drainage below the root zone, R = Run-off, and SS = net subsurface flow.

To determine the rate of ET from a system, Equation 3.1 is used to solve for the unknown ET term. This requires all the terms in Equation 3.1 to be measured. Unfortunately, not all terms in Equation 3.1 can be easily measured; as a result Equation 3.1 is often simplified (Equation 3.2). CR, D, R and SS terms are difficult to measure directly and are therefore often assumed to be negligible or estimated. For example the direct measurement of drainage would require the installation of lysimeters, which are often not practical due their cost. Indirect methods are described by McGowan and Williams (1980) and Maule and Chanasyk (1987). Although practical, assuming these components are negligible can introduce considerable error since drainage values have been reported to be 33% of total growing season precipitation in some instances (Maulé and Chanasyk, 1987).

$$\delta S = P - ET \qquad (3.2)$$

The largest components of the water balance are P and δS, and therefore must be directly measured. Precipitation is measured using a rain gauge. When measuring precipitation, it is important to keep in mind that rainfall events are spatially variable in both magnitude and intensity. As a result, it is important to have rain gauges close to the area of study.

Direct measurement of δS requires periodic gravimetric sampling of the study site which is both labour intensive and destructive. As a result, δS is often measured using instrumentation such as time domain reflectometry (TDR), neutron moisture probes or PR2 profile probes, to name a few. Due to the spatial variability of soil moisture, a representative sample of soil moisture requires multiple measurements per study site (Villagra et al., 1995).

3.3.2 FAO56 Penman-Monteith

The FAO56 Penman-Monteith method uses the concept of a reference surface in order to calculate a reference evapotranspiration (ET_0) (Equation 3.3). A rate of evapotranspiration is determined for a hypothetical reference crop which closely resembles an actively growing grass surface of uniform height with adequate water and completely shading the ground. The surface has an assumed height of 0.12 m, a fixed surface resistance of 0.7 s cm^{-1} and an albedo of 0.23. Crop specific rates of evapotranspiration are derived from the reference surface by using crop and water stress coefficients. The crop coefficient takes into account the differences in crop canopy and aerodynamic resistance relative to the reference surface, while the water stress coefficient takes into account less than adequate soil moisture. Using the reference surface concept eliminates the need for unique parameters such as leaf area index and stomatal resistance for each crop and growth stage.

$$ET_0 = \frac{0.408\,\Delta\,(R_n - G) + \gamma\,\frac{900}{T+273}\,u_2\,(e_s - e_a)}{\Delta + \gamma\,(1 + 0.34\,u_2)} \qquad (3.3)$$

where R_n is net radiation at the crop surface, G is soil heat flux density, T is mean daily air temperature at 2m, u_2 is wind speed at 2 m, e_s is saturation vapour pressure, e_a is actual vapour pressure, Δ is the slope of the vapour pressure curve and γ is the psychrometric constant.

3.3.3 Modified Second-Generation Prairie Agrometeorological Model

PAM2nd calculates evaporation and transpiration separately in order to derive an estimate of ET. Evaporation and transpiration are partitioned using fractional leaf area (L_A). L_A is a measure of the unit area of ground that is covered by a green, transpiring crop canopy (0 to 1). Actual ET is driven by the vapour density deficit which is moderated by canopy, soil and aerodynamic resistances (Equation 3.4, 3.5). Daily estimates of ET are the sum of hourly estimates obtained by fitting the maximum and minimum values of ET to a sinusoidal curve using the daily maximum and minimum air temperatures.

$$E = (1-L_A)\,[h\rho(T_0) - \rho(Td_0)] / (r_a + r_g) \qquad (3.4)$$

$$T = L_A\,[\rho(T_0) - \rho(Td_0)] / (r_a + r_c) \qquad (3.5)$$

where h is the skin humidity term (Raddatz, 1993), ρ is vapor density, Td_0 is the dew-point temperature, T_0 is the air temperature, and r_a ,r_g and r_c are the aerodynamic, soil and canopy resistance terms, respectively.

Aerodynamic resistance is determined by simulating the PBL twice daily (1200 and 0000 Z) using site specific atmospheric temperature and wind speed at heights of 500, 700, 850 and 1000 mb interpolated from regional Global Environmental Multiscale (GEM) model gridded output (Equation 3.6).

$$r_a = [\ln(Z_h/Z_0]^2/[\sigma k^2(V_{MBL} - V_a)] \qquad (3.6)$$

where Z_h is the depth of the atmospheric boundary layer, Z_0 is the roughness length, σ is the stability adjustment term, k is von Karman's constant, V_{MBL} and V_a are the wind speed of the mechanized boundary layer and surface, respectively. ($r_a \geq 0.3$ s cm^{-1}).

To simulate the resistance of water movement from within the top-zone to the soil's surface, a soil resistance term (r_g) is used in the calculation of surface evaporation (Equation 3.7).

$$r_g = r_{g(soil)}[(W_A - W_{PWP})/(W_{FC} - W_{PWP})]^{-2.5} \qquad (3.7)$$

where $r_{g(soil)}$ is a reference value equal to 1.0 s cm^{-1}, W_A is the actual soil water content, W_{PWP} and W_{FC} are the soil water contents at the permanent wilting point and field capacity, respectively. Since the top-zone can reach saturation, PAW can be >1.

Canopy resistance is determined both as a function of fractional leaf area and soil water content (Equation 3.8).

$$r_c = \frac{r_{c\,min}/L_A}{(W_A - W_{PWP})/(W_{FC} - W_{PWP})} \qquad (3.8)$$

where r_{cmin} is the minimum reference canopy resistance value, set at 0.8 s cm^{-1}. L_A is the crop's fractional leaf area which has a minimum of 0.3 when used in Equation 3.8. Canopy resistance for the modified version of PAM2^{nd} (PAM2^{nd}_{1+2}) starts to increase once soil moisture has been depleted beyond 50% of plant available water. Refer to Chapter 2 of this thesis for a more in-depth description and subsequent modification made to the canopy resistance function. A more detailed model description of PAM2^{nd}_{0} prior to modifications can be found in Raddatz (1993).

3.4 Methods

3.4.1 Meteorological Input Parameters

Meteorological requirements for PAM2^{nd}_{1+2} are daily minimum and maximum air temperature and daily rainfall. Weather was monitored at all locations using on site stations. Air temperature and relative humidity was measured at 1.8 m, solar radiation at 2 m and wind speed at 2.6 m. Rainfall was measured using two tipping bucket rain gauges and averaged for a daily total. In order to simulate the planetary boundary layer, PAM2^{nd}_{1+2} requires upper atmospheric data; air temperature, wind speed, dew point depression and geopotential height for the standard levels of 1000 mb, 850 mb, 700 mb and 500 mb. These parameters are determined for each location through interpolation of the regional Global Environmental Multiscale (GEM) model gridded output. The soil parameters required to operate PAM2^{nd}_{1+2} are outlined in Chapter 2.

In addition to mean air temperature, the calculation of the FAO56 P-M reference ET requires the measurement of net radiation and the soil heat flux density. Both these parameters were not measured directly and therefore were estimated as described by Allen et al. (1998). Net radiation was estimated using measured incoming solar radiation and air temperature, while soil heat flux density was estimated from air temperature and day length. Actual and saturated vapour pressure was estimated from daily minimum and maximum air temperature and relative humidity (Allen et al. 1998). In order to determine the water stress coefficient a water balance was calculated as described by Allen et al. (1998) using the same soil water holding parameters used as input for the $PAM2^{nd}_{1+2}$ model.

3.4.2 Crop Water Demand

In order to evaluate methods of determining crop water demand, the potential ET (ET_p) from $PAM2^{nd}_{1+2}$ was compared to the calculated short grass reference FAO56 P-M ET_o with a single crop coefficient (K_c). It was necessary to make the comparison to the FAO56 P-M ET_c since the ET_p as reported by $PAM2^{nd}_{1+2}$ is crop water demand (ET adjusted for both fractional leaf area and canopy resistance (PAW=100%)). Therefore ET_c is a more accurate description of $PAM2^{nd}_{1+2}$ ET_p. As such, they will be referred to from now on as $PAM2^{nd}_{1+2}$ ET_c and FAO56 P-M ET_c.

To remove the determination of crop stage as a factor in this comparison, the crop coefficient for the FAO56 P-M estimate was set to equal the fractional leaf area as calculated by $PAM2^{nd}_{1+2}$. For the FAO56 ET_c a minimum fractional leaf area of 0.3 was used in order to represent the crop coefficient for the initial stages of crop growth when evaporation exceeds transpiration. A value of 0.3 is reported as the typical crop coefficient used for cereal crops during this initial stage (Allen et al. 1998). This value is also used by $PAM2^{nd}$ as the minimum fractional leaf area when calculating canopy resistance.

3.4.3 Actual Evapotranspiration

Actual ET for the entire growing season was compared as determined by the $PAM2^{nd}_{1+2}$ and FAO56 P-M models. Actual ET (ET_a) was obtained via the reference FAO56 P-M method using a crop and water stress coefficient (K_s) (Equation 3.9). The crop coefficient was determined based on field observation of the phenological stages of wheat. Based on these observations, Finlay (2006) developed a model relating growing degree days (base 5) to a crop coefficient for wheat. The methodology described by Allen et al. (1998) was slightly modified to determine the water stress coefficient.

$$\mathrm{ET_a} = K_s\, K_c\, ET_o \qquad (3.9)$$

In order to obtain K_s (Equation 3.10), it is necessary to have daily soil water measurements to be able to calculate the daily root zone depletion (Dr) (Equation 3.11). Since daily soil water measurements were not available, daily soil water measurements were estimated by calculating a daily water balance as described by Allen et al. (1998). In the determination of Dr, Allen et al. (1998) use ET_c to represent the removal of soil water by the crop. However since crop ET is also limited by soil water, the reason why it is necessary to calculate K_s, ET_a should be utilized instead to avoid excess root zone depletion. As a result, ET_a for the daily water balance was calculated by using the K_s from the previous day. Equation 3.11 is the modified version of the equation used by Allen at al. (1998), where run-off and capillary rise from the groundwater are assumed to be insignificant. Deep percolation was estimated as described by Allen et al. (1998), once again run-off was assumed to be negligible.

Total available water (TAW) in Equation 3.10 was determined as available water in the root zone (field capacity – permanent wilting point). The depth of the root zone was estimated using the relationship developed by Rasmussen and Hanks (1978) and also utilized by $\mathrm{PAM2^{nd}}_{1+2}$. Readily available water (RAW) is the average fraction of TAW that can be taken up by a crop before it experiences moisture stress (Allen et al., 1998). At a daily ET_c rate of 5mm/day, RAW is 55% of TAW for wheat (Allen et al., 1998).

$$Ks = \frac{TAW - Dr}{TAW - RAW} \qquad (3.10)$$

where TAW is total available water, Dr is root zone depletion at the end of the day and RAW is readily available water.

$$D_{r,i} = Dr_{,i-1} - P_i + ET_{a,i-1} + DP_i \qquad (3.11)$$

where $Dr_{,i-1}$ is root zone water content at the end of previous day, P is precipitation, $ET_{a,i}$ is actual ET and DP is deep percolation (all units in mm).

3.4.4 PAM2^{nd}_{1+2}, Penman-Monteith and Water Balance Evapotranspiration estimate comparison

The final comparison, between PAM2^{nd}_{1+2}, FAO56 P-M and Water Balance ET_a, was conducted in order to compare model estimates of ET_a to the closest available measurement of a measured ET_a (i.e. water balance). A simplified water balance estimate of ET_a was conducted using bi-weekly (at SK sites) and weekly (at MB sites) measurements of soil water and daily measurements of precipitation (Equation 3.12). Since surface run-off was not measured, it was assumed to be negligible for periods that did not experience daily precipitation events greater than 25.4 mm. To account for deep drainage (also not directly measured), it was assumed that deep drainage did not occur when the measured water content of the 90-120 cm profile was below field capacity. As a result, comparison between modeled estimates and water balance estimates were not made for periods that contained daily rainfall events exceeding 25.4 mm and periods where the 90-120 cm profile soil water content was greater or equal to field capacity. On average, rainfall events greater than 25.4 mm represented only 2% of total events, while 48% of the possible 184 soil water measurements were suspected to have experienced deep drainage.

$$ET_a = \delta S - P \qquad (3.12)$$

Water balance estimates of ET_a are a function of actual soil water content whereas the models utilize modeled estimates of soil water to derive crop ET. As a result, it is not possible to distinguish whether any error in modeled ET is a result of the water balance simulation or the methodology of ET. In Chapter 2 it was concluded there is error in modeled soil water content. To reduce bias in modeled soil water content the water balance for both models were re-set at the beginning of each period of measurement using measured soil water content. ET from this model run was termed adjusted actual evapotranspiration ($ET_{a\ adj}$). It should be noted that the frequency of soil water measurement varied by site and year; therefore each site/year inherited various amounts of error as a result of estimating soil water content.

3.4.5 Statistical Procedure

Daily values of $PAM2^{nd}_{1+2}$ (ET_c and ET_a) and FAO56 P-M (ET_c and ET_a) were compared by calculating the root mean square difference (RMSD) and the correlation coefficient (r^2). RMSD is a measure of absolute error and represented in mm of water while r^2 is a measure of relative error and represented as a ratio (Kahimba et al., 2008). The correlation coefficient was determined via linear regression. By definition, the lower the RMSD the more similar the estimates of ET. The RMSD is defined by Equation 3.13, where N is the number of days and M_1 and M_2 are models 1 and 2:

$$RMSD = \sqrt{\frac{\sum_{i=1}^{N}(M_1 - M_2)^2}{N}} \qquad (3.13)$$

The mean biased difference (MBD), Equation 3.14, was calculated to determine whether the methods were over or underestimating ET compared to each other. Negative values of MBD represent underestimation, while positive values represent overestimation. A MBD of zero represents equal distribution of positive and negative differences.

$$MBD = \frac{1}{n}\left[\sum_{i=1}^{N}(M_1 - M_2)\right] \qquad (3.14)$$

A paired, two-tailed Student's t-Test at an alpha level of 0.05 was conducted in order to assess whether the values from various methods were significantly different from each other.

