A COMPARATIVE ANALYSIS OF THE HYDROLOGICAL PERFORMANCE OF RECONSTRUCTED AND NATURAL WATERSHEDS

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ABSTRACT

An example of watershed disturbance activity undertaken to gain access to the oil sands is large scale mining in the Athabasca basin, Alberta, Canada. One of the remedial activities of this disturbance is the reclamation of the disturbed lands. In the process of reclamation, the overburden soil is placed back into the mined pits and reformed with soil covers (alternatively called reconstructed watersheds). In the design process of reclamation, a major concern is hydrological sustainability, which includes the soil's ability to store enough moisture for the water requirements of vegetation growth and land-atmospheric moisture fluxes. Typically, the goal of the reclamation is to restore the disturbed watersheds, so that they mimic the natural watersheds in terms of the ecological sustainability. Therefore, a comparative evaluation of the hydrological sustainability of the reconstructed watersheds with natural watersheds is required.

The considered reconstructed watershed in this study (the flat top of the South Bison Hill, Fort McMurray, Alberta, which is about 6 years old) constitutes a thin layer of a peat-mineral mix (20 cm thick) overlying an 80 cm thick secondary (glacial till) layer on the shale formation, mimicking the natural soil horizons of undisturbed watersheds. As the reconstructed watershed is located in the boreal forest region, a mature boreal forest (Old Aspen site, about 88 years old) located in the Southern Study Area (SSA), BOREAS, Saskatchewan, Canada, is considered as a representative of natural watershed. The A-horizon with 25 cm of sandy loam texture, the B-horizon with 45 cm-thick sandy clay loam, and the C-horizon with 40 cm of a mixture of sandy clay loam and loam are considered in this study.

An existing System Dynamics Watershed (SDW) model (lumped and site-specific) is modified and adapted to model the hydrological processes of the reconstructed and natural watersheds, such as soil moisture, evapotranspiration, and runoff. The models are calibrated and validated on daily time scale using two years data (growing season) in each case. The hydrological processes are simulated reasonably well despite the high complexity involved in the processes of soil moisture dynamics and the evapotranspiration, for both study areas. Using the modified and calibrated models, long term simulations (48 years) are carried out on both the reconstructed and natural watersheds. Vegetation properties are switched between the reconstructed and natural watersheds and two scenarios are generated. Consequently, long term simulations are performed. With the help of a probabilistic approach, the daily soil moisture results are used to address the comparative soil moisture storage capability of the watersheds.

The results indicate that the selected reconstructed watershed is able to provide its designed store-and-release moisture of 160 mm (a requirement of the land capability classification for forest ecosystems in the oil sands) for the vegetation and meteorological moisture demands at a non-exceedance probability of 93%. The comparative study shows that the reconstructed watershed provides less moisture for evapotranspiration requirements than the natural watershed. The reconstructed watershed is able to provide less moisture than the natural watershed for both small and also mature vegetation scenarios. A possible reason for this may be that the reconstructed site is still in the process of restoration and that it may take a few more years to get closer to natural watersheds in terms of the hydrological sustainability. The study also demonstrates the utility of the system dynamics approach of modeling the case study under consideration. The future addition of a vegetation growth model to the hydrological model, and the development of a generic watershed modeling technique would be helpful in decision making and management practices of watershed reclamation.

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ε_1	Habitat dependent landscape interception parameter (dimensionless)
AET	actual evapotranspiration (mm/day)
AT	air temperature (^{o}C)
c_A	A-horizon evapotranspiration coefficient (mm/day)
c_B	B-horizon evapotranspiration coefficient (mm/day)
c_C	C-horizon evapotranspiration coefficient (mm/day)
c_i	exponent describing the influence of T_I on soil defrosting (dimensionless)
c_P	Peat evapotranspiration coefficient (mm/day)
c_T	Till evapotranspiration coefficient (mm/day)
D_f	degree-day melt factor (millimeters per degree-day above 0 ^{0}C)
D_i	soil moisture deficit (mm)
D_m	maximum annual soil moisture deficit (mm)
Dp	drip from canopy storage (mm/day)
dt	simulation time interval (days)
Ec	water evaporating from the canopy surface (mm/day)
E_I	evaporation of intercepted precipitation (mm/day)
EI_p	potential evaporation rate of the intercepted precipitation (mm/day)
Ic	canopy interception (mm/day)
I_{cB}	B-horizon infiltration coefficient (dimensionless)
I_{cC}	C-horizon infiltration coefficient (dimensionless)
I_{cS}	Shale infiltration coefficient (dimensionless)
I_{cT}	till infiltration coefficient (dimensionless)
k	extinction coefficient (dimensionless)
LAI	leaf area index (m^2/m^2)
M	daily melt (mm/day)
NR	net radiation (W/m^2)
P	gross precipitation (mm/day)
p	precipitation reaching canopy (mm/day)
PET	potential evapotranspiration (mm/day)

P_r	deep percolation (mm)
Q_A	small-scale advection from patches of soils in horizontal direction (Wm^2)
Q_e	convective flux of latent heat ($W\ m^{-2}$)
Q_g	conductive flux of ground flux ($W\ m^{-2}$)
Q_h	convective flux of sensible heat ($W\ m^{-2}$)
Q_m	energy flux available for snowmelt ($W\ m^{-2}$)
Q_n	net radiation flux ($W\ m^{-2}$)
Q_p	advection from rain in vertical direction ($W\ m^{-2}$)
R	gross rainfall (mm/day)
RH	relative humidity (%)
R_s	stem flow (mm/day)
Sc	canopy interception capacity (mm)
S_I	canopy interception storage (mm)
SSA	southern study area
S_t	soil moisture content on day *t* (mm)
S_{t+1}	soil moisture on day *t+1* (mm)
T_a	air temperature (°C)
T_b	base melt temperature (°C)
T_F	throughfall (mm/day)
T_{Imax}	Maximum T_I point at which surface soil is fully defrosted (^0C)
WS	wind speed (m/sec)
ΔS	daily change in soil moisture storage (mm)
$\Delta U/\Delta t$	change in internal energy ($W\ m^{-2}$)
λ	exponent coefficient of AET formulation in SDW model (dimensionless)
ρ_s	snow density (kg/m^3)

AET gross	actual evapotranspiration including canopy interception
AET net	actual evapotranspiration excluding canopy interception

ANN	artificial neural networks
AWHC	available water holding capacity
BERMS	boreal Ecosystem Research and Monitoring Sites
BOREAS	boreal Ecosystem - Atmospheric Study
DA	decision analysis
FFNN	feed forward neural networks
ForHym	forest hydrology and snowmelt model
ForIoM	forest ion flux model
ForSTem	forest soil temperature model
GCM	global climate model
GEM	general ecosystem model
GIS	geographic information system
GP	genetic programming
HEC-HMS	hydrologic engineering centre-hydrologic modeling system
HELP	hydrological evaluation of landfill performance
HSPF	hydrologic simulation package – FORTRAN
LHEM	library of hydro-ecological modules
MARE	mean absolute relative error
MC	Monte Carlo
MCDA	multi-criterion decision analysis
MEND	mine environmental neutral drainage
MSDW model	modified system dynamics watershed model for reconstructed study area
NHRI	national hydrology research institute
NS	natural system
NWS	national weather service
OA	old aspen
OBS	old black spruce
OJP	old jack pine
OO-SD	object oriented system dynamics
RCM	regional climate model
R_f	runoff

RMSE	root mean squared error
RORB	runoff routing model
RS	reconstructed system
RZWQM	root zone water quality model
SBH	south bison hill
SCL	Syncrude Canada Ltd.
SCS	soil conservation system
SD	system dynamics
SDW model	system dynamics watershed model
SDWN	system dynamics watershed model for natural study area
SHE	systeme hydrologique European
SLURP	semi-distributed landuse based runoff processes
SMNN	spiking modular neural networks
SOC	soil organic carbon
SPAW	soil plant air water
SRS	sustainable reclamation strategy
SWAT	soil water assessment tool
SWCC	soil water characteristic curve
SWIM	soil water infiltration and movement
SWSS	south west sand storages
TDR	time domain reflectrometry
TE	terrestrial ecology
TF	tower flux
TMDL	total maximum daily load
U of S	University of Saskatchewan
UBC	University of British Columbia model
UH	unit hydrograph
USDA-ARS	United states department of agriculture – agricultural research service
USLE	universal soil loss equation
WATFLOOD	Waterloo flood system
WBN	watershed bounded network model

WSA	water stable aggregation
YBS	little black spruce
YJP	little jack pine

CHAPTER 1. INTRODUCTION

1.1 Background

Natural watersheds are disturbed in many ways by human activities such as deforestation and land mining. One major human activity disturbing thousands of acres of landscapes is mining for oil. Because of these mining practices, the natural habitats and the surrounding ecosystem are at high risk. One remedial activity of this disturbance is the reclamation of the disturbed lands. The process of reestablishing the disturbed landscape and developing sustainable soil-vegetation-water relationships to achieve land capability corresponding to the undisturbed condition is called land reclamation (Gilley et al., 1977). Reclamation requires understanding the behavior of natural landscapes to reform the disturbed landscapes.

A real life example of watershed disturbance is the large scale oil mining in the Athabasca basin in Alberta, Canada, which involves stripping off large amounts of organic and glacial deposits as well as a layer of saline/sodic cretaceous shale to gain access to the oil sands. In the process of reclaiming these lands, the overburden soil is placed back into the mined pits and reformed with soil covers with a requisite ability to hold enough soil moisture (Boese, 2003; Elshorbagy et al., 2005) for vegetation. These soil covers (also known as reconstructed watersheds) are designed to replicate the hydrological performance of the natural soil horizons such as A-horizon (usually dark colored), B-horizon (brown, moderately permeable), and C-horizon (leached slowly permeable glacial till). The soil covers are important in the processes of soil-atmospheric fluxes, of runoff generation, and of the moisture store-and-release capability of vegetation: Therefore, the design and formation of soil covers are also important. A typical soil cover near Fort McMurray (northern Alberta) constitutes a thin layer of a peat-mineral mix overlying on glacial till layer on a shale formation (Boese, 2003). The objective of this layer formation is to keep enough moisture for evapotranspiration (Barbour et al., 2004) while minimizing the amount of precipitation percolating below the root zone.

1.2 Area of Interest

The reconstructed watersheds evolve over time to the level of the natural watersheds. The process of restoration primarily relies on the restoration of functioning hydrologic systems, to provide sufficient water to sustain re-vegetation (Qualizza et al., 2004). The typical hydrological assessment of reconstructed watersheds includes field measurements of various hydraulic and hydrologic properties and variables (e.g. evapotranspiration, overland flow), as well as modeling. Field measurements are helpful for an initial understanding of the hydrologic performance of the reconstructed watersheds (Boese, 2003). However, in order to examine various designs of reconstructed watersheds under different climatic conditions, hydrological modeling of the reconstructed systems is necessary.

Modeling can be helpful for assessing and predicting the phenomena that occur in reconstructed watersheds. Many studies have been attempted on reclaimed sites in view of their necessity, construction issues, and management issues (e.g., Younos, 1993; Hellawell, 1994; Bonta, 2003). However, modeling practices of the hydrological processes of the reconstructed watersheds to assess their restoration ability are sparse in the literature. It is challenging to understand evolving reconstructed systems, and also to model them for management purposes. In addition, queries such as "do reconstructed watersheds have similar eco-hydrological responses to climatic conditions as the natural systems do?" remained unanswered completely. To address these queries by hydrological modeling, a comparative hydrological assessment of the reconstructed systems relative to the natural systems is needed.

1.3 Problem Definition

Hydrological modeling was conducted on the reconstructed watersheds by Elshorbagy et al., (2005) using the System Dynamics approach (Ford, 1999) to simulate various hydrological processes on a daily time scale. On a 100 cm thick inclined reconstructed sub-watershed, a site-specific System Dynamics Watershed (SDW) model was developed for this purpose. Later, the model was used to simulate two adjacent inclined reconstructed sub-watersheds (35 cm and 50 cm thick) by Elshorbagy et al. (2007). The model was used to further analyze the soil moisture storage capability of three inclined reconstructed sub-watersheds by Elshorbagy and Barbour (2007) using a probabilistic approach with the help of long term hydrological simulations. All findings help to understand the hydrological behavior of the reconstructed watersheds. Knowledge gap still exists regarding understanding the restoration ability of the reconstructed watersheds relative to natural watersheds.

A comparative study of reconstructed watersheds relative to natural watersheds can provide more information about their restoration capabilities. Hydrological components such as evapotranspiration, soil moisture, and runoff of the reconstructed watersheds can be studied relative to the natural landscapes, as the goal of reconstructed watersheds is to restore them to be the same as of natural watersheds in all respects in hydrological performance. For example, actual evapotranspiration (AET) can be studied comparatively on reconstructed and natural watersheds. This helps understand both the moisture requirements (Potential ET) and the moisture that the watersheds are able to release. Such analysis could help to understand the sustainability of reconstructed watersheds.

Negley and Eshleman (2006) made a comparative study of storm flow responses of surface-mined and forested watersheds using the Unit Hydrograph (UH) concept. They noted that storm runoff coefficients, runoff totals, and peak hourly runoff rates were higher for the mined sites compared to natural sites. However, to assess the moisture store-and-release capability of both reconstructed and natural systems, which requires a reliable modeling approach. For this purpose, a boreal forest site in Canada representing natural watersheds is considered in this study.

In order to apply the site-specific SDW model (Elshorbagy et al., 2005) to the considered reconstructed watershed, the model needs some modifications. These modifications include accommodation for canopy interception, removal of the interflow component, and corresponding adjustments in the infiltration formulations. The selected watershed is relatively flat compared to the adjacent inclined reconstructed watersheds on which the SDW model was initially developed. Furthermore, the reconstructed watershed (flat hill top) has considerable vegetation. In order to compare its hydrological performance with that of original watershed, a similar model is required for the natural site. Consequently, models for reconstructed and natural sites should be recalibrated and validated for the purpose of this study.

Yevjevich (1974) provided a theoretical description of determinism and stochasticity in hydrology, and suggested that the integration of both deterministic and stochastic approaches assures the best mathematical-physical understanding and description of hydrologic processes and environments. Therefore, for better management and decision analysis, it is recommended that deterministic modeling attempts are accompanied by probabilistic analysis. In this study, a probabilistic approach is employed for the comparative assessment of the hydrological performance of reconstructed and natural systems. The long term simulations with the help of the probabilistic analysis would assist in learning and in understanding the restoration processes and the sustainability of reclaimed landscapes.

1.4 Objectives

In order to understand the restoration process of the reconstructed watersheds relative to natural watersheds, the broad goal of the study is to assess the hydrological performance of reconstructed watersheds and to compare it with the hydrological functioning of natural forested watersheds. With this goal, the specific objectives of this study are:

1) To modify and recalibrate the available System Dynamics Watershed (SDW) model with necessary modifications and reformulations and to simulate the hydrological processes on a reconstructed watershed;

2) To adapt the modified system dynamics watershed model to a natural forested watershed for hydrological simulation; and

3) To compare the hydrological performance of the reconstructed watershed relative to the natural watershed using a probabilistic approach with the help of long term simulations for understanding the sustainability of the reclaimed landscapes.

1.5 Scope of the Research Work

Syncrude Canada Ltd. has been conducting an extensive monitoring of their experimental reclaimed watersheds to evaluate various reclamation strategies. The present study is part of a research program that aims to develop a framework to help understand the hydrological processes of reclaimed watersheds, and, therefore, to develop a sustainable reclamation strategy. Figure 1.1 (Modified after Jutla, 2006; Parasuraman, 2007) describes the framework of the ongoing research program on reconstructed watersheds.

Initially, modeling the reconstructed watersheds as a partially understood system (initial knowledge with help of field instrumentation of hydrological, meteorological, and soil physical variables) was based on both the mechanistic and also the inductive modeling approaches. .

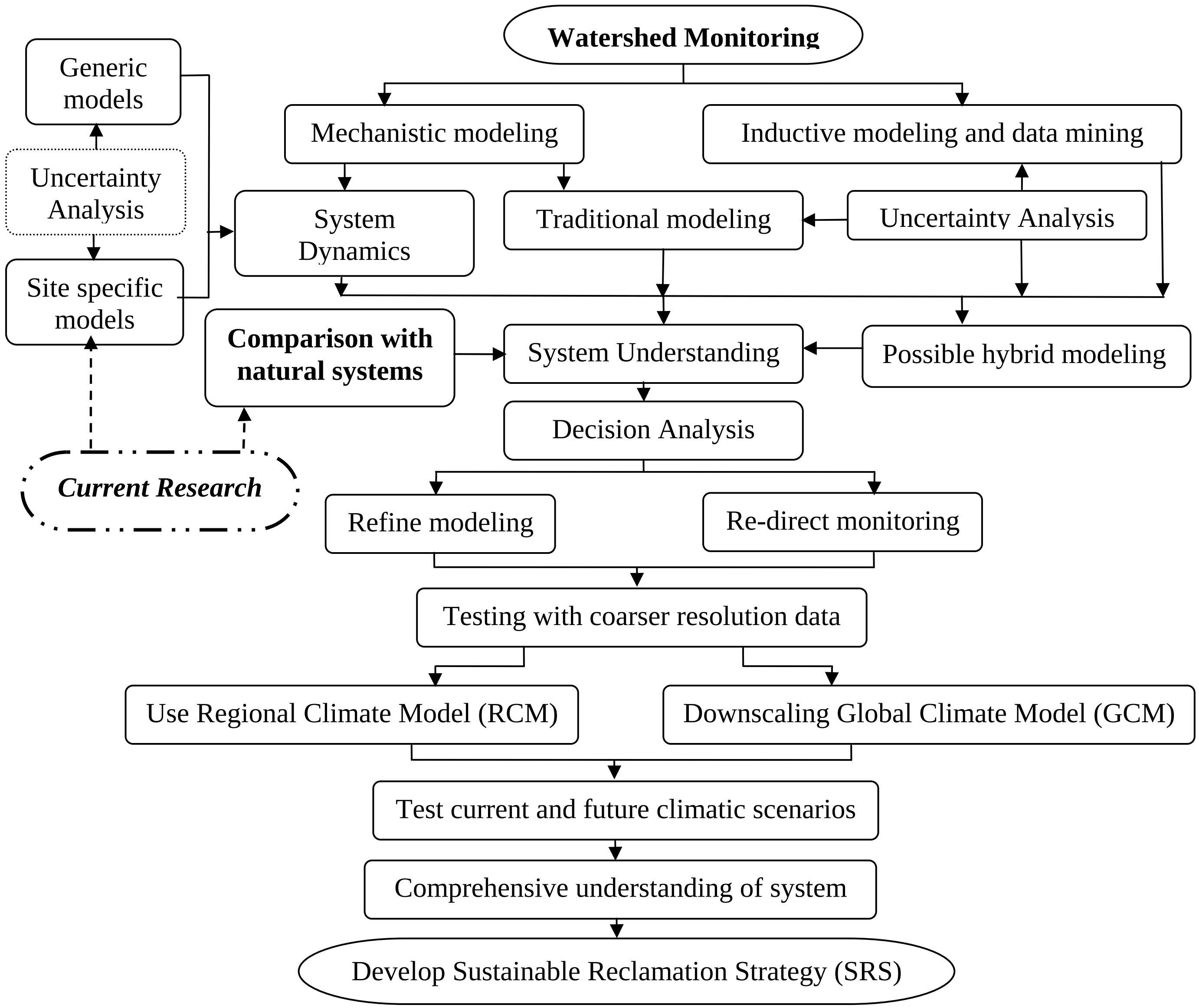


Figure 1.1. Framework of the research program for developing a Sustainable Reclamation Strategy (SRS).

The mechanistic approach includes two hydrological modeling methodologies: traditional watershed modeling (e.g. SLURP by Kite, 1995); and System Dynamics modeling. Site-specific models and generic models can be derived under the classification of System Dynamics modeling based on the model structure and model utility.

These models help to investigate the dynamics of the hydrological processes of reconstructed watersheds. Each fore-mentioned modeling approach should be accompanied with an uncertainty analysis in order to account for the uncertainty involved in the input data, model structure, etc (Wagner and Gupta, 2005; Liu and Gupta, 2007). However, the emphasis of this study is concentrated on the comparative hydrological performance of the reconstructed watershed relative to the natural watershed.

The knowledge gained from the inductive the deductive modeling approaches, supplemented by knowledge gained from comparing reconstructed to natural systems. This system can help to understand "how distant is the reconstructed system from the natural system in terms of its sustainability". Possibly, an integrated or hybrid approach of hydrological modeling could also be investigated. All this knowledge can be encapsulated together to formulate a decision analysis (DA) framework (Elshorbagy, 2006).

Re-directed monitoring and refined modeling can help to achieve a comprehensive understanding of the reconstructed watershed system. The utility of the developed models, testing them with coarser can be improved by, larger spatial data from Regional Climate Models (RCM) and downscaled Global Climate Models (GCM) might be needed. Furthermore, the model should be evaluated with current and future climatic scenarios. A comprehensive system can help to modify the existing regulations and reclamation practices to develop a sustainable reclamation strategy (SRS). Following are the specific tasks pertaining to the overall framework of this large scale research program (After Jutla, 2006; Parasuraman, 2007):

I. Develop a hydrological simulation methodology using system dynamics modeling to provide an understanding of the dynamics of hydrological processes at the reconstructed watersheds. This involves the development and evaluation of site-specific and generic models;

II. Simulate the reconstructed watersheds using some existing watershed models (e.g., SLURP, SWAT), and compare their performance with the model developed in Task I. The purpose of such a comparison is to gauge the utility of different modeling approaches in simulating the dynamics of reconstructed watersheds in the sub-humid regions;

III. Evaluate the added gains, if any, by adapting an inductive modeling approach for modeling the different components of the hydrological cycle;

IV. Develop equivalent models for natural watersheds, and compare their hydrological performance with that of the reconstructed watersheds. This comparison can help in possibly identifying and filling in any knowledge gap, and in characterizing the evolution of reconstructed watersheds over time. This is also helpful in identifying and emphasizing data measurement requirements for decision making and modeling practices;

V. Conduct a comprehensive study to identify the different sources of uncertainty (input data uncertainty, model parameter and structural uncertainty, etc), and to find methods and tools to effectively incorporate uncertainty analysis into the watershed model building exercise;

VI. Develop an integrated or hybrid modeling approach that benefits from the knowledge gained by adapting mechanistic and inductive modeling approaches. The objective of this task is to develop and propose to both industries and also scientists the best possible tools for modeling reconstructed watersheds;

VII. Develop a multi-criterion decision analysis (MCDA) framework that can evaluate different reclamation alternatives. The objective of this task is to encapsulate the knowledge gained regarding reconstructed watersheds into a decision analysis tool, which can then be adapted in orienting the future reclamation strategies; and

VIII. Evaluate the developed models with coarser data with the help of Regional Climate Models (RCM) and with the downscaled Global Climate Models (GCM) in order to enrich the understanding of the system and, in turn, to develop Sustainable Reclamation Strategy (SRS).

Jutla (2006) attempted task I with the help of a site-specific system dynamics model for reconstructed watersheds. The tasks III and V were given a comprehensive attempt by Parasuraman (2007) using data driven techniques (Artificial Neural

Networks and Genetic Programming). The current research work endeavors to complete task I and task IV with the help of system dynamics modeling approach and long term hydrological simulations are highlighted in the research framework (Figure 1.1). A concurrent Ph.D study is focusing on the generic model of task I as well as on completing task VIII.

1.6 Synopsis of the Thesis

This thesis is organized in the following chapters addressing the accomplishment of the research objectives. Chapter 2 provides the literature review on the reclaimed landscapes, hydrological modeling of restored and natural watersheds, a description of the system dynamics approach, and a long term evaluation of the hydrological systems. Chapter 3 describes the study areas (reconstructed and natural study sites) considered in this study as well as field instrumentation for watershed monitoring. The modifications of the SDW model formulations to suit the selected reconstructed and natural watersheds and the overall research methodology of long term simulations and probabilistic assessment are also presented in this chapter. Chapter 4 presents the results and discussions related to the modeling of reconstructed and natural sites, and the comparative hydrological assessment. The summary, research contributions, and limitations followed by possible future extensions of the research are presented in the final chapter, Chapter 5.

CHAPTER 2. LITERATURE REVIEW

In order to achieve the objectives stated in the first chapter of this thesis, hydrological modeling of reconstructed and natural watersheds is necessary. This chapter provides a brief literature review of the three main components of this study, namely, (1) reconstructed watersheds, (2) watershed modeling, and (3) modeling (simulation) of the environment selected for this study, the system dynamics approach.

2.1 Reconstructed watersheds

2.1.1 Overview

Restoration of mined lands is necessary for the environment's sustainability. Therefore, research has been conducted recently on reclamation practices to investigate and help the formation, design, and management of practices (Haigh, 2000; Leskiw, 2004; Barbour et al., 2004; MEND5.4.2d, 2001; Elshorbagy, 2006). In general, soil covers are constructed on the mined sites as part of closure and/or reclamation work. General design and performance objectives of a typical soil cover (reclaimed or reconstructed watershed) constructed over a mine waste disposal may include the following (Rykaart and Caldwell, 2006; Leskiw, 2004):

- To limit deep percolation for achieving maximum soil water storage ability and to prevent water from reaching the underlying strata;
- To resist erosion by wind and water;

- To remain stable statically and seismically, and, in the long term, to prevent creeping or sliding down the sides of the pile;
- To support vegetation; and
- To endure for a defined long term period.

A typical soil cover is constructed with various soil layers to satisfy the aforementioned objectives. As pore pressure decreases (i.e., the soil becomes drier), the hydraulic conductivity of a coarse-grained material quickly drops below that of a fine-grained material. When a fine-grained material is placed over a coarse-grained one, a capillary break is created; consequently, flow into the coarse-grained layer is limited and the pore pressure must increase for significant flow to occur between the different soil types. This results in increased water storage in the fine-grained material (Milczarek et al., 2000).

2.1.2 Hydrological performance of the reconstructed watersheds

Effective hydrological performance is one of the primary objectives in the design and formation issues of reconstructed watersheds (Haigh, 2000; Leskiw, 2004; Elshorbagy and Barbour, 2007). Typical hydrological performance includes the ability of reconstructed watershed to have store-and-release moisture for vegetation growth and evapotranspiration requirements. Understanding the hydrological performance of reconstructed watersheds includes assessing the dominant hydrological processes such as evapotranspiration, soil moisture, and overland flow.

An initial hydrological assessment can be conducted using filed instrumentation of the hydrological and soil physical variables on reclaimed sites. This assessment helps observe the restoration and sustainability of the reclaimed watersheds for an initial understanding of the reconstructed system. Boese (2003) illustrates the comprehensive field instrumentation on reclaimed watersheds constructed on oil sands mined lands located in the Athabasca basin, Alberta, Canada.

Modeling practices of the hydrological processes of reconstructed systems would provide a more comprehensive view of the counterintuitive processes of the reconstructed system (Elshorbagy et al., 2005). Volumetric water content of a small portion of reclaimed land (a reclaimed slope of Southwest Sand Storage Facility of Syncrude Canada Ltd.) was simulated by Mapfumo et al. (2006a) using the Root Zone Water Quality Model (RZWQM). The texture of the topsoil in the study area ranged from sandy clay loam to clay loam with sand content between 42 and 52 % with a clay content between 26 and 37 %. On average, the tailings sand below the topsoil contained 95% sand and 2 % clay. The study under-estimated the moisture conditions of the study site in spite of the model calibration using wet year and dry year data. The results were attributed to the fact that the reclaimed land was in the evolution process.

Swanson et al. (2003) modeled movement of liquid water and water vapor within a soil cover situated in a humid climate (British Columbia, Canada). The study showed that the vapor flow was the dominant flow mechanism near the surface of the cover. Under extreme and normal climatic conditions, the percolation through the cover system was limited to approximately 2% of annual precipitation, and that oxygen flux through the cover was reduced by about 98% from uncovered (without soil cover on mine waste) conditions.

Adu-Wusu et al. (2007) predicted soil water storage, soil temperature and suction using a two-dimensional soil-atmosphere model Vadose/W (Geo-Slope, 2002) on three test cover plots. The cover plots comprise a 0.8 cm thick geo-synthetic clay liner (GCL), a 46 cm thick 92% sand-8% bentonite mixture, and a 60 cm thick sandy silt barrier that covers over 20% of a sloping mine waste rock platform located at Whistle mine, Ontario, Canada. The results indicated that evaporation significantly affected other components of the water balance including percolation, runoff, and soil water storage. Yanful et al. (1993a) explained the design of a composite soil cover on an experimental waste-rock pile near Newcastle, New Brunswick, Canada. The primary objective of the soil cover was to reduce the gaseous oxygen flux and the water percolation into the underlying pile. Dawson and Gilman (2001) described the traditional approaches and their limitations of land reclamation and emphasized the continuous need for improving and developing new technologies.

Chanasyk et al. (2006) estimated actual evapotranspiration of a small reclaimed land using simplified water budget and soil water reduction methods (based on extractable soil water concept). The study described the reliability of each method for the hydrological modeling purposes on reclaimed lands. Their study concluded that the rate at which water infiltrates and seeps from a typical cover system is a function of soil moisture retention characteristics, as well as of climate, vegetation type, and saturation level of its soil (Milczarek et al., 2000).

Elshorbagy et al. (2005) modeled soil moisture, runoff, and evapotranspiration of a small reconstructed watershed and deterministically evaluated the reclamation strategy of reconstructed watersheds by developing and using a system dynamics watershed

(SDW) model. The model simulates vertical balance of the hydrological processes of the young reconstructed watersheds which had light vegetation. The SDW model helps in understanding the counterintuitive mechanisms induced in the reconstructed watersheds. Elshorbagy et al. (2007) explored the model further by using it on two adjacent reconstructed watersheds to assess their hydrological performance.

Camorani et al. (2005) investigated the possible effects of recent land-use changes on the frequency regime of floods for medium scale (76 km^2) reclaimed lands using a semi-distributed rainfall-runoff model. For the analysis, the study implemented a semi-distributed rainfall-runoff model (Storm Water Management Model abbreviated as SWMM developed by Huber and Dickinson, 1992). A considerable impact on the simulated hydrographs was observed, which may significantly increase the flood risk within the reclaimed areas.

In addition to the physically-based modeling attempts mentioned above, research was also initiated using data-driven techniques for hydrological modeling of the reconstructed watersheds. Parasuraman et al. (2006) used Feed Forward Neural Networks (FFNNs) and a novel neural network model called the Spiking Modular Neural Networks (SMNNs) to model evapotranspiration on a reclaimed site (a waster rock overburden pile) in Alberta, Canada. Parasuraman et al. (2007) also used genetic programming (GP) to characterize evapotranspiration of another reclaimed site (south west sand storage, SWSS) in northern Alberta, Canada.

The successful application of these modeling tools on reconstructed watersheds promises a means to understand and characterize the complex processes of restoring watersheds. In spite of all these hydrological modeling attempts on the reclaimed sites, literature on the assessment of the hydrological performance of reclaimed sites is rare, especially in terms of their restoration abilities relative to natural watersheds, particularly in semi-arid regions.

2.1.3 Long term evaluation of land capability and sustainability

The land capability can be defined as "the ability of the land to support a given land use, based on evolution of the physical, chemical and biological characteristics of the land, including topography, drainage, hydrology, soils and vegetation" (Leskiw, 2004). The land capability assessment involves evaluation of soil characteristics (slope stability, erosion, etc) as well as of environmental (water quality, etc), ecological (vegetation restoration) and hydrological (soil-atmospheric water fluxes) performances. Therefore, a land capability assessment helps to understand the sustainability of reconstructed systems.

