Modelling Long-term Soil Moisture Dynamics of Urban Grassland under South-western Ontario Soil and Meteorological Conditions

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Abstract

Soil moisture is at the centre of the water balance and is of great concern with regards to crop growth and yield, irrigation planning, fertilization, climate change and non-point source pollution control. Information on soil moisture is not widely available, resulting in researchers relying on mathematical models to gain insight into soil moisture conditions. This thesis primarily focuses on long-term soil moisture characteristics, under given climate, soil and vegetation conditions. Long-term soil moisture characteristics are best described by statistics such as average soil moisture, and its standard deviation and frequency/probability distribution. After an extensive review of existing explicit or implicit soil moisture models, a deterministic water balance model was developed to simulate soil moisture at a point within the root-zone. The hydrological processes involved in the water balance are modelled using well-established methods. The continuous simulation model is unique from other leading deterministic models as it introduces the ecohydrological perspective by modelling actual evapotranspiration as a function of plant access to soil moisture. The validation of the model demonstrates that simplified soil moisture modelling is rational and practical.

Soil moisture modelling is dependent on various input parameters related to the climate, soil and vegetation. Both local and global sensitivity analyses were carried out to investigate which input parameters influence the soil moisture regime the most. The analyses concluded that parameters representing soil texture are most important and thereby indicated that evapotranspiration is the most dominant process as it is significantly controlled by these parameters. Due to concerns of the impact of climate change and urban stormwater management, a better understanding of urban area soil moisture dynamics is required. The applicability of the continuous simulation model was demonstrated by investigating the influence of global warming on long-term soil moisture and evapotranspiration. Statistical analyses carried out on the post-simulated long-term soil moisture values clearly showed that even though temperatures are

increasing, soil moisture and evapotranspiration have also increased because of the overall increase in precipitation. This phenomenon gives insight into the precipitation characteristics being strong enough to overpower the soil moisture loss process of evapotranspiration. As a part of the overall research, an analysis on antecedent soil moisture values for the purpose of urban stormwater management was performed. Empirical equations were derived to obtain antecedent soil moisture values from soil characteristics. Antecedent soil moisture information is essential in the application of the design storm approach while designing urban stormwater management infrastructure.

The main purpose for the development and use of the deterministic model was to better understand the statistics and sensitivity of soil moisture and not as a predictive tool.

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This dissertation consists of the following papers:

Paper I:

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Paper II:

Nishat, S., Guo, Y. and Baetz, B.W., 'Relative Importance of Input Parameters in Soil Moisture Dynamics Modelling', submitted to the *Journal of Hydrology*.

Paper III:

Nishat, S., Guo, Y. and Baetz, B.W., (2008) 'Climate Change and Urban Grass Land Soil Moisture Conditions in South-Western Ontario, Canada', *Journal of Environmental Informatics*, Vol. 12, No. 2, pp. 105-119.

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Co-Authorship

This thesis is prepared in accordance with the regulation of a 'Sandwich' thesis format by the School of Graduate Studies at McMaster University and was co-authored.

Chapter 2: Development of a Simplified Continuous Simulation Model for Investigating Long-term Soil Moisture Fluctuations
By: Shazia Nishat, Yiping Guo and Brian W. Baetz

The development and application of the one-dimensional water balance model and the statistical analyses were carried out by Shazia Nishat in consultation with Y. Guo. The paper was written by S. Nishat and edited by both Y. Guo, and B.W. Baetz.

The paper was published in June, 2007 in Agricultural Water Management, Vol. 92, pp. 53-63.

Chapter 3: Relative Importance of Input Parameters in Soil Moisture Dynamics Modelling
By: Shazia Nishat, Yiping Guo and Brian W. Baetz

The application of the continuous simulation model and the statistical analyses were performed by Shazia Nishat in consultation with Y. Guo. The paper was written by S. Nishat and edited by both Y. Guo, and B.W. Baetz.

The paper has been submitted to the Journal of Hydrology.

Chapter 4: Climate Change and Urban Grass Land Soil Moisture Conditions in South-Western Ontario, Canada
By: Shazia Nishat, Yiping Guo and Brian W. Baetz

The simulation of the deterministic model, the data analysis and the post simulation statistical analyses were conducted by Shazia Nishat in consultation with Y. Guo. The paper was written by S. Nishat and edited by both Y. Guo, and B.W. Baetz.

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Chapter 5: Antecedent Soil Moisture Conditions of Different Soil Types in South-western Ontario, Canada
By: Shazia Nishat, Yiping Guo and Brian W. Baetz

The hydrologic modeling and the derivation of the empirical equations were performed by Shazia Nishat in consultation with Y. Guo. The paper was written by S. Nishat and edited by both Y. Guo and B.W. Baetz.

The paper has been submitted to Hydrological Processes.

Contents

Abbreviations

A	Average depth of rainfall per rainfall event
λ	the average number of rainfall events per day
Λ	Interception
$\rho_{x,y}$	Correlation Coefficient between parameters x and y
μ_x, μ_y	Mean of input x and output y
σ_x, σ_y	Standard Deviation of input x and output y
$\underline{\Psi}_{sa}$	Matric Potential corresponding to s_a
ψ_s	Saturation Matric Potential
ADAPT	Agricultural Drainage And Pesticide Transport
AET	Actual Evapotranspiration
AGNPS	AGricultural Non-Point Source
AMC	Antecedent Moisture Condition
APSIM	Agricultural Production System SIMulator
ARC	Antecedent Runoff Coefficient
ASM	Antecedent Soil Moisture
$\overline{\text{ASM}}$	Average Antecedent Soil Moisture
b	Empirical exponent based on soil texture
C	Clay
CERES	Crop Environment REsources Synthesis
CL	Clay Loam
CN	Curve Number
COV	Coefficient of Variation
CREAMS	Chemicals, Runoff and Erosion from Agricultural Management Systems
CRM	Coefficient of Residual Mass
DS	Design Storm
DSA	Design Storm Approach
E_m	Maximum Soil Evaporation
ET	Evapotranspiration
FSU	Former Soviet Union
GCM	General Circulation Model
GLEAMS	Groundwater Loading Effects of Agricultural Management Systems
GSA	Global Sensitivity Analysis
GSMDB	Global Soil Moisture Data Bank
GTIERC	Guelph Turfgrass Institute and Environmental Research Centre
h_c	Height of plant
IoA	Index of Agreement

k_c	Crop Coefficient
K_s	Saturated Hydraulic Conductivity
L	Leakage
LAI	Leaf Area Index
LEACHM	Leaching Estimation And CHemistry Model
Lm	Loam
LS	Loamy Sand
LSA	Local Sensitivity Analysis
MAWS	Maximum Available Water Storage
MC	Monte Carlo
n	Porosity
N	Nitrogen
NRCS	National Resources Conservation Services
NRCS-CN	National Resources Conservation Services-Curve Number
P	Precipitation
P_5	Total 5-day antecedent rainfall
PCC	Partial Correlation Coefficient
PEAR	PEARson product moment coefficient
PEs	Potential Soil Evaporation
PET	Potential Evapotranspiration
pdf	Probability Density Function
Ppt	Precipitation
PRCC	Partial Rank Correlation Coefficient
PT	Potential Transpiration
PWP	Permanent Wilting Point
R^2	Coefficient of Determination
R_n	Net Solar Radiation
R_s	Incoming Solar Radiation
RD	Root Depth
RD_m	Maximum Root Depth
RH	Relative Humidity
RMSE	Root Mean Square Error
S	Sand
s^*	Critical Soil Moisture
s_{fc}	Soil Moisture at Field Capacity
s_h	Soil Moisture at Hygroscopic Point
s_w	Soil Moisture at Permanent Wilting Point
SA	Sensitivity Analysis
SC	Sandy Clay
SCL	Sandy Clay Loam
SCS	Soil Conservation Services
SD	Standard Deviation
SI	Sensitivity Index

SiC	Silty Clay
SiL	Silt Loam
SiCL	Silty Clay Loam
SL	Silty Loam
SPEA	SPEArmans Coefficient
SR	Surface Runoff
SRC	Standardized Regression Coefficient
SRRC	Standardized Rank Regression Coefficient
SWAP	Soil Water Atmosphere Plant
SWAT	Soil & Water Assessment Tool
SWIM	Soil Water Infiltration Movement
SWM	Storm Water Management
S_x	Sensitivity Coefficient
t	time in days
t_m	number of days to reach RD_m
T	Temperature
TDR	Time Domain Reflectometry
Temp	Temperature
T_m	Maximum Transpiration
T_{up}	Plant root water uptake
u_1, u_2	Wind Velocity at heights 1 and 2 respectively
u_{10}	Wind Velocity at 10m
WOFOST	WOrld FOod STudy
z_1, z_2	Heights of u_1 and u_2 respectively
Zr	Depth within the soil root zone

Chapter 1

Introduction

Thesis Summary

This dissertation is organized as follows: Chapter 1 is an introduction to the research area. Chapter 2 presents the developed model, and provides its calibration and verification, followed by Local Sensitivity Analysis. Chapter 3 deals with the application of Global Sensitivity Analyses to examine in a comprehensive way the general influence of selected input parameters on selected output variables. Chapter 4 demonstrates the use of the model in investigating the effect of climate change on long-term soil moisture fluctuations. In Chapter 5, the model is used to obtain average antecedent soil moisture conditions prior to rain storms, which is useful in applying the design storm approach to the design of various storm-water management facilities. Finally, Chapter 6 summarizes the research carried out on the modelling of soil moisture, reviews the contributions made, and provides some suggestions for future research.

1.1 General Introduction

This chapter is a prelude to the research leading to this dissertation and is essential for understanding of the motivation behind this study. The objectives of this research are stated and the tasks undertaken to achieve these objectives are discussed. At the centre of this research is the desire to obtain a deeper understanding of soil moisture. Mathematical modelling of soil moisture is the research tool utilized, and the importance of modelling soil moisture is underlined throughout the entire dissertation. This chapter briefly analyzes the different techniques available for the modelling of soil moisture. The rationale behind employing the chosen techniques for modelling moisture for this research is provided. Finally, summaries of the papers included in this research are presented.

1.2 Context and Motivation

There is a growing need to better understand soil moisture dynamics, be it for irrigation scheduling, crop yield prediction, pesticide application and management, fertilization scheduling, and urban Stormwater Management (SWM). The moisture content present in the top surface of the earth, i.e., the soil, is known as soil moisture. Soil moisture is at the centre of the climate-soil-vegetation system, as it is the water that plants are able to access. The climate, via precipitation, is the main source of water to the soil. Depending on the type of soil, its ability to hold onto the infiltrating water will vary, and this will impact the plants' access to this water. Plants survive on water; however they use up only a small fraction of the uptaken soil moisture. The remaining majority of the soil moisture will be released back into the atmosphere as vapour from the pores of leaves. Soil moisture will also evaporate back into the atmosphere directly from the soil surface. This is how soil moisture plays a dictating role in the hydrological cycle.

The availability of soil moisture is of great interest to researchers. There is a direct and positive link between soil moisture and crop yield (other than the case of excessive moisture, which will have a negative impact). Therefore, soil moisture is of great interest to the agricultural community. Rapid urbanization has resulted in increased Surface Runoff (SR) as well as loss of vegetal cover. Higher SR means more non-point source pollution. SR is equal to the precipitation less the moisture holding capacity of the soil and the depression storage of the soil surface. Soil moisture is therefore of great importance to SWM practices. Typical SWM practices include infiltration trenches, dry and wet detention ponds, oil/grit separators, artificial wetlands, and retention ponds (Nnadi et al., 1999) which are designed to reduce adverse impacts on aquatic habitat, streambank erosion, and to improve overall water quality of surface waterbodies. The need for the inclusion of the water balance in SWM practices has been emphasized in recent years. All of the hydrological processes that are involved in the water balance are dependent on soil moisture.

Climate change is a frequently discussed topic of the 21st century. Be it for anthropogenic reasons or natural causes, average temperature and high precipitation events have increased all over the globe. As the climate directly influences soil moisture, it is of significant importance to investigate how climate change will influence the dynamics of soil moisture. This information will in turn shed light on how present agricultural and SWM practices will be affected by climate change. Even though it is possible to measure the moisture present in the soil, it is a relatively new practice. Data on soil moisture are not widely available, and long-term data hardly exist. Therefore, mathematical modelling has been the preferred tool of research on soil moisture. Continuous simulation models provide a viable means to investigate the soil moisture dynamics under different climates, soils and land-use. Information on soil moisture obtained from these mathematical models can be used to better understand and address a wide range of concerns ranging from climate change to urban SWM.

1.3 Rationale and Objectives

The purpose of this research is to develop a simplified deterministic water balance model to simulate soil moisture at a point within the soil system near or at the root zone. The inputs to this model are climate, soil, and land-use data. The output of the model is soil moisture. The model is identified as simplified as it represents the components of the water balance adequately but without over-emphasizing on any one particular process. Research is mainly focussed on the statistics of soil moisture as the long-term dynamics of soil moisture is of principal interest. For this, detailed modelling of the water balance is not required. The objectives of this research are as follows:

(i) To conduct an extensive review of the existing modelling techniques for soil moisture;

(ii) To develop a deterministic continuous simulation model that can model soil moisture under any given climate, soil and land-use characteristics;

(iii) To determine which process within the water balance influences the dynamics of soil moisture most significantly;

(iv) To investigate the effect of climate change on the long-term dynamics of soil moisture which will indicate the suitability of existing water conservation practices; and

(v) To demonstrate the usefulness of the model to the engineering design and operation of urban SWM infrastructure.

The following sections of this chapter will discuss each of these objectives in detail.

1.4 Modelling Soil Moisture

Mathematical modelling is the representation, through formulas and mathematical expressions, of a real-world system that may not be feasible to experiment with, due to time and/or cost. Simulation is defined as the process of operating the mathematical process of a system to gain insight into its functions and to obtain useful results. Simulations are usually carried out to:

(a) Establish relationships between the real-world system components;
(b) Determine how the system will respond under various conditions;
(c) Understand how the system works and/or
(d) Predict how the system will work.

Continuous simulation is the modelling of a system as it evolves over time. Computational models are either stochastic or deterministic. Deterministic models are a mathematical representation in which every variable is altered according to a mathematical framework and not to random fluctuations. Deterministic models produce outcomes which are precisely determined through known relationships among states and events without any consideration of random variation.

An extensive review of various studies involving the modelling of soil moisture was carried out. These studies were carried out to investigate various purposes related to soil moisture such as:

(1) Crop Growth and Yield (Jones and Kiniry, 1986; Morgan et al., 2003; Huang, 2004);
(2) Irrigation Scheduling (Kang et al., 2003; Mahmood et al., 2003);
(3) Nutrient Application and Management (Asseng et al., 2001; Cameira et al. 2003; Leon et al., 2004);

(4) Pesticide Application and Scheduling (Wagenet and Hutson, 1987; Chung et al., 1992; Kalita et al., 1998);

(5) Urban Stormwater Management (Voorhees and Wenzel, 1984, De Michele and Salvadori, 2002; Brocca et al., 2008);

(6) Agricultural Non-point Source Pollution Control (Hagedorn et al., 1997; Tan et al., 2002; Jensen et al., 2003); and

(7) Ecohydrology Studies (Rodriguez-Iturbe et al., 1999; Laio et al., 2001) etc.

A summary of the review of the papers collected on soil moisture modelling is presented in Chapter 2.

A simplified deterministic water-balance model was developed to simulate soil moisture in the root zone on a daily basis. The model is presented and all its components are described in Chapter 2. In order to accurately model all the hydrological processes involved in the water balance, extensive knowledge of the climate, soil and vegetation characteristics is required. Such detailed information is not readily available on a routine basis and is time consuming and costly to acquire (Chopart and Vauclin, 1990). Therefore, extensive data requirements may often limit the usefulness of detailed models. Moreover, long-term soil moisture characteristics are what this dissertation is focussed on. As such, simplified soil moisture modelling is a reasonable approach and is computationally more efficient. For computational purposes, a daily time scale was chosen, and daily time scale are most common in soil moisture modelling (Chopart and Vauclin, 1990; Kalita et al., 1998; Coelho et al.; 2003; Panigrahi and Panda, 2003). The rationales behind the choice of the techniques used in modelling the hydrological processes of the water balance are presented in the following sub-sections.

1.4.1 Infiltration/Surface Runoff

Infiltration was modelled as precipitation minus surface runoff. SR was modelled using the Natural Resource Conservation Services' Curve Number (NRCS-CN) technique. Other options for modelling infiltration are the Horton's Infiltration Model and the Green-Ampt Method. Both these techniques operate on a smaller (< daily) time scale. The NRCS-CN technique is also better-suited for smaller-than-daily time scale. However, unlike the Horton's Infiltration Model and the Green-Ampt Method, the NRCS-CN technique can be easily adjusted to daily time scale. The main reason for not using the Horton Infiltration Model and the Green-Ampt Method is the difficulty in determining values for their detailed input parameters. For the Horton Infiltration Model these are, (i) the initial infiltration capacity; and (ii) the rate of decrease of infiltration capacity. For the Green-Ampt Method these are, (i) capillary suction; and (ii) initial moisture deficit. Both the Horton Infiltration Model and the Green-Ampt Method are more appropriate for ponded surfaces. Also these two methods are better suited for distributed modelling (Ponce and Hawkins, 1996), whereas the model at the centre of this research is, in essence, a lumped model. The NRCS-CN technique is a lumped method compatible to the techniques selected to model other processes.

1.4.2 Evapotranspiration

The Penman's Method was selected for modelling Potential Evapotranspiration (PET). Monteith (1981) made adjustments to the Penman's method and the modified equation is called the Penman-Monteith equation. The modifications were made by introducing two new parameters to the Penman's equation (Monteith, 1981; Temesgen et al., 2005). The new variables are, (1) the aerodynamic resistance function which quantifies boundary layer resistance, and (2) the surface resistance function which accounts for the stomatal resistance (Ward and Elliot, 1995). The Penman-Monteith equation is increasingly popular and is replacing the Penman's method. However, the values of these two new variables are not easily attainable (Brocca et al., 2008). Due to the difficulty in obtaining the values of the aerodynamic resistance function and the surface resistance function, the Penman's method was the method chosen over the Penman-Monteith equation. Also the Penman-Monteith equation is most applicable for hourly estimates, whereas Penman's method is most suitable for a daily time scale.

PET is the maximum ET that can take place under existing climate conditions. PET does not account for vegetation or soil moisture conditions. Therefore, actual ET (AET) needs to be modelled as it is more related to actual crop dynamics. Commonly used methods of obtaining AET are:

(a) SCS Blaney-Criddle Method: first the PET is measured or estimated, and then empirical coefficients are used to convert it to AET. However, this method is best suited for monthly time scale. The empirical coefficient is the seasonal consumptive use coefficient for a specific crop (Ward and Elliot, 1995). This coefficient is not readily available.

(b) Using Crop Coefficients: Directly uses a crop coefficient (k_c) to obtain AET from PET. These coefficients were obtained by relating PET to values of AET, measured with lysimeters. Typical k_c values have been developed for alfalfa or grass (Ward and Elliot, 1995). However, k_c values are highly location-specific and not readily available.

Neither of these methods takes into account soil moisture conditions. In this thesis, an ecohydrological approach was used to obtain AET. This new field of study has emerged from the necessity of combining the two disciplines of Ecology and Hydrology. Rodriguez-Iturbe et al. (2001) identified the position of ecohydrology as the centre in 'the connection between the role of plants in the water balance'. Gurnell et al. (2000) pointed out that "Hydrologists have always been concerned with ecology to the extent that vegetation is an important control on hydrological processes". Leading research in the field of ecohydrology has been carried out by Rodriguez-Iturbe et al. (1999, 2001), Laio et al. (2001), and Porporato et al. (2001). They have successfully derived and used an analytical model for the probabilistic description of soil moisture dynamics under steady state conditions. However, their line of research is more driven by ecosystems where various species survive with each other under situations of water scarcity in semi-arid and arid climates. From an ecohydrology angle, ET is most definitely dependent on soil moisture. Soil moisture flows in the direction of decreasing hydraulic gradient. Water moves from the soil into the plant root system because of lower plant-water potential. The root water then moves up the plant and into the leaves. There it is released through the stomata and the process of transpiration occurs (Porporato et al., 2001). This process will continue until the roots can no longer supply the flow of water, due to the obvious reasons of limiting access to water. When the water supply to the leaves reduces, leaf-water potential decreases and the stomata start to close. The stomatal closure results in the reduction of ET (Nye and Tinker, 1977; Weber, 1995). So ET is in essence controlled by the stomata, which in turn is dependent on the soil moisture conditions.

AET was further modified to represent plant growth stages. Therefore, the deterministic model can account for both vegetation and soil conditions.

1.5 Sensitivity Analysis

The developed continuous simulation model is process-based. The hydrological processes are modelled with various input parameters that drive the processes. An analysis that demonstrates which input parameters have a dominating influence on the model output will give insight into which process(es) is(are) most influential. This type of analysis is known as Sensitivity Analysis (SA). Sensitivity analysis is the study of how the variation in the output of a model (be it numerical or otherwise) can be apportioned, qualitatively or quantitatively, to different sources of variation, and of how the given model depends upon information fed into it (Saltelli et al., 2000). SA can be carried out in two ways: (a) Local Sensitivity Analysis (LSA), and (b) Global Sensitivity Analysis (GSA). LSA determines the relative importance of input parameter under specific surroundings. In a LSA, the input parameter of choice is allowed to vary within a small interval and the effect of this change on the output variables is measured. However, LSA fails to represent the effect of the simultaneous change of multiple input parameters. A more general and comprehensive SA is the GSA, where all possible input conditions are represented. GSA estimates the influence of individual input factors while varying all other input factors as well. GSA is also capable of taking into consideration the interdependency of the input parameters amongst themselves, which is not possible via LSA.

Both LSA and GSA were performed in this research. The methods and results obtained by LSA and GSA are described in Chapters 2 and 3 respectively.

1.6 Climate Change

Over the last 50~60 years, there has been an increase in greenhouse gas concentrations in the earth's atmosphere (Mavromatis and Jones, 1999; Easterling et al., 2000; Chen, 2007; Dang et al., 2007). This has resulted in significant changes in the temperature and precipitation patterns all over the world. These erratic changes in the earth's atmosphere are popularly known as climate change or global warming. The focus of the study is the long-term behaviour of soil moisture. By using the model for a long series of climate data, the soil moisture values for that long climate data can be examined. This is the technique used to investigate the effect of climate change on long-term soil moisture characteristics. By analyzing the characteristics of the model-generated soil moisture statistics, it was possible to directly connect the long-term behaviour of soil moisture characteristics with climate change. The model-generated ET characteristics were also analyzed to better understand the effect of climate change on long-term soil moisture. Global warming has had a negative impact on climate conditions all over the world. The motivation behind this study is to examine whether or not south-western Ontario soil moisture conditions have also been impacted negatively by global warming. And more importantly, if the impacts of climate change on long-term behaviour of soil moisture is of great concern.

1.7 Antecedent Soil Moisture Conditions

Limited information is currently available on Antecedent Soil Moisture (ASM) conditions, and ASM conditions for urban catchments have not been adequately investigated. Statistical analyses of ASM values are not available. Such information could be potentially useful for urban stormwater management purposes. ASM information is needed when modeling runoff and streamflow from urban catchments using the design storm approach. Continuous simulation models provide a more accurate understanding of the hydrological processes, especially during inter-event dry periods. Urban SWM control facilities such as detention ponds and oil/grit separators, etc., are required to be designed to withstand storm events of a specified return period, which could range from 2 to 25 years. The facilities need to be designed to sustain peak discharge. For simulation of peak discharge, soil moisture conditions prior to the storm, i.e., ASM values need to be known. Due to cost and time, the design storm approach (DSA) is the preferred modelling approach. The DSA involves the use of synthetic or historical events of desired return periods that the facility will be able to accommodate. ASM conditions are of great importance when using the DSA.

The continuous simulation model was used to simulate soil moisture conditions under a definite climate. By using a longer time series and investigating various soil types, it was possible to obtain a longer record of soil moisture characteristics as influenced by that particular climate under various soil classes. ASM conditions were extracted. By averaging soil moisture values prior to rainfall events, the average ASM ($\overline{ASM}$) values of that climate typical to that soil were calculated. Empirical equations were formulated between the extracted $\overline{ASM}$ values and input soil parameters. These empirical equations can be used in the future with the DSA.

1.8 Summary of Papers

1.8.1 Paper I

Development of a Simplified Continuous Simulation Model for Investigating Long-term Soil Moisture Fluctuations

A review of existing mathematical models that either directly model soil moisture (Nimah and Hanks model, 1973 a&b; Chopart and Vauclin, 1990; Laio et al., 2001; Panigrahi and Panda, 2003) or have strong soil moisture components (Jones and Kiniry, 1986; Wagenet and Hutson, 1987; Knisel and Davis, 1999) is presented in this paper. From the review of various models including LEACHM, CERES-Maize, GLEAMS, SWIM and SWAP, it was concluded that the models differ from each other in the way the various water balance processes are modelled. The more detailed the hydrological processes are modelled, the more accurate the soil moisture simulated. However, the more detailed the modelling, the more rigorous the data requirements. Since the goal of this research is to understand the long-term dynamics of soil moisture, for which statistical analyses of model-output soil moisture values are sufficient rather than accurate individual soil moisture values, a simplified deterministic continuous simulation model was developed. This one-dimensional water balance model is described in detail in this paper. The AET and Leakage components of this model are unique from other deterministic models in that both processes were modelled as functions of soil moisture. This allows AET to be modelled in a vegetation-sensitive way, as both Permanent Wilting Point (PWP), and hygroscopic point are controlling factors on AET.

Calibration and verification of the model was carried out using field data. A quantitative evaluation of the model performance was carried out by obtaining the Root Mean Square Error (RMSE), the Index of Agreement (IoA), and the Coefficient of Residual Mass (CRM) between the modelled and observed daily moisture content. To gain insight about the degree of fluctuations of soil moisture under south-western Ontario climate conditions, frequency distribution curves (pdfs) of the simulated soil moisture values were obtained. The pdfs indicate bimodal behaviour. Finally LSA was carried out. This SA gives a preliminary idea of the more influential input parameters. The LSA concluded that soil moisture control criteria at PWP and Leaf Area Index (LAI) have the strongest influence.

1.8.2 Paper II

A Global Sensitivity Analysis Determining the Most Influential Input Parameters in Soil Moisture Modelling

The LSA carried out in paper I provided relative importance of the input parameters affecting soil moisture and is valid only for one specific site. Thus, to provide general guidance about the relative importance of the input parameters under all possible site conditions, GSA was carried out. Six parameters were chosen for the GSA over the others due to the relative difficulty in obtaining their values and also because of the likelihood of them being influential. Random samples of each of the six input parameters were generated using Monte Carlo simulation. For each set of input parameters, the continuous simulation model was run for 20 years (1981-2000) and three output variables (namely average soil moisture, its standard deviation and skewness of the distribution) were determined. Regression-based non-parametric GSA techniques (Saltelli et al., 2000) were used to obtain a number of statistics known as sensitivity indices. Parameters representing soil texture were found to be most influential on average soil moisture, whereas parameters representing land-use were found to be most influential on the degree of variation of soil moisture (both standard deviation and skewness). The results obtained from the GSA clearly shows which water balance process dominates soil moisture dynamics. The process that needs to be paid more attention to while modelling average soil moisture conditions is ET. SR is the dominant process when the fluctuations of soil moisture are of concern.

1.8.3 Paper III

Climate Change and Urban Grass Land Soil Moisture Conditions in South-Western Ontario, Canada

To investigate the effect of global warming on soil moisture availability, this paper looks into 45 years (1960-2004) of climate data for south-western Ontario. The precipitation characteristics show an increase of 4-10% in average growing season precipitation, while the temperature patterns indicate a steady 1-2% increase in maximum growing season and a steady 19-20% increase in minimum growing season temperatures. The water balance model was used to simulate soil moisture for two different urban land uses. From the simulated daily soil moisture for each of the 45 years, the average growing season soil moisture for each individual year was calculated. It was concluded that there has been an increase in overall growing season soil moisture for both scenarios. The pdfs of soil moisture were obtained. The pdfs clearly showed a shift to the right, which corresponds to the likelihood of occurrence of higher soil moisture. As mentioned in section 1.6, the ET characteristics of the 45-year time series were also analyzed. Results showed a steady increase in ET values, and higher ET values for the land-use with higher imperviousness. A month to month comparison of average daily precipitation, temperature, soil moisture and ET was performed. It was observed that months in which soil moisture and ET increased were the months in which precipitation increased and temperatures decreased and vice versa. This demonstrated a directly proportional relationship of soil moisture and ET with precipitation, and an inverse relationship with temperature. This observation was further solidified when the correlation coefficients were calculated. This paper concluded that even with increasing temperatures in south-western Ontario, over the past 45 year period, increased precipitation has resulted in an increase in the overall volumetric soil moisture availability.

1.8.4 Paper IV

Antecedent Soil Moisture Conditions of Different Soil Types in South-western Ontario, Canada

In this study, the continuous simulation model was used to obtain information that can be used in SWM practices. The DSA is a popular method used in obtaining the flood peak and volume having the target return period that a facility is designed to accommodate (Voorhees and Wenzel, 1984; Levy and McCuen, 1999). The DSA requires information of antecedent soil moisture conditions. The deterministic continuous simulation model was used to obtain soil moisture values under south-western Ontario climate conditions from which ASM values were extracted. The model was run for eleven soil texture groups under grass covered urban land-use using 25 years (1980-2004) of meteorological data. The $\overline{ASM}$ representing each soil group was calculated for the 25 years. Then by applying the multiple regression technique, both a linear and logarithmic relationship was developed between $\overline{ASM}$ and Porosity (n), saturated hydraulic conductivity (K_s). To evaluate the performance of the obtained empirical equations, the Index of Agreement, the Coefficient of Residual Mass, the Root Mean Square Error, and the Coefficient of Determination (the R-squared value) between the simulated and estimated $\overline{ASM}$ values were calculated. Results showed a good agreement between the simulated and estimated $\overline{ASM}$ values, and indicated that the linear equation better suits the $\overline{ASM}$-n-K_s relationship. Thus, by knowing the n and K_s values of any site under south-western Ontario climate, the $\overline{ASM}$ value can be calculated using the empirical equations obtained. In cases where both n and K_s data are not available together, empirical equations for obtaining $\overline{ASM}$ values by knowing either n or K_s were also derived. It was found that the power empirical equation best described both the $\overline{ASM}$-n and $\overline{ASM}$-K_s relationships.