3.4.6 Water Balance Error Propagation

Since water balance ET is calculated as a residual of the difference between soil water and precipitation, the water balance technique incorporates any error in the measurement of soil water and precipitation into the ET estimates. To quantify this error (ϵ), an error analysis of the water balance ET estimate was calculated using Equation 3.15 (Papakyriakou and McCaughey, 1991).

$$\epsilon WB\ ET = (n\epsilon P^2 + \epsilon W_F^2 + \epsilon W_I^2)^{0.5} \qquad (3.15)$$

where n is the number of precipitation events in the water balance time interval, ϵP is the error in precipitation and ϵW_F and ϵW_I are the error associated with the measurement of the final and initial soil water contents.

Error in the measurement was assumed to be 0.5 mm per rainfall event (Papakyriakou and McCaughey, 1991). Error in soil water measurement was calculated for the gravimetric determination of the 0-15 cm water content and for the neutron probe determination of the 15-120 cm water content. Error in the 0-15 cm measurement was calculated using Equation 3.16.

$$\epsilon W_{0\text{-}15} = (\epsilon BD^2 + \epsilon GMC^2)^{0.5} \qquad (3.16)$$

where ϵBD is the standard error of the determination of bulk density and ϵGMC is the standard error in the gravimetric measurement of soil water content. Standard errors were determined as the standard errors of the two sample populations.

Error associated with the neutron probe measurements were calculated as the standard error of the estimate for the calibration curves. Since the calibration curves were created for the various soil textures, errors associated with a given soil depth were a function of soil texture. Calibration errors in soil water content for the 15-120 cm profile were determined for each individual neutron tube at each site. The average calibration error (ϵ*C*) for each depth at each site was determined using Equation 3.17 (Papakyriakou and McCaughey, 1991).

$$\overline{\epsilon C_z} = \sum_{i=1}^{N}[\epsilon C_z] \frac{1}{N(N-1)^{0.5}} \qquad (3.17)$$

where N is the number of neutron tubes at each site and z is soil depth. The total calibration error of each profile was obtained as the sum of the errors associated with each depth. Instrument error associated with the neutron probe was reported to be 0.34% of volumetric water content (Troxler, 2001). Instrument error was calculated for each depth and averaged for each site using Equation 3.17.

3.5 Results and Discussion

3.5.1 Comparison of daily estimates of evapotranspiration

Daily estimates of ET_c, as estimated by $PAM2^{nd}_{1+2}$ and FAO56 P-M, were significantly different ($p<0.05$) (Figure 3.1). This comparison yielded a RMSD of 1.88 mm/day and an r^2 of 0.45. At low rates of ET_c there is considerable variation between the two models. The deviation of ET_c estimates away from the 1:1 line at higher rates of ET_c indicates that $PAM2^{nd}_{1+2}$ calculates a higher upper range of ET_c values. This indicates that $PAM2^{nd}_{1+2}$ may be more sensitive to the daily variability in the meteorological conditions, in particular daily temperature extremes. The FAO56 P-M method uses mean daily air temperature in the calculation of daily reference ET while $PAM2^{nd}$ calculates daily ET by fitting the maximum and minimum values of ET to a sinusoidal curve using the daily maximum and minimum air temperatures. It was expected that $PAM2^{nd}_{1+2}$ would be more sensitive to daily temperature extremes since the FAO56 P-M method of using mean daily temperatures would not take into account the daily amplitude in air temperature. $PAM2^{nd}$ for potatoes responsiveness to day to day differences in weather conditions was also observed by Raddatz et al. (1996). Even though $PAM2^{nd}_{1+2}$ has a larger range of ET_c estimates, overall this method of estimating daily ET_c only calculates a slightly higher crop water demand compared to the FAO56 P-M method (MBE=0.33 mm/day).

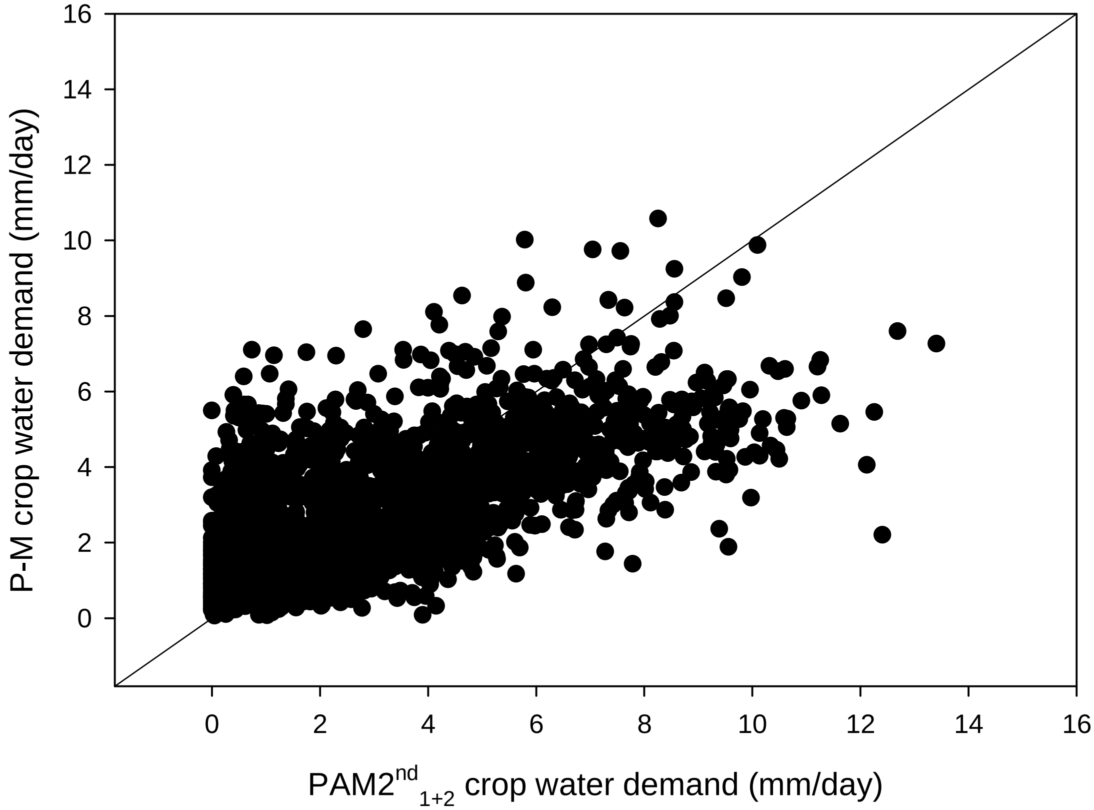

Figure 3.1. Comparison of daily rates of crop water demand as derived from the PAM$2^{nd}{}_{1+2}$ and FAO56 Penman-Monteith models.

A comparison of daily rates of ET_a yielded similar results to that of ET_c (Fig. 3.2). A RMSD of 1.65 mm/day and a r^2 of 0.45 were determined for this comparison indicating considerable differences in the estimation of daily ET_a. The estimates of daily ET_a from the two methods were significantly different ($P<0.05$). The measure of bias (MBE = 0 mm/day) indicated an equal distribution of positive and negative differences. As a result, even though on a daily basis the estimates of ET_a are quite different (RMSD of 1.65 mm/day), over all the site years the overestimations and underestimations are balanced. However, this does not translate into identical cumulative growing season totals for both models. Differences in growing season totals between the two methods vary from 0 mm for Carman 2006 up to 54 mm for Winnipeg 2004 (Table 3.1).

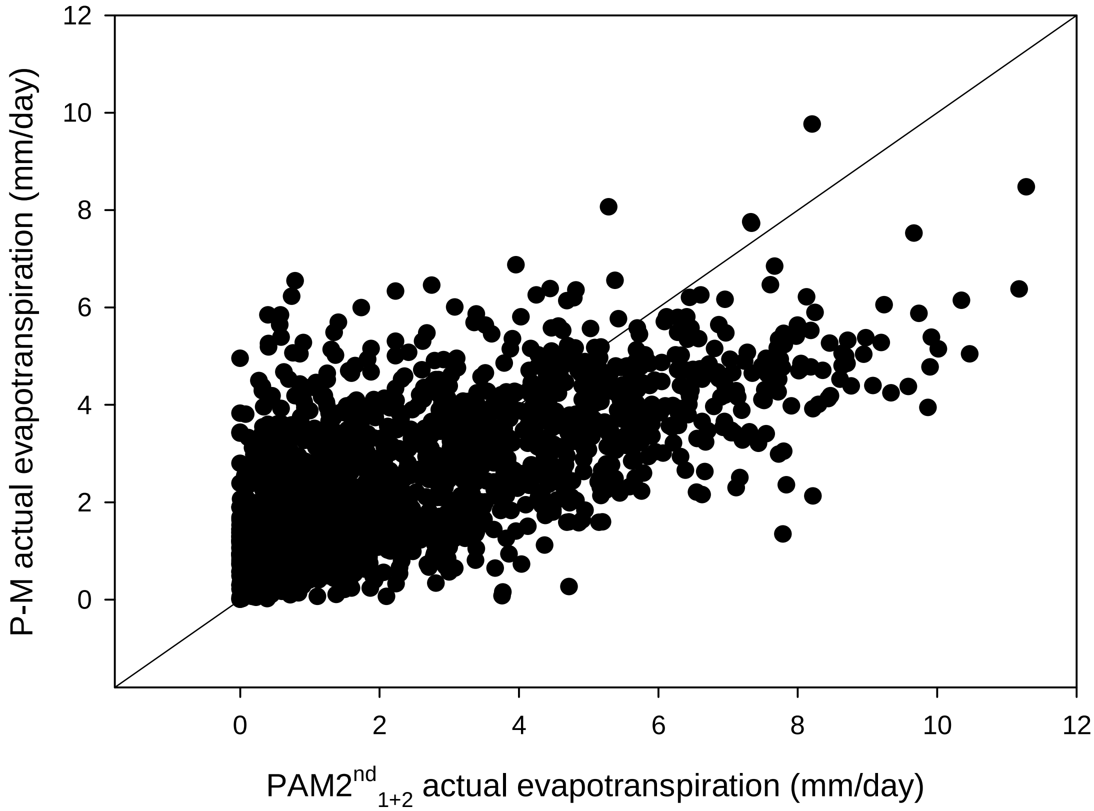

Figure 3.2. Comparison of daily rates of actual evapotranspiration as derived from the PAM2$^{nd}{}_{1+2}$ and FAO56 Penman-Monteith models.

Table 3.1. Cumulative growing season totals of actual evapotranspiration for each site and year as derived from the PAM2$^{nd}{}_{1+2}$ and FAO56 Penman-Monteith models.

Site/Year	Year	PAM2nd ET_a	P-M ET_a	Difference
		mm	mm	mm
Melfort	2003	257	254	3
Melfort	2004	283	267	16
Melfort	2005	220	261	-41
Melfort	2006	161	165	-4
Regina	2003	256	240	17
Regina	2004	274	257	17
Regina	2005	229	243	-14
Regina	2006	219	209	10
Swift Current	2003	177	173	4
Swift Current	2004	243	236	7
Swift Current	2005	223	255	-32
Swift Current	2006	309	329	-20
Winnipeg	2003	235	203	32
Winnipeg	2004	255	201	54
Winnipeg	2005	190	237	-46
Winnipeg	2006	234	244	-9
Carman	2004	225	214	11
Carman	2005	189	195	-6
Carman	2006	191	191	0

The relationship in Figure 3.2 is very similar to that in Figure 3.1. The only difference between the calculation of ET_c and ET_a is the restriction of ET as influenced by the availability of soil water. In this comparison both methods used their respective methods to estimate soil water in order to determine the availability of water for evapotranspiration. The FAO56 P-M method adjusts for soil water content by calculating a water stress coefficient, K_s (Equation 3.9 and 3.10). PAM2$^{nd}{}_{1+2}$ accounts for soil water stress through the soil and canopy resistance terms. Both methods are similar in that they limit the availability of soil water to plant uptake only when the water content is below a threshold where a plant would experience water stress. The FAO56 P-M method uses the concept of readily available water (RAW), which is calculated as the product of the average fraction of total available water that can be depleted from the root-zone before the crop experiences water stress (Allen et al., 1998). The depletion term, p, is a function of crop type and daily ET_c (Equation 3.15). Therefore, as RAW decreases ET_a decreases as well (Equation 3.10). $PAM2^{nd}_{1+2}$ accounts for water stress by increasing both the soil and canopy resistance terms (Equation 3.7 and 3.8). The canopy resistance does not increase until the total available water has been reduced by 50%. Similar to the FAO56 P-M method, ET_a is not reduced until a certain soil water threshold, since crops do not experience water stress immediately after soil water has been depleted below field capacity. These similarities may explain the similarities in the trends between FAO56 P-M and $PAM2^{nd}_{1+2}$ ET_c and ET_a since both methods account for water stress using a similar approach.

$$p = p_5 + 0.04\,(5\text{-}ET_c) \qquad (3.15)$$

where $0.1 \leq p \leq 0.8$ and p_5 is the depletion factor for spring wheat at rate of 5mm/day.