The sustainability is described as the ability of reclaimed plant communities to establish and progress to maturation without the operator's ongoing input of nutrients, water, seeds or seedlings (Leskiw, 2004). In addition, reclaimed lands should have the ability to be resilient and, thus, be able to recover from infrequent, naturally occurring environmental disturbances such as fire, floods or drought at a rate similar to natural watersheds. To examine such scenarios, long term evaluation is required; it is helpful to study the response of reconstructed systems to different meteorological forcings. Typically, long term evaluation can be performed in two steps.

First, for an initial understanding of the system, long term monitoring of the system to measure variables (hydrological, soil physical and ecological) is necessary; and second, modeling and long term simulations are necessary to help examine different scenarios on the reconstructed systems. Typical evaluation of the hydrologic impacts of land use change on watersheds was performed with an event-based modeling approach, such as direct runoff of a storm event (Linsley, 1982). However, in order to study the temporal distribution of soil moisture dynamics, and, thus, to assess the soil-moisture storage ability of reconstructed watersheds, continuous long term simulations are required.

Elshorbagy (2006) presented a multi-criterion decision analysis (MCDA) approach to assess the utility of reconstructed watershed modeling for management decisions with the help of long term simulations (61 years). Elshorbagy and Barbour (2007) presented a probabilistic approach for design and hydrologic performance assessment of reconstructed watersheds using a case study from the oil sands in northern Alberta. These studies emphasize the importance of long term assessment in understanding the long-term hydrological performance of reconstructed systems.

2.1.4 Comparative assessment of the hydrological performance

The goal of land reclamation is to create a land capability equivalent to that which existed prior to the disturbance of natural landscapes. Intuitively, mining alters the soil physical properties. Hence, constructed mine soils typically exhibit physical conditions that might be drastically altered by anthropogenic perturbations rather than natural soil forming processes (McSweeney and Jansen, 1984).

Potter et al. (1988) compared physical soil properties of constructed (reclaimed) and undisturbed (natural) lands. Reclaimed mined soils were studied 4 and 11 years after reclamation. The study reported that bulk density was greater in the topsoil and subsoil materials of the constructed soils than in the undisturbed A and B soil horizons. In their study, the saturated hydraulic conductivity (K_s) of the reclaimed topsoil was about 25 % of the undisturbed A soil-horizon, and the reclaimed subsoil's K_s was less than 10 % of the undisturbed B horizon. The reduction in K_s was attributed to the increase in bulk density and to the disruption of soil structural units and associated interpedal pore spaces during mining and soil construction. However, concerns related to bulk density are negligible in the case of the reconstructed watershed considered in this study since it is constructed during the winter season (Shurniak, 2003).

Shukla et al. (2004) assessed the soil quality of two reclaimed sites (about 27 years old) and on two undisturbed sites in Ohio, United States. The study observed that reclamation improved both physical and also water transmission properties of both sites. Negley and Eshleman (2006) made a comparative study of storm flow responses of surface-mined and forested watersheds using the Unit Hydrograph (UH) concept. They noted that storm runoff coefficients, total storm runoff, and peak hourly runoff rates are higher for the mined sites than the natural sites.

None of the literature appears to have assessed long term hydrological sustainability, in particular, the soil moisture store-and-release ability of reconstructed watersheds compared to the natural watersheds in semi-arid regions.

2.1.5 Probabilistic assessment of the hydrological performance

Considering the stochastic nature of the hydrological processes, it is imperative to account for their randomness in the hydrological modeling practices. This account would help increase the reliability of the outcomes of scientific endeavors in hydrological studies (Chow et al., 1988). "*A deterministic model is one in which every set of variable states is uniquely determined by parameters in the model and by sets of previous states of these variables. Therefore, deterministic models perform the same way for a given set of initial conditions. Conversely, in a stochastic model, randomness is present, and variable states are not described by unique values, but rather by probability distributions*" (Beven, 2001a).

Yevjevich (1974) provided a theoretical description of determinism and stochasticity in hydrology, and suggested that the integration of both deterministic and stochastic approaches assures the best mathematical-physical understanding and description of hydrologic processes and environments. The deterministic modeling attempts are recommended to be accompanied by probabilistic analysis for better management and decision analysis. Apel et al. (2003) made an assessment of flood risks using deterministic-probabilistic modeling system. In their study, a simple probabilistic model was accompanied by a complex deterministic model for the quantification of flood damage and risk. Elshorbagy and Barbour (2007) presented a probabilistic approach for the hydrological performance's assessment of reconstructed watersheds. Their study presented the quantification of the model's predictive uncertainty and the frequency-based assessment of soil moisture deficit.

Elshorbagy et al. (2007a) presented a probabilistic approach to cope with the percentile-based water quality standards based on Monte Carlo (MC) simulation; then, to quantify the margin of safety and the inherent variability of stream flows in the process of total maximum daily loads (TMDL), they compared it to a deterministic approach (Ormsbee et al., 2004). Mapfumo et al. (2006b) conducted a study to characterize the spatial variability of the soil water content on a reclaimed site in northern Alberta. The study used conditional stochastic simulation to address the spatial variability of soil water, and indicated a high degree of uncertainty. Their study implied that generating exhaustive data sets may require more sampling points at closer spacing to reduce uncertainty.

All these studies highlight the need to supplement the traditional deterministic approach in hydrological studies with probabilistic analysis.

2.2 Watershed modeling

2.2.1 Overview

In simple words, Penman (1961) defines hydrology as the science that attempts to answer the question: "What happens to the rain?". In detail, hydrology can be defined as the geosciences that describe and predict the occurrence, circulation, and distribution of the earth's water and its atmosphere. The quantitative descriptions of the water-flux-distribution become extremely complicated, mostly due to its spatial and temporal variations (Singh, 2002). Watershed modeling includes modeling the hydrological components/processes at the watershed scale. Typically, watershed models are employed to understand the dynamic interactions between the climate and land-surface hydrology, and they tend to satisfy the water balance equation, where the dominant processes are mentioned on daily scale:

$$P = R_f + P_r + ET \pm \partial S \quad (2.1)$$

Here P is net precipitation (mm); R_f is runoff (mm); P_r is deep percolation (mm); ET is evapotranspiration (mm); and ∂S is soil moisture storage change (mm). Each hydrological process is induced with high complexity and, thus, is a challenging process to simulate. Many models, both physically based (analytical, and numerical) and also data-driven based, are being used for characterizing these hydrological processes.

Precipitation in the form of snowfall is a major concern in the Canadian prairies. Snowfall during winter accumulates and melts during early spring causing significant overland flow. In addition, snowmelt also governs the soil moisture in the early spring through its infiltration into frozen soil. Many models are available for the characterization of snowmelt (Gray et al., 1989; Gray et al., 2001). Pomeroy et al. (1999) provided detailed study of modeling snow-atmosphere interactions in cold continental environments. Generally, snowmelt is characterized by energy balance or temperature index methods (Dingman, 2002). Typically, energy equation which is based on law of conservation of energy is used to characterize the snowmelt and the equation (Dingman, 2002) is presented as follows:

$$Q_m = Q_n + Q_h + Q_e + Q_g + Q_p + Q_A - \Delta U/\Delta t \quad (2.2)$$

where:

Q_m = Energy flux available for snowmelt (W m^{-2}),

Q_n = Net radiation flux (W m^{-2}),

Q_h = Convective flux of sensible heat (W m^{-2}),

Q_e = Convective flux of latent heat (W m^{-2}),

Q_g = Conductive flux of ground flux (W m^{-2}),

Q_p = Advection from rain in vertical direction (W m^{-2}),

Q_A = Small-scale advection from patches of soils in horizontal direction (W m^{-2}),

$\Delta U/\Delta t$ = Rate of change in internal energy (W m^{-2}).

The amount of melt can be calculated from Q_m from the below equation:

$$M = \frac{Q_m}{\rho_w B h_f} \qquad (2.3)$$

where:

ρ_w = density of water (1000 kg m^{-3}),

B = fraction of ice in a unit of wet snow (0.95 - 0.97),

h_f = latent heat of fusion of ice (333.5 kJ kg^{-1}).

Most of the snowmelt occurs due to solar radiation which is not related to air temperature (Shook and Gray, 1997). In the current study, snowmelt was estimated using a formulation based on the temperature index suggested by Anderson (1976) to account for the spring snowmelt, and the formulation is presented in Chapter 3. This method was used to reduce the model complexity, and to avoid calculation of solar radiation. This method is only valid for the data it is used on. In the present study, snowmelt is relatively small component as the hydrological modeling is focused over growing season. Therefore, the resulting error is not significant in the study. Detailed literature review of other hydrological components is presented in a previous thesis, Jutla (2006), and is not repeated here for the sake of brevity.

The hydrological processes are characterized separately and integrated to form watershed models. Abundant watershed models are available in the literature depending on the size, scale, location, purpose, etc. Primarily, the categorization of watershed models is based on the temporal and spatial distribution scales and on the modeling methodology. Based on temporal scale, models are classified as event and as continuous based models.

An event model is one that represents a single event of a hydrological component that occurs over a period of time ranging from about one hour to several days. The initial conditions in the watershed for each event must be assumed or determined by other means and supplied as input data. A continuous watershed model is one that operates over an extended period of time, determining flow rates and conditions during both runoff periods and periods of no surface runoff. Thus, the model keeps a continuous account of the soil moisture conditions and, therefore, determines the initial conditions applicable to the following events of a hydrological component. At the beginning of the simulation, the initial conditions must be known or assumed.

Based on the spatial distribution scale, watershed models can be classified as either lumped or distributed watershed models. Lumped models do not explicitly take into account the spatial variability of inputs, outputs, or parameters. In this approach, the hydrological components are evaluated based on vertical water balance. Distributed models include spatial variation in inputs, outputs, and parameters. In distributed watershed modeling approach, the watershed area is generally divided into a number of elements and the hydrological components are calculated separately for each element (Dingman, 2002; Beven, 2001a).

Based on the modeling methodology, models can be classified as mechanistic (physically-based or conceptual-based) and data-driven watershed models. In the mechanistic approach of the watershed modeling, the modeling formulations tend to satisfy the physically-based laws, such as conservation of mass and energy. The data-driven models typically include usage of statistical methodologies or soft-computing techniques. The model used in this study is a lumped, continuous, conceptual watershed model.

Indeed there has been proliferation of watershed models in all of the aforementioned categories (Linsley, 1982; El-Kady, 1989; and Singh, 2002). A typical example of a popular watershed model is SLURP (Semi-distributed Land Use-based Runoff Processes), developed at NHRI, Canada. It is a continuous, conceptual model that simulates the behavior of the watershed by carrying out vertical water balances for each element of a matrix of the watershed's landcovers and subareas, and then routing the resulting runoff between subareas (Kite, 1995).

Another popular watershed model, SWAT (Soil and Water Assessment Tool) (Arnold and Allen, 1993), is a long-term, continuous simulation watershed model with good user-friendly architecture. SWAT was developed to predict the impact of land management practices in large complex watersheds with varying soils, landuse, and management conditions over long periods of time. Watersheds with no monitoring data can also be modeled using the SWAT model. Other watershed models are tabulated in Table 2.1 presenting their characteristics.

Table 2.1. Popular watershed models and their characteristics.

Model	Location of application	Developer(s) (year)	Characteristics
Hydrologic Engineering Centre-Hydrologic Modeling System (HEC-HMS)	USA	Feldman (1981), HEC (1981, 2000)	Event based, Physically based, semi-distributed
National Weather Service (NWS)	USA	Burnash et al. (1973) Burnash (1975)	Continuous, Process based, lumped parameter
Hydrologic Simulation Package- Fortran (HSPF)	USA	Crawford and Linsley (1966), Bicknell et al. (1993)	Continuous, Physically based, semi-distributed
University of British Columbia Model (UBC)	Canada	Quick and Pipes (1977), Quick (1995)	Continuous, Process based, lumped parameter
Waterloo Flood System (WATFLOOD)	Canada	Kouwen et al. (1993), Kouwen (2000)	Continuous, Process based, semi-distributed
Runoff Routing Model (RORB)	Australia	Laurenson (1964), Laurenson and Mein (1993, 1995)	Event based, Lumped
Watershed Bounded Network Model (WBN)	Australia	Boyd et al. (1979, 1996), Rigby et al. (1999)	Event based, Geomorphology based, lumped
Physically Based Runoff Production Model (TOPMODEL)	Europe	Beven and Kirkby (1976, 1979), Beven (1995)	Continuous, Physically based, distributed
Systeme Hydrologique European (SHE)	Europe	Abbott et al. (1986a, b), Bathurst et al. (1995)	Continuous, Physically based, distributed
Xinanjiang Model	China	Zhao et al. (1980), Zhao and Liu (1995)	Continuous, Lumped, process based

In spite of the availability of many watershed models, studies are ongoing to answer a basic question: what modeling technology is better? (Singh, 2002). Elshorbagy

(2006) highlighted the reason for the presence of numerous watershed models and addressed that it is a conviction by the model developer that available models do not satisfy the conditions of the situation at hand, and, therefore, that new situation requires a new model (Elshorbagy et al., 2007).

Elshorbagy et al. (2005) listed the typical characteristics of a watershed modeling approach to simulate complex processes. These characteristics are as follows: (i) watersheds can be described and simulated in a simple fashion; (ii) the model should start simple, relying on the available data (similar to data-driven models), and be expandable to benefit from additional data as they become available; (iii) the model should be dynamic to cope with the nature of hydrologic systems; (iv) the model should have the ability to simulate both linear and nonlinear processes; (v) the model should provide a way to represent the feedback mechanism to handle counterintuitive processes; (vi) the model should have the ability to model human intervention and any shocks that might be encountered in the system; and (vii) the model should provide the ability to test different policy or management scenarios for better decision making (Elshorbagy et al., 2005).

These characteristics are well suited in the System Dynamics (SD) approach for watershed modeling. Detailed description of the SD approach is provided in Section 2.3.

2.2.2 Models on reclaimed sites

Modeling hydrological processes of reclaimed landscapes is needed to understand the landscape’s hydrologic behavior, for a vital design criterion is sufficient moisture store-and-release ability. Limited studies are available that focus on modeling reconstructed/restored watersheds. The popular models used on reclaimed sites in the literature are tabulated in Table 2.2. The HELP (Hydrological Evaluation of Landfill Performance) model developed by Schroeder et al. (1994) is a water budget model that performs a sequential daily analysis to determine runoff (based on the SCS curve number method), evapotranspiration (based on a modified form of the Penman equation), and percolation (based on Darcy's law) from waste containment systems that consist of covers, liners, waste material, and leachate collection systems. Woyshner and Yanful (1993) used the HELP model to evaluate the long-term efficiency of a three-layer cover system with respect to its ability to maintain water saturation. The model is useful for long term simulations allowing daily analysis for up to 100 years.

Table 2.2. Summary of typical models used in the literature on the reclaimed watersheds.

Model	Developer (year)
SWIM	CSIRO (1990)
HELP	Schroeder et al. (1994)
SEEP/W	Geo-Slope (1993)
RZWQM	USDA-ARS (1992)
UNSAT-H	Fayer and Jones (1990)
SoilCover	USG (1997)
SDW model	Elshorbagy et al. (2005)

Bruch (1993) used the SWIM (Soil Water Infiltration and Movement) model in the analysis of evaporative fluxes from layered soil covers. The SWIM model is a one dimensional numerical (fixed-grid method) model to simulate saturated and unsaturated flows. The model estimates evaporation calculated as a fraction of potential using a modification of the Dalton mass transfer equation. The transpiration rates are calculated from steady-state radial flow to roots and allow for the specification of up to four concurrent vegetation types with corresponding growth rates.

Shurniak (2003) used SoilCover model for predicting soil-atmospheric fluxes and associated moisture movement in a variety of reclaimed soil cover systems. The SoilCover model is a one-dimensional, transient, finite element, heat and mass transfer model that couples land-atmospheric fluxes. The principles of Darcy's, Fick's, and Fourier's laws are used to describe the movement of moisture, water vapor, and heat respectively. A modified Penman formulation (Wilson et al., 1994) was used in the model for the coupling of soil profile with the atmosphere.

The UNSAT-H (Fayer and Jones, 1990) model was used by Fayer et al. (1992) for hydrologic modeling of protective barriers for radioactive waste disposal. The model is a soil-water and heat flow model that can simulate both liquid and vapor moisture movement. A two-dimensional model SEEP/W (Geo-Slope, 1993) was used by Yanful and Aube (1993) to simulate evapotranspiration from a composite cover consisting of a protective sand layer over a clay cover. Mapfumo et al. (2006a) used RZWQM (Root Zone Water Quality Model) for simulating soil water content of a small, reconstructed watershed in northern Alberta.

The RZWQM is comprehensive, process-based, one-dimension numerical model developed by USDA-ARS (1992). The model has been widely used in agricultural studies. The model constitutes six modules: hydrology; crop growth; chemistry; nutrients; pesticides; and management. The represented hydrological processes in the model include infiltration, runoff, water redistribution, water uptake by roots, transpiration, and soil evaporation. Among these models, two-dimensional flow models have a distinct advantage over one-dimensional models in that they provide a fully mechanistic description of fluxes in two dimensions. However, the disadvantage of most two-dimensional models is that they are not linked to the atmosphere. In addition, the 2-D models require a surface boundary condition that describes the downward and upward fluxes of the land surface (Swanson et al., 2003).

Considering these pros and cons, the current study uses a one-dimensional, site-specific, lumped, conceptual, semi-empirical, system dynamics approach-based watershed model, the SDW model (Elshorbagy et al., 2005), for evaluating the comparative hydrological sustainability of reconstructed watersheds relative to natural watersheds.

2.2.3 Calibration of the hydrologic models

A typical watershed modeling exercise involves an initial understanding of the system, preparation of mental models, and the layout of algorithms of the involved system processes that describe the cause and effect components; it also involves model building, calibration, sensitivity analysis, uncertainty analysis, and validation of the developed model. Calibration is defined as the process of improving algorithms by determining the model parameter's values and sequencing hydrological processes so that the model represents the real world phenomena (Viessman and Lewis, 2003). This is achieved by adjusting the model's parameters to obtain a better fit between observed and predicted variables. In hydrological modeling, runoff is commonly used as an observed variable to calibrate the model. However, depending upon the purpose of the modeling and data availability, one could choose multiple observed variables (e.g., evapotranspiration, soil moisture) for calibration of the model (e.g., Elshorbagy et al., 2005; 2007).

Manual and automatic calibration approaches are in practice in the hydrological modeling exercises. Numerous techniques and methodologies for automatic calibration have been developed for calibrating the hydrological models, taking advantage of the speed and power of digital computers (Duan et al., 2003). The manual approach requires the modeler to adjust the model parameters (calibration process) manually to get the desired fit between observations and predictions. This is the most widely used approach to calibrate watershed models, and involves considerable labor work (Madsen, 2000). However, this approach allows the modeler to have the ability of selecting multiple error measures and objective functions, and also a visual comparison of observations and predictions (Lawson, 2003; Anderson, 1997, Elshorbagy et al., 2005; Boyle et al., 2000).

The automatic calibration approach uses the help of a computer algorithm to search the parameter space and to perform multiple trials of the model. This approach seeks to be objective and is relatively easy to implement (Madsen, 2000; Kim, 2007). However, the model calibrations provided by such methods are not yet popular for reasons such as limited (one or possibly maximum two) objective functions, and the requirement of optimization-related-knowledge (Boyle, 2000). To emulate the benefits of manual and automatic calibration approaches for a single reliable and efficient calibration approach, hybrid or integrated methodologies are being developed (e.g., Boyle, 2000).

The ‘goodness-of-fit’ or ‘closeness’ of observed and simulated hydrological data is generally quantified with the help of error measures such as Root Mean Squared Error (RMSE), and Mean Absolute Relative Error (MARE), etc (ASCE task committee, 1993; Dawson et al., 2007). Legates et al. (1999) suggested that correlation and correlation-based error measures should be accompanied by absolute error measures. This is because correlation and correlation-based error measures are oversensitive to extreme values and are insensitive to additive and proportional differences between model predictions and observations. Attention should be given to select proper error measures for the calibration process, as different error measures may lead to different conclusions for the same set of observed and simulated values.

2.3 System Dynamics (SD) approach

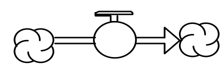
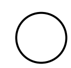
2.3.1 Definition and features of the SD approach

“System Dynamics is a theory of system structure and a set of tools for representing complex systems and analyzing their dynamic behavior” (Forrester, 1961).

“System Dynamics is a method of analyzing problems in which time is an important factor, and which involve the study of how a system can be defended against, or made to benefit from, the shocks which fall upon it from the outside world” (Ford, 1999).

The SD approach characterizes a given system with the help of stocks, flows, converters and connectors; these basic tools are explained in Table 2.3. System dynamics helps analyze complex systems by information feedback, which can be represented by causal loop diagrams. The word *causal* refers to the cause-and-effect relationships. The word *loop* refers to a closed chain of cause and effect. These causal loops are also called feedback loops (considering the influence of system's past behavior).

Table 2.3. Modeling tools using the System Dynamics approach (After Jutla, 2006).

Name	Description	Symbol
Stock	A component of the system where something is accumulated. The contents of the reservoir or stock may go up or down with time.	
Flows	Activities that determine the values of reservoirs or stocks.	
Converters	System quantities that dictate the rates at which processes operate and the reservoirs/stocks change.	
Connecters	Define the cause-effect relationships among the different components of the system	

One class of feedback system is negative feedback loops that seek a goal and that respond as a consequence of failing to achieve the goal, e.g., the thermostat. Another class of feedback system is positive feedback loops that generate growth processes where action builds a result that generates greater action, e.g., population growth. Negative feedback causes balance and stability, and positive feedback causes the system to diverge or to move away from the goal (Ford, 1999).

The system dynamics approach is well suited for analyzing the problems with a long-term time horizon with behavior governed by feedback relationships. (Vennix, 1996). Lee (1993) emphasizes that the model building in hydrology is an art and suggests that models should be built in two stages: (1) model conceptualization, and (2) model programming. These two stages are represented effectively in the SD modeling approach; thus, the SD approach could be an efficient tool for understanding the dynamics of hydrological processes.

2.3.2 SD-based environmental modeling applications

2.3.2.1 Ecological and environmental systems

The system dynamics approach allows users to model all kinds of systems from the simple to the complex. Voinov et al. (2004) designed a Library of Hydro-Ecological Modules (LHEM) with the help of the system dynamics approach (STELLA environment). This helps to create flexible landscape model structures that can be easily modified and extended to suit the requirements of a variety of goals and case studies. The LHEM includes modules that simulate hydrologic processes, nutrient cycling, vegetation growth, decomposition, and other processes both locally and spatially. These model results showed good agreement with data for several components of the model at several scales. Aassine and Jai (2002) proposed a vegetation growth model using system dynamics methodology and introduced a new approach for the study of spatio-temporal dynamical systems. Fitz et al. (1996) developed a General Ecosystem Model (GEM) to simulate a variety of ecosystem types using a fixed model structure. The success of these complex models shows the potentiality of system dynamics modeling approach in simulating the highly non-linear and complex ecosystems.

2.3.2.2 Water resources planning

Simonovic et al. (1997) and Simonovoic and Fahmy (1999) have used the SD approach for long term water resources planning and for policy analysis of the Nile River basin in Egypt. Fletcher (1998) used system dynamics as a decision support tool for the managing scarce water recourses. Using the SD approach, Ahmad and Simonovic (2000) carried out simulation of a multipurpose reservoir for flood management purposes. Their study showed that a SD-based simulation approach is a valuable alternative to conventional simulation techniques. The system dynamics methodology allows for increased speed of model development, ease of model structure modification, ability to perform sensitivity analysis and, more importantly, effective communication of model results.

Simonovic and Li (2003) developed an SD-based modeling framework for the assessment of climate variation and change impacts on the performance of a complex flood protection system. Stave (2003) developed a water system model based on the SD approach to facilitate public understanding of water management options in Las Vegas, Nevada. The SD approach has been also applied to carry out analysis on global systems. Simonovic (2002) developed WorldWater model to simulate world water dynamics and indicated the strong relationship between the world's water resources and its future industrial growth.

2.3.2.3 Hydrological modeling

The system dynamics approach has been used by modelers on both natural and reconstructed watersheds to estimate the water and temperature fluxes between land and atmosphere. Arp and Yin (1992) successfully used the system dynamics approach to develop a process-oriented model (ForHyM) that addresses all major water fluxes through forests. Two watersheds were used to calibrate and test the model: basin 31 of the Turkey Lakes watershed, Ontario; and the Lake Laflamme watershed in Quebec. The model was formulated using STELLA software package.

Using the system dynamics approach, Yin and Arp (1993) developed a process-oriented forest soil temperature model, ForSTeM. It runs in conjunction with the forest hydrologic model (ForHyM). The model was applied to ten different forest cover types in Ontario, Quebec, New Brunswick, and Colorado. The ForHyM model was later used on boreal forests (BOREAS, SSA study areas) by Balland et al (2006) to model snowpack and soil temperatures and soil moisture conditions. All these models are site-specific models and need further calibration to accommodate a different site.

Elshorbagy et al. (2005) used the SD approach to develop the first system dynamics watershed (SDW) model to study the hydrological performance of a reclaimed (reconstructed) watershed. The SDW model was used by Elshorbagy et al. (2007) to study the hydrological performance of two other reconstructed soil covers with different thicknesses. With the help of the SD approach, Elshorbagy (2006) employed a Multicriterion Decision analysis (MCDA) technique to address both the utility of watershed modeling and also the efficacy of watershed monitoring programs. With the help of long term simulations and a probabilistic approach, Elshorbagy and Barbour (2007) used the SDW model (Elshorbagy et al., 2005) to assess the hydrological performance of reconstructed watersheds.

2.3.2.4 Water quality

The system dynamics approach was also employed in water quality related studies. A system dynamics model was developed by Tangirala et al. (2003) using an object-oriented modeling environment (STELLA) to simulate and analyze water quality (TMDL) management strategies for a nutrient impaired stream. Their model helps the user to separate policy questions from the data and provides the facility to generate different modeling scenarios. Elshorbagy and Ormsbee (2006) discussed the potentiality of object-oriented simulation environment for surface water quality management based on the concepts of system dynamics (OO-SD); they provided the characteristics of the OO-SD approach supplemented by a case study in southeastern Kentucky, USA. Yin and Arp (1992) developed a system dynamics approach based model (ForIoM) to simulate ion fluxes through water flows in forests. ForIoM used ForHyM and ForSTeM as feeding modules to provide the necessary hydrologic and soil temperature information.

2.3.3 STELLA software package

STELLA (High Performance Systems, Inc., 2007) is a system dynamics simulation environment software with icon-based simulation tools that uses differential equations to represent stocks and flows. This software has been widely used for modeling purposes in studies of ecology, the environment, socio-economics, and water resources. It is user-friendly with simple graphing and table features for an easy visual and quantitative assessment of the model outcomes. Three numerical integration methods are available in STELLA: Euler; Runge-Kutta 2; and Runge-Kutta 4. The delta time (dt) for the numerical solution is determined by the user (within the limited values) and can be specified according to the user's requirements.

Rizzo et al. (2006) provided a comparison of five dynamic systems-based software packages with a case study of a canopy surface wetness model. They concluded that selecting modeling software includes many factors such as modeling potential, demographics, budget limitations, built-in sensitivity and optimization tools, and user friendliness vs. computational power. Figure 2.1 shows a brief identification and conceptual relationship between five modeling software packages in terms of ease of use and requirement of computational power. In addition to its user-friendliness, STELLA has become a choice of many modelers due to its ease of use and to its low requirement of computational power.

In this study, a developed System Dynamics Watershed (SDW) model (STELLA environment) is modified and used to model the hydrological processes (soil moisture, evapotranspiration, and runoff) of a reclaimed experimental watershed located in the Athabasca mining basin.

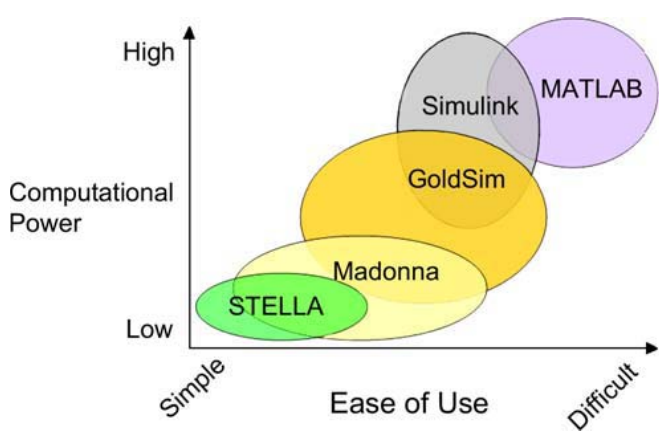


Figure 2.1. Overview of software packages for ease of use and computational power in modeling dynamic systems (After Rizzo et al., 2006)

A similar model is developed and used for modeling the hydrological processes of a natural watershed (boreal forest). Using the above calibrated and validated models, long term simulations (50 years) are carried out on both the reclaimed and natural watersheds. Furthermore, with the help of a probabilistic approach, the daily long term soil moisture results are used to address the comparative hydrological sustainability of reconstructed and natural watersheds.

CHAPTER 3. MATERIALS AND METHODOLOGY

3.1 Overview

This chapter describes the study areas and the model conceptualization adopted using the system dynamics approach for reconstructed and natural watersheds. The methodology carried out for the comparative assessment of the long term hydrological performance with the help of a probabilistic approach is also described in this chapter. Figure 3.1 presents a flow chart of the methodology adopted for evaluating the comparative hydrological sustainability of reconstructed and natural watersheds. It includes:

(a) Modifications to an existing site specific SD watershed model to simulate the hydrological processes of a reconstructed watershed;

(b) Development of a similar model for modeling the hydrological processes of a natural forested watershed;

(c) Calibration and validation of both models using measured hydro-meteorological data;

(d) Long term simulations on both reconstructed and natural watersheds to assess the sustainability of reconstructed watersheds; and

(e) Probabilistic analysis for the comparative assessment of the hydrological sustainability of the reconstructed watershed relative to the natural watershed.