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Chapter 2

Development of a Simplified Continuous Simulation Model for Investigating Long-term Soil Moisture Fluctuations

Shazia Nishat, Yiping Guo and Brian W. Baetz

Abstract

A deterministic continuous simulation model was developed to study soil moisture dynamics under any given soil, vegetation and climate conditions. The model is process-based and is formulated to simulate soil moisture at a point within the crop root zone on a daily basis throughout a growing season. This simplified one-dimensional model takes into account only the hydrological processes that operate in the vertical direction. Actual evapotranspiration is calculated as a function of potential evapotranspiration and soil moisture and is further adjusted to represent various plant growth stages. Leakage is modelled as a function of soil moisture. The model was successfully validated using climate and field data from the Guelph Turfgrass Institute and Environmental Research Centre in Ontario, Canada. The actual evapotranspiration and leakage calculation procedures included in this model emphasize the soil moisture regime's control over these two processes, and is different than the way other deterministic models represent these two processes within the water balance. The resulting model can be used as a tool for the assessment of the general soil moisture dynamics under the influence of soil, vegetation and changing climate conditions.

Keywords: Water Balance, Hydrologic Model, Statistical Analysis, Sensitivity Analysis

2.1 Introduction

Soil moisture is the amount of water present in the soil and is the water that plants access for survival. Soil moisture information is of great importance for various purposes such as irrigation scheduling, crop yield prediction, nutrient management and fertilization scheduling, as well as pesticide application and management. In recent years, there has been a growing urgency to better understand soil moisture dynamics under different soil and climate conditions in order to better assess the impact of climate change and the influence of management alternatives on agricultural and urban systems. In-situ measurement of soil moisture is possible by means of Time Domain Reflectometry (TDR), neutron probes or capacitance probes. However, these are expensive and have not been available until recent years. Throughout Canada, soil moisture values are measured only at a few locations. Due to the lack of instrumentation during earlier years, the measured records at these locations are rather short. Therefore, simulation modelling is necessary to investigate the long-term availability and fluctuations of water within the soil matrix near the root zone.

The role of soil in vegetative growth is twofold, i.e., it stores and conducts water and also retains nutrients and minerals. Texture is a dominant variable that affects soil moisture storage and variability (Cosby et al., 1984; Fernandez-Illescas et al., 2001; Yoo et al., 2001). Climate characteristics play a major role in the dynamics of soil moisture. Precipitation is the main source of soil moisture. The temporal variability of the soil moisture regime as influenced by rainfall is the main concern when studying crop yield, pollution control, impact of climate change, long term water balance under differing land-uses, etc. Besides the input rainfall, other meteorological characteristics play a role in soil moisture losses through the process of Evapotranspiration (ET). To best represent the actual climate-soil-plant system, the Actual Evapotranspiration (AET) needs to be modelled as it is more related to actual vegetation dynamics.

Many models have been developed to investigate soil moisture conditions and the flow of water within the soil matrix. These models differ from each other in representing the processes that take place in the water balance. The Nimah and Hanks model (1973a,b) was one of the earliest models to investigate the flow of water in the soil matrix. The steady state model introduces a root extraction term, which requires detailed water potential data of the soil and the roots. These are not readily available data. The model does not compute AET; rather it demonstrates the insufficiency of Potential Evapotranspiration (PET) in representing ET. The Yoo et al. (1998) and Yoo et al. (2001) models are similar and focus on the spatial variability of soil moisture. Both are complex and site-specific. The 2-layer model developed by Chopart and Vauclin (1990) is heavily dependent on a parameter defined as Maximum Available Water Storage (MAWS), values for which were obtained from field measurements. The Huang (2004) model introduces a rather complex error function to the water balance.

The process of ET is where most models vary from one another. AET is not represented by the Cameira et al. (2003) model; however, their main focus is on nitrogen leaching. Panigrahi and Panda (2003) model AET by using crop factors and a soil water depletion factor. Surface Runoff (SR) is modelled using a location-specific modified United States Natural Resources Conservation Services (NRCS) curve number procedure. The multi-layered Coelho et al. (2003) model includes detailed leaf water potential and actual root water uptake components, and requires detailed multi-layered inputs such as root biomass, etc. Given the difficulties in accurately determining ET, Luo et al. (2007) treats ET as a random variable and models ET stochastically within the soil water balance.

The more well-known simulation models aimed at predicting yield and/or agricultural non-point source pollution have sub-routines that model soil moisture. The soil moisture components of LEACHM, CERES-Maize, GLEAMS, ADAPT, AGNPS, SWIM, WOFOST, APSIM and SWAP were examined. The water regime module of LEACHM simulates vertical water flow, predicts chemical leaching below the root zone and the amount taken up by plants (Wagenet and Hutson, 1987). One of the major limiting factors is its greater input requirements than many simpler models (Johnson et al., 1999; Hagi-Bishow and Bonnell, 2000; Ng et al., 2000). CERES has a multi-layered water balance segment which models SR according to the NRCS curve number technique; however, it is designed to use only CN_1, which represents antecedent soil moisture for dry conditions. The ET component consists of four segments, including a rather complex method of obtaining actual soil evaporation (Jones and Kiniry, 1986).

GLEAMS was created to include Groundwater Loading Effects of Agricultural Management Systems into CREAMS (Leonard et al., 1987). The output options of its hydrology sub-model include average soil moisture, PET and AET, etc (Knisel and Davis, 1999; de Paz and Ramos, 2000). The AET component is essentially similar to that of CERES-Maize. ADAPT incorporates sub-irrigation and subsurface drainage into GLEAMS to evaluate water table management options. The model calculates infiltration using the modified Green-Ampt equation with provisions for macropore flow and surface ponding (Chung et al., 1992; Kalita et al., 1998). ADAPT does not output soil moisture explicitly. AGNPS is a distributed model that requires the watershed to be divided into small homogeneous square cells and deals more with spatial variability. Suitable for use on watersheds up to 20,000 ha in size (Huggins, 2005), the grid-based model requires individual input data for each of its cells, which is difficult to prepare (Ma and Bartholic, 2003). It does not explicitly output soil moisture. The model has been successfully applied to an agricultural watershed in southern Ontario by Leon et al. (2004).

APSIM is a simulation model capable of assessing the impacts of climate variability and the long-term consequences of management practices on the growth and yield of crops, pastures and even forests (Probert et al. 1998). It can simulate crop sequences/crop rotations, multi-cropping/intercropping and mixed species in addition to single cropping (McCown et al., 1996, Verburg et al. 1996). The user can choose between two water balance modules: SoilWat and SWIM. SoilWat is a multi-layer, cascading water balance module that runs on a daily scale. It is largely similar to the CERES-Maize WATBAL module, with its crop-cover and surface residue correction technique of soil evaporation and runoff coming from PERFECT (Verburg, 1996). The SWIM software uses a complex and detailed technique in estimating surface runoff based on surface roughness and Manning's equation. A unique feature of its SR module is that it accounts for slope, surface sealing and crust. SWIM includes its own component for calculating vegetative interception. Transpiration is equated to plant uptake by roots requiring detailed information such as plant xylem potential, osmotic potential, root resistance, etc. (Verburg et al. 1996).

WOFOST is a crop growth model that includes a soil water subroutine. SR is modelled to be proportional to precipitation. PET is partitioned between potential soil evaporation (PEs) and potential transpiration (PT) based on Leaf Area Index (LAI) and a global radiation coefficient (Eitzinger et al., 2004). SWAP adopts its crop growth model from WOFOST, however, its soil water balance component is completely different (Eitzinger et al., 2004). SWAP accounts for shrinking and swelling of soils based on soil moisture and can simulate flow through cracks (Crescimanno and Garofalo, 2005). Its semi-empirical root water uptake component includes correction for water and salinity stress (Feddes et al., 2001; Crescimanno and Garofalo, 2005).

A well-established analytical probabilistic model for obtaining the probabilistic behaviour of the soil moisture is that developed by Rodriguez et al. (D'Odorico et al., 2000; Ridolfi et al., 2000; Laio et al., 2001). However, their model is a steady-state model developed to obtain soil moisture statistics based on average growing season input values. Precipitation characteristics are represented by two parameters: α, which is the average depth of rainfall per rainfall event, and λ, the average number of rainfall events per day. The model has been successfully used for semi-arid and arid regions with well-established natural vegetation. Mature natural vegetation differs widely from vegetation such as crops and lawn grass in that the rooting depths and crop cover of the latter vary throughout the growing season.

There may be other soil moisture models that this review has not covered. The existing soil moisture models differ from each other in the levels of detail in describing the climate, evapotranspiration, soil and vegetation characteristics. Detailed information is not readily available or accessible for many sites of interest. Some of these models neglect SR (Nimah and Hanks, 1973 a,b; Chopart and Vauclin, 1990; Arora et al., 1997; Cameira et al., 2003; Huang, 2004, Luo et al., 2007) which is an important water balance component for humid regions. Some models do not consider AET (Cameira et al., 2003). Other models cannot demonstrate the influence of soil texture on the availability of soil moisture (Chopart and Vauclin, 1990; Panigrahi and Panda, 2003; Huang, 2004). Most of the well-known simulation models developed for crop yield prediction and/or agricultural non-point source pollution do not explicitly output soil moisture. The simulation model proposed in the following section is a simplified representation of the complex processes that take place in the vertical water balance.

The soil moisture and vertical water balance in urban areas have not been studied as extensively as those in agricultural lands. Due to concerns of the impact of climate change and rapid urbanization, a better understanding of urban area soil moisture dynamics is required. Vegetations in urban areas are for landscaping and stormwater management purposes. Our research does not focus on predicting the day-to-day soil moisture values or crop yields but instead captures the general, area-averaged soil moisture fluctuation characteristics under varying land-use and climate conditions. We are more interested in the probability distribution of soil moisture for a specific climate-soil-vegetation combination and its sensitivity.

In this paper we present a simplified continuous simulation model that has been developed with that interest in mind and to share the results obtained from the statistical analysis of soil moisture output from the model. Preliminary calibration and validation runs indicate that the proposed simplifications are acceptable for the intended purpose. Future studies including comparison of results from more complex models to further verify the proposed model and applications of it for urban stormwater management purposes will be conducted and reported.

2.2 Materials and Methods

2.2.1 Simulation Model Development

From a macroscopic point of view, the top soil layer may be considered as a simple reservoir, where the inputs are precipitation plus supplemental irrigation if any, and the outputs are evapotranspiration, surface runoff and leakage losses (Yoo et al., 2001). Based on this concept, a simplified water balance model is developed for the continuous simulation of soil moisture in the root zone on a daily basis. Our continuous simulation model incorporates the well-established models of each of the individual processes that take part in the water-balance.

2.2.1.1 The Soil Water Balance

The soil water balance model, Equation (2.1), is similar to models used by Cameira et al. (2003), Panigrahi and Panda (2003), D'Odorico et al. (2000), Ridolfi et al. (2000), and Chopart and Vauclin (1990). The model is one-dimensional, taking into account only the hydrological processes that operate in the vertical direction. The model represents the soil domain as a single uniform layer. Although this model simulates soil moisture at a point, the output of the model can be viewed as area/site-averaged values if the inputs are all area/site-averaged values.

$$nZr\frac{ds(t)}{dt} = P(t) - SR(t) - ET(s) - L(s) \tag{2.1}$$

where, s = volumetric soil moisture content in cm^3/cm^3;

Zr = depth within the soil root zone in cm;

n = porosity;

P = precipitation in cm/day;

ET = evapotranspiration in cm/day;

SR = surface runoff in cm/day;

L = leakage in cm/day; and

t = time index with an interval length of one day.

Equation (2.1) is solved numerically by using the backward finite difference method. The following assumptions are made in the model:

a) The total depth of rainfall from discrete storm events occurring throughout the day is lumped with supplemental irrigation (if any) and represented by a single value;
b) The portion of rainfall infiltrating into the soil from an event is equal to the depth of rainfall, provided there is enough storage available in the soil to accommodate the depth;
c) When rainfall exceeds the available storage volume, runoff is generated (Nimah and Hanks, 1973 a,b; Laio et al., 2001);
d) The soil reservoir reaches equilibrium instantaneously (Panigrahi and Panda, 2003);
e) The difference between rainfall and surface runoff is the infiltrated water, which is redistributed uniformly over the vegetation root zone;
f) Contributions from capillary rise are ignored (water table located well below root zone);
g) The root zone consists of homogeneous soil; and
h) There is no soil surface evaporation during rainfall events.

2.2.1.2 Precipitation

Precipitation throughout the growing season in most places in the world is in the form of rainfall. A given amount of rainfall gets intercepted by the vegetal covers. Interception is represented by Λ, which is the percentage of rainfall intercepted. The rainfall data can be modified as $\widetilde{P}$ to account for interception (Laio et al., 2001) as follows:

$$\widetilde{P}(t) = P(t)(1 - \Lambda_t) \qquad (2.2)$$

2.2.1.3 Surface Runoff

As mentioned in the above assumptions, Infiltration = Rainfall – Surface Runoff. A more common method for calculating infiltration would be to use Horton's Infiltration Model or the Green-Ampt Model. These models, however, are best suited for shorter time scale (e.g., hourly), whereas our model runs on a daily time scale. Daily values of the surface runoff are, therefore, estimated using the NRCS curve number technique (Chow et al., 1988; McCuen, 1982). The NRCS curve number technique is also better suited for smaller than daily time scale. However, the technique is more flexible and can be more conveniently adjusted to a daily scale than the Horton and Green-Ampt models.

The three antecedent soil moisture conditions (AMC) are defined by the total 5-day antecedent rainfall, P_5 (McCuen, 1982; and Ward and Elliot, 1995). The corresponding curve numbers are CN_1 for dry conditions (AMC I); CN_2 for average conditions (AMC II); and CN_3 for wet or near saturated soil conditions (AMC III). From the value of CN_2, the values of CN_1 and CN_3 can be determined from Equations (2.3) and (2.4) respectively (Chow et al., 1988).

$$CN_1 = \frac{4.2 CN_2}{(10 - 0.058 CN_2)} \qquad (2.3)$$

$$CN_3 = \frac{23 CN_2}{(10 + 0.13 CN_2)} \qquad (2.4)$$

The values of CN_2 are available from Runoff Curve Number Tables (McCuen, 1982; Knisel and Davis, 1999; Viessman and Lewis, 2003).

2.2.1.4 Evapotranspiration

2.2.1.4.1Potential Evapotranspiration

Penman's Method (Ward and Elliot, 1995) is used to model PET. This method accounts for the external energy source and the factors that influence the removal of water vapor from the immediate vicinity of the evaporating surface (the plant leaf). Most of the variables involved in this method are temperature-dependent and are calculated using empirical formulas. AET is then estimated from PET as a function of soil moisture at that time step. To use Penman's method, the wind speed (u_2) at 2 meters above ground needs to be known. However, data regarding the wind speed is not always recorded at that height. Therefore, the following correction technique (Ward and Elliot, 1995) can be used if necessary.

$$\frac{u_1}{u_2} = \frac{\ln[z_1 - 0.67h_c] - \ln[0.123h_c]}{\ln[z_2 - 0.67h_c] - \ln[0.123h_c]} \tag{2.5}$$

where, u_1 = Wind speed at known height in m/sec;

z_1 = height of wind speed u_1 in m;

z_2 = height of wind speed u_2 in m; and

h_c = height of vegetation in m.

($0.67h_c$) is identified as the height where wind velocity approaches zero, known as the roughness height; while ($0.123h_c$) is known as the surface roughness. The solar radiation data available are most likely to be incoming solar radiation, i.e., solar radiation received on a horizontal plane at the earth's surface, R_s. Penman's method requires information on net solar radiation, R_n , which takes into account both incoming and outgoing solar radiation. R_n is calculated from R_s (Ward and Elliot, 1995).

2.2.1.4.2 Crop Transpiration and Root Water Uptake

Crop transpiration is at its maximum value (T_m) when soil moisture is non-limiting. T_m can be calculated using Equation (2.6) from PET as a function of LAI (Coelho et al., 2003):

$$\begin{aligned} T_m &= PET(1 - e^{-LAI}), & \text{if } LAI \leq 3.0 \\ T_m &= PET, & \text{if } LAI > 3.0 \end{aligned} \qquad (2.6)$$

Maximum soil evaporation (E_m) can then be determined as the difference between PET and T_m. A discontinuity exists between the two components of Equation (2.6). However, in this study LAI is always less than 3.0, and therefore the discontinuity in Equation (2.6) does not affect the results. Empirical models have been used to determine the depth of the rooting front (RD) for wheat by Arora et al. (1997), and for rice by Chopart and Vauclin (1990). For the proposed simulation, however, a sigmoidal root growth model, Equation (2.7), as proposed by Borg and Grimes (1986) is used. This model was established from the root depth development of 48 crops and for a wide variety of growing conditions.

$$RD(t) = RD_m \left[0.5 + 0.5 \sin\left\{ 3.03\left(\frac{t}{t_m}\right) - 1.47 \right\} \right] \qquad (2.7)$$

where, t_m represents the number of days to reach the maximum rooting depth, RD_m. The day of planting is taken as time zero. The linear root uptake model developed by Prasad (1988) was used to calculate plant root water uptake. This model is, however, not applicable for depths greater than the rooting front. Therefore, to represent root water uptake from depths greater than the rooting front, the Feddes et al. (1978) model was used. A correction was applied to both these models to calculate plant root water uptake, T_{up}, having units of cm/day. The root water uptake component is as follows in Equation (2.8):

$$T_{up} = 2\frac{T_m}{RD}\left(1-\frac{Z_r}{RD}\right)nZ_r \,, \qquad \text{if } Z_r < RD$$
$$T_{up} = \frac{T_m}{RD}nZ_r \,, \qquad \text{if } Z_r \geq RD \tag{2.8}$$

T_m is, as mentioned earlier, the maximum extraction rate when soil moisture is not limiting.

2.2.1.4.3 AET

From the computed values of E_m and T_{up}, AET is obtained as a function of soil moisture. This introduces an ecohydrological perspective. The dependency of ET on soil moisture has been defined by three different ranges of soil moisture (Rodriguez-Iturbe et al., 1999 a,b; D'Odorico et al., 2000; Ridolfi et al., 2000; Laio et al., 2001). The hourly fluctuations of ET are neglected. The hygroscopic soil moisture, s_h, is defined as soil moisture which is held tightly in the soil and is completely unavailable to plants. s_w is defined as soil moisture at permanent wilting point (PWP), which is the soil moisture level when plants can no longer access water and start to wilt permanently. Plants may suffer water stress long before wilting (Hillel, 1971). Therefore, a critical soil moisture value, s^* is defined as the soil moisture below which plants start to endure water stress (Laio et al., 2001). The value of s^* is often associated with the field capacity (s_{fc}) of the soil; however, it takes a value less than s_{fc}. These three soil moisture control criteria are defined by the empirically determined soil-water retention curve in the form of Equation (2.9) (Clapp and Hornberger, 1978).

$$\psi_{sa} = \overline{\psi}_s \times s_a^{-b} \tag{2.9}$$

where, Ψ_{sa} = Matric Potential corresponding to s_a;

$\overline{\psi}_s$ = Saturation Matric Potential; and

b = Empirical Exponent.

$\bar{\psi}_s$ and b are empirically determined parameters and vary with soil texture. The subscript 'a' corresponds to the three different ranges of soil moisture as mentioned earlier. For example, if ψ_{sw}, i.e., the soil potential at PWP, and $\bar{\psi}_s$ and b are known, s_w can be calculated using Equation (2.9). Thus by knowing the soil potentials at PWP and hygroscopic point, etc., and the $\bar{\psi}_s$ and b for the textured soil, the corresponding three soil moisture control criterion is calculated.

From the definitions it is clear that when soil moisture values are at and below s_w, transpiration completely stops and only E_m takes place. The AET component also contains a soil moisture control criteria that is at or in excess of saturation. That condition results in the cessation of transpiration (Kramer and Boyle, 1995). In summary, AET is mathematically represented by Equation (2.10).

$$\mathrm{AET} = \begin{cases} E_m, & \text{if } s = 1; \\ \mathrm{PET}, & \text{if } s^* < s < 1; \\ E_m + T_{up}\dfrac{s - s_w}{s^* - s_w}, & \text{if } s_w < s \le s^*; \\ E_m\dfrac{s - s_h}{s_w - s_h}, & \text{if } s_h < s \le s_w; \end{cases} \qquad (2.10)$$

2.2.1.4.4 Different Plant Growth Stages

The above-described AET component does not still take into consideration different plant growth stages. To model the entire growing season; the following correction, Equation (2.11) is applied to represent plant growth stages (Coelho et al., 2003):

$$\mathrm{ET} = F \times \mathrm{AET} \qquad (2.11)$$

where, F is a correction factor depending on LAI as follows in Equation (2.12):

$$
\begin{aligned}
F &= 1 + 0.074\,\mathrm{LAI}, && \text{if LAI} \le 2.7 \\
F &= 1.2, && \text{if LAI} > 2.7
\end{aligned}
\qquad (2.12)
$$

It can be seen from the above descriptions that by combining the findings and results from previous studies, we obtain an AET calculation procedure that takes into consideration not only soil moisture content but also different plant growth stages.

2.2.1.5 Leakage Losses

Leakage (L) is modeled as vertical percolation. Losses from leakage are at a maximum when the soil is fully saturated, i.e., at s = 1. This maximum value equals the saturated hydraulic conductivity, K_s. For unsaturated conditions, leakage follows a power law (Rodriguez-Iturbe et al., 1999 a,b; D'Odorico et al., 2000). Finally beyond the PWP, moisture is held so tightly by the soil particles that leakage can no longer take place. Thus, leakage is modelled according to Equation (2.13) as follows:

$$
\begin{aligned}
L(s) &= K_s, && \text{if } s = 1; \\
L(s) &= K_s s^c, && \text{if } s_w < s < 1; \\
L(s) &= 0, && \text{if } s \le s_w;
\end{aligned}
\qquad (2.13)
$$

where, c = 2b+3; this parameter's value is greater than unity and is soil dependent. With the known value of b from the soil-moisture retention curve (i.e., Equation (2.9)), for a specific type of soil, the value of c for that soil can be computed. Leakage losses are thus determined as a function of soil moisture using Equation (2.13).

2.2.2 Field Experiments and Model Input Data

Although the components of the continuous simulation model are well-established and have been validated in their own rights, combining them together and numerically solving them using a daily time scale has not been previously done. To evaluate the accuracy and reliability of the model, data obtained from field experiments are used to verify and validate the model.

Field data were available from the Guelph Turfgrass Institute and Environmental Research Centre (GTIERC: 43°32'50''N, 80°13'50''W), courtesy of Dr. Gary W. Parkin and Mr. Peter von Bertoldi of the Department of Land Resource Science, University of Guelph, Ontario, Canada. Multiple lysimeters have been installed at the site and packed with a three horizon coarse-grained soil layers. The top 2 cm was a thatch (fibrous layer of organic material and soil), the next 25 cm sandy loam, followed by 25 cm of loamy sand and at the bottom a 31 cm sandy layer. The entire site was covered with Kentucky bluegrass sod. The grass was planted in May 1995 and the maximum rooting depth was 50 cm (Roy et al., 2000). The height of the grass was maintained at 6 cm (Martel and Parkin, 1998). The K_s of the three horizons was measured. Volumetric soil moisture was measured using TDR probes placed at the 8 depths of 2, 12.5, 24, 26, 37.5, 49, 51 and 80 cm. A more detailed description of the field set up is available from Roy et al. (2000) and Roy et al. (2001). The average water content (cm^3/cm^3) for each of the 8 depths and N treatment (Control: 0 N; NH_4-NO_3: Ammonium Nitrate (35% N); SCU: Slow release N, Brussels fertilizer, 25/4/10 (25% N)) was observed and available for 1998-2000. There were no replications of any N treatment lysimeter and its soil moisture measurements. The most comprehensive set of data for the growing season was the 1998 data set. Soil characteristics of the individual soil horizons are presented in Table 2.1. Values of porosity (n) are obtained from literature (Chow et al. 1988; Laio et al., 2001; Viessman and Lewis, 2003). The b and $\bar{\psi}_s$ values are taken from Clapp and Hornberger (1978).

Table 2.1: Soil Characteristics Including Porosity and Saturated Hydraulic Conductivity of the Three Horizon Coarse-grained Soil Layers of the GTIERC Lysimeters

Soil Type	n	K_s (cm/day)	b	$\bar{\psi}_s$ (cm)
Sandy Loam (SL)	0.434	260	4.9	21.8
Loamy Sand (LS)	0.421	1200	4.38	9.0
Sand (S)	0.35	8300	4.05	12.1

The data necessary to run Penman's method are available at the University of Guelph website. However, the data are hourly values. Therefore, daily averages were calculated from the hourly values. The total growing season (May-October) precipitation was determined to be approximately 28.5 cm for 1998 and 55.8 cm for 1999. The average growing season temperature was determined to be approximately 16°C for 1998 and 15.5°C for 1999. The monthly averages of these climate data are shown in Table 2.2.

Table 2.2: The Average Monthly Climate Characteristics of the GTIERC for the Growing Seasons (May to October) of 1998 and 1999

Year	Parameters	May	June	July	August	September	October
1998	Ppt (cm/day)	0.11	0.42	0.111	0.111	0.111	0.072
	Temp (°C)	15.56	17.06	19.32	19.24	15.9	8.92
	RH (%)	69.56	73.1	70.53	72.52	71.07	75.79
	R_s (MJ/m^2/day)	22.52	22.9	23.36	23.09	26.73	21.37
	u10 (m^2/sec)	2.97	2.93	2.51	2.21	2.53	3.03
1999	Ppt (cm/day)	0.145	0.338	0.517	0.142	0.458	0.23
	Temp (°C)	13.74	18.12	21.19	17.24	15.15	7.81
	RH (%)	63.44	73.19	72.05	78.11	76.44	78.41
	R_s (MJ/m^2/day)	33.93	33.44	34.9	29.13	28.04	19.88
	u10 (m^2/sec)	3.04	2.45	2.78	2.44	2.36	2.98

Note: Ppt = Precipitation, Temp = Average Temperatures, RH= Relative Humidity, Rs = Incoming solar Radiation, and u10 = Wind Speed at 10 metres.

The lysimeters were not irrigated during 1998-2000. Data regarding the wind speed at the study area are from a height of 10 m. Therefore, the correction technique, Equation (2.5), is used to obtain u_2 at a constant plant height of h_c = 6 cm. The daily time scale of the model may not accurately represent the SR that would occur during a rainfall event at a smaller time scale. In order to compensate for this, we have used slightly higher values of CN_2 from that tabulated in literature for pastures under poor hydrologic conditions. In order to best represent the heterogeneous nature of the three soil horizons, we have treated the entire 83 cm as a single soil column having composite soil characteristics. The composite values were obtained by calculating the weighted average of each of the parameters. The two depths of 37.5 cm and 80 cm were selected for comparison. The input data used for the model are summarized in Table 2.3.

Table 2.3: Soil, Plant and Climate Parameters Used as Input for the Continuous Simulation of Growing Season Soil Moisture under Turfgrass

Parameters	Input Values	Parameters	Input Values
Λ	17%	LAI	0.85 m^2/m^2
n	0.40	s^*	0.50
b	4.2	s_w	0.19
$\bar{\psi}_s$	14.1 cm	s_h	0.05

By calculating the weighted averages at 37.5 and 80 cm, the K_s values of 575 and 3570 cm/day were obtained respectively. Interception (Λ) information was taken from Viessman and Lewis (2003). The values of s^*, s_w and s_h from Equation (2.9) were calculated with the soil water potentials of $\psi_{s,s*}$ = -30 kPa, $\psi_{s,sw}$ = -1500 kPa, and $\psi_{s,sh}$ = -10^6 kPa respectively. The soil water potentials are typical values found in Hillel (1971), Rogers and Sothers (1996); Morgan et al. (2003); Bandyopadhyay and Mallick (2003) and the USDA website. All other necessary data that were not directly available for the study area were taken from literature sources.

2.3 Results and Discussion

The continuous simulation model was run using MATLAB. As the focus of this study did not include nutrient requirements or leaching, only field data under zero nitrogen treatment were used. The model was calibrated using the 1998 field data. The CN_2 and LAI values have been adjusted. As the turfgrass was cut at 6 cm, LAI is kept constant at $0.85 m^2/m^2$. CN_2 was 95 for 37.5 cm and 70 for 80 cm.

2.3.1 Soil Water Balance

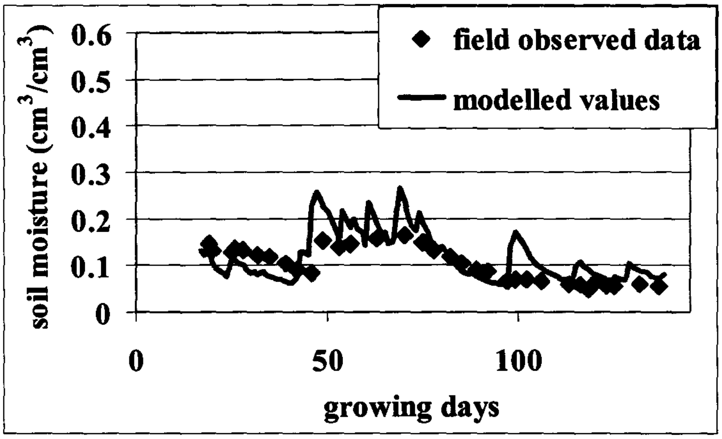
Water balance information, for all the lysimeters, was available for the months of June, July and August of 1998 (Martel and Parkin, 1998). AET was measured by TDR in the lysimeters. Leakage was measured from the bottom of the instruments. SR was not measured and was believed to be zero. The measured and modeled values of the water balance components are tabulated in Table 2.4. It can be seen that the major water balance characteristics of the site, i.e., high ET, low leakage and SR, are well reproduced by the model.

Table 2.4: A Comparison of the Measured Lysimeter and Simulated Precipitation, Evapotranspiration, Surface Runoff and Leakage for 1998 under Turfgrass

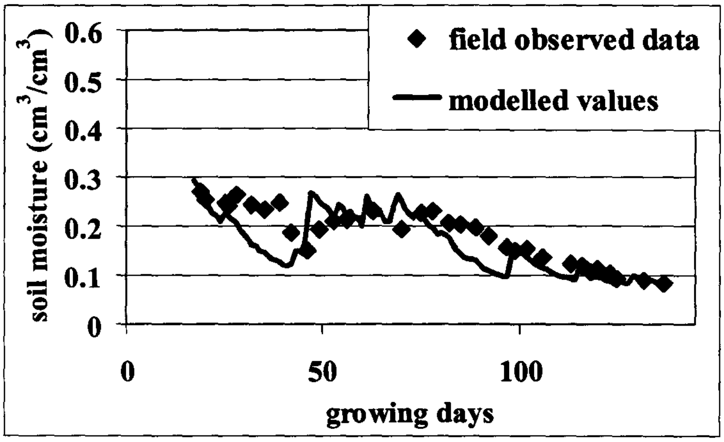
Months	Source	Ppt (cm)	ET (cm)	SR (cm)	L (cm)
June	Field Values	12.6	11.93	0.0	0.007
	Model Simulated	12.6	6.25	1.0	0.004
July	Field Values	3.44	8.15	0.0	0.15
	Model Simulated	3.44	8.94	1.46	0.008
August	Field Values	3.44	4.9	0.0	0.0
	Model Simulated	3.44	5.17	0.4	0.0

Note: Ppt= Precipitation, ET= Evapotranspiration, L= Leakage, and SR= Surface Runoff.