With the exception of Regina 2006, $PAM2^{nd}_{1+2}$ had higher estimates of ET in years 2003 and 2004 compared to FAO56 P-M method and lower estimates in years 2005 and 2006 (Table 3.1). This phenomenon likely coincides with the results found in Chapter 2. $PAM2^{nd}_{1+2}$ performed better in the driers years of 2003 and 2004 compared to the wetter years of 2005 and 2006 due to the use of field capacity as the upper limit of soil water content. The lower estimates of ET by $PAM2^{nd}_{1+2}$ in 2005 and 2006 is likely a result of a greater proportion of precipitation being allocated as deep drainage as a result of soil water content exceeding field capacity and therefore less plant available water for ET. As previously mentioned, both $PAM2^{nd}_{1+2}$ and FAO56 P-M use similar approaches in regulating ET as a function of plant available water. Both models use the field capacity and permanent wilting point concept to model soil water content. However their approaches to moderate ET are different. $PAM2^{nd}_{1+2}$ moderates ET using canopy resistance while the FAO56 P-M uses a water stress coefficient. If the underestimation of cumulative ET by $PAM2^{nd}_{1+2}$ from the 2003/04 to the 2005/06 years compared to the FAO56 P-M method are a result of using field capacity as an upper limit, this may indicate the water stress coefficient method used by the FAO56 P-M method may be less sensitive to this parameter.

$ET_{a\ adj}$ is more of a direct comparison in the methodology of determining ET_a of both the FAO56 P-M and $PAM2^{nd}_{1+2}$ models since it reduces the errors that could accumulate in ET_a output from the errors of the modeling of soil water. By re-setting the soil moisture at the beginning of each measurement period, the relationship between P-M $ET_{a\ adj}$ and $PAM2^{nd}_{1+2}$ $ET_{a\ adj}$ changed only slightly over the comparison of ET_a (Figure 3.3). Both methods of estimating $ET_{a\ adj}$ were significantly different ($P<0.05$). The relationship in Figure 3.3 yielded an RMSD of 1.78 mm/day and a r^2 of 0.49. The adjustment for soil water slightly increased the RMSD by 0.13 mm/day but improved the r^2 by 0.04.

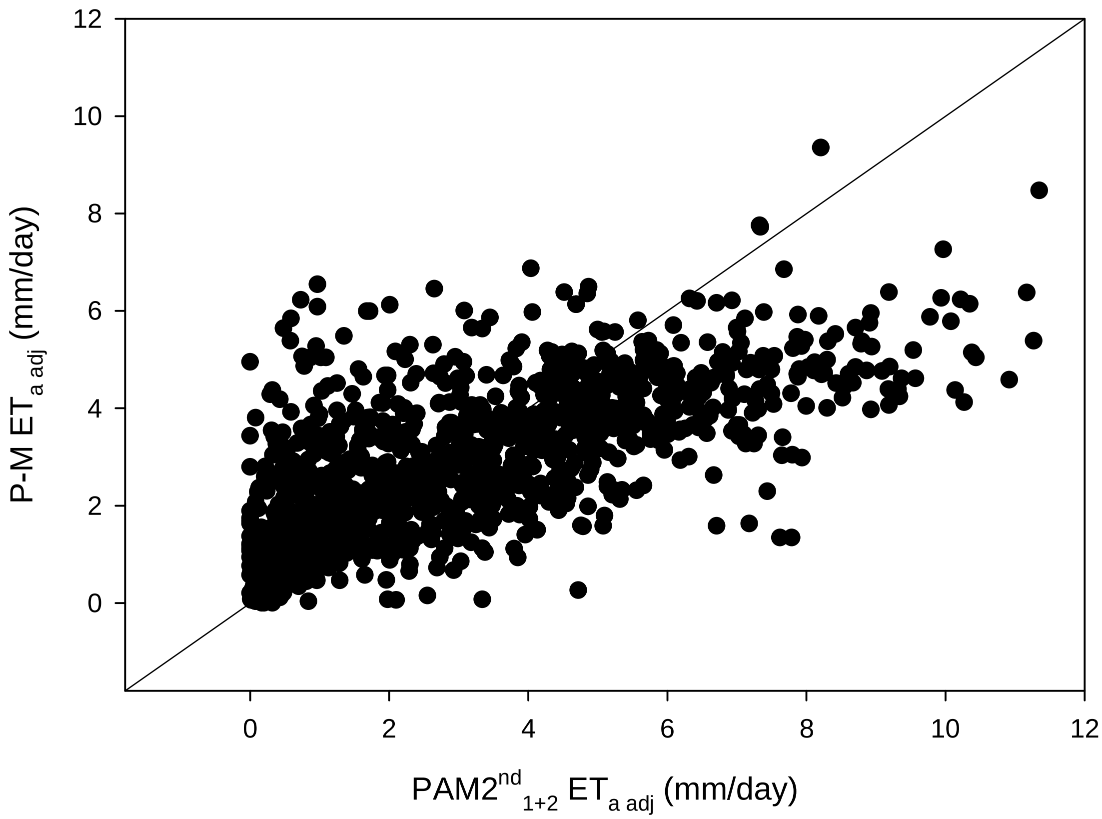

Figure 3.3. Comparison of daily rates of soil water adjusted rates of actual evapotranspiration as derived from the PAM2$^{nd}_{1+2}$ and FAO56 Penman-Monteith models.

3.5.2 PAM2$^{nd}_{1+2}$ and Penman-Monteith daily time series

A set of time series charts showing precipitation, soil moisture, and evapotranspiration from both the modified PAM2$^{nd}_{1+2}$ and FAO56 P-M models yielded several important observations (Appendix E). The time series of both ET models follow the expected growing season parabolic pattern. The ET flux is initially small early in the growing season when vegetation is sparse and evaporation dominates then steadily increases until maximum vegetative cover then declines as the crop starts to senesce and decreased soil moisture increases soil and canopy resistance. Dramatic daily deviation from the idealised parabolic pattern occurs as a result of changes in surface weather conditions. Evaporation and transpiration (Equation 3.4 and 3.5) are functions of the vapour density deficit. As the air temperature approaches the dew-point temperature, the near surface atmosphere becomes saturated (i.e. relative humidity increases) and as a result ET is greatly inhibited. This occurrence can usually be observed shortly after or before a rainfall event (Appendix E). This is typically followed by a sharp increase in the rate of ET the following day as a result of increased moisture and as drier, warmer air is advected into the region, creating a large vapour density deficit and a decrease in resistance due to increased soil moisture.

Generally, the ET series from FAO56 P-M model follows a similar pattern to that of $PAM2^{nd}_{1+2}$, although as indicated earlier, the $PAM2^{nd}_{1+2}$ model produces a larger range of daily ET rates compared to the FAO56 P-M model. As expected soil moisture exhibits a strong relationship with evapotranspiration and precipitation. In most cases the peak in growing season ET is followed with a subsequent decrease in soil moisture. Once crop ET starts to decline soil moisture either levels off or starts to increase if sufficient rainfall occurs.

3.5.3 Comparison of Modeled Versus Water Balance Evapotranspiration

To assess the accuracy of both ET models, output from both models was compared to water balance derived estimates of ET. For $PAM2^{nd}_{1+2}$, the regression analysis produced a slope of 0.65 and an r^2 of 0.62 (Figure 3.4), while the FAO56 P-M comparison gave a slope of 0.50 and an r^2 of 0.61 (Figure 3.5). This suggests that $PAM2^{nd}_{1+2}$ produced more accurate estimates of ET_a compared to FAO56 P-M with similar variability. In general, both models underestimated

$ET_{a\ adj}$ compared to the WB ET (MBE = -14 mm and -16 mm for $PAM2^{nd}_{1+2}$ and FAO56 P-M, respectively), and the modeled estimates of $ET_{a\ adj}$ were significantly different from WB ET ($p<0.05$). The absolute error (RMSE) of both models for the periods used in this comparison is 18 mm and 19 mm for $PAM2^{nd}_{1+2}$ and FAO56 P-M, respectively.

In a comparison of modeled ET to the WB ET it is important to acknowledge the limitations of calculating a WB ET as described in this study. The main concern with using the water balance approach to obtain an ET estimate is that any instrumental error in the measurement of rainfall and soil water will end up in the final ET value, in addition to any error as a result of invalid assumptions about run-off and deep drainage. To limit this type of error, this study limited the periods in which WB ET was determined to insure the assumptions that deep drainage, high water table and run-off were negligible. However, error in soil water measurement was significant. The bulk of the water balance error was due to soil water measurement error as a result of the associated errors of the neutron calibration curves. Instrument and precipitation error was negligible in comparison. Standard error of the calibration curves ranged from 2% of volumetric water content in the silty loam and clay loam soils to 6% of volumetric water content in the clay soil calibrations. The larger error in the clay soil calibration is expected due to the limitation of using a neutron probe in soils with heavy clay content (Evett, 2003). Measurement error in soil water content resulted in considerable error in the water balance estimate of ET (Appendix F). When water balance error and modeling error (RMSE) were considered, there was no difference between the $PAM2^{nd}_{1+2}$ and P-M estimates of ET compared to the water balance ET (Figure 3.4 and 3.5). The majority of ET estimates fell within the range of modeling and measurement error. Only 12 of 45 for $PAM2^{nd}_{1+2}$ (Figure 3.4) and 11 of 45 for P-M (Figure 3.5) ET data points were significantly different when errors associated with WB ET measurement and modeling RMSE were considered. As a result, the majority of modeled values from both PAM2$^{nd}_{1+2}$ and P-M fell within the range of WB ET error. Since WB ET error was largely composed of calibration error, WB ET error could be reduced by increasing the accuracy of the neutron calibration curves. Nonetheless, the results of Figure 3.4 and 3.5 add confidence to the accuracy of the WB ET since the underestimation of modeled ET corresponds to an overestimation of modeled soil water.

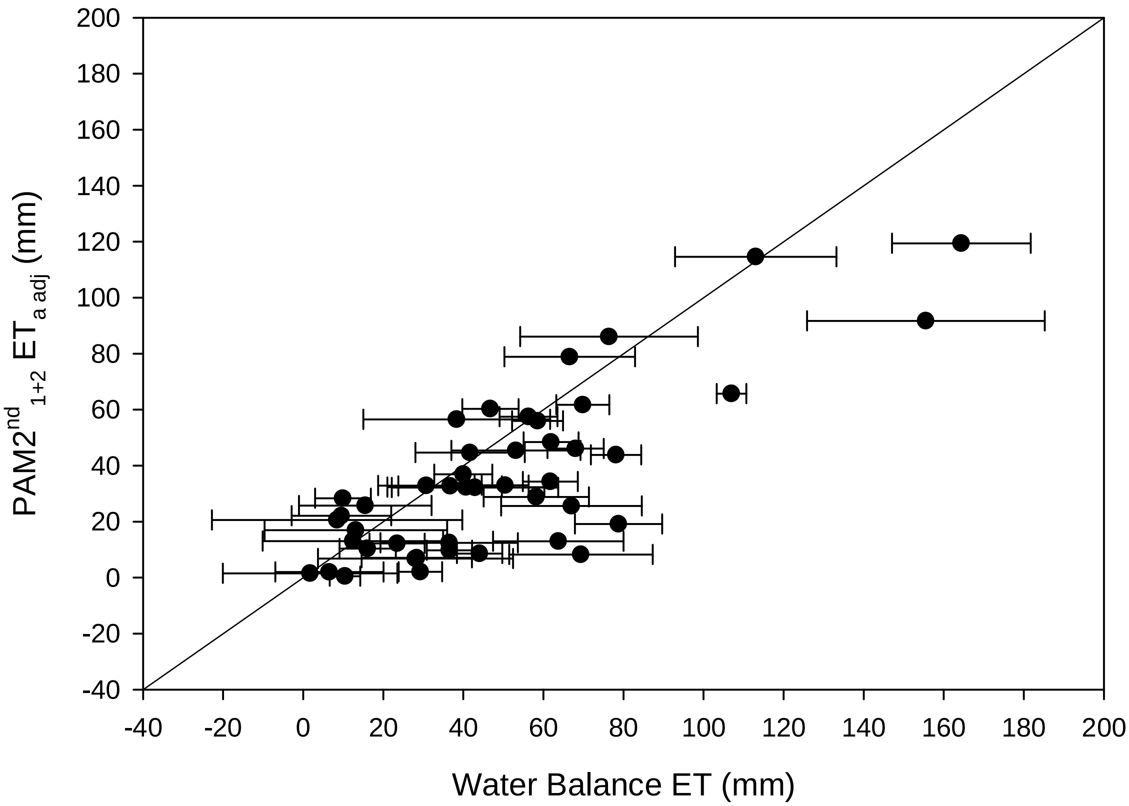

Figure 3.4. Comparison of actual soil water adjusted evapotranspiration derived by PAM2$^{nd}_{1+2}$ to water balance derived evapotranspiration.