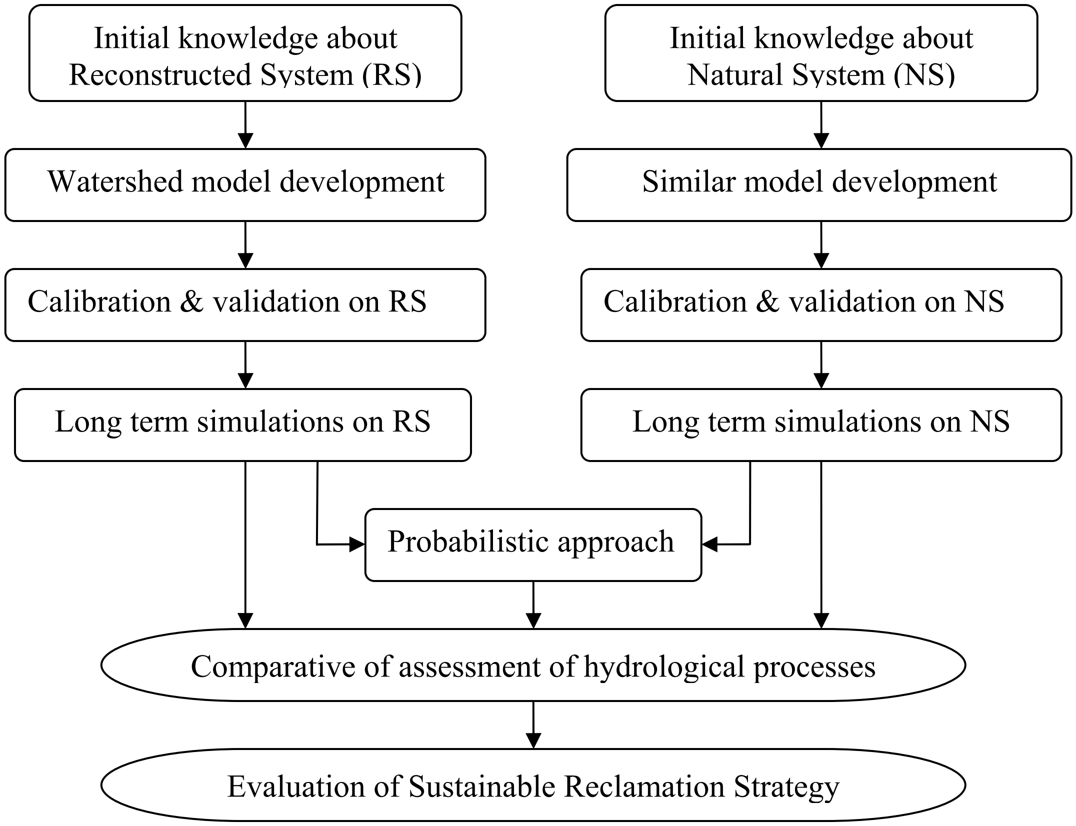


Figure 3.1. Overview of the adopted methodology of evaluation of the comparative hydrological sustainability.

3.2 Study areas description

In this study, case studies of a reconstructed watershed in an oil sands mining area located in northern Alberta and a natural watershed (boreal forest) located in central Saskatchewan were selected. The locations of the study areas are shown in Figure 3.2.

3.2.1 The reconstructed watershed site

Syncrude Canada Ltd. (SCL) has been conducting large scale experiments on its reconstructed watersheds. One such reconstructed landform is the South Bison Hill

(SBH) dump. The SBH ($57^{o}39^{'}$N and $111^{o}13^{'}$W) is a saline-sodic clay shale overburden landform located north of Fort McMurray, Alberta, Canada.

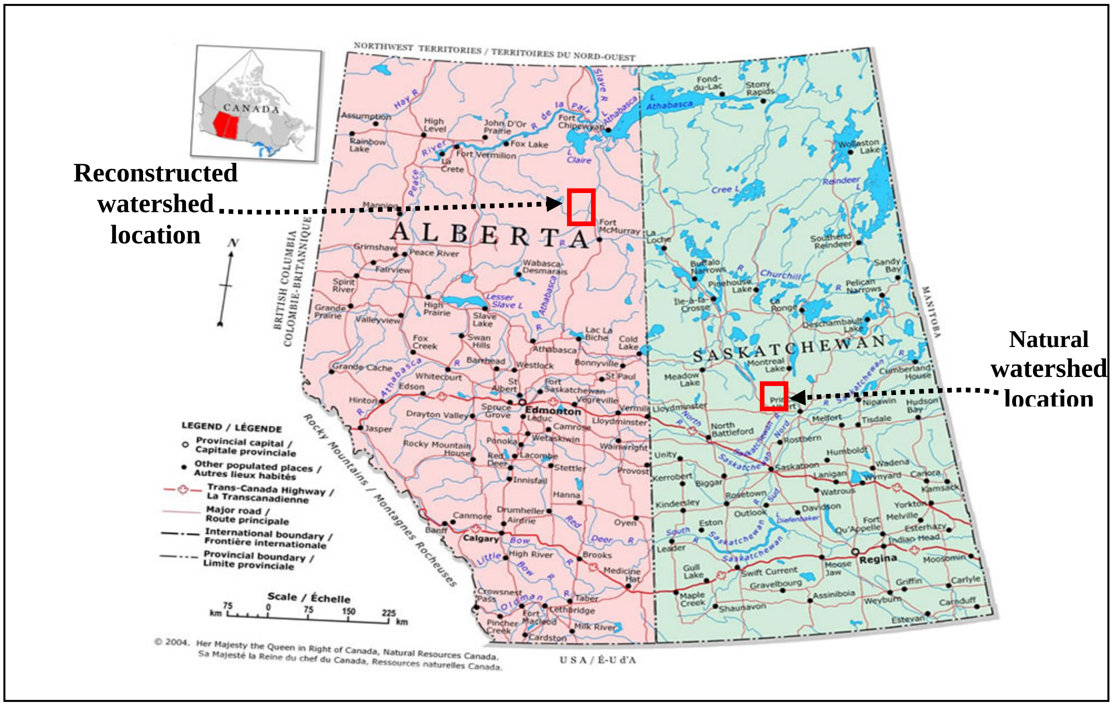


Figure 3.2. Location of reconstructed and natural watershed study areas.

It was constructed in stages with shale overburden from oil sands mining between 1980 and 1996. The area of the study site is approximately 2 km^2, rising 60 m above the surrounding landscape and possessing a large, relatively flat top. Reclamation proceeded in two phases; the soil capping on the north slope of the landform was reconstructed with two different layers in January, 1999. This area was then fertilized and seeded to agronomic barley and planted to white spruce and aspen in the summer of 1999. The top of the structure and the remaining slopes (sub-watersheds) were capped with a peat mineral mix (15-20 cm thick) overlying a secondary (glacial till) layer (20-80 cm thick). The area was fertilized and seeded to agronomic barley in the summer of

2002 and then planted to white spruce and aspen in the summer/fall of 2004 (Carey and Duncan, 2004; Carey, 2006; Parasuraman et al., 2006, 2007). The flat, top area of SBH dump is considered in this current study. The reconstructed study area is located in the semi-arid region of Canada where evapotranspiration is the most moisture demanding hydrological process. Based on the climate data from an Environment Canada meteorological station at Fort McMurray (56^{o} 39' N, 111^{o} 13.2' W), a 30-year period (1971-2000) mean annual temperature was 0.7 °C, and the annual precipitation was 455.5 mm.

The soil properties of the peat, till, and shale layers were similar to those estimated from a 100 cm thick adjacent sloping sub-watershed of SBH dump (Elshorbagy et al., 2005; Jutla, 2006). The porosity of the peat, till, and shale layers were of 50%, 54% and 25% respectively. The saturated hydraulic conductivity for the peat, till and shale layers were taken as 17 cm/hr, 2.1 cm/hr, and 0.03 cm/hr respectively. The wilting point moisture contents for the peat, till and shale layers were 10%, 11%, and 10% respectively (Jutla, 2006; Boese, 2003; Shurniak, 2003). The soil water characteristic curve (SWCC) was also similar to the one used for the watershed modeling of the 100 cm thick sloped reconstructed watershed by Elshorbagy et al. (2005) and Jutla (2006).

Major plant species on the top of the SBH were foxtail barley (*Hordeum Jubatum*), and minor species include fireweed (*Epilobium angustifolium*), sow thistle (*Sonchus arvense*), and white and yellow sweet clover (*Melilotus alba, Melilotus officinalis*) (Carey and Duncan, 2004; Carey, 2006; Parasuraman et al., 2006, 2007). A fully automated meteorological station that monitors air temperature (AT), relative humidity (RH), wind speed (WS) and direction, net radiation (NR), and precipitation (P) was installed in July, 2001. AT and RH were measured with a model HMP45CF probe. A R.M. Little (Model 05103) wind monitor was used to measure wind speed direction. Net radiation (i.e. the algebraic sum of incoming and outgoing all wave radiation) was measured with an NR-Lite Net Radiometer, which is a high-output thermopile sensor mounted approximately 2.5 m above the ground surface. The precipitation was recorded with a model TE225 tipping bucket rain gauge.

Time Domain Reflectrometry (TDR) sensors (Model CS 615) were installed to measure *in situ* volumetric water content of the soil. *In Situ* soil matric suction and temperature were measured using thermal conductivity sensors (Model CS 229). Water content, temperature, and matric suction of the soil were measured four times a day at depths of 5, 15, 25, 40, 95, 115, 125, and 180 cm below the soil surface (O'Kane Consultants Inc., 2001). An eddy covariance technique was used to measure the fluxes of momentum, sensible heat, and latent heat on a continuous basis (sampled at 10 s) with the help of another meteorological tower placed in the approximate centre of SBH in 2003 (Carey and Duncan, 2004, Carey, 2006; Parasuraman et al., 2006) (Figure 3.3 & Figure 3.4).

The leaf area index (LAI) was measured in two week intervals with an LAI-2000 (Li-Cor) leaf area index meter and less frequently by clipping vegetation within a 50 cm by 50cm quadrat. Runoff generated from the SBH top enters a drainage system, which feeds into peat pond (a wetland highlighted in Figure 3.3). A zero-height v-notch weir was constructed in 2001, and was instrumented with a data acquisition system for monitoring flow rate (O'Kane Consultants Inc., 2002). No data has been collected as part of this current study; rather, the available data for 2005 and 2006 were used in this study for the hydrological modeling of the reconstructed study area, the SBH site.

Figure 3.3. South Bison Hill (SBH) of SW-30 Dump of SCL reclaimed landform (looking south).

Figure 3.4. Photograph of the meteorological tower on the SBH site.

3.2.2 The natural watershed site

A boreal forest site was used to represent the natural watershed in this study. Boreal forest represents 77 % of the total forested area in Canada and contributes significantly to the global ecological equilibrium (Jones, 1987). An international, interdisciplinary, large scale experiment, BOREAS (Boreal Ecosystem - Atmospheric Study) was carried out on boreal forests of Canada located in the central Saskatchewan and northern Manitoba, Canada, during 1994-1996. The BOREAS project's main objective was to investigate the interactions (water, carbon, etc) between the boreal forest and the atmosphere (Sellers et al., 1995, 1997; Hall, 1999). The BOREAS project was set on the northern and southern edges of the Canadian boreal forest in a 1000 x 1000 km region covering most of Saskatchewan and Manitoba (Figure 3.5).

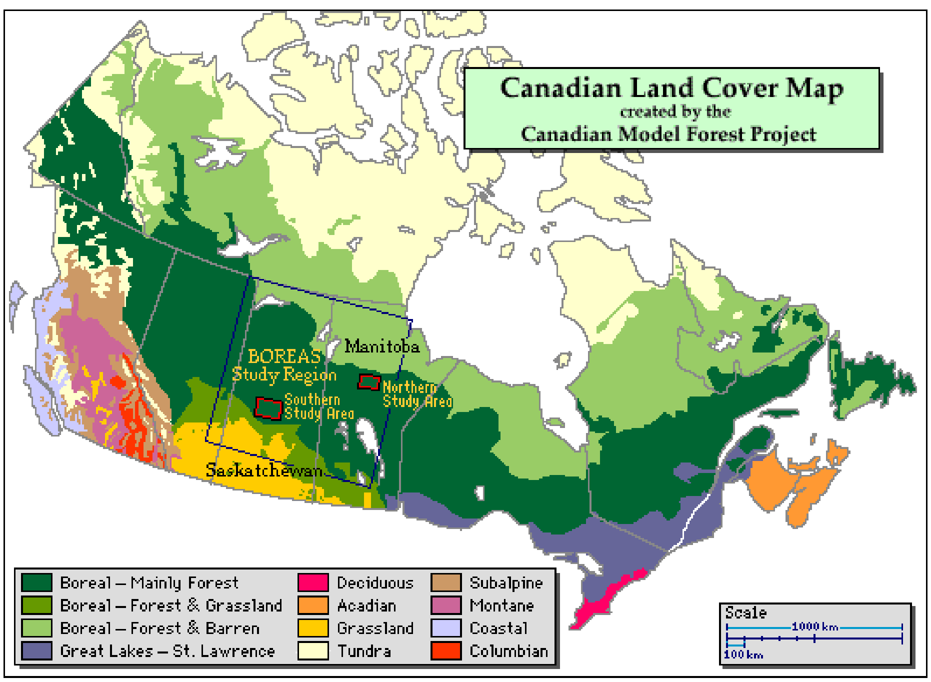


Figure 3.5. Boreal forest region in Canada. (Source: http://www.daac.ornl.gov/)

The project has two major study areas, namely the northern study area (NSA) with a 100 x 80 km covering region, and the southern study area (SSA) with a 130 x 90 km covering region. Each study area has sub-study areas designated by the dominate vegetation type in each area. The vegetation types are old jack pine (OJP), little jack pine (YJP), old black spruce (OBS), little black spruce (YBS), and old aspen (OA). In addition to the above-mentioned five sub-study sites, the SSA has another sub-study area named Fen site. Considering the vegetation and soil properties (described in the following paragraphs), the old aspen site has been chosen in this current study as a natural reference for the comparative assessment of hydrological performance between reconstructed and natural watersheds.

Field instrumentation on the OA site has continued since 1997 as part of the Boreal Ecosystem Research and Monitoring Sites (BERMS) program (http://berms.ccrp.ec.gc. ca; McCaughey et al., 2000) and since 2002 as part of the Fluxnet-Canada research (httt://www.fluxnet-canada.ca/) network. For the sites under their observation, these projects provide data for public access for academic and research purposes.

The old aspen site (53.629^{o}N, 106.198^{o}W) is a mature deciduous forest located near the south end of Prince Albert National Park, Saskatchewan, Canada, with an elevation of about 600.63 m (Figure 3.6). The old aspen site covers about 13.5 % of the SSA region. The forest vegetation canopy has two layers: a trembling aspen (*Populus tremuloides*) overstory with nearly 21 m in height, and an approximately 2 m high hazelnut (*Corylus cornuta*) understory interspersed with alder. The forest was regenerated after a natural fire in 1919, and had a 1998 stand density of ~830 stems ha^{-1}.

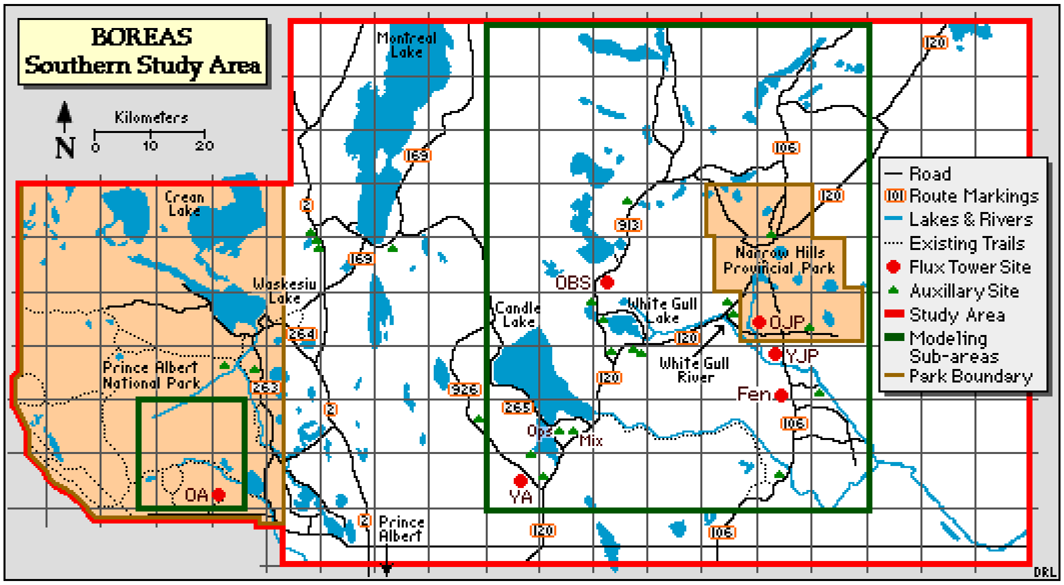


Figure 3.6. Old Aspen (OA) site in the BOREAS-Southern Study Area (SSA). (Source: http://www.daac.ornl.gov/)

The soil surface has 1-7 cm organic layer (decomposed leaf litter, etc), and soil with a clay and sand till exists in between 7-30 cm. Below 30 cm, the soil becomes a more gravelly till, with larger rocks and more clay (http://berms.ccrp.ec.gc.ca/data/data_doc/BERMS_main.doc; Barr et al., 2002, 2004). The soil formation within the root zone depth of the vegetation, which includes A, B, and C soil horizons, is considered in this study. The 30-year period (1971-2000) mean annual temperature was 0.4 °C, and the annual precipitation was 467 mm, based on the climate data from an Environment Canada meteorological station at nearby Waskesiu Lake (53.92 °N, 106.07 °W).

Intensive field instrumentation was installed by BOREAS during year 1993. Later, BERMS organization took over in the year 1997. The measurements of meteorological and soil properties in the old aspen site at the tower flux (TF) location are available for understanding the soil-atmospheric fluxes of the boreal forests. Air temperature and relative humidity were measured at different heights in relation to the structure of the forest canopy using an HMP35CF Temp/Humidity probe at 1, 4, 18, and 37 m above the ground surface. Net radiation was measured using a Middleton CNR-1 net radiometer above the forest canopy. A RMY propeller Anemometer (model 05103) was used to measure the wind speed and direction at 4 and 38 m from the ground surface. A Belfort (Model 5915) weighing gauge was used to measure the precipitation. CS Copper-Constantan 105T thermocouple probes were used to measure the soil temperature at 2, 5, 10, 20, 50, and 100 cm below the ground surface.

All these variables were measured at 30 minutes interval. CS615 soil moisture sensors (TDR) were used six times a day to measure the volumetric moisture content of the soil at different depths below the organic layers of leaf litter at 2.5, 7.5, 15-30, 30-60, 60-90, 90-120 cm below the ground surface. Measurements of the fluxes of momentum, sensible heat, latent heat were made with the eddy covariance technique and reported at 30 minutes interval; the detailed information is available in the following website (http://berms.ccrp.ec.gc.ca/data/data_doc/BERMS_main.doc). Leaf area index (LAI) of both the overstory and also the understory were measured near the flux tower using a plant canopy analyzer (PCA) (model LAI-2000). No data have been collected as part of this current study; rather, the available data for 1999 and 2000 were used for hydrological modeling of the natural watershed.

Considering the heterogeneity of the distribution of the soil horizons as well as the availability of the detailed data of the study area, the selection of the depth and the soil properties of a particular horizon become somewhat subjective. However, based on the information from the soil studies of the BOREAS experiments by the terrestrial ecology (TE) team (http://daac.ornl.gov/BOREAS/ boreas_home_page.html) and the literature (Balland et al., 2006), the most representative depths were chosen for the A, B, and C soil horizons.

The A-horizon with sandy loam texture of 25 cm thick, the B-horizon with sandy clay loam of 45 cm thick, and the C- horizon with a mixture of sandy clay loam of 40 cm thickness were considered in this study. The porosity of the A, B, and C soil horizons of the watershed were 51%, 45% and 46% respectively. The saturated hydraulic conductivity for the A, B, and C soil horizons were taken as 1.04 cm/hr, 0.24 cm/hr, and 0.2 cm/hr respectively. The wilting point moisture contents for the A, B, and C soil horizons were 16%, 12%, and 15% respectively. The soil water characteristic curve (SWCC) from the BOREAS experiments was used for the A-horizon. For B and C soil horizons, the SWCCs were estimated using Soil Water Characteristic module of SPAW hydrology software (Saxton and Rawls, 2006) with the help of the available data of fraction of sand, clay, and organic matter of the respective soil horizons.

The reconstructed watershed study area is a mined land within the boreal forests region of Canada. Hence, for the comparative hydrological assessment, a boreal forest site was chosen in this study. In addition, the observed data (hydro-meteorological and soil physical) required for the watershed modeling were available for the study sites of BOREAS SSA sites. Among the six sites, the Old Aspen site has fairly similar soil characteristics as in the case of the selected reconstructed watershed, whereas other sites in SSA region are more sandy soils. Therefore, in this study an Old Aspen site was chosen as a basis for the comparative hydrological assessment of the reconstructed watershed. The following Table 3.1 presents the soil properties of the layers of the reconstructed and natural watersheds.

Table 3.1. Summary of soil properties of the study areas.

Soil Property	Reconstrcted Watershed			Natural Watershed		
	Peat	Till	Shale	A-Horizon	B-Horizon	C-Horizon
Porosity (%)	50	54	25	51	45	46
Saturated Hydraulic Conductivity (cm/hr)	17	2.1	0.03	1.04	0.24	0.2
Wilting point moisture content (%)	10	11	10	16	12	15

The following Table 3.2 presents summary of meteorological conditions of the reconstructed and natural study areas for a 30-year period (1971-2000). Fort McMurray climate normals (Environment Canada) were considered as representative meteorological conditions of the reconstructed watershed study area. Prince Albert climate normals (Environment Canada) were considered as representative meteorological conditions of the natural watershed study area.

Table 3.2. Summary of meteorological conditions of the study areas.

Climate Variable	Reconstructed Watershed	Natural Watershed
Annual Rainfall (mm)	342.2	323.7
Annual Snowfall (cm)	155.8	111.3
Annual Precipitation (mm)	455.5	424.3
Annual Air Temperature (AT, ^{o}C)	0.7	0.9
Daily Extreme Positive AT (^{o}C)	37.0	38.8
Daily Extreme Negative AT (^{o}C)	50.6	50.0
Wind Speed (km/h)	9.5	12.1
Relative Humidity (%)	56.2	56.1

3.3 Watershed model description

3.3.1 Overview

The current study required a watershed model for simulating the hydrological processes and for assessing reconstructed watersheds long term. Considering the advantages of system dynamics approach in water resources modeling (Li and Simonovic, 2002), the system dynamics watershed (SDW) model (Elshorbagy et al., 2005; 2007) was used in this study. The SDW model was developed by Elshorbagy et al. (2005) as a mechanistic, semi-empirical, site-specific, lumped watershed model built in the STELLA (High Performance Systems, Inc.) environment. The model purpose (Elshorbagy et al., 2005) and applications (Jutla, 2006; Elshorbagy, 2006; Elshorbagy et al., 2007) were described briefly in the literature review chapter of this document. The site-specific model was built, calibrated, and validated on sloped reconstructed watersheds that had little vegetation at the time. In order to accommodate the sloping topography, a provision was made in the model for interflow characterization. Because the sloped study areas did not have significant amounts of vegetation, the model was not provided with a canopy interception module.

In this study, the SDW model was modified and adapted to the selected reconstructed watershed, which had some vegetation and a relatively flat topography. The interflow component in the SDW model was removed since the flat reconstructed soil cover did not contribute a significant amount of runoff in the form of interflow. The precipitation, which was intercepted by the vegetation (canopy), was accounted for using a canopy interception module that was developed and added to the SDW model in this study. Other corresponding modifications (explained in the following sections) were also required for the SDW model to characterize the hydrological processes including snowmelt, peat infiltration, till infiltration, etc. In this study, the modified SDW model for the reconstructed site is referred to as MSDW model. Considering its importance in the hydrological modeling of natural and reconstructed watersheds, a brief review of the canopy interception is provided below.

3.3.2 Canopy interception

Interception loss is the process by which precipitation is intercepted on the vegetation surface, and which subsequently evaporates directly to the atmosphere. Interception losses depend mainly on the precipitation intensity, duration, and frequency (Dingman, 2002). Losses are also affected by the vegetation type and its maturity stage, which can be expressed in terms of Leaf Area Index (LAI). Like evapotranspiration, interception losses cannot be measured directly. As a result, the most commonly adopted approach for estimating the canopy interception losses is through measuring the gross rainfall (R), throughfall (T_F), and the stem flow (R_s) to obtain canopy interception losses (E_c) from the following equation 3.1:

$$R = R_s + T_F + E_c \qquad (3.1)$$

Here R is the rainfall measured above the canopy; T_F is the rainfall that reaches the ground surface directly through the spaces in between and by dripping from the canopy; R_s is the water that reaches the ground surface by running down the trunks and stems; and Ec is water that evaporates from the canopy surface. Measuring the components of this equation is not straightforward. Helvey and Patric (1965a) suggested taking the average of 20 rain gauges distributed randomly on a portion of the catchments under consideration to give an estimate of the throughfall. Also, Helvey and Patric (1965a) used flexible gutters tightly attached to the trees' trunks to measure the average amount of the stem flow. Calder and Rosier (1976) suggested the use of plastic sheets to measure the net rainfall. For litter interception (grass), Merriam (1961) used an artificial rain and measured the net rainfall in a small isolated area. Other studies suggested collecting undisturbed litter samples and weighting them on a recording scale in laboratory (Putuhena and Cordery, 1996).

The interception losses can range typically from 10 to 40% of various plant communities (Dingman, 2002). Considering the uncertainties and the inflexibility associated with the above mentioned methods of measuring the interception losses, there is a need to develop a conceptual model that simulates the interception losses in many hydrological models. Building on the existing model of Elshorbagy et al. (2005; 2007), efforts were made in this study to develop a canopy interception module on a daily time step. This module was incorporated into the existing model. The module is a simplified approach to the Valente et al. (1997) conceptual model, and is presented in the later sections. The module adopted in the SD model uses a simpler approach, due to the difficulty in obtaining some of the required input details such as trunk storage capacity, etc. In this approach, the total precipitation is assumed to be divided into two main components: (i) Canopy Interception (Ic); and (ii) Throughfall (T_F). Figure 3.7 is a demonstration of the simplified approach used in the SD model.

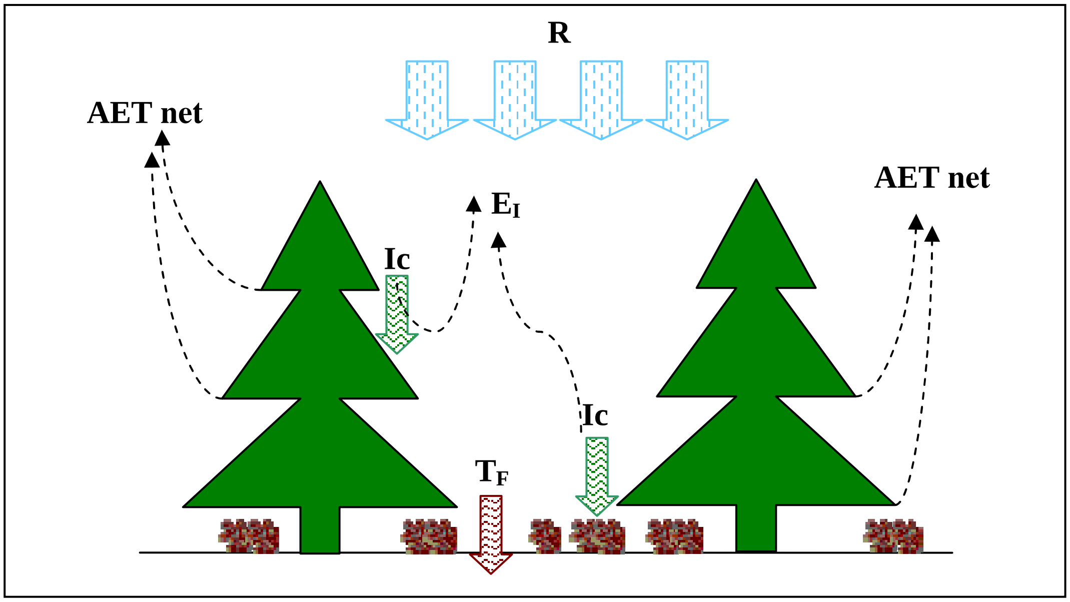


Figure 3.7. The conceptual framework of the canopy interception module in the MSDW model.

The canopy interception loss includes water intercepted and consequently-evaporated by leaves and stems, and also the water intercepted by the under-canopy. Based on the leaf area index of the vegetation, the canopy interception portion of the precipitation is characterized in the MSDW model and is described later in this chapter. The remaining portion of the gross precipitation reaches the watershed floor, and is termed as T_F. Both the evaporated water and the evapotranspiration from the canopy (AET net) represent the actual evapotranspiration losses (AET).

3.4 SD conceptualization of the reconstructed watershed

The modeling hypothesis of the dominant hydrological processes is represented in Figure 3.8 using eight dominant causal loops. The positive and negative signs near the arrowheads in Figure 3.8 represent the positive or negative relationships between the first variable and the following one. The specific feedback loops are listed in Table 3.3.

Loop (1) explains the feedback mechanism for canopy interception. It shows that the interception increases the volume of water in the canopy resulting in a reduction in the interception capacity. Consequently, it limits the water interception rate. The causal loop of interception characterization is similar to the methodology adopted by Li and Simonovic (2002).

Loop (1) is a negative feedback loop that helps create equilibrium in the state of the system. Interception capacity is dependent on the vegetation cover, which is subjected to active temperature accumulation during the snowmelt active period. The remaining seven feedback loops are similar to the corresponding feedback loops as presented by Jutla (2006) and Elshorbagy et al. (2007), and, hence, are not repeated here for the sake of brevity. The modified formulations of the MSDW are described in the following. In the MSDW model, the precipitation can input snow and rain separately, or can supply them together as a single time series to the model.

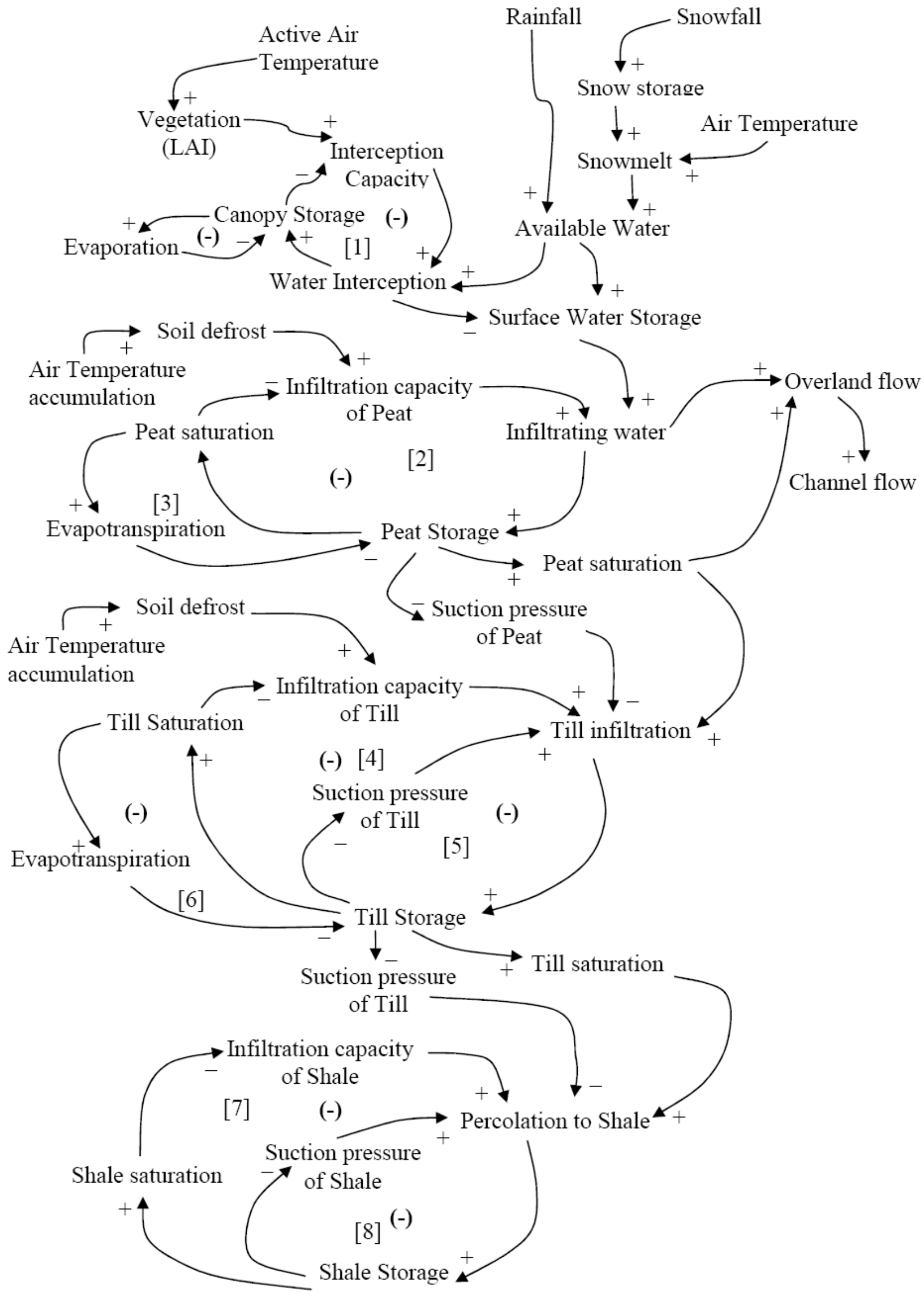


Figure 3.8. The dynamic hypothesis of dominant hydrological components of the reconstructed watershed (Modified after Li and Simonovic, 2002 and Elshorbagy et al., 2007).