Volumetric soil moisture for the 1998 growing season at the depths of 37.5 and 80 cm as simulated by the model and that from the field observations can be seen in Figures 2.1 (a) and (b), respectively.



(a) at 37.5 cm depth



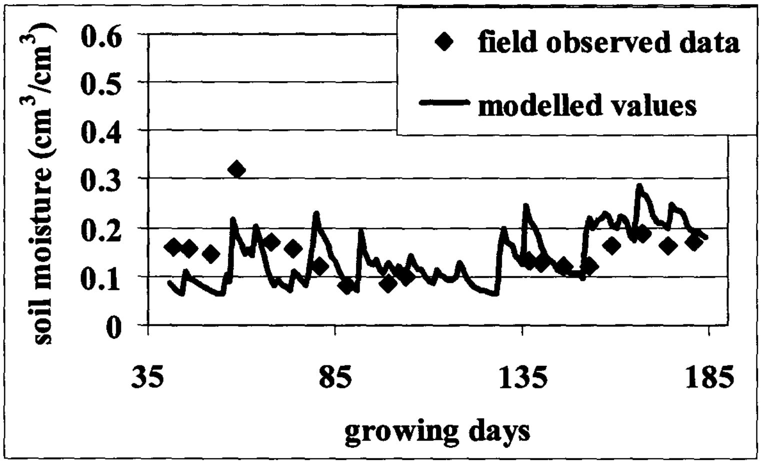
(b) at 80 cm depth

Figure 2.1: Field-observed and Modelled Soil Moisture Content at Two Depths for the Growing Season of 1998

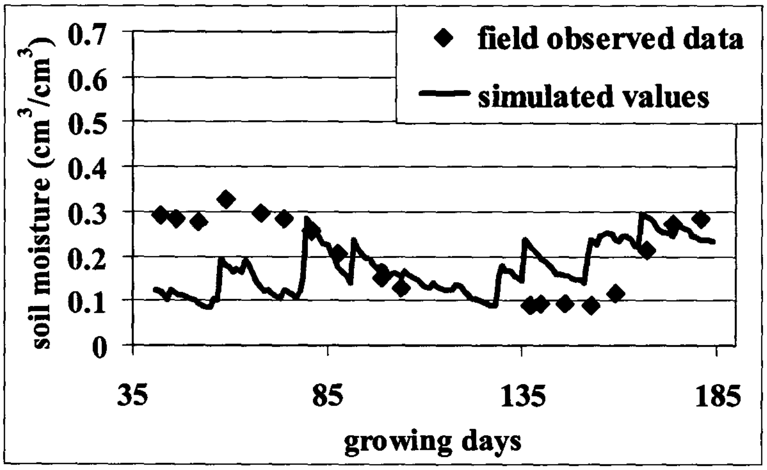
The modelled values were obtained from the calibration of the model. The comparison shows that the model is generally capable of simulating soil moisture conditions at both depths. The likely causes of the differences between the modelled and observed daily soil moisture are:

1) Errors resulting from temporal lumping due to daily time scale;
2) Errors in representing the individual processes involved; and
3) Errors in prescribing values describing the composite soil characteristics.

The calibrated model was validated with the 1999 data. Volumetric soil moisture for the 1999 growing season from the model simulation and the field observations at 37.5 and 80 cm are shown in Figures 2.2 (a) and (b), respectively.



(a) at 37.5 cm depth



(b) at 80 cm depth

Figure 2.2: Field-observed and Modelled Soil Moisture Content at Two Depths for the Growing Season of 1999.

Figure 2.2 shows that the model did not perform as well for 1999 at 80 cm. This is partly due to the low number of the 1999 data points. The data set for 1998 is more extensive, containing 33 data points as compared to 19 values for 1999.

2.3.2 Soil Moisture Fluctuations

The continuous simulation model generates soil moisture values for each day within the simulation period. From these daily simulated values and the observed data the average soil moisture, standard deviation (SD) and coefficient of variation (COV) were calculated for 1998. For a more accurate comparison, before conducting these statistical calculations, the simulated soil moisture values have been extracted for those exact dates when observed data were available. The resulting statistics are given in Table 2.5.

Table 2.5: Mean, Standard Deviation and the Coefficient of Variation of the Model-simulated and Field-observed Soil Moisture Values Obtained for the Growing Season of 1998

Source	Depth (cm)	Average (cm^3/cm^3)	SD (cm^3/cm^3)	COV
Model Simulated	37.5	0.117	0.052	0.446
Field Values		0.102	0.038	0.368
Model Simulated	80	0.162	0.061	0.375
Field Values		0.183	0.057	0.309

Table 2.5 shows that, in terms of daily soil moisture variation statistics, the simulation model is capable of matching the field data. The average soil moisture content simulated by the model is reasonable as compared to that obtained from field experiments at both depths: the simulation model overestimates by 14.6% at 37.5 cm and underestimates by only 11.7% at 80 cm. The SD's and COV are also reasonable, indicating that the model is capable of simulating the degree of variability that occurs in the field. Similarly, the mean, SD and COV of the simulated and the observed data of 1999 were also calculated. The resulting statistics are presented in Table 2.6.

Table 2.6: Mean, Standard Deviation and the Coefficient of Variation of the Model-simulated and Field-observed Soil Moisture Values Obtained for the Growing Season of 1999

Source	Depth (cm)	Average (cm^3/cm^3)	SD (cm^3/cm^3)	COV
Model Simulated	37.5	0.152	0.059	0.390
Field Values		0.150	0.051	0.340
Model Simulated	80	0.186	0.056	0.300
Field Values		0.212	0.086	0.405

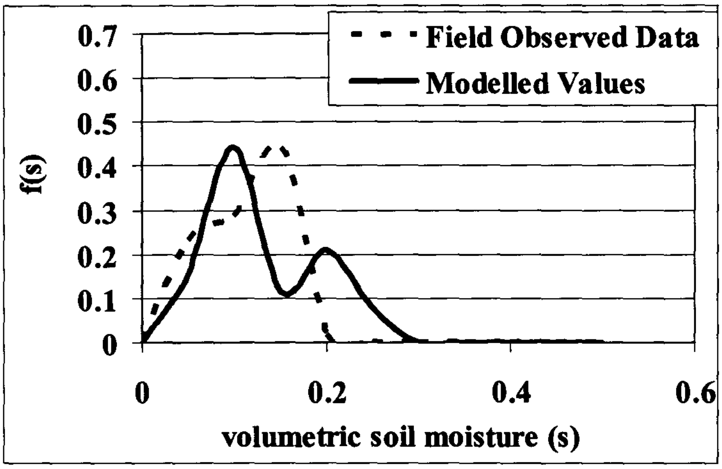
Table 2.6 illustrates that the simulation model is capable of matching the observed data in terms of daily soil moisture statistics. The average soil moisture content simulated by the model at 37.5 cm is very close, within 1.65% of field-observed values. The simulation model underestimates soil moisture content by only 12% at 80 cm. The comparisons of the standard deviations from Tables 2.5 and 2.6 indicate that the model is capable of simulating the extent of variability that occurs in the field, especially at 80 cm for 1998 and 37.5 cm for both years. To evaluate the performance of the continuous simulation model more quantitatively, the Root Mean Square Error (RMSE), the Index of Agreement (IoA), and the Coefficient of Residual Mass (CRM) between the modelled and observed daily moisture content were calculated as well. The results are presented in Table 2.7.

Table 2.7: Results from the Three Techniques used in order to evaluate the Performance of the Continuous Simulation Model

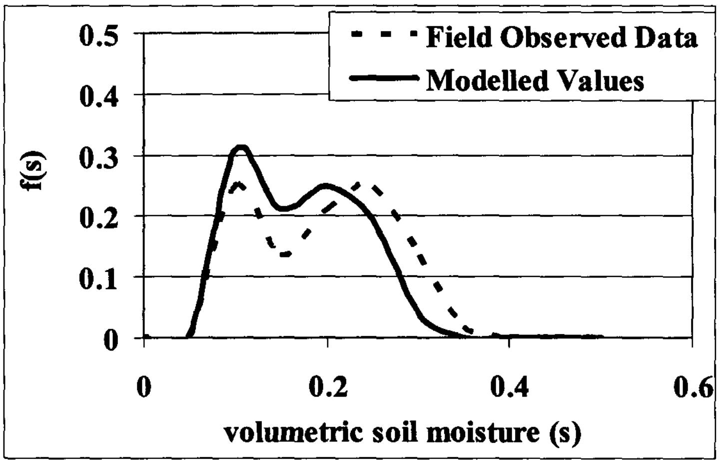
Year	Depth (cm)	RMSE	IoA	CRM
1998	37.5	0.045	0.725	-0.146
	80	0.046	0.839	0.117
1999	37.5	0.065	0.531	-0.016
	80	0.115	0.263	0.122

From Table 2.7, it can be seen that the RMSE values are close to zero for 1998 at both depths and for 1999 at 37.5 cm. The RMSE for 1999 at 80 cm is much higher than the other three. The IoA measures the agreement between the simulated and the observed values and varies within 0.0 and 1.0 (Willmott, 1982). The closer the IoA is to 1.0, the better the model performance. From Table 2.7, it can be seen that for the 1998 simulation at both depths IoA>0.7. The 1999 simulation at 37.5 cm is within acceptable limits as IoA>0.5. Much poorer agreement can be seen for the 1999 simulation at 80 cm where IoA<0.5. The CRM represents the difference between the simulated and observed relative to the observed data. CRM values at zero indicate a perfect fit, positive value indicate underestimation and negative values overestimation (Ginting and Mamo, 2006). From Table 2.7, it can be seen that the model slightly overestimates at 37.5 cm for both years and slightly underestimates at 80 cm for both years as well. This level of accuracy must be considered if the model is used for prediction purposes. The reported comparisons serve as a reminder of the achievable accuracy in the simulation of soil moisture using simplified models such as ours.

Given our interest in the degree of fluctuation of soil moisture under given climate, crop, and soil conditions, the probability/frequency distributions of the daily soil moisture level may be obtained. To increase the number of observed data points so that such frequency distribution curves can be prepared, the data sets of 1998 and 1999 were combined. The probability/frequency distributions are obtained for both depths and are presented in Figure 2.3.



(a) at 37.5 cm



(b) at 80 cm

Figure 2.3: The Probability Density Functions of the Growing Season Soil Moisture at the Two Different Depths Obtained from both Modelled and Field-Observations

The probability distributions indicate a bimodal behaviour of soil moisture. They clearly indicate that with depth, there is a definite increase in soil moisture availability, which is expected for the coarser textured soils existing in the lysimeters. At 37.5 cm, the simulated bimodal behaviour is more distinct than the field one. At 37.5 cm, the simulated probability distribution indicates a distinct peak at 0.1 cm^3/cm^3, while the field probability distribution indicates the dominance of soil moisture higher than 0.15 cm^3/cm^3. The simulated distribution shows a less dominant wetter mode peaking at 0.2 cm^3/cm^3. At 80 cm, the field bimodal behaviour is much more similar to the simulated one. At 80 cm, the simulated distribution indicates a higher tendency to lower soil moisture contents (defined peak at 0.1-0.15 cm^3/cm^3). The differences between the distributions are partly due to the limited availability of field data. More field data are required before more definitive conclusions can be made.

2.3.3 Sensitivity Analysis

A local sensitivity analysis was performed to investigate the relative influence of the different parameters, namely LAI, K_s, n, s^*, s_w and s_h on the dynamics of soil moisture. It was carried out by calculating the Sensitivity Coefficient, S_x, of a corresponding parameter x. S_x was obtained using Equation (2.14).

$$S_x = \left[\frac{ds}{dx}\right]_{\bar{x}} \tag{2.14}$$

where, $\bar{x}$ represents the local point of interest for parameter x. The quantity S_x represents the rate of change of soil moisture, s, in response to the rate of change of x. S_x can be approximated by finite difference taken at the vicinity of $\bar{x}$. For ease of comparison, this local sensitivity analysis was carried out by increasing the value of each parameter by 20% of its calibrated or literature-based value. This way a comparison of sensitivities to each individual parameter is possible. A summary of the results are presented in Table 2.8.

Table 2.8: The Sensitivity Coefficients (at a 20% Increase) Obtained from the Sensitivity Analysis Performed on the Selected Six Parameters

Parameter	1998		1999		Average
	80 cm	37.5 cm	80 cm	37.5 cm	
LAI	0.090	0.103	0.088	0.027	0.077
s^*	0.026	0.015	0.005	0.077	0.031
s_w	0.098	0.097	0.107	0.020	0.081
s_h	0.022	0.040	0.010	0.054	0.032
K_s	0.002	0.014	0.023	0.079	0.029
n	0.031	0.017	0.015	0.087	0.037

The higher the value of S_x the more significant the parameter. The highest values of S_x were obtained for s_w, ranging from 0.020 to 0.107 depending on the depth and year, closely followed by LAI, having a similar range of 0.027 to 0.103. This is a clear indication that the soil moisture control criterion at the wilting point and LAI are the most influential to soil moisture dynamics. Maximum transpiration and plant water uptake are modelled based on LAI, from which AET is determined based on the availability of soil moisture. The sensitivity analysis illustrates the significance of AET in the water balance. The significance of LAI shows that plant growth stage representation is necessary for the continuous simulation of soil moisture. From Table 2.8 it is also clear that soil moisture is less sensitive to n, s_h, s^*, and K_s values. Less effort may be spent in obtaining accurate values of these parameters for a study site. However, because of the simplified local nature of this sensitivity analysis, the results are only valid for the local parameter value regions and cannot be generalized for other parameter value regions. A complete global sensitivity analysis is possible but is beyond the scope of this paper.

2.4 Concluding Remarks

The continuous simulation model presented here is a simplified representation of the natural processes involved in the vertical water balance of a site. With reasonable simplification of the individual processes, the model demonstrates its ability to simulate soil moisture dynamics as influenced by the precipitation pattern, soil and vegetation type throughout the growing season. The model was able to obtain the average soil moisture values within 1-14% of the average observed soil moisture values. The SD's indicate that the model successfully reproduces the degree of variations of soil moisture conditions throughout the growing season. The RMSE's were close to zero for three of the four simulations. For two of the four simulations, the model achieves the desirable IoA > 0.7, while the third simulation achieves IoA > 0.5 which is also acceptable. CRM values indicate that the model slightly overestimates at lower depths and slightly underestimates at higher depths.

This study shows that average soil moisture conditions under the climate and lysimeter soil conditions of the GTIERC site are close to its PWP (0.19 cm^3/cm^3). However, the probability distributions show that there is a likelihood of soil moisture being higher than 0.2 cm^3/cm^3 at any given time. The probability distributions indicate bimodal behaviour and also confirm that the dominant soil moisture values are close to the PWP. The SD's show moderate variation about the average soil moisture values. Sensitivity analysis shows the significance of the soil moisture control criteria corresponding to the vegetation's wilting point and that of plant growth stages represented by the daily LAI. The numerical sensitivity measures corresponding to the six parameters provide some guidance for a more complete sensitivity analysis in the future.

The proposed continuous simulation model generates daily averages of soil moisture at any desired depth. The daily time scale lumps the precipitation from individual events into a single daily total. Therefore, the SR that might have occurred due to a short intense rainfall event may not be simulated because of this lumping. Infiltration was modeled as precipitation minus SR; the challenge was to allow surface runoff to take place at a daily time scale under southern Ontario conditions. For this, a CN_2 value higher than the recommended was used.

The leading deterministic models that directly model soil moisture or which have strong soil moisture components do not necessarily focus on the ability of the vegetation to control ET by closing their stomata when under stress. For urban grasslands, where the interest is mainly stormwater quantity and quality, it is necessary to incorporate an ecohydrological perspective into the continuous simulation of soil moisture. It is in response to this need that the simplified continuous simulation model was developed. In the proposed model both AET and leakage losses are modelled as soil moisture dependent. This makes the time step-by-time step solution of the water balance, i.e., Equation (2.1), not straight-forward. One of the limitations of the AET component is the representation of vegetation PWP and hygroscopic point. It was only possible to obtain realistic values of the matric potentials at field capacity, PWP and the hygroscopic point from the literature and then use Equation (2.9) to calculate the corresponding soil moisture criteria. The soil moisture control on AET, i.e., Equation (2.10), provides a realistic representation of the process. This AET calculation process has not previously been applied at a daily time scale or included in any of the more detailed deterministic models for predicting crop yields.

It must be recognized that the model was not developed to focus individually on SR, ET or leakage. Simplified representations of each of these processes are believed to be reasonably accurate to generate realistic soil moisture values. The input data required to run the model are widely available. Given the state-of-the-art in modeling the individual processes, the model should be used with caution as a predictive tool. The main purpose for the development and use of this model was to better understand the statistics and sensitivity of soil moisture under different plant, soil, and climate conditions. Direct measurement of soil moisture fluctuations is costly and it will take a long time to accumulate sufficient data for statistical analysis. Mathematical modeling provides a viable means of examining the long-term soil moisture fluctuations under different land uses. As a research tool, the simplified model will be further used to investigate the statistical behaviour of soil moisture and to analyze the effect of urbanization and climate change on soil moisture.

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Chapter 3

Relative Importance of Input Parameters in Soil Moisture Dynamics Modelling

Shazia Nishat, Yiping Guo and Brian W. Baetz

Abstract

A series of global sensitivity analyses were performed to evaluate the response of outputs from a continuous-simulation soil moisture model to variations of input parameters. Random samples were generated for selected input parameters through Monte Carlo simulation. Using each set of random input parameters, the soil moisture model was run with 20 years (1981-2000) of meteorological data from Toronto, Ontario, Canada. Three output statistics, namely, average soil moisture, the standard deviation and the skewness of the output daily soil moisture values were determined from each model run. Regression-based non-parametric techniques were then used to obtain sensitivity indices between the output statistics and the input parameters. Based on these sensitivity indices, the parameters representing soil texture were found to be most influential on average soil moisture, whereas parameters representing land-use were found to be more influential on standard deviation. Land-use and soil texture parameters were found to be almost equally influential on the skewness of the output daily soil moisture values. Overall it was shown that evapotranspiration has the strongest influence on long-term soil moisture fluctuations.

Keywords: Continuous Simulation, Water Balance, Evapotranspiration, Global Sensitivity Analysis, Monte Carlo Technique, Sensitivity Indices

3.1 Introduction

Sensitivity Analysis (SA) involves quantification of the change in a model output corresponding to a change in one or more model inputs (Mishra 2004; Mishra et al. 2003). Studies in various fields such as crop-water relations (Liu 2009), evapotranspiration (Bois et al. 2008), water-quality modelling (Pastres et al. 1999; Arhonditsis & Brett 2005; Manache & Melching 2008), nuclear fuel storage and safety (Hedin 2003; Jacques et al. 2005), photosynthesis and plant respiration (Tingey et al. 2007), grassland desertification (Zeng et al. 2005), climate response to vegetation and soil moisture (Douville et al. 2007), rainfall-runoff modelling (Ratto et al. 2007; Jacquin & Shamseldin 2009), climate-control on vegetation (Manobavan et al. 2003) and soil moisture (Mahmood & Hubbard 2003), streamflow analysis (Qian et al. 2006; Quader & Guo, 2009), flood inundation (Hall et al. 2005; Pappenberger et al. 2008) and non-point source pollution modelling (Francos et al. 2003; Kanso et al. 2005), have all successfully demonstrated which input parameters have a dominating influence on the model output using SA.

SA techniques may be classified into two groups: Local Sensitivity Analysis (LSA) and Global Sensitivity Analysis (GSA). LSA deals with the local impact of the parameters on the model output. LSA is conducted by varying one input parameter at a time within a small interval around its nominal value (Saltelli et al. 1999; Mertens et al. 2005; Zeng et al. 2005) and analyzing the effects of this small change upon the model output. LSA is capable of handling small variations in parameter values, and is not suitable for cases with possible dramatic changes in input parameter values. GSA, on the other hand, incorporates the influence of the whole range of variation of the input parameter on the output variable. By definition, it apportions the output variability to the variability of the input parameters (Saltelli et al. 2000). Calculation of LSA is much faster than that of GSA. However, LSA is truly local, and is incapable of capturing the effect of any significant change in the input parameters. The information provided by LSA is related to a single point in the space of parameters, whereas GSA deals with the assumed probability density functions of the input parameters. Detailed descriptions of the two groups of SA methods are available in Saltelli et al. (2000).

In recent years, there has been a growing need to better understand soil moisture dynamics under different soil and climate conditions due to concerns of climate change and rapid urbanization. Direct measurement of soil moisture fluctuations remains a relatively new practice and it will take a long time before sufficient measured data become available. For example, throughout Canada, soil moisture values are measured only at a few locations (Wittrock & Ripley 1999). Due to the lack of instrumentation during earlier years, the measured records at these locations are still short. Mathematical modeling provides a viable means of examining the long-term soil moisture dynamics at a particular site; it can be used to investigate the long-term availability and fluctuations of water within the soil matrix at the root zone.

For the modelling of soil moisture dynamics, a continuous simulation model was developed and an LSA was carried out in Nishat et al. (2007) to gain insight into the relative importance of input parameters affecting the output of interest for a specific site. The relative importance of input parameters determined through LSA is only valid for the site represented by the base parameter values. Different site conditions will result in different parameter values. The sensitivity coefficient values obtained through LSA for one site are different from those for another site. To provide general guidance to future modeling efforts, all possible site conditions must be considered in a sensitivity analysis. GSA is such an analysis that can provide measures of relative importance of parameters under all possible site conditions. In this study, a GSA was carried out to incorporate the influence of wide ranges of variations of input parameters on the output variable of interest and thus better determine the input parameters that are most influential and require more attention for all possible site conditions.

3.2 Methodology

The previously developed continuous simulation model is briefly described below, followed by an explanation of the input parameters selected, the data, and then a description of the GSA steps executed.

3.2.1 The Continuous Simulation Model

The continuous-simulation water balance model (Nishat et al. 2007) was developed to simulate soil moisture in the root zone throughout a growing season (e.g., May through October in Ontario, Canada). The soil water balance model, represented by Equation (3.1), is one-dimensional, taking into account only the hydrological processes that operate in the vertical direction. Vertically, the model represents the soil domain as a single homogeneous layer. The output of the model can be viewed as area/site-averaged values since the inputs are all area/site-averaged values. By specifying different vertical layer depths and vertically averaged soil characteristics, the continuous simulation model generates daily averages of soil moisture at any desired depth.

$$nZ_r \frac{ds(t)}{dt} = P(t) - SR(t) - ET(s) - L(s) \tag{3.1}$$

where, s = volumetric soil moisture content in cm^3/cm^3;

Z_r = depth within the soil root zone in cm;

n = porosity;

P = precipitation in cm/day;

ET = evapotranspiration in cm/day;

SR = surface runoff in cm/day;

L = leakage in cm/day; and

t = time index with an interval length of one day.

This continuous simulation model incorporates the well-established models of each of the individual processes that take part in the water balance. SR is estimated using the United States Natural Resources Conservation Services (NRCS) curve number (CN) procedure. This SR component was modified to better represent urban land-uses (Nishat et al. 2008). Potential Evapotranspiration (PET) is estimated using Penman's Method. Actual Evapotranspiration (AET) is then modelled from PET as a function of soil moisture and is further adjusted to represent various plant growth stages. Plant growth stages are represented by Leaf Area Index (LAI). Only the daily totals of ET are calculated, the hourly fluctuations of ET are not accounted for. Leakage is modelled as vertical percolation and is a function of soil moisture. Soil moisture in turn is a function of time. For simplicity of notation, the dependency of ET and leakage on time is not shown in Equation (3.1). The AET and leakage calculation procedures included in this model emphasize the soil moisture regime's control on these two processes, and is different from the way other deterministic models represent these two processes within the water balance.

The dependency of ET on soil moisture is defined for three different ranges of soil moistures (Rodriguez-Iturbe et al. 1999 a,b; D'Odorico et al. 2000; Ridolfi et al. 2000; Laio et al. 2001) as shown in Figure 3.1. The hygroscopic soil moisture, s_h, is defined as the soil moisture which is held tightly in the soil and is completely unavailable to plants. s_w is defined as the soil moisture at the permanent wilting point (PWP), which is the soil moisture level when plants can no longer access water and start to wilt permanently. The critical soil moisture value, s^*, is defined as the soil moisture below which plants start to endure water stress (Laio et al. 2001). Above s^*, evapotranspiration occurs at its maximum value, i.e., AET = PET. The value of s^* is often associated with the field capacity (s_{fc}) of the soil; however it takes a value less than the soil moisture at field capacity. E_m is the maximum soil evaporation. When soil moisture is lower than s_w, plant transpiration stops, only soil evaporation occurs. Root water uptake was also taken into account whilst modelling AET. Losses from leakage are at a maximum when the soil is fully saturated, i.e., when $s = 1$. This maximum leakage rate equals the saturated hydraulic conductivity, K_s. For unsaturated conditions, leakage follows a power law relationship describing the reduction of leakage rate as soil moisture levels lower (Rodriguez-Iturbe et al. 1999 a,b; D'Odorico et al. 2000).

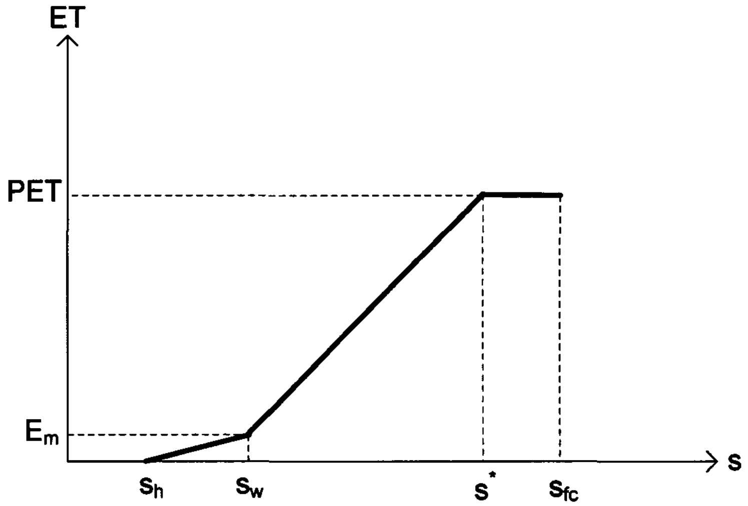

Figure 3.1: Conceptual Diagram of the Soil Moisture Control on Evapotranspiration

One of the limitations of the AET component is the difficulty in the determination of the PWP of the vegetation and the hygroscopic point for a specific site. It was only possible to obtain realistic values of the matric potentials at field capacity, PWP and the hygroscopic point from the literature and then using an empirical equation representing the soil-water retention curve (Clapp & Hornberger 1978) to calculate the corresponding soil moisture values. s_h, s_w and s^* are referred to as the soil moisture control criteria due to their impact on ET. In this study, the three soil moisture control criteria for a specific soil texture group were estimated using the empirically determined soil-water retention curve in the form of Equation (3.2) (Clapp & Hornberger 1978).

$$\psi_s = \overline{\psi}_s \times s^{-b} \tag{3.2}$$

where, Ψ_S = Matric Potential corresponding to s;

$\overline{\psi}_S$ = Saturation Matric Potential; and

b = Empirical Exponent.

$\overline{\psi}_S$ and b are empirically determined parameters.

Assembling previous study findings in the above-described way, a mathematical model for the study of long-term soil moisture behaviour is obtained. Different from all existing models, this model looks into the soil moisture and plant growth stage control on the processes of evapotranspiration and leakage. Equation (3.1) is solved numerically by using the backward finite difference method. Detailed description of the continuous simulation model is provided in Nishat et al. (2007).

3.2.2 Selection of Input Parameters for Analysis

The purpose of this study is to generate guidelines as to which input parameters are more influential and require more attention for their quantification in the modeling of soil moisture for any site. Therefore, the continuous soil-moisture simulation model was not set up for a specific site; rather it was set up for all possible soil texture conditions under a specific type of climate. This way, the GSA guidelines can be used to guide modeling studies for any possible soil texture conditions so that more accurate results may be obtained under given input data and budget limitations. Due to the number of simulation runs that need to be completed and the length of each simulation run, it is desirable to include less input parameters in the GSA. Thus, selection of input parameters included in the GSA was based on two considerations: (1) Is the parameter likely to have a large influence on the output? If so, then the parameter needs to be included in the GSA; and (2) Can the value of the parameter be accurately determined for a given site? If it can, then it is unnecessary to include it in the GSA. At the end, six parameters were selected for the GSA. The selection of these parameters was also partly done considering the earlier LSA results (Nishat et al. 2007). The parameter that was a part of the LSA but not included in the GSA is soil porosity, n. Porosity was not included in the GSA because its values are easily attainable. For example, it can be measured on site or obtained from the widely accepted charts for all of the soil texture groups with little uncertainty. The six selected parameters are:

(a) LAI - Leaf Area Index, which is representative of vegetation. The sensitivity coefficient associated with LAI obtained from the earlier LSA was the second highest. LAI plays a significant role in determining ET. First it is introduced to partition between transpiration and soil evaporation. And then after AET is calculated based on the soil moisture control criteria, a correction factor is applied to take into consideration different plant growth stages (Nishat et al. 2007). LAI values are not readily available, and for this study they were obtained from the literature.

(b) s_w - defined earlier as the soil moisture at the PWP. It attained the highest sensitivity coefficient in the LSA. It plays a major role in ET, which is clear from its definition as well as from Figure 3.1. Leakage is modelled as a function of soil moisture, and s_w influences leakage (Nishat et al. 2007). It is representative of soil texture (Equation (3.2)). There is no direct data available for s_w, it was calculated from soil matric potential at PWP and soil texture characteristics.

(c) s_h – defined earlier as the soil moisture at hygroscopic point. The method of obtaining s_h values is the same as s_w. This parameter obtained low sensitivity coefficient values in the earlier LSA. However, its correlation with the other soil moisture control criteria was not taken into account when performing the LSA. Like s_w, s_h plays a major role in ET and is representative of soil texture.

(d) s^* - defined earlier as soil moisture below which plants start to endure water stress. The method of obtaining s^* values is the same as s_w and s_h. Similar to s_w and s_h, s^* also plays a major role in ET, which is clear from Figure 3.1. However, unlike s_w, it plays no role in leakage. This parameter also obtained low sensitivity coefficient in the LSA. However, its correlation to both s_w, s_h and soil texture warrants the inclusion of it in the GSA.

(e) K_s - the saturated hydraulic conductivity, dependent on soil texture. K_s controls leakage, which is a major process of vertical water balance. Even though it had the lowest sensitivity coefficient in the LSA, this parameter was still included because it is always difficult to determine its value unless exact field measurements are taken and field measurements can be difficult. Also, its correlation to the soil moisture control criteria was not taken into account when performing the LSA.