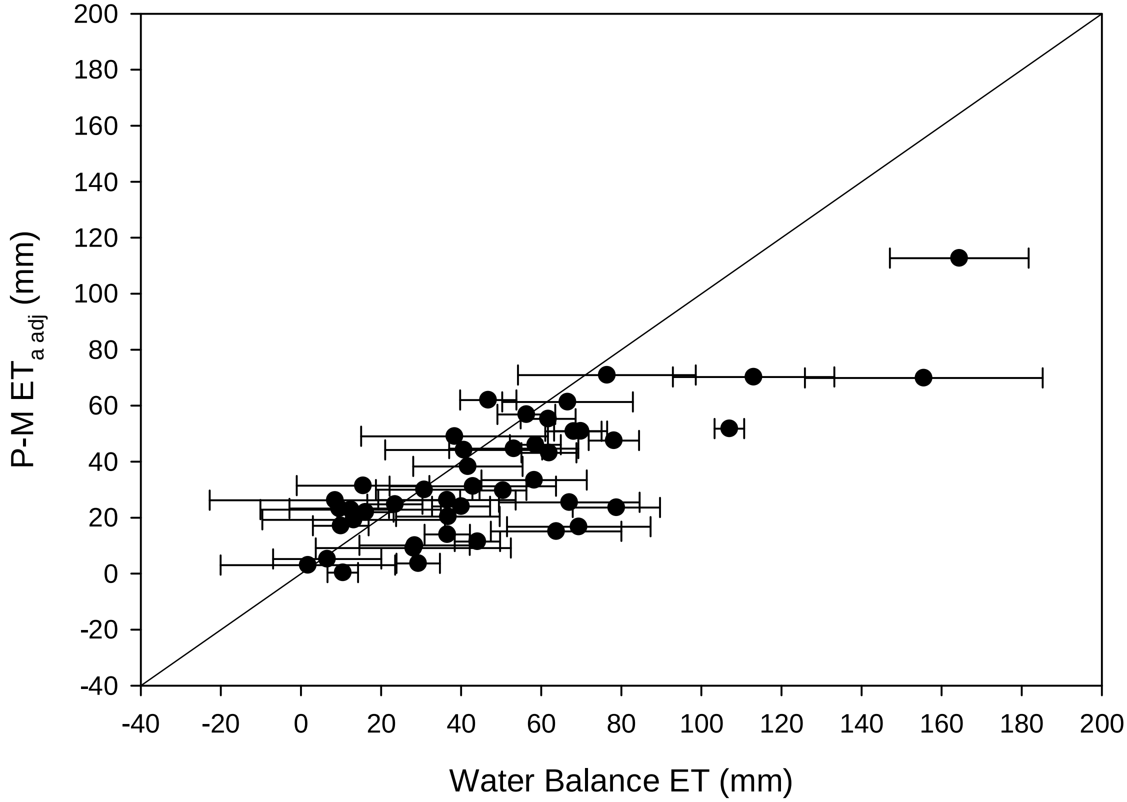

Figure 3.5. Comparison of actual soil water adjusted evapotranspiration derived by the FAO56 Penman-Monteith method to water balance derived evapotranspiration. (—) 1:1 line.

The underestimation of ET by $PAM2^{nd}_{1+2}$ is consistent with the results of Chapter 2 where it was concluded that soil water content was overestimated by $PAM2^{nd}_{1+2}$. Figure 3.6 demonstrates that the overestimation of modeled soil water at the time of soil water sampling corresponds to an underestimation of ET. Since the majority of the sample points fall within this quadrant, this indicates that a significant proportion of the overestimation of soil water is a result of an underestimation of ET. However this is not a perfect relationship, the overestimation of soil water is greater than the underestimation of ET. Therefore, there is still another factor that is influencing this relationship. There are two possibilities, either the underestimation of modeled

ET should be greater compared to the water balance ET or there are other components of the soil water balance that are being underestimated. Underestimation of deep drainage and run-off would both cause overestimation of modeled soil water. Due to the relatively flat terrain of the study sites and the limited occurrence of large rainfall events that would cause significant run-off, the underestimation of deep drainage is a probable cause. $PAM2^{nd}_{1+2}$ assumes deep drainage occurs when the water content of the root-zone exceeds field capacity. However, it does not take into account water that is lost through cracks in the soil. Soil textures that have significant clay content such as in Winnipeg and Regina are prone to cracking when the soil profile dries up. Cracks at these sites were observed to be at least 1 m in depth and several mm in width. Preferential flow of rainfall through these cracks could result in a significant amount of water that is being drained out of the profile that is not being accounted for by the model.

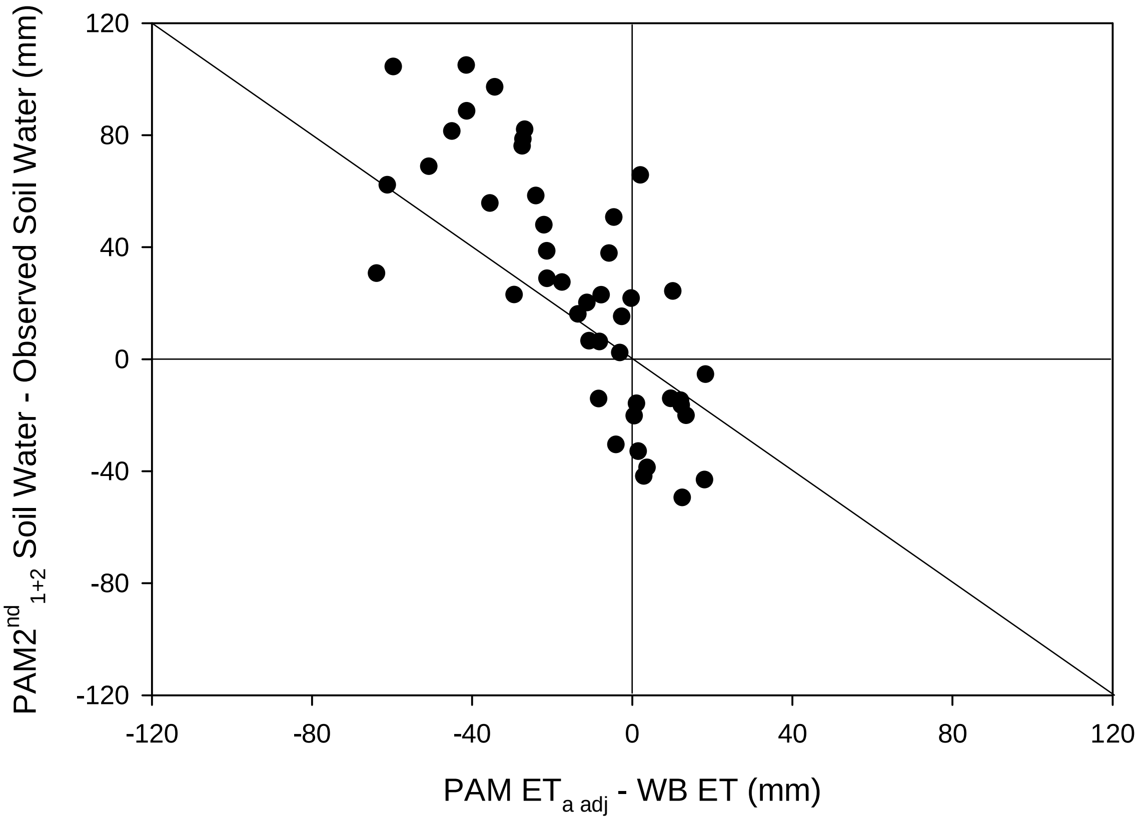

Figure 3.6. Relationship between the overestimation of modeled soil water and the underestimation of modeled evapotranspiration.

It is important to note this assessment of model performance against WB ET only applies to drier conditions when no run-off or deep drainage is suspected. To assess the performance of the models to estimate ET under all conditions, a more in-depth calculation of WB ET would be required to account for run-off, deep drainage and an elevated water table. Alternatively, another technique to measure actual ET such as eddy covariance could be utilized. Nonetheless, the Canadian Prairies often experience a moisture deficit during the growing season. For the most part the assumption that the water table is below the rooting depth and that run-off and deep drainage is negligible is likely accurate. These assumptions are more likely to be valid during drought periods and therefore representative of model performance if the models were to be used for drought monitoring.

3.6 Conclusion

The $PAM2^{nd}_{1+2}$ and FAO56 P-M methods differed in their estimation of crop water demand and in their estimation of actual ET. $PAM2^{nd}_{1+2}$ exhibited a greater daily range of ET_c and ET_a estimates compared to FAO56 P-M. When compared to the water balance derived ET, $PAM2^{nd}_{1+2}$ produced more accurate and less variable estimates of spring wheat ET_a compared to the FAO56 P-M method, however both models produced estimates that fell within the range of WB ET measurement error. Due to the large error associated with the WB ET estimates, there is a level of uncertainty that must be acknowledged when concluding that $PAM2^{nd}_{1+2}$ was more accurate then the FAO56 P-M method in this study. Both $PAM2^{nd}_{1+2}$ and FAO56 P-M underestimated actual ET compared to the water balance. The underestimation of ET by $PAM2^{nd}_{1+2}$ is consistent with the findings of the previous chapter where it was concluded that $PAM2^{nd}_{1+2}$ overestimated soil water content.

Since the accuracy of each model was based on the water balance ET and was only compared during periods where run-off and deep drainage were not suspected, model assessment from this study only applies to drier growing season conditions. Due to the similar performance of both models compared to the WB ET, the adoption of either model for the purpose of ET estimation could be justified and the selection of either would depend on the availability of input weather parameters. The surface weather requirements for $PAM2^{nd}_{1+2}$ are only daily maximum/minimum temperature and precipitation but the model also requires upper atmospheric data in order to model the planetary boundary layer. FAO56 P-M does not require upper atmospheric data but does require additional surface weather parameters including daily humidity, net radiation and wind speed that are not often readily available. Both models require measurements of the soil water holding capacity in order to simulate the daily water balance. Since $PAM2^{nd}_{1+2}$ requires fewer surface input parameters which are readily available from Environment Canada and produced more accurate estimates of crop ET when compared to the water balance derived ET, this model would be best suited for the monitoring of soil moisture status on the Prairies.

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4. OVERALL SYNTESIS

4.1 Conclusion

The role of soil moisture and evapotranspiration on meteorological and agronomic processes are well documented, however difficulties in quantifying these processes have been problematic. The Canadian Prairies normally experience a moisture deficit during the growing season (Nadler, 2007). However, with the increasing threat of climate change, the temperatures and moisture status on the Prairies will likely change resulting in different growing conditions for Prairie farmers. Some scenarios predict earlier planting dates and decreased aridity (McGinn and Shepherd, 2003) while others predict an increase in aridity (Wheaton et al., 2007). Regardless of the scenario, it is acknowledged that our climate is facing change and farmers and other weather dependent industries will have to adapt to these new conditions. Whether growing conditions improve or worsen, the key to adaptation is to quantify the extent and spatial distribution of the change. The latter is important since not all regions on the Prairies are likely to be equally effected. By actively monitoring soil moisture, farmers would be able to make more informed decisions about which crop to grow and which seeding date and rate would optimize crop water use. In addition, farmers could optimize fertilizer applications by applying when soil moisture is conducive to crop uptake and growth. Rates of crop evapotranspiration would also be beneficial for marketing information. Crop transpiration has been found to be a strong indicator of crop yield and quality (Jarvis et al. 2008). Marketing organizations such as the Canadian Wheat Board would be able to forecast wheat yields and quality on a regional basis. Soil moisture and crop evapotranspiration are also important input parameters for many other agronomic models such as pest development and risk models.

Soil moisture monitoring has many applications beyond the agricultural sector. Soil moisture and crop evapotranspiration drive convective activity on the Prairies. They are also key components in the daily energy balance affecting daily temperatures. During wetter conditions a greater proportion of net solar radiation is dedicated to latent heat flux rather than sensible heat. Increased surface evaporation results in a net cooling effect, creating cooler surface conditions. During drier conditions, a greater proportion of solar radiation is dedicated to sensible heat flux, increasing soil and surface air temperatures. Daily soil moisture and evapotranspiration monitoring would provide important information for severe weather forecasting such as thunderstorms, tornadoes, hail and droughts.

This study validated an operational model that could be implemented to monitor the soil moisture status on the Prairies. PAM2nd was validated at 5 different locations across Manitoba and Saskatchewan, encompassing various soil and climatic regions. Validation at these sites revealed the model was overestimating soil water content during the second half of the growing season at most of the sites. In addition, it was observed soil water content was underestimated during periods that experienced consecutive days of rainfall. To solve these issues, modifications were made to the crop and soil water component of the model. To address the underestimation of soil water, the canopy resistance function was modified to restrict the increase of canopy resistance until plant available water is below 50%. This modification reflects the fact that wheat does not experience water stress until at least 50% of plant available water is depleted (Shen et al., 2002). Overestimation of soil water during consecutive rainfall events was addressed by allowing rain to continue to infiltrate, regardless of topzone moisture content. The modifications were successful in improving soil water estimates, while increasing confidence in the evapotranspiration estimates. When compared to a simplified water balance derived rate of evapotranspiration, the modified version of $PAM2^{nd}$, $PAM2^{nd}_{1+2}$, produced more accurate estimates compared to the FAO56 Penman-Monteith model. $PAM2^{nd}_{1+2}$ was also more responsive to daily variation in weather conditions.

Even though the results from the model validation are encouraging, there are some issues that need to be addressed before implementing $PAM2^{nd}_{1+2}$. Model validation was conducted using the most accurate input parameters available, most of which were directly measured at each study location. Unfortunately, on a Prairie-wide scale, site specific information will not likely be available. Of greatest concern is the soil water holding capacity input parameters; field capacity and permanent wilting point. When $PAM2^{nd}_{1+2}$ was operated using soil water holding capacity parameters obtained from the Soil Landscapes of Canada database, the accuracy of modeled soil water content decreased significantly. Despite the improvements made to the model, the use of inaccurate soil input parameters will overshadow any other potential shortcoming of the model. It is recommended that this issue be addressed before any further improvements are attempted for $PAM2^{nd}_{1+2}$.

Another foreseeable limitation of implementing $PAM2^{nd}_{1+2}$ is the need for spring soil water content in order to initialise the soil water balance. Since $PAM2^{nd}_{1+2}$ was not designed to operate throughout the winter months and spring soil moisture for the Prairies ie not available, a method must be devised to address this issue. Without accurate measurements of initial water content, $PAM2^{nd}_{1+2}$ will not be able to accurately simulate water content for the rest of the growing season.