The snowfall during the winter was accumulated and melted during the spring when the accumulated positive air temperature reached a threshold temperature.

Table 3.3. Simplified notation of feedback loops for the reconstructed watershed hydrology.

Loop	Description
Loop [1]	Water Interception +> Canopy storage +> Interception Capacity +> Water Interception
Loop [2]	Infiltrating water +> Peat storage +> Peat saturation -> Peat infiltration capacity +> Infiltrating water
Loop [3]	Peat storage +> Peat saturation +> Evapotranspiration -> Peat storage
Loop [4]	Peat saturation +> Till infiltration +> Till storage +> Till saturation -> Till infiltration capacity +> Till infiltration
Loop [5]	Peat storage -> Suction pressure of peat -> Till infiltration +> Till storage -> Till suction pressure +> Till infiltration
Loop [6]	Till Storage +> Till saturation +> Evapotranspiration -> Till Storage
Loop [7]	Till saturation +> Shale percolation +> Shale storage +> Shale saturation-> Shale infiltration capacity +> Percolation to Shale
Loop [8]	Till storage -> Suction pressure of till -> Shale percolation +> Shale storage -> Shale suction pressure +> Percolation to Shale

The snowmelt rate was calculated using the degree-day factor (Anderson, 1976). The daily snowmelt can be represented as:

$$M = D_f\left(T_a - T_b\right) \tag{3.2}$$

$$D_f = 0.011\rho_s \tag{3.3}$$

Where M is the daily melt (mm/day), D_f is the degree-day melt factor in millimetres per degree-day above 0 ^{0}C, T_a is the air temperature (°C), T_b is the base melt temperature (°C), and ρ_s is the snow density (kg/m^3). The interception dynamics of the watershed characterized in the system dynamics is explained below.

$$\frac{dS_I}{dt} = p - E_I - D_P \tag{3.4}$$

Where, S_I is the canopy interception storage (mm), p is the precipitation reaching canopy (mm/day), E_I is the evaporation of intercepted precipitation (mm/day), and *Dp* is drip from canopy storage (overflow of precipitation from canopy storage, mm/day).

The precipitation reaching the canopy (p) was defined as $P \times \varepsilon_1$, where P is the gross precipitation, which is an observed variable; ε_1 is the habitat dependent landscape interception parameter (Voinov et al., 2004) which is a calibration parameter (dimensionless). The evaporation from the canopy storage (E_I) was calculated as Min [p, EI_p], where EI_p is the potential evaporation rate of the intercepted water defined as $PET\left(1 - e^{-k*LAI}\right)$, k is extinction coefficient (dimensionless), which is a parameter from the literature (Collins and Bras, 2007) with a value of 0.4, LAI is leaf area index (m^2/m^2). This is an observed variable, and PET is potential evapotranspiration which was calculated using Penman's equation. The excess water from the canopy storage as the drip of water from the canopy storage (*Dp*) is released and joins the through fall.

The other storages such as surface water storage, peat moisture storage, till moisture storage, and shale moisture storage are very similar to those in the SDW model (Elshorbagy et al., 2005). The modifications such as interflow module removal of the original SDW model formulations (Elshorbagy et al., 2005, 2007; Jutla, 2006) are presented in Appendix I.

Being a site-specific model, the SDW model (Elshorbagy et al., 2005) was developed initially for a particular soil cover. Later, when it was adapted to other reconstructed watersheds (soil covers) of different thicknesses (Jutla, 2006; Elshorbagy et al., 2007), it was cumbersome insofar as modifications were needed in every formulation and component or module in the model. Searching and identifying each formulation and model component in the SDW model where a particular layer thickness was used, and completing its corresponding editing are time consuming and not very user-friendly. Care was taken in this study to overcome these problems by providing separate converters for the layer thicknesses of the soil cover or reconstructed watershed.

The same issue applies to other variables (e.g., soil layer porosity, wilting point, etc) in the model, which restricts the adaptation of the SDW model to soil covers of different thicknesses. With these modifications, model users can input the site-specific parameter into a single converter. Consequently the provided converter mechanism in the MSDW model takes care of propagating the information and adjusts the subsequent calculations. Moreover, these provisions help open the door to develop a generic model of reconstructed watershed systems.

In addition, these types of features will be useful for optimization issues such as having an objective function of minimizing the soil cover construction cost and maximizing the soil cover store-and-releasing functioning. In the current study, this feature of user-friendliness was useful in adapting the model structure for the natural watershed simulation.

3.5 SD watershed model development for the natural site

A watershed model similar to the SD conceptualization as that of the reconstructed MSDW model was developed to simulate the watershed hydrology of the natural study area. The natural watershed study area is located in the boreal forest of Central Saskatchewan as described in Section 3.2.2. The soil horizons within the root zone depth of a typical Aspen tree (120 cm) were characterized in the model development and simulation. As the depths of the horizons varied over the study area, representative thicknesses of the soil horizons were considered and were as follows: A-horizon is 25 cm, B-horizon is 45 cm, and C-horizon is 40 cm thick.

The watershed model built for the natural site in this study is referred to as SDWN (System Dynamics Watershed model for Natural study area) model. The adopted hypothesis describing the natural watershed hydrology dynamics is presented in Figure 3.9 with the help of causal loop diagrams (summarized in Table 3.4). The structure of the hypothesis is similar to the one applied in the case of the reconstructed watershed model (MSDW). However in this case the peat, till, and shale soil layers were replaced by A, B, and C soil horizons, and their corresponding properties were used in the SDWN model development.

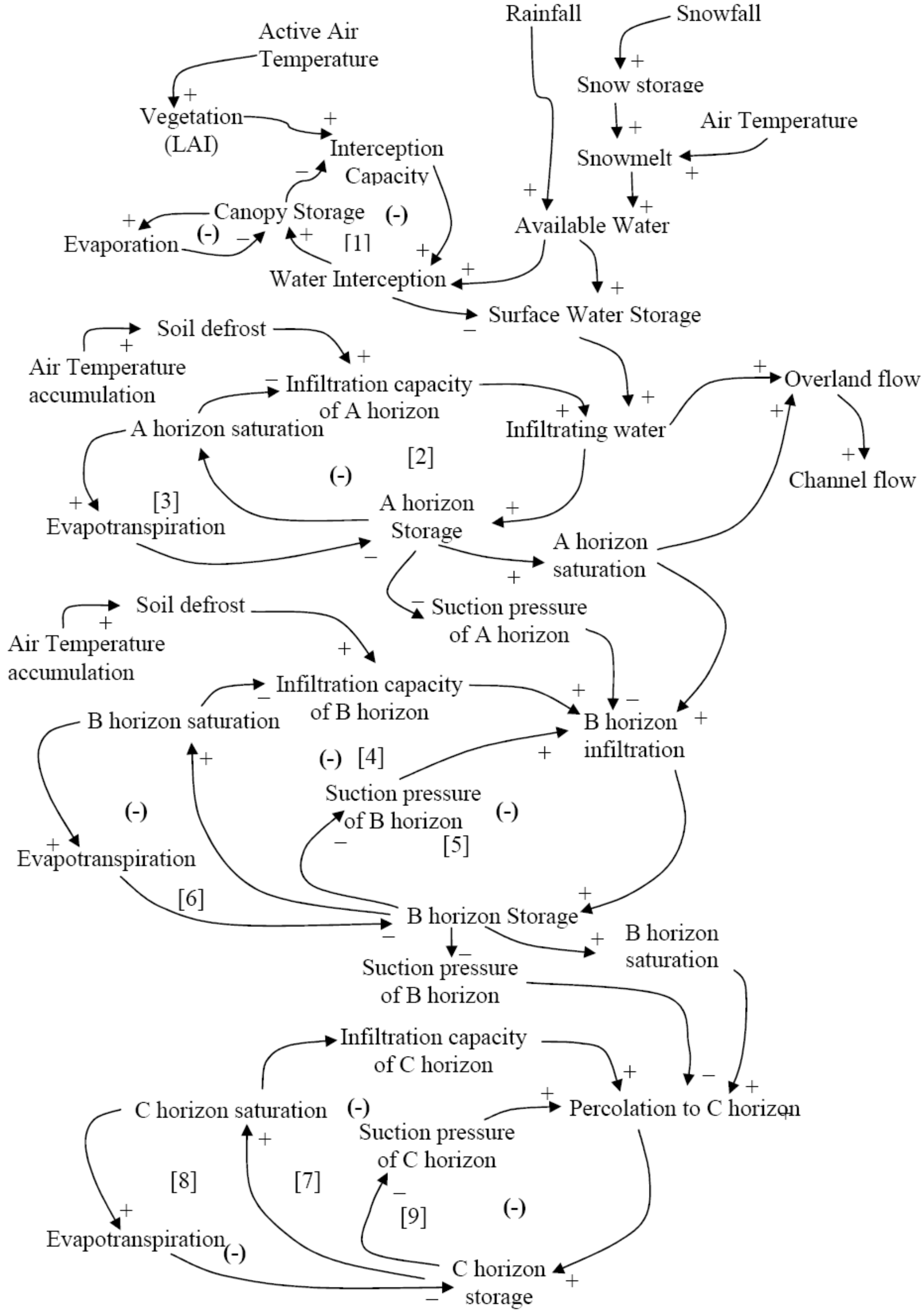


Figure 3.9. The dynamic hypothesis of dominant hydrological components of the natural watershed.

Table 3.4. Simplified notation of feedback loops for the natural watershed hydrology.

Loop	Description
Loop [1]	Water Interception +> Canopy storage +> Interception Capacity +> Water Interception
Loop [2]	Infiltrating water +> Horizon A storage +> Horizon A saturation -> Infiltration capacity of Horizon A +> Infiltrating water
Loop [3]	Horizon A storage +> Horizon A saturation +> Evapotranspiration -> Horizon A storage
Loop [4]	Horizon A saturation +> Horizon B infiltration +> Horizon B Storage +> Horizon B saturation -> Infiltration capacity of Horizon B +> Horizon B infiltration
Loop [5]	Horizon A Storage -> Suction pressure of Horizon A -> Horizon B infiltration +> Horizon B Storage -> Suction Pressure of Horizon B +> Horizon B infiltration
Loop [6]	Horizon B Storage +> Horizon B saturation +> Evapotranspiration -> Horizon B Storage
Loop [7]	Horizon B saturation +> Percolation to Horizon C +> Horizon C Storage +> Horizon C saturation-> Infiltration capacity of Horizon C +> Percolation to Horizon C
Loop [8]	Horizon C Storage +> Horizon C saturation +> Evapotranspiration -> Horizon C Storage
Loop [9]	Horizon B Storage -> Suction pressure of Horizon B -> Percolation to Horizon C +> Horizon C Storage -> Suction Pressure of Horizon C +> Percolation to Horizon C

3.6 Evaluation of the comparative hydrological sustainability

It is imperative for reconstructed watersheds to have hydrological sustainability to ensure proper functioning of vegetation and the ecological system. The hydrological sustainability includes effective long term (years) functioning of the hydrological processes of the watersheds. When disturbed watersheds are reconstructed, the natural soil physical and structural properties are altered (Potter et al., 1988; Mapfumo et al., 2006a), and, consequently, the hydraulic and hydrological functions of the reconstructed watersheds are disturbed. Restoration of these soil properties takes years before achieving the effective functioning of hydrological systems.

Assessment of the hydrological sustainability of reconstructed watersheds helps in developing a sustainable reclamation strategy (Figure 1.1). As mentioned in the previous chapters, one of the vital design criteria for reconstructed watersheds is to have ability to sustain and survive through various meteorological forcings. This typically includes storing and releasing enough moisture to maintain land-atmospheric fluxes and vegetation growth.

An essential requirement in the design of reclamation covers to meet this objective is that all covers must have a sufficient water holding capacity (AWHC) in order to supply adequate moisture for vegetation over the summer moisture deficit typical in the region. In the current practices, AWHC is usually based on static and deterministic evaluations of wilting point and field capacity under a constant annual evapotranspiration demand. For the considered reconstructed study area, the AWHC requirement is 160 mm for ecological sustainability of the forested sites (Leskiw, 2004). In the current study, soil moisture storage and evapotranspiration were considered the primary hydrological factors to understand the hydrological sustainability of the reconstructed site.

Using the calibrated and validated MSDW model, long term hydrological simulations were carried out for a period of 48 years (1955-2002) using the historical meteorological input data. The simulated long term daily soil moisture results were used to deduce a soil moisture deficit index (explained below). This helps to assess the store-and-release moisture ability each year. The methodology is similar to the soil moisture deficit index deduction adopted by Elshorbagy and Barbour (2007). The daily moisture deficit (D_i), which could be attributed to evapotranspiration, was then calculated as follows:

$$\partial S = S_t - S_{t+1} \tag{3.5}$$

$$D_i = (S_t - S_{t+1}) - P_r \tag{3.6}$$

Where S_t is the soil moisture content on day t, and S_{t+1} is the soil moisture on day $t+1$, P_r is the deep percolation (all are in mm). The soil moisture on a particular day (S) represents the summation of the soil moisture in the peat and till layers. A negative value of ∂S (moisture change) means that there is a soil moisture surplus (i.e., the soil moisture content increases), whereas a positive value of ∂S means that the soil cover is able to release moisture from the storage:

A positive value of D_i quantifies the amount of this water release, which was made available for evapotranspiration, since the other water losses (percolation in this case) have been taken into consideration (Eq. 3.6). The daily values of D_i are accumulated over the growing season (mid May – mid October). The maximum value of the cumulative D_i in each year is marked as the maximum annual soil moisture deficit (D_m). The rare negative values of D_m indicate a year of water surplus, which is not of concern in this study.

The values of D_m can be used as indicators of the hydrologic behavior of the sub-watershed as they quantify the ability of the reconstructed watershed to continue to release moisture for vegetation under a variety of climatic conditions. The simulated value of D_m could replace the value of AWHC if the reconstructed watershed is simulated under an extended climatic record that encompasses the full range of possible variations in climate and climatic cycles. The D_m values reflect the performance of the sub-watershed considering the wetness and dryness of the year as well as the distribution of summer rainfall with respect to actual evapotranspiration. The values of the D_m will vary based on the distribution of rainfall within each year as well as the sequence of wet and dry years (Elshorbagy and Barbour, 2007).

In this study, the probabilistic methodology proposed by Elshorbagy and Barbour (2007), which was described in this section, was adopted for the long term hydrological performance assessment, in addition to the deterministic modeling assessment. The obtained annual D_m and the annual evapotranspiration (AET) values were treated as random variables and used to fit probability distribution curves. Best fit distributions were selected by testing with more than twenty distributions with the help of @Risk software (Palisade Corporation, 2005) using Chi-squared test as well as visual inspection. These probability curves help to explain and visualize the store-and-release ability of the reconstructed watershed. The typical guidelines adopted in the long term hydrological assessment are summarized as below (after Elshorbagy and Barbour, 2007).

1. Select and validate a hydrologic model to simulate the hydrologic processes on the reconstructed watershed;

2. Apply the model to a data set of continuous, daily, meteorological data over a sufficient number of years;

3. Estimate the daily moisture change and deficit (Eqs.3.5 and 3.6) and the series of annual maximum moisture deficit (D_m) as explained earlier, as well as the annual AET values; and

4. Use the D_m and annual evapotranspiration values to construct suitable probability distributions that represent the overall hydrologic performance of the soil cover over a long period of time.

This assessment provides an individual assessment of hydrological sustainability of the reconstructed watershed. To examine how different the reconstructed watershed is from the natural watershed in terms of hydrological performance, long term simulations were also carried out on the natural watershed using the similar MSDW model prepared for the natural watershed. The same probabilistic framework explained earlier was adopted to obtain probability curves of D_m, and AET for the natural watershed.

In addition, two model scenarios were generated and long term simulations were carried out on the reconstructed and natural watershed systems to help understand their hydrological performance. Consequently, different statistical tests (explained in chapter 4) were conducted on the simulated and theoretical D_m values to learn their statistical inference. The probability curves of the hydrological performance of reconstructed and natural watersheds and the statistical analyses were used to describe the comparative hydrological sustainability of the reconstructed watershed relative to the natural watershed.

CHAPTER 4. RESULTS AND DISCUSSIONS

4.1 Overview

This chapter presents the description of the modeling data and the results of hydrological modeling of the reconstructed and natural watersheds. To assess the hydrological effects of the vegetation (canopy) and the comparative hydrological sustainability, long term hydrological simulations with different scenarios were carried out on both the reconstructed and also the natural watersheds. These assessments are presented in this chapter with analysis and discussion. As the reconstructed watershed is less mature than the natural watershed, the current study proceeds with the initial hypothesis, "The hydrological performance of the reconstructed watershed is not mimicking the hydrological performance of the natural watershed".

4.2 Hydrological modeling data

The modified system dynamics watershed (MSDW) model and the system dynamics model for natural watershed (SDWN) both require similar input data as well as similar initial and boundary conditions as the existing system dynamics watershed (SDW) model. Input data for the watershed modeling of the reconstructed and natural watersheds include daily meteorological (precipitation, average air temperature, net radiation), soil physical (soil wilting point, field capacity, porosity, soil water characteristic curve, and saturated hydraulic conductivity), and vegetation (leaf area index) data. Wind speed, net radiation, and relative humidity were the secondary meteorological input parameters, and were needed for the estimation of potential evapotranspiration (PET) by the model. The usage of PET in the model was limited to establish an upper limit for the predicted actual evapotranspiration (AET). Further assessment was carried out using AET to evaluate the comparative hydrological performance of reconstructed and natural watersheds. The initial and boundary conditions include initial soil moisture storage values in both the reconstructed and also the natural watershed models. The respective measured parameters of the reconstructed and natural watersheds used for calibration and validation of the MSDW and SDWN models and their descriptive statistics are described below.

4.2.1 Reconstructed watershed data

The study focuses on the evaluation of the hydrological processes during the growing period (mid May - mid October) of a typical calendar year. The current study considers the available data of years 2005 and 2006 for the watershed modeling of the reconstructed site. Table 4.1 and Table 4.2 present their descriptive statistics of the daily meteorological data during the growing season. Years 2006 and 2005 data were used to calibrate and validate the watershed model respectively. Over the growing season of year 2005, the precipitation (mostly rain) was about 267.6 mm, with a daily maximum of about 21.1 mm and a daily average value of 1.53 mm.

Table 4.1. Descriptive statistics of the modeling data of the reconstructed watershed study area for the validation year (2005).

	Max	Min	Average	SD	Skew
P (mm)	21.10	0.00	1.53	3.57	3.63
AT (^{0}C)	21.80	-0.50	12.75	4.73	-0.36
WS (m/sec)	6.10	1.10	2.75	1.00	0.76
RH (%)	94.00	36.00	68.32	12.29	-0.08
NR (W/m^2)	174.77	-10.42	67.67	46.75	0.37

P is precipitation in mm, AT is average air temperature in ^{0}C, WS is wind speed in m/sec, RH is relative humidity in percentage, NR is net radiation in W/m^2, Max is maximum value, Min is minimum value, and SD is standard deviation.

The daily average air temperature ranged between -0.5^{0}C to 21.8^{0}C, and indicated the typical spring and summer seasons. The precipitation (mostly rain as well) in 2006 was 236 mm, with a maximum daily precipitation of about 41 mm and with a daily average precipitation of 1.53 mm. Both years had less precipitation than the 30-year climate normal for Fort McMurray, which received an average of more than 270 mm for the May – October period. The daily average air temperature ranged between – 3 ^{0}C to 25.1 ^{0}C in 2006. The net radiation was calculated as the difference between incoming and outgoing radiation fluxes. The minimum daily average net radiation flux was about -10.5 and - 28 W/m^2 for 2005 and 2006 respectively. The daily maximum net radiation flux was about 175 and 176 W/m^2 for 2005 and 2006 respectively. Positive ground temperatures of peat, till, and shale layers were observed throughout the growing seasons of 2005 and 2006.

Table 4.2. Descriptive statistics of the modeling data of the reconstructed watershed study area for the calibration year (2006).

	Max	Min	Average	SD	Skew
P (mm)	40.90	0.00	1.53	4.46	5.60
AT (^{0}C)	25.10	-3.00	14.25	5.41	-0.73
WS (m/sec)	5.50	1.20	2.50	0.94	0.88
RH (%)	94.50	32.40	67.07	13.74	-0.24
NR (W/m^2)	175.93	-27.78	79.70	49.90	-0.06

4.2.2 Natural watershed data

The natural watershed study area considered in this study has slightly different meteorological and hydrological conditions than the reconstructed watershed study area. The descriptive statistics of the meteorological data used in the calibration and validation of the watershed model (SDWN) for the natural watershed study area are presented in Table 4.3 and Table 4.4

Table 4.3. Descriptive statistics of the modeling data of the natural watershed study area of the validation year (1999).

	Max	Min	Average	SD	Skew
P (mm)	60.00	0.00	2.14	6.22	6.28
AT (^{0}C)	25.10	-0.65	12.65	5.60	-0.35
WS (m/sec)	6.04	1.35	2.96	0.83	0.65
RH (%)	96.92	29.25	66.69	15.60	-0.10
NR (W/m^2)	199.86	-24.73	97.48	56.20	-0.02

The study area had about 330 and 370 mm of total precipitation (mostly rain) during 1999 and 2000 respectively. These totals are higher than the modeling data of the reconstructed watershed study area for 2005 and 2006. The maximum daily precipitations during the growing season were about 60 and 36 mm in 1999 and 2000, and average daily precipitations were 2.14 and 2.41 mm respectively. Similar to the case of the reconstructed watershed, the ground temperatures of the soil layers (A, B, and C soil horizons) were positive during the growing seasons in both years. Soil layer temperatures were observed to be slightly lower in magnitude on average, which could be due to the mature vegetation and prevailing meteorological conditions. The maximum and minimum daily average air temperatures were 25.1 and -0.65^{0}C for year 1999 and 24.22 and -3.02^{0}C for year 2000.

The maximum daily average net radiation fluxes were about 200 and 220 W/m^2 during the growing seasons of 1999 and 2000 respectively. The net radiation fluxes were higher than those in the case of reconstructed watershed system, which could be attributed to the different geographical location of the study area, as well as to the prevailing meteorological and vegetation conditions and their dynamic interactions. Considering the limited data availability, 2000 and 1999 were selected for the calibration and validation of the SDWN model respectively.

Table 4.4. Descriptive statistics of the modeling data of the natural watershed study area of the calibration year (2000)

	Max	Min	Average	SD	Skew
P (mm)	36.00	0.00	2.41	5.83	3.80
AT (^{0}C)	24.22	-3.02	11.59	5.76	-0.24
WS (m/sec)	5.25	1.04	3.09	0.78	0.40
RH (%)	96.42	29.04	67.71	14.95	-0.49
NR (W/m^2)	220.00	-29.89	99.72	70.49	0.94

4.3 Hydrological simulation of the reconstructed watershed

The MSDW model was developed in this study to model the hydrological processes of the SBH top. The SBH site has 20 cm thick peat-mineral mix layer on top of 80 cm thick secondary (glacial till) layer on the shale overburden. The output variables of the MSDW model are daily soil moisture storages within the peat and till layers, daily evapotranspiration, and overland flow from the reconstructed watershed. The respective observed variables were used to the model performance during calibration and validation.

It should be noted that comparisons between the predicted and observed values in the winter season should be done with extreme caution. The TDR sensors used to monitor the soil moisture content fails to provide reliable readings under frozen conditions (Boese, 2003). Hence, in this research, it was assumed that the sensors did not work during the entire time that the soil temperature was below 0^0C. A procedure adopted in Jutla (2006) was carried out in this study for initial conditions of the model. The last moisture observation of the soil temperature when it was positive was taken as the last correct moisture observation recorded by the sensors. The moisture observations on subsequent days were subtracted from the preceding day's moisture content to get an estimate of the net change in moisture content in a day. This difference obtained in the moisture content was then added to the moisture content when the soil temperature was positive. In this way, the moisture content was corrected so that the temporal trend in the moisture data could be saved (Jutla, 2006).

The model was calibrated by tuning the model parameters until a desired level of match is obtained between the observed and simulated values of soil moisture and evapotranspiration fluxes. Model error measures shown in Eq. 4.1 and 4.2 were used to check the simulation accuracy in addition to visual inspection of soil moisture profiles and evapotranspiration fluxes. Calibration parameters of reconstructed watershed are presented in Table 4.5.

Interception parameter (ε_1) with a value of 0.08 indicates the small contribution of the rainfall interception of the reconstructed watershed due to the presence of little vegetation, which has a range of leaf area index of about 0.67 to 0.83 m^2/m^2. Calibration parameters of c_P and c_T with values of 1.35 and 1.3 mm/day respectively indicate a higher moisture contribution of the surface layer (peat-mineral mix) toward the evapotranspiration and vegetation water requirements than the secondary layer (glacial till). More description of the calibration parameters can be found in Elshorbagy et al., (2005; 2007) and Jutla (2006).

Table 4.5. Model parameters of the reconstructed system model (MSDW).

Calibration Parameter	Value
Till infiltration (I_{cT}) (dimensionless)	0.015
Shale infiltration (I_{cS}) (dimensionless)	0.75
Exponent describing the influence of T_I on soil defrosting (c_i) (dimensionless)	6
Maximum T_I point at which surface soil is fully defrosted (T_{Imax}) (^{0}C)	50
Canopy interception parameter (ε_1) (dimensionless)	0.08
Peat evapotranspiration (c_P) (mm/day)	1.35
Till evapotranspiration (c_T) (mm/day)	1.3
Lambda (λ) (dimensionless)	1.1
Melt factor (dimensionless)	1.9

4.3.1 Calibration results of the reconstructed watershed

The model performance was evaluated based on the mean absolute relative error (MARE), and root mean squared error (RMSE); the error measures are defined in Eq. 4.1 and 4.2.

$$MARE = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{O_i - S_i}{O_i}\right| \tag{4.1}$$

$$RMSE = \left[\frac{1}{n}\sum_{i=1}^{n}\left(O_i - S_i\right)^2\right]^{0.5} \tag{4.2}$$

where O_i is the observed variable on i^{th} day, S_i is the simulated variable on i^{th} day, and n is the number of observations.

Table 4.6 presents the model error measures of the reconstructed system. The following description presents the discussion of the error measures for the calibration period of the reconstructed watershed modeling. The MARE and RMSE values of the simulated peat moisture content during the calibration year (2006) were 4.4 % and 4.1 mm respectively. For the till layer, the MARE and RMSE values were 3.5 % and 10 mm respectively.

The soil moisture profiles of peat and till layers are presented in Figure 4.1 for the calibration year. During the soil frozen conditions where the soil temperature is below $0^{o}C$, the model performance should be taken cautiously, because the observed soil moisture values when the soil is frozen are not accurate due to the errors in the TDR sensors (Boese, 2003). The model was able to capture the trends of the dynamics of the peat and till soil moisture during the growing season. This helps to view the hydrological response (soil moisture) of the reconstructed system that corresponds to the precipitation events. For example, in Figure 4.1a, the peaks in the soil moisture trend corresponds to instances of precipitation events during the growing season.

Table 4.6. Error measure values of the calibration and validation years for the reconstructed system.

	MARE		RMSE	
	Peat %	**Till** %	**Peat** mm	**Till** mm
Calibration (2006)	4.4	3.5	4.1	10.0
Validation (2005)	9.6	4.0	9.0	12.0

The error measures (Table 4.6) and the moisture profiles of the peat and till layers (Figure 4.1) indicate that the model simulated the soil moisture of the peat and till layers quite well during the calibration year. The MSDW model also simulated cumulative evapotranspiration fluxes of the reconstructed watershed. Figure 4.2 shows observed and simulated cumulative evapotranspiration fluxes. The simulated values are presented in two parts: one is total evapotranspiration (AET gross); and the other one is AET net, which is defined as AET gross minus canopy evaporation.

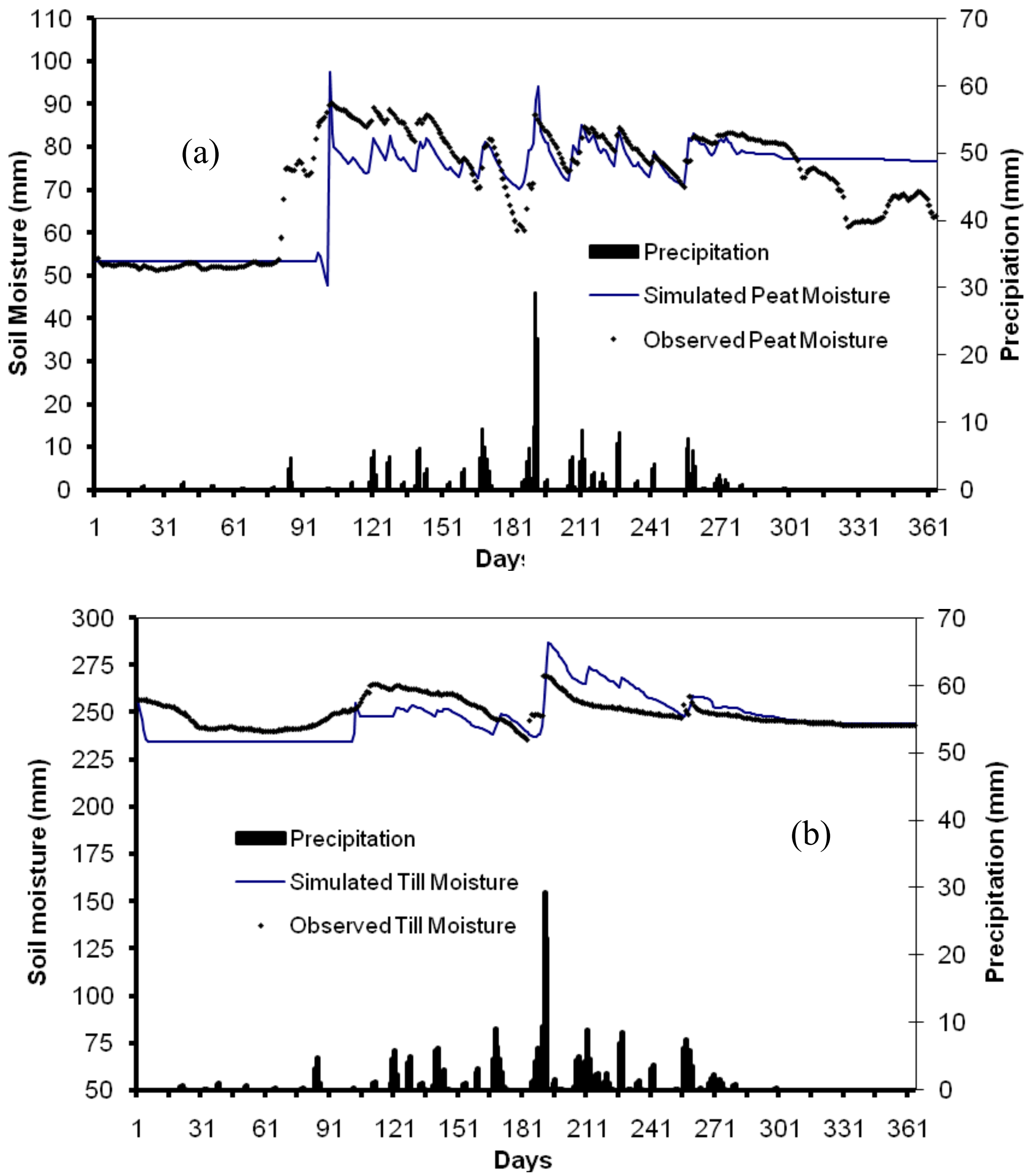


Figure 4.1. Simulated and observed soil moisture content of the reconstructed system during calibration (year 2006) (a) peat layer; (b) till layer.