(f) CN_2 - the curve number corresponding to average antecedent soil moisture conditions. CN_2 is the major variable required in the NRCS-CN procedure, which was used to calculate surface runoff. Soil texture and land-use control the value of CN_2. As CN_2 is representative of land-use, its correlation with LAI was incorporated into the GSA. Even though it was not included in the LSA, it is important for GSA as SR is a vital component of the water balance and estimation of CN_2 involves considerable uncertainty.

3.2.3 Meteorological and Other Input Data

Urban areas with grasslands are the focus of this study. The study area is not an actual site but hypothetical urban lands adjacent to the Toronto Pearson International Airport (43°40′12″N, 76°36′W), in Toronto, Ontario, Canada. Each hypothetical urban site contains both grass covered areas (pervious) and impervious areas. The simulation period is from 1981 to 2000. Meteorological data including precipitation, temperature, solar radiation, relative humidity, and wind speed were obtained from the Ontario Climate Centre (station No. 6158733, Toronto Pearson Airport). The original data are hourly values, daily totals or averages were calculated from the hourly values. There were few missing data, and the missing data were replaced with data from an adjacent weather station (No. 6158350). The growing season was identified as from May through October, which is typical for this location. Average annual precipitation is 83 cm. Summer is the wettest season, with the bulk of rainfall falling during thunderstorms. The value of interception typical of grasslands was found to be 17% (Viessman & Lewis 2003). Depending on the land-use scenarios area-averaged interception was varied between 10-17%. The maximum rooting depth is taken as 30 cm, which is typical for grass lands. The range of values for each of the input parameters analyzed in this GSA varies across six soil texture groups: sand, loamy sand, sandy loam, silt loam, clay loam, and clay. The other parameters not included in the GSA but needed for each model run are presented in Table 3.1.

Table 3.1: Additional Characteristics Typical of the Six Soil Texture Groups

Soil Type	Porosity	b	S_{alb}
Sand	0.35	4.05	0.13
Loamy Sand	0.421	4.38	0.13
Sandy Loam	0.434	4.90	0.13
Clay Loam	0.465	8.52	0.13
Silt Loam	0.425	5.30	0.14
Clay	0.50	11.4	0.12

S_{alb} is the soil reflectivity, values of which are required for modelling PET. b (and ψ_s) is empirically determined parameter used in Equation (3.2). Six values of each of the soil moisture control criteria, i.e., s_h, s_w, and s^*, were obtained for each of the six soil texture groups using Equation (3.2). The values of n, b, S_{alb} and K_s for the six soil groups were obtained from the literature (Clapp & Hornberger, 1978; Jones & Kiniry, 1986; Knisel & Davis, 1999; Laio et al. 2001; USDA website).

3.2.4 Global Sensitivity Analyses

GSA was used to determine the most critical input parameters (other than climate variables) influencing the values of average soil moisture, standard variation and skewness of daily soil moisture values. GSA was the preferred technique because firstly, GSA can measure the relative importance of parameters under all possible site conditions whereas LSA is site-specific, and secondly, LSA does not account for correlation amongst input parameters while GSA does. In this study, regression-based non-parametric GSA techniques were used. Quantitative GSA measures indicating the relative importance of input parameters can only be obtained by investigating the entire range over which the input parameters may vary. Generating random series of values of input parameters is therefore an essential component of GSA. First, a sample (x_1, x_2, ..., x_n) of the desired dimension n equalling the number of input parameters under investigation, is generated from the joint distribution of the input parameters . Samples generated this way cover the widest variety possible, as a result, the GSA results are generally applicable to any possible case in nature. A continuous simulation run was then carried out using this sample as input to the model. The total number of continuous simulation runs executed should not be smaller than 1.5 times the number of input parameters; possibly a much larger value (e.g., 10 times the number of input parameters) should be used.

3.2.5 Correlation between Input Parameters

Values for the six input parameters were randomly generated to represent all possible site conditions under the described climate. The ranges of the parameter values used for generating random samples are shown in Table 3.2.

Table 3.2: Ranges of Input Parameter Values

Parameter (units)	Lower Limit	Upper Limit
s_w (cm^3/cm^3)	0.17	0.59
LAI (cm^2/cm^2)	0.102	0.85
K_s (cm/day)	0.864	864
CN_2	39	96
s_h (cm^3/cm^3)	0.06	0.41
s^*(cm^3/cm^3)	0.44	0.83

Because s_w, s_h, s^*, and K_s are all related to soil texture; there are correlations between these parameters. Similarly, correlations between LAI and CN_2 exist as they are both related to imperviousness. These correlations were taken into account when generating random samples of parameters. The correlations between the input parameters were established within the GSA according to the Iman-Conover correlation method. The Iman-Conover correlation method induces desired rank-correlation on pairs of input parameters (Iman & Conover 1989). This method introduces a nonparametric regression procedure that only requires the assumption of a monotonic regression function (linear or nonlinear). The procedure conducts the usual ordinary least squares regression analysis on the ranks of the original values (Headrick & Rotou 2001). Its characteristics are:

- It is distribution-free;
- It is simple to use as no advanced mathematical techniques are required to implement the method;
- The same numbers originally selected as input values are retained only their pairing is affected to achieve the desired rank correlations;
- The marginal distributions of input parameters remain intact.

To facilitate the establishment of correlation between CN_2 and LAI, it was assumed that the grass is sheared and kept at a height of 5-6 cm throughout the growing season (May-October). Based on calibration results reported in Nishat et al. 2007, LAI for such grassland was 0.85. However, the effect of LAI would vary depending on the percentage of grasslands present on a given site. The percentage of grasslands of urban areas varies from 10% to over 80%, which translates to area averaged leaf area indices varying from 0.101 to 0.85. The range of CN_2 values were found from the curve number tables of Chow et al. (1988) and Viessman & Lewis (2003). Purely impervious areas will not be taken into consideration in this study. The range of CN_2 is 39 to 96, where 96 is for areas with the highest imperviousness and 39 is for areas with the lowest imperviousness. The NRCS tables provide CN_2 values for different land-uses. Based on soil texture, NRCS identifies four soil groups (i.e, Group A, B, C, or D). For every land-use, there are four CN_2 values for the four NRCS soil groups. In establishing the CN_2-LAI correlation, the average of the four CN_2 values for each land-use was taken. It is noted here that while this average allows only the correlation of CN_2-LAI to be established, different soil groups can still be combined with different imperviousness in sample generation. With the percentage of grassland known for each land-use and its CN_2, the corresponding LAI was calculated accordingly. For example, an average CN_2 of 86 represents residential districts consisting of lot sizes on average of 1/8th of an acre (Viessman & Lewis 2003). For this type of land-use, grassland was assumed to cover 35% of the total, which corresponds to a LAI of 0.3. Thus one pair of CN_2 and LAI values representing one possible site is obtained. Twelve more such pairs of CN_2 and LAI values were obtained to establish the correlation between CN_2 and LAI.

The correlations between s_w, s_h, s^*, and K_s are more straight forward to establish as six values of each of the four parameters can be directly linked to each other since they individually represent the six soil groups. In order to calculate the correlation between s_h, s_w, s^*, and K_s, they were taken two at a time. The seven pairs of values (including those for CN_2-LAI), were then used to calculate the correlation coefficients. The calculated correlation coefficients, for each of the seven input parameter pairs, are shown below in Table 3.3.

Table 3.3: The Calculated Correlation Coefficients among Input Parameters

Parameters	s_w - s^*	s_w - s_h	s_h - s^*	s_w - K_s	s_h - K_s	s^* - K_s	CN_2 - LAI
Correlation Coefficient	0.96	0.99	0.90	-0.61	-0.55	-0.66	-0.97

3.2.6 Monte Carlo Generation of Sample Sites

The Monte Carlo (MC) sampling technique is used to generate a series of random samples of input parameters. By ensuring that the random sets fall within the ranges of the parameter values shown in Table 3.2, it is guaranteed that the random values are realistic. In this study, two sample sets were obtained. The first includes 50 sets of random values, and the second consists of 60 sets of random values for the six parameters. These two sets allow the investigation of various soil and land-use combinations.

During the generation of random values, correlations between parameters are important and must be provided. As mentioned earlier, the calculated correlations between the input parameters shown in Table 3.3 were induced into the GSA using the Iman-Conover correlation method. The selected input parameters are treated as random variables uniformly distributed within their specified ranges shown in Table 3.2. Uniform distributions were imposed so that no bias towards any specific soil texture and land-use density is introduced. By ensuring that the correlation among the parameters are also taken into consideration, it is guaranteed that any given set of random variables generated by the MC procedure represents a case made up of one soil texture and having one imperviousness.

3.2.7 Model Simulations

A simulation run was then conducted using a set of random parameter values generated by MC. Each simulation was run using 20 years (1981-2000) of climate data in south-western Ontario, Canada and, as output, the daily soil moisture levels at a depth of 30 cm were determined. The soil moisture dynamics of interest are average soil moisture, the standard deviation and the skewness of the daily soil moisture values. Average soil moisture is a widely investigated output and is suitable for representing long-term average conditions. Traditionally, less focus is placed on the degree of fluctuations and detailed frequency distributions of soil moisture throughout the growing season. The standard deviation represents the variation of soil moisture values about the average, while the skewness of soil moisture represents the asymmetry of the variations or, in other words, whether soil moisture values are higher or lower than the average for the most part of the growing season. The three output characteristics from each of the 20-year runs were obtained thereby providing three output variables corresponding to each set of the six input parameters.

The annual totals of the processes show directly which processes are dominant. The processes that are influenced by the composite impervious and pervious land-uses are SR, ET, and leakage. To gain an idea of the annual totals, the continuous simulation model was run for one urban land-use case with 70% vegetation and 30% impervious areas. CN_2 was taken as 72. This is representative of typical residential neighbourhoods where impervious and pervious areas are intertwined. CN_2=72 was computed assuming that the runoff from houses and driveways is directed towards streets with a minimum of roof water directed to the lawn (Chow et al. 1988). To model ET and leakage properly over composite areas, the ET and leakage modules of the original model were modified. LAI was reduced by 30% from that of 100% grass cover. Values of LAI needed to represent plant growth stages were varied between 0.2-0.9 m^2/m^2 throughout the growing season. Similarly, leakage is first modeled for 100% perviousness, and then reduced by 30% as leakage will not occur over the impervious portion. From the simulated daily ET, SR, and leakage for each growing season, the total ET, SR, and leakage for that individual year was obtained.

3.2.8 Calculation of Sensitivity Indices

The final step of GSA is the calculation of Sensitivity Indices (SIs) quantifying the degree of influence of each input parameter on each output of interest (Saltelli et al. 2000). SIs are numerical values that characterize the relationship between the output(s) under investigation and the input parameter(s) selected. It is required to determine several types of SIs so that the conclusions drawn from them can be more reliable. For the calculation of some types of SIs, rank transformation is used to mitigate the problems associated with nonlinear input-output relationships. Both input and output data are replaced with their corresponding ranks, and then the usual regression and correlation procedures are performed on these ranks. Specifically, the smallest value in each data set is assigned rank 1; the next largest value is assigned rank 2, and so on up to the largest value (Helton 2004, Sieber and Uhlenbrook, 2005). The analysis is then performed with these ranks being used as the values for the input and output variables.

The use of rank-transformed data results in an analysis based on the strength of monotonic relationships rather than on the strength of linear relationships. Using original and rank-transformed data, four types of SIs were deemed suitable and versatile enough for this study. They are (i) SPEArman coefficient (SPEA); (ii) Standardized Rank Regression Coefficient (SRRC); (iii) Partial Rank Correlation Coefficient (PRCC); and (iv) the Smirnov test results. A brief description of these four types follows.

1) SPEA is a preferred measure of correlation for non-linear models. It is best suited when the model output varies monotonically with each independent variable (Saltelli et al. 2000; Helton 2004). SPEA is essentially the same as PEARson product moment correlation (PEAR), as expressed in Equation (3.3) (Saltelli et al. 2000; Mishra 2004), between output y and input x_i, but instead of using the numerical values of both output variable y and input parameter x_i, it uses their ranks as shown in Equation (3.4) (Saltelli et al. 2004).

$$\mathrm{PEAR}(y, x_i) = \frac{\sum_{k=1}^{j} (y_k - \bar{y})(x_{ik} - \bar{x}_i)}{\sqrt{\sum_{k=1}^{j} (y_k - \bar{y})^2} \sqrt{\sum_{k=1}^{j} (x_{ik} - \bar{x}_i)^2}} \tag{3.3}$$

$$\mathrm{SPEA}(y, x_i) = \mathrm{PEAR}(R(y), R(x_i)) \tag{3.4}$$

In Equations (3.3) and (3.4), j is the sample size, x_{ik} is the kth sampled value of parameter x_i, y_k is the corresponding output value, and R(.) denotes the rank of the variables.

2) SRRC is also a rank transformed measure (Saltelli et al. 1999; Helton 2004). This non-parametric index is best suited for non-linear models but when the output varies monotonically with each independent parameter (Saltelli et al. 1999; Saltelli et al. 2000, Sieber and Uhlenbrook, 2005). Standardization in regression analysis takes place in the form of a transformation by ranks or by the ratio of the parameters standard deviation to its mean (Hambly 1995). The effect of

standardization is to remove the influence of units and place all parameters on an equal level (Hambly and Tarantola 1999). The generalized form of a regression model or equation is shown in Equation (3.5) (Hamby & Tarantola 1999; Mishra 2004).

$$\hat{y} = b_0 + \sum_{i=1}^{j} b_i x_i \tag{3.5}$$

where, x_i is the ith input, and the 'hat' signifies a regression-fitted value of the variable (Hamby 1995, Mishra 2004). In Equation (3.5) b denotes a regression coefficient. Equation (3.5) represents a linear regression model built between y and x_i (Pastres et al. 1999, Mishra 2004). SRRC is calculated by applying rank transformation to the Standardized Regression Coefficient (SRC) expressed through Equation (3.6) (Hambly and Tarantola 1999, Saltelli et al. 2000, Manache and Melching 2008).

$$SRC_i = \frac{b_i s_i}{s} \tag{3.6}$$

where, s_i and s are the standard deviations of the inputs and the output respectively.

3) PRCC is the measure calculated using Equation (3.7) (Mishra 2004), when input-output relationships are built using the ranks of the variables to linearize the relation. This technique is used with the understanding that the input-output pair of interest has already been rank transformed (Mishra 2004; Saltelli et al. 2004). Similar to SPEA and SRRC, this index is best suited for model outputs varying non-linearly or at least monotonically with each independent variable (Saltelli et al. 1999; Saltelli et al. 2000).

$$PRCC(y, z_i) = PEAR(y - \hat{y}, x_i - \hat{z}_i) \tag{3.7}$$

$$\hat{z}_i = d_0 + \sum_{i=1}^{j} d_i x_i \tag{3.8}$$

where, z_i is a function of $(x_1, x_2, \ldots\ldots x_j)$, d denotes a regression coefficient (Mishra 2004) and like Equation (3.5) the 'hat' signifies a regression-fitted value of the variable (Hamby 1995, Mishra 2004). Equation (3.8) represents a linear regression model built between z_i and the other input parameters (Mishra 2004).

4) The Smirnov test is applicable when a qualitative definition for the 'good' or 'acceptable' behaviour of a model can be defined, e.g., through a set of constraints: thresholds, time bounds, etc., based on available information from the system. A range is defined for input parameters reflecting uncertainties in the model and a number of MC simulations are made. Each MC simulation generates a vector of values of the input parameter. The corresponding model outputs are classified according to the specification of the 'acceptable' model behaviour; quantifying a simulation as behaviour (B) if the model output lies within the constraints and non-behaviour ($\bar{B}$) if not. Smirnov test scores are calculated independently for each input parameter. Samples of input parameter x_i used in the model runs are divided into the two sub-sample sets of (x_i / B) of m elements and $(x_i / \bar{B})$ of q elements based on a threshold value (where, m + q = N, the total number of MC simulations) (Saltelli et al. 2004, Saltelli et al. 2006). For this study the 90th quantile was used for the threshold i.e., one sub-sample corresponds to the output above the 90th quantile and the other sub-sample corresponds to all the output below the 90th quantile (Tarantola 2009). The cumulative distributions of the two sets i.e., B and $\bar{B}$ are obtained. The degree of similarity, measured as the greatest absolute difference in the vertical direction between the distributions, is used to indicate the sensitivity between the input and output values (Hamby 1995, Hamby and Tarantola 1999). If the frequency distribution of x_i in the two subsets can be shown to be dissimilar, then the input parameter x_i is considered influential (Saltelli et al. 2000).

Positive values of SIs imply that an increase in the input corresponds to an increase in the output, and vice versa. The larger the absolute value of the SIs, the stronger the relationship between the output and the input (Mishra 2004, Sieber and Uhlenbrook, 2005). The input parameters are representative of the processes controlled or affected. Hence, carrying out this GSA will also in fact give insight into the processes that dominate the water balance under specific land-use and climate conditions. As mentioned earlier, further investigations on the dominant process(es) were carried out by calculating the annual totals of ET, SR, and leakage.

3.3 Results and Discussion

3.3.1 Annual Totals

From the calculations of the annual (growing season only) totals, it was found that the 20-year average growing season precipitation, ET, SR, and leakage are 39.4cm, 35.3 cm, 1.12 cm, and 0.8 cm, respectively. The imbalance between the four water balance components may be caused by the daily time scale used in the simulation. The daily scale lumps the precipitation from individual events into a single value for each day. Therefore, SR that may have occurred due to short intense rainfall events would not occur or occur less when a daily time scale is used. This may result in an underestimation of SR. Nevertheless, the annual totals clearly show that ET is the dominant process. To confirm this, the maxima of each individual component were compared. The maximum annual ET, SR, leakage and precipitation obtained from the 20 year analysis were found to be 46.9, 10.05, 5.3, and 65.27 cm/growing season, respectively. These values demonstrate that ET is almost 5 times that of SR and SR is 2 times that of leakage, confirming that ET is the most influential process of the water balance.

3.3.2 Analysis of Average Soil Moisture

Using the paired input and output values, GSA was conducted and the SIs between inputs and outputs were determined. The first output of interest is the average soil moisture during growing seasons. Using results from the set with 50 samples the SIs obtained with average soil moisture as the output are presented in Table 3.4.

Table 3.4: Sensitivity Indices between Average Soil Moisture and Each of the Input Parameters Based on 50 Samples

Input Parameter	SPEA	Smirnov	SRRC	PRCC
s_w	**0.984**	**0.978**	**0.395**	0.189
LAI	0.251	0.622	0.074	0.1488
K_s	-0.617	0.844	-0.067	**-0.381**
CN_2	-0.215	0.467	0.002	0.003
s_h	**0.987**	**0.978**	**0.557**	**0.365**
s^*	0.907	0.933	0.013	0.018

In Table 3.4, the top two highest absolute values of the SIs under each of the GSA techniques are in bold. The SPEA analysis indicates that all three of the soil moisture control criteria had SIs values close to 1.0. Indices close to 1.0 suggest strong input-output relationships. The next highest absolute value of SPEA is that of K_s. Both the soil moisture control criteria and the hydraulic conductivity are soil texture related parameters. This means that these soil texture parameters have the strongest influence on average soil moisture among the six selected parameters, and that ET and leakage strongly influence long-term average soil moisture. SI values of SPEA for K_s and CN_2 are negative, indicating an inverse relationship with average soil moisture, i.e., any increase in K_s and CN_2 results in a decrease in average soil moisture. This can be easily explained by the fact that with increasing hydraulic conductivity, leakage is increased thereby reducing the availability of soil moisture. As for CN_2, it is clear that the higher the CN_2 the lower the perviousness, which translates to lower infiltration and thus, lower average soil moisture. The SPEA values for LAI and CN_2 are the lowest of the six, indicating that these two land-use based parameters are not as dominant on average soil moisture as the soil-texture related parameters. The Smirnov test results match the SPEA values very well. However, the difference between SPEA and the Smirnov test is that the SIs for K_s and CN_2 have positive values instead of negative ones. This is because Smirnov test is incapable of capturing the nature of the input-output relationship, i.e., whether they are positively or negatively related to each other. The Smirnov test only gives absolute values, and only to indicate relative importance of the parameters. SRRC analysis ranks s_w and s_h as the top two parameters which is in good agreement with SPEA and Smirnov test. PRCC, on the other hand, fails to do that, it ranks K_s first followed by s_h and s_w.

The same procedure was followed, only this time the model simulation was run 60 times using the set with 60 samples of input parameters. The separate calculation of SIs using results from the 50 and 60 sample sets is for the purpose of verifying how large the sample size has to be in order to achieve converging and reliable SI values. The SIs obtained for average soil moisture based on 60 simulation runs are presented in Table 3.5.

Table 3.5: Sensitivity Indices between Average Soil Moisture and Each of the Input Parameters Based on 60 Samples

Input Parameter	SPEA	Smirnov	SRRC	PRCC
s_w	**0.987**	**0.982**	**0.392**	0.18
LAI	0.326	0.630	0.106	0.225
K_s	-0.653	0.815	-0.064	**-0.382**
CN_2	-0.296	0.463	0.028	0.062
s_h	**0.987**	**0.982**	**0.524**	**0.336**
s^*	0.918	0.907	0.018	0.023

Again, the bold values are the highest absolute values of the SIs under each of the techniques. It can be seen from Table 3.5 that the top two dominating input parameters are the same as that shown in Table 3.4. For example, SPEA analysis showed that all three of the soil moisture control criteria have SI values close to 1. The next highest absolute value of SPEA is also that of K_s. The results of SPEA and the Smirnov test are almost identical. SRRC analysis also ranks s_w and s_h to be the top two parameters. PRCC again fails to do that.

3.3.3 Analysis of the Degree of Fluctuation of Soil Moisture

The SIs obtained between the standard deviation of the soil moisture and each of the input parameters using results from the set with 50 samples are presented in Table 3.6.

Table 3.6: Sensitivity Indices between Standard Deviation and Each of the Input Parameters Based on 50 Samples

Input Parameter	SPEA	Smirnov	SRRC	PRCC
s_w	0.355	0.467	-0.066	-0.007
LAI	**0.731**	**0.644**	**0.665**	**0.281**
K_s	-0.29	0.333	-0.192	**-0.246**
CN_2	**-0.713**	**0.689**	-0.116	-0.057
s_h	0.344	0.533	-0.376	-0.057
s^*	0.378	0.356	**0.578**	0.160

The two highest absolute values of the SIs under each of the techniques are, again, in bold. SPEAs for K_s and CN_2 have negative values, meaning any increase in K_s and CN_2 results in a decrease in the variability of soil moisture. LAI and CN_2 have the highest absolute SPEA values, meaning that these land-use parameters have stronger influence on the variability of soil moisture among the six selected parameters. The next highest values of SPEA are those of the three soil moisture control criteria; however, the difference is not as significant as that shown in Table 3.4, indicating that the two land-use based parameters are slightly more dominant on the standard deviation than the soil-texture related parameters. The results of the Smirnov test are similar to the SPEA values. None of the indices obtained by the SPEA or Smirnov techniques in Table 3.6 are close to 1.0, which means that all parameters are moderately influential. The results from the SRRC and PRCC show that the most dominating input parameter is LAI which agrees with the SPEA and Smirnov tests.

The SIs obtained for the standard deviation of soil moisture using results from the set with 60 samples are presented in Table 3.7.

Table 3.7: Sensitivity Indices between Standard Deviation and Each of the Input Parameters Based on 60 Samples

Input Parameter	SPEA	Smirnov	SRRC	PRCC
s_w	0.430	0.463	-0.118	-0.01
LAI	**0.724**	**0.5926**	**0.554**	**0.205**
K_s	-0.325	0.407	-0.068	-0.071
CN_2	**-0.714**	**0.6296**	-0.147	-0.056
s_h	0.4159	0.537	-0.146	-0.017
s^*	0.4335	0.333	**0.507**	**0.113**

The bold numbers are the highest absolute values of the SIs for each of the techniques. From Table 3.7, it can be seen that the SPEA, SRRC and the Smirnov test values are quite similar to those in Table 3.6. However, for PRCC, there is an improvement in that PRCC now matches the ranking of SRRC. The most dominant input parameter is LAI, as shown by all four techniques. CN_2 is the second dominant parameter from SPEA and the Smirnov test, while the second dominating parameter is s^* from SRRC and PRCC. However, it should be noted that, the SRRC and PRCC are rank based coefficients and should not be compared directly with SPEA and Smirnov test results.

3.3.4 Analysis of the Skewness of Soil Moisture Distribution

Skewness is a measure of the degree of asymmetry of a distribution around its mean. Positive skewness characterizes a distribution with an asymmetric tail extending toward larger values. This in our case translates to soil moisture values in excess of the average growing season value. Negative skewness indicates a distribution with an asymmetric tail extending toward lower values, meaning that soil moisture was for the most part below the average growing season mark. The determination of the skewness of soil moisture is therefore an interesting study in itself, as it will be able to show whether or not, for the most of the growing season, soil moisture values are higher or lower than the average. The average soil moisture obtained from the 60 continuous simulations of the simplified water balance model is 0.291 cm^3/cm^3, with an average skewness of 0.191. For the 60 different soil type and land-use combinations used in the GSA, it was found that only 15 of the random sets resulted in negative skewness. This indicates that, under Toronto's climate, soil moisture in general has a greater chance of exceeding the average growing season value. The SIs obtained for skewness using the set with of 50 samples are presented in Table 3.8.

Table 3.8: Sensitivity Indices between Skewness and Each of the Input Parameters Based on 50 Samples

Parameters	SPEA	Smirnov	SRRC	PRCC
s_w	-0.611	**0.889**	**0.229**	0.026
LAI	**-0.652**	**0.889**	-0.172	-0.083
K_s	0.153	0.4	-0.206	**-0.286**
CN_2	**0.634**	**0.933**	**0.331**	**-0.16**
s_h	**-0.661**	**0.911**	**-0.854**	**-0.141**
s^*	-0.501	0.8	-0.059	0.018

The results in Table 3.8 show that the four techniques do not perfectly agree with each other when it comes to skewness. s_h and CN_2 were found to be one of the influential parameters. LAI also proves to be influential on skewness. Thus, land-use patterns control, to some extent, the skewness of the soil moisture distribution. SPEA shows an inverse relationship between skewness and the soil moisture control criteria. This means that the higher the value of s_w, s_h, and s^* the lower the values of skewness. The SIs obtained for skewness using the set with 60 samples are presented in Table 3.9.

Table 3.9: Sensitivity Indices between Skewness and Each of the Input Parameters Based on 60 Samples

Parameters	SPEA	Smirnov	SRRC	PRCC
s_w	**-0.638**	**0.907**	0.23	0.023
LAI	**-0.646**	**0.907**	-0.089	0.041
K_s	0.204	0.444	**-0.262**	**-0.339**
CN_2	0.623	**0.944**	**0.387**	**0.178**
s_h	**-0.684**	**0.926**	**-0.986**	**-0.141**
s^*	-0.517	0.796	0.041	0.113

Results in Table 3.9 show a reasonably good match with those in Table 3.8. s_h and CN_2 are still the two most influential parameters.

The relative stability of the SIs depends upon the sample size. When increasing the sample size, the non-parametric indices (SPEA, PRCC, SRRC and the Smirnov test) tend to converge to their lowest asymptotes (Saltelli et al. 2000). This study demonstrates how a minimum sample of 50 sets is required. This is confirmed by the fact that the results from the sample of 60 are similar to the results from the sample of 50. The SPEA and Smirnov test values close to 1.0 in the case of average soil moisture indicate that a sample size of approximately 50-60 is sufficient for average soil moisture. This is not the case for the SRRC and PRCC techniques, as the majority of their SIs are much smaller than 1.0, suggesting that a larger sample size was required for convergence of these techniques. A larger sample size may be needed for the standard deviation and skewness of soil moisture if SRRC and PRCC are to be used as well. However, consistent results among at least two types of SIs suggest that the sample size used in this study is large enough. Conclusions are therefore drawn based on consistent results of SPEA and Smirnov test.

As indicated by the SIs for standard deviation of soil moisture, SR is the dominant process on the variation of soil moisture. The average soil moisture level is more dependent on the balance between total precipitation, ET and leakage losses; SR does not play a major role in this balance because of its small magnitude. For the standard deviation of soil moisture, the role of SR becomes more important because it affects how high the soil moisture level can go during a rainfall event. The difference between the soil moisture levels during rainfall events and dry periods affect the standard deviation of soil moisture the most; while the soil moisture levels during dry periods affects its average value to a greater degree simply because dry periods last much longer on average than the durations of rainfall events. Clearly skewness is significantly affected by both SR and ET.

3.4 Summary and Conclusions

Dramatic increase in urban land-use has resulted in loss of forests, croplands and wetlands. These land-use and land-cover changes have not only drastically altered the land surface characteristics, but also soil moisture availability to on-site or adjacent vegetation. Mathematical modeling provides a viable means of examining the long-term soil moisture dynamics at a particular site. The leading deterministic models that directly model soil moisture or have strong soil moisture components do not necessarily focus on the ability of the vegetation to control ET by closing their stomata when under stress. Modeling of this phenomenon is necessary for urban grasslands where grass may intentionally be left under stress for water conservation purposes. In the Nishat et al. (2007) model, both AET and leakage losses are modelled as soil moisture dependent, while incorporating an ecohydrological perspective. This AET calculation process has not previously been applied at a daily time scale or included in any of the more detailed deterministic models for simulating soil moisture. This study was therefore also performed to better understand the behaviour of this improved soil moisture model.

Based on the consistent SPEA and Smirnov test-based SIs obtained through a series of GSA, the parameters representing soil texture (s^*, s_w, and s_h) are the most influential inputs on average soil moisture, whereas parameters representing land-use (LAI and CN_2) are slightly more influential input parameters on the degree of variation of soil moisture as represented by its standard deviation. The skewness of the soil moisture frequency distribution was found to be positive for most of the simulation runs. Positive skewness means that, for the most part of the growing season, there is a higher likelihood of having soil moisture values (under the Toronto climate conditions and a variety of soil and land-use scenarios) greater than the average. Unlike average soil moisture and the standard deviation, where either soil texture or land-use parameters are most influential, both land-use parameters (LAI and CN_2) and soil texture parameters (s_h and s_w) exert significant influence on skewness results.

By determining the parameters that influence the output characteristics the most, GSA gives insight into the processes that are most dominant. The input parameters affect the magnitude of the related processes. Therefore, greater SIs mean that the process affected by the corresponding parameters is more dominant on the water balance. Since the parameters representative of soil moisture control criteria were found to be most influential on average soil moisture, and because those three parameters affect ET, it can be concluded that ET has a strong influence on long-term average soil moisture. This conclusion is also supported by the analysis of the average total and maximum growing season ET, SR and leakage values, where it was found that for the climate under investigation, ET is much more dominant than SR and leakage. Hence, in order to better understand the average condition and the variation of soil moisture, much attention is required to model the process of ET and SR respectively.