It is uncertain to what degree climate change may impact the Canadian Prairies or any other part of the world. What is certain is that we are vulnerable to weather and we have become habituated to the climate we currently experience. In order to properly adapt to any changes, we must first identify and understand the mechanisms and magnitude of change. The first step is to properly quantify the processes in our current climate so that we can track any future changes. Soil moisture and evapotranspiration are key components of the energy balance and hydrological cycle which dictate our climate. Without this fundamental knowledge of our current environment, it seems unlikely we will be able to recognize change as it unfolds in years to come.

4.2 References

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Shen, Y., Kondoh, A., Tang, C., Zhang, Y., Chen, J., Li, W., Sakura, Y., Liu, C., Tanaka, T. and Shimada, J. 2002. Measurement and analysis of evapotranspiration and surface conductance of a wheat canopy. Hydrol. Processes **16**:2173-2187.

5. APPENDICES

5.1 Appendix A- Measured Soil Characteristics

Table A.1. Measured soil texture, water holding capacity and bulk density at each study site.

Location	Depth (cm)	% Clay	% Sand	% Silt	Soil Texture	PWP (mm)	FC (mm)	AWC (mm)	BD (g/cm^3)
Melfort	0-15	26	14	60	SiL	30	54	24	0.94
	15-30	36	12	52	SiCL	41	72	31	1.36
	30-45	58	10	32	C	44	89	44	1.56
	45-60	58	6	36	C	48	83	36	1.60
	60-90	68	4	28	HC	100	147	46	1.65
	90-120	78	4	18	HC	110	121	11	1.70
	0-120					**373**	**566**	**193**	**1.47**
Regina	0-15	40	16	44	SiC	36	58	22	0.99
	15-30	52	10	38	C	50	73	23	1.35
	30-45	56	8	36	HC	51	88	37	1.41
	45-60	66	6	28	HC	54	87	33	1.51
	60-90	70	4	26	HC	105	164	59	1.52
	90-120	70	6	24	HC	114	150	36	1.67
	0-120					**409**	**620**	**211**	**1.41**
Swift Current	0-15	10	32	58	SiL	16	49	33	1.23
	15-30	18	30	52	SiL	19	47	27	1.35
	30-45	24	26	50	SiL	21	46	25	1.41
	45-60	18	20	62	SiL	21	53	33	1.41
	60-90	22	28	50	SiL	50	90	40	1.62
	90-120	22	34	44	L	53	95	43	1.81
	0-120					**179**	**380**	**201**	**1.47**
Winnipeg	0-25	52	5.6	43	SiC	66	117	51	1.18
	25-61	52	4	44	SiC	99	169	71	1.28
	61-120	59	1.2	40	SiC	170	295	124	1.36
						334	**581**	**246**	**1.27**
Carman	0-15	18	52	30	SL	21	53	32	1.15
	15-30	28	42	30	CL	29	55	26	1.49
	30-45	50	26	24	C	42	69	28	1.46
	45-60	56	20	24	C	42	62	20	1.54
	60-90	58	12	30	C	93	131	38	1.66
	90-120	64	4	32	HC	97	131	34	1.60
	0-120					**324**	**502**	**178**	**1.48**

5.2 Appendix B- Soil Survey Soil Characteristics

Table B.1. Soil characteristics obtained from Soil Landscape of Canada soil survey database

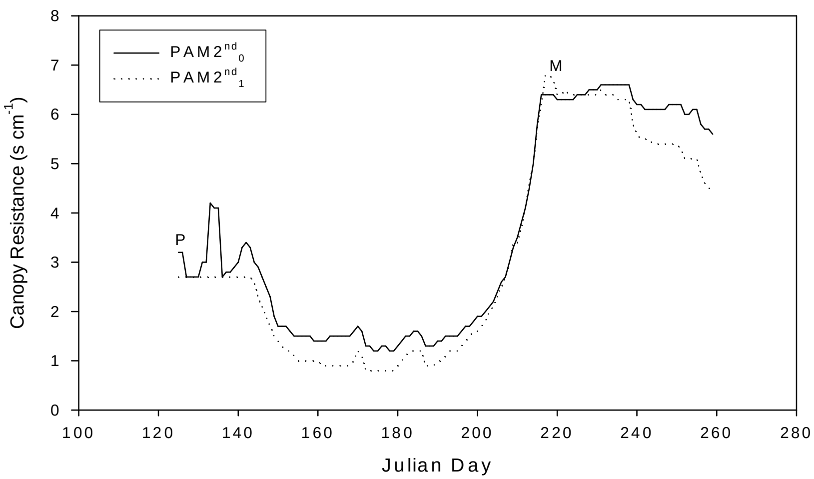
Location	% polygon	Depth (cm)	% CLAY	% SAND	% SILT	Sat (mm)	FC (mm)	PWP (mm)	AWC (mm)
Melfort	60	0-19	50	10	40				
		19-58	49	7	44				
		58-100	52	3	45				
		100-120	52	3	45				
Total						620	550	332	218
Regina	87	0-13	62	8	30				
		13-46	64	6	30				
		46-100	69	6	25				
		100-120	69	6	25				
Total						617	567	348	219
Swift Current	57	0-12	20	35	45				
		12-30	24	25	51				
		30-64	20	27	53				
		64-100	28	43	29				
		100-120	28	43	29				
Total						554	395	227	168
Winnipeg	50	0-14	56	8	36				
		14-22	57	8	35				
		22-30	57	3	40				
		30-100	56	5	39				
		100-120	56	5	39				
Total						619	537	253	284
Carman 1	20	0-15	24	52	24				
		15-28	26	50	24				
		28-60	21	62	17				
		60-80	21	54	25				
		80-100	39	8	53				
		100-120	39	8	53				
Total						526	357	162	195
Carman 2	20	0-20	47	28	25				
		20-30	49	23	28				
		30-60	44	21	35				
		60-100	46	17	37				
		100-120	46	17	37				
Total						592	526	264	262

5.3 Appendix C- Additional Soil, Crop and Geographic Input Parameters for PAM2nd

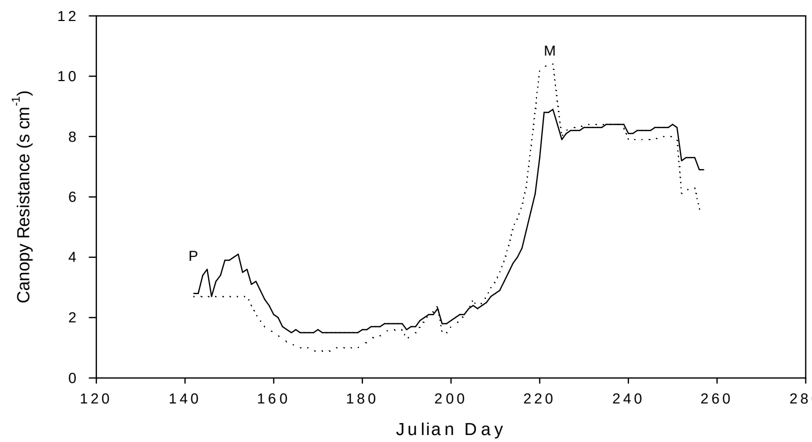
Table C.1. Geographic location of study sites, top-zone soil characteristics and crop roughness length.

Name	Melfort	Regina	Swift Current	Winnipeg	Carman
Latitude (°N)	52.82	50.41	50.27	49.8	49.5
Longitude (°W)	104.6	104.57	107.72	97.17	98.02
Elevation (m)	472.74	571.5	818.08	224.64	268.2
Terrain Drag	234.5	504.9	1208.4	291	325.4
C_2(ref)	0.8	0.3	0.8	0.3	0.3
b	10.39	10.39	5.33	10.39	11.55
si	75.86	32.36	75.86	32.36	46.77
Roughness length (m)	0.12	0.12	0.12	0.12	0.12

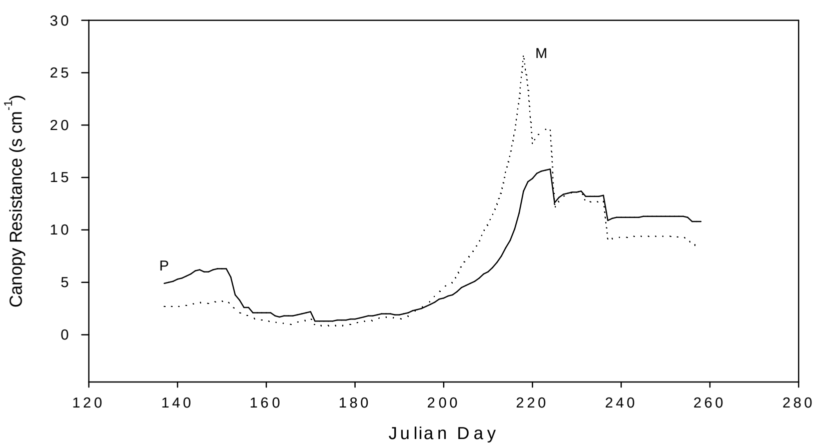
5.4 Appendix D- Canopy Resistance


Canopy Resistance (s cm-1)
Julian Day
PAM2nd0
PAM2nd1
P
M

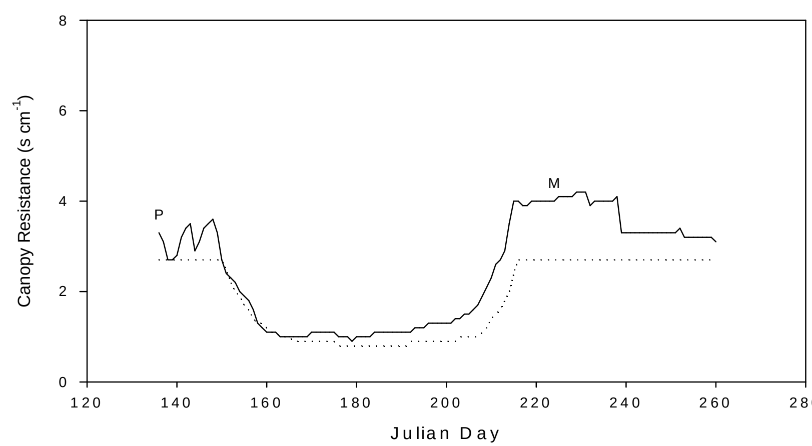
a)


Canopy Resistance (s cm-1)
Julian Day
P
M

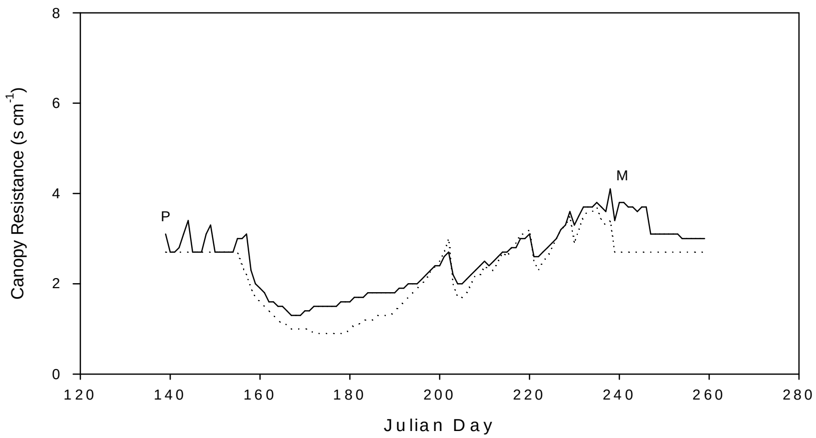
b)


Canopy Resistance (s cm-1)
Julian Day
P
M

c)

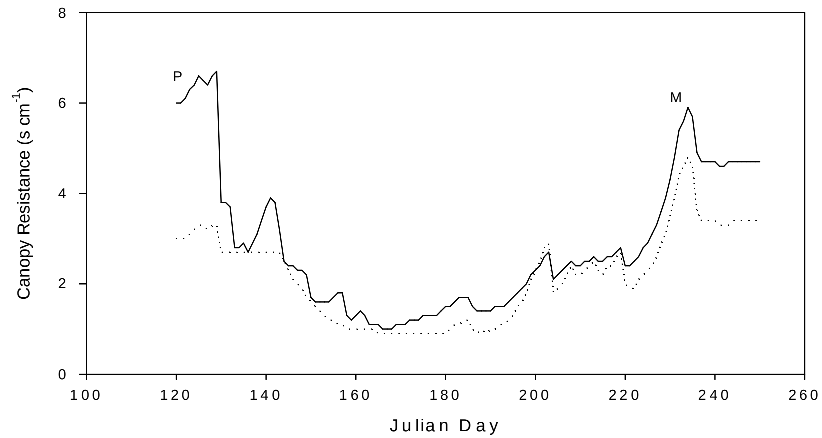

Canopy Resistance (s cm-1)
Julian Day
P
M

d)



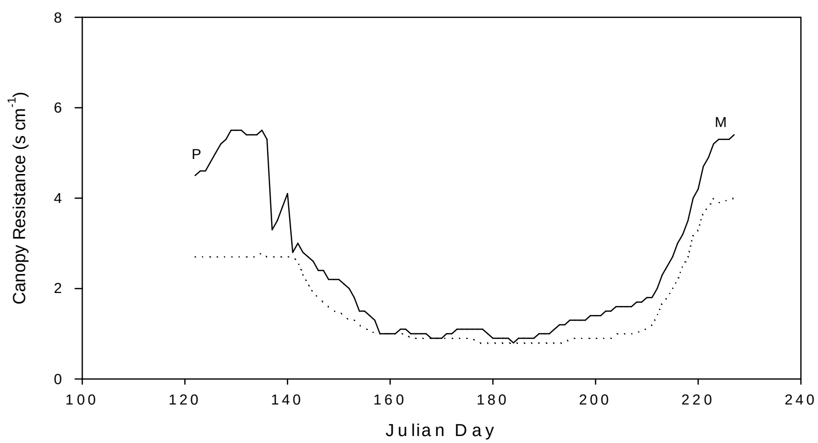
Canopy Resistance (s cm^{-1})
Julian Day
P
M

e)