The light vegetation on the SBH site had a maximum leaf area index of about 0.67 m^2/m^2, and was able to intercept only small amount of rain. The model slightly overestimated the total cumulative evapotranspiration fluxes, with measured AET gross of 276.3 mm and simulated AET gross of 280 mm, and with a canopy interception of about 9 mm. However, missing observed data during the initial period of the growing season should also be considered while looking at the match between observed and simulated fluxes, particularly during the beginning of the growing season.

Carey (2008) described the details of the field instrumentation (eddy covariance tower) of evapotranspiration fluxes including its corresponding accuracy levels. Typical factors affecting the accuracy of the observed fluxes include: 1) underestimation of turbulent fluxes (sensible heat and latent heat) by the eddy covariance; 2) removal of fluxes when the friction velocity measured by eddy covariance is less than 0.1 m s^{-1} due to the poor energy balance closure at low wind speeds; 3) flux measurement's removal during the periods of rainfall; and 4) interpolation of the missing fluxes.

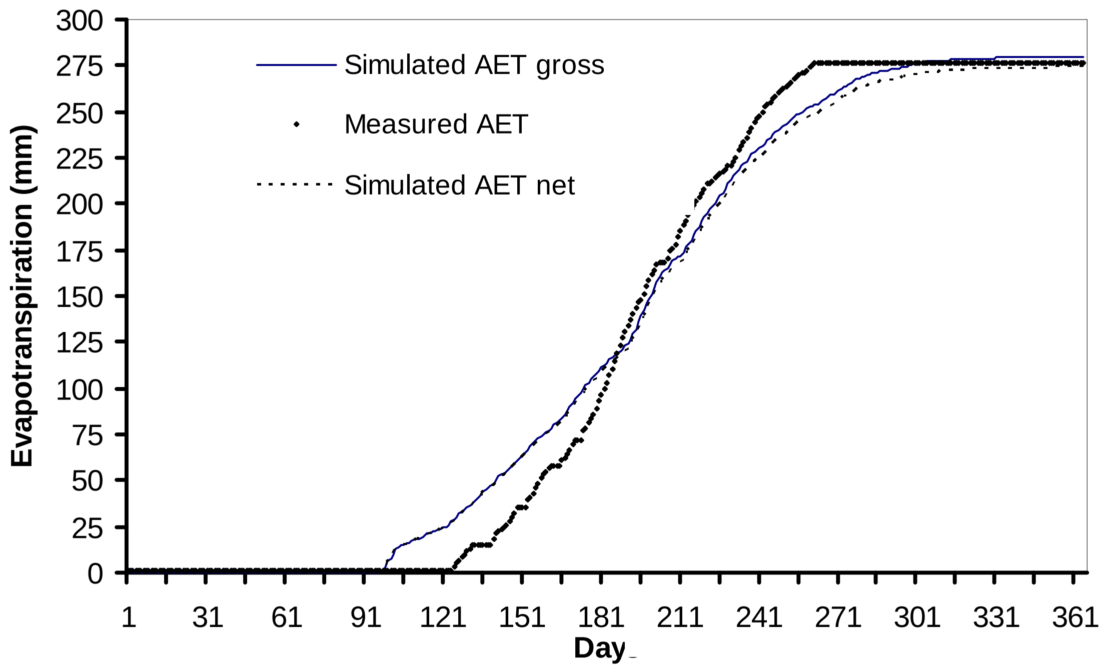


Figure 4.2. Observed and simulated cumulative evapotranspiration fluxes of reconstructed watershed (top of SBH site) for calibration year (2006).

During the growing season of year 2006, the model overestimated the evapotranspiration till the early days of July and underestimated resulting overall overestimation of the fluxes. In the one dimensional hydrological characterization (vertical water balance) of the reconstructed system, the MSDW model also simulates the overland flow. The model accumulates snow during the winter and produces the snow melt runoff during the spring using the Degree-day method of snow melt. Over the summer season, the model estimates the overland flow after satisfying the infiltration requirements meaning that considerable overland flow prevails when the surface layer saturates. As shown in Figure 4.3, the MSDW model overestimated the overland flow compared to the observed overland flow with a couple of days lag time during the calibration year. This could be attributed to the lack of accurate snowmelt modeling data and to the ability of the model to characterize snowmelt dynamics and its related processes such as sublimation.

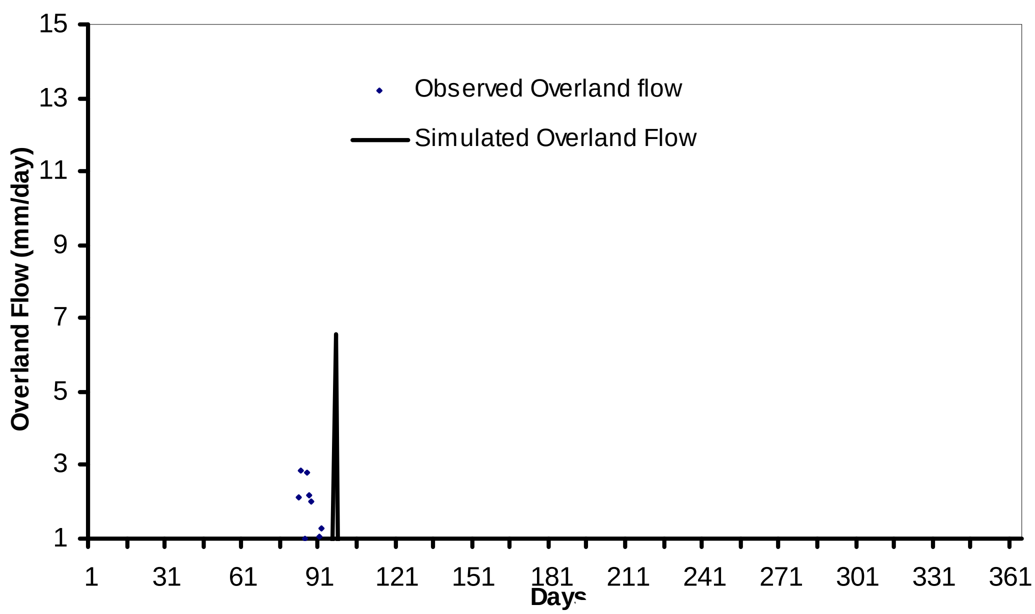
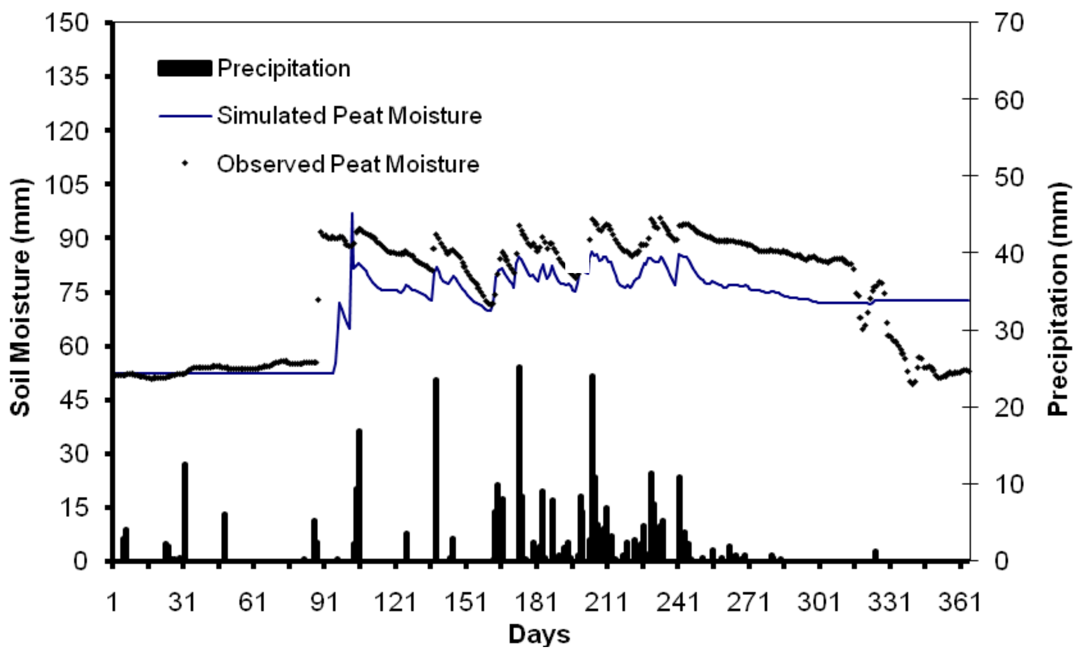


Figure 4.3. Observed and simulated overland flow of the reconstructed system for the calibration year (2006).

The topography of the study area is relatively flat, which results in little overland flow in response to the snowmelt during the spring. In the 1-D watershed modeling, accurate prediction of the overland flow in northern semiarid regions appears to be quite challenging and difficult with the lack of complete representation of snow accumulation and melting dynamics.

4.3.2 Validation of the MSDW model on the reconstructed system

The MSDW model was validated using 2005 data on the top of the SBH site. MARE and RMSE values of the peat layer moisture for the validation year (2005) were 9.6 % and 9 mm respectively. For the till layer, the MARE and RMSE values were 4 % and 12 mm respectively. The daily soil moisture profiles of the peat and till layers are presented in Figure 4.4.



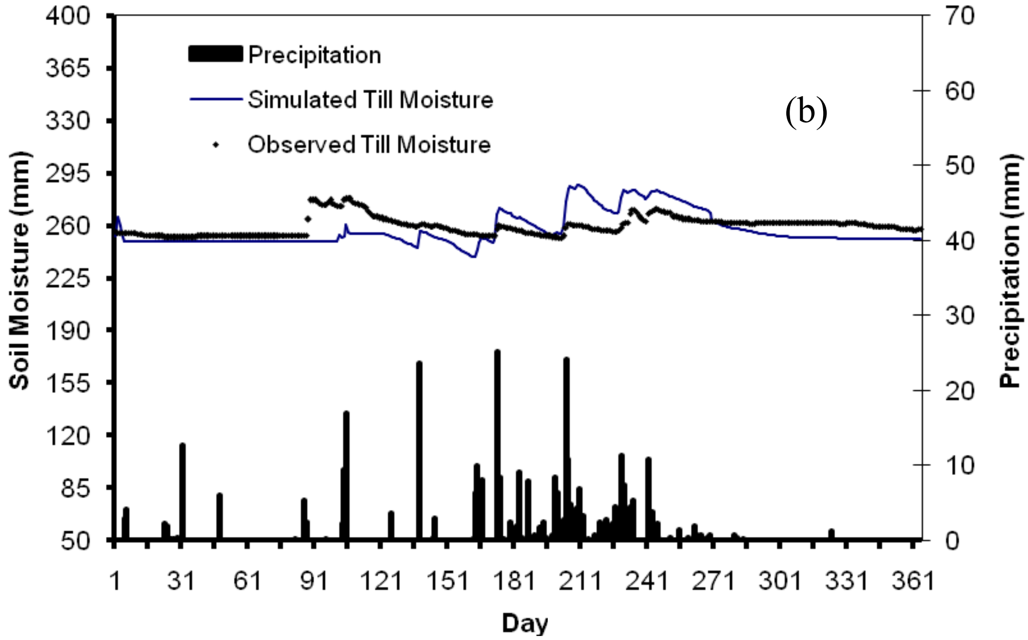


Figure 4.4. Simulated and observed soil moisture content of the reconstructed system during validation (year 2005) (a) peat layer; (b) till layer.

During the validation year, the MSDW model underestimated the peat soil moisture relative to the observed values. For the till moisture, the model overestimated until the middle of the growing season and underestimated afterwards. Nevertheless, the results are encouraging as the model was able to mimic the pattern or the dynamics of the moisture profiles. In addition, based on the error measures (Table 4.6), and the moisture profiles of the peat and the till layers (Figure 4.4), it can be observed that during the validation year, the model simulated the soil moisture of the peat and till layers reasonably well. The peat moisture profile has more fluctuations (Figure 4.4a). This is due to the higher moisture demand from the peat layer towards evapotranspiration requirements.

Moreover, the lower saturated hydraulic conductivity of the till material, compared to the peat-mineral mix, keeps the fluctuations relatively low compared to the peat soil moisture dynamics. Figure 4.5 shows the observed and simulated cumulative evapotranspiration fluxes of the reconstructed site during the validation year (2005). The model slightly overestimated the fluxes, with total values of measured AET of 277 mm where the simulated AET gross of 291 mm, and with a canopy interception of about 10.5 mm. The sparse vegetation on the SBH site during the validation year had a maximum leaf area index of 0.83 m^2/m^2, and was able to intercept a small amount of rain.

The model overestimated the evapotranspiration until the mid of July, resulting a slight overestimation of the fluxes. However, the observed data must be taken with caution as there exist some missing data to a maximum of a week during the growing season. Figure 4.6 shows the observed and simulated overland flow for the validation year of the reconstructed system. Due to the higher snowfall than the calibration year (2006), the model produced higher overland flow, with a peak of about 19 mm/day. Relative to the observed values, the model underestimated the overland flow.

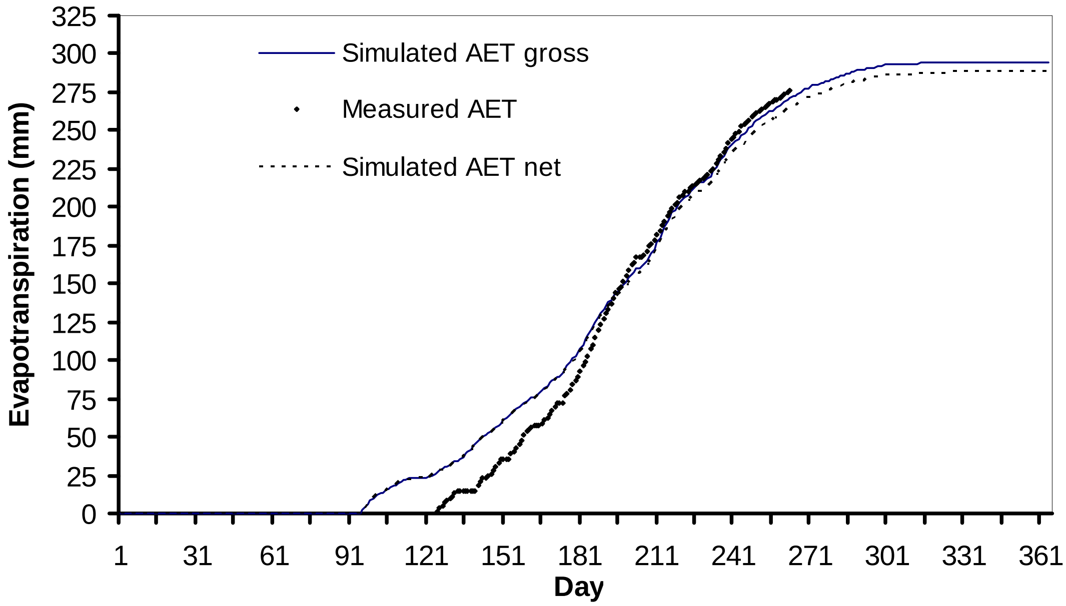


Figure 4.5. Observed and simulated cumulative evapotranspiration fluxes of reconstructed watershed (top of SBH site) for validation year (2005).

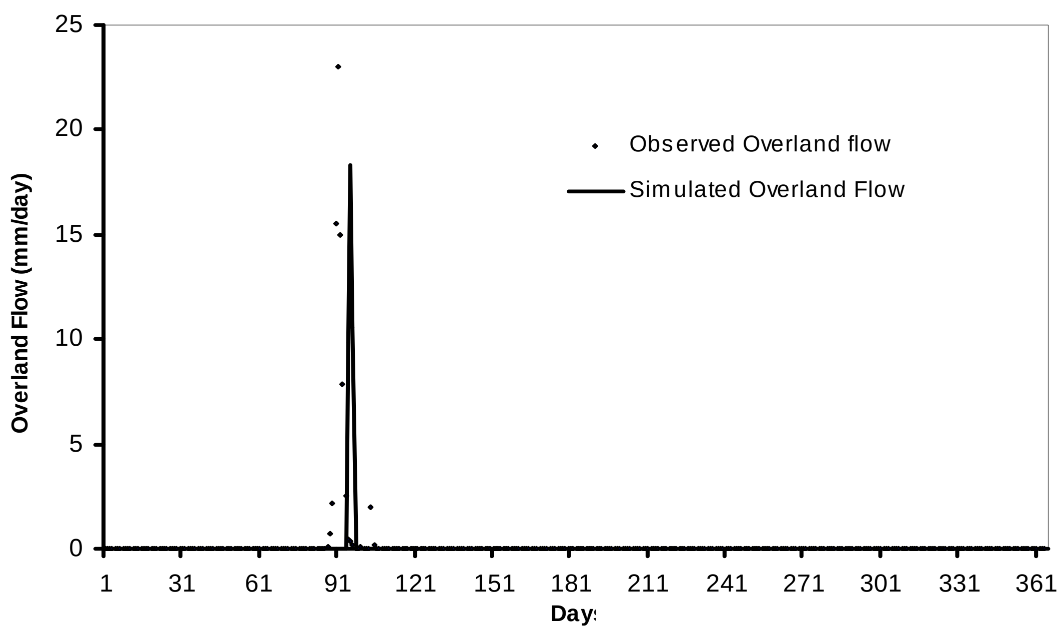


Figure 4.6. Observed and simulated overland flow of the reconstructed system for the validation year (2005).

4.4 Hydrological simulation of the natural watershed

In the current study, an old aspen (OA) site from the boreal forest represents the natural watershed system. The similar watershed model, SDWN, was developed, calibrated, and validated on the OA site for the purpose of comparative hydrological evaluation of the reconstructed watershed. The 25 cm-thick A-horizon, 45 cm-thick B-horizon, and 40 cm-thick C-horizon of the soil formation, which are within the root zone depth, were considered in the 1-D watershed modeling for the natural site. The calibration parameters are presented in Table 4.7.

It can be observed that the canopy interception calibration parameter of the natural watershed (ε_1) that has a value of 0.45 is higher than the value of that of the reconstructed watershed (0.08). This represents the effect of the mature vegetation on rainfall interception.

Table 4.7. Model parameters of the natural system model (SDWN).

Calibration Parameter	Value
B-horizon infiltration (I_{cB}) (dimensionless)	0.05
C-horizon infiltration (I_{cC}) (dimensionless)	0.0001
Exponent describing the influence of T_I on soil defrosting (c_i) (dimensionless)	5
Maximum T_I point at which surface soil is fully defrosted (T_{Imax}) (^{0}C)	50
Canopy interception parameter (ε_1) (dimensionless)	0.45
A-horizon evapotranspiration (c_A) (mm/day)	1.5
B-horizon evapotranspiration (c_B) (mm/day	0.6
C-horizon evapotranspiration (c_C) (mm/day)	0.2
Lambda (λ) (dimensionless)	5.9
Melt factor (dimensionless)	1.9

Evapotranspiration calibration coefficients are 1.5, 0.6, and 0.2 mm/day for A, B, and C soil horizons respectively. This indicates the least contribution from the lowest layer and higher contributions from the upper soil horizons. This makes sense as the plant rooting system is mostly developed in the upper soil horizons and demands more water from the upper layers of the soil formation to meet the transpiration requirements.

4.4.1 Calibration results of the natural system

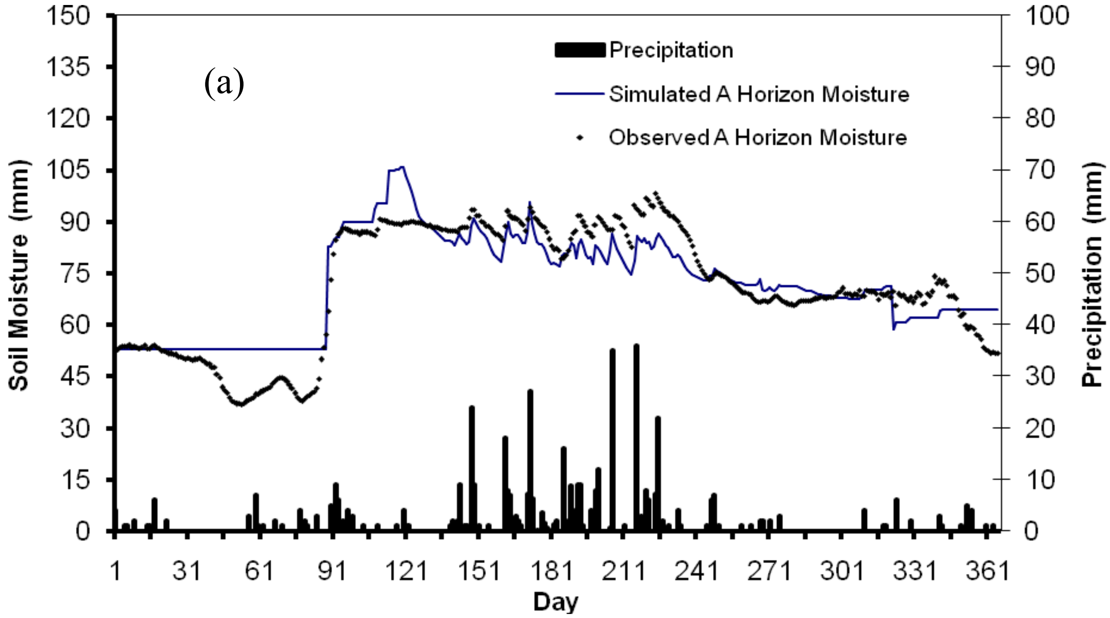
The SDWN model error measures of the natural system are presented in Table 4.8. The MARE and RMSE values for the A-horizon layer moisture for the calibration year (2000) were 6.2 % and 6.3 mm respectively. For the B-horizon layer, 6.4 % and 12.1 mm were the values of the MARE and RMSE, respectively. 13.6 % and 20.1 mm were the values of the MARE and RMSE respectively for the C-horizon of the natural system during the calibration year (2000). The daily values of the observed and simulated soil moistures of A-, B-, and C-horizon layers for the calibration year are presented in Figure 4.7.

Table 4.8. Error measure values of the calibration and validation years of the natural system.

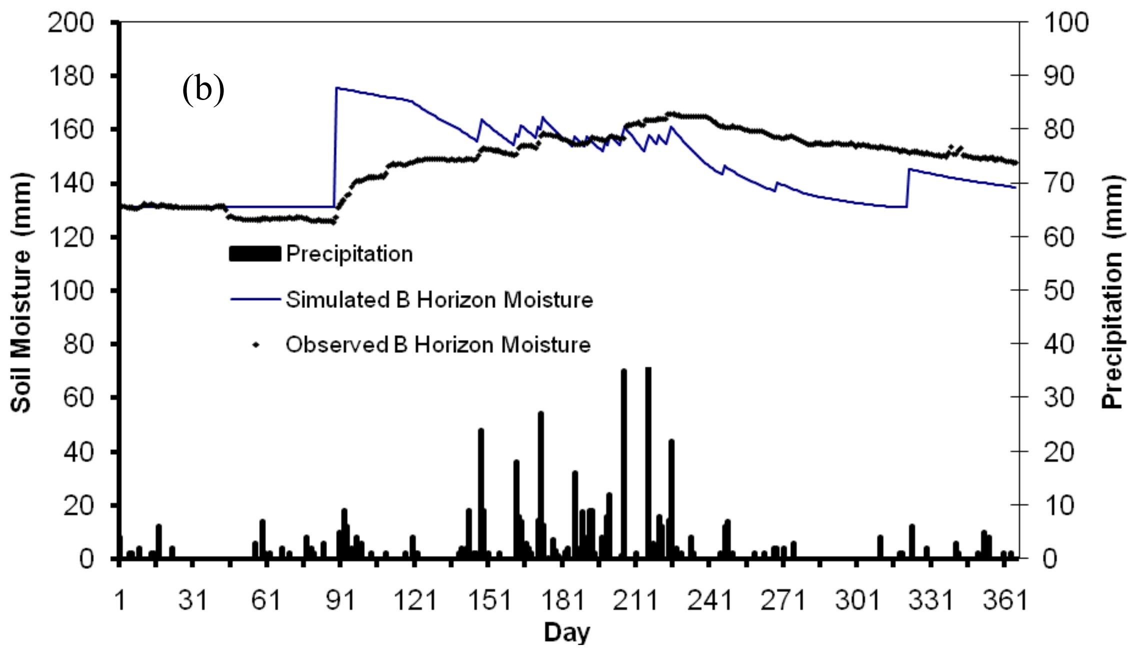
	MARE			RMSE		
	A-horizon %	B-horizon %	C-horizon %	A-horizon mm	B-horizon mm	C-horizon mm
Calibration (2000)	6.2	6.4	13.6	6.3	12.0	20.0
Validation (1999)	13.9	5.7	8.5	10.5	10.0	15.0

The model was able to capture the trends of the dynamics of the A-horizon and B-horizon soil moisture during the growing season of the calibration year (2000). As mentioned in the case of the reconstructed system, the soil moisture observations during the winter period must be taken with caution as the TDR sensors were not able to measure the soil moisture content accurately due to the frozen conditions of the soil layers.

The model could not characterize the soil moisture of the C horizon layer well (Figure 4.7c). As the C-horizon layer exists nearer to the ground water table, it becomes harder to characterize all the dominant hydrological and soil physical processes in the one-dimensional watershed modeling. This layer is the upper part of the transition layer between the vadose zone and the saturated zone (below ground water table). This leads to less than satisfactory accuracy in modeling the soil moisture dynamics of the C-horizon of the natural watershed system. However, based on the error measures (Table 4.8) and on the moisture profiles of the A-horizon and B-horizon layers (Figure 4.7), a good match can be observed during the calibration year between the simulated and observed soil moisture storage values. The SDWN model simulated the cumulative evapotranspiration fluxes of the natural watershed reasonably well. Figure 4.8 shows the observed and simulated cumulative evapotranspiration fluxes of the OA site.



(a)
Precipitation
Simulated A Horizon Moisture
Observed A Horizon Moisture
Soil Moisture (mm)
Precipitation (mm)
Day
150
135
120
105
90
75
60
45
30
15
0
100
90
80
70
60
50
40
30
20
10
0
1
31
61
91
121
151
181
211
241
271
301
331
361



(b)
Precipitation
Simulated B Horizon Moisture
Observed B Horizon Moisture
Soil Moisture (mm)
Precipitation (mm)
Day
200
180
160
140
120
100
80
60
40
20
0
100
90
80
70
60
50
40
30
20
10
0
1
31
61
91
121
151
181
211
241
271
301
331
361

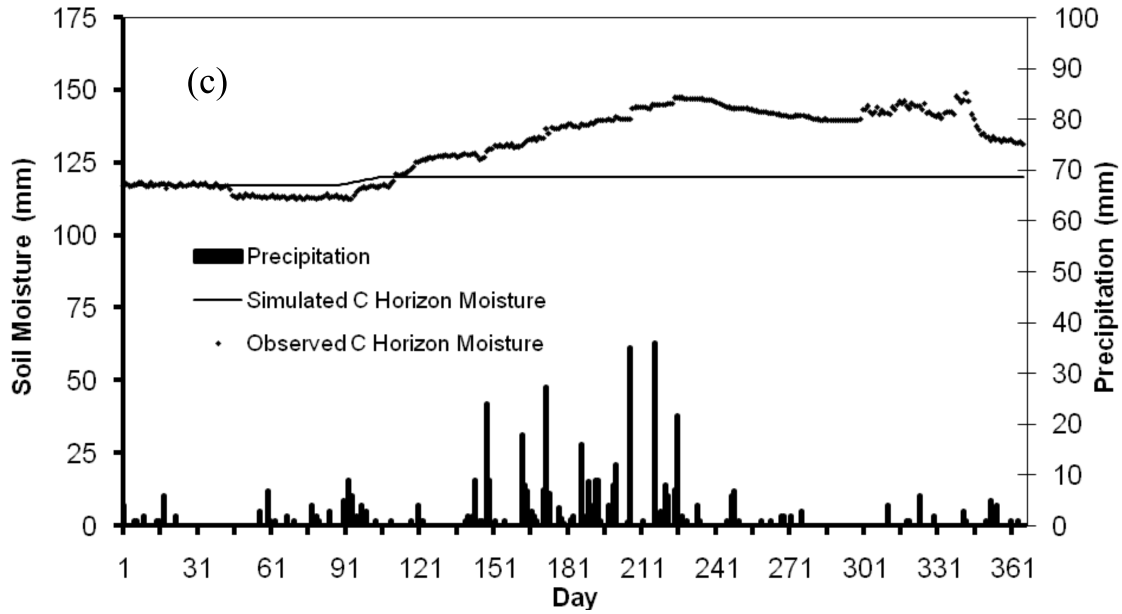


Figure 4.7. Simulated and observed soil moisture content of the natural system during calibration (year 2000) (a) A-horizon; (b) B-horizon; (c) C-horizon.