For the first time, this quantitative study sheds light on the relative importance of input parameters for different soil moisture modelling purposes. The results can be used as a guidance to set priorities in future data collection and model calibration so that the most accurate results can be obtained under a given budget. For example, if average soil moisture is the only concern, then more attention should be paid to the modelling of the ET process. If variation of soil moisture is of significant concern, then finer time scales may be needed in order to model SR more accurately. Of course, findings reported herein are only valid for the Toronto (or southern Ontario) climate. Similar studies may be conducted for other regions.

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Chapter 4

Climate Change and Urban Grass Land Soil Moisture Conditions in South-western Ontario, Canada

Shazia Nishat, Yiping Guo and Brian W. Baetz

Abstract

Using the past 45 years of climate data in south-western Ontario, Canada and a deterministic continuous simulation model, this study investigates the long-term variability in rain-fed soil moisture in urban areas as influenced by climate change. Statistical analyses of four variables, i.e., soil moisture, precipitation, temperature and evapotranspiration were carried out. As found from other studies for other locations, these analyses confirm increasing temperatures and average growing season precipitation in south-western Ontario. Results show that both overall soil moisture and evapotranspiration have increased throughout the 45-year period. The probability/frequency distributions of soil moisture were obtained and the analysis shows an increasing average growing season soil moisture availability from the 1960's to the 1990's. The direct influence of precipitation and temperature on soil moisture and evapotranspiration were examined, revealing a stronger relationship of soil moisture and evapotranspiration with precipitation rather than temperature. Overall increasing average growing season soil moistures have likely resulted from overall increasing rainfall during the growing seasons in south-western Ontario.

Keywords: Temperature, Precipitation, Evapotranspiration, Continuous Simulation, Frequency Distributions

4.1. Introduction

Studies have successfully shown that during the latter part of the 20th century an increase in green house gas concentrations has resulted in not only increased temperatures (Chen, 2007; Dang et al., 2007; Vinnikov and Grody, 2003; Easterling et al., 2000; Whitfield and Cannon, 2000; Mavromatis and Jones, 1999) but also higher annual precipitations (Groisman et al., 2005; Changnon and Westcott, 2002; Easterling et al., 1999; Kunkel et al., 1999; Angel and Huff, 1997). Changes in temperature characteristics have been identified as higher minimum temperatures more than higher maximum temperatures (Hamlet et al., 2007; Wilby et al., 2002; Easterling et al., 2000; Zhang et al., 2000) and also higher average winter temperatures (Trenberth, 1999; Lewis, 1989). As the temperature increases, the moisture holding ability of the near-surface atmosphere also increases, resulting in the possibility of higher magnitude rainfall events (Trenberth, 1999). For regions of Canada, it was established that annual precipitation has increased during the latter part of the 20th century (Wilby et al., 2002; Easterling et al., 2000; Stone et al., 2000; Zhang et al., 2000). According to Trenberth (1999), there is firm evidence that atmospheric moisture has increased. Studies have shown that there are higher heavy ($\geq$50.8mm/day) rainfall events (Groisman et al., 2005; Kunkel et al., 2003; Changnon and Westcott, 2002; Easterling et al., 2000; Karl et al., 1995) and that there is a decline in moderate (12.7-25.4 mm/day) and light (2.54-12.7 mm/day) precipitation events and also an increase in the frequency of occurrence of dry days (Trenberth, 1999; Karl et al., 1995; Smit, 1989). The detailed characteristics of this increase in heavy rainfall events depend on geographic locations. For example, in the UK, heavy precipitation events have increased in winter and decreased in summer (Fowler and Kilsby, 2003; Osborn et al., 2000; Mitchell and Warrilow, 1987). In contrast, increasing trends of heavy precipitation in the US (except the West Coast) and Southern and Eastern Canada for springs and summers were observed (Stone et al., 2000; Kunkel et al., 1999; Groisman and Easterling, 1994; Lewis, 1989).

Nemec and Schaake (1982) predicted that the most prominent effect of global warming is that snowmelt will increase and sea levels (due to glacial melt) will rise. The other concerns include decreasing availability of plant water (Varanou et al., 2002; Mavromatis and

Jones, 1999; Zweirs and Kharin, 1997; Smit, 1989), increase in non-point source pollution (Chen et al., 2007; Tong et al., 2007), and anomalies in vegetal patterns (Dang et al., 2007, Manobavan et al., 2003; Lewis, 1989; Smit, 1989). Knowledge of the impact of climate change on vegetation is limited (Manobavan et al., 2003; Smit, 1989). In their study, Dang et al. (2007) investigated the influence of global warming on seven vegetal land-use groups ranging from tropical forests to bare soils. They have shown that the most significant influence was during 1950-2004. Porporato et al. (2004) examined the impact of rainfall amounts and frequency on grasslands in arid regions. Their study showed that decreasing total rainfall amounts and frequency have a great impact on leaf carbon assimilation. Smit (1989) predicted that climate change will affect forestry more than agriculture due to the longer growing cycle of trees allowing less adaptability. Other studies have predicted that at the current increasing rate, grasslands will replace the rainforests (Dang et al., 2007). It has been predicted that in south-western Ontario and nearby US states, there is a possibility of reduced yields of many crops due to the expected deficits of available soil moisture coupled with temperature increases (Smit, 1989). Mavromatis and Jones (1999) used an atmosphere-ocean General Circulation Model (GCM) to simulate future temperature and precipitation and predicted decreasing yields in 2011-2099 due to decreasing soil moistures and increasing evapotranspiration (ET), as winter temperatures will continue to increase. It is therefore paramount to study the response of soil moisture to global climate change, especially in the agricultural sector.

As mentioned in various studies, long-term soil moisture data are not readily available (Nishat et al., 2007; Guo and Dirmeyer, 2006; Hirabayashi et al., 2005; Maurer et al. 2002; Entin et al., 1999; Wang and Kumar, 1998). Only in recent years a few soil moisture databases have been established. Soil moisture data sets are now available for the Former Soviet Union (FSU), Illinois, USA and China (Guo et al., 2006; Srinivasan et al., 2000). Robock et al. (2000) have created a Global Soil Moisture Data Bank (GSMDB) with soil moisture data from over 600 stations across India, China, the US and Mongolia. The GSMDB was identified as the most complete collection of long term global soil moisture data by Guo and Dirmeyer (2006). However, not all GSMDB stations have complete data coverage for the time span of interest (Guo et al., 2006). Another long-term soil moisture data set (1950-2000) is that of Maurer et al. (2002). Mahmood and Hubbard (2003, 2004) described the preparation of a data set (from 1982) for soils and soil moisture from 150-200 sites. A long-term (since 1957) data set from 35 stations across the Canadian Prairies is available from Saskatchewan and southern Manitoba (Wittrock and Ripley, 1999). Unfortunately, these data sets are limited to a few locations and significant differences exist between locations. Therefore, simulation models are still the best tool available to examine soil moisture conditions for many locations of interest. The dependency of soil moisture on climate conditions has always been the center of many investigations and even more so now with our changing climate.

4.2. The Climate and Soil Moisture

The availability of soil moisture depends on the climate as precipitation is the principal source of soil moisture and surface temperature, relative humidity, wind speed and solar radiation etc. influence the loss of soil moisture via ET. Increasing temperatures will result in an increase in ET (Hamlet et al., 2007; Smit, 1989; Nemec and Schaake, 1982). ET is also closely related to precipitation (Mahmood and Hubbard, 2003; Liang et al., 1994) and soil moisture (Hamlet et al., 2007; Srinivasan et al., 2000). China and North America have witnessed increasing magnitudes in relative humidity due to climate change (Easterling et al., 1999). Changes in temperatures have also resulted in changes in wind speeds (Zwiers and Kharin, 1997; Lewis, 1989). Many have projected that increases in precipitation is small compared to the increase in ET due to increasing temperatures (Lewis, 1989). For example, in the warmer parts of the world soil moisture availability has decreased even with increasing precipitation (Easterling et al., 2000; Zwiers and Kharin, 1997). In parts of Asia, Africa, and North America, there has been a decrease in soil moisture due to increasing temperatures (Easterling et al., 2000). Whereas Sridhar et al. (2006) found from their six year study that annual ET never exceeds annual precipitation. Interestingly, higher average winter temperatures have resulted in more precipitation than snowfall (Lewis, 1989), allowing an increase in Surface Runoff (Hamlet et al., 2007) and soil moisture (Trenberth, 1999). Surface Runoff (SR) has increased in various parts of the world due to an increase in precipitation frequencies (Hirabayashi et al., 2005; Angel and Huff, 1997). Other studies have found an increase in summer growing season soil moisture due to increasing summer rainfall (Hirabayashi et al., 2005; Mahmood and Hubbard, 2004; Wittrock and Ripley, 1999).

The strong relation between climate characteristics and long-term soil moisture has been demonstrated in many studies. Guo et al. (2006) showed a strong influence of radiation on soil moisture. Research illustrated that soil moisture availability is temperature dominated (Zhang et al., 1999; Wang and Kumar, 1998). Time series studies of precipitation and soil moisture have demonstrated a strong relationship between the two (Guo et al., 2006; Mahmood and Hubbard, 2003; Srinivasan et al., 2000; Zhang et al., 1999; Mitchell and Warrilow, 1987). Varanou et al. (2002) used GCM to simulate future climate characteristics and predicted, using the SWAT model, decreasing soil moisture and SR due to decreasing summer precipitation in Central Greece in the year 2050. Robock et al. (2000) analyzed soil moisture data of more than 15 years from over 600 stations located all over the world under grasslands and agricultural land uses. They concluded that soil moisture availability has increased as, contrary to popular belief, increasing precipitation compensates for increasing ET due to increasing temperatures. In their study of 100 years of soil moisture from various parts of the globe, Hirabayashi et al. (2005) support Robock et al. (2000) in that soil moisture levels have gone up.

Many studies have shown that soil moisture in return is an excellent predictor of surface temperature and precipitation (Guo et al, 2006; Robock et al., 2000; Wang and Kumar, 1998). Soil moisture is an important component in the climate system (Douville and Chauvin, 2000; Mintz and Walker, 1993) as it influences surface heat fluxes, surface temperatures (Guo and Dirmeyer, 2006; Srinivasan et al., 2000; Robock et al., 1998; Huang et al., 1996) and precipitation (Guo and Dirmeyer, 2006; Hirabayashi et al., 2003; Srinivasan et al., 2000). GCMs widely used in predicting future temperature and precipitation patterns require information of soil moisture for accurate simulation (Guo and Dirmeyer, 2006; Hirabayashi et al., 2003; Douville and Chauvin, 2000). The purpose of this study is to identify the temporal patterns of growing season soil moisture in the urban areas of south-western

Ontario, Canada, and to investigate the influence of climate on long-term soil moisture characteristics under urban land-use.

4.3. Materials and Methods

4.3.1. The Model

The water balance model developed by Nishat et al. (2007) was used to simulate soil moisture in the root zone throughout the growing season (May to October). The soil water balance model, schematically represented by Equation (4.1), is one-dimensional, taking into account only the hydrological processes that operate in the vertical direction. The model represents the soil domain as a single homogeneous layer. The model simulates soil moisture at a point, and the output of the model can be viewed as area/site-averaged values as the inputs are all area/site-averaged values. The model was validated and its performance was evaluated with observed field data (Nishat et al., 2007).

$$\mathrm{nZr}\frac{ds(t)}{dt} = P(t) - SR(t) - ET(s) - L(s) \tag{4.1}$$

where, s = volumetric soil moisture content in cm^3/cm^3;

Zr = depth within the soil root zone in cm;

n = porosity;

P = precipitation in cm/day;

ET = evapotranspiration in cm/day;

SR = surface runoff in cm/day;

L = leakage in cm/day; and

t = time index with an interval length of one day.

This continuous simulation model incorporates the well-established models of each of the individual processes that take part in the water-balance. SR is estimated using the US National Resources Conservation Services (NRCS) curve number technique. This SR component was modified from that of Nishat et al. (2007) to better represent urban land-use.

Very heavy precipitation events were given special attention. Very heavy precipitation events will likely result in even the pervious areas to function as impervious. The soil may become fully saturated allowing more SR to take place. As the NRCS curve number technique models SR based on pre-existing soil conditions, i.e., dry conditions, average conditions and wet conditions, it was taken into consideration that high precipitation days should fall into the wet condition criteria. It is assumed that precipitation events greater than 2 inches (5 cm) fall into the very heavy precipitation category. Potential Evapotranspiration (PET) is estimated using Penman's Method. Actual Evapotranspiration (AET) is then modelled from PET as a function of soil moisture and is further adjusted to represent various plant growth stages. Plant growth stages are represented by Leaf Area Index (LAI). Leakage is modelled as vertical percolation and as a function of soil moisture. The AET and leakage calculation procedures included in this model emphasize the soil moisture regime's control over these two processes, and is different from the way other deterministic models represent these two processes within the water balance. Equation (4.1) is solved numerically by using the backward finite difference method. Detailed description of the continuous simulation model is provided in Nishat et al. (2007).

4.3.2. The Study Area and Data

The study area is not an actual site but hypothetical urban lands adjacent to the Toronto Pearson International Airport (43°40′12″N, 76°36′W), in Toronto, Ontario, Canada. An urban area is comprised of both pervious and impervious parts. Pervious areas may be covered by natural vegetation or open soils and impervious areas are covered by roads and buildings. Two scenarios were examined in this study. For the first scenario, it was assumed that a piece of land represented by the point scale model is completely covered with grass. This scenario is representative of large open spaces in urban areas. The second scenario represents a composite land use with the existence of both grass cover (pervious) and impervious areas. The second scenario is representative of average residential neighbourhoods where impervious and pervious areas are intertwined. In this study, scenario 2 considers a specific case with 70% vegetation and 30% impervious area. The processes that are directly influenced by this composite land-use are SR, ET, and leakage. For SR a CN_2 that represents 70% vegetation and 30% impervious area is used to represent this composite land-use. To model ET and leakage properly over composite areas, the ET and leakage module of the point scale model were modified. PET was still determined using Penman's method. PET was then partitioned between Transpiration and Evaporation using LAI. For scenario 2, LAI was reduced by 30% from that of 100% grass cover. Similarly, leakage is first modeled the same as in scenario 1 and then reduced by 30% as leakage will not occur over the impervious portion.

The methodology used here simplifies the hydrological cycle over urban areas. However, the major influential factors are considered because the main focus is to understand better the long-term fluctuations of soil moisture. By modeling the two scenarios, it is hoped that average conditions in urban areas are well represented. The study period is from 1960 to 2004. Climate data including precipitation, temperature, solar radiation, relative humidity, and wind speed were collected from the Ontario Climate Centre (station No. 6158733, Toronto Pearson Airport). The original data are hourly values, daily totals or averages were calculated from the hourly values. There were few missing data, and the missing data were replaced with data from an adjacent weather station (St. No. 6158350). The growing season at this location was identified as from May to October. The climate here is humid continental with warm humid summers and fairly low diurnal temperatures. Average annual precipitation is 83 cm. Summer is the wettest season, with the bulk of rainfall falling during thunderstorms. Soil characteristics were available from Hoffman and Richards (1953). Coarse textured sandy loam soils dominate the top 30-40 cm, followed by medium textured loam soils, with the last 30-40 cm of fine textured clay loam soils followed by clay soils. Soil moisture is simulated for rooting depths of 30cm, which is typical for grass lands. At this depth the soil type is sandy loam. The input data used for the model are summarized in Table 4.1.

Table 4.1: Soil, Plant and Climate Parameters Used as Input for the Continuous Simulation of Growing Season Soil Moisture under Urban Land-use

Parameters	Input Values	Parameters	Input Values
Λ	5-17%	n	0.434
K_s	86.4 cm/day	s^*	0.55
b	4.9	s_w	0.26
$\bar{\psi}_s$	21.8 cm	s_h	0.11

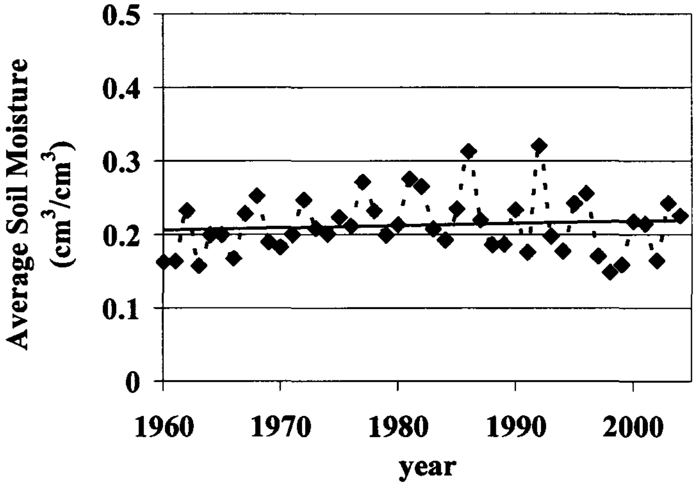
In Table 4.1, n represents porosity and Λ rainfall interception. K_s is the saturated hydraulic conductivity required for calculating leakage. $\bar{\psi}_s$ and b are empirically determined parameters required for obtaining soil moisture control criteria at no water stress, s^*, permanent wilting point, s_w, and hygroscopic point, s_h. The values of s^*, s_w and s_h were calculated with the soil water potentials of $\psi_{s,s*} = -30$ kPa, $\psi_{s,sw} = -1500$ kPa, and $\psi_{s,sh} = -10^6$ kPa respectively. From the curve number tables of Chow et al. (1988) and Viessman and Lewis (2003), CN_2 was taken as 61 for scenario 1 and 72 for scenario 2. For scenario 2, this is the average of the CN_2 values for residential areas of $^1/_4$, $^1/_3$ and ½ acres. CN_2=72 was computed assuming that the runoff from the house and driveway is directed towards the street with a minimum of roof water directed to the lawn (Chow et al., 1988). This is often seen in practice although the current Ontario stormwater management policy encourages directing house and driveway runoff to lawns. Values of LAI needed to represent plant growth stages were varied between 0.2-0.9 m^2/m^2 throughout the growing season. The sources of these input data values and other data necessary to run the model that could not be shown here due to space limitations can be found in Nishat et al. (2007).

4.4. Results and Discussion

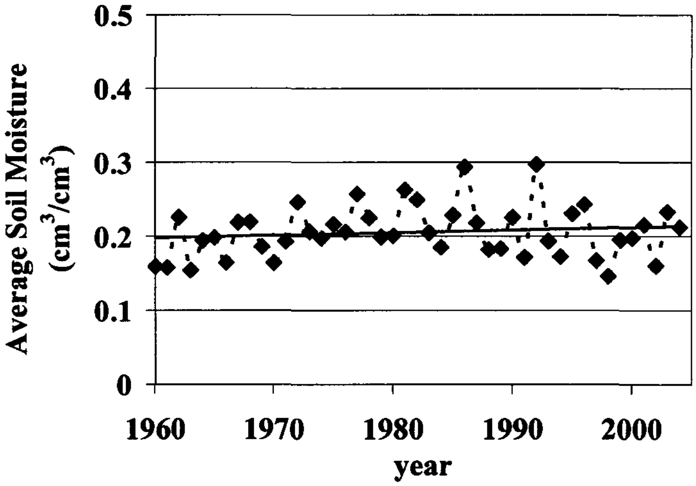
Driven by the required climate data input, the model was run for each individual growing season from 1960 to 2004 for the two scenarios. Daily SR, ET, leakage and soil moisture etc. were calculated for each year. In order to represent long-term soil moisture characteristics in a concise way, various statistical calculations were performed using the simulated time series. For example, taking the average of May 1st 1960, May 1st 1961, May 1st 1962, etc. will determine the typical May 1st characteristics for the 45 year time series.

4.4.1. Soil Moisture

From the simulated daily soil moisture for each growing season (1960-2004), the average soil moisture for each individual year was obtained. The graphical representation of the 45 year average growing season soil moisture time series as simulated by the continuous simulation model is presented in Figure 4.1.



(a) Scenario 1



(b) Scenario 2

Figure 4.1: Model-Simulated Average Growing Season Soil Moisture for 1960-2004

Simulation results from scenario 1 are most representative of large open spaces (e.g., parks, baseball fields etc.) where soil moisture is not affected by nearby roads and buildings. Whereas those from scenario 2 are most representative of average neighbourhoods or commercial districts where soil moisture is affected by both the soil(s) at the point and nearby impervious areas. The two sets of results can give us an idea of soil moisture behaviours in urban areas. Simulation of the two scenarios is necessary, given the point nature (i.e., only the vertical components of the water balance are considered) of the model. Inter-annual growing season soil moisture variability is evident from Figure 4.1. A linear regression line was fitted to the simulated time series. It is evident from this trend line that there has been a slight increase in overall growing season soil moisture for both scenarios, since 1960, despite the fluctuations from one year to the next. The Standard Deviations (SD) and the Coefficients of Variation (COV) of the daily soil moisture values for each growing season were calculated. The results are presented in Figure 4.2.

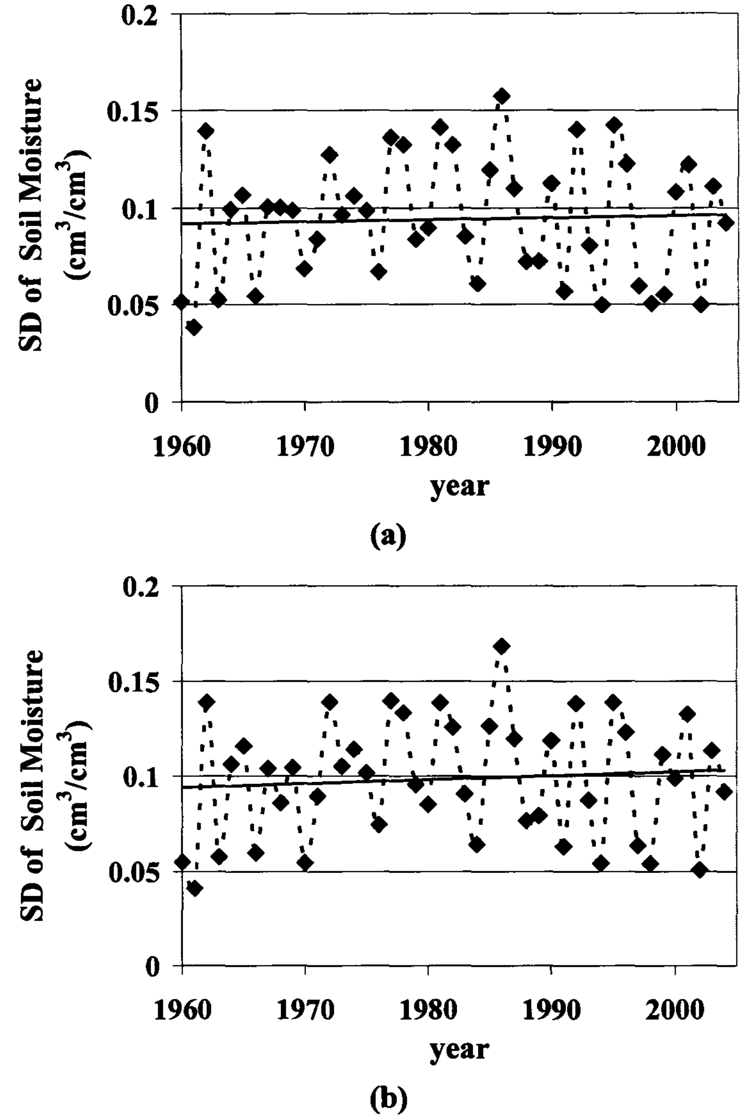
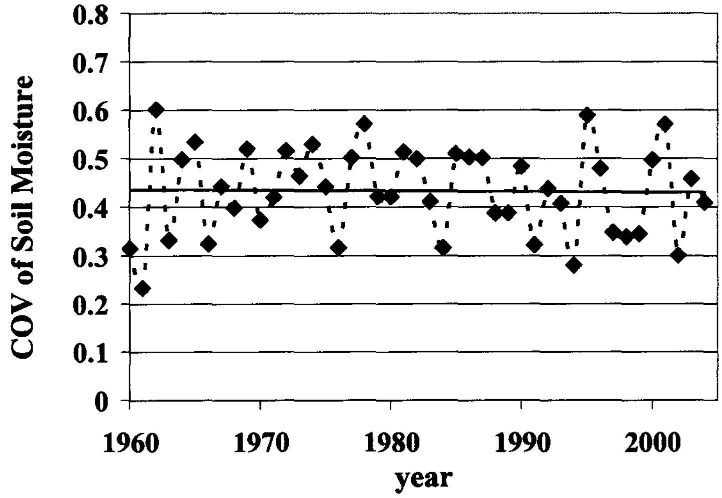
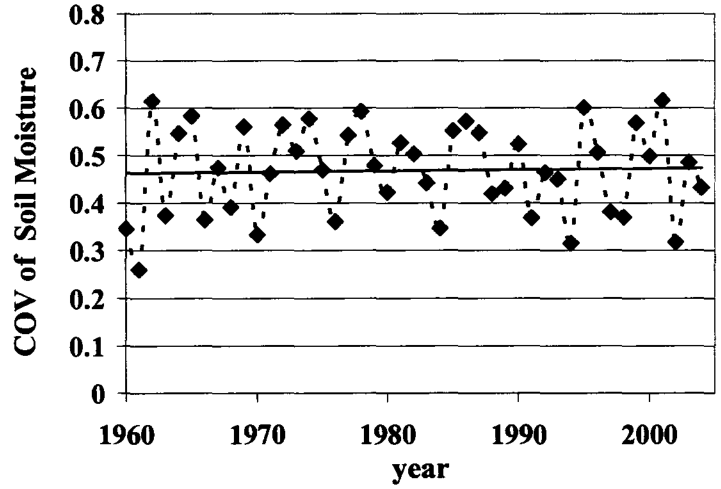


Figure 4.2: The Standard Deviations of the Simulated Growing Season Soil Moisture from 1960 to 2004 (a) Scenario 1 and (b) Scenario 2

From Figure 4.2 (a) and (b), we see that there has been a slight increase in the SD values from 1960 to 2004, which means that the day to day variation of soil moisture has steadily increased from the 1960's to 2004. The COV of the soil moisture time series were calculated for each individual growing season. These results are presented in Figure 4.3.



(a)

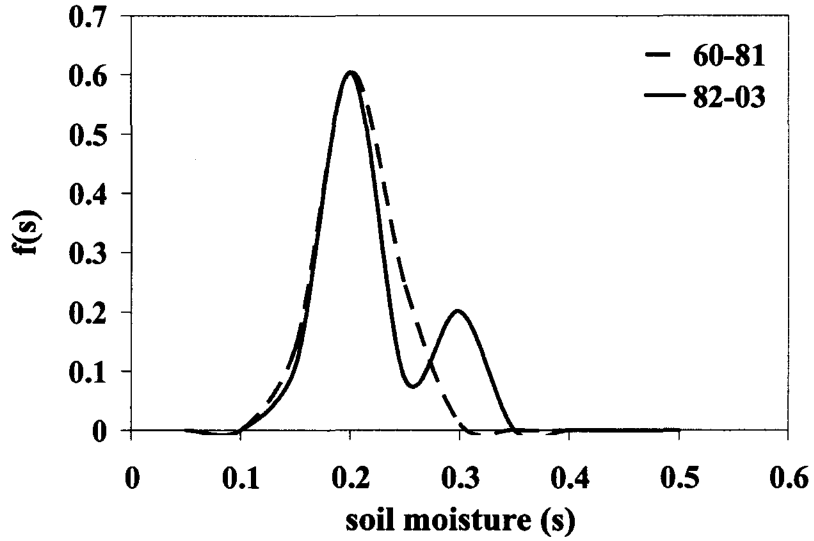


(b)

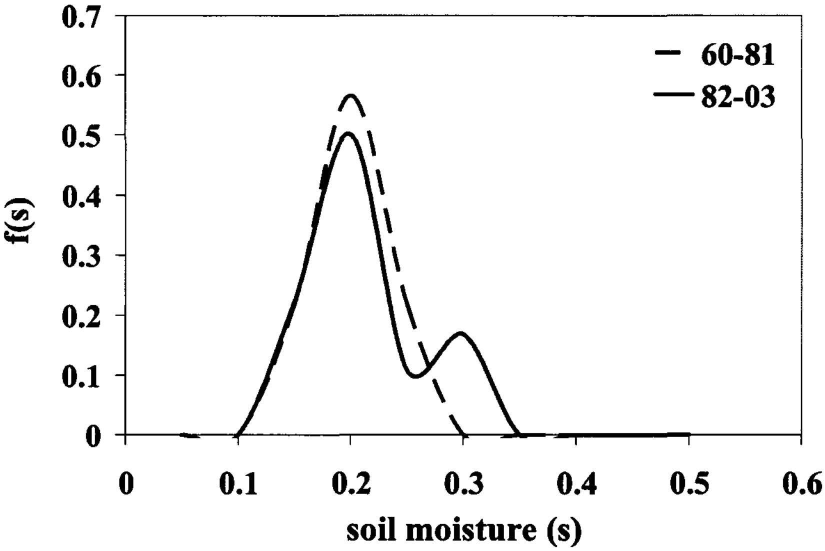
Figure 4.3: The Coefficients of Variation of the Simulated Growing Season Soil Moisture from 1960 to 2004 (a) Scenario 1 and (b) Scenario 2

Figure 4.3 (a) and (b) shows that the inter-annual COV vary widely (0.2-0.6) from one another and the linear regression line indicates that there is no significant increase or decrease from 1960 to 2004. The fact the COV neither increases nor decreases is a result of slightly increased average growing season soil moisture accompanied by increased standard deviation of daily soil moistures in each growing season. To better detect any possible changes in soil moisture, the simulated soil moisture time series was divided into to equal parts, 1960-1981 and 1982-2003 each consisting of 22 years. Given our interest in the degree of fluctuation of soil moisture due to climate change, the probability/frequency distributions (pdf) of soil moisture during the two 22 year periods were obtained. The pdfs are presented in Figures 4.4 (a) and (b).

The pdfs clearly indicate that there has been a shift to the right, indicating the more likelihood of occurrence of higher soil moistures. The 1960-1981 pdf is unimodal, indicating the dominance of soil moisture at 0.2 cm^3/cm^3. Whereas, the 1982-2003 pdf is bimodal, indicating the dominant peak at 0.2 cm^3/cm^3 and a second less dominant peak at 0.3 cm^3/cm^3. It is evident from Figure 4.4 that 0.2 cm^3/cm^3 is still the most common amount of soil moisture likely to exist throughout the growing season (May-October). However, in recent years there is an increased probability that soil moistures may attain a higher value of 0.3 cm^3/cm^3. There is a significant difference noticeable between Figures 4.4 (a) and (b). When 30% imperviousness is taken into consideration, i.e., Scenario 2, the possibility of the existence of higher soil moistures is less than that of complete grass cover, i.e., Scenario 1. This is because more water is lost through SR in scenario 2.