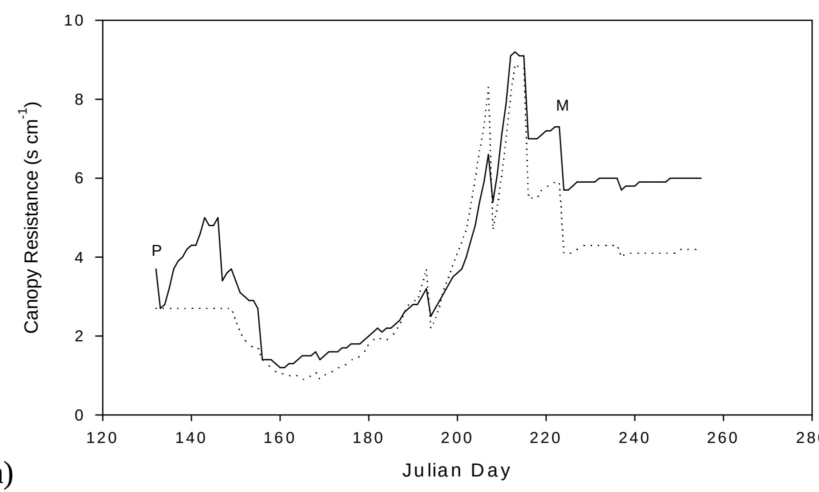
Canopy Resistance (s cm^{-1})
Julian Day
P
M

f)



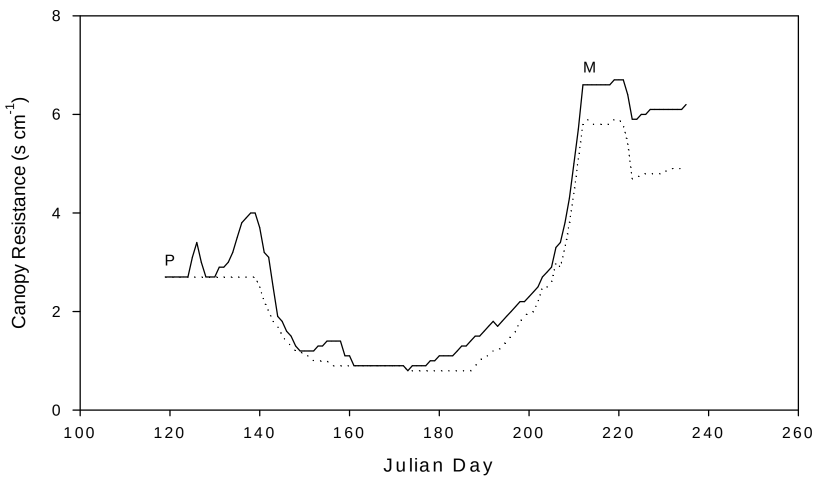
Canopy Resistance (s cm^{-1})
Julian Day
P
M

g)



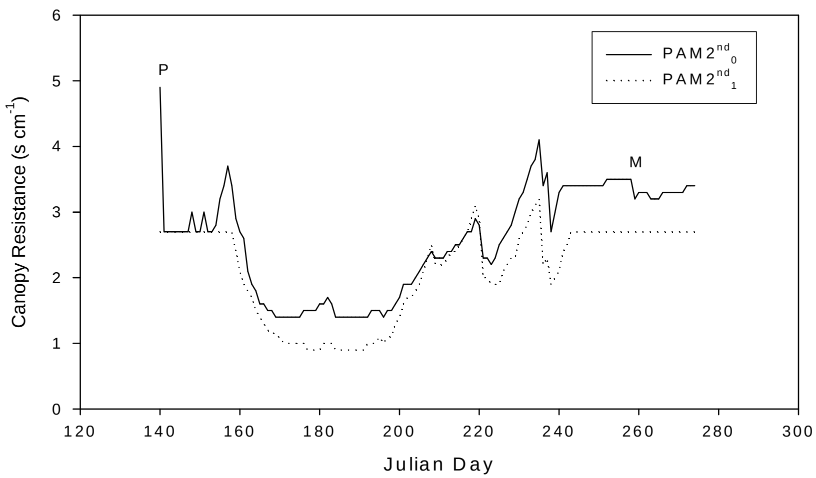
Canopy Resistance (s cm^{-1})
Julian Day
P
M

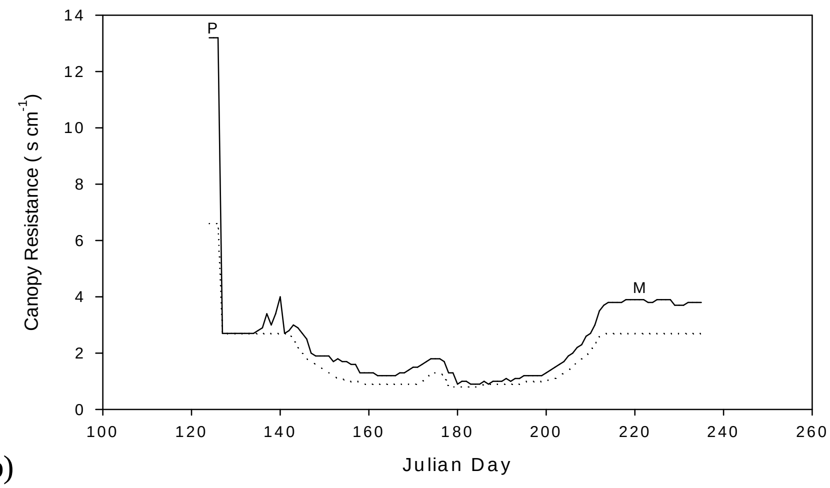
h)

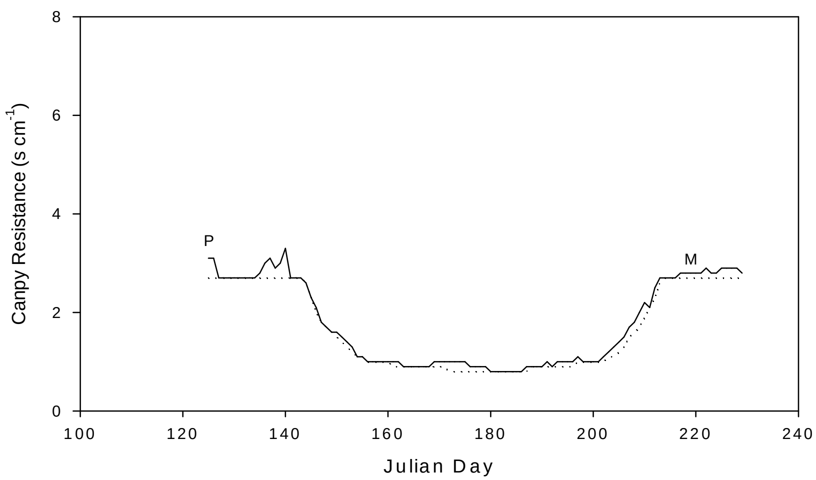


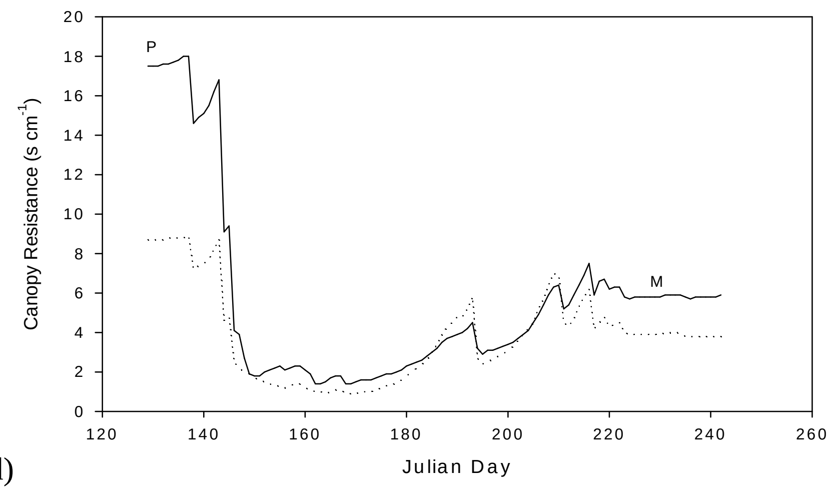
i)

Figure D.1. Comparison of modeled canopy resistance from versions PAM2$^{nd}_{0}$ and PAM2$^{nd}_{1}$ for a) Melfort 2003 b) Regina 2003 c) Swift Current 2003 d) Winnipeg 2003 e) Carman 2004 f) Swift Current 2004 g) Swift Current 2005 h) Carman 2006 and i) Swift Current 2006. P and M indicate planting date and physiological maturity date of crop.


PAM2nd0
PAM2nd1
P
M
Canopy Resistance (s cm-1)
Julian Day
a)


P
M
Canopy Resistance (s cm-1)
Julian Day
b)


P
M
Canpy Resistance (s cm-1)
Julian Day
c)


P
M
Canopy Resistance (s cm-1)
Julian Day
d)

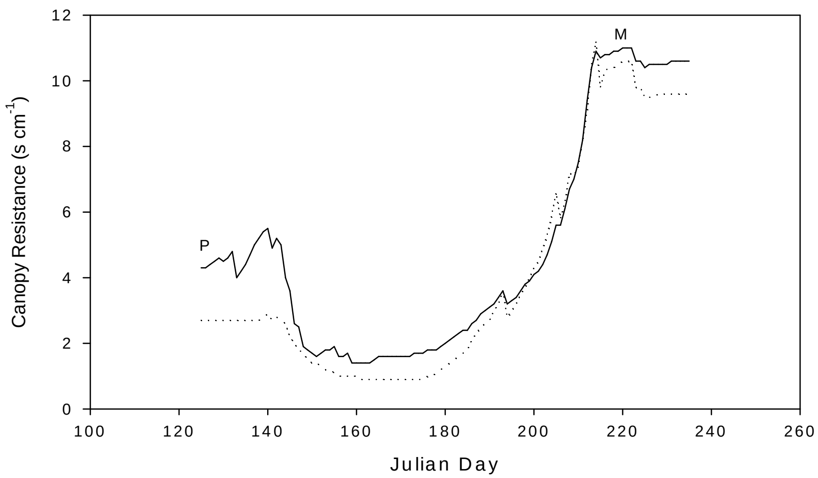
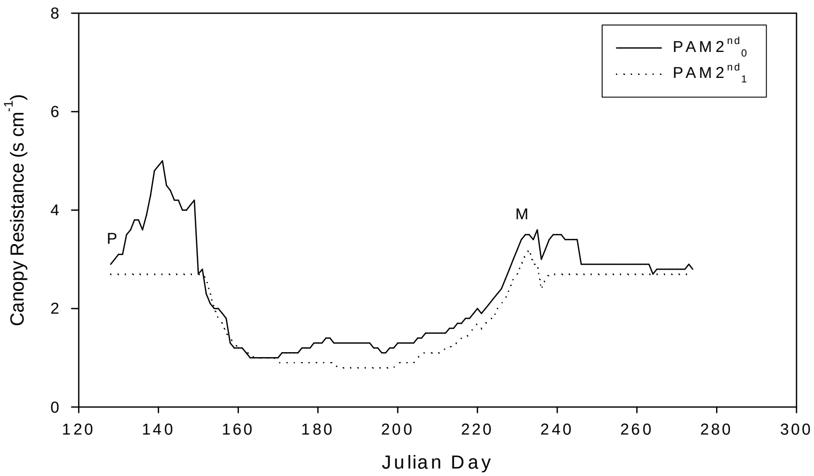
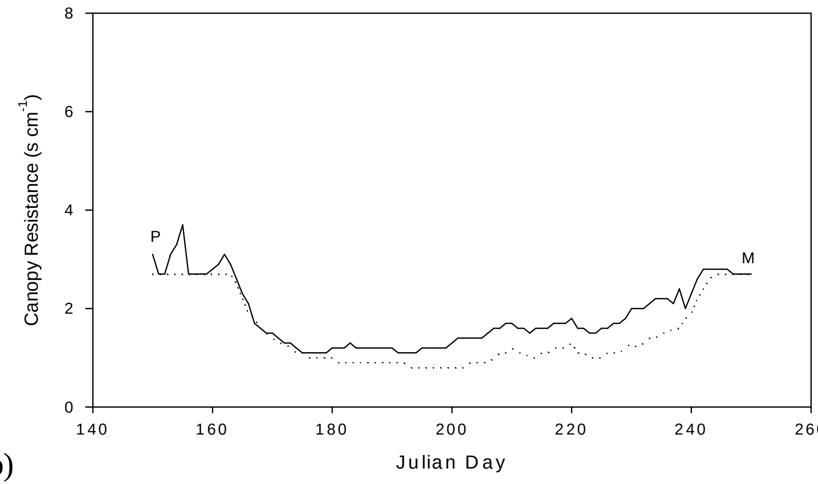
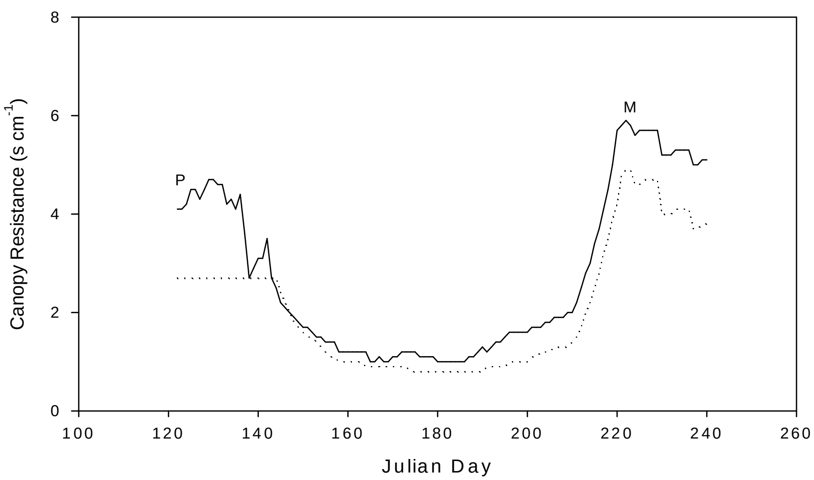
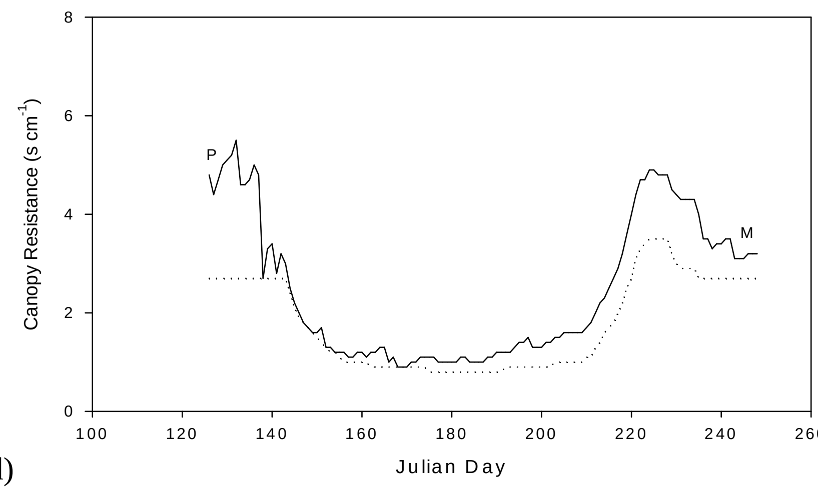
e) 