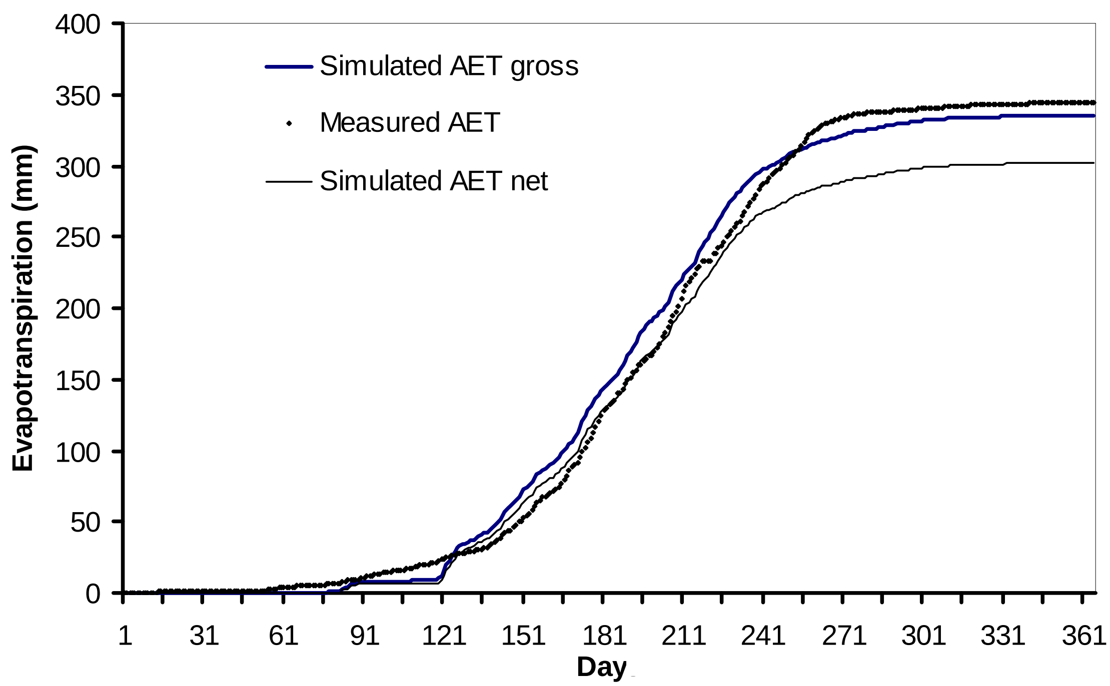


Figure 4.8. Observed and simulated cumulative evapotranspiration fluxes of natural watershed (OA site) for calibration year (2000).

Similar to the case of the reconstructed system, the simulated values are presented in two parts: the total evapotranspiration (AET gross); and AET net, which is defined as AET gross minus canopy evaporation. The model slightly underestimated the cumulative evapotranspiration fluxes, with values of measured total AET of about 345 mm, with a simulated AET gross of about 335 mm, and with a canopy interception of about 33.3 mm. The mature vegetation on the OA site has a maximum leaf area index of 4.5 m^2/m^2 (which includes both under storey and top storey vegetation), and was able to intercept significant amounts of rain. During the 2000 growing season, the model slightly overestimated the evapotranspiration fluxes most of the time. As shown in Figure 4.9, for the calibration year, the SDWN model produced a few instances of overland flow.

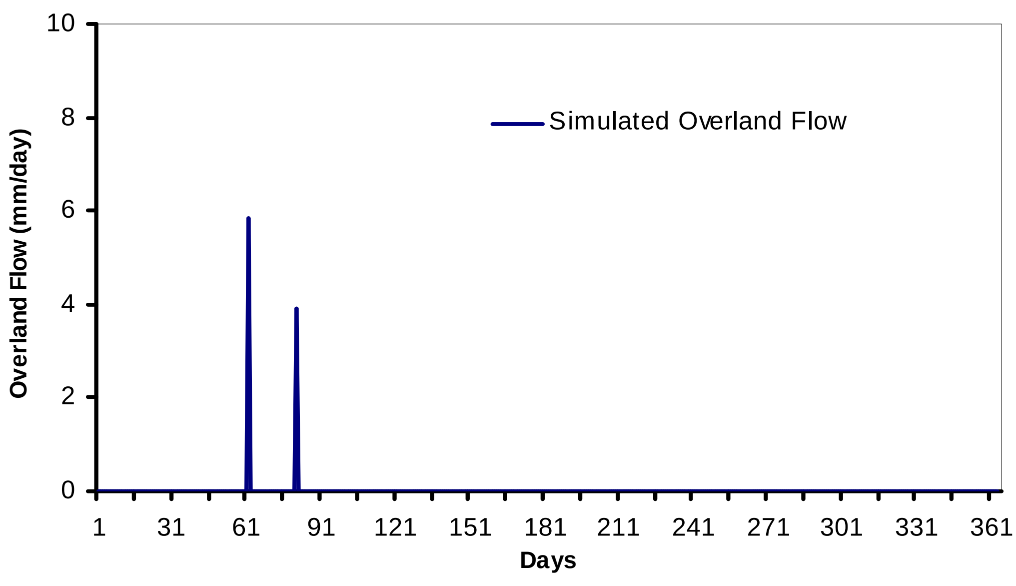


Figure 4.9. Simulated overland flow of the natural system for the calibration year (2000).

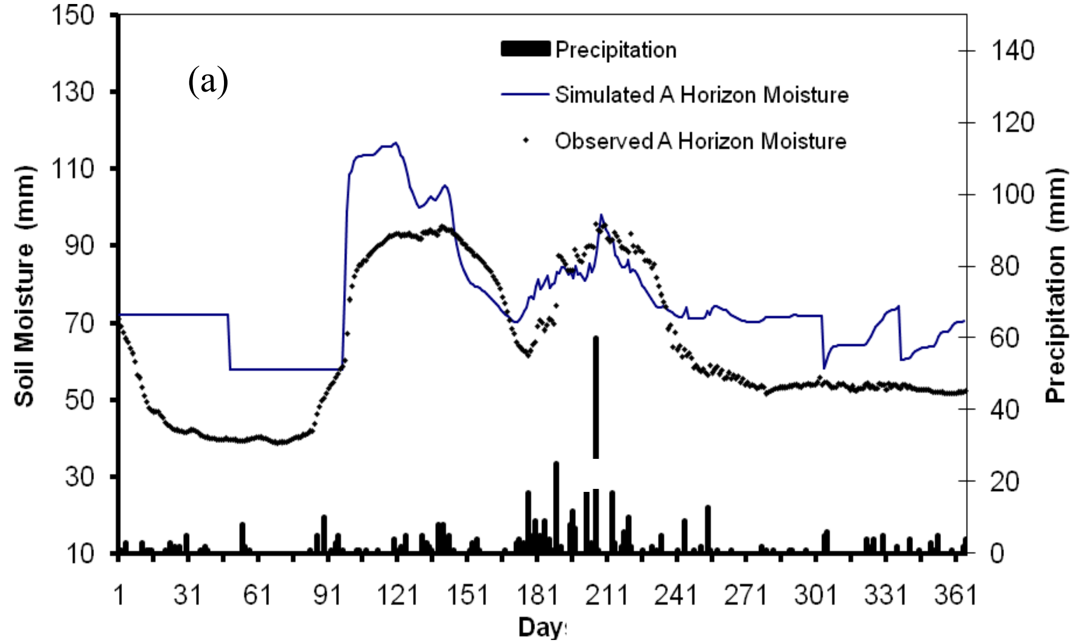
Observed overland flows were not available for the study area, and hence could not be presented here. However, according to personal information from the principal investigators of the OA site of the BERMS team, overland flow was insignificant in the study area.

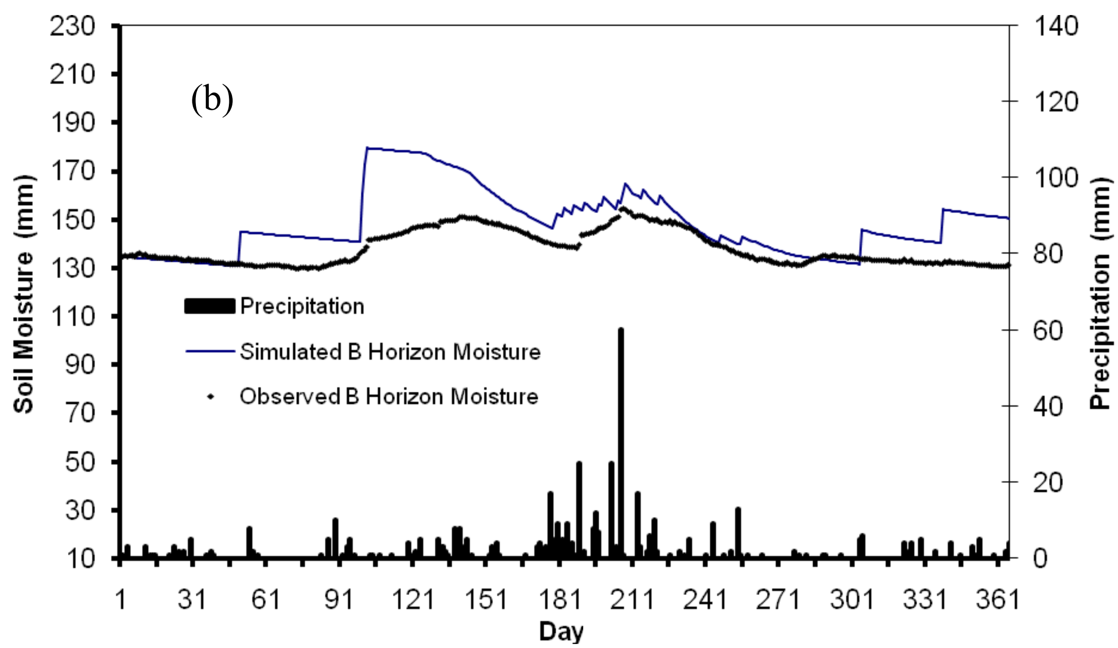
4.4.2 Validation of the SDWN model on the natural system

The SDWN model was validated using 1999 data of the OA site. The MARE and RMSE values of A-horizon layer moisture simulation of validation year (2005) are 13.9 % and 10.5 mm respectively. For the B-horizon layer, 5.7 % and 10 mm are the values of the MARE and RMSE, respectively. For the C-horizon layer, 8.5 % and 15.3 mm are the values of the MARE and RMSE, respectively. The observed and simulated daily values of the soil moisture content of A-horizon and B-horizon layers are presented in Figure 4.10 for the validation year.

Based on the error measures (Table 4.8), and the moisture profiles of the A-horizon and B-horizon layers (Figure 4.10a & b), it can be observed that during the validation year, the model simulated the soil moisture of the A-horizon and B-horizon layers quite well. The model was able to produce the trend of low and high values of soil moisture in A and B soil horizons during the growing season.

The sudden large rise in the profile of observed soil moisture (particularly during the late winter or early spring season) values should be taken cautiously due to measurement errors in the soil moisture observations. Similar to the case of the calibration year, the model could not exactly mimic the trends of the soil moisture dynamics of the C-horizon. However, unlike the case of the calibration year, the model showed variation in the soil moisture storage values having positive increases similar to the pattern of observed soil moisture of the C-horizon. This shows that the model is sensitive to the meteorological forcing in characterizing the soil moisture dynamics of the C-horizon of the natural system.





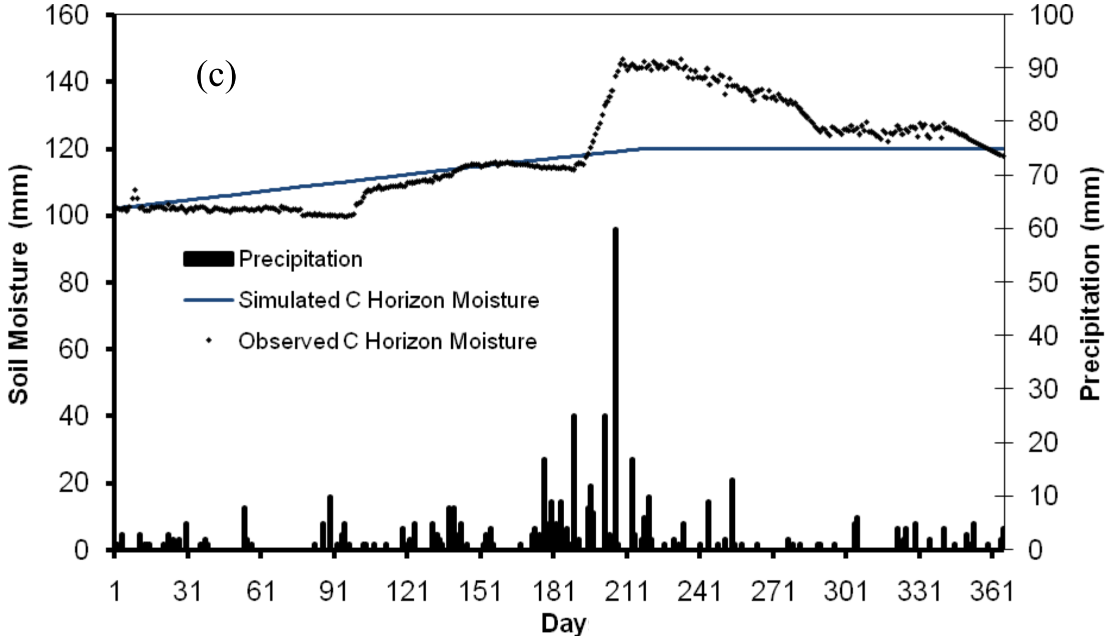


Figure 4.10. Simulated and observed soil moisture content of the natural system during validation (year 1999) (a) A-horizon; (b) B-horizon; (c) C-horizon.

Figure 4.11 shows the observed and simulated cumulative evapotranspiration fluxes of natural system for the validation year. The model slightly underestimated the cumulative evapotranspiration fluxes, with the available values of the measured AET of about 355 mm, where the simulated AET gross is 349 mm with a canopy interception of about 35 mm. The mature vegetation on the OA site, having a maximum leaf area index of 4.5 m^2/m^2 (which includes top and under canopy), was able to intercept a significant amount of rain.

During the growing season of year 1999, the SDWN model slightly overestimated the evapotranspiration most of the time. The observed data of the fluxes are quite reliable as the existence of missing data is rare during the growing season. Figure 4.12 shows the simulated overland flow for the validation year of the natural system.

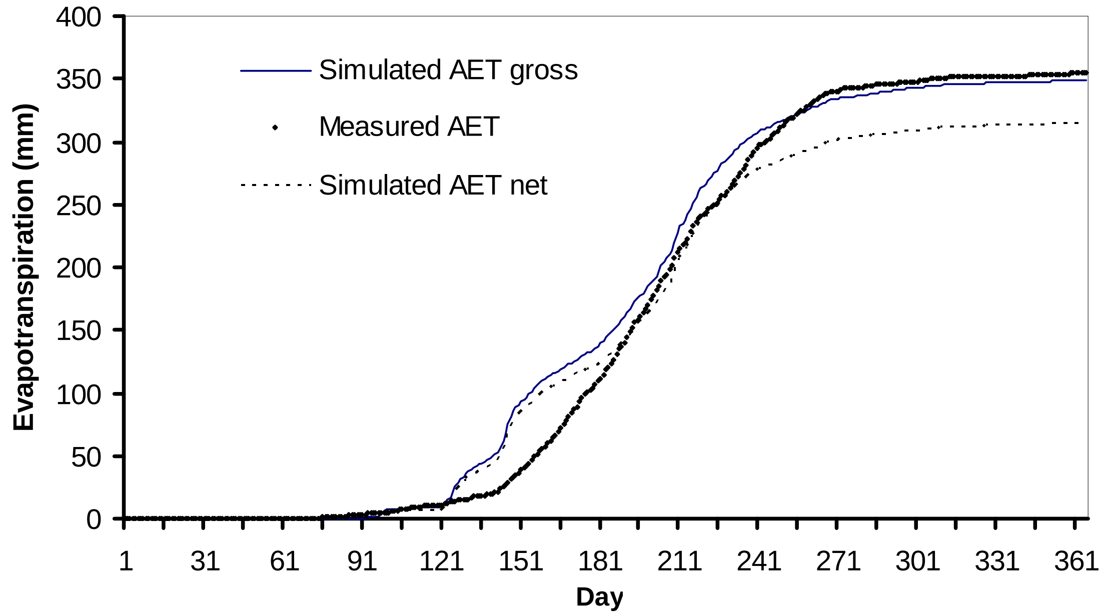


Figure 4.11. Observed and simulated cumulative evapotranspiration fluxes of natural watershed (OA site) for validation year (1999).

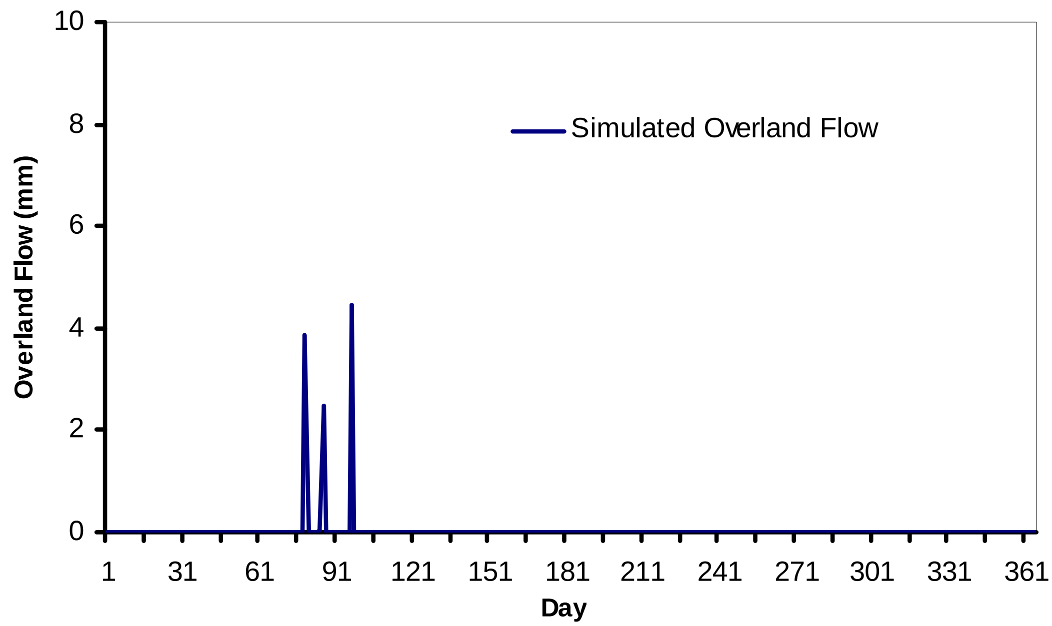


Figure 4.12. Simulated overland flow of the natural system for the validation year (1999).

A few instances of overland flow can be observed for the validation year during the spring time. With this, the watershed models that can simulate the hydrological processes of both the reconstructed and natural systems were ready for further hydrological analysis.

Table 4.9 presents the calibration parameters of the reconstructed and natural watershed models. The model parameters represent the individual watershed systems. Intuitively, the two different watershed systems have different set of model parameters, and exhibit their hydrological performance correspondingly.

Table 4.9. Comparison of model calibration parameters of the reconstructed and natural watersheds.

Calibration Parameter	Reconstructed System	Natural System
Secondary layer infiltration	0.05	0.015
Third layer infiltration	0.0001	0.75
Exponent on soil defrosting	5	6
Maximum T_I defrosting point	50	50
Canopy interception parameter	0.45	0.08
Surface layer evapotranspiration	1.5	1.35
Secondary layer evapotranspiration	0.6	1.3
Third layer evapotranspiration	0.2	-
Lambda	5.9	1.1
Melt factor	1.9	1.9

For example, canopy interception parameters are 0.08 and 0.45 for reconstructed and natural watersheds respectively due to their corresponding vegetations that contain little and mature vegetations correspondingly. Similarly, infiltration and evapotranspiration coefficients are different, which attributes to their individual soil and climatic characteristics. In order to generate modeling scenarios for comparative hydrological assessment, vegetation parameters, Leaf area index, ε_1, and λ were switched between the reconstructed and natural watershed models. Typically, ε_1 represents the vegetation interception ability, whereas λ represent the transpiration process of vegetation. In this study, it is assumed that switching these three parameters acts as switching the total vegetation on watershed in the modeling scenario.

4.5 Long term hydrological evaluation of the watershed systems

To evaluate the comparative hydrological sustainability of the reconstructed system relative to the natural system, long term simulations were carried out on both the systems using 48 years (1955-2002) of available meteorological data. Using the calibrated and validated models of the reconstructed (MSDW) and natural systems (SDWN), long term simulations were carried out on both watershed systems. Furthermore, additional long term scenarios were generated (explained below) to study both the hydrological performance and also the vegetation effect over the long term period. The long term meteorological data was obtained from Environment Canada for the location of Fort McMurray, Alberta.

In order to study the comparative hydrological response of the reconstructed watershed, the same long term data was used in each long term simulations including the generated scenarios. The descriptive statistics of all the long term simulations are presented in Appendix II. As explained in the methodology chapter, maximum annual moisture deficit (D_m) was derived in each case. Consequently, the frequency curves were generated for the annual maximum soil moisture deficit (D_m) and for the annual evapotranspiration fluxes obtained from the long term simulations.

4.5.1 Long term hydrological performance of the reconstructed and natural watersheds

Figure 4.13 shows a typical example of the best distribution fitting using @Risk software (Palisade Corporation, 2005). The dots represent the data to which the distribution was fitted, and the smooth line shows the best fitted theoretical distribution, which is selected based on Chi-squared best fit test. All other sets of data (D_m, and AET net) for both reconstructed and natural sites are treated similarly, and the fitted graphs are presented in Appendix III. Figure 4.14 presents the frequency curves of the annual maximum soil moisture deficit (D_m) of the reconstructed and natural watershed systems.

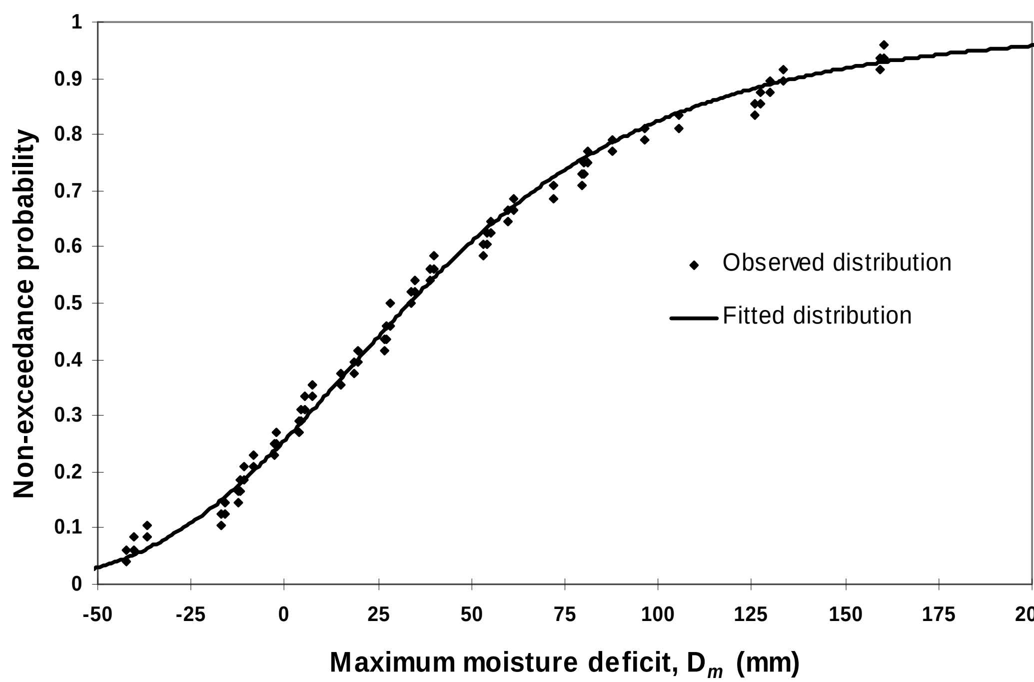


Figure 4.13. Best-fitted distribution of Dm values of the reconstructed system using @Risk software package.

The best fit distributions of the D_m values were found to be Log-Logistic distribution (γ, β, and α) for the reconstructed system, and normal distribution (μ, σ) for the natural watershed system. In the Log-Logistic distribution, the values of the distribution parameters, γ, β, and α represent the continuous location, scale, and shape parameters respectively (Palisade Corporation, 2005).

In the normal distribution, the values of the distribution parameters, μ, σ represent the continuous location and shape parameters, respectively. The values of the D_m distributions' parameters are presented below.

- Reconstructed system: Log-Logistic (-112.8, 146.0, 4.1)
- Natural system: Normal (80.3, 75.2)

The D_m frequency curves provide more information about the hydrological performance of a particular watershed system, in particular about the moisture store-and-release ability of the watershed system. Figure 4.13 shows the D_m frequency curves with the observed and fitted distributions for the reconstructed system (top of SBH site). Very few negative D_m values can be observed in Figure 4.13, indicating that only a few instances of surplus moisture occurred. The focus of this study is on the positive values of the D_m, which help to understand the store-and-release ability of the system. The D_m values may be taken as the probabilistic alternative index of available water holding capacity (AWHC). According to the land capability classification for forest ecosystem in the oil sands (Leskiw, 2004), the considered reconstructed watershed of the oil sands should be able to provide moisture of 160 mm for the vegetation and climatic requirements towards the ecological sustainability.

From Figure 4.13, it can be observed; that the reconstructed system considered in this study is capable of releasing moisture of 160 mm at a non-exceedance probability of

93 %, which also means that in a period of 100 years, the soil cover requires release of 160 mm of stored moisture of about seven times. This shows that when there is considerable amount of moisture requirement, the reconstructed watershed is able to respond positively to the meteorological forcings ensuring its hydrological sustainability. This serves as the primary objective of the design of the reconstructed watershed (store-and-release soil cover). In addition, there is always the question of uncertainty that exists at different levels right from data measuring to decision making throughout the modeling exercises. Hence, proper attention must be given to safety practices when dealing with design uncertainties and with decision making. However, focus of the study is not preoccupied with the effects of these uncertainties, as they are not part of the objectives of the current study.

The long term simulations on the reconstructed and natural systems were carried out using the same climatic conditions. A hydrological performance-based comparison can be made using the frequency curves between the reconstructed and natural systems. The frequency curves help to visualize how much moisture the reconstructed system is capable of releasing (in terms of D_m) for a particular non-exceedance probability when it is required to release a particular amount of moisture.

For instance, as indicated in Figure 4.14, for 90 % non-exceedance probability it was required to release an amount equal to or more than about 178 mm by the natural system, where the reconstructed system provides only of 135 mm moisture for the same climatic conditions. This shows the difference in terms of hydrological sustainability in between the reconstructed and natural systems. Counter-intuitively, the difference is little less than a general value of expectation, as the discussion here is between a very little reconstructed system and a mature natural forest. However, the location parameters of the theoretical and actual distributions show that there exist significant differences between the hydrological performance of the reconstructed and natural watersheds.

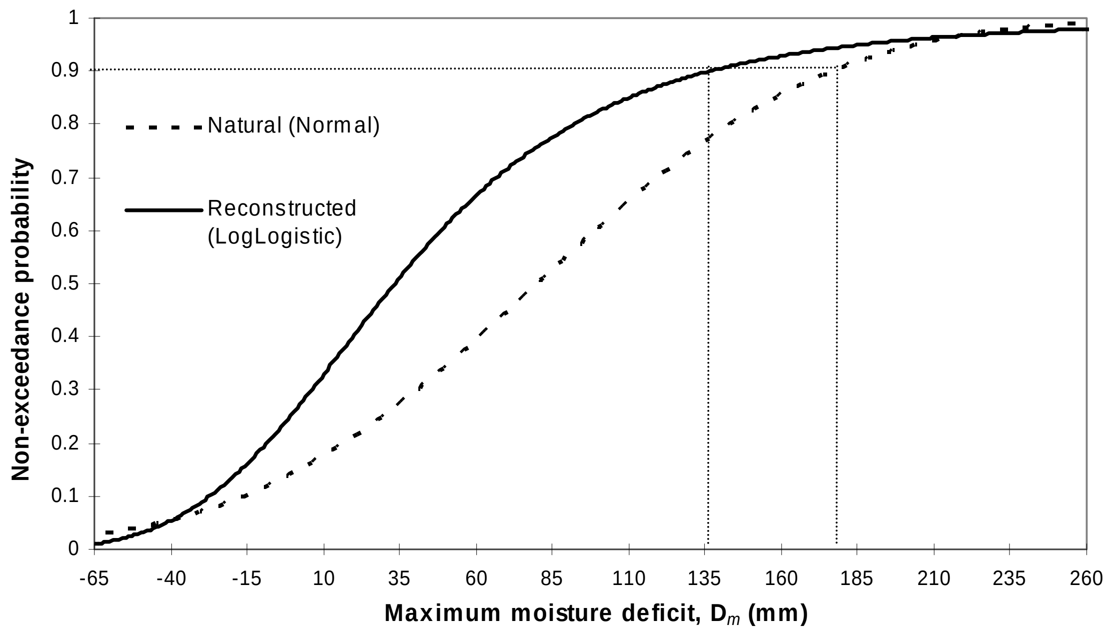


Figure 4.14. Stochastic comparison of the store-and-release ability (Dm index) of the reconstructed and natural watersheds.

Similarly, the distributions were also fitted to the annual growing season evapotranspiration (AET net) fluxes to visualize the soil-atmospheric moisture fluxes. The details of the distributions are presented below.

- Reconstructed system: Normal (314.5, 26.0)
- Natural system: Weibull (1.8, 99.5)

From Figure 4.15, it can be observed that the reconstructed system allows for a lower amount of evapotranspiration fluxes than the natural watershed system with the same meteorological conditions. The superior ability of the natural system to release moisture for meteorological forcing and its consistency in terms of D_m and evapotranspiration can be observed from the Figure 4.14 and Figure 4.15. This response might be due to the incomplete evolution of the reconstructed system relative to the natural one.

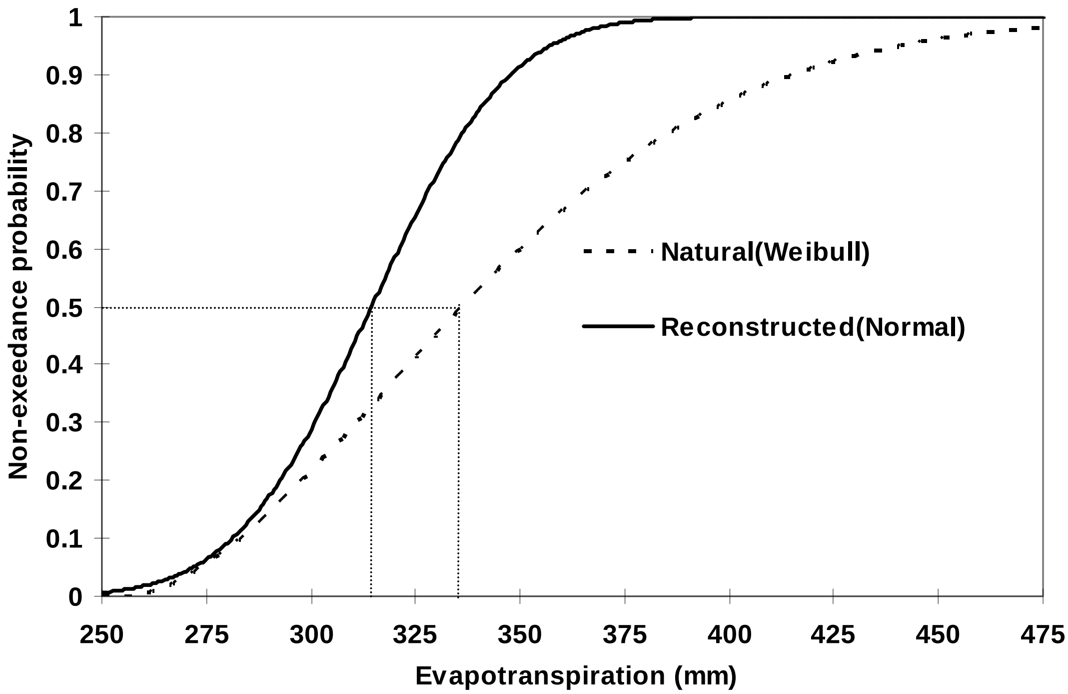


Figure 4.15. Frequency curves of growing season evapotranspiration (AET net) fluxes of the reconstructed and natural watersheds.