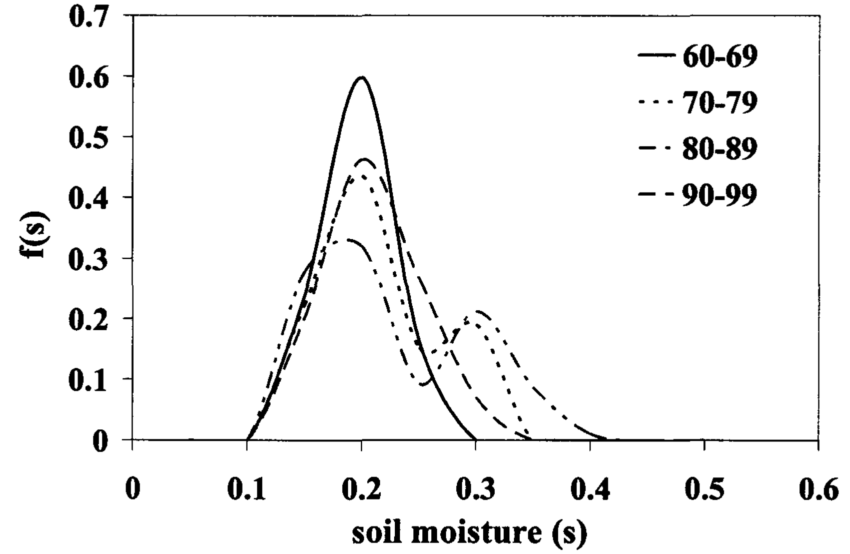
(a)



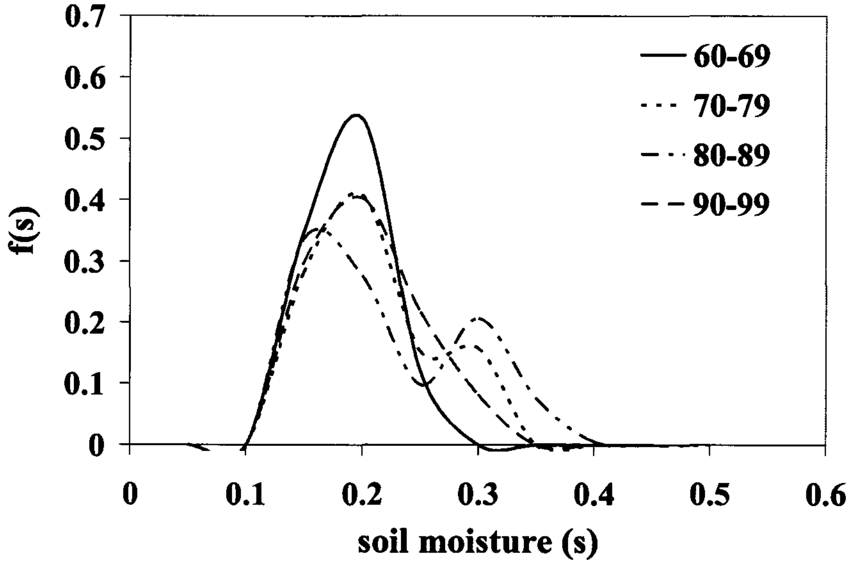
(b)

Figure 4.4: The Probability Density Functions of the Growing Season Soil Moisture for the Two Time Periods of 1960-1981 and 1982-2003 (a) Scenario 1 and (b) Scenario 2

Soil moisture characteristics per decade in response to global warming were investigated by splitting the entire 45 year time-series into individual decades. The four decades of the 60's, 70's, 80's and 90's were separated and analyzed. The probability/frequency distributions of the four decades of soil moisture values were obtained and are presented in Figures 4.5(a) and (b).



(a)



(b)

Figure 4.5: The Probability Density Functions of the Growing Season Soil Moisture for the Time Periods of 1960-1969, 1970-1979, 1980-1989 and 1990-1999 (a) Scenario 1 and (b) Scenario 2

The comparison clearly shows that there has been a shift to the right, again indicating the more likelihood of occurrence of higher soil moistures. The 1960-1969 pdf for both scenarios is unimodal, indicating the dominance of soil moisture at 0.2 cm^3/cm^3. The most significant difference between decades is that between the 60's and the 70's. The 1970-1979 pdf for scenario 1 is clearly bimodal, indicating the dominant peak at 0.2 cm^3/cm^3 and a second less dominant peak at 0.3 cm^3/cm^3. For scenario 2, the 1970-1979 pdf is similar to that of scenario 1 only that the higher soil moisture peak is less defined. The bimodal trend continues in the following decade of 1980-1989, having again two peaks at 0.2 and 0.3 cm^3/cm^3. The overall distribution of 1970-1979 and 1980-1989 pdfs are similar to each other however, the dominant peak in the 1980's pdf attains a smaller value than that in the 1970's and in the third decade for scenario 1, the falling limb is less steeper than that from the previous decade, indicating the higher probability of attaining higher moisture levels. The 1990-1999 pdf for both scenarios is also unimodal, again indicating the dominance of soil moisture at 0.2 cm^3/cm^3. However, the falling limb ends near the 0.35 cm^3/cm^3 mark. The pdfs also show that the probability of soil moisture amounts near 0.4 cm^3/cm^3 no longer exists in the 1990s. Figure 4.5 confirms that 0.2 cm^3/cm^3 is the most common amount of soil moisture likely to exist throughout the growing season and the increasing trend of soil moisture shown in the 1970s and 1980s does not seem to continue into the 1990s.

4.4.2. Precipitation

The precipitation characteristics of each individual growing season (1960-2004) were analyzed. The total growing season precipitation as well as the average daily growing season precipitation were calculated. The results are shown in Figures 4.6 (a) and (b).

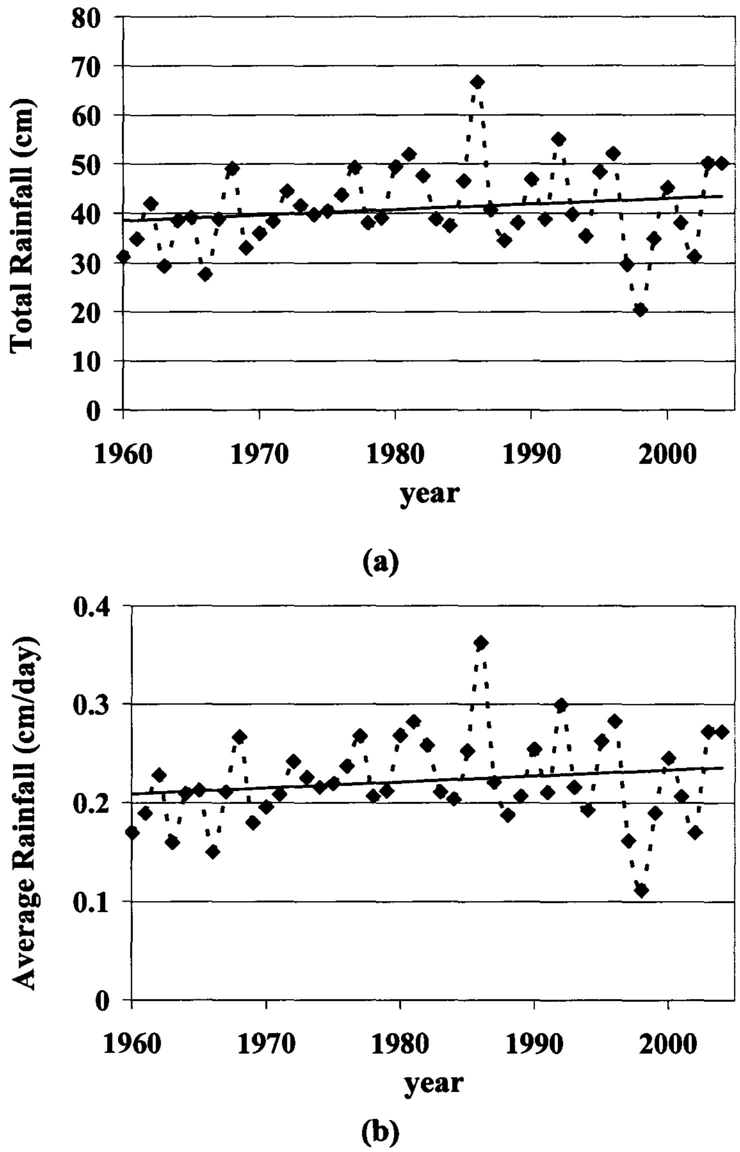


Figure 4.6: Growing Season Precipitation Characteristics from 1960 to 2004 (a) Total Precipitation and (b) Average Daily Precipitation

Figure 4.6 clearly shows the year to year fluctuations in growing season precipitation. As can be seen from Figure 4.6, linear regression analysis was carried out and it shows that there has been a steady increase in growing season precipitation from 1960 to 2004. Similar to the soil moisture analysis, the precipitation time series was divided into the two sets of 1960-1981 and 1982-2003. The means, the SD, and the COV of the two sets were calculated and are shown in Table 4.2.

Table 4.2: Some Statistical Characteristics of Precipitation during 1960-1981 and 1982-2003

Period	1960-1981	1982-2003	Increase
Average	0.22 cm/day	0.23 cm/day	4.6%
SD	0.140	0.126	-10%
COV	0.643	0.557	-13.4%

There has been a 4.6% increase in average growing season precipitation in the 22 year period of 1982-2003 from that of 1960-1981. What is interesting from Table 4.2 is that, even though precipitation amounts have increased, the variation of precipitation from the previous 22 year period to the next has decreased. As with the soil moisture time series, the precipitation time series was also split up into the four decades of the 60's, 70's, 80's and 90's and analyzed. The means, the SD, and the COV of the four decades were calculated and are presented in Table 4.3.

Table 4.3: Some Statistical Characteristics of Precipitation (cm/day) during the 1960's, 1970's, 1980's and 1990's

Period	1960-1969	1970-1979	1980-1989	1990-1999
Average	0.198	0.223	0.246	0.218
SD	0.189	0.197	0.225	0.174
COV	0.958	0.884	0.916	0.799

From the decadal analysis of precipitation it was found that, average growing season precipitation has increased 12.6% from the 1960's to the 1970's, and 10.3% from the 1970's to the 1980's. There has been a 12.8% decrease in average growing season precipitation from the 1980's to the 1990's. However, since the 1960's to the 1990's the average growing season precipitation has increased by 10%. There has been an increase in overall average growing season precipitation. The SD and the COV analyses show no obvious trend in daily growing season precipitation variations.

4.4.3. Temperature

The temperature characteristics of each individual growing season (1960-2004) were examined. The average daily growing season temperatures were calculated and are presented in Figure 4.7.

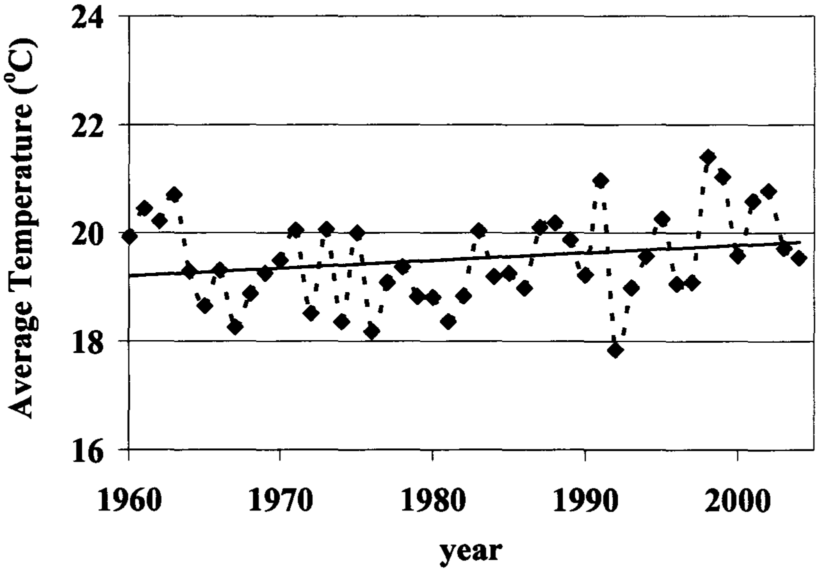


Figure 4.7: Average Growing Season Temperature Characteristics from 1960 to 2004

The inter-annual growing season temperature fluctuations are evident from Figure 4.7. Linear regression analysis was carried out and the result is shown in Figure 4.7. As can be seen from the figure, there is a definite long-term increase in Toronto temperatures. The analysis determines that there has been a steady 1°C increase in average growing season temperatures in the Toronto area from 1960 to 2004. The trend line analysis confirms global warming in south-western Ontario. The temperature time series was split into the two sets of 1960-1981 and 1982-2003 as well. The means, the SD, the maximums and the minimums of the two sets were calculated and are presented in Table 4.4.

Table 4.4: Some Statistical Characteristics of the 1960-1981 and 1982-2003 Temperature (°C)

Period	1960-1981	1982-2003	Increase
Average	19.63	20.03	2%
Standard Deviation	4.4	4.64	5.45%
Maximum	25.83	26.08	0.8%
Minimum	8.42	9.55	13.4%

There has been a 2% increase in average growing season temperatures in the 22 year period of 1982-2003 from that of 1960-1981. Unlike precipitation, the variation of temperature from the earlier 22 year period to the next has also increased. An analysis of the maximum and minimum growing season temperatures indicates that there has been only a 1.0% increase in maximum growing season temperatures compared to a 13% increase in minimum growing season temperatures. As with the soil moisture and precipitation time series, the temperature time series was also divided up into the four decades of the 60's, 70's, 80's and 90's and analyzed. The means, the SD, the maximums and the minimums of the four decades were calculated and are presented in Table 4.5.

Table 4.5: Statistical Characteristics of Temperature (°C) during the 1960's, 70's, 80's and 90's

Period	1960-1969	1970-1979	1980-1989	1990-1999
Average	19.85	19.65	19.64	20.05
Standard Deviation	4.39	4.56	4.88	4.59
Maximum	26.11	26.42	27.09	26.69
Minimum	8.075	7.513	8.943	9.655

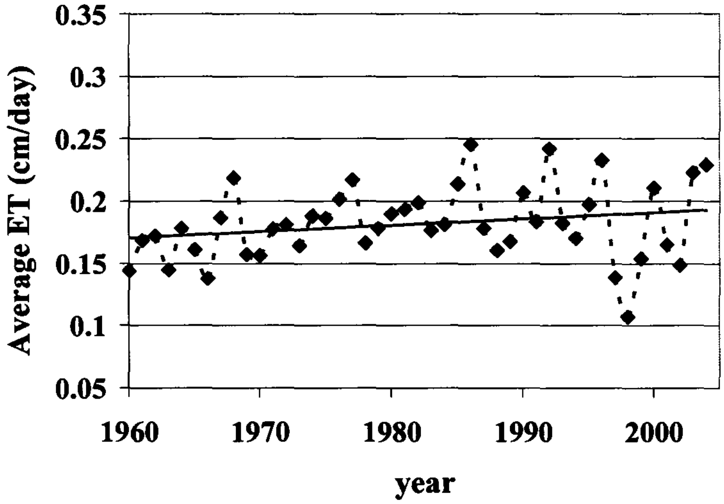
From the decadal analysis of temperature it was found that, average growing season temperature had actually decreased 1% from the 1960's to the 1970's. Average growing season temperatures remained at 19.65°C throughout the 1970's to the 1980's. However, there has been a 2.1% increase in average growing season temperature from the 1980's to the

1990's. The SD and the COV analyses indicate that daily growing season temperature variations have increased but only slightly. There has been a steady 1-2% increase in the average maximum growing season temperature, with the exception of the 1990's. There has been a steady 19-20% increase in the overall minimum growing season temperature, with the exception of the 1970's.

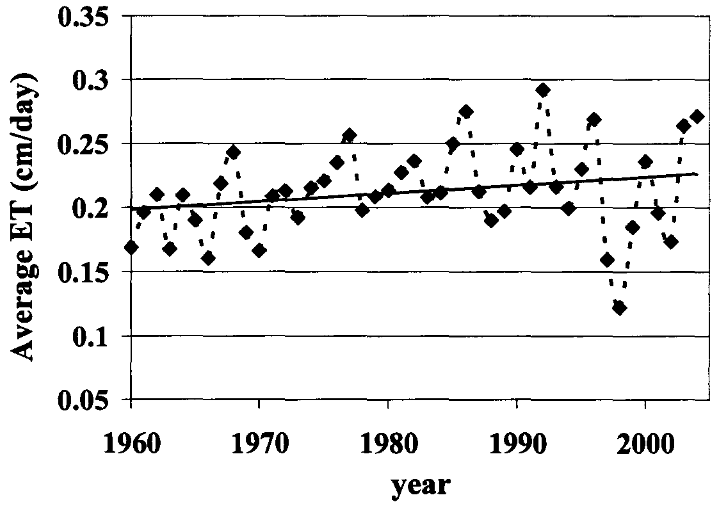
4.4.4. Evapotranspiration

To investigate the effect of global warming on ET and its relation with soil moisture, the ET characteristics of each individual growing season (1960-2004) were analyzed. From the simulated daily ET for each growing season the average ET for that individual year was obtained. The resulting annual ET time series of the Toronto area as simulated by the continuous simulation model is shown in Figure 4.8.

Linear regression analysis was carried out and it shows that even though there are significant inter-annual growing season ET variations, there has indeed been a steady increase from 1960 to 2004. The pattern of ET appears to be similar for both scenarios, however, with 30% imperviousness, scenario 2 has higher ET values. The SDs of the simulated daily ET values were also calculated for each individual growing season. The results are presented in Figure 4.9.



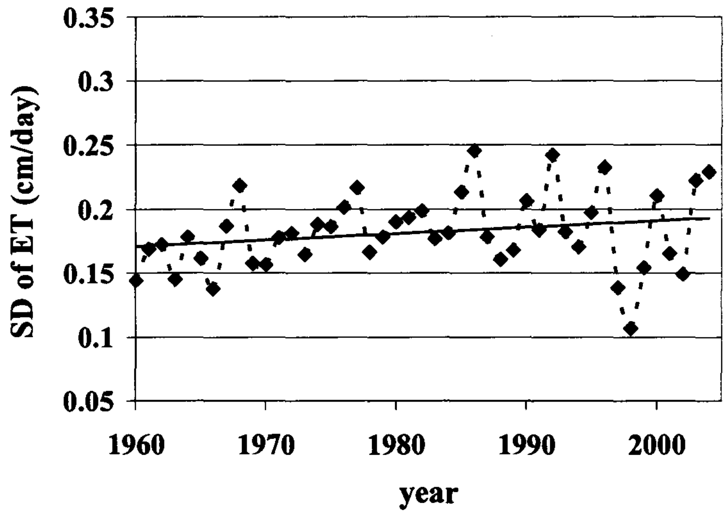
(a)



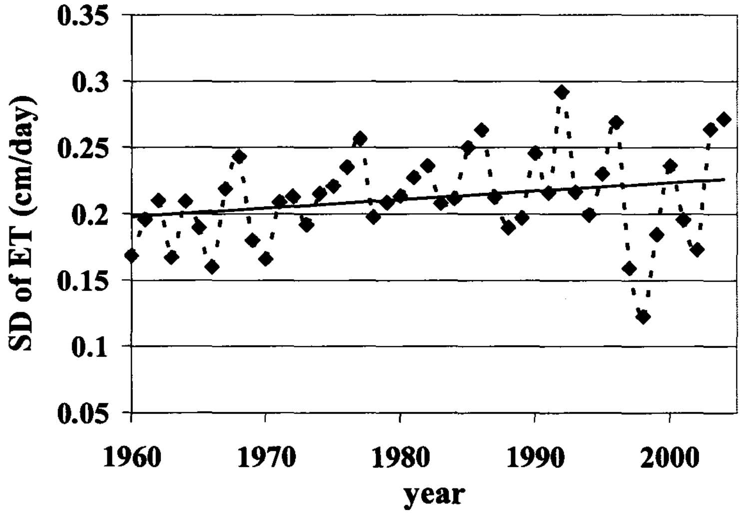
(b)

Figure 4.8: Model-Simulated Average Growing Season ET from 1960 to 2004

(a) Scenario 1 and (b) Scenario 2



(a)

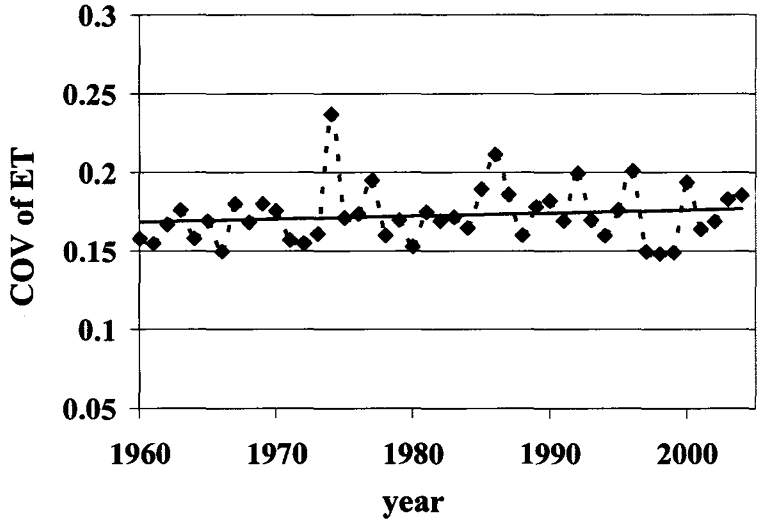


(b)

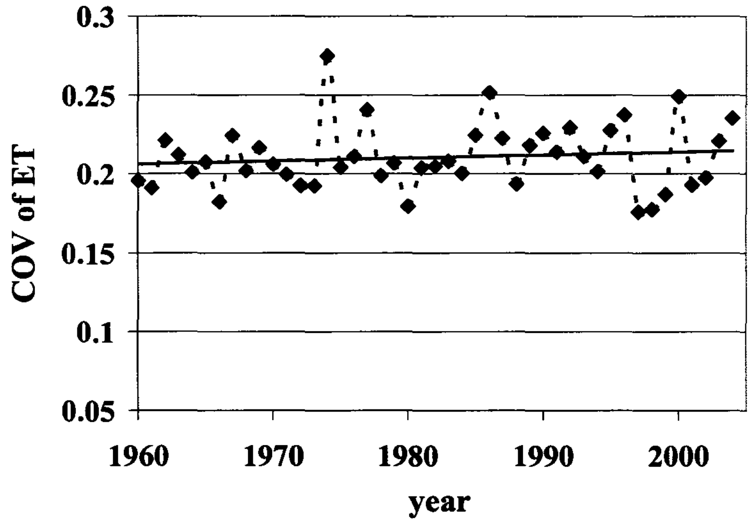
Figure 4.9: The Standard Deviations of the Simulated Growing Season Evapotranspiration from 1960 to 2004 (a) Scenario 1 and (b) Scenario 2

From the SD analysis we see that there has been a slight increase in the SD values from 1960 to 2004 which means that the day to day variation of ET has steadily increased from the 1960's to 2004. Again, the pattern of scenarios 1 and 2 appear to be similar, however, scenario 2 SD are higher than those of scenario 1. The range of SD of ET for scenario 1 falls within 0.1-0.25 cm/day while the range of SD of ET for scenario 2 falls within

0.1-0.3 cm/day. The COV of the simulated daily ET values have been calculated for each individual growing season. The results are presented in Figure 4.10.



(a)



(b)

Figure 4.10: The Coefficients of Variation of the Simulated Growing Season Evapotranspiration from 1960 to 2004 (a) Scenario 1 and (b) Scenario 2

From the COV analysis we see that there has been a slight increase in the COV values from 1960 to 2004 which means that the day to day variation of ET has steadily increased from the 1960's to 2004. Again, the pattern of scenarios 1 and 2 appear to be similar, however, the range of COV of ET for scenario 1 falls within 0.15-0.25 cm/day while the range of COV of ET for scenario 2 falls within 0.17-0.28 cm/day.

4.4.5. Influence of Precipitation and Temperature on Soil Moisture and ET

The main focus of this study is to investigate the long-term characteristics of soil moisture and to investigate the influence of climate change on soil moisture availability. The daily averages were used to calculate monthly values for month to month comparison of daily precipitation, temperature, soil moisture and ET. It was found that in May and June, averaging over the entire 45 years (1960-2004) for both scenarios 1 and 2, there is an increasing trend (not shown here due to space limitations) in all of the four parameters. Figure 4.11 shows the comparison for the month of July.

This comparison seems to reveal a direct relationship of soil moisture and ET with precipitation and an inverse relationship with temperature. This is because overall July precipitation, soil moisture and ET are deceasing from 1960 to 2004, whereas overall July temperatures are increasing. A similar relationship, i.e., decreasing soil moisture and ET with decreasing precipitation and increasing temperatures, was found for both scenarios for the month of August (not shown here to save space). However, for the following month of September there is an increasing trend (not shown here) in all the four parameters and for both scenarios, similar to May and June. For the month of October (1960-2004) it was found that overall daily soil moisture and ET have increased with increasing precipitation but overall daily temperatures have decreased, as can be seen in Figure 4.12.

It is interesting to see that in contrast to the finding that growing season temperatures have on average increased throughout the 45-year period, in the month of October there is a general trend of decreasing temperatures. This may be an indication that the temperatures for the colder months have decreased overall. However, as the autumn and winter months are beyond the scope of this paper, no such trend can be verified. Figure 4.12 confirms the inverse relationship between temperature and soil moisture.

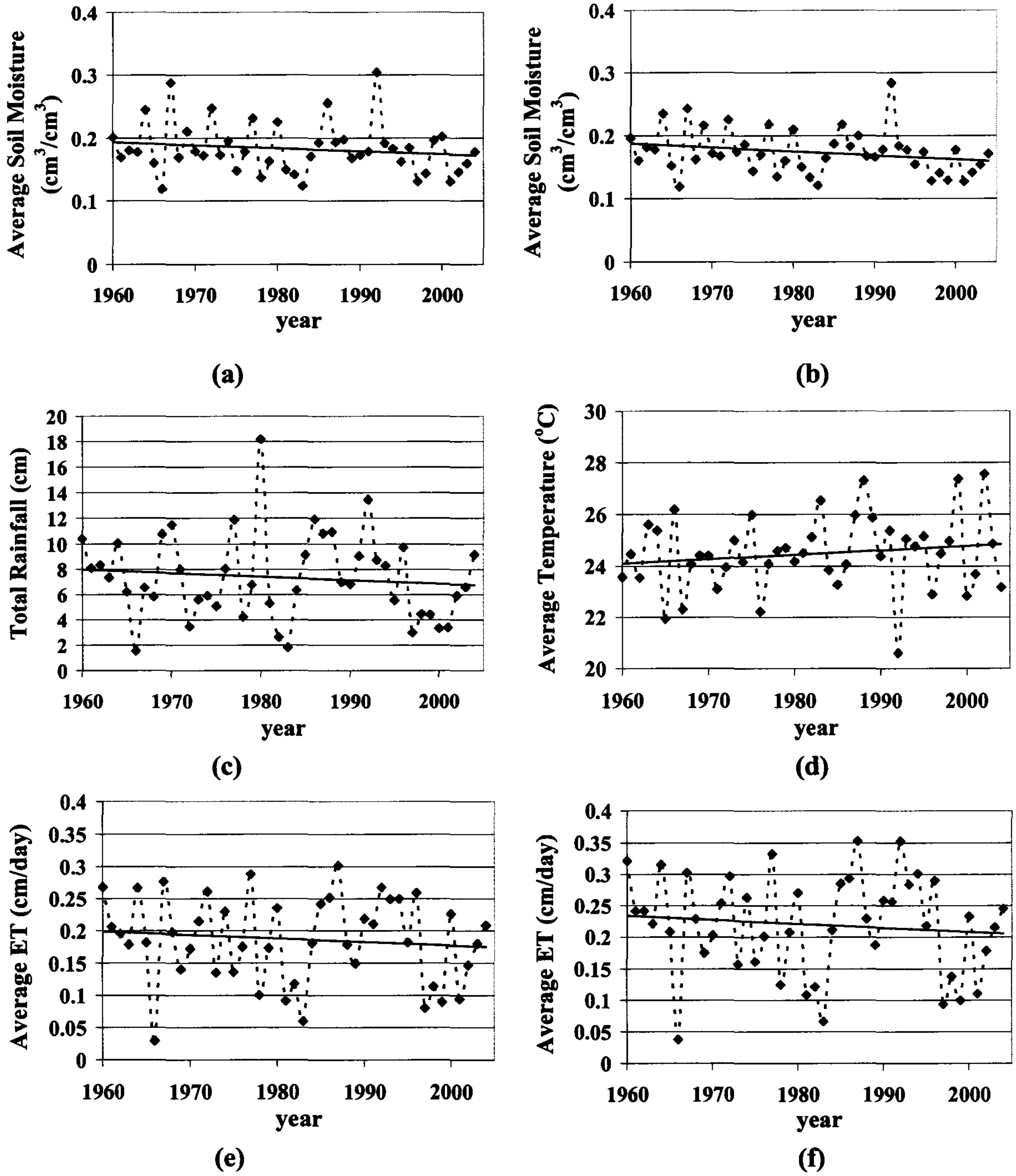


Figure 4.11: Daily July Characteristics of the 45-year period of (a) Soil Moisture of Scenario 1, (b) Soil Moisture of Scenario 2, (c) Total Precipitation, (d) Temperature, (e) ET of Scenario 1, and (f) ET of Scenario 2

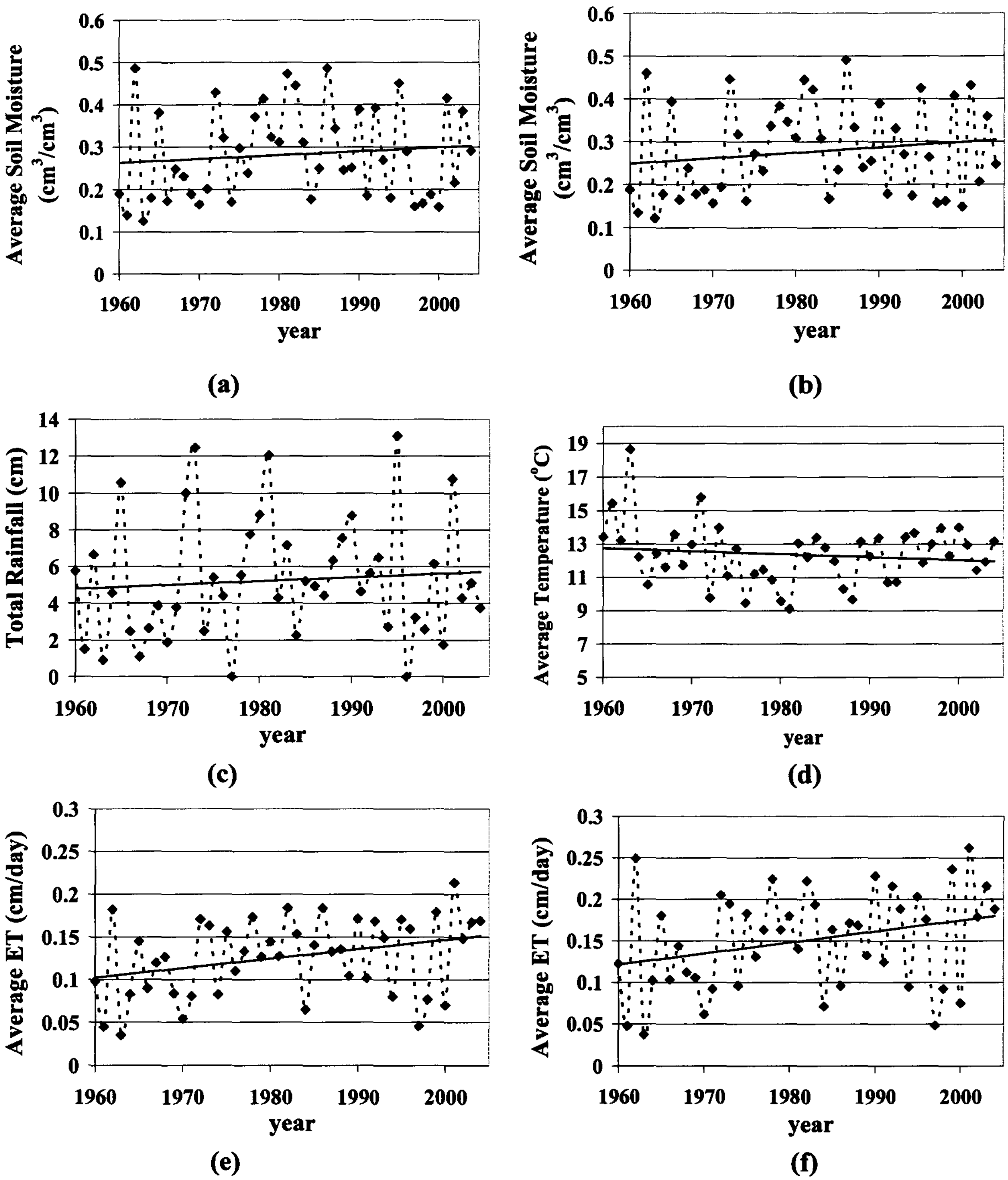


Figure 4.12: Daily October Characteristics of the 45 year period (a) Soil Moisture of Scenario 1, (b) Soil Moisture of Scenario 2, (c) Total Precipitation, (d) Temperature, (e) ET of Scenario 1, and (f) ET of Scenario 2

An analysis was carried out to find out if there is any direct link between the wettest and driest years with the hottest and coldest years, and the years registering the most and least soil moisture and ET. It was found that 1986 was the wettest year recording a total of 66.73 cm of precipitation, and 1998 was the driest year recording a total of 20.5 cm of precipitation during the growing season of May-October.