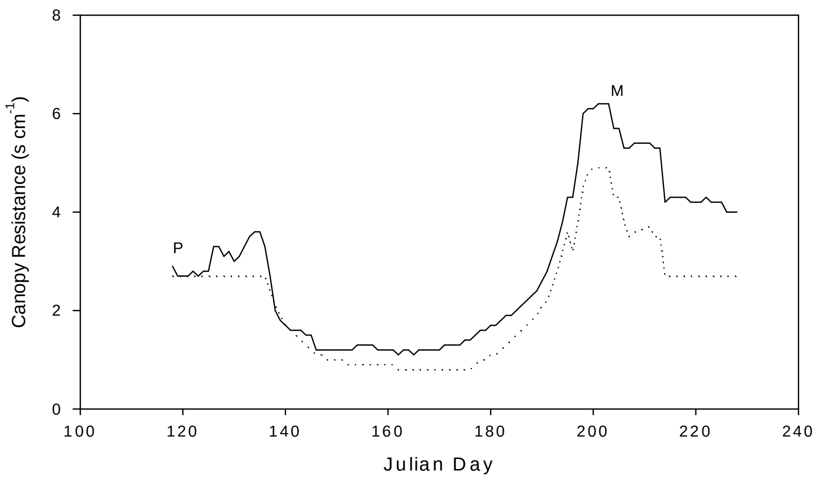
Figure D.2. Comparison of for modeled canopy resistance from versions PAM2$^{nd}_{0}$ and PAM2$^{nd}_{1}$ for a) Regina 2004 b) Carman 2005 c) Winnipeg 2005 d) Melfort 2006 e) Regina 2006. P and M indicate planting date and physiological maturity date of crop.


Canopy Resistance (s cm-1)
Julian Day
PAM2nd0
PAM2nd1
P
M
a)


Canopy Resistance (s cm-1)
Julian Day
P
M
b)


Canopy Resistance (s cm-1)
Julian Day
P
M
c)


Canopy Resistance (s cm-1)
Julian Day
P
M
d)



e)

Figure D.3. Comparison of for modeled canopy resistance from versions PAM2$^{nd}_{0}$ and PAM2$^{nd}_{1}$ for a) Melfort 2004 b) Winnipeg 2004 c) Regina 2005 d) Melfort 2005 e) Winnipeg 2006. P and M indicate planting date and physiological maturity date of crop.

5.5 Appendix E- Soil moisture, rainfall and actual evapotranspiration time series

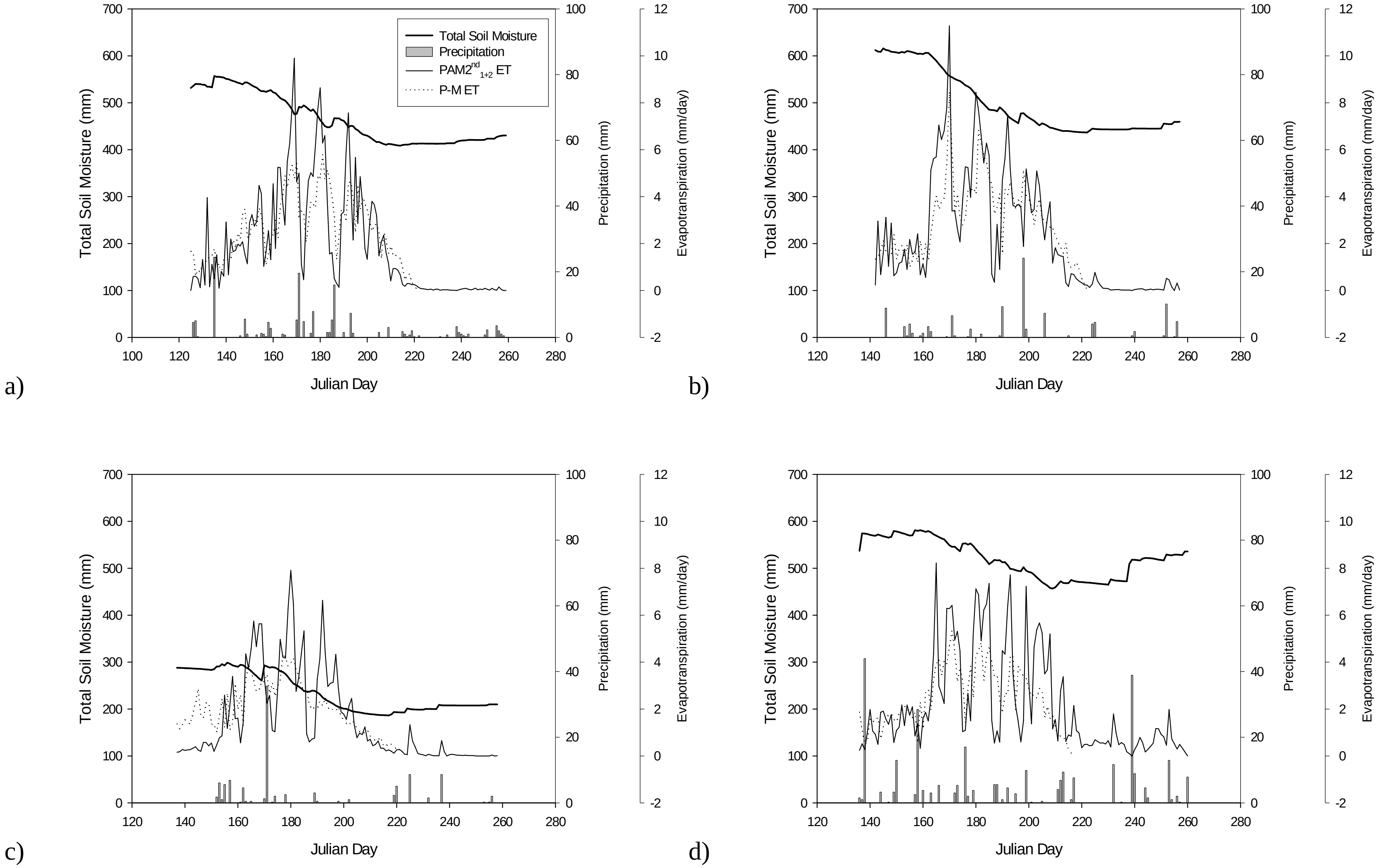
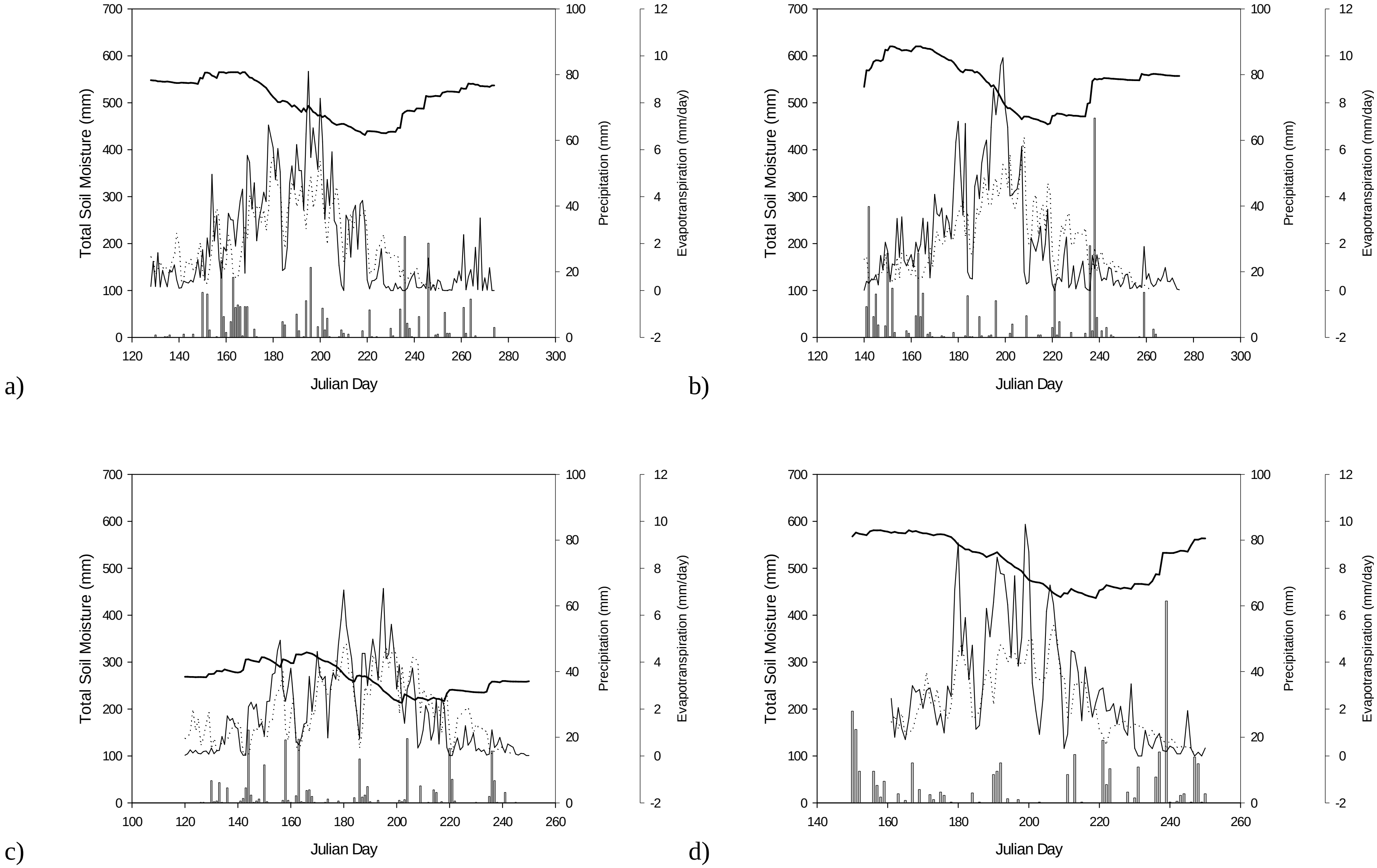
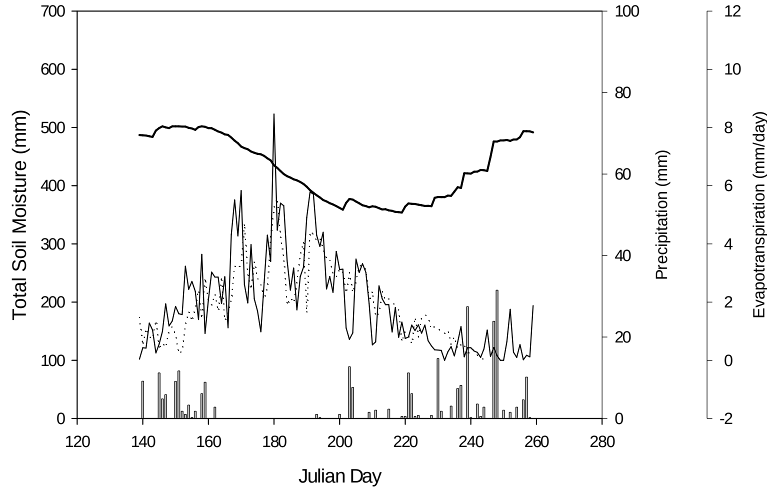