On average, (50 % non-exceedance probability), the natural watershed releases about 335 mm of moisture towards evapotranspiration requirements, whereas the reconstructed watershed releases about 315 mm moisture for the same meteorological factors. More importantly, under extreme conditions (e.g., 99 % non-exceedance probability), the natural system may allow for as much as about 460 mm of evapotranspiration when the reconstructed site may fail to exceed about 380 mm. The reason for this difference is that the reconstructed system (SBH site) is a young site (about 6 yrs old) with light vegetation (mostly grass), whereas the natural watershed is quite mature (about 88 yrs old) with mature vegetation (old aspen). The soil properties of the natural watershed are stable compared to the case of the reconstructed watershed. This helps store more moisture in the watershed system. The frequency curves of the AET net fluxes and the D_m values help to visualize such hydrological responses of the reconstructed and natural watersheds.

4.5.2 Scenario generation and watershed performance discussion

The primary objective of the restoration of the disturbed watersheds is to bring them back to the level (at least equivalent) of the natural watersheds in all aspects of hydrological sustainability. In order to compare the D_m and evapotranspiration fluxes, and thereby to assess the comparative hydrological performance on the same platform—and to evaluate the vegetation effect, two scenarios were generated, and, consequently, long term simulations were carried out on both systems. In the first scenario, the vegetation of the natural system was brought on to the reconstructed system by replacing the vegetation model parameters (ε_1 and λ) of the reconstructed system with the parameters of the natural system. Hereafter, this scenario is referred 'RS with NS vegetation'. In the second scenario, the vegetation of the reconstructed system was brought on to the natural system by replacing the canopy model parameters of the natural system with the vegetation parameters of the reconstructed system. Hereafter, this scenario is referred 'NS with RS vegetation'.

It should be noted that the above-mentioned parameters are the ones obtained during the calibration and validation of the respective systems, which represent the individual watershed systems. However, it should also be noted that the models used in this study did not have a vegetation growth simulation module (which could serve as a future scope of this study). Long term simulations were carried out for both scenarios using the same meteorological conditions used in the regular long term simulations discussed earlier. These long term scenarios and consequent D_m frequency curves would help address the following query: "How does the reconstructed watershed perform to support the mature vegetation, relative to the case of small vegetation, in terms of its long term hydrological response?"

To attempt answering the query, the D_m frequency curves of the reconstructed system with its own vegetation and the scenario of 'RS with NS vegetation' are used and the effect is described. When the mature vegetation exists on the reconstructed system, intuitively the vegetation demands more moisture to satisfy higher evapotranspiration requirements. Hence, the D_m frequency curve of the scenario (RS with NS vegetation) is expected to appear to the right side of the D_m frequency curve of the reconstructed system with its own vegetation, if the reconstructed watershed has more store-and-release capability. Figure 4.16 shows this explanation pictorially. For instance, at a 70 % non-exceedance probability, the reconstructed watershed has a D_m value of about 66 mm. Correspondingly at the same probability, the RS with NS Vegetation system showed a D_m value of about 78 mm, indicating that the system was able to respond positively accordingly to the requirement of meteorological forcings, but to a smaller extent. The slight difference in the hydrological responses of the two cases indicates that the reconstructed watershed is vegetation controlled. However, the evolution of the reconstructed watershed over the long period may help to have higher store-and-release ability for the climatic and vegetation moisture requirements.

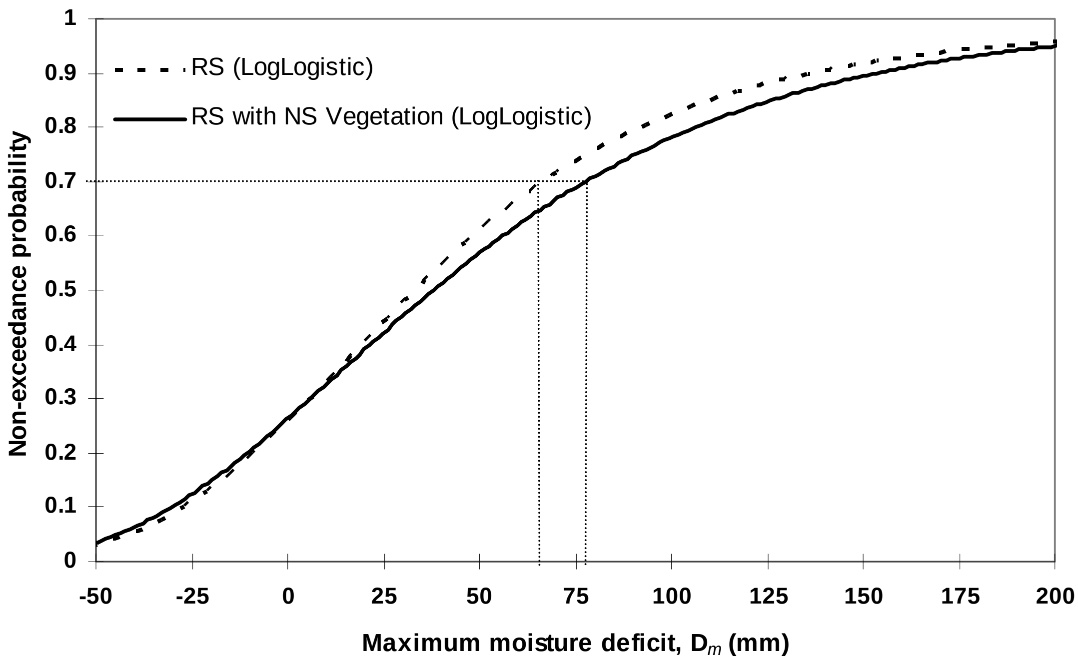


Figure 4.16. Stochastic comparison of the scenarios of reconstructed watershed to evaluate vegetation effect using the annual maximum moisture deficit frequency curves.

Another complementary query is, "how does the natural watershed perform when it has the same small vegetation as the reconstructed watershed does?" This query was addressed by using the scenario of reconstructed watershed with its own vegetation and the natural watershed with the vegetation of the reconstructed watershed (NS with RS vegetation). Figure 4.17 shows the D_m frequency curves of the long term simulations of both conditions. At a particular non-exceedance probability, the reconstructed watershed appears have less store-and-release ability than the natural watershed. For example, at 70 % non-exceedance probability, the reconstructed watershed has about 66 mm, where the natural one has D_m of about 105 mm. This result shows that the natural watershed is required to store-and-release only 105 mm about 30% of the time, whereas for the same climatic forcing, the reconstructed watershed is able to store-and-release only about 66 mm. This indicates that the reconstructed watershed needs to have more store-and-release ability in order to match the hydrological sustainability of the natural watershed.

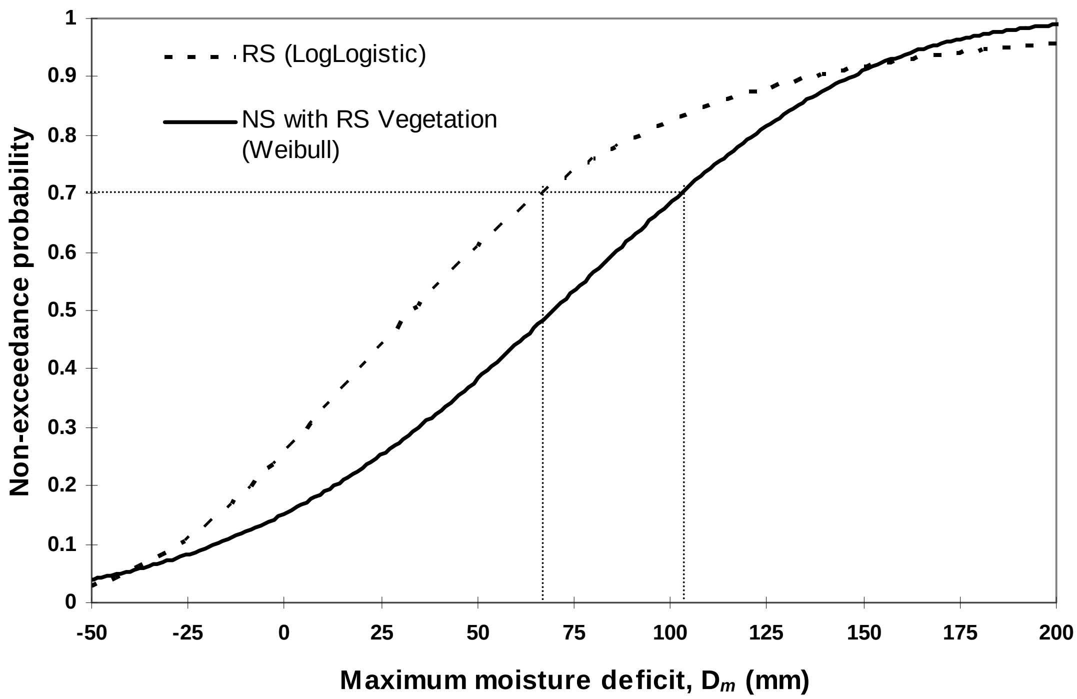


Figure 4.17. Stochastic comparison of the scenarios of reconstructed and natural watershed with the small vegetation using the annual maximum moisture deficit frequency curves.

The last query is, “What would be the long term hydrological performance of the reconstructed system relative to the natural one when both have mature vegetation?” This third query was addressed using the scenario of the reconstructed system with NS vegetation and the natural system with its own vegetation. This helps to understand the comparative hydrological response of the systems when both systems have mature vegetation. Figure 4.18 shows the D_m frequency curves of this scenario. The natural watershed provides more moisture than the reconstructed one for the same vegetation and climatic conditions.

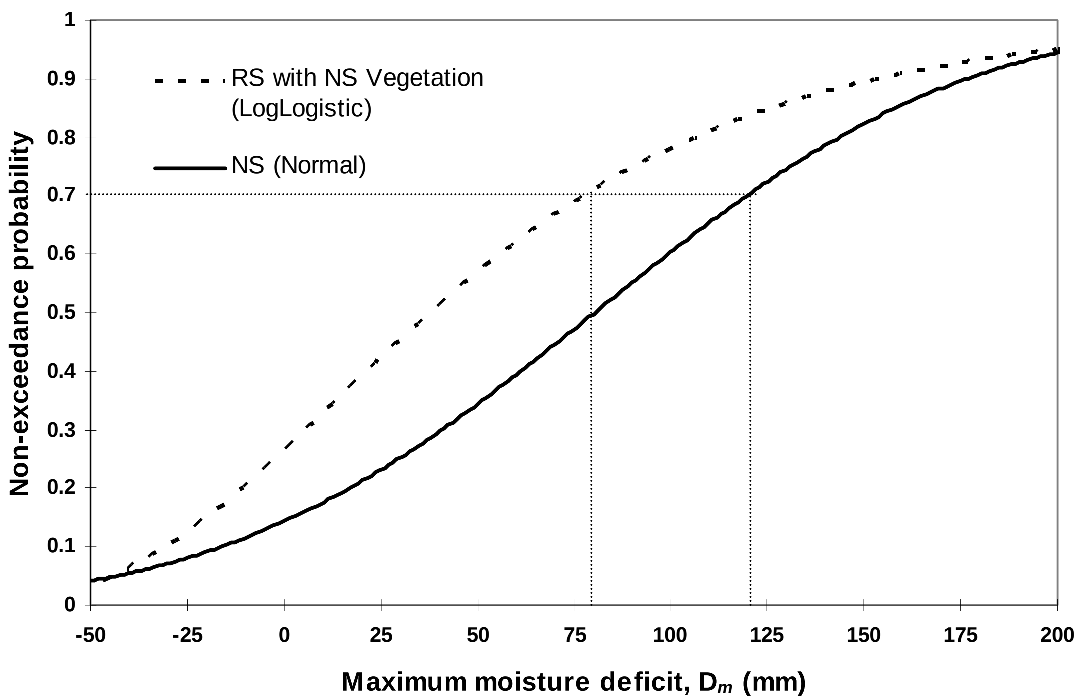


Figure 4.18. Stochastic comparison of the scenarios of reconstructed and natural watershed with the mature vegetation using the annual maximum moisture deficit frequency curves.

The hydrological responses, that is, the D_m values of the long term analysis of the reconstructed and natural watersheds, were statistically tested to learn the statistical inference in their means and variances. The statistical software, SPSS 15.0 (SPSS Inc., 2006), was used in this study to perform the statistical tests. First, a statistical test was carried out on the four sets of the simulated D_m values (RS, NS, RS with NS vegetation, and NS with RS vegetation) to learn the significant difference in their means and variances. The simulated D_m values have the following characteristics: 1) the four D_m

sets are the four watershed scenario simulations for the same climatic conditions; and 2) they may have different distributions rather than assuming unique normal distribution. Hence, to test the statistical significant differences among the four sets, a nonparametric test of multiple related samples, was performed. The SPSS 15.0 uses Friedman test (Wadsworth, 1990) for this analysis. The details of the test are presented in Appendix IV. This is similar to the ANOVA test in the case of parametric tests, rather on the side of nonparametric test.

When the test was conducted for a 95% confidence level, a Chi-square value of 19.3 having degrees of freedom 3 with a p-value of 0.00 was observed. This shows that there are significant differences in the means and variances of the four D_m values. In conclusion, by testing the simulated D_m values, it was observed that the hydrological responses (store-and-release ability) of the watershed systems for the same climatic conditions had statistically significant differences in their means and variances.

As the four scenarios did not have similar watershed conditions (e.g., soil and vegetation conditions), a second statistical test was carried out on the simulated D_m values, treating them as independent samples. The test was carried out using a non-parametric test of multiple independent samples; the specific test is the Kruskal-Wallis test (Hines et al., 2003). The details of the test are presented in Appendix IV. A Chi-square value of 8.6 with a p-value of 0.035 was observed indicating the significant difference in the means and variances of the four sets of the simulated D_m values, and thereby revealing the statistically significant differences in their respective store-and-release abilities.

Similarly, Friedman and Kruskal-Wallis tests were conducted on the theoretical D_m values (fitted distributions, Figure 4.19) of the watershed systems' hydrological responses. When the response of the watershed systems for the same climatic forcing was tested (Friedman test), statistically significant differences (Chi-Square value of 1497 and p-value of 0.00) were observed among the four theoretical D_m values. This indicates significant difference in the watershed responses for the same climatic conditions. In addition, in treating the four sets as independent values, the statistical test (Kruskal-Wallis test) ensured the statistical significant difference among the four D_m values, with a p-value of 0.00 and Chi-Square value of 65.89.

Another set of statistical tests were conducted to check the statistical significant differences among the hydrological responses of each of the two individual systems (e.g., in between RS and NS). These tests were carried out using a non-parametric test of two related samples; the specific test is the Wilcoxon signed ranks test (Hines et al., 2003). The details of the test are presented in Appendix IV. Application of the test of related samples helps to see the statistical inference of the watersheds hydrological response when the same conditions of vegetation and climate prevail.

When the D_m sets of RS and 'RS with NS vegetation' (Figure 4.16) were tested, a p-value of 1.00 with a z-value of 0.00 was noticed, indicating that at the 95%

confidence level there were no statistically significant differences in the D_m values. This could be due to the inability of the reconstructed watershed to supply more moisture for the mature vegetation. However, when the D_m sets of the RS and 'NS with RS vegetation' (Figure 4.17) were tested, a p-value of 0.00 was observed with a z-value of -19.35, indicating very significant differences at 95% confidence level. This shows that when the reconstructed and natural systems have the same small vegetation, there exists a statistically significant difference in their store-and-release abilities. Similar values of p-value and z-value statistics (as in the case of RS and NS with the RS vegetation, Figure 4.17) were observed in the statistical testing of the D_m values of the sets of NS - 'RS with NS vegetation' (Figure 4.18), and NS - RS (Figure 4.14).

In addition, another statistical test named the Kolmogorov-Smirnov (K-S) test (Hines et al., 2003) has been conducted on the simulated values of D_m of the various scenarios to learn the statistical significant differences among paired samples. The K-S test considers the pairs as independent samples and evaluates the statistical significant differences among them. The results of the K-S test showed significant differences among the hydrological performances of the reconstructed and natural system in the cases of supporting small vegetation, mature vegetation, and present systems. However, in the case of reconstructed system's ability to support mature vegetation (Figure 4.16), the K-S test showed that there were no statistically significant differences between the corresponding D_m values. These conclusions are the same as in the case of the other tests. The details of the K-S test results are presented in Appendix V. All these analyses help to provide the statistical inference in the comparative hydrological sustainability of the reconstructed and natural watersheds regarding the moisture store-and-release ability.

4.5.3 Overall summary of the results

The primary objective of the reconstructed watershed is to have high moisture store-and-release ability for the water requirements of vegetation and land-atmospheric fluxes similar to the case of the natural watershed. Therefore, in this study, an attempt was made to assess the hydrological performance of the reconstructed watershed relative to the natural watershed over the growing season with the help of hydrological modeling, long term simulations, probabilistic approach, and statistical tests. The feedback loop mechanism of the system dynamics watershed models was able to capture the moisture dynamics of the soil layers and the evapotranspiration fluxes of reconstructed and natural watersheds during the growing seasons of the calibration and validation years.

Where long term performance is concerned, the probabilistic curves that indicate the hydrological performance of the reconstructed and natural watersheds over the long term period are shown in Figure 4.19. As aforementioned, inclination of the frequency curves towards the right side indicates the higher moisture store-and-release ability of the watershed system. From Figure 4.19, it can be observed that the reconstructed watershed was able to provide moisture for the mature vegetation, but not as well as the natural system does.

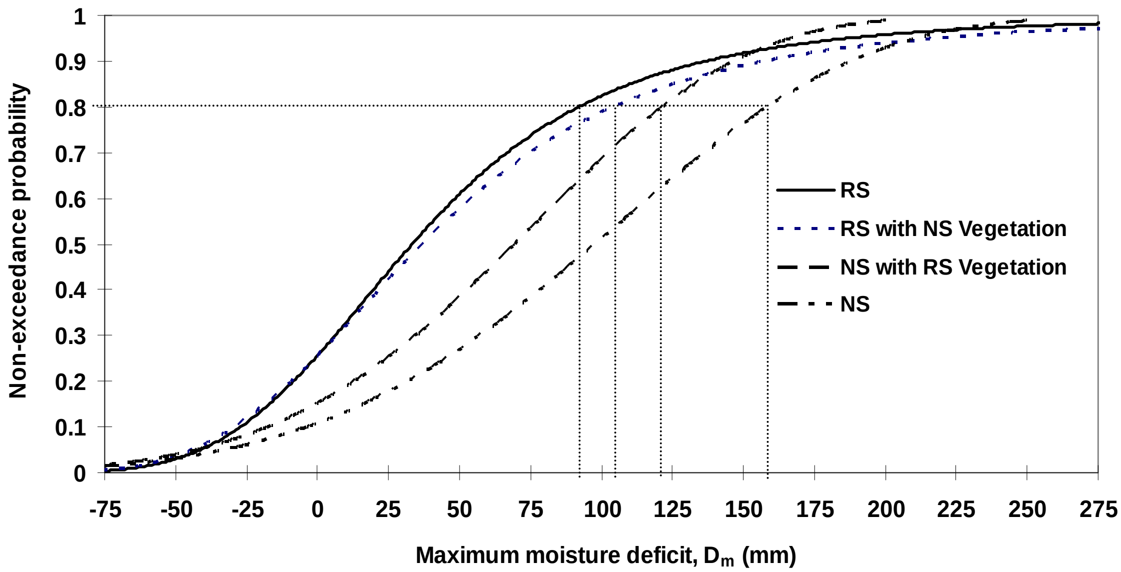


Figure 4.19. Stochastic comparison of the soil moisture store-and-release ability of the reconstructed and natural watersheds.

For the same meteorological conditions, the natural watershed system appeared to have a higher moisture store-and-release ability than the reconstructed system. The statistical tests carried out on values of the scenarios also support this comment. Intuitively, the mining altered the physical and structural properties of the soil of reconstructed watershed. Consequently, in the process of restoration of the watersheds, the rate of change in the soil properties became high particularly during the initial period after reclamation. Stabilization of the soil properties would help to create a better moisture store-and-release ability of the reconstructed watershed comparable to the ability of the natural watershed.

The modeling objective also includes of having minimum data and less number of calibration parameters in the hydrological characterization of the reconstructed and natural watersheds with the desired accuracy level. For instance, the accuracy of the simulation of rainfall interception was limited in this study due to use of daily rainfall data, whereas the duration and intensity of the rainfall highly influenced the rainfall interception. The averaged point measurements of meteorological and soil physical variables were used to characterize the spatial and temporal distributed variables. This might be also a restricting factor in the accuracy of the simulation of dynamics of the soil moisture and evapotranspiration processes of the reconstructed and natural watersheds. However, the reasonable accuracy in the hydrological modeling and the long term analysis help in developing the sustainable reclamation strategy, and also initiate the research in this direction.

CHAPTER 5. SUMMARY AND CONCLUSIONS

This chapter presents a summary of the models and a comparative study of the hydrological performances of the reconstructed and natural watersheds. The research contribution of the current study is elucidated, followed by possible research extension, and limitations of the study.

5.1 Summary of the thesis

The thesis work was focused on the assessment of the success of a reconstructed watershed regarding its hydrological sustainability relative to a natural watershed. A real life example of a reconstructed watershed (located in the Athabasca mining basin, Alberta, Canada) that was constructed after oil sands mining in an existing boreal forests was considered in this study. To mimic the soil horizons of the natural watersheds (within the root zone of vegetation) for effective hydrological and ecological sustainability, the reconstructed watershed is constructed with peat-mineral mix (20 cm thick) as a surface layer and with a glacial till layer (80 cm thick) as a secondary layer.

The specific objectives of the research work involve modeling the hydrological processes of both the reconstructed and natural watersheds and evaluating the comparative hydrological sustainability using long term simulations with the help of a probabilistic approach. An old aspen site from the boreal forests represents the natural watershed in this study. The A-horizon with sandy loam texture of 25 cm thick, B-horizon with sandy clay loam texture of 45 cm-thick, and C- horizon with a mixture of sandy clay loam and loam of 40 cm thicknesses were considered in this study. A system dynamics-based lumped watershed model (Elshorbagy et al., 2005) was modified and used for hydrological modeling in this study. The modified model was calibrated and validated on both flat reconstructed and natural watersheds.

5.1.1 Hydrological modeling of the reconstructed and natural watersheds

The hydrological characterization of the reconstructed and natural watersheds was carried out over the growing season (mid May- mid October) using the modified system dynamics watershed models MSDW and SDWN respectively. For the given meteorological, vegetation, and soil conditions, the model output variables include the different layers' soil moisture, evapotranspiration fluxes, and the overland flow of both the reconstructed and natural systems.

Small amounts of rainfall interception values of about 9 and 10.5 mm were predicted in the reconstructed watershed due to the little vegetation (little foxtail barley and aspen species) with LAI of about 0.67 and 0.83 m^2/m^2 during the calibration (2006) and validation (2005) years respectively. In the case of the natural watershed, the mature Aspen vegetation (LAI of about 4.5 m^2/m^2 in both years) intercepted significant amounts of rain with interception values of about 33 and 35 mm during the calibration (2000) and validation (1999) years respectively.

The simulated annual (growing season) evapotranspiration fluxes (including canopy evaporation), the AET gross values, were about 280 and 290.5 mm for the calibration and validation years respectively; these closely match the observed values on the reconstructed watershed. In the case of the natural watershed, 335 and 349 mm were the simulated evapotranspiration values; these also closely match the observed fluxes during the calibration and validation years. The higher values of evapotranspiration in the natural watershed case were, obviously, because the mature vegetation demanded more moisture for transpiration requirements. In both cases (reconstructed and natural watersheds), the dynamics of the soil moisture was reasonably well captured by the model during the growing season, despite the high complexity of the hydrologic systems' soil moisture process. Overall, with the capability of the feed-back mechanism, the system dynamics models were successfully able to characterize the vertical water balance of both the reconstructed and also the natural watersheds in the one-dimensional watershed modeling.

5.1.2 Comparative evaluation of the hydrological sustainability

With the calibrated MSDW and SDWN models, long term hydrological simulations (48 years) were carried out to investigate the hydrological sustainability of the reconstructed watersheds relative to the natural watersheds. Different modeling scenarios (reconstructed system with the vegetation of the natural system and vice versa) were generated and, consequently, long term simulations with all scenarios were carried out. Using the soil moisture and evapotranspiration fluxes of all these simulations, comparative analyses were carried out with the help of a probabilistic approach. From the study results, the following conclusions can be made regarding the hydrological sustainability of the reconstructed watershed:

- The current reconstructed watershed is able to provide its designed store-and-release moisture of 160 mm (a requirement of the land capability classification for forest ecosystems in the oil sands as suggested by Leskiw, 2004) for the vegetation and meteorological moisture demands;

- The study showed that the reconstructed watershed has less store-and-release ability, and allows less evapotranspiration fluxes than the natural watershed;
- The study indicated that the current reconstructed watershed could not provide the moisture demands of vegetation and soil-atmospheric fluxes at the same level as the natural watershed under the same meteorological conditions. This could be due to a lower available water holding capacity (AWHC) and to the light vegetation of the reconstructed system as a consequence, obviously, of its newness in the evolution process;
- In evaluating the reconstructed watershed response to support mature vegetation, the store-and-release performance is compared between the vegetation of reconstructed and natural systems (RS with NS vegetation) and the 'RS with its own vegetation'. The analysis shows that the reconstructed watershed is able to respond positively by providing more moisture for the mature vegetation. This could reflect the success of the design of the current reconstructed watershed;
- The scenario of RS with NS vegetation is also compared with NS having its own vegetation. This indicated the superior ability of the natural watershed compared to the reconstructed watershed by providing more moisture for the same climatic conditions; and
- In another attempt of evaluating the hydrological sustainability of the reconstructed watershed, the performance of the RS with its own vegetation and NS with RS vegetation is compared. The natural system responds with higher

moisture than the reconstructed one. This indicated that for the same small vegetation and climatic conditions, the natural watershed performs better than the reconstructed watershed.

In conclusion, the watershed models characterized the hydrological processes of both reconstructed and natural watersheds reasonably well. The long term simulations showed that the store-and-release ability of the reconstructed watershed was satisfactory and it was capable of responding to higher moisture demands with mature vegetation. This is because it had a surface layer (peat-mineral mix) with high saturated hydraulic conductivity that allowed more infiltration and less runoff of a typical precipitation event. In addition, the secondary layer (glacial till) acted as a moisture storage reservoir by minimizing the downward and transverse flows. However, the natural watershed responded even better to the same climatic conditions in providing the moisture requirements for the vegetation and soil-land-atmospheric moisture demands. The reconstructed watershed model may need to be recalibrated in a few years; the analysis could then be repeated to test whether the watershed was evolving closer to the natural system or not.

5.2 Research contribution

In the present study, an attempt was been made to evaluate the hydrological performance of a reconstructed watershed relative to the natural watershed. This study included the modifications and adaptation (calibration and validation) of an existing system dynamics model (Elshorbagy et al., 2005) on a relatively flat reconstructed watershed and on a natural (boreal forest) watershed.

Although a new modeling technique of watershed modeling is not claimed in this study, the adopted models helps in the hydrological characterization of reconstructed and natural watersheds, which have flat topography. In particular, these models assist in the understanding of the soil moisture dynamics and evapotranspiration fluxes of the watersheds on a daily scale. In addition, the models include a user-friendly mechanism for an easy-provision of soil layer properties. This type of feature is useful for optimization issues, such as the objective function of minimizing the soil cover construction cost and maximizing the soil cover moisture store-and-release ability.

As mentioned above, the primary objective of the restoration of the disturbed watersheds is to bring them back to the level of the natural watersheds (which existed prior to the mining disturbance) in all aspects of effective hydrological sustainability. The long term simulations and frequency curves in the current study help to understand the store-and-release capability in order to meet the moisture requirements of reconstructed watersheds relative to the natural watersheds. In the literature, no contribution was found regarding the comparative evaluation of hydrological performance of the reconstructed watersheds relative to the natural ones. Hence, the current research study initiates the research in this direction, which works to develop a sustainable reclamation strategy.

5.3 Possible research extension

As mentioned in the Chapter 1, the current research work is part of a research program (Figure 1.1) that aims at developing a framework to understand the hydrological processes of reclaimed watersheds, and to assist in developing a sustainable reclamation strategy to restore the functions of natural watersheds. The following are possible future extensions of the research work:

- A vegetation growth model would help to make comparisons between it and the natural watersheds. In this way, vegetation issues such as root water uptake and transpiration can be quantified separately;
- A generic SDW model could also help test various reclamation strategies and minimize the site-specific adaption efforts;
- In addition to lumped hydrological characterization, evaluating comparative hydrological sustainability can also be done using the distributed watershed modeling for a better understanding of the moisture and energy fluxes in the transverse directions;
- An integrated or hybrid modeling approach that assimilates the modeling potentiality of mechanistic and data-driven simulation tools would also help in understanding the dynamic nature of the evolving reconstructed watersheds;
- Automatic calibration of the models assists in the estimation of model parameters. Quantification of uncertainty at different sources, from data observation to decision making through to the modeling exercise, would be helpful for management and decision making purposes; and
- Consideration of different vegetation species on the watershed system could also be done to assess the moisture store-and-release ability of the reconstructed watershed to support different vegetation species and their moisture requirements.

5.4 Study limitations

The assumptions and limitations of the current study are as follows.

- Depth-averaged point observations (e.g., soil moisture) assumed to represent the entire watershed area;
- The observations of the soil moisture during the winter season were not reliable due to insensitiveness of TDR sensors during the frozen conditions of the soil;
- A fairly similar natural site was considered in this study for comparing hydrological sustainability, as it was difficult to find a natural study site with exactly same vegetation, soil, and topographic properties and with available observed variables as the reconstructed watershed, and;
- Moisture fluxes in the transverse directions were not considered as the study was carried out using lumped watershed modeling approach.

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APPENDIX I

SD formulation of the reclaimed watershed

(i) Surface water storage

$$\frac{dS_{SW}}{dt} = P_S - f_P - O_F \tag{I.1}$$

Where S_{SW} is the surface water storage (mm), P_S represents the precipitation reaching the surface after the interception loss (mm/day), which can be in the form of either snow or rainfall, f_P is the infiltration rate to the peat layer (mm/day) and is described in detail in the following sections, and O_F corresponds to overland flow (mm/day).