However, the highest average growing season soil moisture of 0.32 and 0.297 cm/day was found to exist in 1992 for scenarios 1 and 2 respectively. The hottest year was found to be 1998, recording average growing season temperatures of 21.4°C, which also is the year with the lowest average growing season soil moisture and ET for both scenarios 1 and 2. Similarly, the year with the highest average soil moisture, 1992, is the coolest growing season year having an average temperature of 17.8°C. A summary of this analysis has been tabulated in Table 4.6.

Table 4.6: A Summary of the Wettest, Driest, Coolest, and Hottest Growing Season Characteristics of the 45 year Period

Year	Aspect	Total Precipitation (cm)	Average Temperature (°C)	Average Scenario 1 Soil Moisture (cm/day)	Average Scenario 2 Soil Moisture (cm/day)	Average Scenario 1 ET (cm/day)	Average Scenario 2 ET (cm/day)
1986	Wettest	66.73	18.98	0.31	0.24	0.25	0.26
1992	Coolest	55.03	17.83	0.32	0.30	0.24	0.29
1998	Driest & Hottest	20.54	21.41	0.15	0.15	0.11	0.12

This analysis concludes that lowest soil moistures were found in the year with the highest temperatures and lowest precipitation. Whereas, the highest soil moistures were available in the year with the lowest temperatures and second highest precipitation. As for ET, the highest year coincides with the highest average growing season precipitation. The analysis found a strong relationship between precipitation and ET as contained in the results of the simplified continuous simulation model. The results presented in Table 4.6 demonstrate that average growing season temperatures have a direct influence on average growing season soil moisture, more than precipitation; this is in contrast to the monthly comparisons presented in Figures 4.11 and 4.12. Similar to Sridhar et al. (2006), it was found that average growing season ET is less than average growing season precipitation. A direct measure of the relationship between the two time series is the Correlation Coefficient, $\rho_{x,y}$, calculated using Equation (4.2).

$$\rho_{x.y} = \frac{\frac{1}{j}\sum_{i=1}^{j}(x_i - \mu_x)(y_i - \mu_y)}{\sigma_x \cdot \sigma_y}; \qquad -1 \leq \rho_{x.y} \leq 1 \tag{4.2}$$

where, μ = average of the time series;

σ = standard deviation of the time series;

x = variable 1;

y = variable 2; and

j = total number of observations in the time series.

A correlation coefficient value closer to positive 1 indicates a strong direct linear relationship, while a value closer to negative 1 indicates a strong inverse linear relationship. The values of correlation coefficients between different average growing season characteristics were obtained and are presented in Table 4.7.

Table 4.7: The Calculated Correlation Coefficients between Precipitation, Temperature, Soil Moisture and Evapotranspiration

Correlation Coefficient From	Soil Moisture vs. Precipitation	Soil Moisture vs. Temperature	ET vs. Precipitation	ET vs. Temperature	Soil Moisture vs. ET
Scenario 1	0.90	-0.58	0.93	-0.51	0.83
Scenario 2	0.83	-0.55	0.90	-0.50	0.81

Table 4.7 shows that both soil moisture and ET have a strong positive correlation with precipitation, whereas both soil moisture and ET have a moderate negative correlation with temperature. Therefore the correlation coefficient analysis supports the earlier conclusion that the influence of precipitation is stronger than that of temperature on soil moisture and ET. Table 4.7 also shows that there is a strong linear relationship between ET and soil moisture, which is expected. A clearer understanding of the correlation analysis for scenario 1 is shown in Figure 4.13. Similar analysis was carried out for scenario 2 but is not shown here due to limitation of space.

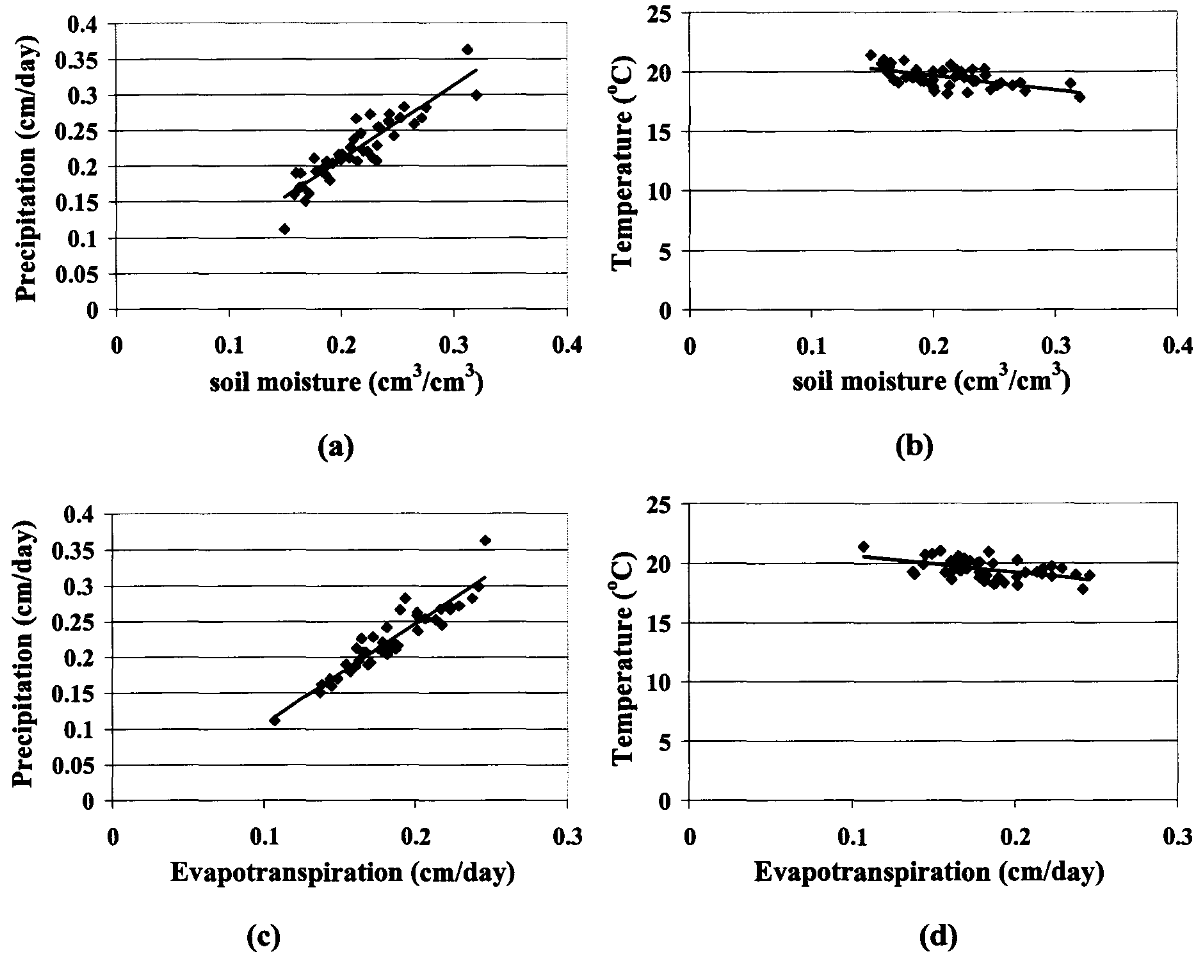


Figure 4.13: Correlation of Average Growing Season Characteristics from Scenario 1: (a) Soil Moisture and Precipitation, (b) Soil Moisture and Temperature, (c) Evapotranspiration and Precipitation, and (d) Evapotranspiration and Temperature

4.5. Conclusions

With rising temperatures, increasing evapotranspiration will significantly impact vegetation, particularly in the agricultural community. Little attention however, has been paid to urban areas. Using 45-years of climate data and a vertical water balance model, this study investigated the growing season soil moisture characteristics of urban land-use with changing climate conditions. This study focused on urban grass lands in the largest urban area of Canada.

The climate data confirm both a gradual increase in long-term average temperatures and precipitation in south-western Ontario, Canada during the growing season of May-October. Since the 1960's, average growing season temperature and precipitation have increased by 2% and 4% respectively. The study found that average growing season minimum temperatures have increased more than the average growing season maximum temperatures. This agrees with the findings of Wilby et al. (2002), Easterling et al. (2000, 1999), and Zhang et al. (2000). The monthly analyses showed an overall increase in May-September temperatures but an overall decrease in October temperatures. The monthly precipitation analyses also showed non-uniformity, with increasing precipitation in May, June, September and October and overall decreasing precipitation in July and August. An analysis of the model-simulated soil moisture values indicates that there has been a slight increase in soil moisture from 1960 to 2004, despite fluctuations from year to year. The model-simulated ET characteristics also exhibit similar patterns (i.e., even though there are significant inter-annual growing season ET variations, there has been an overall increase from 1960 to 2004).

The probability/frequency distributions give insight into the long-term soil moisture characteristics. All the pdfs generated showed the most likelihood of occurrence of volumetric soil moisture values near 0.2 cm^3/cm^3, the overall range being 0.15-0.35 cm^3/cm^3. The pdf comparison between the 1960-1981 and 1982-2003 periods, each consisting of 22 years, clearly indicates that there has been a shift to the right, meaning the more likelihood of occurrence of higher soil moistures. The 1960-1981 period pdf is unimodal, whereas, the 1982-2003 period pdf is bimodal, showing a second peak at a higher soil moisture (0.3 cm^3/cm^3) value. The simulated soil moisture for the four decades of the 60's, 70's, 80's and 90's were separated, their pdfs were derived and compared. The comparison again shows that there has been a shift to the right. The most significant difference between decades is that between the 60's and the 70's. The 1960-1969 period pdf is unimodal, whereas the 1970-1979 period pdf is clearly bimodal, with a second peak at a higher soil moisture value. The bimodal trend continues in the following decade of the 80's, and shows the probability of even higher soil moisture levels; between 0.35 and 0.4 cm^3/cm^3. The 1990-1999 period pdf is, however, unimodal and shifts to the left from the 80's pdf. 0.2 cm^3/cm^3 is the most common amount of soil moisture likely to exist throughout the growing season (May-October).

It was shown in this study that precipitation has a stronger control over soil moisture and ET in south-western Ontario, Canada. The monthly analyses showed that even in months (May, June, and September) where temperatures are increasing, both soil moisture and ET have also increased due to an overall precipitation increase. In contrast, there are months (July, August and October) where the inverse relationship is exhibited. The inverse relationship has also been supported by the correlation analysis and the coolest and driest year analysis. However, the average growing season analysis showed an overall increase in temperature, precipitation, soil moisture, and ET throughout the 45-year period. Therefore, it is concluded that even though temperatures have indeed increased throughout the 45 years analyzed, increasing precipitation has allowed the overall volumetric soil moisture availability to increase as well. This can be explained by the precipitation increase being higher than the ET increase. This observation has interesting implications on urban lawn care. With higher temperatures comes the general anticipation that there will be a need for increased lawn watering. The findings from this study shows that water saving practices should be continued out in south-western Ontario, Canada. More frequent watering of urban grass lands in the Toronto area is perhaps not necessary as the climate continues to change in the same direction.

Direct measurement of soil moisture is not a common practice and it will take a long time to accumulate sufficient data for statistical analysis. This is especially true for south-western Ontario, Canada, where long-term soil moisture data are not available. In the absence of long-term observed soil moisture data, simplified continuous simulation models are excellent tools in analyzing the general soil moisture characteristics for climate-soil-vegetation systems. What is presented in this paper is an example of this type of analysis.

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Chapter 5

Antecedent Soil Moisture Conditions of Different Soil Types in South-western Ontario, Canada

S. Nishat, Y. Guo and B.W. Baetz

Abstract

Soil moisture conditions prior to input design storms need to be known in the planning and design of urban stormwater control facilities using the design storm approach. Limited information is available on these soil moisture conditions which are commonly referred to as the antecedent soil moisture conditions. In this study, a deterministic continuous simulation model was used to simulate antecedent soil moisture conditions under south-western Ontario climate conditions. A wide range of different soil types were investigated and various statistical analyses on the simulated antecedent soil moisture results were performed. Frequency analyses showed the typical distributions of antecedent soil moisture conditions and the influence of finer and coarser textured soil particles. Empirical equations were developed for the estimation of average antecedent soil moisture conditions based on commonly known soil characteristics. These empirical equations can be used in urban stormwater studies incorporating the design storm approach.

Keywords: Design Strom Approach, Continuous Simulation, Empirical Equations, Frequency Distributions

5.1 Introduction

The abilities of soils to retain water are critical to the water balance of a location. Adequate knowledge of soil moisture levels is required in modelling overland hydrological processes. When using single-event hydrologic models, the soil moisture level (or the value of some directly related parameter) at the start of the rainfall event must be specified since the soil moisture changes occurring during the dry periods between rainfall events are not modelled. For example, the initial infiltration capacity of the soil (which is directly related to the initial soil moisture level) has to be specified if the Horton infiltration model is used. If the Green-Ampt model is used, the initial moisture deficit is provided as an input. Soil moisture content preceding rainfall events, which is known as antecedent moisture conditions, is a critical parameter when using the United States Natural Resource Conservation Services curve number (NRCS-CN) technique, previously known as the NRCS-CN technique (De Michele and Salvadori, 2002; Sahu et al., 2007; Senior, 2007; Lamont et al., 2008).The NRCS-CN technique is probably the most widely used technique in estimating direct Surface Runoff (SR) from rainfall events (Hawkins, 1993; Mishra et al., 2005; Kannan et al., 2008; Lamont et al., 2008). Antecedent conditions most commonly used in NRCS-CN surface runoff prediction are (i) Antecedent Moisture Conditions (Nnadi et al., 1999; De Michele and Salvadori, 2002; Mishra et al., 2005; Sahu et al., 2007) which are defined by the preceding 5-day rainfall amounts, (ii) Antecedent Precipitation Index (Packman and Kidd, 1980; Descroix et al., 2002), and (iii) Antecedent Runoff Condition (Lamont et al., 2008) which is a function of both previous rainfall and soil moisture conditions. Which antecedent-condition definition is used depends on the modeller and the purpose of the model (Ponce and Hawkins, 1996).

Soil moisture values prior to rainfall events, defined in this study as antecedent soil moisture (ASM), directly influences infiltration and SR. Studies have clearly shown that ASM values are required in modelling the hydrological processes properly (Descroix et al., 2002; De Michele and Salvadori, 2002; Castillo et al., 2003; Brocca et al., 2008). The modelling of the rainfall-runoff relationships can be significantly improved when the ASM conditions are properly estimated and accounted for (Descroix et al., 2002; Sahu et al., 2007). The purposes of rainfall-runoff modelling may include flood forecasting, stormwater management planning and design, non-point source pollution control analysis, and crop growth prediction. Where observed flow data are not readily available, the most widely used approach for practical design purposes is the design storm approach (DSA) (Viessman and Lewis, 2003; McCuen, 2005).

A design storm (DS) is a precipitation event, having a target return period, either synthetic or historical, that the system is designed to accommodate (Wenzel and Voorhees, 1984; Levy and McCuen, 1999). While selecting design storms, rainfall hyetographs believed to have the characteristics that are critical to the safety of the project (Levy and McCuen, 1999) are commonly chosen. The design of hydraulic structures for different purposes is based on the estimation of peak flows of different return periods. For example, the sizing of storm drainage conduits is based on the concept of a DS to convey the maximum peak flow (Marselak, 1978; Beaudoin et al., 1983). Many drainage policies require the use of design storms (Levy and McCuen, 1999). The DSA is also used in designing various stormwater control facilities (Ahmed et al., 2003), facilities that are required to reduce adverse effects on aquatic life forms, streambank erosion, and surface water quality. To control stormwater flooding, design storms used are usually of long-return periods. When dealing with extremely heavy rainfall events, ASM information may not be of great importance. The design of many stormwater management facilities such as infiltration trenches, dry and wet detention ponds, oil/grit separators, vegetated filter strips, soakaway pits, artificial wetlands, grassed swales, and retention ponds (Nnadi et al., 1999; City of Toronto, 2003) are usually based on shorter return period design storms. In the latter case, i.e., design based on shorter-return period (e.g., as 2, 5, 10, and 25-year) design storms, ASM conditions affect significantly the design results and therefore play an important role (Nnadi et al., 1999).

A basic assumption made in the DSA is that the return period of the resulting runoff and peak flow is the same as that of the input DS (Guo and Zhuge, 2008). Inaccurate estimation of ASM conditions when applying the DSA would further weaken the foundation of this basic assumption. The critical DS concept refers to the rainfall events that produce the largest peak flow for a particular watershed (Voorhees and Wenzel, 1984; Nnadi et al., 1999).

ASM affects runoff volume and peak discharge, therefore ASM information is important for use with the DSA (Voorhees and Wenzel, 1984; Wenzel and Voorhees, 1984; Tan et al., 2008). However, ASM values before the peak discharge producing DS are not readily available. ASM conditions for urban catchments have not been widely investigated. The ASM values used in most research work and practice are assumed or arbitrarily assigned values (Wenzel and Voorhees, 1984; Quader, 2007) with no support from computational or measured results and no empirical relationships are available for one to estimate a reasonably accurate value.

The focus of this study is the determination of soil moisture conditions preceding rainfall events in urban areas. Since it may be possible to treat the ASM conditions as another random variable in the application of the DSA to ensure consistency between various projects and to assist in strengthening the foundation of the basic assumption associated with the DSA, the statistical characteristics of ASM under south-western Ontario, Canada climate conditions were carefully examined. A previously developed simplified continuous simulation model was used to obtain sample soil moisture levels prior to rainfall events. As soil texture is one of the main factors that controls soil moisture under a given climate (Nishat et al., under review), different types of soils were investigated and the relationships between soil texture characteristics and the behaviour of ASM distribution were illustrated using continuous simulation results. For practical applications, empirical equations between average ASM ($\overline{ASM}$) and soil moisture characteristics were also developed.

5.2 Methodology

Once continuous simulation runs were completed for an urban catchment, it was possible to analyze soil moisture conditions prior to each rainfall event. Statistical analyses on these individual ASM values were then carried out. The continuous simulation model is briefly described below, followed by a description of the study area and the input data.

5.2.1 The Soil Moisture Continuous Simulation Model

The water balance model developed by Nishat et al. (2007) was used to simulate soil moisture in the root zone throughout the growing season (May to October) in south-western

Ontario, Canada. The soil water balance model, schematically represented by Equation (5.1), is one-dimensional, taking into account only the hydrological processes that operate in the vertical direction. The model represents the soil domain as a single homogeneous layer and simulates soil moisture at a point. The output of the model can be viewed as area/site-averaged values, and the inputs are all area/site-averaged values.

$$nZr\frac{ds(t)}{dt} = P(t) - SR(t) - ET(s) - L(s) \qquad (5.1)$$

where, s = volumetric soil moisture content in cm^3/cm^3;

Zr = depth within the soil root zone in cm;

n = porosity;

P = precipitation in cm/day;

ET = evapotranspiration in cm/day;

SR = surface runoff in cm/day;

L = leakage in cm/day; and

t = time index with an interval length of one day.

Equation 5.1 incorporates the well-established models of each of the individual processes that take part in the water-balance. SR is estimated using the NRCS-CN technique. This SR component was modified from that of Nishat et al. (2007) to better represent urban land-uses (Nishat et al., 2008). Potential Evapotranspiration (PET) is estimated using Penman's Method. Actual Evapotranspiration (AET) is then modelled from PET as a function of soil moisture and is further adjusted to represent various plant growth stages. Plant growth stages are represented by Leaf Area Index (LAI). Root water uptake was also taken into account whilst modelling AET. Leakage is modelled as vertical percolation and as a function of soil moisture. Soil moisture in turn is a function of time. For simplicity of notation the dependency of ET and leakage on time is not shown in Equation (5.1). The AET and leakage calculation procedures included in this model emphasize the soil moisture regime's control on these two processes, and is different from the way other deterministic models represent these two processes within the water balance. Equation (5.1) is solved numerically by using the backward finite difference method. Detailed description of the continuous simulation model is provided in Nishat et al. (2007). For this study, the continuous simulation model was modified to obtain ASM values. The model was run with different soil types to obtain the necessary data.

5.2.2 Study Area

The study area is urban lands adjacent to the Toronto Pearson International Airport (43°40′12″ N, 76°36′ W), in Toronto, Ontario, Canada. For this study, it was assumed that a piece of land represented by the point-scale model is completely covered with grass. This may represent a typical open space in urban areas or pervious portions of individual lots. While the major influential factors are taken into consideration, the methodology used here simplifies the hydrological cycle over urban grasslands by representing the detailed SR processes using the NRCS-CN procedure and assuming that any SR generated from a site would flow away from the site immediately. The study period is from 1980 to 2004. Meteorological data including precipitation, temperature, solar radiation, relative humidity, and wind speed were collected from the Ontario Climate Centre (Meteorological Services Canada station No. 6158733, Toronto Pearson Airport). The original data are hourly values, and daily totals or averages were calculated from the hourly values. There were few missing data, and the missing data were replaced with data from an adjacent weather station (Station No. 6158350). The growing season at this location was identified as from May to October. The climate here is humid continental with warm humid summers. Average annual precipitation is 83 cm. Summer is the wettest season, with the bulk of rainfall falling during thunderstorms. Soil characteristics for this region were available from Hoffman and Richards (1953). Soil moisture is simulated for rooting depths of 30 cm, which is typical for grass lands.

5.2.3 Input Data

The model was run using the above-described 25 years (1980-2004) of meteorological data. Eleven possible soil texture characteristics were studied. The soil characteristics pertaining to these eleven soil classes are shown in Table 5.1.

Table 5.1: The Characteristics Typical of Different Soil Types

Soil Type	n	K_s (cm/d)	b	$\bar{\psi}_s$ (MPa)	S_{alb}
Sand	0.35	864	4.05	$-1.184*10^{-3}$	0.13
Sandy Loam	0.434	86.4	4.90	$-2.133*10^{-3}$	0.13
Loamy Sand	0.421	121.9	4.38	$-0.89*10^{-3}$	0.13
Loam	0.439	60	5.39	$-1.8*10^{-3}$	0.13
Silt Loam	0.425	21.2	5.30	$-7.69*10^{-3}$	0.13
Sandy Clay Loam	0.404	47.5	7.12	$-1.13*10^{-3}$	0.13
Clay Loam	0.465	8.64	8.52	$-6.16*10^{-3}$	0.14
Silty Clay Loam	0.47	14.7	7.75	$-1.35*10^{-3}$	0.12
Sandy Clay	0.40	18.7	10.4	$-0.58*10^{-3}$	0.12
Silty Clay	0.43	10	10.4	$-1.85*10^{-3}$	0.14
Clay	0.50	0.864	11.4	$-3.96*10^{-3}$	0.12

In Table 5.1, n represents porosity and K_s is the saturated hydraulic conductivity; ψ_s and b are empirically determined parameters required for obtaining soil moisture control criteria at no water stress (s^*), permanent wilting point (s_w) and hygroscopic point (s_h); S_{alb} is the soil reflectivity, values of which are required for modelling PET. The values presented in Table 5.1 were obtained from the literature (Clapp and Hornberger, 1978; Jones and Kiniry, 1986; Knisel and Davis, 1999; Laio et al., 2001; USDA website). Values of LAI needed to represent plant growth stages were varied between 0.2-0.9 m^2/m^2 throughout the growing season. The values of s^*, s_w, and s_h were calculated with the soil water potentials of $\psi_{s,s*} = -30$ kPa, $\psi_{s,sw} = -1500$ kPa, and $\psi_{s,sh} = -10^6$ kPa, respectively. For each soil type, the soil moisture controlling criteria were obtained by using an empirical relationship [Equation (5.2), Clapp and Hornberger, 1978]. Results are presented in Table 5.2.

$$\psi_s = \overline{\psi}_s \times s^{-b} \qquad (5.2)$$

where, Ψ_s = matric potential corresponding to s;

$\overline{\psi}_s$ = saturation matric potential; and

b = Empirical Exponent.

Table 5.2: The Soil Moisture Controlling Characteristics Typical of Different Soil Types

Soil Type	Abbr. (i) Of Soil Name	s^*	s_w	s_h
Sand	S	0.44	0.17	0.06
Sandy Loam	SL	0.57	0.26	0.11
Loamy Sand	LS	0.44	0.18	0.07
Loam	Lm	069	034	016
Silt Loam	SiL	0.76	0.37	0.17
Sandy Clay Loam	SCL	0.71	0.42	0.23
Clay Loam	CL	0.82	0.52	0.32
Silty Clay Loam	SiCL	0.75	0.46	0.27
Sandy Clay	SC	0.74	0.51	0.34
Silty Clay	SiC	0.83	0.58	0.38
Clay	C	0.83	0.59	0.41

(i) Note: Abbr. stands for abbreviated version.

The sources of these input data values and other data necessary to run the continuous simulation model which could not be shown here due to space limitations can be found in Nishat et al. (2007).

5.3 Results and Discussion

The continuous simulation model was run for each typical soil type under the given climate and for each individual growing season from 1980 to 2004. The ASM values were extracted from each simulation run. The simulated individual ASM values for each of the eleven soil types were analyzed to better understand the nature of the fluctuation of the ASM. As the eleven texture classes ranged from coarse textured sand to fine textured clay, it was possible to examine the role of texture on ASM conditions. Statistical analyses were performed on the simulated ASM values for each soil type. Reported below are the main results.

5.3.1 Frequency Distribution of ASM

The average ($\overline{ASM}$), standard deviation (SD) and Coefficient of Variation (COV) of the ASM for all soil classes analyzed in this study were calculated and are shown in Table 5.3.

Table 5.3: The Average, Standard Deviations and COVs of the Antecedent Soil Moisture Values Corresponding to the Eleven Soil Types

Soil Type	% Sand (ii)	% Clay (ii)	Average	SD	COV
S	90	5	0.105	0.064	0.614
SL	60	15	0.199	0.043	0.218
LS	84	8	0.143	0.038	0.262
Lm	45	20	0.258	0.042	0.165
SiL	20	20	0.277	0.049	0.176
SCL	55	25	0.327	0.038	0.116
CL	35	35	0.427	0.053	0.123
SiCL	15	35	0.367	0.049	0.135
SC	50	40	0.433	0.069	0.160
SiC	10	45	0.484	0.067	0.139
C	20	50	0.501	0.048	0.096

(ii) Note: The % of Sand and Clay particle values were derived from Knisel and Davis (1999).

Table 5.3 indicates that the higher the percentage of clay, the higher the values of $\overline{ASM}$. Table 5.3 also shows that there is no clear evidence that with the increase in sand particles, the $\overline{ASM}$ decreases. This means that clay particles have a stronger influence on the soils' moisture retaining characteristics than sand particles. Both the SD and the COVs indicate that the finer the soil, the lower the fluctuations of the ASM values about its mean. The frequency distributions of the ASM values for each soil type were analyzed. Normal distributions were fitted to the simulated frequency distribution of the ASM values (1980-2004) for each soil type using the method of moments. To save space, not all eleven distributions are shown here; instead six representative ones are presented as Figures 5.1(a)-(f). The simulated frequency distributions are indicated by the solid lines, while the fitted normal distributions are illustrated by the dashed lines.

Figures 5.1(a)-(f) show the overall goodness-of-fit. Due to the lack of other better fitting theoretical distribution models, ASM may be treated as approximately normally distributed. This was true for the other five soil types not presented in Figure 5.1. As can be seen from Figure 5.1, the fitted normal distributions (indicated by the dashed lines) slightly overestimate the simulated main models as a result of the positive skewness of the simulated frequency distributions. The positive skewness of the distributions is quite small and may not be sufficient to justify the use of a wetter than $\overline{\text{ASM}}$ for all soil types. What is also obvious from this analysis is that the peaks of the obtained ASM distributions shift to the right from Figure 5.1(a) to Figure 5.1(f), meaning that there is an increase in the ASM levels with the increase in the percentage of clay particles.