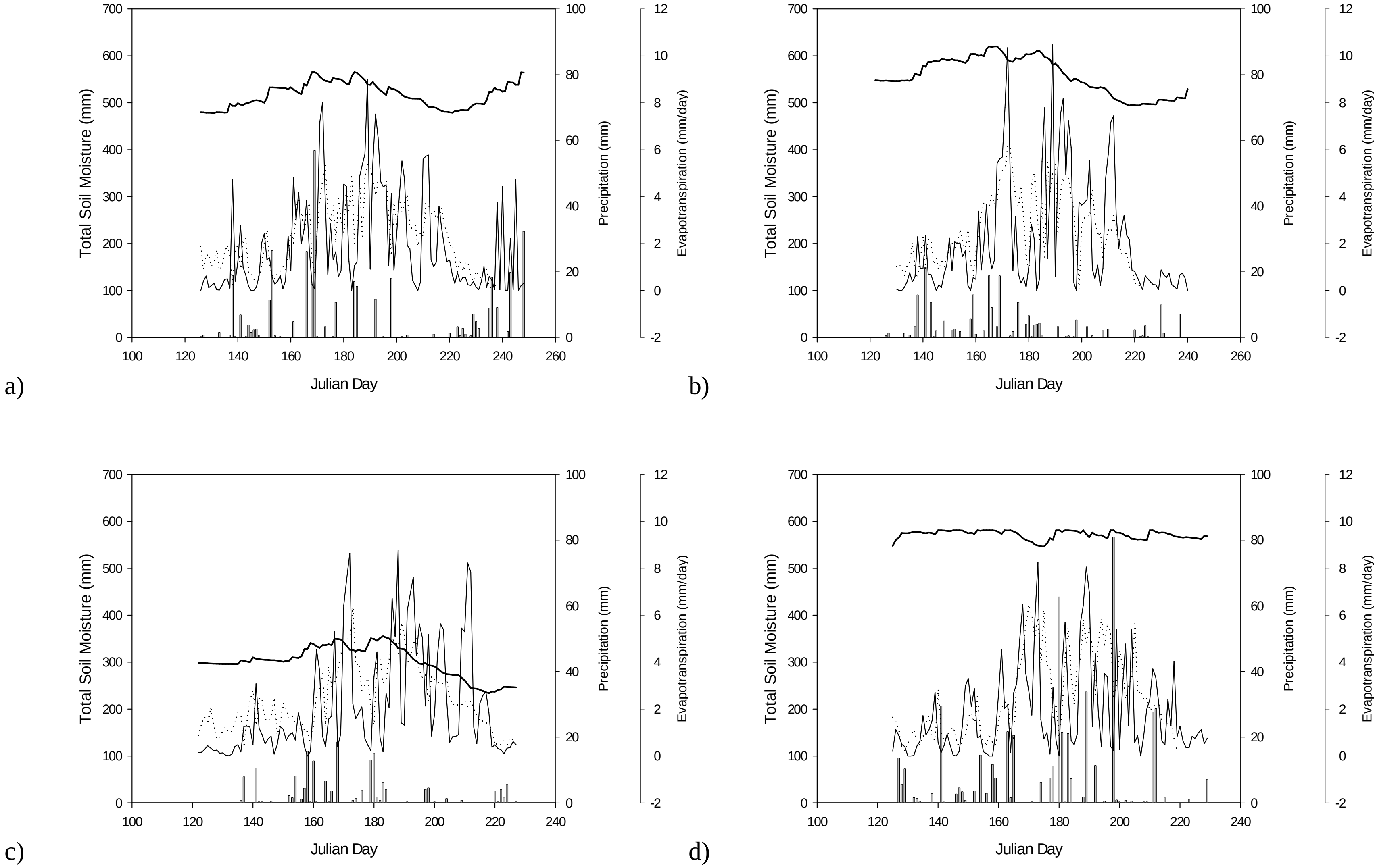
Figure E.1. Time series of total soil moisture, rainfall and actual evapotranspiration as derived from PAM2^{nd}_{1+2} and FAO56 Penman-Monteith for a) Melfort b) Regina c) Swift Current and d) Winnipeg, for the 2003 growing season.

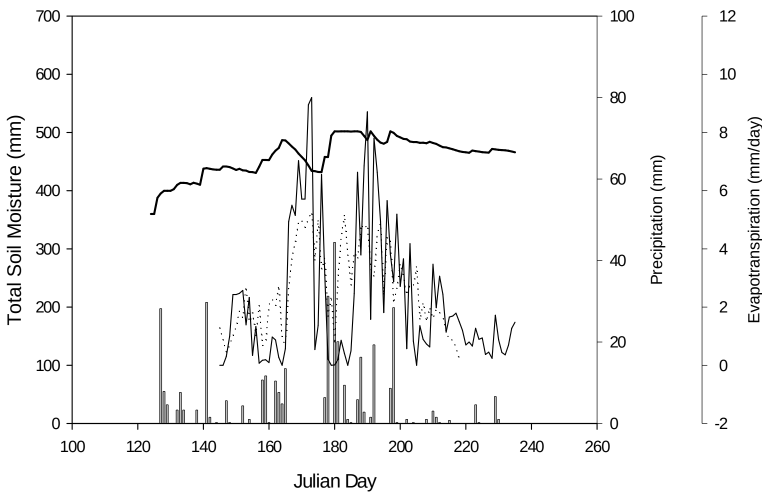

a)
b)
c)
d)
Total Soil Moisture (mm)
Precipitation (mm)
Evapotranspiration (mm/day)
Julian Day



e)

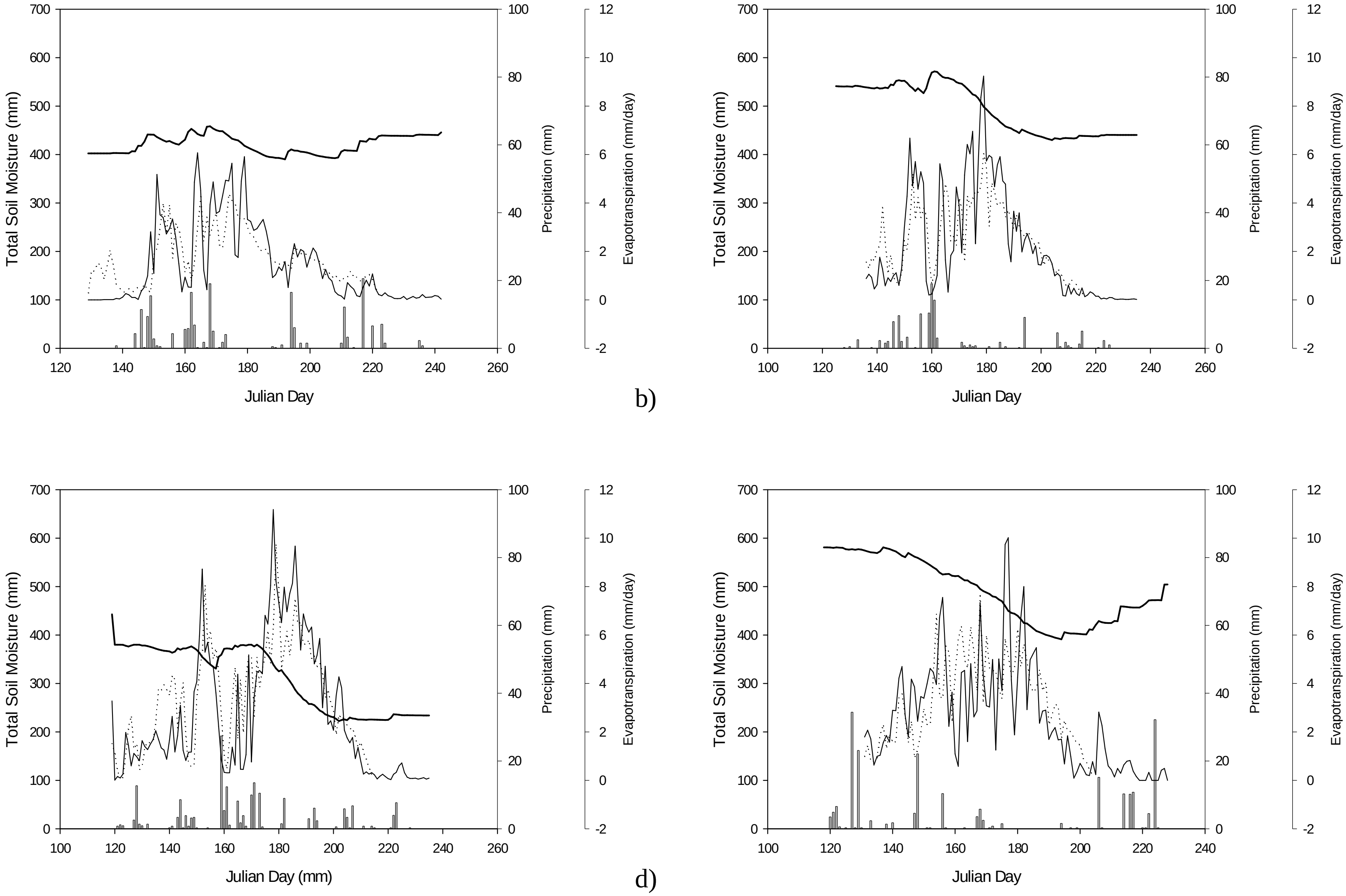
Figure E.2. Time series of total soil moisture, rainfall and actual evapotranspiration as derived from $PAM2^{nd}_{1+2}$ and FAO56 Penman-Monteith for a) Melfort b) Regina c) Swift Current d) Winnipeg e) Carman, for the 2004 growing season.


Total Soil Moisture (mm)
Precipitation (mm)
Evapotranspiration (mm/day)
Julian Day
a)
Total Soil Moisture (mm)
Precipitation (mm)
Evapotranspiration (mm/day)
Julian Day
b)
Total Soil Moisture (mm)
Precipitation (mm)
Evapotranspiration (mm/day)
Julian Day
c)
Total Soil Moisture (mm)
Precipitation (mm)
Evapotranspiration (mm/day)
Julian Day
d)

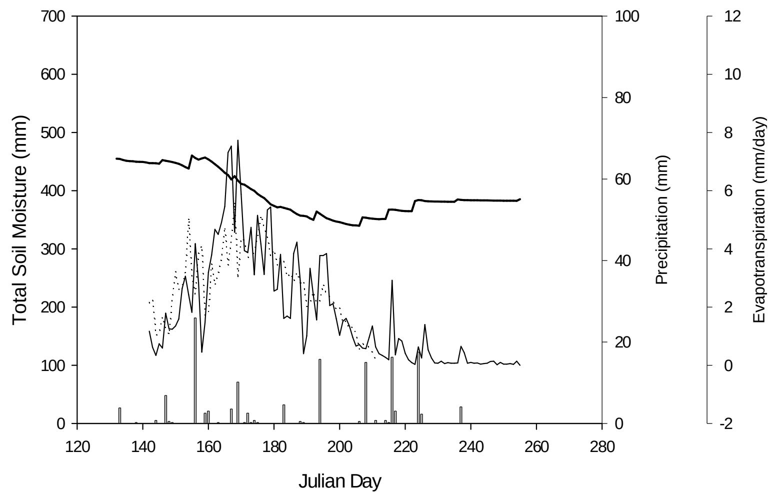


e)

Figure E.3. Time series of total soil moisture, rainfall and actual evapotranspiration as derived from PAM2$^{nd}_{1+2}$ and FAO56 Penman-Monteith for a) Melfort b) Regina c) Swift Current d) Winnipeg e) Carman, for the 2005 growing season.


Total Soil Moisture (mm)
Precipitation (mm)
Evapotranspiration (mm/day)
Julian Day
Julian Day (mm)

a) b) c) d)



e)

Figure E.4. Time series of total soil moisture, rainfall and actual evapotranspiration as derived from PAM2$^{nd}_{1+2}$ and FAO56 Penman-Monteith for a) Melfort b) Regina c) Swift Current d) Winnipeg e) Carman, for the 2006 growing season.

5.6 Appendix F- Water Balance Error

Table F.1. Water balance evapotranspiration and measurement error in comparison to modeled evapotranspiration estimates for the same time period.

	Water Balance Period		WB ET	WB ET	PAM2nd $ET_{a\ adj}$	P-M $Et_{a\ adj}$
Site/Year	Start Date	End Date	error (mm)	(mm)	(mm)*	(mm)*
Mel03	190	205	16	53	45	45
Reg03	189	204	22	76	86	71
	204	219	21	43	32	31
SC03	161	176	7	56	57	57
	176	190	7	47	60	62
	190	205	7	70	62	51
Wpg03	144	157	10	79	**19**	**24**
	197	210	12	31	33	30
Mel04	128	141	13	69	**8**	**17**
Reg04	194	208	20	113	115	**70**
	208	222	20	41	32	44
SC04	141	155	7	10	28	17
	155	169	7	40	37	24
	169	181	7	62	48	43
	181	196	6	59	56	46
	196	209	6	50	33	30
	209	223	6	44	**9**	**11**
	223	237	5	29	**2**	**4**
	237	253	4	10	0	0

Table F.1. continued

Wpg04	201	206	12	10	22	23
	206	216	14	42	45	38
	216	229	13	37	33	20
Car04	187	201	16	67	79	61
	201	211	13	58	29	33
	211	219	14	28	7	10
	219	229	14	7	2	5
Mel05	215	228	17	36	12	26
Reg05	186	199	20	107	**66**	**52**
	199	214	18	67	**26**	**25**
SC05	131	145	7	23	12	25
	145	159	7	16	10	22
	159	173	7	68	46	51
	173	187	7	62	**34**	55
	187	200	6	78	**44**	**48**
	200	215	6	37	**10**	14
Reg06	137	151	31	8	**21**	26
	185	200	30	156	**92**	**70**
	200	213	34	2	1	3
SC06	165	186	17	164	**119**	**113**
	186	201	17	15	26	31
	201	214	16	64	**13**	**15**
Car06	198	205	24	28	7	9
Wpg06	179	188	23	38	57	49
	188	192	23	13	17	19
	192	199	23	12	13	23

***** Values in bold indicate model estimates that are significantly different then the WB ET