(ii) Peat storage

$$\frac{dS_P}{dt} = f_P - f_T - ET_P \tag{I.2}$$

where S_P is the peat storage (mm), f_T is the infiltration rate of the till layer (mm/day), and ET_P is the evapotranspiration rate from the peat layer (mm/day). Peat infiltration, f_P is explained as follows. Before soil saturation occurs, the infiltration rate of the peat layer is equal to the rainfall intensity. If the layer becomes saturated or the rainfall intensity exceeds the saturated hydraulic conductivity of the peat, then the infiltration is governed by the Green–Ampt equation. In addition, when the three layers (peat, till and shale) are saturated, the peat infiltration rate equals the outflow of the system (considering the three layers as a control volume), i.e., shale saturated hydraulic conductivity rate. When the peat and till layers are saturated, the peat infiltration rate equals the saturated hydraulic conductivity of the till layer. In all the cases, infiltration excess water always gets accumulated in the surface water storage, and consequently contributes to the overland flow. The infiltration capacity (rate) based on total infiltration volume takes the below form:

$$f_P = K_{sP}\left(1 - \frac{M_P \psi_P}{F_P}\right) \tag{I.3}$$

$$M_P = \theta_{sP} - \theta_{iP} \tag{I.4}$$

where K_{sP} is the saturated hydraulic conductivity of the peat layer (mm/day), M_P is the initial moisture deficit (mm), θ_{sP} is the saturated moisture content of the peat layer (%), θ_{iP} is the initial moisture content of the peat layer (%), ψ_P is the suction pressure head at the wetting front in the peat layer (mm), and F_P is the cumulative volume of the infiltration in the peat layer (mm). The snowmelt infiltration is calculated using the set of formulae (Eq. 3.9) proposed by Li and Simonovic (2002).

$$\begin{aligned}
C_{tP} &= \begin{cases} (T_I / T_{Imax})^{c_i} & \text{if } T_I < T_{Imax} \\ 1 & \text{if } T_I \geq T_{Imax} \end{cases} \\
T_I &= \begin{cases} \sum(T_a) & \text{if } T_a > 0 \text{ and } N < N_n \\ 0 & \text{if } N \geq N_n \end{cases} \\
N &= \begin{cases} \sum(N_o) & \text{if } T_a \leq 0 \\ 0 & \text{if } T_a > 0 \end{cases} \\
N_o &= \begin{cases} 1 & \text{if } T_a \leq 0 \\ 0 & \text{if } T_a > 0 \end{cases}
\end{aligned} \tag{I.5}$$

The actual evapotranspiration from the peat layer is estimated using empirical formulations (Li and Simonovic, 2002) that take into account the available soil moisture and air temperature. These formulations can be expressed as:

$$AET_P = c_P S_{mP}^{\lambda} T_a C_{tP} \tag{I.6}$$

$$S_{mP} = \frac{\dfrac{S_P}{S_{nP}} - S_{rP}}{1 - S_{rP}} \tag{I.7}$$

where AET_P is the actual evapotranspiration rate (mm/day) from the peat layer, c_P is the evaporation constant (mm/^{o}C/day) from the peat layer and is determined during calibration, S_{mP} is the effective moisture saturation in the peat layer (dimensionless), λ is exponential coefficient estimated while calibrating, S_{nP} is the maximum water storage (mm) in the peat layer, and S_{rP} is the minimum storage (wilting point moisture content).

(iii) Till Layer Storage

$$\frac{dS_T}{dt} = f_T - f_S - ET_T \tag{I.8}$$

where S_T is till layer storage, f_S is the shale percolation rate (mm/day), f_T is the till infiltration rate (mm/day), and ET_T is the evapotranspiration rate from the till layer (mm/day),

$$f_T = K_{sT}\left(1 - \frac{M_T \psi_T}{F_T}\right) \tag{I.9}$$

$$M_T = \theta_{sT} - \theta_{iT} \tag{I.10}$$

where, K_{ST} is the saturated hydraulic conductivity of till layer (mm/day), M_T is the initial moisture deficit (mm), θ_{sT} is the saturated moisture content of the till layer (%), and θ_{iT} is the initial moisture content of the till layer (%), ψ_T is the pressure head in the till layer (mm) and F_T is the cumulative volume of the infiltration in the till layer. The model formulation of the calculation of till infiltration is as follows. d_P is the drainable water from peat layer and can be defined as the excess moisture stored in the peat layer over the its field capacity.

if (soil temperature of till greater than 0 °C)
    then (if ($\Psi_P > \Psi_T$)
            then (no movement of water)
            else (if ($\theta_P >$ *wilting point moisture content in peat layer*)
                then (if (*peat layer is saturated*)
                    then if (*shale layer is saturated*) then Min[d_P or (follow Eq. I.16)]
                        else Min[d_P or (follow Eq. I.9)]
                    else Min [d_P or (follow Eq. I.11)]
                else (no movement of water))
else (follow the same concept used for frozen peat layer))

where Equation I.11 is an empirical equation which can be written as:

$$f_T = \frac{\theta_P}{\theta_T} \frac{S_P}{\Delta t} I_{cT} \tag{I.11}$$

where d_P is the drainable water from peat layer and can be defined as the excess moisture stored in the peat layer over the its field capacity I_{cT} is the coefficient of till infiltration (unitless), which is determined during calibration of the model, and Δt is the solution time interval. Under frozen conditions, the same concept followed in the peat layer (Eq. I.5) is replicated for the till layer to estimate $C_{tT},$ the till infiltration coefficient. The only difference is that the air temperature in Equation I.5 is replaced by the temperature of the peat layer. Actual evapotranspiration from the till layer is treated in the same way as that in the peat layer and is computed using the following equations:

$$AET_T = c_T S_{mT}^{\lambda} T_{sP} C_{tT} \quad \text{(I.12)}$$

$$S_{mT} = \frac{\frac{S_T}{S_{nT}} - S_{rT}}{1 - S_{rT}} \quad \text{(I.13)}$$

where AET_T is the actual evapotranspiration rate (mm/day) from till layer, c_T is the evapotranspiration constant (mm/°C/day) from the till layer estimated while calibrating the model, S_{mT} is the effective moisture saturation in the till layer (dimensionless), λ is an exponent determined while calibrating the model, S_{nT} is the maximum water storage (mm) in the till layer, S_{rT} is the minimum storage (wilting point moisture content) that can be attained, and T_{sP} is the temperature of the peat layer (^{0}C). The evapotranspiration from the till layer (ET_T) is computed only when the soil temperature of the peat and till layers is greater than zero. The potential evapotranspiration is calculated using Penman equation (Penman, 1956) stated below (After Dingman, 2002).

$$\left.\begin{aligned} PET &= \frac{R_n 86720}{2.5E^6 - 2370T_a}\left(\frac{\Delta}{\gamma+\Delta}\right) + \frac{0.102u}{77.52}\left(e_s - e_s R_H\right)\left(\frac{\gamma}{\gamma+\Delta}\right) \\ \Delta &= \frac{2503878e^{\frac{17.27T_a}{237+T_a}}}{(237+T_a)^2} \end{aligned}\right\} \quad \text{(I.14)}$$

where R_n is the net radiation from the soil surface, Δ is the slope of the psychrometric saturation line (mm/^{0}C), u is the wind speed (m/s) at 2 m height, e_s is the saturated vapour pressure (mm) and R_H is the relative humidity (%). γ is the psychometric constant (mm/^{0}C), $\frac{PC_p}{\lambda_{le}\varepsilon}$, P is the atmospheric pressure, C_p is the specific heat of air, ε is the ratio of molecular weight of water to molecular weight of dry air, and λ_{le} is the latent heat flux density. The total actual evapotranspiration (AET) is the sum of evaporation from the canopy and evapotranspiration (ETnet) from the land surface. The evapotranspiration of soil (PETsoil) is distributed in between peat and till layers, similar to Elshorbagy et al. (2005). The PETsoil is calculated by subtracting the canopy evaporation from the PET calculated using Penman's formula, Eq. I.14.

(iv) Shale Layer Storage

$$\frac{dS_S}{dt} = f_S - P_r \tag{I.15}$$

Where, S_S is the shale storage (mm), P_r is the deep percolation from the shale layer, and is calculated as when the shale temperature is positive Water will percolate from the till layer to the shale layer following the Green–Ampt equation in the case of a fully saturated soil.

$$f_S = K_{sS}\left(1 - \frac{M_S \psi_S}{F_S}\right) \tag{I.16}$$

$$M_S = \theta_{sS} - \theta_{iS} \tag{I.17}$$

where f_S is the infiltration rate (capacity) of shale layer in mm/day, K_{sS} is the saturated hydraulic conductivity of the shale layer (mm/day), M_S is the initial moisture deficit in the shale layer(%), θ_{sS} is the saturated moisture content(%) of the shale layer and θ_{iS} is the initial moisture content(%) of the shale layer, Ψs is the suction head of the shale layer (mm) and F_S is the cumulative volume of the percolation in the shale layer. Shale infiltration is represented as follows.

if ($\Psi_T > \Psi_S$)
    then (no movement of water)
else (if ($\theta_T > \theta_{rT}$ *wilting point moisture content in the till layer*)
        then (if (*till layer is saturated*)

then Min[d_T or (follow Eq. I.16)]

else Min[d_T or (follow Eq. I.18)]

else (no movement of water))

Equation I.18 is similar to equation I.11 and takes the following form:

$$f_S = \frac{\theta_T}{\theta_S}\frac{S_T}{\Delta t} I_{cS} \qquad \text{(I.18)}$$

where d_T is the drainable water from till layer and can be defined as the excess moisture stored in the till layer over the its field capacity, I_{cS} is the coefficient of till infiltration and is determined during calibration of the model, and θ_S is the moisture content of the shale layer.

(v) Overland Flow

Overland flow is estimated in the same way as in the SDW model (Elshorbagy et al., 2005). Since the model structure uses reservoir-based mechanisms to simulate the different hydrological processes, water in excess of the infiltration capacity of the peat layer is directed as overland flow (O_F) in the unfrozen season. During soil frozen conditions, part of the available water (AW) from both rainfall and snowmelt infiltrates into the frozen soil (Eq. I.5), while the remaining portion contributes to overland flow. In the summer, the overland flow occurs only when the peat layer becomes saturated and is computed as follows:

$$O_F = \frac{S_{SW}}{\Delta t} - f_P \qquad \text{(I.19)}$$

where O_F is in mm/day.

APPENDIX II

The following table presents the descriptive statistics of the D_m values of the long term simulations including the generated scenarios of the reconstructed and natural watersheds.

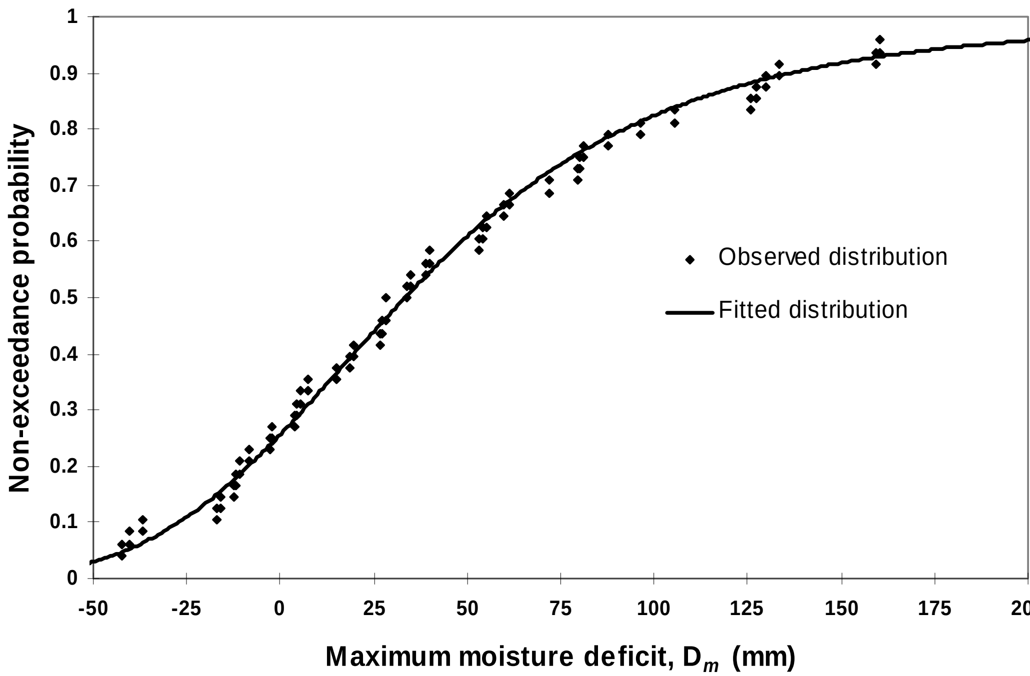
Statistic	RS	RSn	NSr	NS
Max (mm)	188.75	225.15	258.04	293.57
Min (mm)	-61.56	-64.64	-86.12	-87.44
Average (mm)	45.93	52.59	66.55	80.29
SD (mm)	68.21	77.08	64.59	75.19
Skew	0.98	1.02	-0.21	-0.10

Where RS is reconstructed system; RSn is reconstructed sysem with the canopy of the natural system; NSr is natural system with the canopy of the reconstructed system; NS is the natural system; Max is the maximum values; Min is the minimum values; and SD is the standard deviation.

APPENDIX III

The best fitted distributions (based on Chi-squared best fit test) using @Risk software package for the different scenarios are presented in here. The distribution details of the scenarios are presented below.

1) D_m frequency curve of reconstructed system with its own canopy (D_m – RS with RS Canopy):

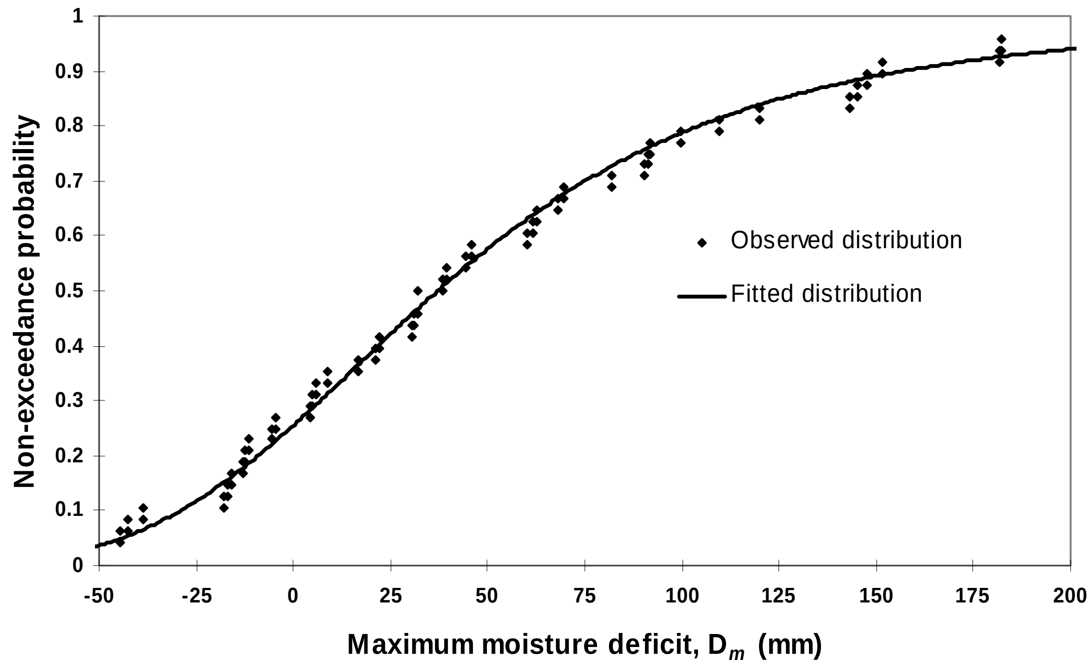


Distribution: Log-Logistic

Parameters: γ, β, and α are -112.7, 146, and 4.1 respectively.

Chi-Square test value: 2.33

2) D_m frequency curve of reconstructed system with the canopy of the natural system (D_m – RS with NS Canopy):

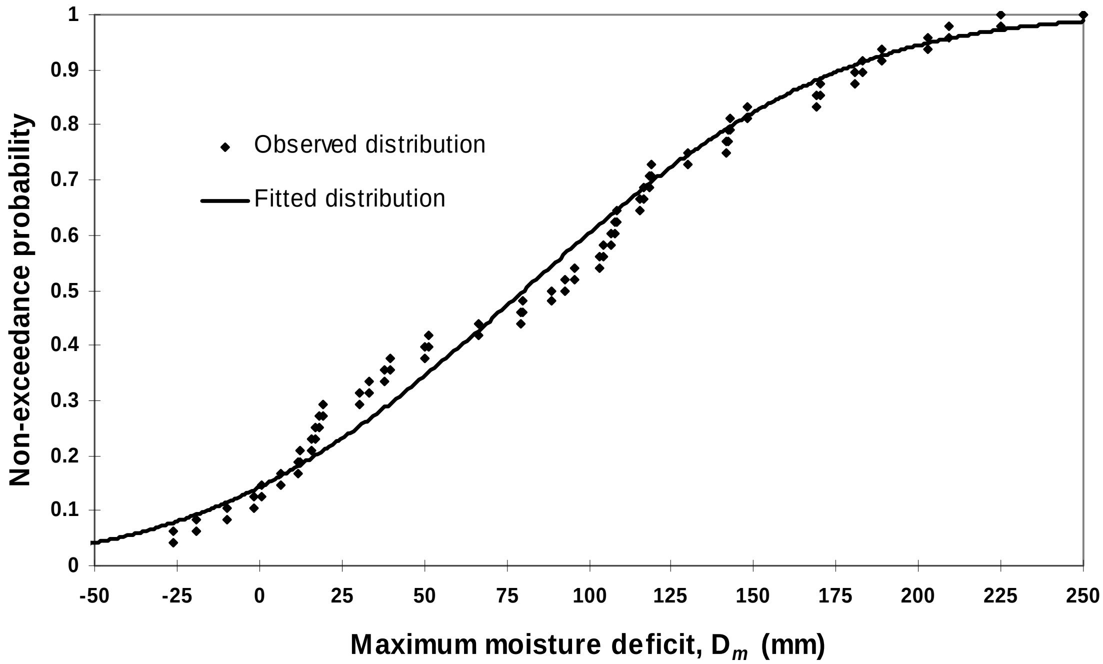


Distribution: Log-Logistic

Parameters: γ, β, and α are -110.9, 148, and 3.7 respectively.

Chi-Square test value: 2.33

3) D_m frequency curve of the natural system with its own canopy (D_m – NS with NS Canopy):

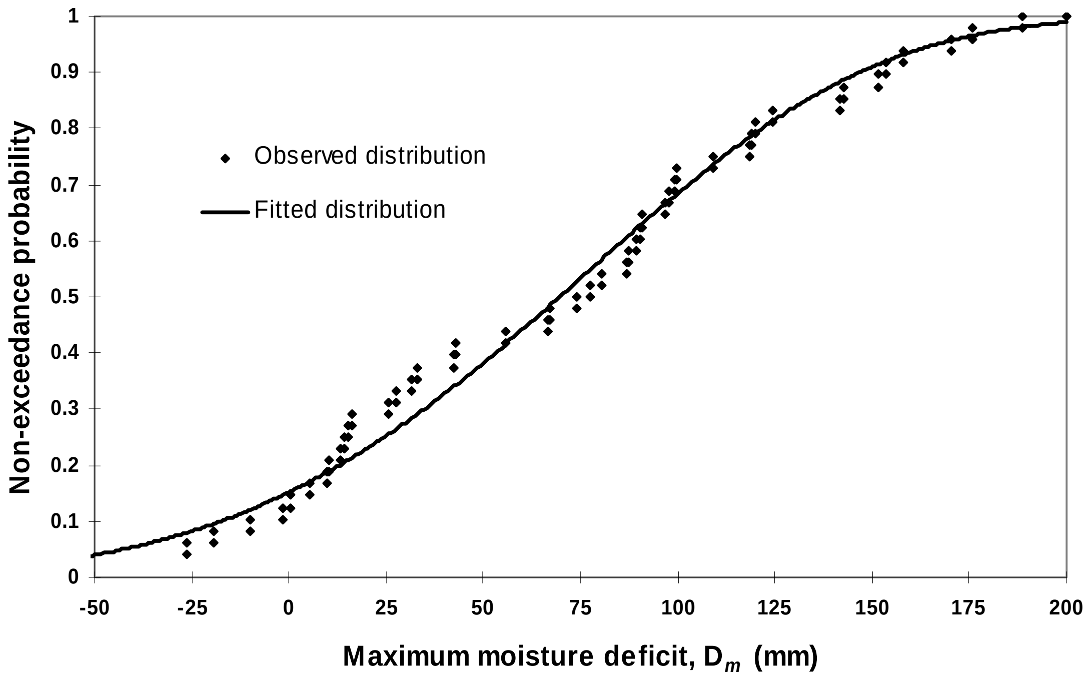


Distribution: Normal

Parameters: μ and σ are 80.3 and 75.2 respectively.

Chi-Square test value: 5.33

4) D_m frequency curve of the natural system with the canopy of the reconstructed system (D_m – NS with RS Canopy)

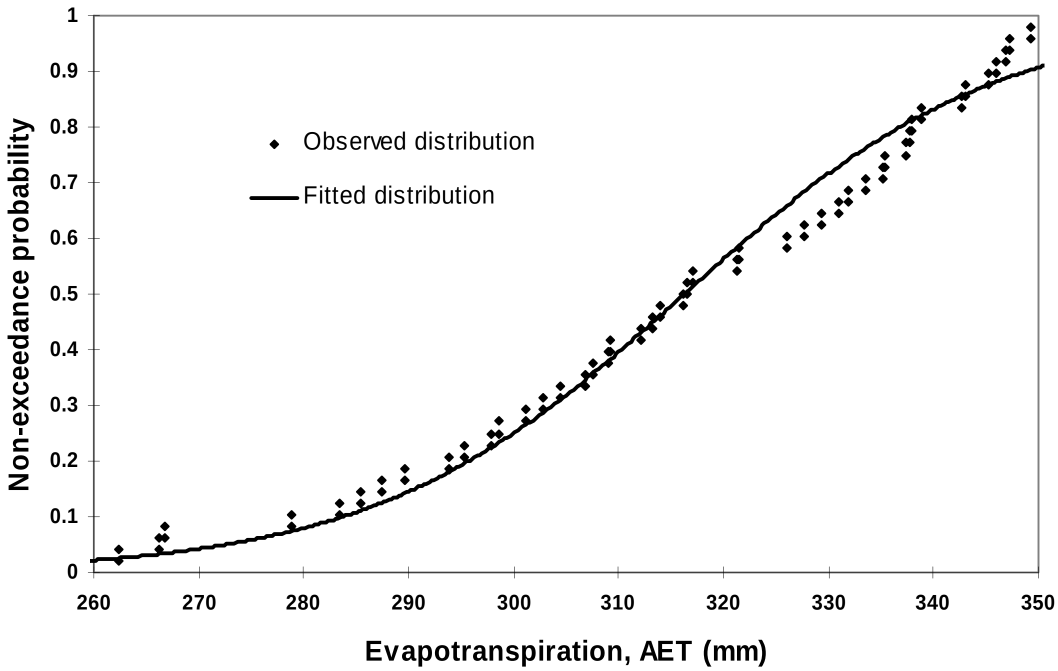


Distribution: Weibull

Parameters: α and β are 4.65 and 283.7 respectively with a shift of -192.6.

Chi-Square test value: 4.66

5) AET frequency curve of the reconstructed system with its own canopy (AET – RS with RS Canopy)

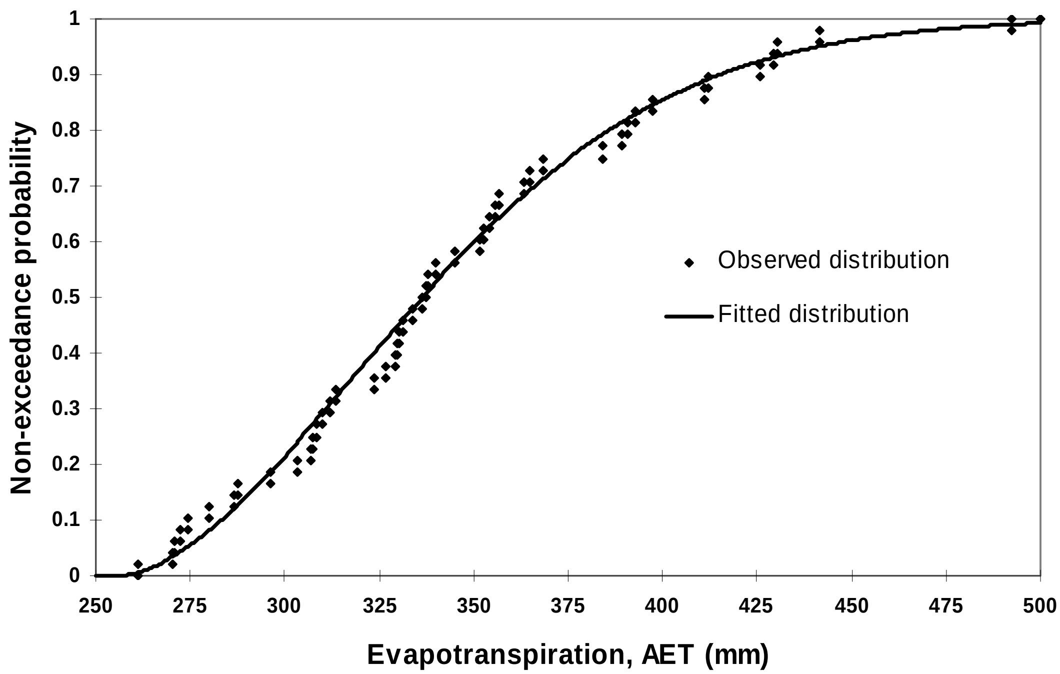


Distribution: Normal

Parameters: μ and σ are 314.4 and 26 respectively

Chi-Square test value: 2.34

6) AET frequency curve of the natural system with its own canopy (AET – NS with NS Canopy)



Distribution: Weibull

Parameters: α and β are 1.76 and 99.5 respectively with a shift of -255.5.

Chi-Square test value: 2.66

APPENDIX IV

The descriptions of the non-parametric statistical tests conducted in this study are presented in this section. The advantages of using the non-parametric tests include: 1) the assumptions regarding populations are less restrictive (e.g., no assumption of normality in the data), and so are applicable to wider range of conditions 2) the computations used are easier to carry out and understand 3) the tests are more useful for the conditions of small sample of data to obtain statistical conclusions. The tests used in this study are described below.

1) Wilcoxon signed ranks test:

It is a non-parametric test alternative to the paired Student's t-test for the case of two related samples, and hence the test can be used for learning the statistical differences of two sets of paired samples with no assumption of normality in the data. The test procedure is as follows.

Null hypothesis: $H_0: \mu_0 = \mu_1$ (IV.1)

Alternative hypothesis: $H_1: \mu_0 \neq \mu_1$ (IV.2)

The Wilcoxon signed rank statistic W is computed by ordering the absolute values of Z_i (where Z_i is the set of differences between the paired samples), the rank of each ordered $|Z_i|$ is given a rank of R_i. Denote $\psi_i = I(Z_i > 0)$, where $I(.)$ is an indicator function. The Wilcoxon signed rank statistic z is defined as: $z = \sum_{i=1}^{n} \psi_i R_i$.

The z statistic is used to compare with the tabled values for a desired level of significance value (e.g., 0.05) to determine whether the null hypothesis be accepted or rejected.

2) Kruskal-Wallis test:

This non-parametric test can be used to test the statistical difference among three or more independent groups. The steps of the methodology in this test are as follows.

a. Rank all data from all groups together; i.e., rank the data from 1 to N ignoring group membership. Assign any tied values the average of the ranks they would have received had they not been tied.

b. The tests statistic is given by:

$$K = (N-1)\frac{\sum_{i=1}^{g} n_i(\bar{r}_{i.} - \bar{r})^2}{\sum_{i=1}^{g}\sum_{i=1}^{n_i} n_i(\bar{r}_{i.} - \bar{r})^2} \quad \text{(IV.3)}$$

where:

- n_i is the number of observations in group i
- r_{ij} is the rank (among all observations) of observation *j* from group *i*
- N is the total number of observations across all groups
- $\bar{r}_{i.} = \frac{\sum_{j=1}^{n_i} r_{ij}}{n_i}$
- $\bar{r} = (N+1)/2$ is the average of all the r_{ij}.

  Notice that the denominator of the expression for K is exactly $((N-1)N(N+1))/12$, thus $K = \frac{12}{N(N+1)}\sum_{i=1}^{g} n_i(\bar{r}_{i.} - \bar{r})^2$.

c. A correction for ties can be made by dividing K by $1 - \frac{\sum_{i=1}^{G}\left(t_i^{3} - t_i\right)}{N^3 - N}$, where G is the number of groupings of different tied ranks, and t_i is the number of tied values within group *i* that are tied at a particular value. This correction usually makes little difference in the value of K unless there are a large number of ties.

d. Finally, the p-value is approximated by $\Pr\left(\chi_{g-1}^{2} \geq K\right)$. If some n_i's are small (i.e., less than 5) the probability distribution of K can be quite different from this chi-square distribution. If a table of the chi-square probability is available, the critical value of chi-square, $\chi^2_{\alpha:g-1}$, can be found by entering the table at g-1 degrees of freedom and looking under the desired significance or alpha level. The null hypothesis of equal population would then be rejected if $K \geq \chi^2_{\alpha:g-1}$.

3) Friedman test:

This non-parametric test can be used to test the statistical difference among three or more related groups. The steps of the methodology of performing this test are as follows.

a) Given data $\{x_{ij}\}_{n \times k}$, that is, a tableau with n rows, k columns and a single observation at the intersection of each row and column, calculate the ranks within each block. If there are tied values, assign to each tied value the average of the ranks that would have been assigned without ties. Replace the data with a new tableau $\{r_{ij}\}_{n \times k}$ where the entry r_{ij} is the rank of x_{ij} within block *j*.

b) Find the values:

$$\bar{r}.j = \frac{1}{n}\sum_{i=1}^{n} r_{ij}$$

$$\bar{r} = \frac{1}{nk}\sum_{i=1}^{n}\sum_{j=1}^{k} r_{ij}$$

$$SS_t = n\sum_{j=1}^{k}\left(\bar{r}._j - \bar{r}\right)^2$$

$$SS_e = \frac{1}{n(k-1)}\sum_{i=1}^{n}\sum_{j=1}^{k}\left(\bar{r}._j - \bar{r}\right)^2$$

c) The test statistic is given by $Q = \frac{SS_t}{SS_e}$. Note that the value of Q as computed above does not need to be adjusted for tied values in the data.

d) Finally when *n* or *k* is large (i.e. *n*>15 or *k*>4), the probability distribution of Q can be approximated by that of a chi-square distribution. In this case the p-value is given by $\Pr\left(\chi^2_{g-1} \geq Q\right)$. If n or k is small, the approximation to chi-square becomes poor and the p-value should be obtained from table of Q specially prepared for the Friedman test.

APPENDIX V

The Kolmogorov-Smirnov test (K-S test) helps to determine if two datasets differ significantly. The K-S test has the advantage of making no assumption about the distribution of the given data. The below listed Four pairs of data sets were tested using the K-S test.

1. RS and NS with RS vegetation (Evaluates watersheds ability in supporting small vegetation) - The Z statistic of the K-S test in this case is 1.225 with a p-value of .049;
2. RS and RS with NS vegetation (Evaluates watersheds ability in supporting mature vegetation) - The Z statistic of the K-S test in this case is 1.327 with a p-value of .003;
3. RS and NS (individual cases) - The Z statistic of the K-S test in this case is 1.531 with a p-value of .009; and,
4. RS with NS vegetation and NS (Evaluates reconstructed watershed ability to support mature vegetation relatively to the small vegetation) - The Z statistic of the K-S test in this case is with a p-value of .049.