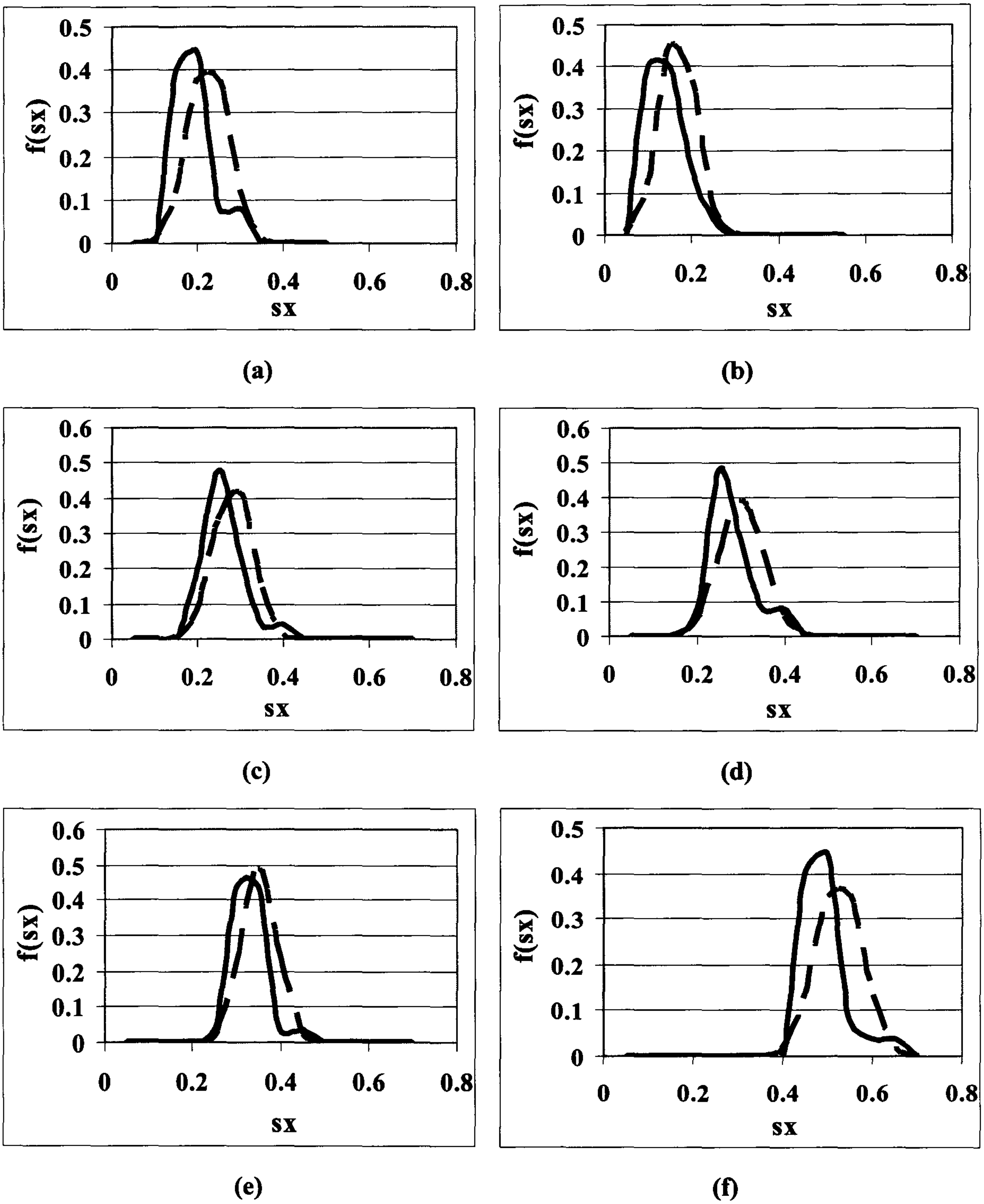


Figure 5.1: Distribution Analysis of the Simulated Individual Antecedent Soil Moisture Values: (a) SL, (b) LS, (c) Lm, (d) SiL, (e) SCL, and (f) C

The influence of the percentage of clay particles is also evident from the bimodal behaviour observed from the frequency distributions in Figures 5.1(a)-(f). With the higher percentage of clay particles, the second mode on the right of the dominant dry mode appears. For example, LS soils have 84% sand and 8% clay (Table 5.3), and as can be seen in Figure 5.1(b), exhibit a single mode. A single mode was also obtained for sand (not shown in Figure 5.1), which has the lowest fraction of clay particles (5%). Whereas, SL soils having 60% sand and 15% clay, attains a second slightly wetter mode [Figure 5.1(a)] due to the increase of clay particles. All the other four types of soils have clay percentages higher than that of LS; therefore, their ASM distributions all have a wetter second mode. Similar observations have been found by D'Odorico et al. (2000). Their study concluded that the occurrence of a second mode on the wet regimes is more important for finer-grained soils due to their ability to retain water longer.

5.3.2 Empirical Relationships

For a specific type of soil, the individual ASM values are largely controlled by the length of the dry period (referred to as the inter-event time) preceding each individual rainfall event. Statistical analyses for many locations including Toronto (Adams and Papa, 2000; Laio et al., 2001) have found that the inter-event time and the volume, duration and average intensity of the subsequent rainfall event are statistically independent. Since design storms are used to represent the statistical characteristics of observed actual storms, the antecedent moisture conditions specified in the use of DS may be established by treating ASM as an independent random variable. To ensure that the SR generated from the application of a DS has the same return period as the DS, it is most reasonable to adopt the $\overline{\text{ASM}}$ of the specific soil type under the given climate.

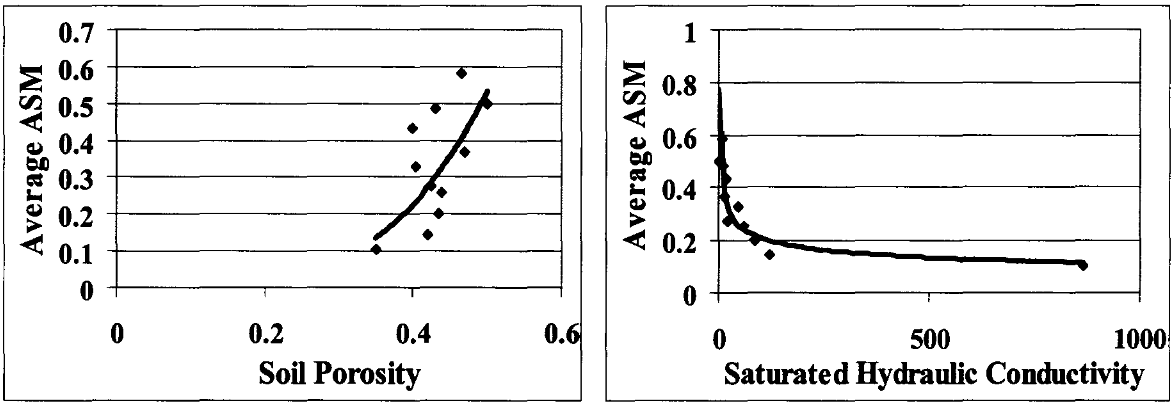
The annual $\overline{\text{ASM}}$ was obtained for each soil type. Then the $\overline{\text{ASM}}$ of the 25 years for each individual soil type were calculated. The ASM values for each soil type were related to the two soil texture input parameters, namely porosity and saturated hydraulic conductivity. The relationship between these two parameters and the $\overline{\text{ASM}}$ values was then obtained through multiple linear regressions. In order to check whether other functional forms better fit the data, logarithmic regression analysis was also performed. The empirical equations that best fit the simulated data are listed in Table 5.4. These empirical equations are only valid for south-western Ontario climate conditions. To evaluate the performance of the obtained empirical equations, the Index of Agreement (IoA), the Coefficient of Residual Mass (CRM), the Root Mean Square Error (RMSE), and the coefficient of determination or the R-squared (R^2) value between the simulated and estimated $\overline{ASM}$ values were calculated. The results are presented in Table 5.4 as well. As mentioned earlier, the n and K_s values used in the continuous simulation runs were obtained from the literature. In a design situation, both n and K_s values may be difficult to obtain. In case K_s values are not available a set of calculations were carried out to obtain a possible $\overline{ASM}$-n relationship. An $\overline{ASM}$-n data set was fitted to examine the four possible options of (i) a power; (ii) an exponential; (iii) a linear; and (iv) a logarithmic relationship. In order to select the best–fit equation, the R^2 value of all the equations were calculated and compared. The R^2 value is an indicator with values from 0-1 that reveals how closely the calculated values from the fitted equation correspond to the simulated data. An R^2 value close to 1.0 is desirable. The same analysis was carried out in searching for an $\overline{ASM}$-K_s relationship as well, in case n values are not available. From the R^2 values, it was found that both the $\overline{ASM}$-n and $\overline{ASM}$-K_s relationship is best explained by a power equation. These two empirical equations are shown in Table 5.4. To evaluate the performance of the obtained $\overline{ASM}$-n and $\overline{ASM}$-K_s equations, the IoA, the CRM, and the RMSE between the simulated and estimated $\overline{ASM}$ values were calculated. The results are also presented in Table 5.4.

Table 5.4: Regression Analysis Results

Relationship	equation	IoA	CRM	RMSE	R^2
$\overline{ASM}$-n-K_s (Linear)	$\overline{ASM}$=1.5*n-0.0002*Ks-0.289	0.76	0.0006	0.11	0.43
$\overline{ASM}$-n-K_s (Logarithmic)	ln $\overline{ASM}$=n*ln40+Ks*ln0.99+0.0693	0.76	0.06	0.11	0.51
$\overline{ASM}$-n (power)	$\overline{ASM}=7.57n^{3.83}$	0.75	0.06	0.12	0.44
$\overline{ASM}$-K_s (power)	$\overline{ASM}=0.744K_s^{-0.273}$	0.86	0.01	0.11	0.79

The IoA measures the agreement between the simulated and the calculated values and varies within 0.0 and 1.0 (Willmott, 1982). The closer the IoA is to 1.0, the better the performance of the equation. From Table 5.4, it can be seen that for all four equations IoA was greater than 0.7, indicating the equations are capable of providing reasonably close estimates. However, the better match was obtained from the $\overline{ASM}$-K_s relationship. The CRM represents the difference between the simulated and calculated values relative to the simulated data (Ginting and Mamo, 2006). CRM values at zero indicate a perfect fit, positive values indicate underestimation and negative values indicate overestimation. Again for all four equations, CRM<<0, which means good agreement exists between the simulated and estimated $\overline{ASM}$ values. The linear $\overline{ASM}$-n-K_s relationship CRM results are better than the logarithmic one and again the $\overline{ASM}$-K_s equation results are better than the $\overline{ASM}$-n equation. As for the RMSE results, the closer the RMSE values are to 0 the better the comparison. The RMSE values obtained show good performance for all four empirical relationships. The R^2 values are acceptable considering the difficulties involved in accurately modeling soil moisture fluctuations. The logarithmic IoA and RMSE values closely follow the linear ones, with the linear IoA being slightly better. However, the CRM value from the linear equation is much better than that of the logarithmic equation. Therefore, the linear relationship between $\overline{ASM}$, n and K_s is recommended. A comparison of all four IoA, CRM, RMSE, and R^2 tests presented in Table 5.4 shows that the best agreement was obtained from the $\overline{ASM}$-K_s power equation with respect to IoA and R^2. However, CRM values show that the best results are achieved by the $\overline{ASM}$-n-K_s linear relation. The RMSE results are reasonably consistent across all four model equations.

The regression analysis results for (a) $\overline{ASM}$-n and (b) $\overline{ASM}$- K_s are presented as Figure 5.2.



(a) $\overline{ASM}$ -n relationship (b) $\overline{ASM}$ -K_s relationship

Figure 5.2: The Relationships between Average Antecedent Soil Moisture and (a) Soil Porosity, and (b) Saturated Hydraulic Conductivity

5.4 Application of Modelling Results

The empirical relationships presented in this paper can assist in determining the $\overline{ASM}$ conditions for the application of design storms in south-western Ontario. Under a specific climate condition, soil texture and vegetation characteristics have a direct influence on soil moisture conditions. If both porosity and saturated hydraulic conductivity are known for a south-western Ontario site, the following linear equation can be used to estimate the $\overline{ASM}$:

$$\overline{ASM} = 1.5n - 0.0002K_s - 0.289$$

However, if the K_s values are unknown and the porosity values are available, the following power equation can be used:

$$\overline{ASM} = 7.57n^{3.8272}$$

Similarly, if the n values are unknown and the K_s values are available, the following equation can be used:

$$\overline{ASM} = 0.7438K_s^{-0.2734}$$

In the application of the DSA, if the n and/or K_s of the soil is known, the $\overline{ASM}$ values can be calculated using the above-obtained empirical equations. Using the values of Table 5.1 in the empirical equations of Table 5.4, the $\overline{ASM}$ values for all the eleven soil groups were calculated. Two sets of results are presented here. Calculations show, if a soil is predominantly CL, the calculated $\overline{ASM}$ was 0.407. If only the n information is known, $\overline{ASM}$ was obtained as 0.404 using the power equation in Table 5.4. If only the K_s information is known, $\overline{ASM}$ = 0.412 was obtained using the other power equation of Table 5.4. This example calculation shows how the results obtained from the empirical equations match each other reasonably well. In contrast, it was found that if the soil is C, $\overline{ASM}$ was estimated to be 0.386 when both n and K_s are known. Whereas, $\overline{ASM}$ would be estimated to be 0.356 or 0.774, respectively, when only n or K_s is known. This calculation shows that the results from at least two out of the three empirical equations match each other reasonably well.

This $\overline{ASM}$ information can be used as a guidance to obtain (a) the initial abstraction and the curve number (CN) if the NRCS-CN method is used, (b) the initial infiltration rate if the Horton's infiltration method is used, or (c) the initial moisture deficit if the Green-Ampt model is used. More consistent and reliable results may be obtained if design storms are applied with these estimated $\overline{ASM}$ values. It should to be pointed out here that the above equations are for the $\overline{ASM}$ within the top 30 cm of soil. With different soil depths, the $\overline{ASM}$-n- K_s relationship may or may not vary. However, 30 cm is appropriate for most urban grasslands.

5.5 Concluding Remarks

From surface water quality concerns rises the need to install or construct oil/grit separators, sediment control retention ponds, infiltration trenches, and artificial wetlands. The sizing and design of these facilities relies on the use of either the DSA or continuous simulation approaches. Even though continuous simulation is more accurate, the DSA is still more popular due to its simplicity, limited data requirements, and lower computational requirements (Beaudoin et al, 1983; Voorhees and Wenzel, 1984, Ponce and Hawkins, 1996).

The four essential elements of the DSA are: (i) event depth or average event intensity; (ii) event duration; (iii) event hyetograph; and (iv) antecedent soil moisture conditions (Packman and Kidd, 1980; Voorhees and Wenzel, 1984). Extensive research has been carried out for the first three elements. Traditionally less focus is placed on the fourth element. The purpose of this study was to determine what ASM conditions should be used when applying the DSA in south-western Ontario, Canada.

Continuous simulation of the vertical water balance was conducted for different soil types in south-western Ontario. From each of the simulation runs, the ASM values were extracted from the results and statistically analyzed. The ASM frequency distributions showed the likelihood of higher ASM conditions associated with finer grained soils. Bimodal behaviour was more evident with finer grained soils as well. Normal distributions were fitted to the distribution of the extracted ASM data sets. This analysis showed that the major portion of the $\overline{ASM}$ distribution was reasonably approximated by a Gaussian distribution. On the other hand, a closer look into the relationship between the percentage of sand and clay particles in each of the eleven soil texture classes failed to provide any clear evidence that, with an increase in sand particles, there is a decrease in $\overline{ASM}$. Whereas it was found that the higher the percentage of clay, the higher the values of $\overline{ASM}$. Therefore, an interesting finding is that clay particles have a stronger influence on soil moisture-retaining characteristics than sand particles.

For urban grass lands, it is desirable to regress the $\overline{ASM}$ conditions with soil characteristics only; since grass is the predominant plant type of urban lands and its characteristics are relatively stable throughout the growing season. Due to the ease in obtaining values, porosity and saturated hydraulic conductivity were the selected soil characteristics. Based on the empirical relationships obtained from this research, an engineer simply needs to know the sites' porosity and/or saturated hydraulic conductivity in order to approximate the average soil moisture level preceding rainfall events for the site. Use of average soil moisture level preceding a rainfall event is most appropriate for the majority of urban stormwater design. Findings reported herein are only valid for the Toronto (representative of south-western Ontario) climate. Similar studies may be conducted for other regions.

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Chapter 6

Conclusions and Recommendations for Future Research

6.1 Conclusions

The research presented in this dissertation originated from the need to gain insight into the long-term behaviour of soil moisture as influenced by the inter-relationships of the climate-soil-vegetation system. Soil moisture is a major driving force in the Earth's hydrological cycle. Due to the lack of readily available soil moisture data, continuous simulation models are a more effective means of studying long-term soil moisture conditions. The major concerns in using the existing water-balance models are how each of the hydrological processes are represented and the data requirements for the models. Also the general applicability of the model can be an issue as many of the existing models are site-specific. The simplified water balance model developed for this research has successfully demonstrated its ability to simulate daily soil moisture values near or at the soil root-zone under any given climate, soil and land-use conditions. In the remainder of this section, the major conclusions of this dissertation obtained through its four papers are outlined.

❖ Mathematical modeling intended for simulating soil moisture gives insight into the possible behaviour of soil moisture under a particular climate, soil, and land-use. A process-based continuous simulation model was developed to simulate soil moisture at a point within the root zone on a daily basis throughout the growing season. The major conclusions from the first paper that presents this model are as follows:

1. Verification and validation of the model was carried out using data obtained from field experiments. The model is generally capable of simulating soil moisture conditions at different depths. The model was able to obtain the average soil moisture values within 14% of average field observed soil moisture values. Statistical analysis indicated that the model successfully reproduced the degree of variations of soil moisture conditions throughout the growing season. The goodness-of-fit tests confirmed that the model

achieved a desirable match. The Coefficient of Residual Mass values indicated that the model slightly overestimates at lower soil depths and slightly underestimates at higher soil depths.

2. Simplified representations of each of the water balance processes proved to be sufficient in generating realistic soil moisture values. Nevertheless, the model should be used with caution as a predictive tool.
3. The ET and Leakage components of the model are unique due to the introduction of the ecohydrological perspective. The successful validation of the newly developed continuous simulation model showed that this unique perspective was worth pursuing.
4. The pdfs indicate bimodal behaviour of soil moisture under Guelph climatic conditions, and Kentucky bluegrass sod.
5. The sensitivity analysis performed was in the form of a LSA and it showed the significance of the soil moisture control criteria and plant growth stages. The LSA provided some guidance for a more complete sensitivity analysis, i.e., GSA.

❖ The need to perform GSA on top of LSA rises from LSA only being valid for the base parameter values representing a specific site. As different site conditions will result in different local parameter value regions, it would be useful if all possible site conditions can be considered in a sensitivity analysis. GSA is such an analysis technique as it is the measure of the relative importance of parameters under all possible site conditions. Furthermore, LSA cannot make provisions for the inputs under examination to be correlated to one another. Correlations between variables are important and, ideally should be provided. Correlations are a component of GSA. A summary of the GSA findings are as follows:

1. A regression-based non-parametric technique was used in the GSA. The Monte Carlo sampling technique was used to generate a series of samples for the selected input parameters. During the generation of random values, the correlations between input parameters were considered. The relative stability of GSA indicators depends upon the sample size. When increasing the sample size, the agreement between non-parametric statistics (SPEA, PRCC, SRRC and the Smirnov test) tend to increase (Saltelli et al.

2000). The study demonstrated how a moderate sample size is large enough for this study.

2. It was concluded from the GSA that the parameters representing soil texture (s^*, s_w, and s_h) were the most influential variables on average soil moisture.
3. However, the parameters representing land-use (LAI and CN_2) were found to be slightly more influential input factors on the degree of variation of soil moisture, which was represented by the standard deviation of the soil moisture values.
4. Unlike average soil moisture and the standard deviation, both land-use parameters (LAI and CN_2) and a soil texture parameter (s_h) were found to have a significant influence on the skewness results. The skewness of the soil moisture frequency distribution was found to be positive for most of the simulation runs. Positive skewness means that, for the largest part of the growing season, there is a higher likelihood of having soil moisture values (under the Toronto climate conditions and a variety of soil and land-use scenarios) greater than the average.
5. As parameters representative of soil moisture control criteria were found to be most influential on average soil moisture, and as those parameters affect ET, it was concluded that ET has a strong influence on long-term average soil moisture.
6. From the simulated daily ET, SR, and leakage for each growing season, the maximum growing season ET, SR, and leakage for that individual year was obtained. It was found that ET is almost 5 times that of SR and SR is 2 times that of leakage, confirming that ET is the most dominant process on the water balance under south-western Ontario climate conditions.

❖ The investigations into the relative importance of the soil texture and land-use characteristics demonstrated which of the hydrological processes are the most influential upon long-term soil moisture conditions. However, the GSA technique as used in this study cannot incorporate climate parameters. Therefore, studies about the control of climate characteristics on long-term soil moisture and ET (as it was defined as the most influential in Paper 2) were conducted in Paper 3. The major conclusions from this study are:

1. The long-term meteorological data confirmed that there was both a gradual increase in long-term average temperatures and precipitation in south-western Ontario, Canada, during the growing season (May-October). Since the 1960's, average growing season temperature and precipitation have increased by 2% and 4% respectively.
2. The study found that average growing season minimum temperatures have increased more than the average growing season maximum temperatures. This agrees with findings for other areas.
3. The monthly analyses showed an overall increase in May-September temperatures but an overall decrease in October temperatures. The monthly precipitation analyses also showed non-uniformity.
4. An analysis of the model-simulated long-term soil moisture values indicated that there has been a slight increase in soil moisture, despite fluctuations from year to year. The model-simulated ET characteristics also exhibit similar patterns (an overall increase with significant inter-annual growing season variations).
5. Precipitation has a strong control over soil moisture and ET under this climate. The monthly analyses showed that even in months where temperatures were increasing, both soil moisture and ET had also increased due to an overall precipitation increase. Therefore, it was concluded that even though temperatures had indeed increased throughout the 45 years analyzed, increasing precipitation had resulted in the overall volumetric soil moisture availability to increase as well. This can be explained by the observation that the precipitation increase was higher than the ET increase.
6. The probability/frequency distributions gave insight into the long-term soil moisture characteristics. All the generated pdfs clearly indicated that there has been a shift to the right (i.e., greater likelihood of higher soil moistures).

❖ Continuous simulation models are effective tools in obtaining desired outputs, be it for crop growth analysis, agricultural non-point source pollution and/or for urban SWM purposes. Continuous simulations are more accurate than single event models using the design storm approach. However, for the design of urban SWM facilities, typically based on rain storm events with various return periods, the DSA is still more popular due to its simplicity, limited data requirements, reduced expense and lower computational requirements. The fourth and final paper investigated soil moisture at the time of arrival of storms. This has been defined as the ASM condition. The following are the major findings from Paper 4:

1. Empirical relationships presented in this paper can help determine the ASM condition for the application of DSA in south-western Ontario. For urban grasslands, it is meaningful to regress the ASM conditions with soil characteristics since the grass land characteristics are more or less stable and fixed.
2. Normal distributions were fitted to the distributions of the obtained ASM series. It was found that ASM was approximately normally distributed, and was slightly skewed to the right.
3. A closer look into the relationship between the percentage of sand and clay particles in each of the eleven soil texture classes failed to provide any clear evidence that an increase in sand particles results in decreasing $\overline{ASM}$ values. On the other hand, it was found that a higher percentage of clay particles provide higher $\overline{ASM}$ values. Thus, it was concluded that clay particles have a stronger influence on the soil's moisture retaining characteristics than sand particles.

6.2 Research Contributions

The temporal variability of the soil moisture regime as influenced by rainfall is of great concern when studying crop yield, pollution control, impact of climate change, the effect of differing land-uses, etc. Direct measurement of soil moisture is relatively new and will take a long time to accumulate sufficient data for statistical analysis. Mathematical modeling, therefore, provides a practical option for examining long-term soil moisture fluctuations under different land uses. The continuous simulation model presented in this thesis is a simplified representation of the natural processes involved in the vertical water balance of a site. With reasonable simplification of the individual processes, the model demonstrates its ability to simulate soil moisture dynamics as influenced by the climate, soil and vegetation type throughout the growing season. This research does not focus on predicting the day-to-day soil moisture values or crop yields but instead captures the general, area-averaged soil moisture fluctuation characteristics under varying land-use and climate conditions. The main interest lies in the probability distribution of soil moisture for a specific climate-soil-vegetation combination and its sensitivity.

The contributions of the thesis can be summarised as follows:

- A simplified deterministic water-balance model that simulates soil moisture on a daily basis at a point in the root zone has been developed. In order to accurately model the hydrological processes involved in the water balance, extensive knowledge of the climate, soil and vegetation characteristics are required. Such detailed information is not readily available and is time consuming and costly to obtain. Therefore, extensive data requirements may often limit the use of detailed models. Simplified soil moisture modelling is physically possible and computationally practical. The continuous simulation model presented in this thesis can be applied to study soil moisture conditions under any climate, soil and land-use conditions.
- The purpose of vegetation in urban areas is typically for landscaping and stormwater management. The soil moisture and vertical water balance in urban areas have not been studied as extensively as those in agricultural lands. The research presented in this dissertation has investigated the vertical water balance under urban land-use and has shed light onto important details related to soil moisture under urban grass covers.
- Both the LSA and GSA shed light on the important processes that dominate the water balance. The analyses also point out which parameters need special attention for different modelling purposes. Average soil moisture is a widely investigated parameter. Traditionally less focus is placed on the degree of fluctuations and detailed frequency distributions of soil moisture throughout a growing season. The information from the GSA can be used as a guidance to set priorities in future data collection and model calibration so that the most accurate results can be obtained within a given budget.
- It was found that even though temperatures have indeed increased in south-western Ontario, increasing precipitation has resulted in the overall increase of volumetric soil

moisture availability. This observation has interesting implications on urban lawn care. With higher temperatures it is common to expect that there will be a need for increased lawn watering. Thus findings from this study show that water conservation practices should be continued in the region. More frequent watering of urban grass lands in this area is perhaps not necessary as the climate continues to change in the same direction.

- Use of proper ASM is important for urban stormwater design. ASM values are not readily available, and are usually assumed in practice. The $\overline{\text{ASM}}$ values for a site can be determined using the empirical relationships obtained from this dissertation.

6.3 Future Research Directions

The continuous simulation model presented in this thesis has been used in the studies included in this dissertation. Beyond the work carried out for this thesis, additional research dealing with soil moisture can be undertaken. The following are some possible avenues for future research.

i. Comparison of the results from more complex models to further verify the proposed model. The AET component of the model was similar to the Laio et al. (2001) analytical model. The continuous simulation model results should thus be compared with that of the analytical model. The analytical model is the Rodriguez-Iturbe et al. (1999) model. This is a leading ecohydrological model.

ii. The effect of climate conditions on soil moisture values can be more extensively investigated by consideration of different climates. This would require the investigation of climate characteristics for different places, for example Alberta, and Quebec climates, in addition to Ontario. The model would be run using the climate data for each region, while keeping the land-use and soil characteristics similar.

iii. The SAs have successfully shown the significant role of land-use on soil moisture characteristics. However, a direct analysis of the effect of land-use on soil moisture values needs to be investigated. The model can be applied to agricultural and/or mature vegetation systems. This will yield information as to how land-use or different vegetation actually affects soil moisture conditions. In addition, this type of study will also test the model's ability to simulate soil moisture under agricultural and/or mature vegetation systems.

iv. The contributions of mathematical models such as the one presented in this dissertation are obvious in the field of irrigation. By knowing the amount of soil moisture available in the soil and the amount of water the plants need for growth, one can calculate how much irrigation may or may not be required. A possible future research direction may be the optimization of irrigation scheduling to ensure that the soil moisture levels do not go below the PWP.

v. The deterministic model can be used to determine the availability of nutrients to plants. The availability of nutrients to plants is very much dependent on the available soil moisture and thereby on rainfall. Studies have shown that the moisture availability in the top soil layer dictates plant access to nutrients (Read et al., 1982). There are various mathematical models that have been used to investigate the uptake of nutrients by plants (Grant and Robertson, 1997; Dunbabin et al., 2002). Water extraction by plant roots depends on the soil water pressure head as well as the plant transpirative demand (Feddes et al., 1978; Wu et al., 1999). The key concept in plant water uptake is evapotranspiration.

6.4 Concluding Remarks

It is voiced throughout this thesis that the model developed within can be applied to any climate, vegetation and soil condition. This statement is made bearing in mind the assumptions (Section 2.2.1.1) upon which the model is based. The simplified water balance model is not designed to allow specific situations such as:

(a) lateral redistribution within the root zone;

(b) groundwater contribution to the soil moisture profile;

(c) runoff from adjacent areas;

(d) backwater effects from flooded zone; etc.

With increased urgency in conserving natural water a better understanding of urban area soil moisture dynamics is required. As mentioned earlier, the study of the soil moisture and vertical water balance in urban areas is relatively new. Urban landuse exhibits great complexity that can hardly be truly represented by any model. The simplified model presented in this dissertation cannot address the following problems associated with urban landuse:

(i) redistribution from roof tops, roads and parkways to infiltration zones;

(ii) wind and solar effects that reflect and concentrate solar and kinetic energy;

(iii) urban heat islands;

(iv) highly disturbed soils;

(v) huge variation in land-use in close proximity; and

(vi) leaking swimming pools, etc.

One of the challenges in presenting the developed model is the use of the NRCS-CN technique. The NRCS-CN technique is an empirical relation developed for single events and the hourly time scale. Whereas the developed model is a continuous simulation model which uses the daily time scale. Even though its use is still questioned by many, it is still very popularly used in continuous simulations. The technique has been successfully used by other continuous models including the Panigrahi and Panda model (2003), GLEAMS, ADAPT, and AGNPS. The NRCS-CN technique is argued as being unsuitable for continuous simulations as it originally did not include time as a variable and does not contain any expression for time. However, the method is now being used in continuous simulations for a different context than originally intended. For continuous simulations the CN is assumed as a random variable that is a function of prior rainfall amount or soil moisture content, soil texture and land-use. Taking the above-mentioned complexities (i-vi) of urban land-use into consideration, the performance of the developed model needs to be tested. The NRCS-CN approach has not been used under these complex urban conditions as this research mainly focussed on urban grasslands. The model performs satisfactorily for urban grasslands under south-western Ontario climate and soil conditions.

It is not possible to accurately model nature as many natural details have not and/or cannot be represented by mathematics while others remain unknown. Modelling of the real world must always be viewed as a conditional exercise. As no model can be fully accurate, the decision of what to include and what technique are suitable is left to the choice of the modeller.

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